SYNERGY INSTITUTE OF ENGINEERING & TECHNOLOGY

Department of Electrical Engineering

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MODULE – 1

Basic ideas of Relay Protection

A good electric power system should ensure the availability of electrical power without any interruption to every load connected to it. Generally power is transmitted through high voltage transmission line and lines are exposed, there may be chances of their breakdown due to storms, falling of external objects, and damage to the insulators etc. These can result not only mechanical damage but also in an electrical fault.

Protective relays and relaying systems detect abnormal conditions like faults in electrical circuits and automatically operate the switchgear to isolate faulty equipment from the system as quick as possible.

This limits the damage at the fault location and prevents the effects of the fault spreading into the system. The switch gear must be capable of interrupting both normal currents as well as fault current. The protective relay on the other hand must be able to recognize an abnormal condition in the power system and take suitable steps so that there will be least possible disturbance to normal operation.

Relay does not prevent the appearance of faults. It can take action only after the fault has occurred. However, there are some devices which can anticipate and prevent major faults. For example, Buchholz relay is capable of detecting the gas accumulation produced by an incipient fault in a transformer.

Nature and causes of faults

The nature of fault simply implies any abnormal condition which causes a reduction in the basic insulation strength between phase conductors, between phase conductor and earth or any earth screen surrounding the conductors.

The reduction of the insulation is not considered as a fault until it produces some effect on the system i.e. until it results either in an excess current or in the reduction of the impedance between the conductors, between the conductor and earth to a value below the lowest load impedance normal to the circuit.

Power systems mainly consist of generator, switch gear, transformer and distribution system. The probability of failure is more on the power system due to their greater length and exposure to atmosphere.

(a) Breakdown at normal voltage may occur on account of:

  i) The deterioration of insulation

  (ii) Damage due to unpredictable causes such as perching of birds, accidental short-circuiting by snakes, tree branches, etc.

(b) Breakdown may occur because of abnormal voltages: This may happen because of (i) switching surges (ii) surges caused by lightning

The present practice is to provide a high insulation level of the order 3 to 5 times the normal voltage, but still:

(i) The pollution on an insulator string caused by deposited soot or cement dust in industrial area.

(ii) Salt deposited wind borne see spray in coastal area.

These will initially lower the insulation resistances and causes a small leakage current to be diverted, thus hastening the deterioration.

Secondly, even if the insulation is enclosed, such as sheathed and armoured, the deterioration of the insulation occurs because of:

(a) Ageing

(b) Void formation in the insulation compound of underground cable due to unequal expansion and contractions caused by the rise and fall of temperature.

Thirdly, insulation may be subjected to transient over voltages because of switching operation.

- The voltage which rises at a rapid rate may achieve a peak value which approaches three times phase to neutral voltages.
- Lightning produces very high voltage surges in the power system in the order of million volts. These surges travel with the velocity of light in the power circuit. The limiting factors are the surge impedance and the line resistance.

Consequences of Faults

Serious results of the uncleared fault, is fire which may not only destroy the equipment of its origin but also may spread in the system and cause total failure.

Consequences;

1. A great reduction of the line voltages.

2. Damage caused to the element of the system by the electrical arc.

3. Damage to other parts due to overheating.

4. Disturbanceto the stability of the electrical system and this may even lead to a complete shutdown of the power system.

5. Reduction in the voltage may fail the pressure coil of the relay.

6. Considerable reduction in the voltage on healthy feeder connected to the system having fault. This may cause either an abnormally high current being drawn by the motor or the operation of no volt coils of the motors. (Considerable loss of industrial production as the motors will have to be restarted).

Fault Statistics

Equipments	% of total faults
O H line	50
Cables	10
Switchgear	15
Transformer	12
CTs & PTs	2
Control Equipment	3
Miscellaneous	8

L-L-L fault are called symmetrical 3-φ fault generally due to carelessness operating personnel. Usually the three phase lines are tied up together a bare conductor in order to protect the lineman working on the line against inadvertent-charging of the line. After work is over, if the linesman forgets to remove the tie-up and CB is closed, a symmetrical fault occurs.

Line to ground fault occurs most commonly in overhead line. A large no of these faults are transitory in nature and may vanish within a few cycles (if twig falls across a line and cross arm and burns itself out or just falls down).

Essential Qualities of Protection

Every protective system which isolates a faulty element must satisfy four basic requirements:1. Reliability 2. Selectivity 3. Fastness of operation 4. Discrimination

Reliability

Reliability is a qualitative term. It can be expressed as a probability of failure.

- Quality of personnel i.e. mistakes by personnel are most likely causes of failure.
- high contact pressure
- dust free enclosures

Records show that the order of likelihood of failure is relays, breakers, wiring, current transformers, voltage transformers and battery.

When relays using transistors are considered, the failure rate goes up still further.

Selectivity : The property by which only the faulty element of the system is isolated and the remaining healthy sections are left intact.

Selectivity is absolute if the protection responds only to faults within its own zone and relative if it is obtained by grading the setting of protections of several zones which may

respond to a given fault. The systems of protection which in principle are absolutely selective are known as **unit system**. The systems which selectivity is relative are **non unit system**.

Fastness of Operation

Protective relays are required to be quick acting due to the following reasons:

(a) Critical clearing time should not be exceeded.

(b) Electrical apparatus may be damaged, if they are made to carry fault currents for a long time.

(c) A persistent fault will lower the voltage resulting in crawling and overloading of industrial drives.

The figure below shows the typical values of power, which can be transmitted as a function of time. On the other hand, relays should not be extremely fast; otherwise the relay will operate for transient conditions.

Discrimination

- Protection must be sufficiently sensitive to operate reliably under minimum fault condition for a fault within its own zone while remaining stable under maximum load i.e. a relay should be able to distinguish between a fault and an overload.
- In the case of transformers, the inrush of magnetising current may be comparable to the full current, being 5 to 7 times the full load current. The relay should not operate for inrush current.
- In interconnected systems, there will be power swing, which should also be ignored by the relay.

The word discrimination is sometimes used to include selectivity.

Primaries and Backup Protection

The relay operates usually from current and voltage derived from current and potential transformers. A station battery usually provides the circuit breaker trip current. Successful clearing depends on the condition of the battery, continuity of the wiring and trip coil and the proper mechanical and electrical operation of the circuit breaker, as well as the closing of the relay trip contact.

If there is failure of these elements, so that the fault in a given zone is not cleared by the main or primary protection scheme, some of the backup protection is generally provided.

The backup protection is normally different from main protection and preferably of non-unit type.

Ex: overcurrent or distance protection

Selectivity is absolute if the protection responds only to faults within its own zone and relative if it is obtained by grading the settings of protection of several zones which may respond to a given fault.

Systems of protection which in principle are absolutely selective are known as unit system.

Ex: Differential protection, frame leakage protection

The systems in which selectivity is relative are non-unit systems. Ex: current time graded protection, distance protection.

Basic Principle of Operation of Protective relay

Each relay in a protection scheme performs a certain function and responds in a given manner to a certain type of change in the circuit quantities.

Example:

- One type of relay may operate when the current increases above a certain magnitude known as   over current relay
- While another may compare current & voltage and operate when the ratio V/I is less than a given value. It is known as under-impedance relay

Similarly various combinations of these electrical quantities could be worked out according to the requirementsat a particular situation.

Economic Considerations

The cost of protection is linked with cost of the plant to be protected and increases with cost of the plant. Usually, the protective gear should not cost more than 5% of the total cost. However, when the apparatus to be protected is of paramount importance like the generator or the main transmission line, the economic consideration are subordinated.

Average Costs in units per circuit ;

	Indoor 33 kV	132 kV	275 kV	400 kV
Total Avg. ckt cost	10	50.0	100	230
Relay	0.7	2.5	2.4	4.6
Relay Panel	0.4	0.6	1.5	2.3
Wiring	0.9	2.0	0.8	0.9
Relay Room	0.32	0.5	0.5	1.0
CTs	0.4	4.7	12.0	25.7
PTs	1.0	3.4	7.0	9.0

References

1. B Ravindranath& M Chander, "Power system Protection and switchgear"New age International Publishers
2. Y.G Paithankar & S.R Bhide, "Fundamentals of powersystem Protection"PHI Publication

CHAPTER- 2

Basic Principles and Components of Protection

There must be able to discriminate the appropriate disconnecting device. The method of discriminating the faults are two types.

(a) Those which discriminate as to the location of fault.
(b) Type of fault

Methods discriminate the type of faults are:

The main aim is that the fault section of the system be isolated and in the minimum time.

a) Discrimination by time
b) Discrimination by current magnitude
c) Discrimination by time and direction
d) Discrimination by distance measurement
e) Time as an addition to current magnitude or distance discrimination
f) current balance discrimination
g) Power direction comparison discrimination
h) Phase comparison discrimination

(a) Discrimination by time:

By adding time lag features to the controlling relay a number of CBs it is possible to trip the CB nearest to fault in prior to those which are farther from the part of fault.
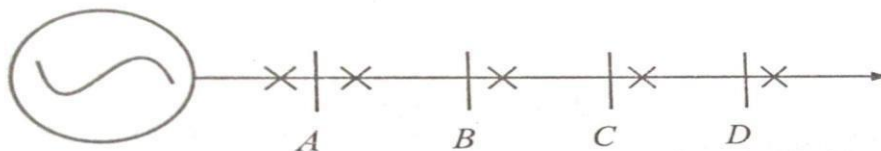
Figure 2.1: Radial feeder

Let in a radial feeder as shown, the circuit breakers at ABCD are identical and are set operate for a given value of current. For a fault at any section CD, if the fault current exceeds the set value the breakers at A,B and C will trip and whole feeder beyond A becomes dead.

For providing time lag to the circuit breakers at ABCD the tripping is delayed in the following manner.

D- no added time lag
C- .4 sec added time lag
B- .8 sec added time lag
A- 1.2 sec added time lag

Now if the fault occurs in the section CD the breaker at C will trip after a time of .4s and will clear the fault as a result feeder up to c will remain aline.
A .4s step time is necessary to account for the operation CB and its relay operation time.

(b) Discrimination by current magnitude (Also known as current graded scheme)

7

This depends on the current magnitude. As the fault current will also very with location of fault.If the relays are set to pick up at a progressively higher current towards the source then a simple feeder system of above fig. can be protected.

(c) Discrimination by time and direction:
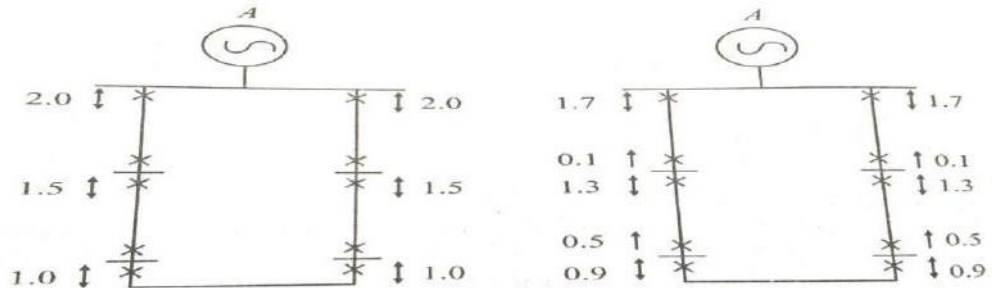
Non-directional relays : with same current setting but different time lag. Here proper discrimination cannot be obtained.

Directional relays: with same current setting and different time lag. Fault occurring on any section will be discriminating cleared without loss of supply.

(d) Discrimination by distance measurement:
Measurement of distance achived in various way known as distance relay

(e) Time as an addition to current magnitude or distance discrimination:
1. time + current grading gives the most practical protection schemes
2. time + distance discrimination forms another practical protection scheme

(f) Current balance discrimination:
Another form of discrimination which is limited in its scope to one system element which will cause isolation of this element only in the event of fault in this element and will not respond to any other fault external to this element, even through fault current passes through it.

Such a protection is known as unit protection.

This form of protection is based on one of the following 2 principles.
1. Circulating current principle
2. Opposed voltage principle or balanced voltage principle.
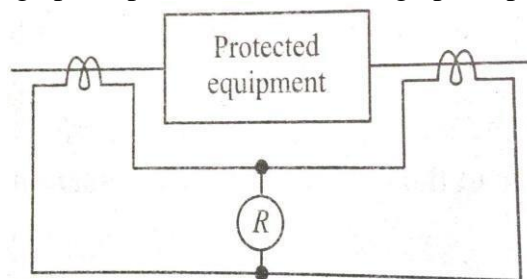
Circulating current principle

For an external fault the balanced current flow and there will be no current in the relay. So the apparatus will not be isolated.
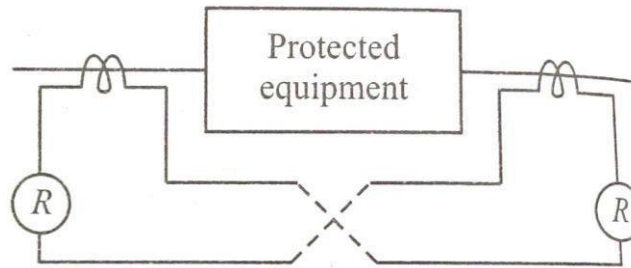
Balanced voltage protection

The relay time polarity of CTs at the two ends is such that there is no pilot current for the condition of load or external fault. For internal fault, the CTs voltage will no longer be balanced and current will be flow in the relay will trip.

(g) Power direction comparison discrimination:
                    i) Power flow out at both end
                    ii) Power flow in at both end.
                    iii)No power flow either in or out at the other end.

Methods of discrimination to type of fault:

When fault currents may not be very high or may differ little in magnitude from loud currents as result the current magnitude detection fails to point out such a fault. Such a fault current has some peculiarity which distinguish itself from the normal load currents.
Ex- in a 3-ph system the currents and voltages can be resolved in to their phase sequence components which would ultimately give some idea about the nature of the current or voltages presents.

(a)Zero phase sequence networks:
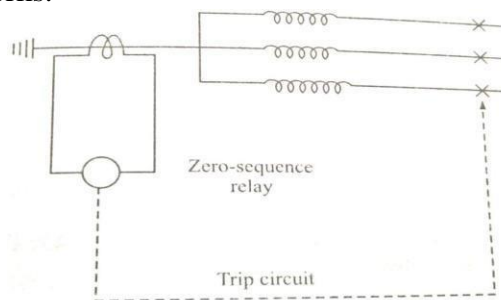
Zero phase sequence networks

 Relay will be energized only by zero sequence current. This relay will ignore load currents or phase to phase short circuits.

(b) Negative-phase sequence networks:
Negative phase sequence current represents some form of unbalanced condition such as
    • Phase to phase faults other than symmetrical three phase faults.
    • Broken conductors
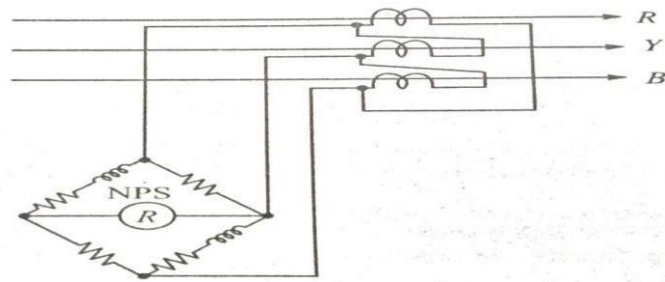
Negative-phase sequence networks

Derivation of a single phase quantity from a three phase quantities:

Auxiliary or pilot wires are used to transmit information from one end of the line to the other end of the line. For normal 3ph system three pilot would ordinarily be required which would obviously be a very costly affair for longer system, particularly in transmission circuit.

It would naturally be preferable to have a mean of deriving a single phase quantities which under both normal and abnormal conditions will be representative of the three phase conditions.

Sometimes, it becomes necessary to the sequence current or voltages from correspond line currents or voltages in order to simplify the protection scheme by reducing the no of relay required.

There are two commonly used methods for deriving single phase quantities from a three phase system.

a. summation transformers
b. sequence transformers

(a) Summation transformers:
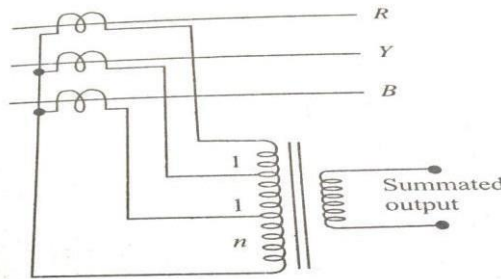
Summation transformers

Each CT energized a different number of turns as the primary with a resulting single phase output from the secondary. The output is seen to be proportional to the vector sum.

$$(n+2)I_R + (n+1)I_Y + n\, I_B$$

It is also possible to control independently the outputs for earth fault and phase faults. The output on the earth faults is usually considerably more than that on phase faults is usually considerably more than that on phase faults so as to provide more sensitive action on earth faults.

Pick up setting can be expressed in term of combination of n and 1 for the various faults.

Zero output or a negligible small output may occur under through fault condition when there is a phase to phase fault on the star side of the delta/star transformer giving 1:2:1 current distribution on the protected feeder

(b) Sequence network:

In some cases it is desirable to make the protection respond to a particular phase sequence component of the three phase system of currents and voltages.
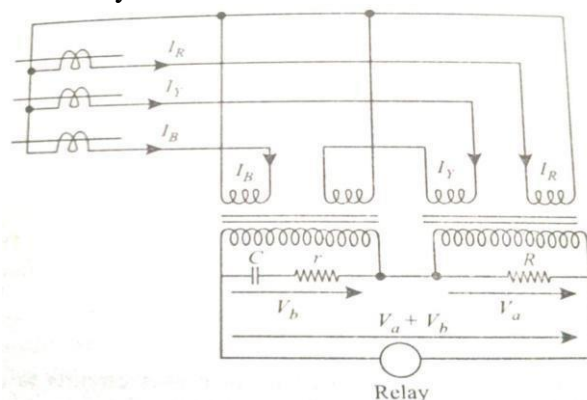
Zero sequence and negative phase sequence networks are frequently used in power system protection.
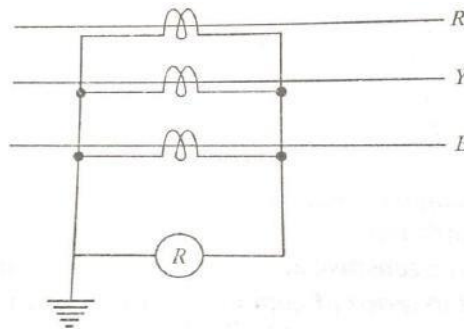
Zero sequence networks

Zero sequence networks are extensively used for earth fault protection. During the normal operation and for three phase and phase to phase faults the current passing through the relay is zero. When a single or double earth fault occurs, the zero sequence current flow through the relay.

For unbalanced condition or unsymmetrical faults:

Negative phase sequence network

Negative phase sequence network are used. The values of r and c are there to give a phase sift of 60 degrees. It can be seen from the phasar diagram that for the +ve sequence currents the output voltage(Va+Vb) is zero where as for the negative sequence currents the output voltage is of considerable magnitude to operate the relay.

The protection responding to positive phase sequence components alone is not in relaying practice. Because under unsymmetrical faults, such a protection will have less sensitivity due to the fact that the positive phase is only a part of the fault current.
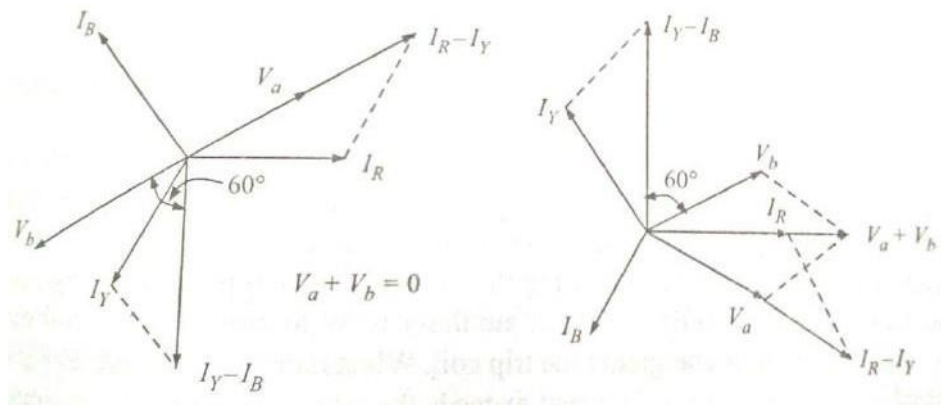
Positive sequence current   Negative sequence current

It is possible to use a combination of the positive sequence, negative sequence and zero sequence networks as a general rule. A combination of positive and negative sequence networks is wore common.

Components of Protection

Some of the commonly used components of the protective schemes are described here in brief. Those are

1. Relays
2. CB
3. Tripping and Auxiliary Supplies
4. CTs
5. Voltage Transformers

Relays

When any abnormal condition develop, the main function of a protective relay is to isolate the faulty section with the least interruption to the service by controlling or operation the circuit breaker.

The relay may be designed to detect and to measure abnormal condition and close the contacts of the tripping circuit.

The two categories of relay are most commonly used in protective relay

    a) Secondary indirect acting relays
    Example: Current, Voltage, Power, Impedance, Reactance and frequency whether minimum or maximum
    b) Secondary directing acting relay
    A group of over current and under voltage relays designed to operate immediately or with time lag.

These are relays of the electromagnetic type which are built into circuit breaker operating mechanism.

Circuit Breakers

It is desirable to switch on or off the various circuits like transmission line, distributors generating plants under both normal and abnormal condition.

This can be done by a switch and a fuse but the limitations are

1. It take some time to replace
2. It cannot successfully interrupt heavy fault current.

So we use CB.

It can make or break a circuit either manually or automatically under all conditions (no load, full load and fault) i.e.

a) It can make or break a circuit manually or by remote under normal condition
b) Break a circuit automatically under fault condition
c) Make a circuit either manually or by remote under fault condition

For operation of CB a relay is necessary. A protective relay is a device that detects the faults and initiate the operation of the circuit breaker to isolate the defective element from the rest of the system.

The electrical quantities which may change under fault condition are voltage, current, frequency and phase angle. Any changes in these quantities indicate presence of the fault.

Tripping and other Auxiliary Supplies

For protective relay and automatic control scheme in power system use two kinds of auxiliary supplies: DC and AC

DC auxiliary power supply is provided from batteries which is maintained continuously charged. The advantages of storage batteries are their high reliability and independent of power circuit conditions and of existence of fault.

Usually the voltage of the auxiliary supplies is maintained at 110 V

Mainly the auxiliary supplies power to protective relays, automatic control and the circuit breakers tripping circuit.Separate buses may also be provided for supplying power to relays, CB and other indicating circuit such as alarm and warning signals.
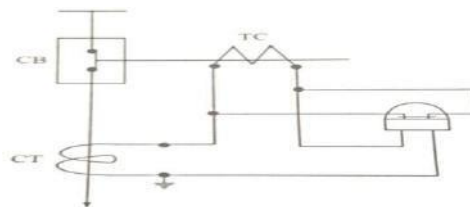
Relay with ac operative power from current transformer

In this scheme the relay has normally closed contacts. During normal operation the relay contacts continuously shut the circuit breakers trip coil and this keep the breaker closed.

When abnormal condition are approached the relays operates to open its contacts this put the trip.

Current Transformer (CT)

High magnitude primary current are reduce to a value suitable for relay operation to a value suitable for relay operation with the help of current transformers (CTs). (Then CTs provide current in the relay which are proportional to those in primary.)

The primary winding of the CTs is connected in series whit the load and carries the actual power system current (normal or fault). The secondary is connected to the measuring circuit or the relay.

The working range of a protective CT extends over the full range between the ankle and the knee points and beyond. Whereas the measuring CT usually operate in region of ankle point. Why?
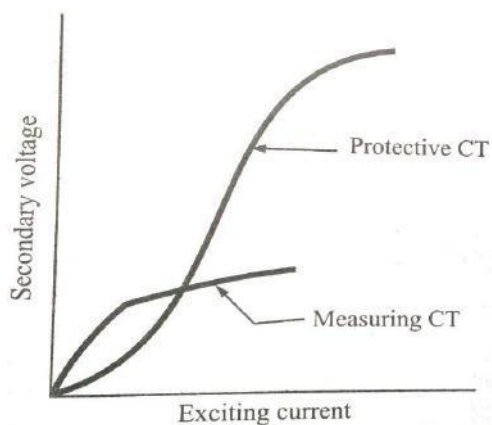
Measuring CTs require comparatively high accuracy over the range of 10% to 120% of rated.

Grain oriented steels having high saturation level are used As core materials for protective CTs and nickel iron alloys having low exciting ampere turn per unit length of the core use4d for measuring CTs.

It is common practice to use 1A secondary rating CTs.

The secondary of the bus bar primary CT is usually about 1500 secondary turn.

When rated primary currents much in excess of 1500 A are encountered then the main bar CTs with rated secondary current of 5A and 10A along with auxiliary CTs of 5/1 or 10/1 respectively are used.

Voltage Transformers

It is not possible to connect the voltage coils of the protective device directly to the system in case of high voltage systems. So it is necessary to step down the voltage, also to insulate the protective equipment from primary circuit. This is achieved by using a voltage transformers. Also known as potential transformer (PTs) which is similar to a power transformer. The voltage transformer is rated in terms of the maximum burden (VA) output it delivers without exceeding specified limits of errors. Whereas the power transformer is rated by the secondary output it delivers without exceeding a specified temperature rise.

The output of PTs is usually limited to a few hundred volt amperes and the secondary voltage is usually 110V between phases. Ideally a VT should produce a secondary voltage exactly proportion al to the primary voltage and exactly in phase opposition. This cannot

obviously be achieved in practice owing to the voltage drops in the primary and secondary coil due to the magnitude and power factor of the secondary burden. Thus ratio errors and phase angle errors are introduced.

There are two types of Voltage devices

a) The conventional wound type voltage transformers up to (132kV)
b) Capacitor Voltage Transformer (>132 kV)

When Appreciable current flows in the burden both ratio and phase are introduced because of the load current flowing through the capacitor C_1.

The voltage drop on load due to reluctance of the capacitors can be compensated by inserting an inductance reactance in series with the load.

Linear Coupler

An iron core CT has limitation of saturation. Also owing to dc offset transient component present in the fault current, the stability on heavy through faults may be difficult to obtain.

With air cored CTs, also known as linear coupler, the problem of saturation and dc offset transient are overcome.

Two major difficulties with relay transient problem are

a) Differential saturation
b) Transference of DC through the iron cored CT

$$i_p = I_m \left(\cos \omega t - e^{-\frac{Rt}{L}}\right)$$

The secondary voltage is given by $M \dfrac{di}{dt}$

$$v_s = -\omega M \log \sin \omega t + \frac{R}{L} e^{-Rt/L}$$

$$v_s = -\omega M \log \left(\sin \omega t - \frac{R}{\omega L} e^{-Rt/L}\right)$$

It can be seen that the dc component voltage has been attenuated by a ratio R/X which may be 1/10 to 1/20 depending on the system.

References

3. B Ravindranath& M Chander, "Power system Protection and switchgear"New age International Publishers
4. Y.G Paithankar & S.R Bhide, "Fundamentals of powersystem Protection"PHI Publication

Chapter-3

Operating principles and constructional features of relay

Relay classification

The actuating quantity is normally in electrical signal. Sometimes the actuating quantity may be pressure and temp.

Protective relay can be classified as

- According to the function in protection scheme.
- According to the nature of actuating quantity.
- According to the connection of the sensing element
- According to the method by which the relay acts upon the circuit breaker

Generally the electrical protective relays can be broadly classified in two categories

(a) Electromagnetic relays
(b) Static relays

A relay in which the measurement or comparison of electrical quantities are done in a static network. The output signal operates a tripping device which may be electronic , semiconductor or electromagnetic.

The static relays are classified according to the types of measuring units or the comparator

1) Electronic relays
2) Transducer(magnetic amplifier relay)
3) Rectifier bridge relay
4) Transistor relay
5) Hall effect relay
6) Gauss effect relay

Principal types of electromagnetic relays
There are two types of electromagnetic relays

a) Attracted armature type
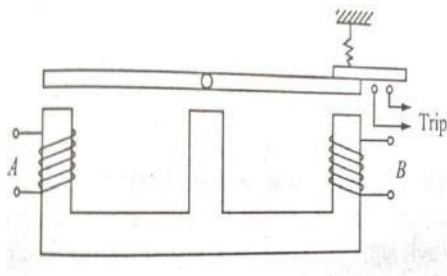b) Induction type

Attracted armature type

- This includes plunger, hinged armature, balanced beam and moving iron polarised relay. These are simplified types which respond to A.C as well as D.C.
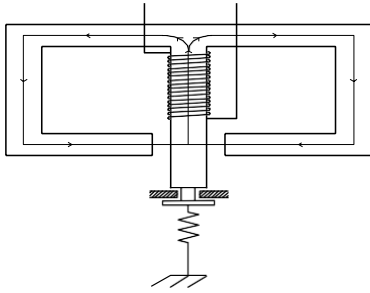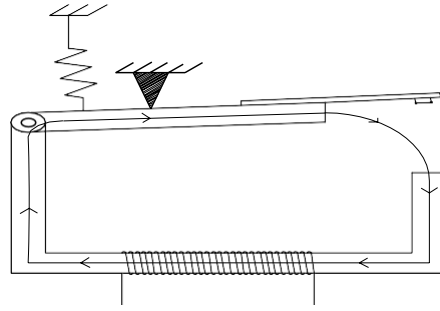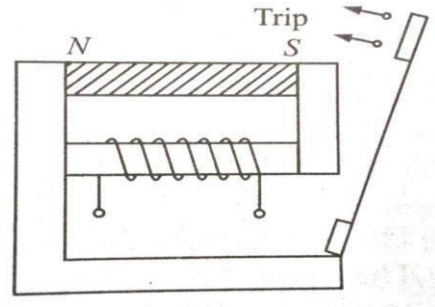
Plunger type)   Hinged armature type


Balanced beam type   Polarized moving iron type

In dc the electromagnetic force exerted on the moving element is proportional to the square of the flux or square of the current. In dc electromagnetic relay this force is constant. If this force exceeds the restraining force, the relay operates.

In ac electromagnetic relays the electromagnetic force is given by

$$Fe = kI^2$$

$$= k(I_{max}sinwt)^2$$

$$= \tfrac{1}{2}k\, I_{max}^{\,2}(1 - coswt)$$

$$= \tfrac{1}{2}k(\, I_{max}^{\,2} - I_{max}^{\,2}cos\,2wt)$$

This indicates that the electromagnetic force consists of two components (i) One constant(independent of time) and (ii)Another dependent on time and pulsating at double the frequency of the applied alternating quantities.
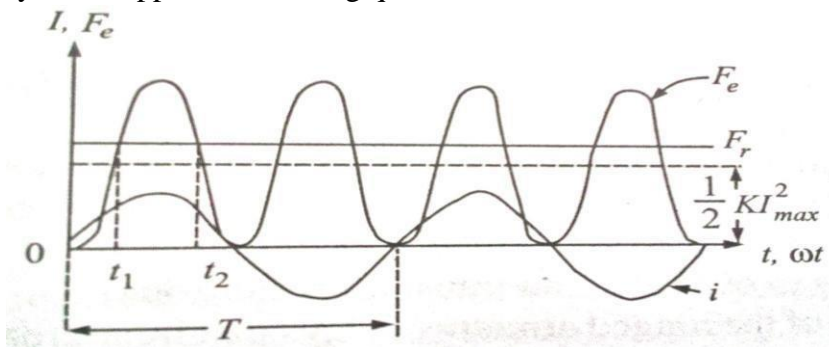
The total electromagnetic force pulsates at double the freq. the force is plotted graphically which shows that Fe =0 in every half period.

If F_r is produced with the help of a spring then it is constant.

Then the relay armature will be picked up at t1 and the armature drops off at t2. Hence the armature vibrates at double the frequency. This causes the relay to hum and produces noise and also is a source of damage to relay contacts. This leads to sparking and unreliable operation of the relay operating circuit contacts due to make and break of the circuits.

To overcome this difficulties in ac electromagnetic relay the flux that produce electromagnetic force is divided into two fluxes among simultaneously but differing in time phase. So that the resultant electromagnetic force is always positive and this is always greater the restraining force so that the armature will not vibrate. This is achieved through shaded pole or by providing two windings having a phase shift.
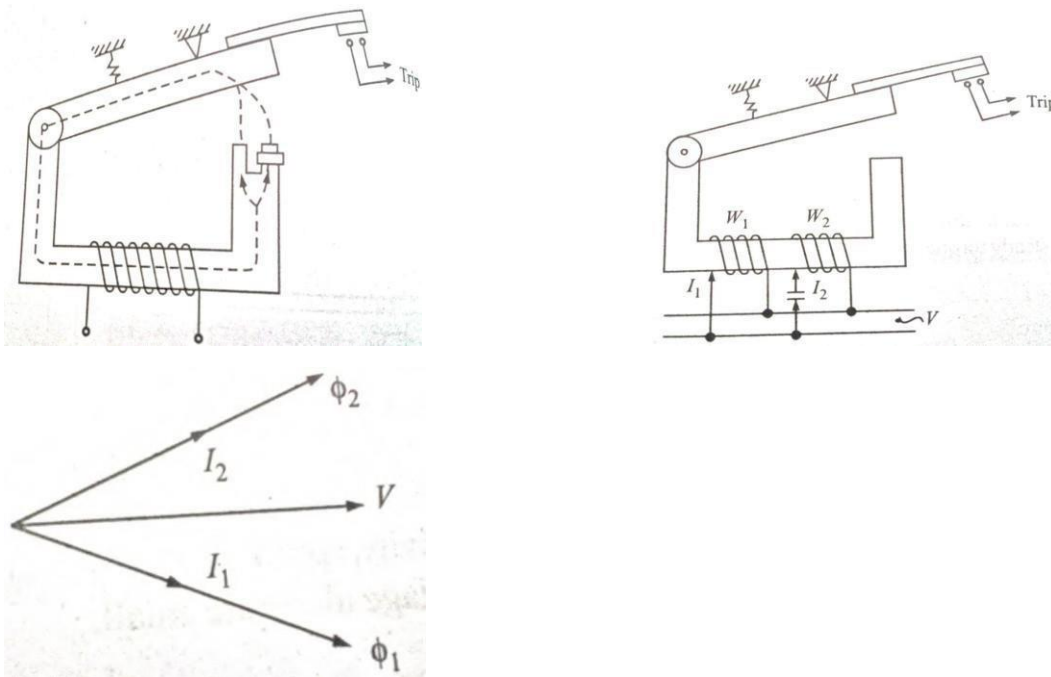
The flux through the shaded pole lags behind the unshaded pole. In case of balanced beam type two quantities A and B are compared. Actually $|A|^2$ and $|B|^2$ are compared because the electromagnetic forces are proportional to (ampere turns)^2. It has low ratio of reset by operating current.

Sensitivity of hinged armature relays can be increased for dc operation by the addition of a permanent magnet. This is known as a polarised moving iron relay.

Induction type relay

An induction relay essentially consists of aluminium disc placed in two alternating magnetic flux of same frequency but displaced in time and space. The torque is produced in the disc by the interactions of one of the magnetic field with the currents induced in the disc by the other. Induction relays are widely used for protective relaying involving AC quantities. High, low and adjustable speeds are possible and the various shapes of time/operating curve can be obtained.

Types of structure

a) Shaded pole

b) Wattmeter or double pole winding structure
c) Induction cup structure

(a) Shaded pole
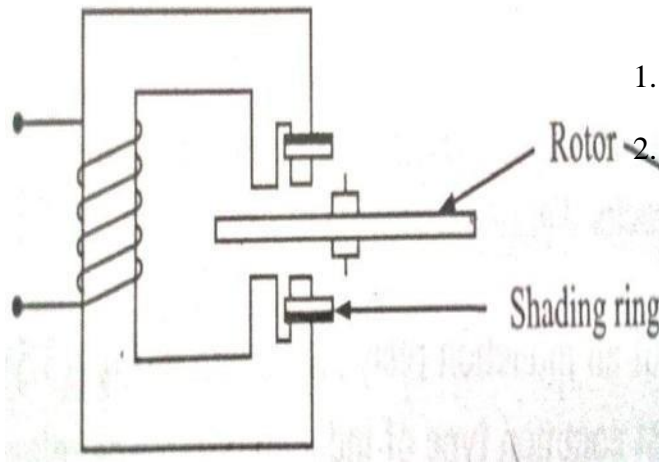
It consists of

1. 1. Pivoted aluminium disc free to rotate in the air gap of an electro magnet.
2. 2. One half is surrounded by copper band known as shaded ring.

The alternating flux in the shaded portion of the poles will lag behind the flux in the unshaded portion by an angle α due to the reaction of the current induced in the ring.

These two a.c fluxes differing in phase will produce the necessary torque to rotate the disc.

(b)Wattmeter structure or double winding structure
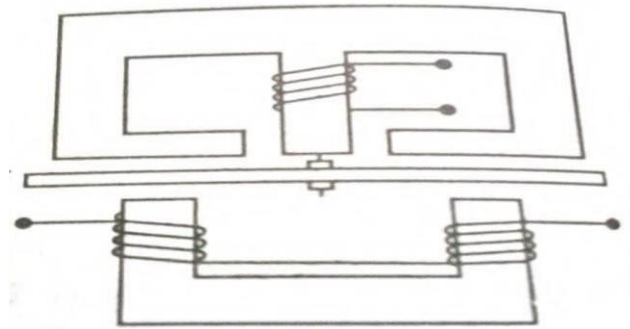
Wattmeter structure

In the wattmeter type these are two magnetic systems. A phase displacement between the fluxes is obtained either by having different inductance and resistance for the two circuits or energizing these from two different sources whose outputs are relatively displaced in phase as shown.

(c)Induction cup structure
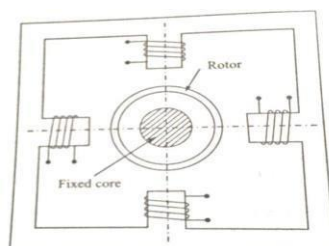
The rotating field is produced by two pairs of coils wound on four poles.The rotating field induced current in the cup to provide the necessary driving torque.

If Φ_1 and Φ_2 represent the fluxes produced by the respective pair of poles, then the torque produced is proportional to Φ_1. $\Phi_2 \sin\alpha$ i.e
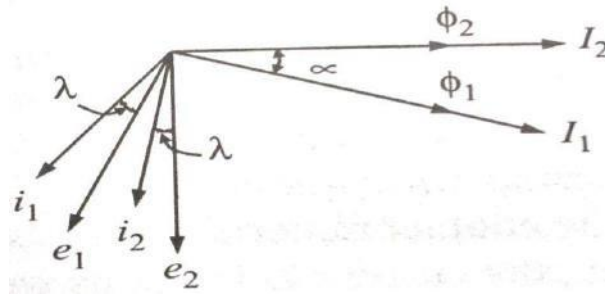
$$T \, \alpha \, \Phi_1.\Phi_2 \sin\alpha$$

A control spring and the back stop is provided for closing of the contacts that are attached to the spindle of the cup to prevent the continuous rotation.

Induction cup structure is more efficient torque producers than shaded pole and wattmeter type. So this type of relay has very high speed. The operating time is less than 1 second.

Theory of induction relay torque

Two magnetic fluxes $\Phi1$ and $\Phi2$ differing in time phase penetrate through a disc. These alternating fluxes induce e.m.f.s e1 and e2 in the disc which lag their respective fluxes by 90 degrees.

$\Phi1 = \Phi1m \, \sin \omega t$

So $i_1 \, \alpha \dfrac{d\,\Phi1}{d} \, a \, \dfrac{d\emptyset1}{dt}(\Phi1m \sin \omega t) \quad a \, \Phi_{1m} \cos mt$

$\Phi_2 = \Phi m \, \sin(\omega t + a) \quad i_2 \, \alpha \dfrac{d\,\Phi2}{dt} \quad a \, \dfrac{d\emptyset2}{dt}(\Phi_{2m} \sin(\omega t + a)) \quad a \, \Phi_{2m} \cos(mt + a)$

$F_1 \, \alpha \, \Phi_1 \, i_2, \qquad F_2 \, a \, \Phi_2 \, i_1$

Net force (F) $\alpha \, (F_2 - F_1)$

$\quad \alpha \, (\Phi_2 \, i_1 - \Phi_1 \, i_2)$

$\quad \alpha \, (\Phi_{2m} \, \Phi_{1m} \, (\sin(\omega t + \alpha)\cos\omega t - \sin \omega t \cos(\omega t + \alpha))$

$\quad \alpha \, (\Phi_{2m} \, \Phi_{1m} \, (\sin(\omega t + \alpha - \omega t))$

$\quad \alpha \, \Phi_{1m} \, \Phi_{2m} \sin \alpha$

$\quad \alpha \, \Phi_1 \, \Phi_2 \sin \alpha$

where Φ_1 and Φ_2 are the rms values of the fluxes.

$\Phi1 \, \alpha \, I_1$

$\Phi2 \, \alpha \, I_2, \qquad$ For $T \, \alpha \, I_1 \, I_2 \sin(\alpha)$

The maximum torque is developed when α is 90 degree or 270 degree and zero torque when $\alpha=0$ or 180 degree.

Relay design and construction

The design of protective relay is normally divided into the following stages:

    (a) Selection of the operating characteristics
    (b) Selection of proper construction
    (c) Design of the contact moment from the point of view of utmost reliability.

The relay operating characteristic must match with the abnormal operating characteristics of the system i.e. it should clearly show the conditions for tripping under various abnormal operating conditions.

The most important considerations in the design for construction are:

- Reliability
- Simplicity of construction
- Circuitry

The construction of the relay is divided into the following:

    i.   Contacts
    ii.   Bearing
   iii.   Electromechanical design
   iv.   Termination and housing

Contacts

Contact performance is probably the most important item affecting reliability of the relay. Corrosion or dust deposit can cause non-operation of relay.

Thus material and shape of relay are of considerable importance.

A good contact system design provides restricted contact resistance, reduced contact wear.

The contact material used are gold, gold alloy, platinum, pelledium and silver.

The selection of the contact material depends on a number of factors like:

- The voltage per contact break
- The current to break
- The type of atmospheric pollution under which the contacts are operate

The following factors are to be considered for selecting a suitable contact material:

    1) The nature of the current to be interrupted (ac or dc)
    2) Voltage at break and make operation
    3) Value of current magnitude
    4) Frequency of operation
    5) The actual speed of contact at make or break
    6) Contact shape

Some rules or points recommended in the design of contact system of a relay :

    (a) The contacts should be bounce proof to avoid arcing at the contacts.
    (b) There should be increased contact-pressure that leads to decrease in voltage drop or contact resistance.

(c) To promote accuracy and avoid sticking after a long period of inaction. So the relay should be designed to have maximum torque/friction ratio.

(d) The value of current that can be interrupted by a pair of contacts in ac circuit is 2 to 8 times than in a dc circuit.

Generally dome shaped contacts give best performances.

Bearing

(a) Single ball bearing
(b) Multi ball bearing
(c) Pivot and jewel bearing – This is the most common type for precision relay.

Electromechanical Design

It consists of the design of the magnetic circuit and the mechanical features of core, yoke, and armature.The reluctance of the magnetic path is kept to a minimum by enlarging the pole face which makes the magnetic circuit more efficient.AC electromagnets made from soft iron, low carbon steel core having a slot for mounting shaded rings are more common.

The relay coil current is usually limited to 5A and the coil voltage to 220 V but the insulation for the relay coil is designed to withstand at least 4kV.The relay coil is designed to carry about 15 times the normal current foe one second.

Termination and housing

Material used for springs are stainless steel, nickel steel, phosphorous bronze and Beryllium copper.
The spring is insulated from the armature by moulded blocks. For moulded blocks nylon is used.

References

5. B Ravindranath& M Chander, "Power system Protection and switchgear"New age International Publishers
6. Y.G Paithankar & S.R Bhide, "Fundamentals of powersystem Protection"PHI Publication

Chapter-4

SYMMETRICAL COMPONENTS AND FAULT CALCULATIONS

1. Introduction

According to the method of symmetrical co-ordinates applied to a solution of polyphase network a system of n vectors or quantities may be resolved when n is prime, into n different symmetrical groups or systems, one of which consists of n equal vectors, and the rest (n-1) system consist of n equispaced vectors which with the first mentioned group of equal vectors forms an equal number of symmetrical n-phase systems.

2. 3-Phase Systems

Any three coplanar vectors V_a, V_b and V_c can be expressed in terms of three new vectors V_1, V_2 and V_3 by three simultaneous equation with constant coefficients. Thus

$$V_a = a_{11}V_1 + a_{12}V_2 + a_{13}V_3$$

$$V_b = a_{21}V_1 + a_{22}V_2 + a_{23}V_3$$

$$V_c = a_{31}V_1 + a_{32}V_2 + a_{33}V_3$$

Each of the vectors has been replaced by new vectors thereby making a new set of nine vectors. The objective of making this transformation is done because

1. Calculations become simplified on the basis of this transformation.
2. The system of components chosen must have some physical significance.

According to the theorem, the three unbalanced vectors can be expressed by a set of three balanced system of vectors. A balanced system of three vectors is one in which the vectors are equal in magnitude and are equispaced. Hence the symmetrical components are:

1. Positive sequence components which have three vectors of equal magnitude and are displaced by 120° and has the same phase sequence as that of the original vectors.
2. Negative sequence components which have three vectors of equal magnitude and are displaced by 120° and has the opposite phase sequence as that of the original vectors.
3. Zero sequence components which have three vectors of equal magnitude and are also in phase with each other.

The subscripts 1, 2 and 0 represents positive, negative and zero sequence respectively.
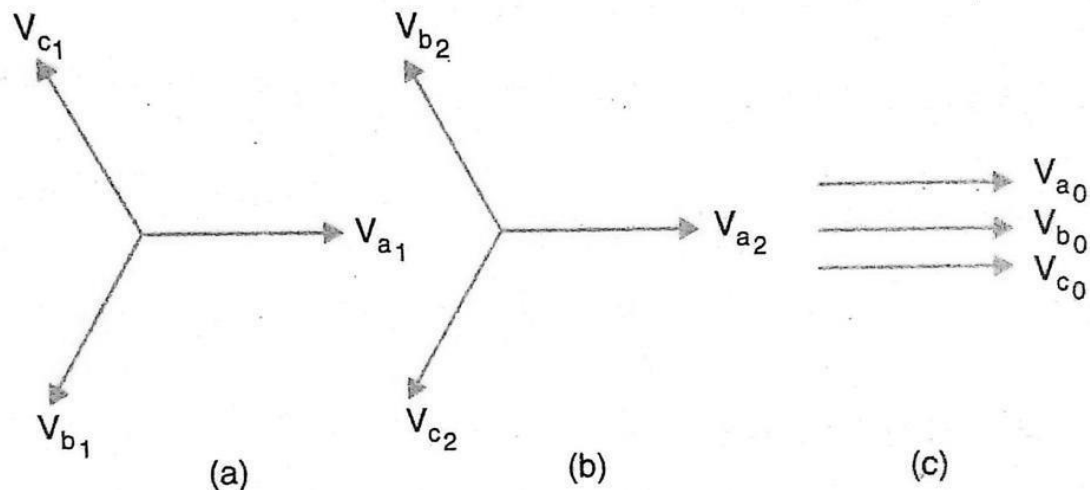
Figure 1 (a) Positive sequence component (b) Negative sequence component (c) Zero sequence component

3. Significance of Positive, Negative and Zero sequence Components

The positive sequence system of vectors is meant that vectors are equal in magnitude and differs by 120° in phase with the same phase sequence. The real meaning is that if the stator winding of the alternator is supplied with a set of positive sequence voltages, the direction of rotation of the stator field is the same as the rotor. If the direction of rotation of the stator field is opposite to the direction of the rotor, the set of voltages are known as negative sequence voltages. The zero sequence voltages are the single phase voltages, and gives rise to the alternating field in the space.

From the above figure, it can be found out that the relation between the original set of unbalanced vectors and their corresponding symmetrical components is

$$V_a = V_{a_1} + V_{a_2} + V_{a_0}$$

$$V_b = V_{b_1} + V_{b_2} + V_{b_0}$$

$$V_c = V_{c_1} + V_{c_2} + V_{c_0}$$

Considering phase a as the reference vector, the relationship between the symmetrical components of phase b and c in terms of a can be written by the use of operator λ which has a magnitude of unity and a phase angle of 120° which rotates any vector by 120°. Thus

$$\lambda = 1\angle 120°$$

In the complex form

$$\lambda = \cos 120° + j \sin 120° = -0.5 + j\,0.866$$

Similarly

$$\lambda^2 = -0.5 - j\,0.866$$

24

$$\lambda^3 = 1.0 = 1\angle 360°$$

Or

$$\lambda^3 - 1 = 0$$

Or

$$(\lambda - 1)(\lambda^2 + \lambda + 1) = 0$$

Since λ G 1 as λ is a complex number

$$\lambda^2 + \lambda + 1 = 0$$

So for the positive sequence the symmetrical components of phase b and c in terms of symmetrical components of phase a can be written as

$$V_{b_1} = \lambda^2 V_{a_1}$$

$$V_{c_1} = \lambda V_{a_1}$$

For negative sequence vectors

$$V_{b_2} = \lambda V_{a_2}, \qquad V_{c_2} = \lambda^2 V_{a_2}$$

For zero sequence vectors

$$V_{b_0} = V_{c_0} = V_{a_0}$$

Substituting these relations on to the above equations

$$V_a = V_{a_1} + V_{a_2} + V_{a_0}$$

$$V = \lambda^2 V_{a_1} + \lambda V_{a_2} + V_{a_0}$$

$$V_c = \lambda V_{a_1} + \lambda^2 V_{a_2} + V_{a_0}$$

Similar relations can be also derived for the phase currents in terms of symmetrical components of currents taking phase a as reference

$$I_a = I_{a_1} + I_{a_2} + I_{a_0}$$

$$I_b = \lambda^2 I_{a_1} + \lambda I_{a_2} + I_{a_0}$$

$$I_c = \lambda I_{a_1} + \lambda^2 I_{a_2} + I_{a_0}$$

From the above relation we can find the relation of symmetrical components in terms of phase components

$$V_{a_1} = \frac{1}{3}(V + \lambda V_b + \lambda^2 V_c)$$

Similarly

$$V_{a_2} = \frac{1}{3}(V + \lambda^2 V_b + \lambda V_c)$$

$$V_{a_0} = \frac{1}{3}(V + V_b + V_c)$$

Similar relations can be achieved for currents also.

4. Average Three Phase Power in terms of Symmetrical Components

The average power is given as

$$P = V_a I_a \cos\phi + V_b I_b \cos\phi_b + V_c I_c \cos\phi_c$$
$$P = V_a . I_a + V_b . I_b + V_c . I_c$$
$$P = (V_{a_1} + V_{a_2} + V_{a_0}) . (I_{a_1} + I_{a_2} + I_{a_0}) + (\lambda^2 V_{a_1} + \lambda V_{a_2} + V_{a_0}) . (\lambda^2 I_{a_1} + \lambda I_{a_2} + I_{a_0})$$
$$+ (\lambda V_{a_1} + \lambda^2 V_{a_2} + V_{a_0}) . (\lambda I_{a_1} + \lambda^2 I_{a_2} + I_{a_0})$$

Taking the first term on RHS

$$(V_{a_1} + V_{a_2} + V_{a_0}) . (I_{a_1} + I_{a_2} + I_{a_0})$$
$$= V_{a_1} . I_{a_1} + V_{a_2} . I_{a_2} + V_{a_0} . I_{a_0} + V_{a_1} . I_{a_2} + V_{a_1} . I_{a_0} + V_{a_2} . I_{a_1} + V_{a_2} . I_{a_0} + V_{a_0} . I_{a_1}$$
$$+ V_{a_0} . I_{a_2}$$

For second and the third term the dot product of two vectors doesn't change when both are rotated by the same angle.

For example,

$$\lambda^2 V_{a_1} . \lambda^2 I_{a_1} = V_{a_1} . I_{a_1}$$

$$\lambda^2 V_{a_1} . \lambda I_{a_2} = \lambda V_{a_1} . I_{a_2}$$

So the addition of the terms after expanding and rearranging,

$$P = 3V_{a_0} I_{a_0} + 3V_{a_1} . I_{a_1} + 3V_{a_2} . I_{a_2} + V_{a_1} . I_{a_2} (1 + \lambda + \lambda^2) + V_{a_0} . I_{a_1} (1 + \lambda + \lambda^2)$$
$$+ V_{a_2} . I_{a_1} (1 + \lambda + \lambda^2) + V_{a_0} . I_{a_2} (1 + \lambda + \lambda^2) + V_{a_2} . I_{a_0} (1 + \lambda + \lambda^2)$$
$$+ V_{a_0} . I_{a_2} (1 + \lambda + \lambda^2)$$

$$P = 3(V_{a_1} . I_{a_1} + V_{a_2} . I_{a_2} + V_{a_0} . I_{a_0})$$
$$P = 3[|V_{a_1}||I_{a_1}| \cos\theta_1 + |V_{a_2}||I_{a_2}| \cos\theta_2 + |V_{a_0}||I_{a_0}| \cos\theta_0]$$

The same power expression can be very easily derived using matrix manipulation

$$P + jQ = V_a I_a^* + V_b I_b^* + V_c I_c^*$$

$$= [V_a \quad V_b \quad V_c] \begin{bmatrix} I_a^* \\ I_b \\ I_c \end{bmatrix} = [V_b]^T \begin{bmatrix} I_a^* \\ I_b \\ I_c \end{bmatrix}$$

From previous equations

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \lambda^2 & \\ 1 & \lambda & \lambda^2 \end{bmatrix} \begin{bmatrix} V_{a_0} \\ V_{a_1} \\ V_{a_2} \end{bmatrix} = AV$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}^T = (AV)^T = V^T A^T$$

$$P + jQ = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}^T \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}^* = \begin{bmatrix} V_{a_0} & V_{a_1} & V_{a_2} \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \lambda^2 & \lambda \\ 1 & \lambda & \lambda^2 \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}^*$$

Since λ and λ^2 are conjugates, so

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}^* = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \lambda^2 & \lambda \\ 1 & \lambda & \lambda^2 \end{bmatrix}^* \begin{bmatrix} I_{a_0} \\ I_{a_1} \\ I_{a_2} \end{bmatrix}^* = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \lambda & \lambda^2 \\ 1 & \lambda^2 & \lambda \end{bmatrix} \begin{bmatrix} I_{a_0} \\ I_{a_1} \\ I_{a_2} \end{bmatrix}^*$$

$$P + jQ = \begin{bmatrix} V_{a_0} & V_{a_1} & V_{a_2} \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \lambda^2 & \lambda \\ 1 & \lambda & \lambda^2 \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \lambda & \lambda^2 \\ 1 & \lambda^2 & \lambda \end{bmatrix} \begin{bmatrix} I_{a_0} \\ I_{a_1} \\ I_{a_2} \end{bmatrix}^*$$

$$= \begin{bmatrix} V_{a_0} & V_{a_1} & V_{a_2} \end{bmatrix} \begin{bmatrix} 3 & 0 & 0 \\ 0 & 3 & 0 \\ 0 & 0 & 3 \end{bmatrix} \begin{bmatrix} I_{a_0} \\ I_{a_1} \\ I_{a_2} \end{bmatrix}^*$$

$$= 3 \begin{bmatrix} V_{a_0} & V_{a_1} & V_{a_2} \end{bmatrix} \begin{bmatrix} I_{a_0} \\ I_{a_1} \\ I_{a_2} \end{bmatrix}^*$$

$$= 3 [V_{a_0} I_{a_0}^* + V_{a_1} I_{a_1}^* + V_{a_2} I_{a_2}^*]$$

$$P = 3 [|V_{a_0}||I_{a_0}| \cos\theta_0 + |V_{a_1}||I_{a_1}| \cos\theta_1 + |V_{a_2}||I_{a_2}| \cos\theta_2]$$

5. Sequence Impedances

Like the symmetrical components for the current, voltage and power, the impedances are also composed of symmetrical components known as the sequence impedances. These can be defined as follows:

The positive sequence impedance of equipment is the impedance offered by the equipment to the flow of positive sequence impedance. Similarly, the negative and zero sequence impedance of the equipment is the impedance offered by the equipment to the flow of corresponding sequence currents.

Measurement of Sequence Impedance of Rotating Machines

Measurement of positive sequence impedance: The positive sequence impedance depends upon the working of the machine, i.e. whether it is working under sub-transient, transient or steady state condition. The impedance measured under steady state is known as synchronous impedance and is measured by the well known open circuit and short circuit test. The impedance is defined as

$$\text{Synchronous impedance in p.u.} = \frac{\text{Normal open circuit voltage at the field current corresponding to the rated armature current}}{\text{Rated Armature current at that particular field current}}$$

Method of test for synchronous Impedance: The machine here is run at a proper direction with the help of a prime mover. The shorting link switch is kept in off position to perform open circuit test and noted the readings of the voltmeter by varying the field current. Similarly, the short circuit test is done by putting the shorting switch on and noting the readings of armature current with the variation of the field current.
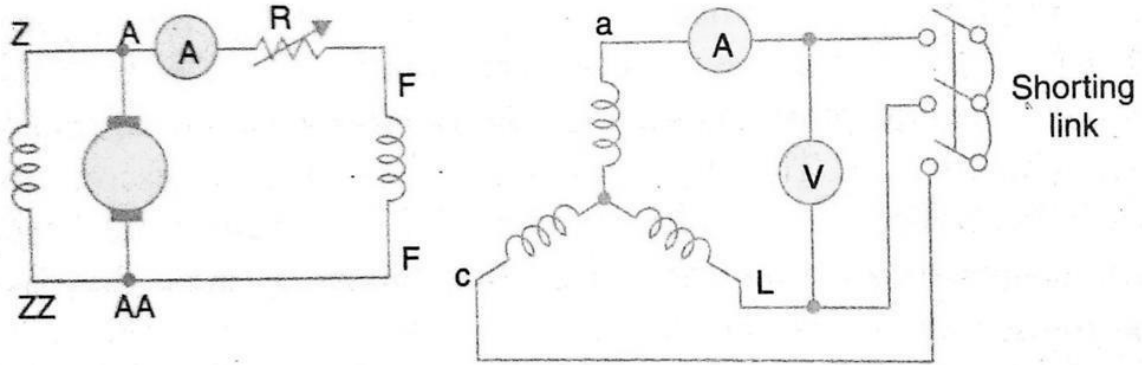

Figure 2 Connection Diagram for open circuit and short circuit test of an alternator

Measurement of Negative sequence Reactance: It is the impedance offered to the flow of negative sequence current.
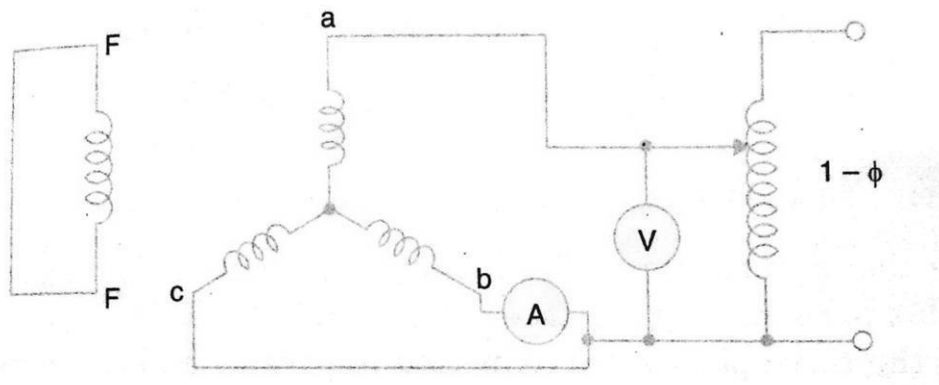
Figure 3 Measurement of negative sequence impedance

The machine here is driven at rated speed, and a reduced voltage is applied till the rated current flows in the armature. When there is a flow of negative sequence current there may be a possibility of hunting which would cause the pointer to deflect. This allows the mean reading to be taken. The negative sequence impedance is given by

$$Z_2 = \frac{V}{\sqrt{3}I}$$

Where V is the voltmeter and I is the ammeter reading.

This can be proved mathematically as follows

From the experiment, since it is similar to line-to-line fault with alternator unloaded,

$$I_a = 0, I_b = I, I_c = -I$$

Under these conditions, the positive sequence and negative sequence currents are opposite to each other and the positive and negative sequence voltages are equal.

$$V = V_a - V_b$$

$$V = V_1 + V_2 - (\lambda^2 V_{a1} + \lambda V_{a2}) = 2V_{a2} + V_{a2} = 3V_{a2}$$

And the current in the ammeter

$$I = I_b = \lambda^2 I_1 + \lambda I_{a2} = (\lambda - \lambda^2) I_{a2}$$

$$\lambda - \lambda^2 = -0.5 + j0.866 + 0.5 + j0.866 = |\sqrt{3}| \angle 90°$$

Current measured $=I = \sqrt{3} I_{a_2}$

$$\frac{V_a - V_b}{\sqrt{3}I} = \frac{V_a - V_b}{\sqrt{3}I_b} = \frac{3V_{a_2}}{\sqrt{3}.\sqrt{3}I_{a_2}} = \frac{V_{a2}}{I_{a2}} = Z_2$$

Measurement of zero sequence impedance: Zero sequence impedance is the impedance offered by the machine to the flow of zero sequence current. This impedance depends on the distribution of the windings on the factors like pitch and breadth factors. The value is much smaller as compared to zero and negative sequences.
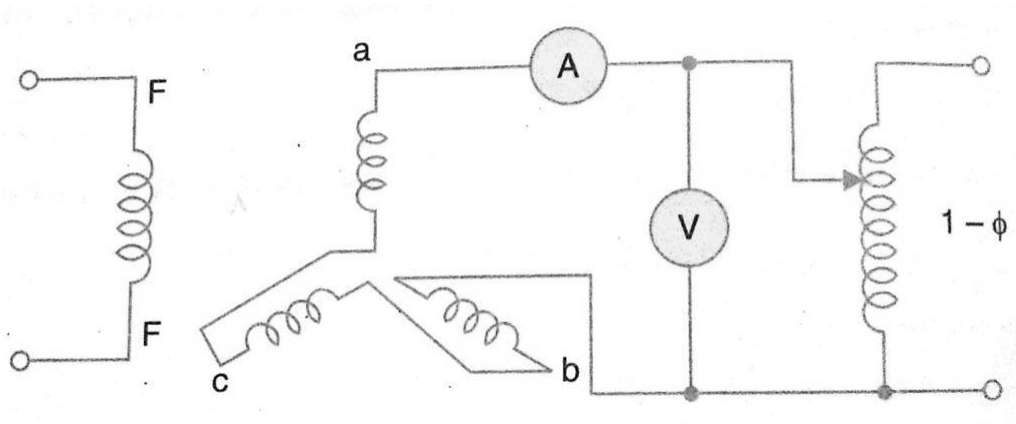
Figure 4 Measurement of Zero sequence impedance

The machine is at standstill and a reduced voltage is applied. The zero sequence impedance is $Z_0 = V/3$.

6. Fault Calculation

The faults in a power system can be classified as:

1. Shunt Faults
2. Series Faults

Shunt type of faults involve power conductors or conductors-to-ground or short circuit between conductors. When the circuits are controlled by fuses and in which

one or two phases of the circuit gets opened while the other phase is closed, such type of faults is known as series faults.

Shunt faults may be classified as *(i)* Line-to ground fault; *(ii)* Line-to-line fault; *(iii)* Double line to ground fault; and *(iv)* 3-phase fault. Of these, the first three are unsymmetrical faults as the symmetry is distributed over one or two phases while the 3-phase fault is a balanced fault.

Series faults are classified as: *(i)* one open conductor; and *(ii)* two open conductors. These faults disturb the symmetry in one or two phases and are unbalanced faults.

We are mainly concerned with symmetrical faults.

Voltage of the neutral

The potential of the neutral when it is grounded through some impedance is not equal to the ground potential under unbalanced operation. The potential of the neutral is given as $V_n = -I_n Z_n$, where Z_n is the neutral grounding impedance and the I_n is the neutral current. Here negative sign is given as the current flows from the ground to the neutral of the system and the potential of the neutral is lower than the ground

$$\begin{aligned}
I_n &= I_a + I_b + I_c \\
&= (I_{a_1} + I_{a_2} + I_{a_0}) + (\lambda^2 I_{a_1} + \lambda I_{a_2} + I_{a_0}) + (\lambda I_{a_1} + \lambda^2 I_{a_2} + I_{a_0}) \\
&= I_{a_1}(1 + \lambda + \lambda^2) + I_{a_2}(1 + \lambda + \lambda^2) + 3I_{a_0} \\
&= 3I_{a_0}
\end{aligned}$$

$$V_n = -3I_{a_0} Z_n$$

Since the positive and negative sequence currents are absent through the neutral are absent, hence the drops due to these currents are also zero. Also for the balanced set of currents or voltages, the neutral is at the ground potential. Therefore for positive and negative sequence networks, neutral of the system will be taken as reference.

Reference of Voltages

The phase voltages at any point in a grounded system and their zero sequence components of voltage will be referred to the ground at that point. The positive and negative sequence components of voltage are referred to neutral. Therefore the voltage to ground and voltage to neutral is use alternatively but for the zero sequence system it is important to distinguish between the two terms.

7. **Sequence network Equations**

The equations will be derived for an unloaded transformer with neutral solidly grounded, assuming that the system is initially balanced, i.e. the generated voltages are of equal magnitude and displaced by 120°.
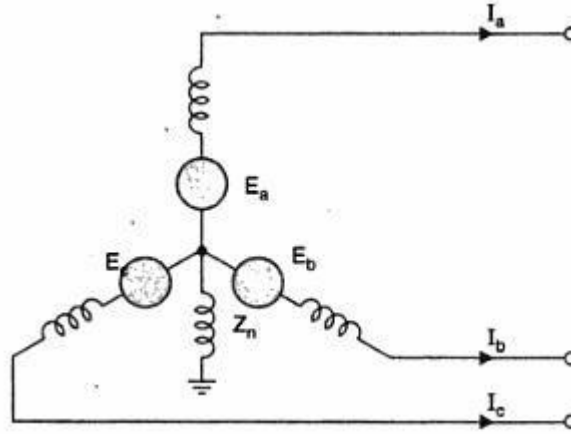
Figure 5 A balanced three phase system

Since the sequence impedances per phase are same for all three phase and we are considering initially a balanced system, the fault analysis will be done on single phase basis.

The positive sequence component of voltage at the fault point is the positive sequence generated voltage minus the drop due to the positive sequence current in the positive sequence impedance.

$$V_{a_1} = E_a - I_{a_1}Z_1$$

Similarly for the negative sequence component of voltage at the fault point is the negative sequence generated voltage minus the drop due to the negative sequence current in the negative sequence impedance.

$$V_{a_2} = E_{a_2} - I_{a_2}Z_2$$

Since the negative sequence voltage generated is zero, therefore

$$E_{a_2} = 0$$
$$V_{a_2} = -I_{a_2}Z_2$$

Similarly for zero sequence voltage

$$E_{a_0} = 0$$
$$V_{a_0} = V_n - I_{a_0}Z_{g_0} = -3I_{a_0}Z_n - I_{a_0}Z_{g_0} = -I_{a_0}(Z_{g_0} + 3Z_n)$$

Where Z_{g0} is the zero sequence impedance of the generator and Z_n is the neutral impedance.

The three sequence network equations are therefore

$$V_{a_1} = E_a - I_{a_1}Z_1$$

$$V_{a_2} = -I_{a_2}Z_2$$

$$V_{a_0} = -I_{a_0}Z_0$$

Where $Z_0 = Z_{g_0} + 3Z_n$ and the corresponding sequence networks for the unloaded alternator is shown in the figure below
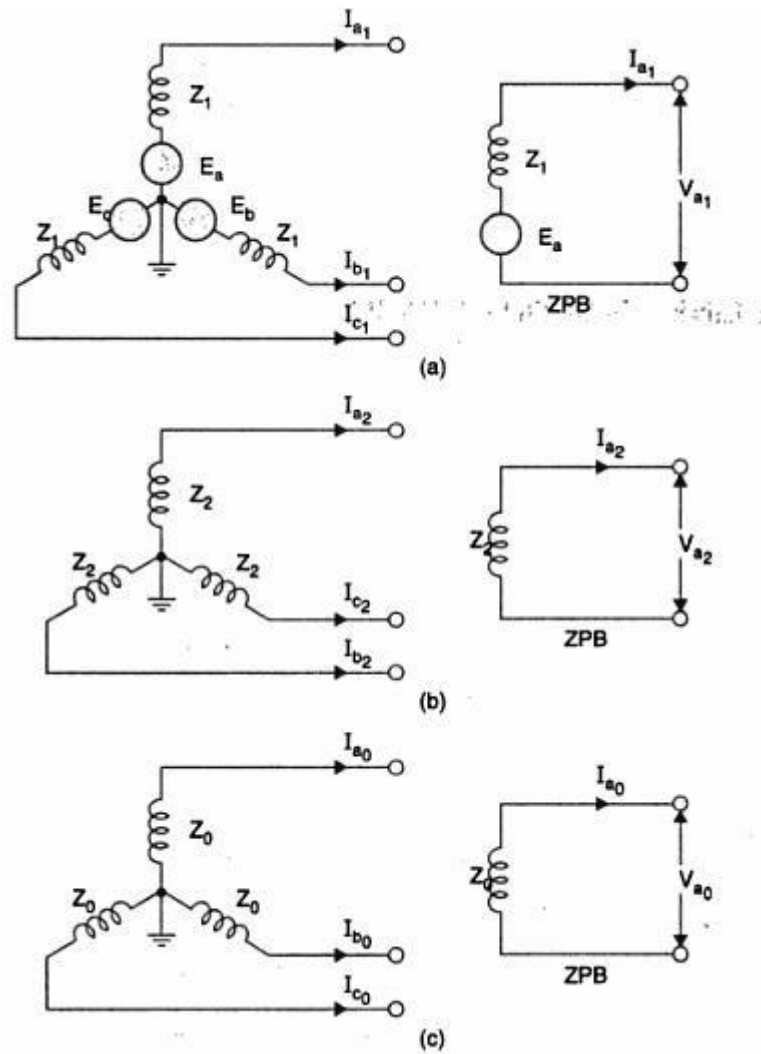
Figure 6 Sequence networks (a) Positive Sequence network (b) Negative sequence network (c) Zero Sequence network

8. Single Line-to-Ground Fault

The system to be analyzed is given below. If there is a line-to-ground fault at phase *a*, the boundary conditions are
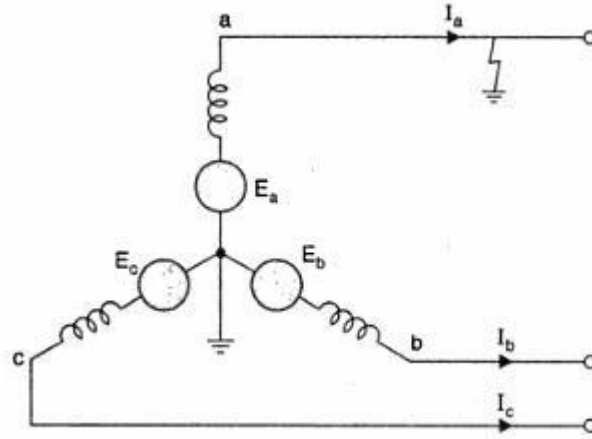
$$V_a = 0$$

$$I_b = 0$$

$$I_c = 0$$

Figure 7 A solidly grounded, unloaded alternator: L-G fault on phase a

The sequence network equations are

$$V_{a_0} = -I_{a_0}Z_0$$

$$V_{a_1} = E_a - I_{a_1}Z_1$$

$$V_{a_2} = -I_{a_2}Z_2$$

The solution of these six equations will give all the six sequence components of voltage and current.

From the sequence current equations

$$I_{a_1} = \frac{1}{3}(I_a + \lambda I_b + \lambda^2 I_c)$$

$$I_{a_2} = \frac{1}{3}(I_a + \lambda^2 I_b + \lambda I_c)$$

$$I_{a_0} = \frac{1}{3}(I_a + I_b + I_c)$$

Substituting the values of I_b and I_c in the above equations

$$I_{a_1} = I_{a_2} = I_{a_0} = I_a/3$$

Similarly according to the symmetrical component of voltage

$$V_a = 0 = V_{a_1} + V_{a_2} + V_{a_0}$$

Substituting the values of sequence voltages from the sequence network equation,

$$E_a - I_{a_1}Z_1 - I_{a_2}Z_2 - I_{a_0}Z_0 = 0$$

Since,

$$I_{a_1} = I_{a_2} = I_{a_0}$$

The above equation becomes

$$E_a - I_{a_1}Z_1 - I_{a_1}Z_2 - I_{a_1}Z_0 = 0$$

$$I_{a_1} = \frac{E_a}{Z_1 + Z_2 + Z_0}$$

From the above equation it is evident that to simulate an L-G fault all the three sequence networks are required, and all these sequence networks are to be connected in series, as the sequence currents are equal in magnitude and phase. The interconnection is shown in the figure below
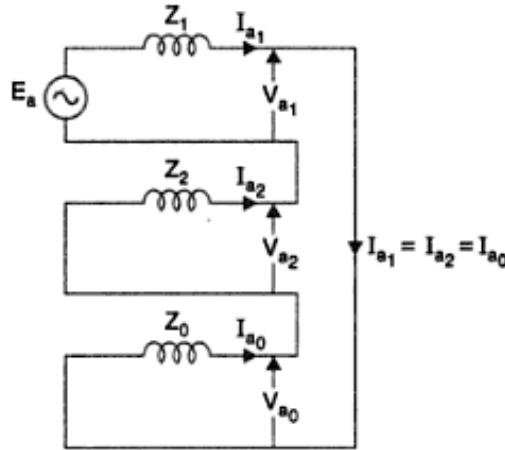
Figure 8 Interconnection of sequence networks for L-G fault

9. Line-to-Line Fault

As given in the figure below, the line-to-line fault takes place on phase b and c. The boundary conditions are

$$I_a = 0$$

$$I_b + I_c = 0$$

$$V_b = V_c$$

And the sequence network equations are same as above. The solution of these six equations will give the six unknowns.
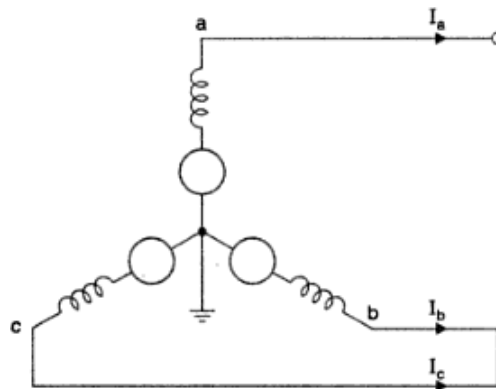
Figure 9 L-L fault on an unloaded and neutral grounded alternator

Using the relation

$$I_{a_1} = \frac{1}{3}(I_a + \lambda I_b + \lambda^2 I_c)$$

$$I_{a_2} = \frac{1}{3}(I_a + \lambda^2 I_b + \lambda I_c)$$

$$I_{a_0} = \frac{1}{3}(I_a + I_b + I_c)$$

And substituting for I_a, I_b and I_c

$$I_{a_1} = \frac{1}{3}(I_a + \lambda I_b + \lambda^2 I_c) = \frac{1}{3}(\lambda - \lambda^2)I_b$$

$$I_{a_2} = \frac{1}{3}(I_a + \lambda^2 I_b + \lambda I_c) = \frac{1}{3}(\lambda^2 - \lambda)I_b$$

$$I_{a_0} = \frac{1}{3}(I_a + I_b + I_c) = 0$$

So from the above relation, the zero sequence component of current is absent and the positive and negative sequence is equal in magnitude but opposite in phase.

$$I_{a_1} = -I_{a_2}$$

To simulate the L-L fault, the zero sequence network is not necessary and the positive and negative sequence networks must be connected in phase opposition.

From the voltage equation,

$$V = \lambda^2 V_{a\,1} + \lambda V_{a\,2} + V_{a\,0}$$

$$V_c = \lambda V_{a_1} + \lambda^2 V_{a_2} + V_{a_0}$$

Substituting the voltage relation

$$V_b = V_c$$
$$\lambda^2 V_{a_1} + \lambda V_{a_2} + V_{a_0} = \lambda V_{a_1} + \lambda^2 V_{a_2} + V_{a_0}$$

So, solving this we get

$$V_{a_1} = V_{a_2}$$

So the positive sequence component of voltage equals the negative sequence component of voltage.

$$V_{a_1} = V_{a_2}$$

$$E_a - I_{a_1}Z_1 = -I_{a_2}Z_2 = I_{a_1}Z_2$$

$$I_{a_1} = \frac{E_a}{Z_1 + Z_2}$$

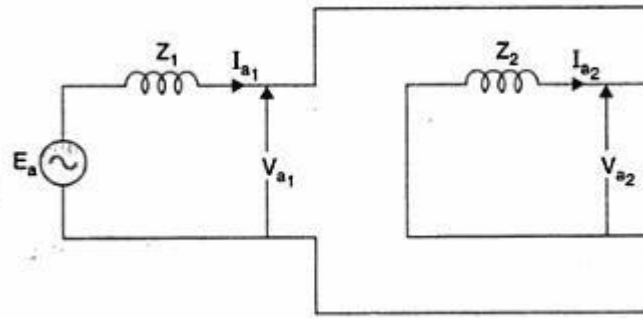The interconnection of the sequence network can be simulated as below

Figure 10 Interconnection of sequence networks for L-L fault

10. Double Line to Ground Fault

Assuming a double line to ground fault on phases b and c. The boundary conditions are

$$I_a = 0$$

$$V_b = 0$$

$$V_c = 0$$

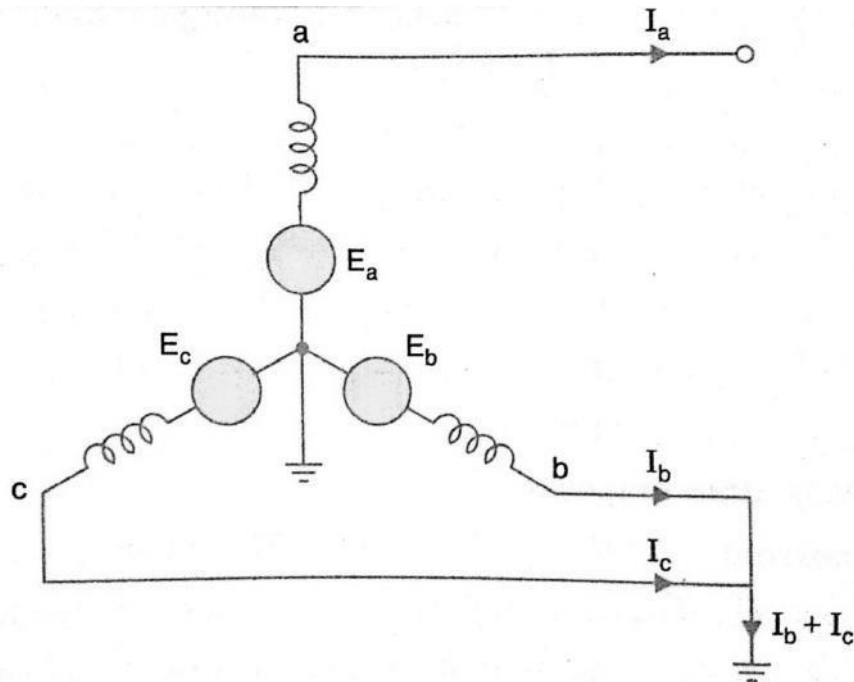And the sequence network equations are given.

Figure 11 A solidly grounded, unloaded alternator, L-L-G fault

The solution of these six equations will give six unknown symmetrical components. Using the symmetrical components of voltage

$$V_{a0} = \frac{1}{3}(V_a + V_b + V_c) = \frac{V_a}{3}$$

$$V_{a_1} = \frac{1}{3}(V_a + \lambda V_b + \lambda^2 V_c) = \frac{V_a}{3}$$

$$V_{a_2} = \frac{1}{3}(V_a + \lambda^2 V_b + \lambda V_c) = \frac{V_a}{3}$$

$$V_{a_0} = V_{a_1} = V_{a_2}$$

Using the above relations,

$$V_{a_0} = V_{a_1}$$

$$-I_{a_0}Z_0 = E_a - I_{a_1}Z_1$$

$$I_{a_0} = -\left(\frac{E_a - I_{a_1}Z_1}{Z_0}\right)$$

Similarly,

$$V_{a_2} = V_{a_1}$$

$$-I_{a_2}Z_2 = E_a - I_{a_1}Z_1$$

$$I_{a_2} = -\frac{E_a - I_{a_1}Z_1}{Z_2}$$

Now from the boundary condition,

$$I_a = I_{a_1} + I_{a_2} + I_{a_0} = 0$$

Substituting the expression for sequence components of current

$$I_{a_1} - \frac{E_a - I_{a_1}}{Z_0} - \frac{E_a - I_{a_1}Z_1}{Z_2} = 0$$

Solving the above equation we get,

$$I_{a_1} = \frac{E_a}{Z_1 + \frac{Z_0 Z_2}{Z_0 + Z_2}}$$

From the above equation it is clear that all the three sequence networks are required to simulate L-L-G fault and also that the negative and zero sequence networks are connected in parallel. The interconnection of the network is shown below
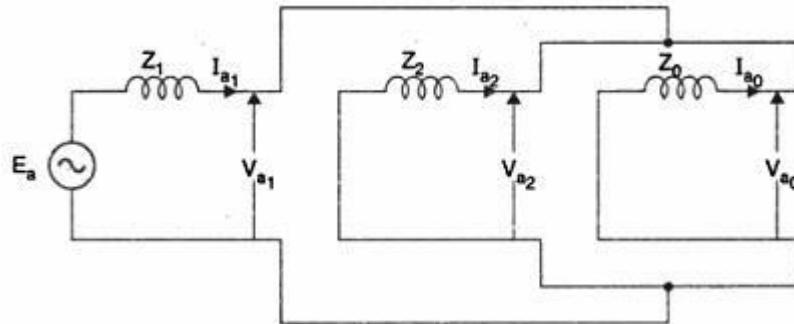
Figure 12 Interconnection of sequence networks for L-L-G fault

The neutral current

$$I_n = I_b + I_c$$
$$= \lambda^2 I_{a_1} + \lambda I_{a_2} + I_{a_0} + \lambda I_{a_1} + \lambda^2 I_{a_2} + I_{a_0}$$
$$= (\lambda^2 + \lambda)_a + (\lambda + \lambda^2) I_a + 2 I_{a_0}$$
$$= -I_{a_1} - I_{a_2} + 2I_{a_0}$$
$$= I_{a_0} + 2I_{a_0} = 3I_{a_0}$$

11. Three Phase Fault

As per the figure given below, the boundary conditions are
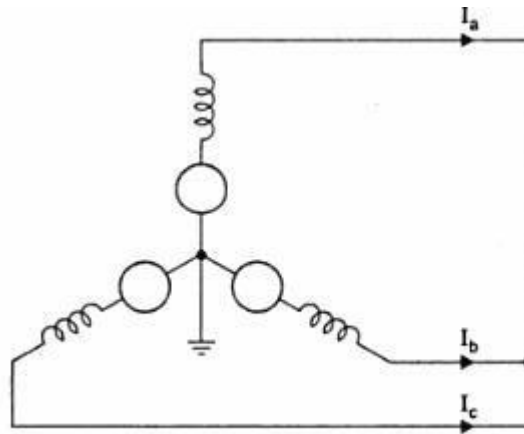
$$I_a + I_b + I_c = 0$$

$$V_a = V_b = V_c$$

Figure 13 A 3-phase neutral grounded and unloaded alternator 3-phase shorted

Since the phase currents are equal in magnitude, taking I_a as the reference

$$I_b = \lambda^2 I_a \text{ and } I_c = \lambda I_a$$

Using this relation

$$I_{a_1} = I_a$$

$$I_{a_2} = 0$$

$$I_{a_0} = 0$$

Similarly, for the sequence voltages, it can be found out as according to the boundary condition

$$V_{a_1} = 0$$

$$V_{a_2} = 0$$

$$V_{a_0} = 0$$

Since,

$$V_{a_1} = 0$$

$$E_a - I_{a_1}Z_1 = 0$$

$$I_{a_1} = \frac{E_a}{Z_1}$$

The sequence networks is shown as below
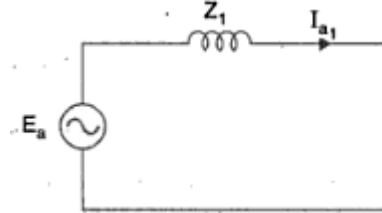
Figure 14 Interconnection of sequence network 3-phase fault

12. Line-to-ground fault with Z_F

When the fault impedance and the neutral impedance are included, the analysis of the single line to ground fault can be analyzed as follows

The boundary conditions are

$$V_a = I_a Z_F$$

$$I_b = 0, I_c = 0$$

$$V_{a_0} = -I_{a_0}(Z_{g_0} + 3Z_n)$$

$$V_{a_1} = E_a - I_{a_1}Z_1, V_{a_2} = -I_{a_2}Z_2$$

From the above equations, the sequence components can be derived as

$$I_{a_1} = I_{a_2} = I_{a_0} = I_a/3$$

$$V_{a_1} + V_{a_2} + V_{a_0} = V_a = 3 I_{a_1}Z_F$$

$$E_a - I_{a_1}Z_1 - I_{a_1}Z_2 - I_{a_1}(Z_0 + 3Z_n) = 3 I_{a_1}Z_F$$

$$I_{a_1} = \frac{E_a}{Z_1 + Z_2 + (Z_0 + 3)_n + 3Z_F}$$

The fault diagram and the interconnection is given below
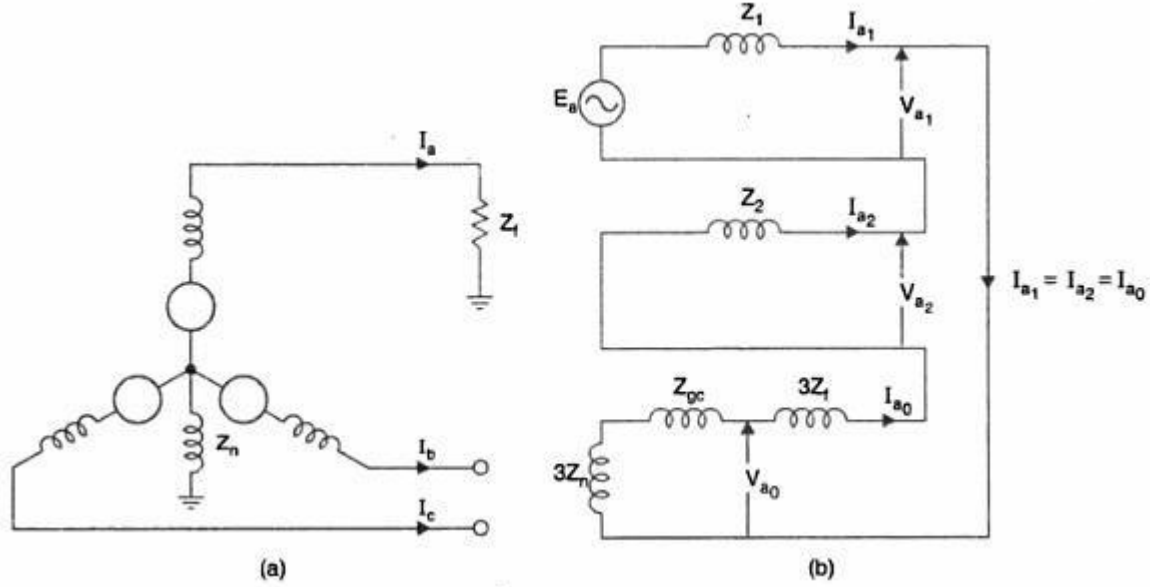
Figure 15 (a) A 3 phase unloaded with neutral grounded through impedance Z_n and fault impedance Z_F, L-G fault (b) Interconnection of sequence network for L-G fault

13. Line-to-line fault with Z_F

The boundary conditions for the same are

$$I_a = 0$$

$$I_b + I_c = 0$$

$$V_b = V_c + I_b Z_F$$

And the sequence network equations

$$V_{a_0} = -I_{a_0} Z_0$$

$$V_{a_1} = E_a - I_{a_1} Z_1$$

$$V_{a_2} = -I_{a_2} Z_2$$

By using the symmetrical component analysis, we get

$$I_{a_1} = -I_{a_2} \text{ and } I_{a_0} = 0$$

Using the above boundary condition, we get

$$V_b = V_c + I_b Z_F$$

$$\lambda^2 V_{a_1} + \lambda V_{a_2} + V_{a_0} = \lambda V_{a_1} + \lambda^2 V_{a_2} + V_{a_0} + (\lambda^2 I_{a_1} + \lambda I_{a_2}) Z_F$$

$$(\lambda^2 - \lambda) V_{a_1} = (\lambda^2 - \lambda) V_{a_2} + (\lambda^2 - \lambda) I_{a_1} Z_F$$

$$V_{a_1} = V_{a_2} + I_{a_1} Z_F$$

Substituting the values by sequence networks, we get

$$E_a - I_{a_1} Z_1 = -I_{a_2} Z_2 + I_{a_1} Z_F$$

$$I_{a_1} = \frac{E_a}{Z_1 + (Z_2 + Z_F)}$$
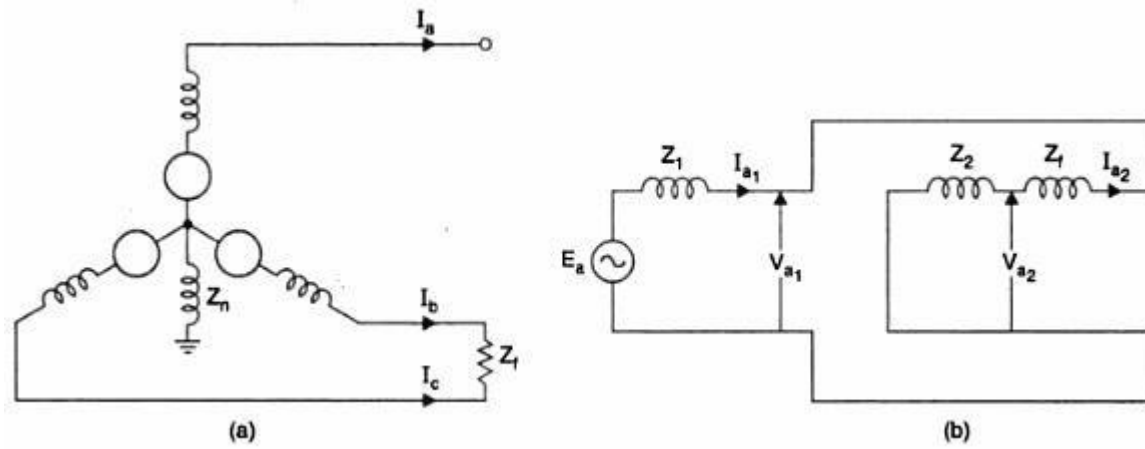
The interconnection is shown in the figure below

Figure 16 (a) L-L fault; (b) Interconnection of sequence network, fault impedance Z_F, L-L fault

14. Double Line to Ground fault with Z_F

The boundary condition for this type of fault is
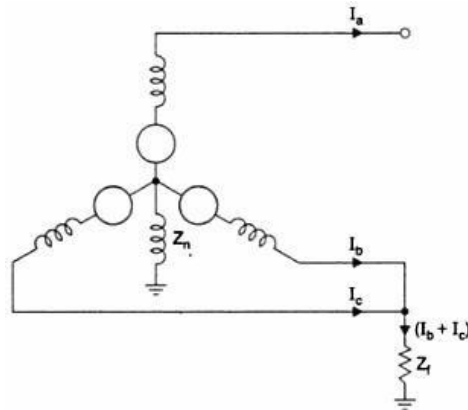
$$I_a = 0$$

$$V_b = V_c = (I_b + I_c)Z_F$$

Figure 17 L-L-G fault. Fault impedance Z_F and neutral impedance Z_n.

And the sequence network equations

$$V_{a_0} = -I_{a_0}(Z_0 + 3Z_n)$$

$$V_{a_1} = E_a - I_{a_1}Z_1$$

$$V_{a_2} = -I_{a_2}Z_2$$

We know that

$$I_b + I_c = 3I_{a_0}$$

According to the boundary condition

$$V_b = V_c$$

$$\lambda^2 V_{a_1} + \lambda V_{a_2} + V_{a_0} = \lambda V_{a_1} + \lambda^2 V_{a_2} + V_{a_0}$$

$$V_{a_1} = V_{a_2}$$

Using the relation

$$V_b = 3 I_{a_0} Z_F$$

$$\lambda^2 V_{a_1} + \lambda V_{a_1} + V_{a_0} = 3 I_{a_0} Z_F$$

$$-V_{a_1} + V_{a_0} = 3 I_{a_0} Z_F$$

$$V_{a_1} = V_{a_0} - 3 I_{a_0} Z_F$$

Substituting the network sequence equations

$$E_a - I_{a_1} Z_1 = -I_{a_0}(Z_0 + 3Z_n) - 3 I_{a_0} Z_F$$

$$I_{a_0} = -\frac{E_a - I_{a_1} Z_1}{Z_0 + 3Z_n + 3Z_F}$$

Similarly,

$$E_a - I_{a_1} Z_1 = -I_{a_2} Z_2$$

$$I_{a_2} = -\frac{E_a - I_{a_1} Z_1}{Z_2}$$

And

$$I_a = I_{a_1} + I_{a_2} + I_{a_0} = 0$$

$$I_{a_1} - \frac{E_a - I_{a_1} Z_1}{Z_2} - \frac{E_a - I_{a_1} Z_1}{Z_0 + 3Z_n + 3Z_F} = 0$$

$$I_{a_1} = \frac{E_a}{Z_1 + \frac{Z_2(Z_0 + 3Z_n + 3Z_F)}{Z_2 + Z_0 + 3Z_n + 3Z_F}}$$

The sequence network for the same is given by the figure below
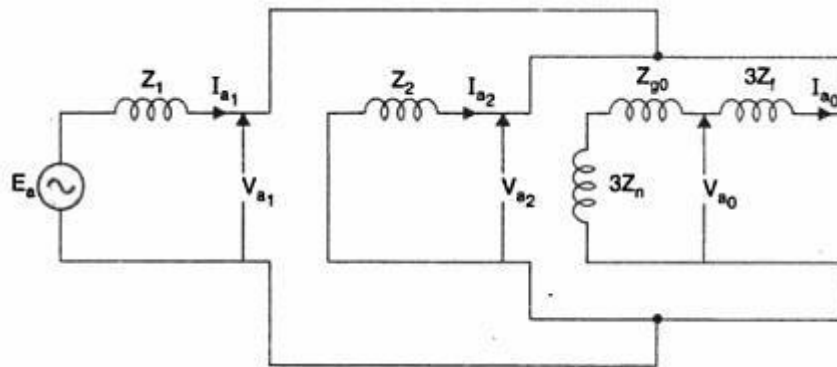

Figure 18 Interconnection of sequence network

15. Faults in Power Systems

The faults in the power system are analyzed by making use of Thevenin's theorem about the point of fault location. The theorem is important as it can determine the changes in currents and voltages of a linear network when additional impedance is added between two nodes of the network.

To determine the distribution in current and voltage in the system, the distribution in each of the sequence networks must be determined. The Thevenin's equivalents of positive, negative and zero sequence networks are equivalent to those of the networks for a single generator.

Considering the system given below, it is needed to find the Thevenin equivalent network for determining the positive, negative and zero sequence networks about the point P.

Figure 19 Single line diagram of a balanced 3-phase system

The Thevenin equivalent of the positive sequence network is obtained from the positive sequence network. The Thevenin equivalent voltage source is the prefault voltage at the fault point P and the equivalent impedance Z_{1eq} is the impedance as seen between the fault point and the zero potential bus shorting the voltage sources.

Similarly, the Thevenin equivalent negative and zero sequence networks are obtained from the negative and zero sequence networks respectively. Since the system is balanced, no negative or zero sequence currents are flowing before the fault occurs. Hence the prefault voltage of both negative and zero sequence are equal to zero.

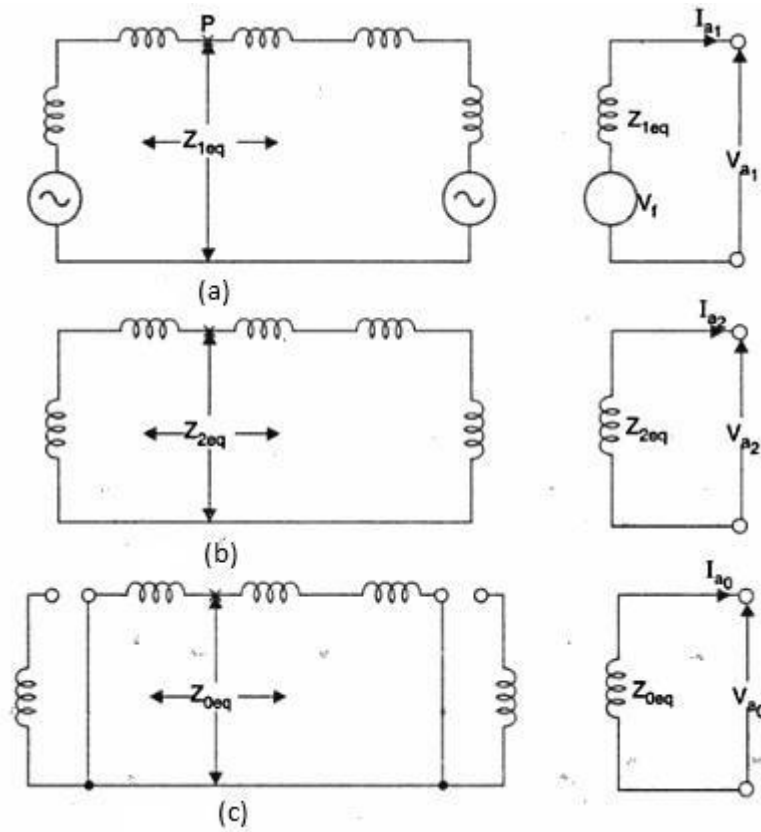The Thevenin Equivalent Network can be given as below

Figure 20 Thevenin's equivalent network of (a) Positive network (b) Negative sequence network (c) Zero sequence network

Chapter-5

APPARATUS PROTECTION

1. Introduction

The two major equipments in a power system are the generators and the transformers. Even though the occurrences of faults in these are very less as compared to that of the lines, the damage due to these faults is severe in lieu of time and money as compared to that of the lines. Rapid reclosing of circuit breakers can clear the fault in case of lines and it helps in saving the amount of damage. But in case of these apparatus, it needs the aid of some attention or supervisory staff. Therefore fast clearing of the faults is necessary to minimize the damage and reduces the interruption to power services from reduced voltage and instability.

2. Transformer Protection

Nature of Transformer Faults

Power Transformers generally develop rare faults as it is static, totally enclosed and oil immersed but if these faults sustain the results may be serious unless the transformer is disconnected. The faults that generally occur in the transformer can be divided as:

1. Faults in auxiliary equipment which is a part of the transformer
2. Faults in the transformer winding and connections
3. Overloads and external short circuits.

Faults in Auxiliary Equipment

The detection of faults in auxiliary equipment is necessary to prevent ultimate failure of the main transformer windings. In these the components are

(i) *Transformer oil*: Oil is used as an insulator in transformer. So when low oil is present the live parts and the bushing leads gets exposed which are supposed to be beneath the oil. Oil level can be determined by the means of alarm indicators for immediate attention.

(ii) *Gas cushion*: The presence of oxygen or moisture may lead to deterioration of the transformer oil. Hence exclusion of this presence is necessary. Since the operating pressure varies within the tank, hence sealing of the tank is not an option. Pressure indicators and conservators are used to counter the expansion and contraction of oil. Whereas silica gel is provided in the breathing vent to absorb the moisture content. Sometimes a nitrogen cylinder is provided to provide an inert atmosphere maintaining the pressure between 0.5 and 0.8 atm.

(iii) *Oil pumps and forced air fans*: The top oil temperature normally gives the indication of the load on the transformer. A rise in temperature would indicate an overloading situation or due to the fault in cooling system. A

thermometer with alarm contacts will indicate the temperature rise in oil due to any of these faults.

(iv) *Core and winding insulations*: These faults can turn into major faults if not taken care of. Insulation failures may develop if

(a) The insulation of the laminations and core bolts may be of poor quality.

(b) Poor quality of insulation between windings or between winding and the core.

(c) Badly made joints or connections.

Winding Faults

Electrical Faults that can cause immediate serious damage and are determined by the presence of unbalanced current or voltage may be divided into following classes:

(i) Faults between adjacent turns or parts of coils such as phase-to-phase faults on the HV and LV external terminals or on the winding itself or short circuits between turns of HV and LV windings.

(ii) Faults to ground or across complete windings such as phase-to-earth faults on either HV or LV side.

A short circuit between turns can start with a point contact resulting from mechanical forces or insulation deterioration due to excessive overload. The puncture of the turn insulation would cause a path through which the normal frequency voltage can maintain an arc. But if the voltage is insufficient to maintain the arc, it would be quenched by the oil present.

In the second case the ground faults are easy to detect as they are characterized by emission of large amount of gas due to decomposition of oil as well as in large values of fault currents. Rapid clearance is necessary to avoid excessive damage and to maintain stability.

Overload and External Short Circuits

Overloads can be persistent in the system provided the temperature rise in the windings is within the limits. Excessive overloading can cause deterioration in insulation and subsequent failure. An alarm indication can be initiated when the temperature limits exceed. External short circuits may only be limited by the transformer reactance, so a low value would result in excessive fault currents.

Differential Protection of Transformers

The best way of protection of any apparatus against an internal fault is by the method of differential protection scheme since it covers the apparatus' zone of protection. So for a transformer having ratings of 5 MVA and above, the differential scheme serves as an important protection against internal phase-to-phase and phase-to-earth faults. Any fault in the protected part would result in the deviation

of the current intensities at the input and output. So the result of this unbalance current can be employed for the tripping of the relay. For this reason the differential scheme combines the characteristics of selectivity and highest tripping time of the relay. A particular differential scheme is given below for a three-phase star delta transformer.
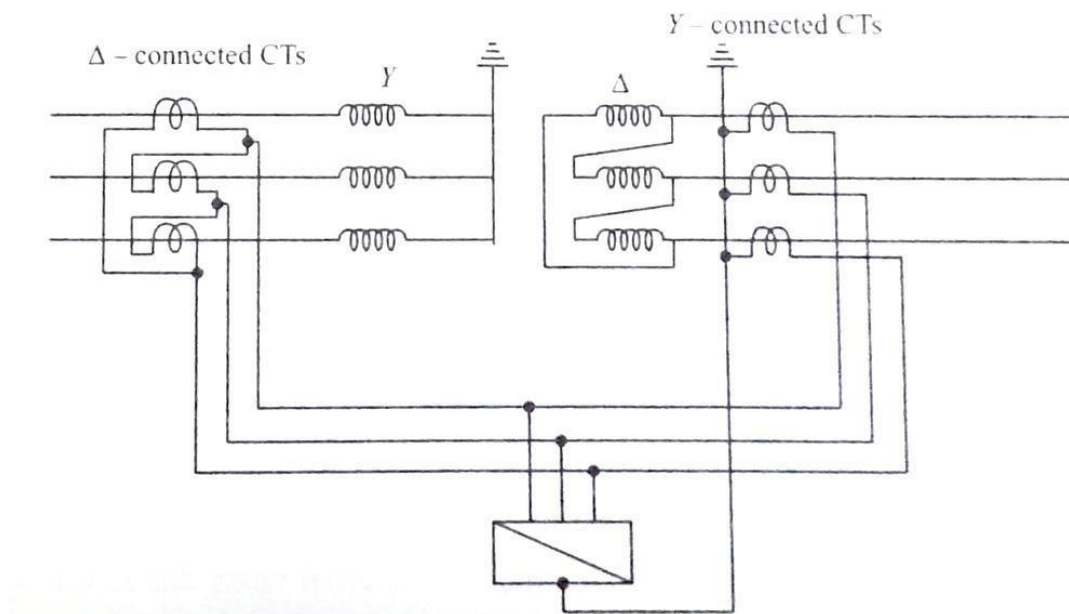

Figure 21 Differential Protection Scheme of star-delta transformer

For the relay to detect 0 spill current in normal operation, the currents incoming from both the CTs should be in direct opposition. Since in a star delta transformer the line currents have a displacement of 30°, so the CTs have to be connected in delta on the star side of the transformer and in star for the delta side to avoid any spill current through relay in normal operation. Another advantage of this connection is the avoiding of triplet harmonics to appear on the line currents due to delta windings.

Problems Encountered in Differential Protection of Transformer
Even though setting of the ratios are done the scheme also suffers from drawbacks in it like

(i)   *Unmatched characteristics of CTs*: The differential scheme employed for protection fails in the case of different CT ratio characteristics. Since the saturation characteristics are different, if they are not avoided would result in appreciable amount of spill current flowing through the relay.

(ii)   *Ratio change as a result of tapping*: Most of the power transformers are provided with a tap changing equipment used for altering the turns ratio. It is impracticable to change the CT ratio for compensating this effect of tap changers. Biased relay can be employed for the overall protection of variable-ratio transformers.

(iii)   *Magnetizing Inrush current*: When the transformer is re-energized, the transient inrush of the magnetizing current flowing is as high as ten

times the full load current as it depends on the flux trapped in the core of the transformer and the instant of the voltage cycle at which it is switched. Even though it's not a faulty condition, but depending on the magnitude of the current the differential scheme would trip.

Percentage or Biased Differential Relays

Since there is a mal-operation of the normal differential scheme and their associated drawbacks in the through fault and variable tap changing conditions, the scheme is modified by providing a restraining winding which is energized by the through current. This makes the operating winding biased or in other words it is made to operate by some percentage of the through current. This makes the relay more sensitive at low current without tripping for external fault.

If the ratio of restraining and operating coils is given as T, i.e.

$$\frac{N_r}{N_o} = T$$

Then the criterion for operation for a static comparator is:

$$|\frac{I_1 - I_2}{T}| > |\frac{I_1 + I_2}{2}|$$

Or for an electromagnetic comparator

$$|\frac{I_1 - I_2}{T}|^2 > |\frac{I_1 + I_2}{2}|^2$$

The value of this turns ratio T is generally 0.05 for generators and between 0.1-0.4 for transformers. Higher values are used if the transformer ratio is varied by tap changing equipment.
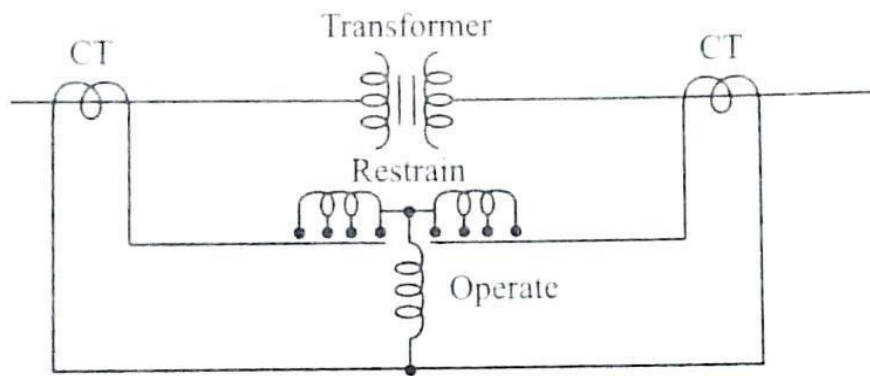

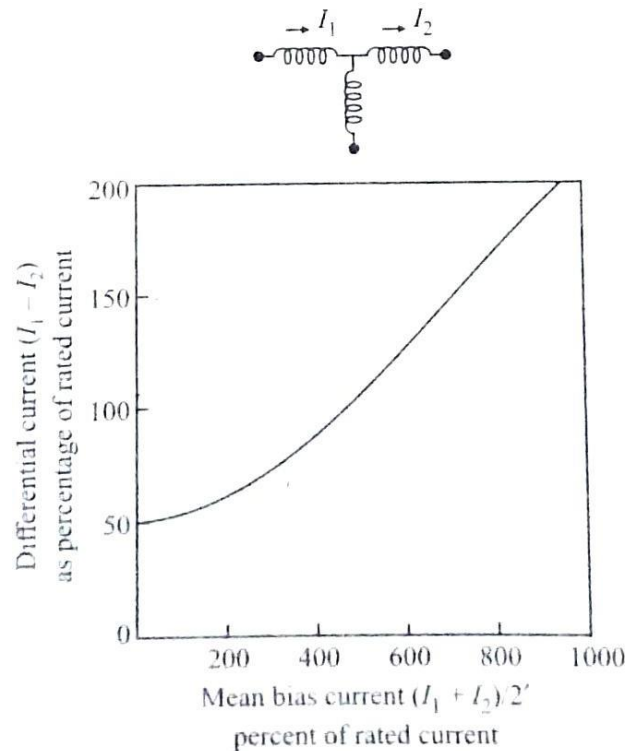**Figure 22 Biased Differential Protection for a transformer**

Figure 23 Biased Characteristics of biased differential relay for transformer protection. Setting 50% and bias 20%

Figure 2 shows the single line diagram for the biased differential scheme for the transformer. Figure 3 gives the bias characteristics for a typical relay.

Methods for Preventing Operation on Inrush Currents

Magnetizing inrush currents is rich in harmonics unlike that in internal faults where the current is sinusoidal. So modifications are made in the construction of the relay. Since, the inrush current is rich in harmonics; the operating current is made to filter out these harmonics before being fed to the operating coil. This helps in the high speed and low operating current condition. Some of the methods are:

(i) *Even Harmonic cancellation*: For a typical inrush current waveform the harmonics as a percentage of fundamental is given as

		HARMONICS						
Component	Fundamental	D.C.	2nd	3rd	4th	5th	6th	7th
Typical Value percent	100	55	63	26.8	5.1	4.1	3.5	2.5

In this the 3rd harmonics and its multiples are removed since the connections are made in delta on the transformer for star connected CTs and CTs in delta for the star side of the transformer. The dc components and even harmonics can be cancelled out in the operating circuit of the rectifier bridge relay and can be diverted on to the restraining circuit. Since the magnitudes of the 5th and 7th are small so they can be ignored.

(ii) *Harmonic restraint*: This is the most extensively used methods for making the relays immune to harmonics caused by inrush. The restraint coils is

energized by the dc equivalent of bias winding current as well as the harmonics. Harmonic restraint circuit is formed by tuning $X_C X_L$ which would permit only currents of only fundamental frequency to enter the operating circuit while the dc and higher harmonics are diverted onto the restraining winding. But this circuit may prove to be failure if the internal faults are also rich in harmonics which may be caused due to an arc or if the CT saturates and produce harmonics. For this purpose an instantaneous over current relay is provided in the differential circuit which is set above the maximum inrush current but will operate in less than one cycle on internal faults. The circuit for the same can be given as below
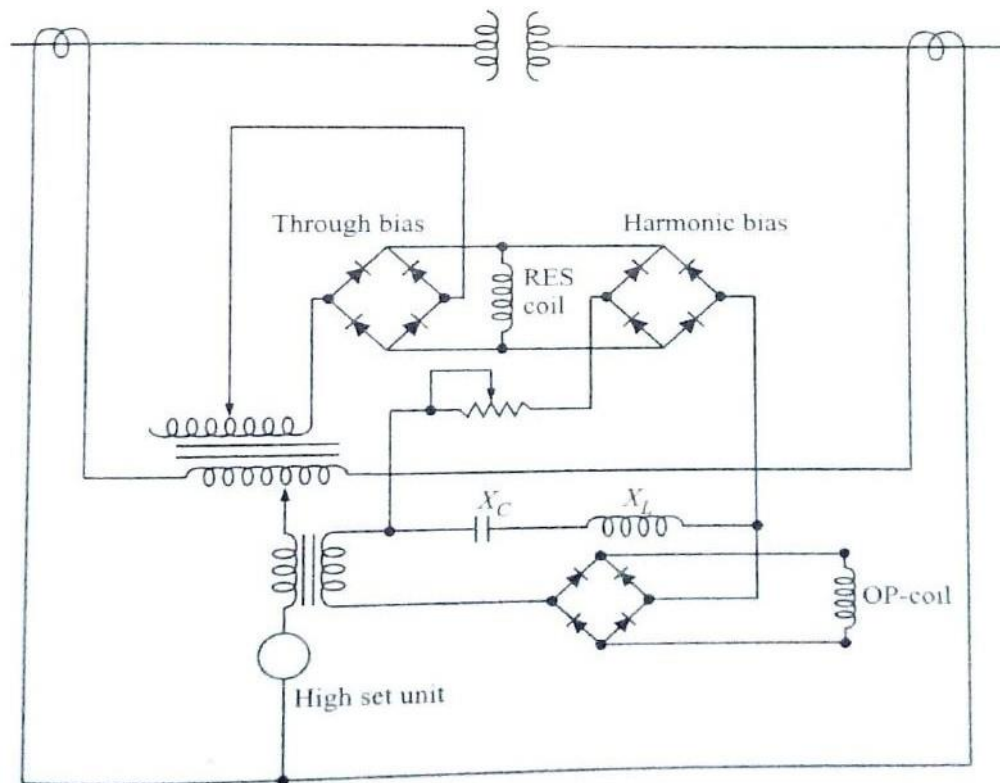
Figure 24 Basic Circuit of harmonic restraint relay

Influence of Winding connections and Earthing on Earth fault Current

The intensity of the earth fault current depends on the point in the winding where the fault has occurred and also on the winding connection and the method of neutral earthing. The conditions required for the flow of earth fault current from winding to earth are:

(i)   A path must be there for the flow of current in and out of the winding.
(ii)   The ampere-turns balance must be maintained between the windings.

From the first condition it is not necessary for the windings to be earthed for the current to flow as in case of star grounded side of the transformers. For the delta side windings, the earthing is done by the use of earthing transformers.

Star Winding with Resistance Earthed Neutral

In the case of resistance earthed neutral on the star side the magnitude of fault current depends on the value of earthing resistance and is proportional to the distance from the neutral end of the winding where the fault has occurred. If we consider a delta star transformer, having a neutral earthed resistor of 1:1 voltage ratio or the turns ratio on the primary to secondary side is $\sqrt{3}$:1. So for an earth fault current I_F at 100% of the winding on the secondary side the primary current corresponding to the same would be $1/\sqrt{3}$ times the fault current on the secondary, i.e., $(1/\sqrt{3})I_F$. Now as the fault position on the secondary varies, the magnitude of the fault current as well as the effective turns ratio between the primary and the secondary varies. For example, if the earth fault occurs at $x\%$ of the winding, the current on the secondary side would be $(x/100)\,I_F$. Hence the effective turns ratio would be $\sqrt{3}$: $x/100$, since $x\%$ of the winding would be active through which the current flows. This results in primary current having a value $(x/100)^2 I_F/\sqrt{3}$. Thus the primary current is proportional to square of the percentage of winding that is short circuited. The variation is shown in the figure below.
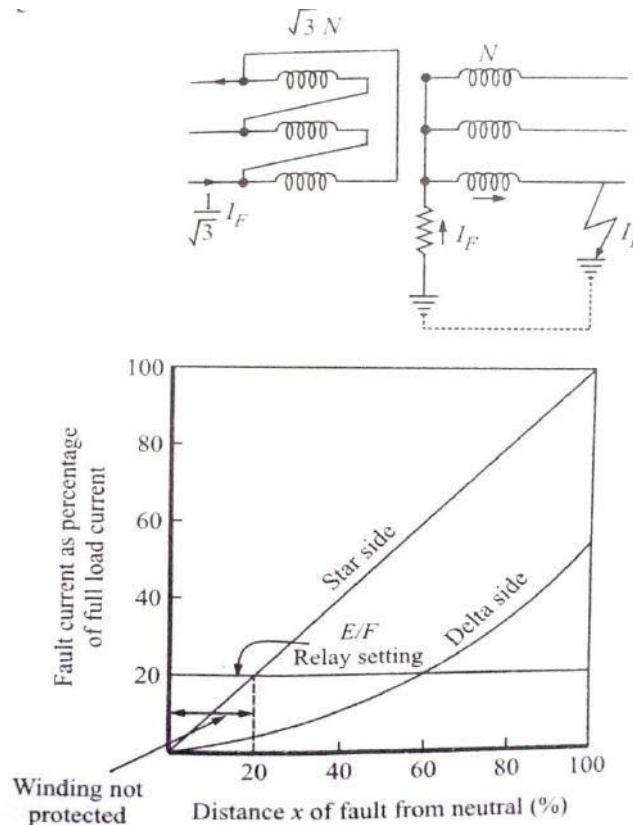
Figure 25 Transformer earth fault for resistance-earthed star winding

Star Winding with Neutral Solidly Grounded

The earth fault current unlike is resistance earthed is limited only by the impedance of the winding itself, and since the impedance is a variable quantity depending on the amount of winding that is faulted, the current no longer bears a linear relationship. The reason is that the leakage reactance of the faulted winding

is more near to the star point, but the reactance of the other windings are reduced owing to the change in the transformation ratio. So the minimum fault occurs close to the middle of the winding.
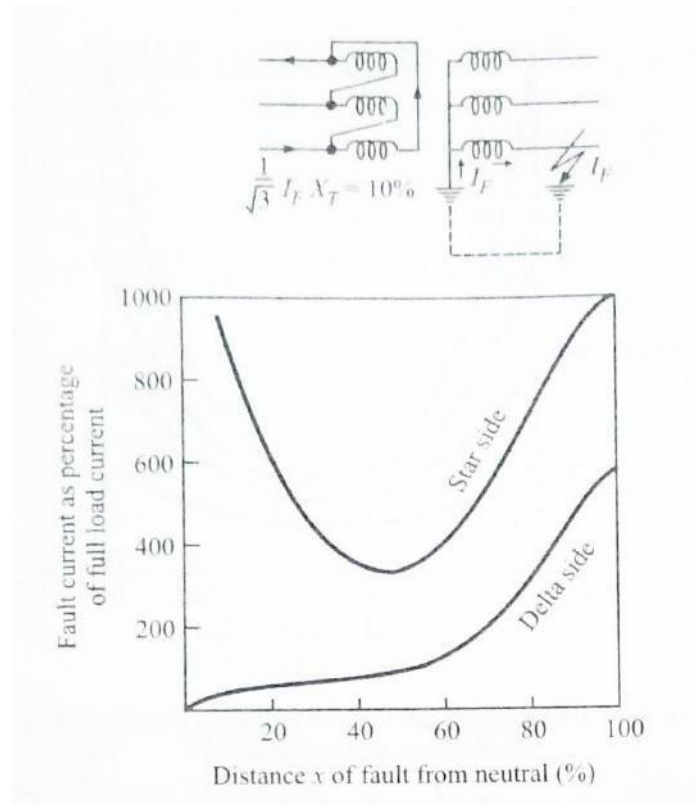

Figure 26 Transformer earth fault for solidly earthed star winding

Delta Winding

The minimum voltage that can appear in the delta winding is only half the phase voltage and occurs at the midpoint of the winding. If the windings are not resistance earthed, depending on the leakage reactance the current may rise to about 200% of the full load current. If resistance earthing is employed the net impedance rises by the vector addition of resistance with the net reactance. But if the resistance is made to counter the orders of full load current, the minimum current that can flow would be V/2R.
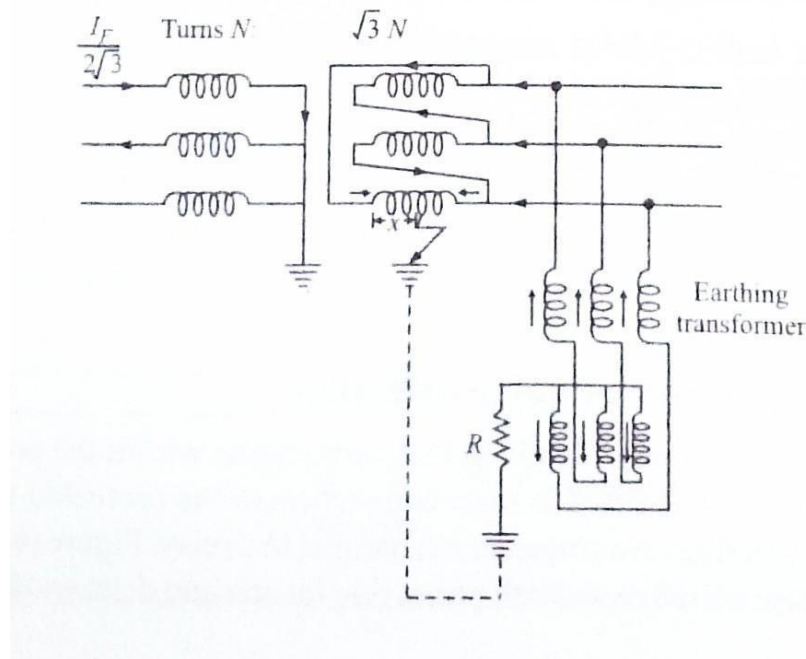
Figure 27 Transformer earth fault for a delta winding system, resistance earthed

Overcurrent and Earth Fault (Unrestricted)

The Overcurrent protection can be done by the use of IDMT relays for protection against excessive overloads and external short circuits. This protection scheme acts as a backup protection for the transformer. The current setting is so chosen that it would cater for above the permitted overload allowance and below the minimum short circuit current. This types of relay is kept on the supply side and would operate for both the LV and HV side breakers.

Tank Leakage Protection

If the tank is not highly insulated or where the insulation resistance is of 10 ohms, there might exist a chance of insulation breakdown between the transformer tank and earth. So an earth fault protection scheme can be employed by connecting a relay to the CT secondary whose primary is connected between the tank and the ground.

Restricted Earth Fault Protection

This type of protection if there is an earth fault within the internal zone of protection of the transformer. In this CTs are connected in each phase and the secondary of each CT is connected in parallel. The connections are made so because this leads to the addition of currents which is proportional to the zero sequence currents, which exists if and only if there is an earth or ground fault. When it is an internal fault the current adds up to twice the fault current. But in case of external faults this sum is zero. A typical connection in restricted earth fault protection for transformer is given as below
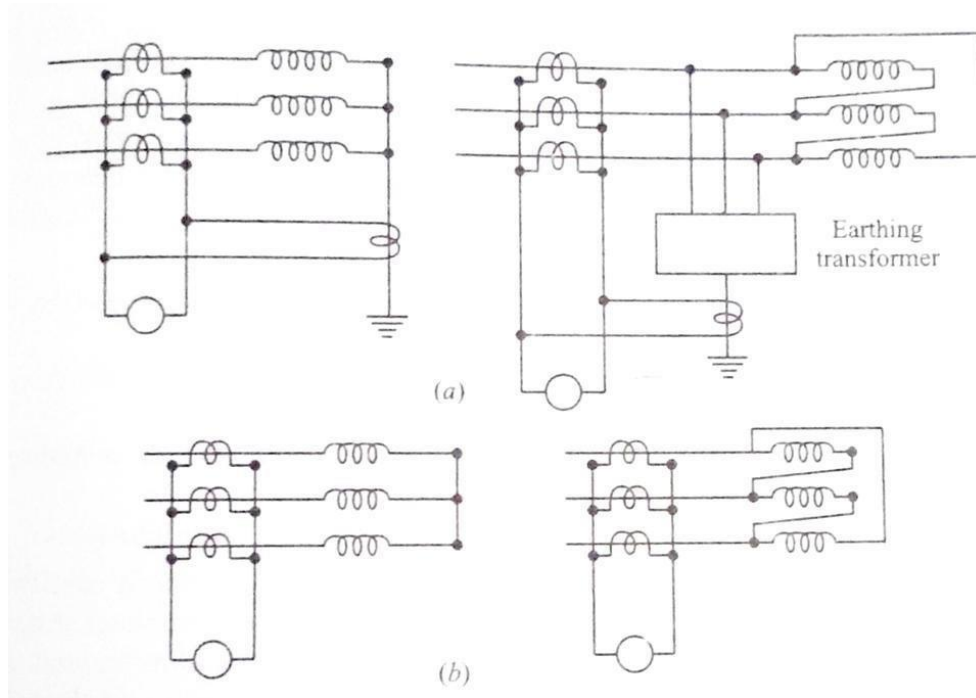
Figure 28 Restricted Earth Fault Protection: *(a)* **neutral earthed within the protected zone;** *(b)* **neutral not earthed within the protected zone**
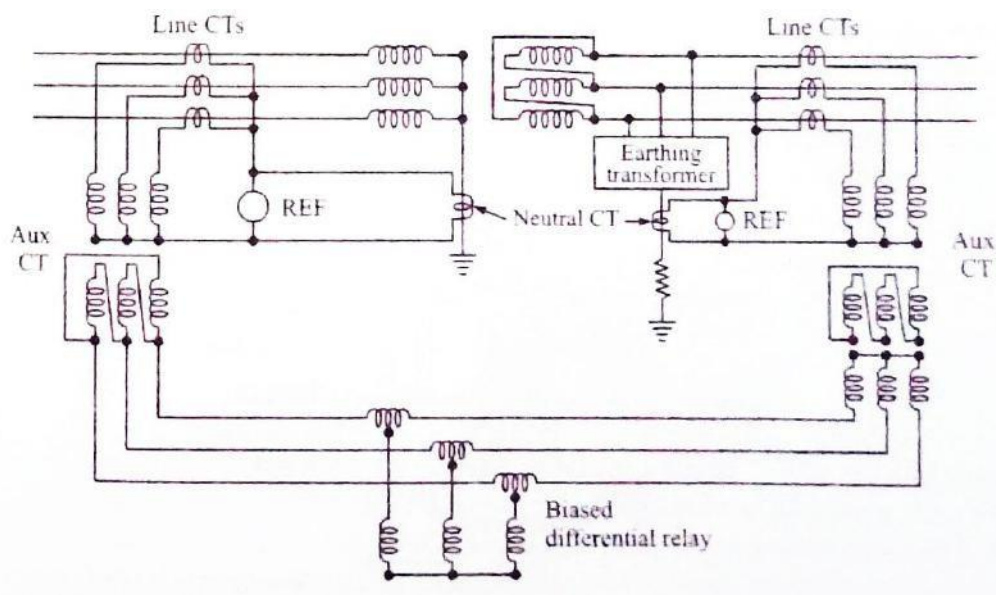

Figure 29 Differential and restricted earth-fault protection of a star-delta transformer

Gas Actuated Relays

When there is a fault in the transformer tank, it leads to the gas formation in the tank itself, which is slow for the incipient faults and violently for heavy faults. The gas which is formed due to decomposition of the oil which is caused by the high amount of heat produced by the local currents can be made use of for detecting the faults. One of the famous relays in this context is the Buchholz Relay.

It is the simplest type of relay consisting of a chamber connected between the conservator and the transformer main tank. Within the chamber, it consists of two cylindrical floats, one at the top of the chamber and the other opposite orifice of the pipe to the transformer. In the normal conditions the floats are up, but when there is an incipient fault like an inter turn fault, the gas which is formed due to it moves up in the direction of conservator. On moving up they are trapped inside the relay chamber and thereby reducing the oil level. This results in upper float to fall down which was initially kept up by the oil level. When this float reaches a predetermined distance, it closes the contact and gives an alarming signal to the personnel.

But when the fault is heavy, the surge of gas and oil engages the lower float also to be pushed down which in turn trips the circuit breaker.
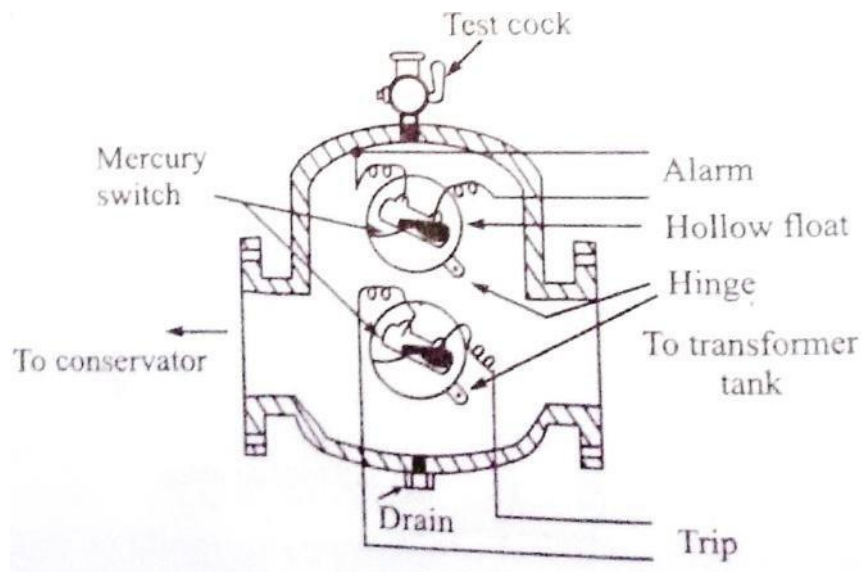
Figure 30 Buchholz Relay

Transformer Feeder Protection

In a method to supply bulk power from a major switching station, sometimes the transformer is connected directly without any provision of switchgear. Even though it is cost effective, but it would require adequate protection schemes. In addition to the protection provided for transformer and feeder when considered separately, the need for some means of inter-tripping between the HV and LV circuit breakers becomes essential.

For countering this, two basic systems of protection can be done: unit and non-unit systems. In unit systems, the differential scheme can be applied separately for the transformer and feeder or considering both the transformer and feeder as an overall unit. In both the cases pilot wire is required. In non-unit systems, it provides back up protection for both the faults occurring outside the protected zone as well as that in the zone faults.
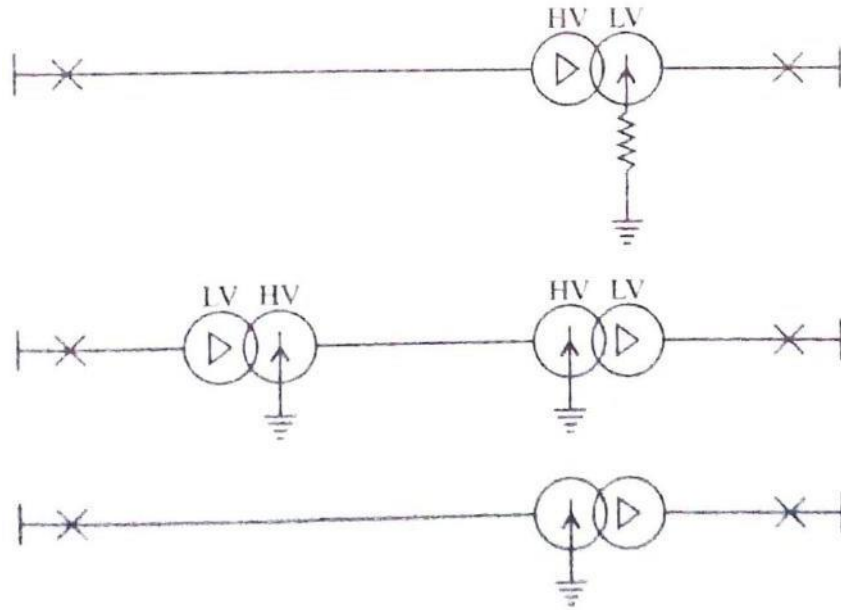
Figure 31 Typical transformer feeder circuit

3. Generator Protection

The generator is the prime equipment in the power system. The increased size of the generators and even greater increase in their capacity makes the imperative to protect them against fault. Unlike other apparatus only isolating the circuit breaker is not enough to prevent further damage as the generator would still supply power to its stator windings until the excitation is suppressed. So for isolation it is needed to open the field to avoid any excitation, and to stop the fuel supply to the prime mover.

Generator faults

Generator faults can be considered as follows.

(a) *Stator faults*: These include the following
  (i) Phase to earth faults.
  (ii) Phase to phase faults
  (iii) Inter turn faults

  The stator is prone to maximum amount of faults in the system with phase to earth fault being the most common. The inter turn faults and phase faults are less common but develop into an earth fault in the long run.

(b) *Rotor faults*: The faults that exist in the rotor can be either earth fault or an inter turn fault. These faults are mainly caused by the mechanical and thermal stress acting upon the winding insulation. The existence of such fault may be taken care of as the incidence of second fault may short circuit some part of the field winding which would result in the asymmetrical air gap flux which may cause vibrations and result in damage to the bearings. In the modern era, the practice is to operate the field winding isolated from

the earth so that a single fault between field winding and rotor body due to insulation breakdown can be tolerated.

(c) Abnormal running conditions: The abnormal running conditions that can occur are: *(i)* loss of excitation, *(ii)* unbalance loading, *(iii)* overloading, *(iv)* failure of prime mover, *(v)* over speeding, and *(vi)* over-voltage.

Field failure may occur due to a faulty field breaker. When a generator loses its excitation, the amount of reactive power supplied to the system is lost. Instead it would draw excitation from the system while delivering real power at leading power factor. This leads to an operation of an induction generator where the speed is slightly increased. Also due to loss of excitation there would be a voltage fall which would lead to loss of synchronism. The situation may also lead to overheating in rotor and damper windings.

If there is any unbalance in the system due to a phase fault or due to the unbalance loading, it gives rise to negative sequence currents. It produces an armature reaction field which rotates in a direction opposite to that of the rotor and hence produces a flux which is twice the frequency. These currents are linked to the rotor and damper windings which produces heating in the windings.

When there is an overloading in the generator, it would draw more current and as a result would produce more heating loss in the stator which may damage the insulation.

When there is a failure of prime mover, the real power delivering capacity is lost and instead it would draw power from the system making it to run as a motor. This affects the drive of the system due to opposite torque being applied on to the shaft.

When a sudden load is removed then according to the AGC control, the machine is going to over speed. This happens mainly in the hydraulic generators since the water flow cannot be immediately stopped for the inertia in water motion.

Over voltages may occur due to the failure in the AVR control in the excitation or may be due to over speeding.

Stator Protection

As discussed, the most common fault that happens in stator is the earth faults. Since an earth fault near the generator is very critical as the magnitude of the current is very high, so the current is limited by either a resistance connected in the neutral circuit. Depending on this value the current can be limited to either 200 to 250 A which is done by resistor earthing or 4 to 10 A by distribution transformer earthing. Even though the second method has an advantage of reducing the damage on to the stator core, the practicability of this method is limited if the transformer is connected in delta.

In the resistor earthing, the resistance is connected between the neutral and the ground and the CT is mounted on the neutral with an IDMT or an instantaneous attracted armature type relay. The maximum value of resistance is given by

$$R_n = \frac{10^6}{6\pi f C} \; ohms$$

Where C is the capacitance of the stator circuit to earth per phase in microfarad and f is the system frequency.
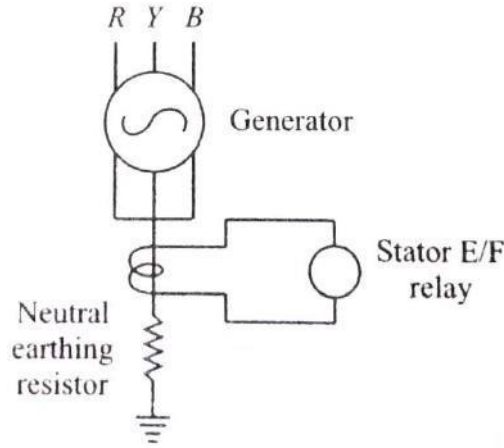

Figure 32 Location of E/F relay in a resistance earthed generator

If the neutral is earthed through the primary winding of a distribution transformer, earth-fault protection is provided by connecting an over-voltage relay across its secondary, then the maximum value of resistance is equal to

$$R_n = \frac{10^6}{6\pi f N^2 C} \; ohms$$

Where N is the turn ratio of the transformer.

Generator differential protection: The best form of protection for the stator windings against all the internal faults is by the use of differential protection. The relay recommended for this application is instantaneous attracted armature type which is immune to ac transients and has the high speed feature if the CTs are reasonably matched. But when the CTs have dissimilar characteristics, biased differential relay can be applied as it would result in high amount of spill current flowing through the relay.

A particular longitudinal biased differential relay protection scheme for the generator is given as below
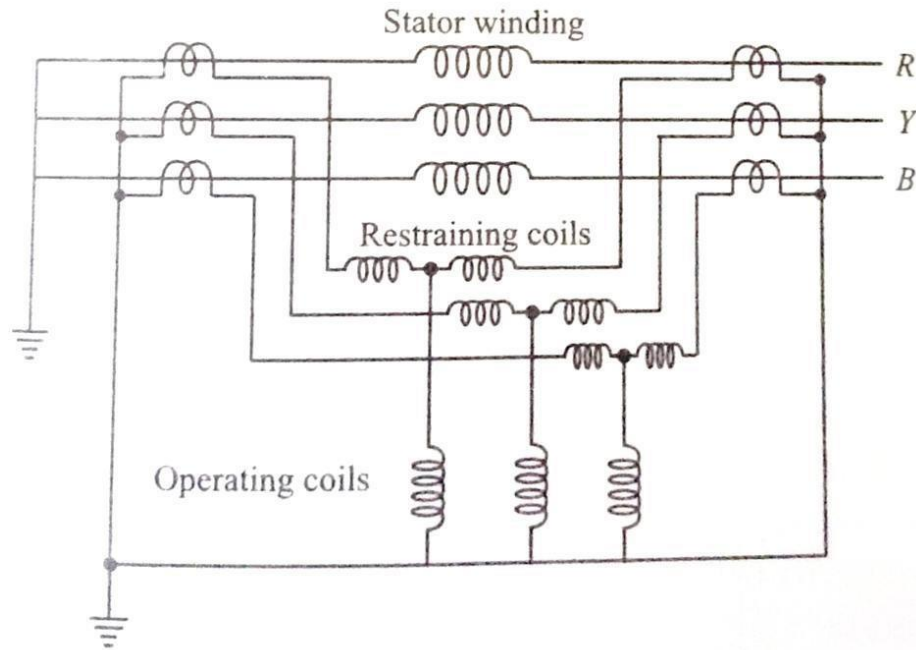
Figure 33 Percentage Biased differential relay

Stator Inter turn fault protection: An inter-turn fault occurring on the same phase of the stator winding do not disturb the neutral current, hence by the use of longitudinal differential relay it is not possible to detect such type of fault. This results to another modification in the protection designing whereby we make the transverse differential relay in case of the generators where the stators have two windings per phase. The protection scheme is given as
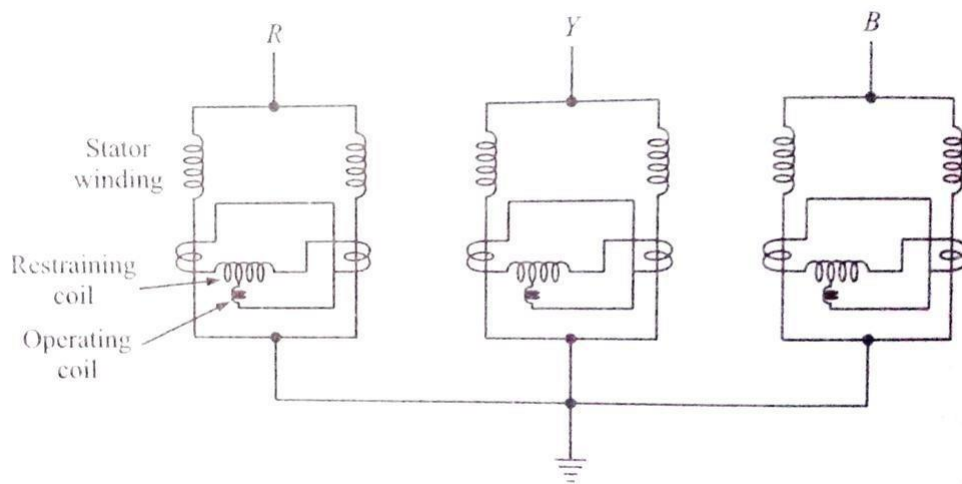
Figure 34 Biased Transverse differential protection for inter turn fault protection for 2 winding stator

Wherever single winding is present the protection of generators against inter turn fault is done by using zero sequence voltage caused by the reduction of emf in the faulted phase. One of the connections is given as
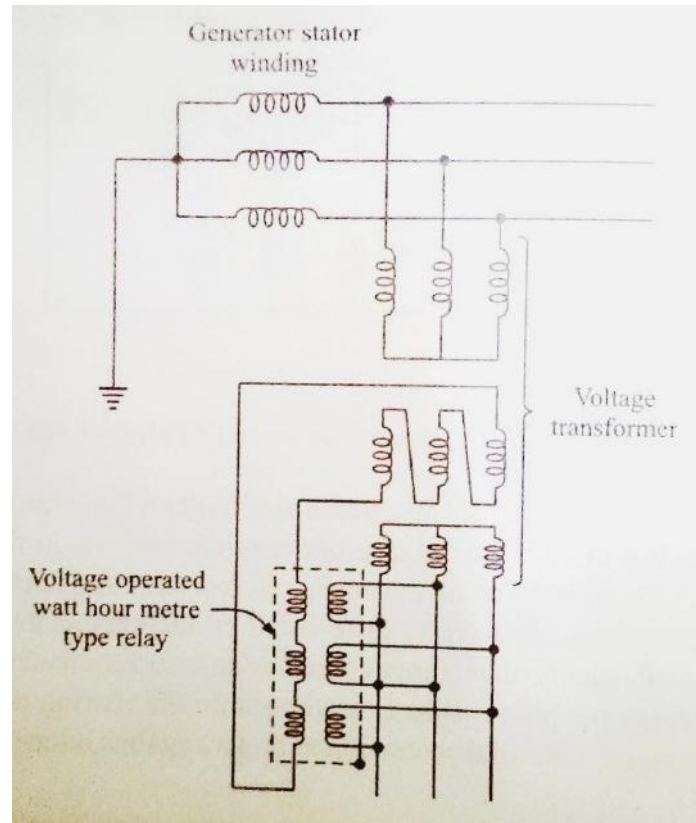
Figure 35 Inter Turn fault detection

Rotor Protection

The rotor windings as discussed earlier may be due to earth faults or open circuits. The figure shows a modern method of rotor earth fault detection. The field is biased by a dc voltage which causes current to flow through R for an earth fault.
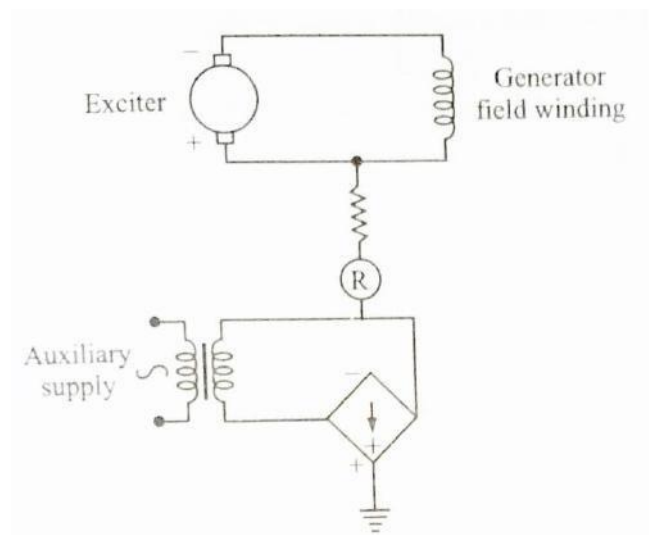

Figure 36 Rotor Earth Fault Detection

Loss of Excitation (Field Failure) Protection

As discussed, the loss of field circuit imposes the circuit to draw reactive VAR from the system. This results in machine being operated as an induction generator. This causes overheating in the circuit.

Loss of excitation is detected by the import of VAR indicating either actual or prospective loss of synchronism. So the transients in such phenomena can be allowed for 1 to 5 seconds in tripping sequence of the relay.

Due to the loss of excitation, there would be a drop in voltage and resulting in the drop of current. This can be detected by an undercurrent moving coil relay in the field circuit. Even this method is not suitable for generators having wide range of operation in the field excitation.

The alternative solution that can be implemented is to apply an offset impedance or mho relay. Its operating characteristics are arranged so that during conditions of low excitation the effective generator impedance falls in the tripping zone.
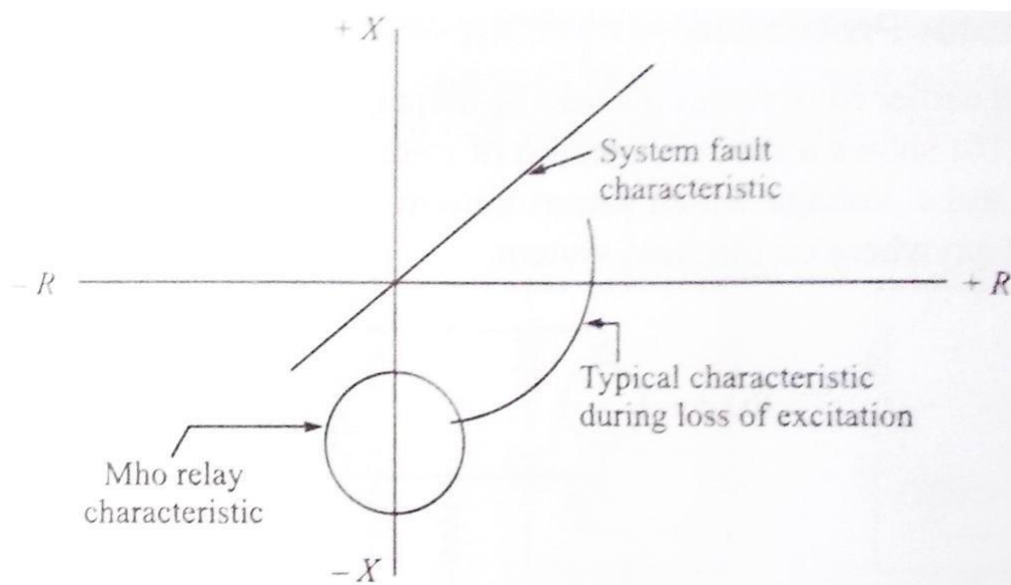

Figure 37 Loss of excitation characteristic

Unbalance Loading Protection

An unbalance loading situation gives rise to negative sequence currents in the rotor circuit which causes the heating in the circuit. The negative sequence currents move at twice the supply frequency and follow a normal resistance law. In case of high speed turbo generators this value is about 10 to 15% of the positive sequence currents. The heating time constant is expressed by a rating equation

$$I_2^2 t = K$$

Where I_2 is the negative sequence current based on per unit basis of continuous maximum rating, t is the time in seconds and K is a constant usually varying between 3 and 20.

An IDMT relay almost matches the heating characteristic of the negative sequence current and can be detected by using an NPS filter as given below
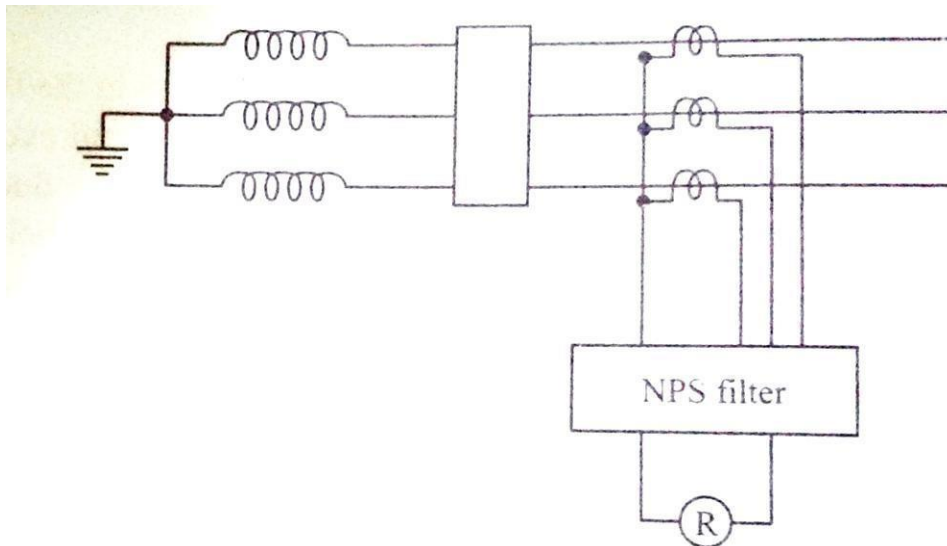
Figure 38 Protection against unbalanced load using negative sequence filter

Overload Protection

Overloading in the generator causes the stator windings to overheat. A provision of overcurrent relay is not an obvious solution as it wouldn't be able to discriminate on the basis of time. The relay must be so chosen so as to counter for the slowest relay on the system the generator is feeding. The simplest way is to detect the overloading condition by the means of temperature detection coil connected in a Wheatstone bridge.
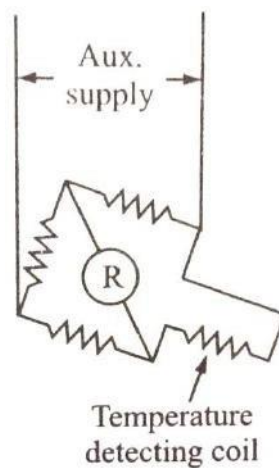
Figure 39 Stator overheating protection using temperature detector coils

Prime mover protection

When there is a failure of prime mover, the machine starts to act as a motor drawing real power from the system and thereby driving the prime mover. This condition imposes a balanced load on the system. A reverse power relay can be used to detect the tripping characteristics in this type situation since there is a change in the direction of flow of power working over the full power factor range.

Under such conditions, the load coming on the machine is very low of the order of 1% of the machine rating. Even though it is a small amount, the condition can be harmful sometimes in case of steam turbines where the steam acts as coolant, maintaining the turbine blades at a constant temperature and the failure of steam results in overheating along with distortion of blades.
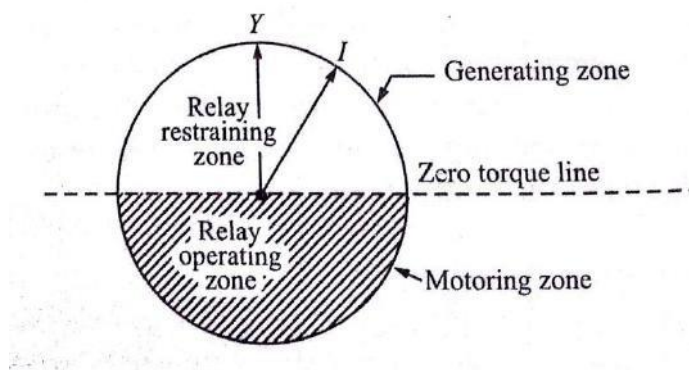

Figure 40 Reverse Power Relay operating characteristics

Over-speed Protection

Over speed protection is the most necessary protection in case of hydraulic generator sets unlike the case in steam sets which as fast acting governors. A provision of reverse or under power interlock relay is provided to prevent the main generator CB from tripping in non emergency situations. A provision of centrifugal switch is provided at the shaft which flies out and closes the valve when speed exceeds 10%.

Overvoltage Protection

Overvoltage protection is provided on machines which are subjected to over speed on loss of load. The relay is energized from a single phase voltage transformer, having the characteristics similar to IDMT characteristics.

Protected Scheme for a Direct Connected Generator

Direct Connected generators normally of smaller ratings consists of the following protections

   (i)   Unbiased differential protection
   (ii)   Back up overcurrent protection
   (iii)   Negative phase sequence protection
   (iv)   Standby earth fault

In addition to these protections the following may also be provided

   (i)   Field failure protection
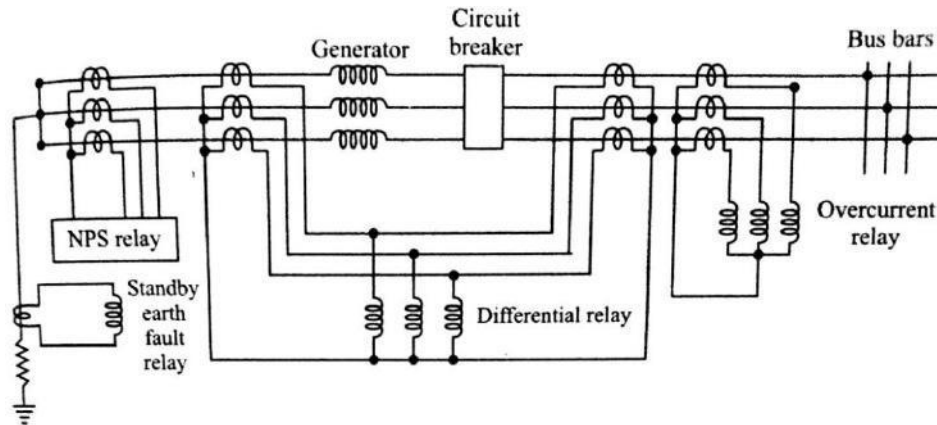   (ii)   Rotor earth-fault protection
   (iii)   Reverse power protection

Figure 41 Typical Protective scheme for a 30 MW direct connected generator

4. Motor Protection

The motor acts as the important loads in the power system as they compose mostly 90% of the loads. The protection of these apparatus becomes very important. The motors that are taken into consideration are synchronous and induction motors.

Types of Faults

The faults that occur mostly in the motor are almost similar to that of the generators. The faults can be classified as:

(a) Stator Faults
(b) Rotor Faults
(c) Overloads
(d) Unbalanced supply voltages including single phasing.
(e) Under voltage
(f) Reverse or open phase starting
(g) Loss of synchronism

Stator Protection

The faults that occur in the stator can be either between phases or to the earth. The protection of the motors against these faults can be done by the help of overcurrent tripping device which would give an inverse time-current characteristics.

Phase fault protections are provided by two high-set instantaneous relay elements; the current setting is chosen above the maximum starting current.

Earth fault protection is provided in a motor operating on an earthed neutral system by using a simple instantaneous relay having a setting of approximately 30% of the full load current. Since the earth fault relay shouldn't trip at the initial switching due to CT saturation of high starting current, so the voltage setting of the relay is increased by inserting a stabilizing resistance in series with it. The scheme can be described as below
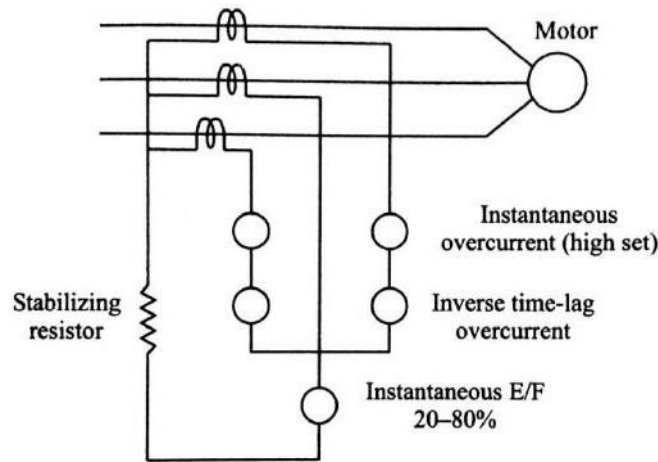
Figure 42 Induction motor-protection relay

Rotor Protection

Any unbalance in the supply or in the loading pattern will cause high amount of negative sequence current in the stator. This induces high frequency currents in the rotor circuit also. The frequency of this current is (2-s) times the normal frequency. The heating value of the negative sequence current is high as compared to positive sequence current, which is proportional to *(2-s) f* (approximately 100 Hz) a.c. resistance value. Hence motor protection must be taken into account the allowable voltage unbalance without overheating.

Overload Protection

The overload protection of the motor is designed so as to match the heating curve of the motor. The motor must not be allowed for most of the time for heating. For this reason the characteristics of the relay must not be more than the heating characteristics of the motor for protection. The protection must also have the capability to adjust its characteristics and should not allow the motor to restart until the motor winding temperature is high. For this reason the IDMT relay is best suited for this purpose.
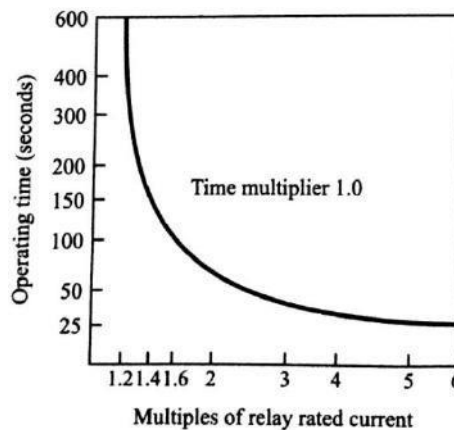

Figure 43 Operating time characteristic of IDMT relay induction type

Unbalance and Single Phasing Protection

An unbalance in the system causes the negative sequence currents to flow in the motor. This would result in overheating of the machine windings. Unbalanced loads or accidental opening of one phase of the supply (single phasing) depending on the load still keeps the motor running with the induction of negative sequence in the motor.

For star connected motors the unbalance can be protected by two overload elements. For delta connected motors such arrangement is satisfactory when the motor is running for more than 70% of the full load. A better scheme for detecting unbalance in motors is by the way of using bimetal strips as explained below:

In this arrangement, the bimetal relay has two slides S_1 and S_2 such that the slider S_1 is moved by the deflection of the bimetal strips, whereas the slider S_2 is kept in position due to non-bending of the bimetal strips. On symmetrical loading all the three bimetallic strips bend equally and both sliders move equally in the same direction by distance d thereby initiating the tripping. When there is a single phasing in the system, so that phase remains cold while the other two phases gets overloaded. This results in bending of these two phases while the other remains fixed. Hence the slider S_1 moves accordingly while the slider S_2 is held by bimetal strip of the cold phase. This bending initiates the tripping of the relay. Thus, the bimetal relay responds accordingly in case of single phasing.
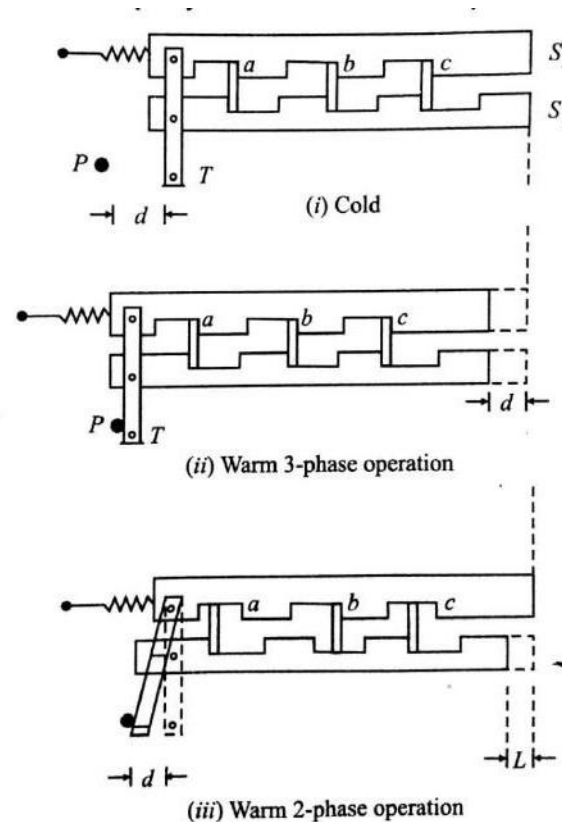

Figure 44 Bimetal relay with single phasing trip feature

In case of large motors the use of bimetal relay becomes sluggish because of the level of fault current being high. In this case we make the use of thermistors which

causes the tripping action due to the change in resistance. The figure below illustrates the use of an over temperature protective scheme for a three phase over DOL starting type induction motor which has the NTC type thermistors connected in it.
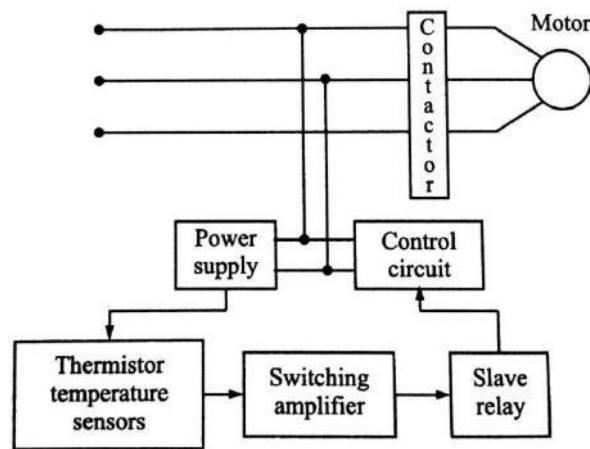

Figure 45 Temperature operated scheme

Under voltage Protection

A motor working in over voltage situation would generally be associated with overcurrent and thus can be protected by overload devices. A time delay is generally given to avoid transient behaviour of the voltage drop.

Reverse Phase Protection

The direction of rotation of the motor changes if the phase sequence is changed. In some motors this becomes very important. In order to ensure the direction of rotation an induction disc, poly phase voltage relay is used to protect the motor from starting when there is a mismatch of the sequence. Such a connection is shown in the figure below, where the torque is proportional to the sine product of two voltages. So when there is a mismatch of sequence, there would be no torque and restrains the motor from operating.
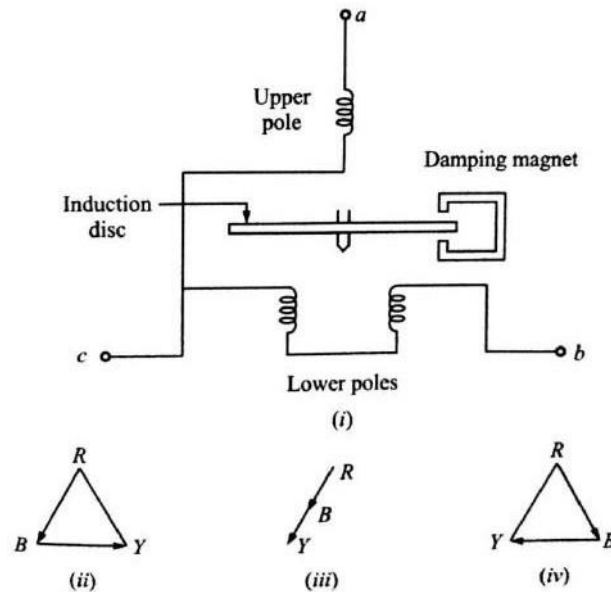
Figure 46 Open and reversed phase relay

Loss of synchronism

A synchronous motor becomes out of synchronism when there is a severe overload or a reduction in the voltage. Such a condition would result in change in power factor due to pole slipping and is detected by the relay. Such circuit is given below where the voltage between two phases is measured and the current in third phase is measured.
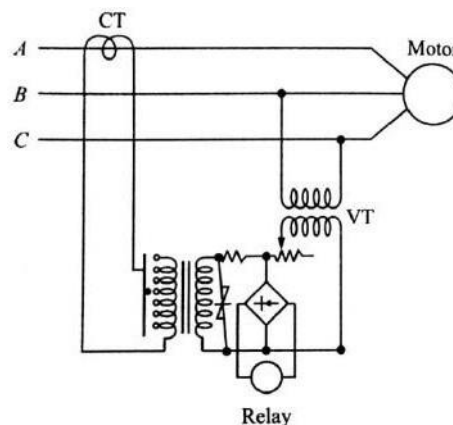

Figure 47 Out-of-step protection relay

5. Bus Faults

Bus zone protection includes the bus itself as well as circuit breakers, disconnecting switches, instrument transformers and bus sectionalizing reactors. These faults occurs rarely in the system but the provision of bus bar protection is necessary at the large and important station as the bus zone fault would result in interruption of high amount of power.

Bus Zone Faults

The faults in the bus zone can be divided as follows:

(i) Failure of circuit breaker to interrupt fault current or failure to clear under through fault conditions.

(ii) Insulation failure due to material deterioration.

(iii) Flashover causes by prolonged and excessive over voltages.

(iv) Errors in the operation and maintenance of switchgears.

(v) Foreign objects accidentally falling across bus bars.

Bus Backup Protection

When no separate protection is provided for the bus bars but there is a provision of distance protection, so any fault that is occurring at the bus zone protection would come under the zone 2 protection of the distance relay where it covers the bus bar and the next line also. This is satisfactory for the small switchgear case but not in the case of prime installations. Therefore a separate bus zone protection may be provided for the same.

Differential Scheme of Bus Bar Protection

It is based on the simple circulating current principle that during the normal condition or external fault condition, the incoming current must be equal to the leaving current. Since the bus in a power system acts as a node in an electrical circuit, if the summation of currents is not equal to zero, it means that there is a short circuit due to ground fault or phase to phase fault. The differential scheme can be given as below, whose CT ratio are given according to the highest current that is flowing in the feeder circuits.
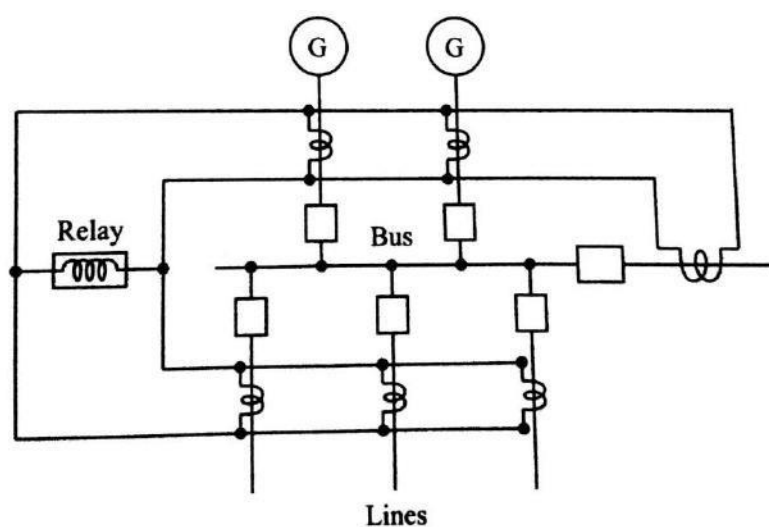

Figure 48 Differential Protection of a bus section

Since the CTs used here are of the same ratio, when there is a through fault condition, the magnetic conditions of the iron cored CTs would result in false operation due to saturation. Even with biasing of the relay, the improvement is not satisfactory.

An improvement can be done by the use of non iron cored CT also known as linear coupler to overcome the difficulties of iron cored CTs. In this the secondary voltage is proportional to the primary current. So when there is an external fault, the addition of the voltages won't result to zero since the current is still balanced, but when there is an internal fault there is an unbalance in current and hence results to some voltage in the linear coupler scheme.
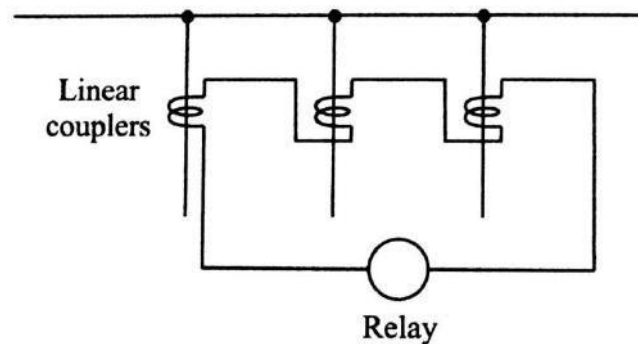

Figure 49 Linear Coupler scheme

Frame Leakage Protection

It is possible to design a station so that the faults which develop are mostly earth faults, by providing earthed metal barrier surrounding each conductor in the bus structure. With this arrangement every fault that might occur must involve a connection between the conductor and an earthed metal part.

The figure below shows the metal supporting structure also known as a fault bus earthed through a CT. Sometimes, the structure is earthed by the means of impedance connected in the neutral.
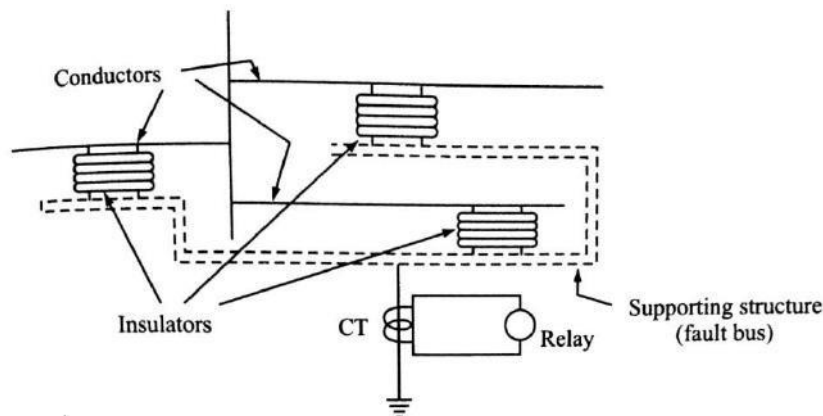

Figure 50 Frame leakage protection

In the resistance earthed neutral, the advantage is that besides limiting the value of current it is also used to protect certain part of the generator or transformer windings which are connected in the feeder circuits. The earth fault current for protecting $x\%$ of the winding is given as

$$I_F = (1 - x)\frac{V}{R}$$

This must be also the primary fault setting of the differential protection I_S for minimum operating current.
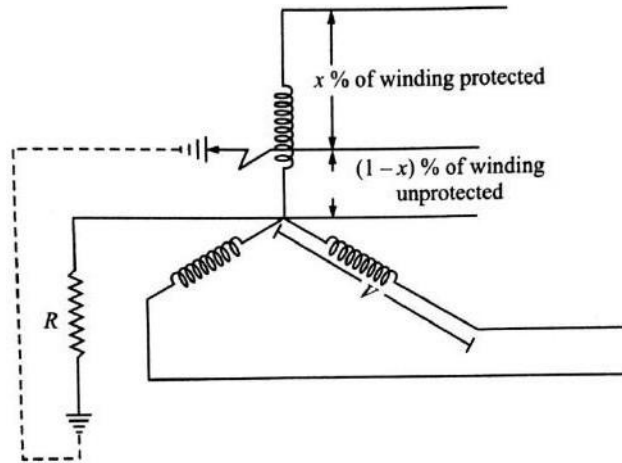

Figure 51 Percentage of unprotected winding against phase to earth fault

$$I_S = (1 - x)\frac{V}{R}$$

Or % of winding unprotected is

$$(1 - x) = \frac{I_S.R}{V} \times 100$$