Protection And Switch Gear

REGULATION 2017

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING (SYLLABUS)

Sub. Code :EE8602 **Branch/Year/Sem** : EEE/IV/VIII

Sub Name : **Protection And Switch Gear** **Staff Name** : E.MUTHUKUMARAN

UNIT I PROTECTION SCHEMES **9**

Principles and need for protective schemes – nature and causes of faults – types of faults – faultcurrent calculation using symmetrical components – Methods of Neutral grounding – Zones of protection and essential qualities of protection – Protection schemes

UNIT II ELECTROMAGNETIC RELAYS **9**

Operating principles of relays - the Universal relay – Torque equation – R-X diagram – Electromagnetic Relays – Overcurrent, Directional, Distance, Differential, Negative sequence and Under frequency relays.

UNIT III APPARATUS PROTECTION **9**

Current transformers and Potential transformers and their applications in protection schemes - Protection of transformer, generator, motor, busbars and transmission line.

UNIT IV STATIC RELAYS AND NUMERICAL PROTECTION **9**

Static relays – Phase, Amplitude Comparators – Synthesis of various relays using Static comparators – Block diagram of Numerical relays – Overcurrent protection, transformer differential protection, distant protection of transmission lines.

UNIT V CIRCUIT BREAKERS **9**

Physics of arcing phenomenon and arc interruption - DC and AC circuit breaking – re-striking voltage and recovery voltage - rate of rise of recovery voltage - resistance switching - current chopping - interruption of capacitive current - Types of circuit breakers – air blast, air break, oil, SF6 and vacuum circuit breakers – comparison of different circuit breakers – Rating and selection of Circuit breakers.

TOTAL : 45 PERIODS

OUTCOMES:

Ability to understand and analyze power system operation, stability, control and protection.

TEXT BOOKS:

1. Sunil S.Rao, 'Switchgear and Protection', Khanna Publishers, New Delhi, 2008.
2. B.Rabindranath and N.Chander, 'Power System Protection and Switchgear', New Age International (P) Ltd., First Edition 2011.
3. M.L.Soni, P.V.Gupta, U.S.Bhatnagar, A.Chakrabarti, 'A Text Book on Power System Engineering', Dhanpat Rai & Co.,1998.

REFERENCES:

1. Badri Ram ,B.H. Vishwakarma, 'Power System Protection and Switchgear', New Age International Pvt Ltd Publishers, Second Edition 2011.
2. Y.G.Paithankar and S.R.Bhide, 'Fundamentals of power system protection', Second Edition,
Prentice Hall of India Pvt. Ltd., New Delhi, 2010.

Unit I

PROTECTION SCHEMES

Principles and need for protective schemes – nature and causes of faults – types of faults – fault current calculation using symmetrical components – Methods of Neutral grounding – Zones of protection and essential qualities of protection – Protection schemes

1.1 Principles and need for protective schemes

1.1.1 Principles of PS

- The objective of power system protection is to isolate a faulty section of electrical power system from rest of the live system so that the rest portion can function satisfactorily without any severer damage due to fault current.
- Actually circuit breaker isolates the faulty system from rest of the healthy system and this circuit breakers automatically open during fault condition due to its trip signal comes from protection relay.
- The main philosophy about protection is that no protection of power system can prevent the flow of fault current through the system, it only can prevent the continuation of flowing of fault current by quickly disconnect the short circuit path from the system.

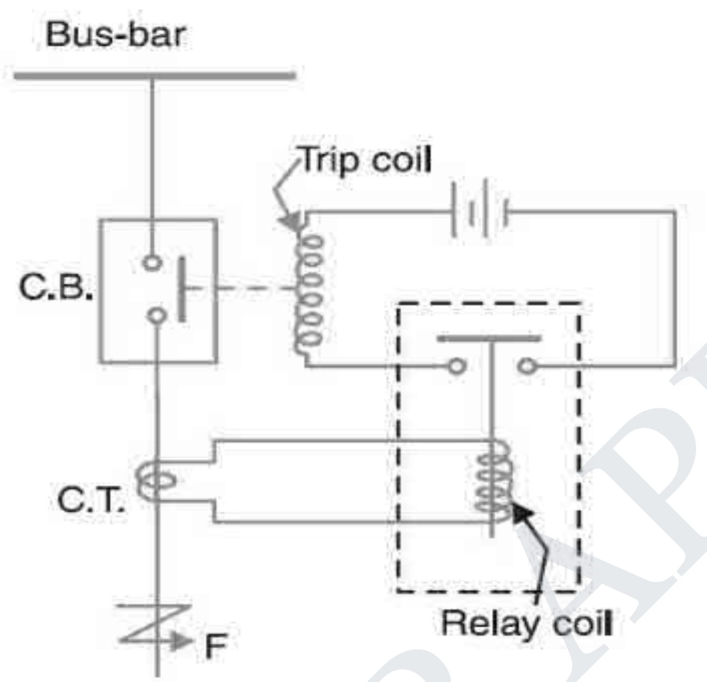
1.1.2Essential qualities

Essential qualities of protective relaying are,

1. Reliability
2. Selectivity and Discrimination
3. Speed and Time
4. Sensitivity
5. Stability
6. Adequateness
7. Simplicity and Economy

1. 1.3Functions of Protective relaying

The basic connection of protection relay has been shown. It is quite simple. The secondary of current transformer is connected to the current coil of relay. And secondary of voltage transformer is connected to the voltage coil of the relay. Whenever any fault occurs in the feeder circuit, proportionate secondary current of the CT will flow through the current coil of the relay due to which mmf of that coil is increased. This increased mmf is sufficient to mechanically close the normally open contact of the relay. This relay contact actually closes and completes the DC trip coil circuit and hence the trip coil is energized. The mmf of the trip coil initiates the mechanical movement of the tripping mechanism of the circuit breaker and ultimately the circuit breaker is tripped to isolate the fault.



1.2.Nature and causes of faults

1.2.1 Causes

• **Weather conditions:** It includes lighting strikes, heavy rains, heavy winds, salt deposition on overhead lines and conductors, snow and ice accumulation on transmission lines, etc. These environmental conditions interrupt the power supply and also damage electrical installations.

• **Equipment failures:** Various electrical equipments like generators, motors, transformers, reactors, switching devices, etc causes short circuit faults due to malfunctioning, ageing, insulation failure of cables and winding. These failures result in high current to flow through the devices or equipment which further damages it.

• **Human errors:** Electrical faults are also caused due to human errors such as selecting improper rating of equipment or devices, forgetting metallic or electrical conducting parts after servicing or maintenance, switching the circuit while it is under servicing, etc.

• **Smoke of fires:** Ionization of air, due to smoke particles, surrounding the overhead lines results in spark between the lines or between conductors to insulator. This flashover causes insulators to lose their insulting capacity due to high voltages.

1.2.2Fault statistics

Type of fault	Precentage of occurence
3-phase faults	. . . . 5%
LLG faults	. . . . 10%
LL faults	. . . . 15%
LG faults	. . . . 70%

1.2.3Consequences of faults

- Damage to the equipment due to abnormally large and unbalanced currents and low voltages produced by the short circuits
- Explosions may occur in the equipments which have insulating oil, particularly during short circuits. This may result in fire and hazardous conditions to personnel and equipments
- Individual generators with reduced voltage in a power station or a group of generators operating at low voltage may lead to loss of synchronism, subsequently resulting in islanding.
- Risk of synchronous motors in large industrial premises falling out of step and tripping out.

1.3. Types of faults

Under normal conditions, a power system operates under balanced conditions with all equipments carrying normal load currents and the bus voltages within the prescribed limits. This condition can be disrupted due to a fault in the system. A fault in a circuit is a failure that interferes with the normal flow of current. A short circuit fault occurs when the insulation of the system fails resulting in low impedance path either between phases or phase(s) to ground. This causes excessively high currents to flow in the circuit, requiring the operation of protective equipments to prevent damage to equipment. The short circuit faults can be classified as:

- Symmetrical faults
- Unsymmetrical faults

1.3.1Symmetrical faults

All 3 phases are shorted to each other and to ground also.

a) Occurrence is rare.

b) Severest of all the types of faults.

c) Fault current is maximum.

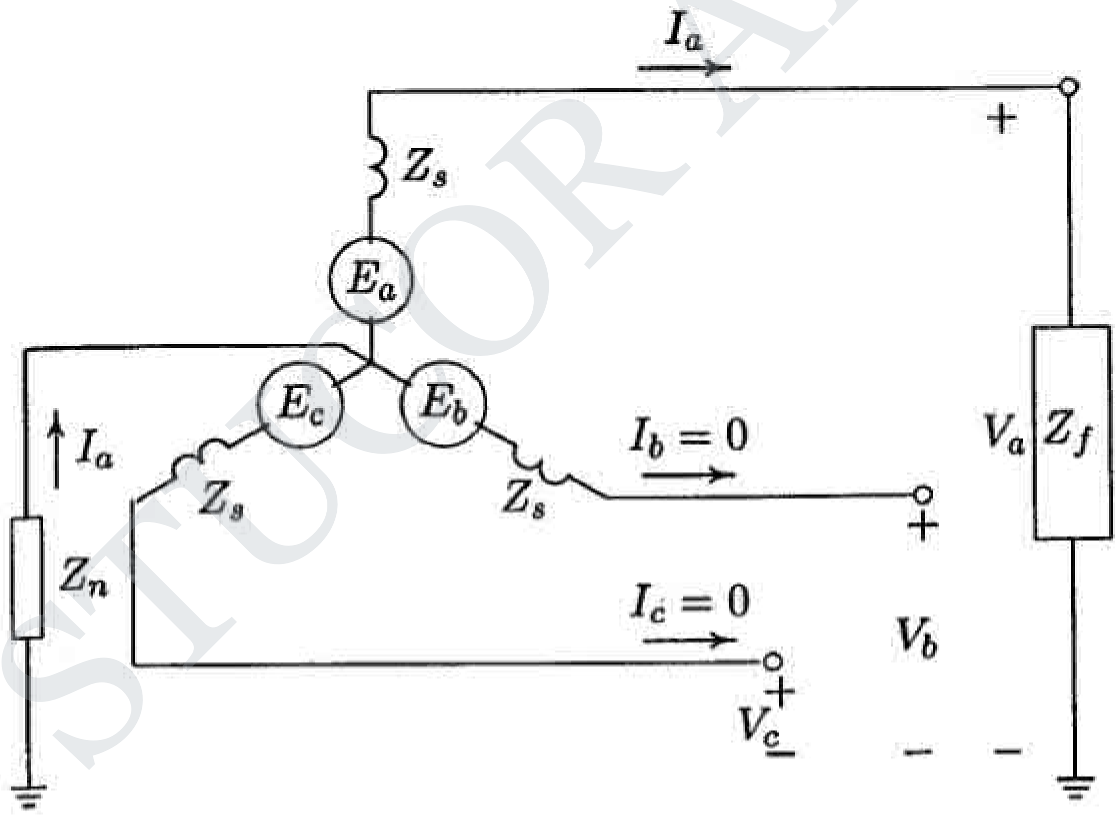
1.3.2Unsymmeterical faults

Only one phase or two phases are involved.

1. Line to Ground fault (LG fault)
2. Line to Line fault (LL fault)
3. Line to Line to Ground fault (LLG fault)

(i)Line to Ground fault (LG fault)

Let us consider a general case of single line to ground fault or L-G fault. Assume that a ground fault takes place in A phase (In many industries and numerical relays, normally the phases are said as A, B and C instead of R, Y and B, though they represent the same thing i.e. A phase means R phase, B means Y phase and C means B phase). E_a, E_b and E_c are the Generator terminal voltage per phase.



Since only phase **a** is connected to ground at the fault, phase b and c are open circuited and carries no current; i.e fault current is I_a and $I_b = 0$, $I_c = 0$. The voltage at the fault point F is $V_a = Z_f I_a$.

The symmetrical component of the fault current in phase "a" at the fault point can be written as

$$I_{a0} = \frac{1}{3}(I_a + I_b + I_c) = \frac{1}{3}(I_a + 0 + 0) = \frac{1}{3}I_a$$

$$I_{a1} = \frac{1}{3}(I_a + \alpha I_b + \alpha^2 I_c) = \frac{1}{3}(I_a + 0 + 0) = \frac{1}{3}I_a$$

$$I_{a2} = \frac{1}{3}(I_a + \alpha^2 I_b + \alpha I_c) = \frac{1}{3}(I_a + 0 + 0) = \frac{1}{3}I_a$$

$$I_{a0} = I_{a1} = I_{a2} = \frac{1}{3}I_a$$

This relation can also be found by matrix method as follows:-

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \frac{I_a}{3}\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$$

$$I_{a0} = I_{a1} = I_{a2} = \frac{1}{3}I_a$$

In the case of a single line-to-ground fault, the sequence currents are equal. The sequence voltage at the fault point is determined by the equations:-

$$V_{a0} = E_{a0} - Z_{a0}I_{a0}$$

$$V_{a1} = E_{a1} - Z_{a1}I_{a1}$$

$$V_{a2} = E_{a2} - Z_{a2}I_{a2}$$

Where, E_{a0}, E_{a1}, and E_{a2} are the sequence voltages of phase a, and Z_{a0}, Z_{a1} and Z_{a2} are the sequence impedances to the flow of currents I_{a0}, I_{a1}, and I_{a2} respectively. For a balanced system

$$E_{a0} = 0, \quad E_{a2} = 0, \quad E_{a1} = V_f$$

We know that

$$V_a = V_{a0} + V_{a1} + V_{a2}$$

$$Z_f I_a = -Z_{ao}I_a + V_f - Z_{a1}I_{a1} - Z_{a2}I_{a2}$$

On substituting the $I_{a0} = I_{a1} = I_{a2} = I_a$ in above equation we get,

$$Z_f I_a = V_f - \frac{I_a}{3}(Z_{a0} + Z_{a1} + Z_{a2})$$

$$Z_f I_a + \frac{I_a}{3}(Z_{a0} + Z_{a1} + Z_{a2}) = V_f$$

$$I_a\left[Z_f + \frac{1}{3}(Z_{a0} + Z_{a1} + Z_{a2})\right] = V_f$$

$$I_a = \frac{V_f}{Z_f + \frac{1}{3}(Z_{a0} + Z_{a1} + Z_{a2})}$$

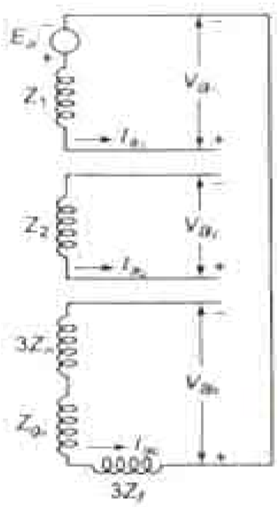
The sequence current is given by equation,

$$3I_{a0} = 3I_{a1} = 3I_{a2} = \frac{V_f}{Z_f + \frac{1}{3}(Z_{a0} + Z_{a1} + Z_{a2})}$$

$$I_{ao} = I_{a1} = I_{a2} = \frac{V_f}{3 \times [Z_f + \frac{1}{3}(Z_{a0} + Z_{a1} + Z_{a2})]}$$

$$I_{ao} = I_{a1} = I_{a2} = \frac{V_f}{[3Z_f + (Z_{a0} + Z_{a1} + Z_{a2})]}$$

From the above expression of fault current, it is quite clear that positive, negative and zero sequence impedance are connected in series for Single Line to Ground Fault and the equivalent circuit may be represented as shown below.



(ii)Line to Line fault

A line to line fault or unsymmetrical fault occurs when two conductors are short circuited. In the figure shown below shows a three phase system with a line-to-line fault phase's b and c. The fault impedance is assumed to be Z_f. The LL fault is placed between lines b and c so that the fault be symmetrical with respect to the reference phase a which is un-faulted.

The symmetrical components of a fault current in phase '**a**' at the fault point can be divided into three components. The zero sequence component of current at phase a is

$$I_{a0} = \frac{1}{3}(I_a + I_b + I_c)$$

$$I_{a0} = \frac{1}{3}(0 + I_b - I_b) \dots\dots\dots\dots\dots equ(1)$$

In the equation(1) $I_b = -I_c$. Positive sequence component of phase a is expressed as

$$I_{a1} = \frac{1}{3}(I_a + \alpha I_b + \alpha^2 I_c)$$

$$I_{a1} = \frac{1}{3}(0 + \alpha I_b - \alpha^2 I_b)$$

$$I_{a1} = \frac{1}{3}(\alpha - \alpha^2) I_b \dots\dots\dots\dots equ(2)$$

and the negative sequence component of phase a is given by the equation,

$$I_{a2} = \frac{1}{3}(I_a + \alpha^2 I_b + \alpha I_c)$$

$$I_{a2} = \frac{1}{3}(0 + \alpha^2 I_b - \alpha I_b)$$

$$I_{a2} = \frac{1}{3}(\alpha - \alpha^2) \dots\dots\dots\dots equ(3)$$

The sequence current can also be found by matrix method

$$\begin{bmatrix} I_{ao} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

$$\begin{bmatrix} I_{ao} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix}\begin{bmatrix} 0 \\ I_b \\ I_c \end{bmatrix}$$

Therefore, we get

$$I_{a0} = 0 \quad and \quad I_{a1} = -I_{a2}$$

Expressing V_a, V_b and V_c regarding voltages at the fault point are found by the relations given by

$$(V_{ao} + \alpha^2 V_{a1} + \alpha V_{a2}) - (V_{a0} + \alpha V_{a1} + \alpha^2 V_{a2}) = Z_f(I_{a0} + \alpha^2 I_{a1} + \alpha I_{a2})$$

$$\ldots\ldots\ldots.equ(5)$$

Combination of equation (1), (4) and (5) gives

$$(\alpha^2 - \alpha)V_{a1} - (\alpha^2 - \alpha)V_{a2} = Z_f(\alpha^2 - \alpha)I_{a1}$$

$$V_{a1} - V_{a2} = Z_f I_{a1} \ldots\ldots\ldots\ldots\ldots\ldots..equ(6)$$

The sequence current of voltage at the fault point are determined by the relations shown below

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \begin{bmatrix} 0 \\ V_{a1} \\ 0 \end{bmatrix} - \begin{bmatrix} Z_{a0} & 0 & 0 \\ 0 & Z_{a1} & 0 \\ 0 & 0 & Z_{a2} \end{bmatrix} \begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix}$$

$$V_{a0} = -Z_{a0} I_{a0} \ldots\ldots\ldots.equ(7)$$

$$V_{a1} = -V_f - Z_{a1} I_{a1} \ldots\ldots equ(8)$$

$$V_{a2} = -Z_{a2} I_{a2} \ldots\ldots\ldots equ(9)$$

From equation (8) and (9) we get

$$V_{a1} - V_{a2} = V_f - Z_{a1} I_{a1} + Z_{a2} I_{a2} \ldots\ldots\ldots\ldots\ldots..equ(10)$$

Combination of equation (4), (10) and (9) gives

$$Z_f I_{a1} = V_f - Z_{a1} I_{a1} + Z_{a2} I_{a2}$$

$$(Z_{a1} + Z_{a2} + Z_f) I_{a1} = V_f$$

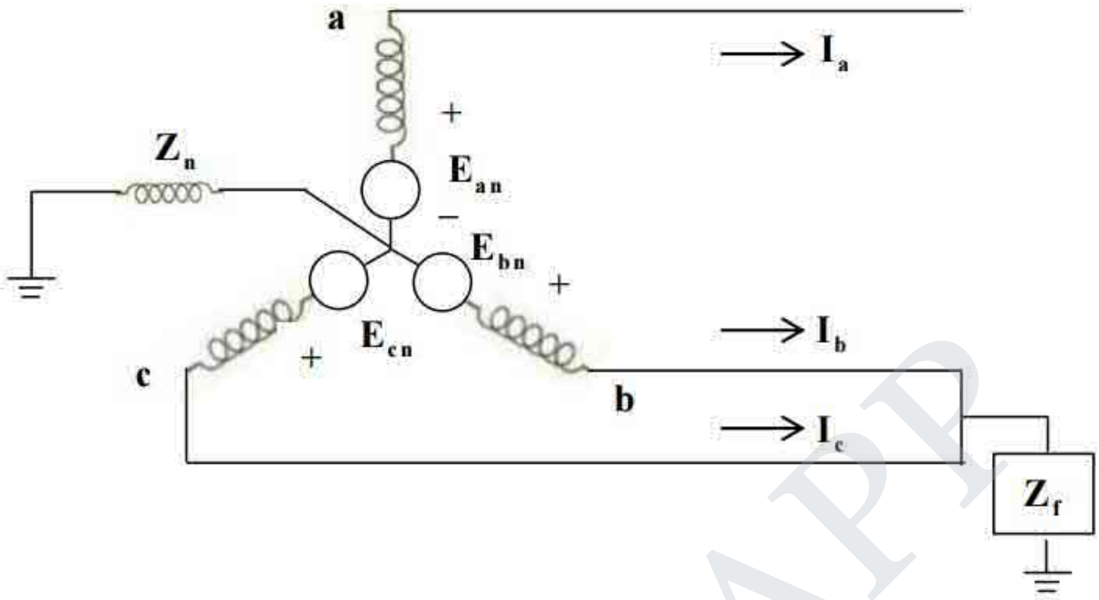
$$I_{a1} = \frac{V_f}{Z_{a1} + Z_{a2} + Z_f} \ldots\ldots.equ(11)$$

The fault current is given by the equation

$$I_f = \frac{(\alpha^2 - \alpha)V_f}{Z_{a1} + Z_{a2} + Z_{a3}} \ldots\ldots\ldots\ldots equ(12)$$

(iii)Double line to ground fault

The circuit diagram is shown in



$I_a = 0$; $\quad V_b = Z_f\ (I_b + I_c)$ and $\quad V_c = Z_f\ (I_b + I_c)$

Because of $I_a^{(0)} = 1/3\ (I_a + I_b + I_c)$, $I_b + I_c = 3\ I_a^{(0)}$

Therefore

$V_b = 3\ Z_f\ I_a^{(0)}$

$V_c = 3\ Z_f\ I_a^{(0)}$

$V_a^{(1)} = 1/3\ (V_a + a\ V_b + a^2\ V_c\ ) = 1/3\ [\ V_a + (a+a^2)\ V_b\ ]$

$V_a^{(2)} = 1/3(\ V_a\ + a^2\ V_b + a\ V_c\ ) = 1/3\ [\ V_a + (a^2 + a)\ V_b\ ]$

Therefore $\quad V_a^{(1)} = V_a^{(2)}$

Further $V_a^{(0)} = 1/3\ (V_a + V_b + V_c)$ i.e.

$3\ V_a^{(0)} = V_a^{(0)} + V_a^{(1)} + V_a^{(2)} + 3\ Z_f\ I_a^{(0)} + 3\ Z_f\ I_a^{(0)}$ i.e. $\ 2\ V_a^{(0)} = 2\ V_a^{(1)} + 6\ Z_f\ I_a^{(0)}$

i.e. $\ V_a^{(1)} = V_a^{(0)} - 3\ Z_f\ I_a^{(0)} = -Z_0\ I_a^{(0)} - 3\ Z_f\ I_a^{(0)} = -(Z_0 + 3\ Z_f\ )\ I_a^{(0)}$

i.e. $\ V_a^{(1)} = -(\ Z_0 + 3\ Z_f\ )\ I_a^{(0)}$

From eqn. (33) $\ I_a^{(0)} + I_a^{(1)} + I_a^{(2)} = 0$ i.e.

$$-\frac{V_a^{(1)}}{Z_0 + 3Z_f} + I_a^{(1)} - \frac{V_a^{(2)}}{Z_2} = 0 \qquad \text{i.e.} \quad -\frac{V_a^{(1)}}{Z_0 + 3Z_f} + I_a^{(1)} - \frac{V_a^{(1)}}{Z_2} = 0$$

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Therefore $I_a^{(1)} = V_a^{(1)} \left(\frac{1}{Z_0 + 3Z_f} + \frac{1}{Z_2} \right) = V_a^{(1)} \frac{Z_2 + Z_0 + 3Z_f}{Z_2 (Z_0 + 3Z_f)}$

i.e. $V_a^{(1)} = \frac{Z_2 (Z_0 + 3Z_f)}{Z_2 + Z_0 + 3Z_f} I_a^{(1)}$

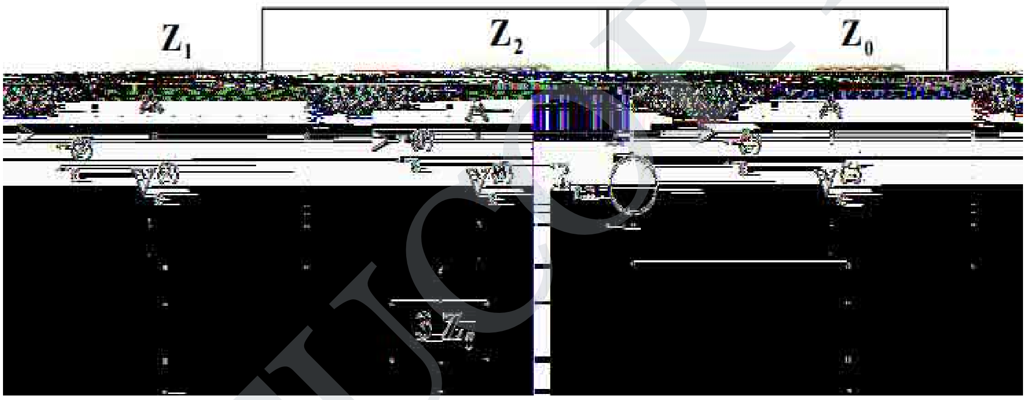
i.e. $E_{an} - I_a^{(1)} Z_1 = \frac{Z_2 (Z_0 + 3Z_f)}{Z_2 + Z_0 + 3Z_f} I_a^{(1)}$

Thus $I_a^{(1)} = \frac{E_{an}}{Z_1 + \frac{Z_2 (Z_0 + 3Z_f)}{Z_2 + Z_0 + 3Z_f}}$

$$V_a^{(1)} = V_a^{(2)} = -Z_2 I_a^{(2)} = \frac{Z_2 (Z_0 + 3Z_f)}{Z_2 + Z_0 + 3Z_f} I_a^{(1)}$$

$$I_a^{(2)} = -I_a^{(1)} \frac{Z_0 + 3Z_f}{Z_2 + Z_0 + 3Z_f}$$

$-(Z_0 + 3Z_f) I_a^{(0)} = \frac{Z_2 (Z_0 + 3Z_f)}{Z_2 + Z_0 + 3Z_f} I_a^{(1)}$ Thus $I_a^{(0)} = -I_a^{(1)} \frac{Z_2}{Z_2 + Z_0 + 3Z_f}$

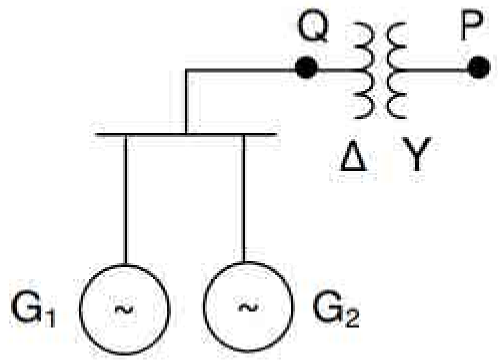


1.4. Fault current calculation

1.4.1 Symmetrical fault-Problems

Problem 1:

Two synchronous generators are connected in parallel at the low voltage side of a three-phase -Y transformer as shown in Fig.. Machine 1 is rated 50 MVA, 13.8 kV. Machine 2 is rated 25 MVA, 13.8 kV. Each generator has subtransient reactance, transient reactance and direct axis synchronous reactance of 25%, 40% and 100% respectively. The transformer is rated 75 MVA, 13.8/69Y with a reactance of 10%. Before the fault occurs, the voltage on high voltage side of the transformer is 66 kV. The transformer is unloaded and there is no circulating current between the generators.



(a) Find the current supplied by the generators. (b) A three-phase short circuit occurs at P. Determine the subtransient, transient and steady state short circuit current in each generator. (c) A three-phase short circuit occurs at Q. Determine the subtransient, transient and steady state short circuit current in each generator. Select a base of 75 MVA and 69 kV in the high tension circuit.

Solution

Base voltage at the low tension circuit = 13.8 kV

Prefault voltage at the LV side = 69 13.8 X 66 = 13.2 kV

Base current at the LV side = 3 x 13.8 75 x 103 = 3137.77 amp

. On the selected base

Generator 1: Xd" = 0.25 x 5075 = 0.375 p.u. Xd' = 0.4 x 5075 = 0.6 p.u.

Xd = 1.0 x 5075 = 1.5 p.u. Eg1 = 13.8 13.2 =0.9565 p.u.

Generator 2: Xd" = 0.25 x 2575 = 0.75 p.u. Xd' = 0.4 x 2575 = 1.2 p.u.

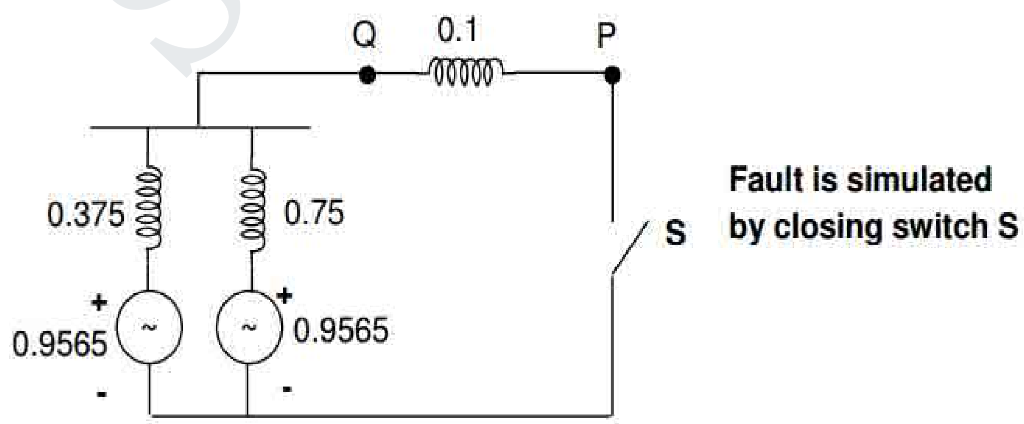
Xd = 1.0 x 2575 = 3.0 p.u. Eg2 = 13.8 13.2 = 0.9565 p.u

Transformer: X = 0.1 p.u.

(a) Transformer is unloaded.

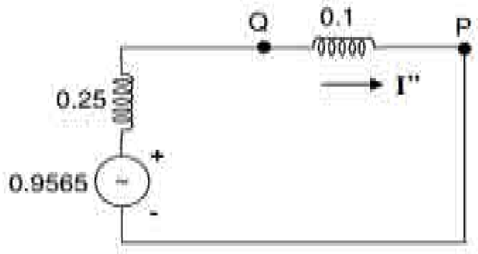
Therefore Ig1 = Ig2 = 0

(b) per unit subtransient reactance diagram is shown in Fig



Using Thevenin's equivalent above reactance diagram for the faulted condition can be reduced as shown

$$\frac{0.375 \times 0.75}{0.375 + 0.75} = 0.25 \text{ p.u.}$$



Subtransient current I '' = 0.9565/ j0.35 = - j 2.7329 p.u.

Voltage at Q = j 0.1 x (- j 2.7329) = 0.27329 p.u.

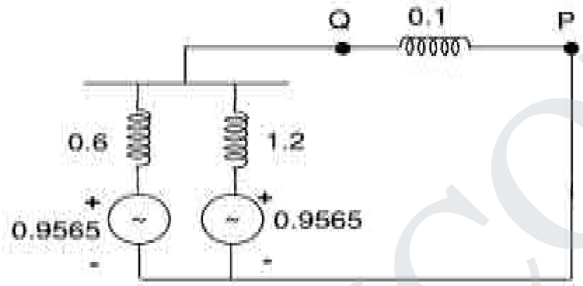
Current supplied by generator 1 = (0.9565 - 0.27329)/ j0.375 = - j 1.8219 p.u.

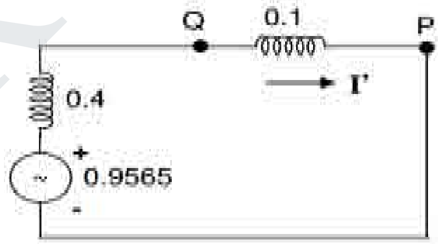
Subtransient current in machine 1 |I1 '' | = 5716.7 A

Current supplied by generator 2 = (0.9565 - 0.27329)/ j0.75 = - j 0.9109 p.u.

Subtransient current in machine 2 |I2 '' | = 2858.3 A

per unit transient reactance diagram is shown in





Subtransient current I ' = 0.9565/ j0.5 = - j 1.913 p.u.

Voltage at Q = j 0.1 x (- j 1.913) = 0.1913 p.u.

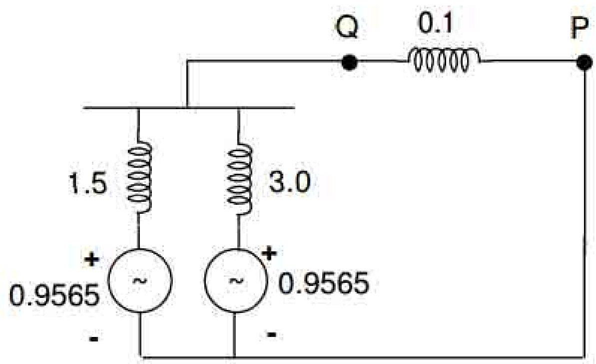
Current supplied by generator 1 = (0.9565 - 0.1913)/ j0.6 = - j 1.275 p.u.

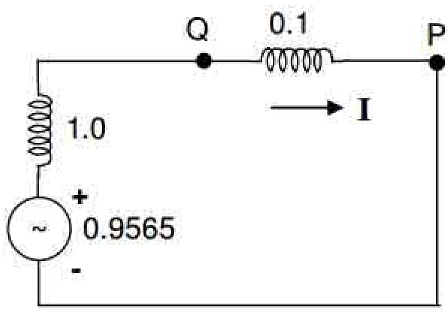
Transient current in machine 1 |I1 ' |= 4001.7 A

Current supplied by generator 2 = (0.9565 - 0.1913)/ j1.2 = - j 0.6377 p.u.

Transient current in machine 2 |I2 ' | = 2000.9

A per unit direct axis reactance diagram is shown in





Steady state short circuit current I = 0.9565/ j1.1 = - j 0.8695 p.u.

Voltage at Q = j 0.1 x (- j 0.8695) = 0.08695 p.u

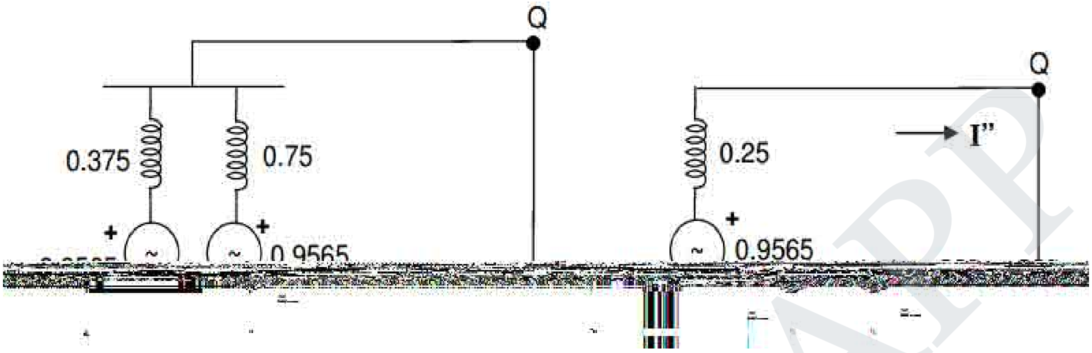
Current supplied by generator 1 = (0.9565 - 0.08695)/ j1.5 = - j 0.5797 p.u.

Steady state short circuit current in machine 1 |I1| = 1819 A

Current supplied by generator 2 = (0.9565 - 0.08695)/ j3.0 = - j 0.2899 p.u.

Steady state short circuit current in machine 2 |I2| = 909.48 A

(b) Fault occurs at point Q. per unit subtransient reactance diagram is shown in



Subtransient current I ” = 0.9565/ j0.25 = - j 3.826 p.u.

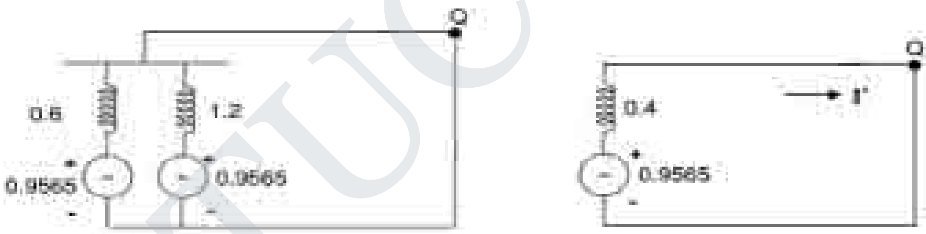
Current supplied by generator 1 = (0.9565 – 0)/ j0.375 = - j 2.5507 p.u.

Subtransient current in machine 1 |I1 ” | = 8003.4

A Current supplied by generator 2 = (0.9565 – 0) / j0.75 = - j 1.2753 p.u.

Subtransient current in machine 2 |I2 ” | = 4001.7 A

per unit transient reactance diagram is shown in



Transient current I ’ = 0.9565 / j0.4 = - j 2.3913 p.u.

Current supplied by generator 1 = (0.9565 – 0)/ j0.6 = - j 1.5942 p.u.

Transient current in machine 1 |I1 ’ | = 5002.2 A

Current supplied by generator 2 = (0.9565 – 0)/ j1.2 = - j 0.7971 p.u.

Subtransient current in machine 2 |I2 ’ | = 2501.1

A per unit direct axis transient reactance diagram is shown in

Direct axis steady state short circuit current I = 0.9565/ j1.0 = - j 0.9565 p.u.

Current supplied by generator 1 = (0.9565 – 0)/ j1.5 = - j 0.6377 p.u.

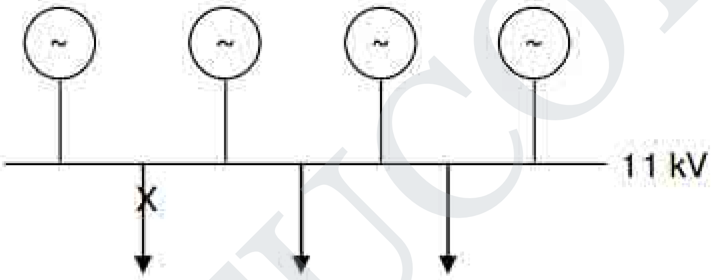
Steady state short current in machine 1 |I1| = 2000.9 A

Current supplied by generator 2 = (0.9565 – 0)/ j3.0 = - j 0.3188 p.u.

Steady state short circuit current in machine 2 |I2| = 1000.4 A

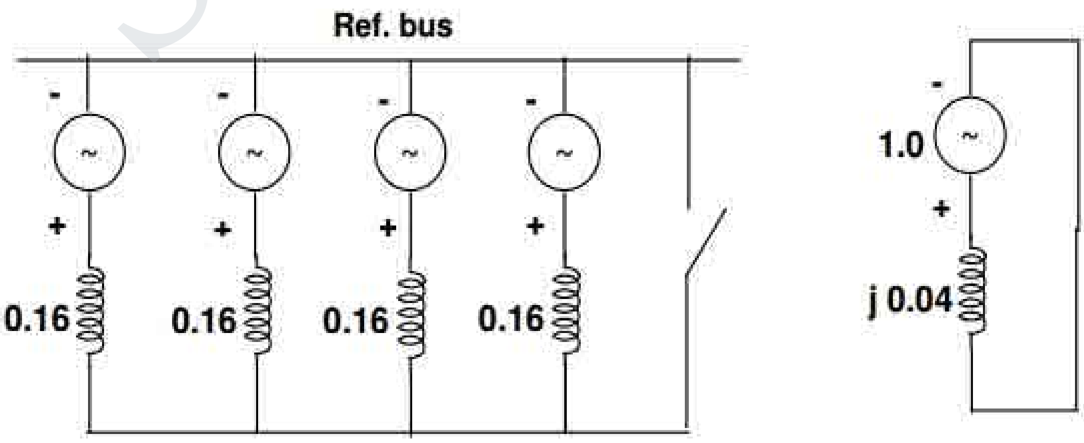
Problem 2

Four identical alternators in parallel. Each machine is rated for 25 MVA, 11 kV and has a subtransient reactance of 16 % on its rating. Compute the short circuit MVA when a three phase fault occurs at one of the outgoing feeders.



Solution

Fault is simulated by closing the switch shown in the p.u. reactance diagram shown in and Its Thevenin's equivalent is shown in



Fault current |IF| = 0.041 = 25 p.u.

Short circuit MVA = prefault voltage in p.u. x fault current in p.u. x Base MVA

= 1.0 x 25 x 25 = 625

1.4.2Unsymmetrical fault-Problems

Problem 1

The reactances of an alternator rated 10 MVA, 6.9 kV are X1 = X2 = 15 % and Xg0 = 5 %. The neutral of the alternator is . Single line to groundΩgrounded through a reactance of 0.38 fault occurs at the terminals of the alternator. Determine the line currents, fault current and the terminal voltages.

Solution

$X1 = X2 = 0.15$ p.u.

$Xn = 0.38 \times 10/6.9^2 = 0.0798$ p.u.

$X0 = Xg0 + 3\ Xn = 0.05 + 0.2394 = 0.2894$ p.u.

$Ia1 = Ia2 = Ia0 = 1.0 / j\ (0.2894 + 0.15 + 0.15) = -\ j\ 1.6966$ p.u.

Corresponding phase components are $Ia = -j\ 5.0898$ p.u. $Ib = Ic = 0$ 42

Base current = $10 \times 1000/(\sqrt{3}*6.9) = 836.7$

A Line currents are $Ia = -\ j\ 4258.8$ A ; $Ib = Ic = 0$

Fault current, $I_f = Ia = -\ j\ 4258.8$ A

$Va1 = 1.0 - (j\ 0.15)(-\ j\ 1.6966) = 1.0 - 0.2545 = 0.7455$ p.u.

$Va2 = -\ (j\ 0.15)(-\ j\ 1.6966) = -\ 0.2545$ p.u.

$Va0 = -\ (j\ 0.2894)(-\ j\ 1.6966) = -\ 0.491$ p.u.

Corresponding phase components are

$Va = 0$; $Vb = 1.1386\ \angle -130.38$ p.u. ; $Vc = 1.1386 \angle 130.38$ p.u.

Multiplying by $6.9/\sqrt{3}$

$Va = 0$; $Vb = 4.5359\ \angle -130.38$ kV ; $Vc = 4.5359 \angle\ 130.38$ kV

Problem 2

The reactances of an alternator rated 10 MVA, 6.9 kV are X1 =15 %; X2 = 20 % and Xg0 = 5 %. The neutral of the . Line to lineΩalternator is grounded through a reactance of 0.38 fault, with fault impedance j 0.15 p.u. occurs at the terminals of the alternator. Determine the line currents, fault current and the terminal voltages.

Solution :

$X1 = 0.15$ p.u. ; $X2 = 0.2$ p.u. ; $XF = 0.15$ p.u. $X0 = ?$

I a1= 1.0 / j (0.15 + 0.2 + 0.15) = - j 2 p.u.

Ia2 = - Ia1 = j 2 p.u.

and Ia0 = 0

Corresponding phase components are

Ia = 0 ; Ib = - 3.4641 p.u. ; Ic = 3.4641 p.u.

Base current = 836.7 A

Line currents are Ia = 0 ; Ib = - 2898.4 A ; Ic = 2898.4 A

Fault current I_f = Ib = - 2898.4 A

Va1 = 1.0 – (j 0.15) (- j 2) = 0.7 p.u.

Va2 = - (j 0.3) (j 2) = 0.4 p.u.

Va0 = 0

Corresponding phase components are

Va = 1.1 ;

Vb = 0.6083 $\angle$-154.72 p.u. ;

Vc= 0.6083$\angle$154.72 p.u.

Multiplying by 6.9/ $\sqrt{3}$,

Va = 4.3821 kV

Vb = 2.4233 $\angle$-154.72 kV

Vc = 2.4233 $\angle$154.72 kV

Problem 3:

An unloaded, solidly grounded 10 MVA, 11 kV generator has positive, negative and zero sequence impedances as j 1.2 Ω, j 0.9 Ω and j 0.04 Ω respectively. A double line to ground fault occurs at the terminals of the generator. Calculate the currents in the faulted phases and voltage of the healthy phase.

Solution

Base impedance = 11^2 /10= 12.1 Ω ;

Z1 = j 0.09917 p.u. ; Z2 = j 0.07438 p.u. ; Z0 = j 0.00331 p.u.

Z1+(Z2Z0/(Z1+Z2)) = j 0.10234 p.u.

Ia1 = 1.0/ j 0.10234 = -j 9.7714 p.u.

Ia2 = j 9.7714* 0.00331 /0.07769 = j 0.4163 p.u.

Ia0 = j 9.7714* 0.07438/0.07769 = j 9.3551 p.u.

Corresponding phase components are Ia = 0 ; Ib = 16.5758 $\angle$122.16 p.u. ;

Ic = 16.5758$\angle$ 57.84 p.u.

Base current = 10x1000 /(√3 x11)= 542.86 A

Current in faulted phases are Ib = 8998.3 ∠122.16 A

Ic = 8998.3∠ 57.84 A

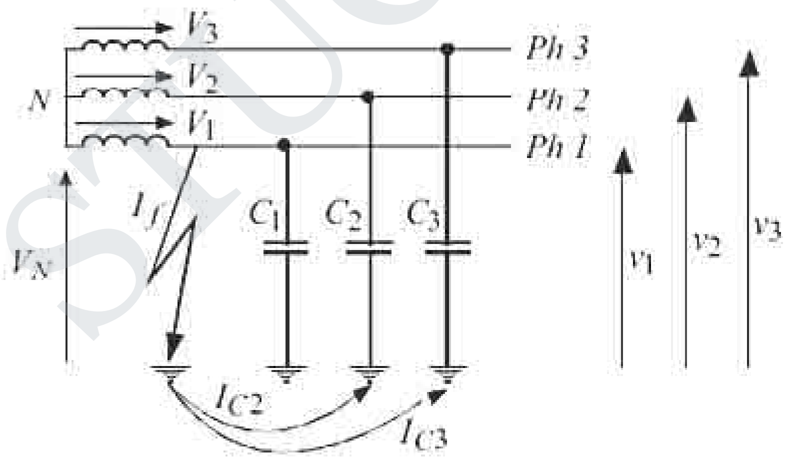
Va1 = Va2 = Va0 = - (j 0.07438) (j 0.4163) = 0.03096 p.u.

Voltage of the healthy phase Va = 0.09288 x (11/√3)= 0.5899 kV

1.5. Methods of Neutral grounding

1.5.1Ungrounded system

- In ungrounded system there is no internal connection between the conductors and earth. However, as system, a capacitive coupling exists between the system conductors and the adjacent grounded surfaces. Consequently, the "ungrounded system" is, in reality, a "capacitive grounded system" by virtue of the distributed capacitance.
- Under normal operating conditions, this distributed capacitance causes no problems. In fact, it is beneficial because it establishes, in effect, a neutral point for the system; As a result, the phase conductors are stressed at only line-to-neutral voltage above ground.
- But problems can rise in ground fault conditions. A ground fault on one line results in full line-to-line voltage appearing throughout the system. Thus, a voltage 1.73 times the normal voltage is present on all insulation in the system. This situation can often cause failures in older motors and transformers, due to insulation breakdown.



$$I_f = I_C = I_{C2} + I_{C3}$$

Advantage:

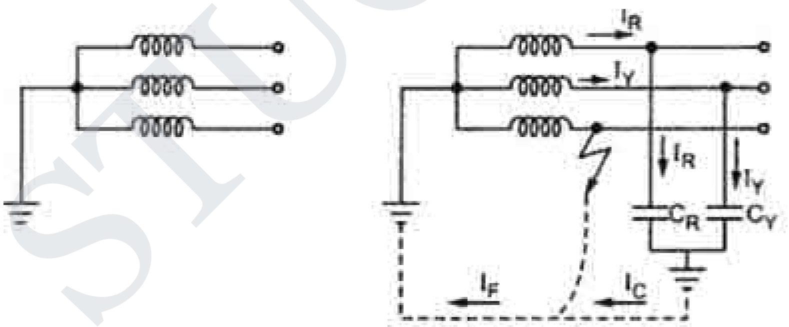
1. After the first ground fault, assuming it remains as a single fault, the circuit may continue in operation, permitting continued production until a convenient shut down for maintenance can be scheduled.

Disadvantages:

1. The interaction between the faulted system and its distributed capacitance may cause transient over-voltages (several times normal) to appear from line to ground during normal switching of a circuit having a line-to ground fault (short). These over voltages may cause insulation failures at points other than the original fault.
2. A second fault on another phase may occur before the first fault can be cleared. This can result in very high line-to-line fault currents, equipment damage and disruption of both circuits.
3. The cost of equipment damage.
4. Complicate for locating fault(s), involving a tedious process of trial and error: first isolating the correct feeder, then the branch, and finally, the equipment at fault. The result is unnecessarily lengthy and expensive down downtime.

1.5.2Solid grounding

- Solidly grounded systems are usually used in low voltage applications at 600 volts or less.
- In solidly grounded system, the neutral point is connected to earth.
- Solidly Neutral Grounding slightly reduces the problem of transient over voltages found on the ungrounded system and provided path for the ground fault current is in the range of 25 to 100% of the system three phase fault current. However, if the reactance of the generator or transformer is too great, the problem of transient over voltages will not be solved.



- While solidly grounded systems are an improvement over ungrounded systems, and speed up the location of faults, they lack the current limiting ability of resistance grounding and the extra protection this provides.
- To maintain systems health and safe, Transformer neutral is grounded and grounding conductor must be extend from the source to the furthest point of the system within the same raceway or conduit. Its purpose is to maintain very low impedance to ground

faults so that a relatively high fault current will flow thus insuring that circuit breakers or fuses will clear the fault quickly and therefore minimize damage. It also greatly reduces the shock hazard to personnel.

- If the system is not solidly grounded, the neutral point of the system would “float” with respect to ground as a function of load subjecting the line-to-neutral loads to voltage unbalances and instability.
- The single-phase earth fault current in a solidly earthed system may exceed the three phase fault current. The magnitude of the current depends on the fault location and the fault resistance. One way to reduce the earth fault current is to leave some of the transformer neutrals unearthed.

Advantage:

- The main advantage of solidly earthed systems is low over voltages, which makes the earthing design common at high voltage levels (HV).

Disadvantage:

- This system involves all the drawbacks and hazards of high earth fault current: maximum damage and disturbances.
- There is no service continuity on the faulty feeder.
- The danger for personnel is high during the fault since the touch voltages created are high.

Applications:

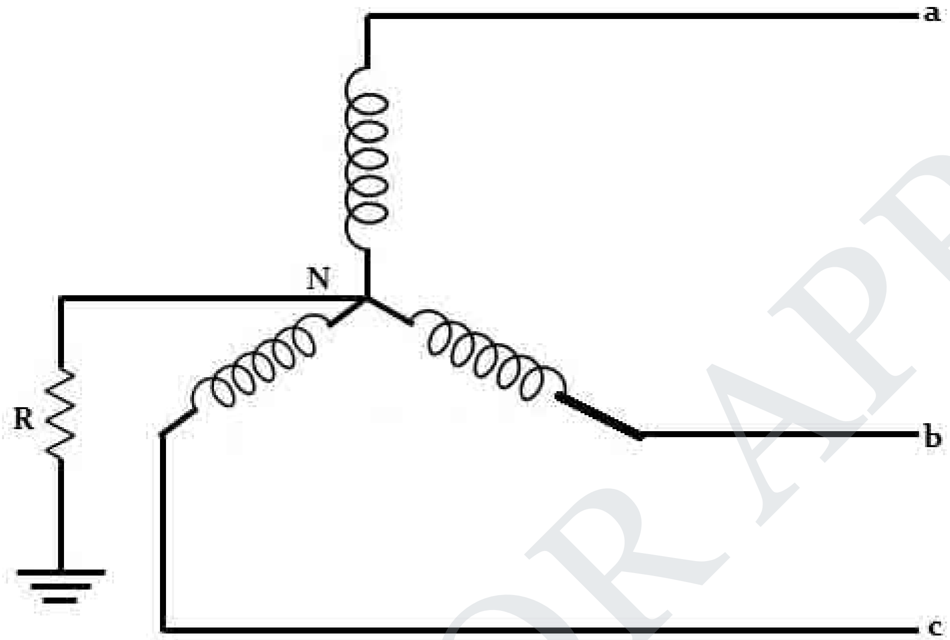
- Distributed neutral conductor.
- 3-phase + neutral distribution.
- Use of the neutral conductor as a protective conductor with systematic earthing at each transmission pole.
- Used when the short-circuit power of the source is low

1.5.3Resistance Earthing

- Resistance grounding has been used in three-phase industrial applications for many years and it resolves many of the problems associated with solidly grounded and ungrounded systems.
- Resistance Grounding Systems limits the phase-to-ground fault currents. The reasons for limiting the Phase to ground Fault current by resistance grounding are:

1. To reduce burning and melting effects in faulted electrical equipment like switchgear, transformers, cables, and rotating machines.
2. To reduce mechanical stresses in circuits/Equipments carrying fault currents.

3. To reduce electrical-shock hazards to personnel caused by stray ground fault.
4. To reduce the arc blast or flash hazard.
5. To reduce the momentary line-voltage dip.
6. To secure control of the transient over-voltages while at the same time.
7. To improve the detection of the earth fault in a power system.



➢ Grounding Resistors are generally connected between ground and neutral of transformers, generators and grounding transformers to limit maximum fault current as per Ohms Law to a value which will not damage the equipment in the power system and allow sufficient flow of fault current to detect and operate Earth protective relays to clear the fault. Although it is possible to limit fault currents with high resistance Neutral grounding Resistors, earth short circuit currents can be extremely reduced. As a result of this fact, protection devices may not sense the fault.

➢ Therefore, it is the most common application to limit single phase fault currents with low resistance Neutral Grounding Resistors to approximately rated current of transformer and / or generator.

➢ In addition, limiting fault currents to predetermined maximum values permits the designer to selectively coordinate the operation of protective devices, which minimizes system disruption and allows for quick location of the fault.

➢ There are two categories of resistance grounding:

- Low resistance Grounding.
- High resistance Grounding.

- Ground fault current flowing through either type of resistor when a single phase faults to ground will increase the phase-to-ground voltage of the remaining two phases. As a result, conductor insulation and surge arrestor ratings must be based on line-to-line voltage. This temporary increase in phase-to-ground voltage should also be considered when selecting two and three pole breakers installed on resistance grounded low voltage systems.
- The increase in phase-to-ground voltage associated with ground fault currents also precludes the connection of line-to-neutral loads directly to the system. If line-to neutral loads (such as 277V lighting) are present, they must be served by a solidly grounded system. This can be achieved with an isolation transformer that has a three-phase delta primary and a three-phase, four-wire, wye secondary
- Neither of these grounding systems (low or high resistance) reduces arc-flash hazards associated with phase-to-phase faults, but both systems significantly reduce or essentially eliminate the arc-flash hazards associated with phase-to-ground faults. Both types of grounding systems limit mechanical stresses and reduce thermal damage to electrical equipment, circuits, and apparatus carrying faulted current.
- The difference between Low Resistance Grounding and High Resistance Grounding is a matter of perception and, therefore, is not well defined. Generally speaking high-resistance grounding refers to a system in which the NGR let-through current is less than 50 to 100 A. Low resistance grounding indicates that NGR current would be above 100 A.
- A better distinction between the two levels might be alarm only and tripping. An alarm-only system continues to operate with a single ground fault on the system for an unspecified amount of time. In a tripping system a ground fault is automatically removed by protective relaying and circuit interrupting devices. Alarm-only systems usually limit NGR current to 10 A or less.

Rating of the Neutral grounding resistor:

1. Voltage: Line-to-neutral voltage of the system to which it is connected.
2. Initial Current: The initial current which will flow through the resistor with rated voltage applied.
3. Time: The “on time” for which the resistor can operate without exceeding the allowable temperature rise.

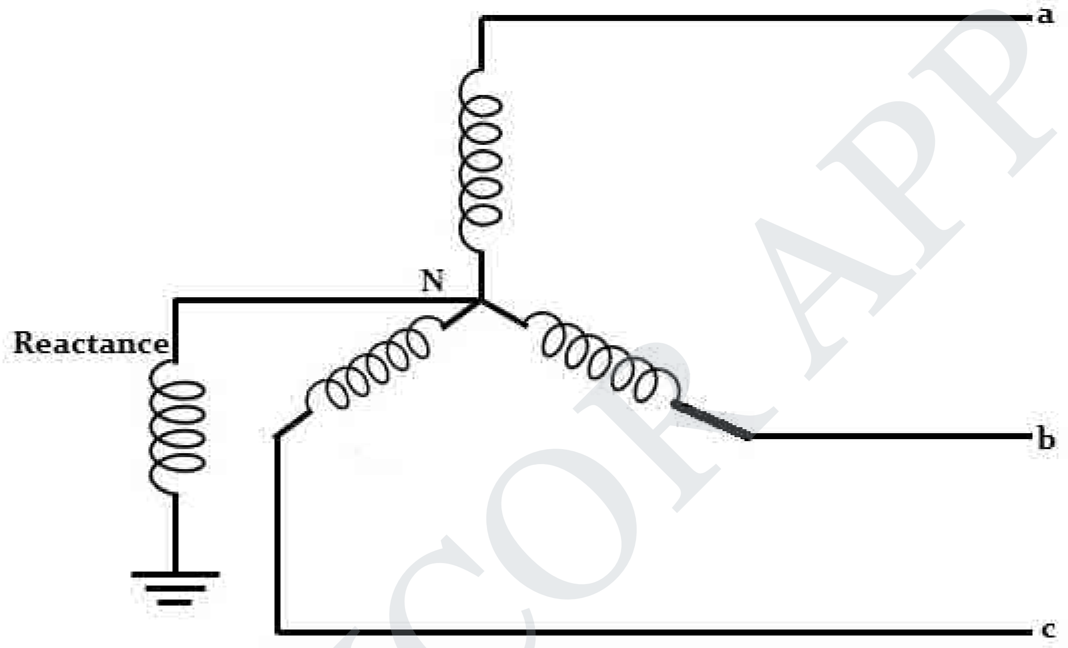
1.5.4Reactance Earthing

In this, a reactor is used in place of resistor. Similar to the resistance, reactance must be chosen to suit the requirements of protection, or to control the inductive interference. The reactive part of the fault current is compensated by this reactor.

These are used when the amount of current reduction is small. This is because reactor of low resistance to handle large quantities of current can be built at low cost as compared with the resistor for the same current limitation.

The disadvantage of this system is that high transient voltages appear across the system under fault conditions.

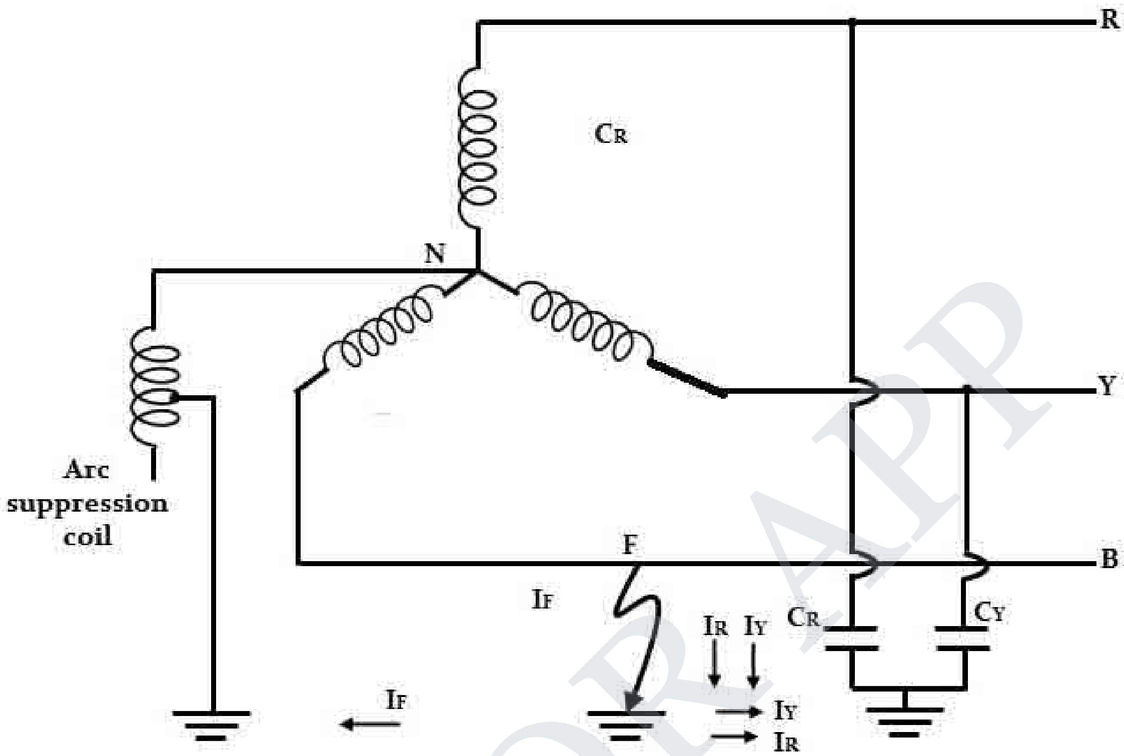
Also, for the same fault conditions, the fault current required to operate the protective device in resonant grounding is higher than that of resistance grounding. Due to these disadvantages, this method of grounding is not employed nowadays.



1.5.5Resonant grounding

- Adding inductive reactance from the system neutral point to ground is an easy method of limiting the available ground fault from something near the maximum 3 phase short circuit capacity (thousands of amperes) to a relatively low value (200 to 800 amperes).
- To limit the reactive part of the earth fault current in a power system a neutral point reactor can be connected between the transformer neutral and the station earthing system.
- A system in which at least one of the neutrals is connected to earth through an Inductive reactance.
- Petersen coil / Arc Suppression Coil / Earth Fault Neutralizer.
- The current generated by the reactance during an earth fault approximately compensates the capacitive component of the single phase earth fault current, is called a resonant earthed system.
- The system is hardly ever exactly tuned, i.e. the reactive current does not exactly equal the capacitive earth fault current of the system.

- A system in which the inductive current is slightly larger than the capacitive earth fault current is over compensated. A system in which the induced earth fault current is slightly smaller than the capacitive earth fault current is under compensated



- However, experience indicated that this inductive reactance to ground resonates with the system shunt capacitance to ground under arcing ground fault conditions and creates very high transient over voltages on the system.
- To control the transient over voltages, the design must permit at least 60% of the 3 phase short circuit current to flow underground fault conditions.
- Example. A 6000 amp grounding reactor for a system having 10,000 amps 3 phase short circuit capacity available. Due to the high magnitude of ground fault current required to control transient over voltages, inductance grounding is rarely used within industry.

1.6.Zones of protection

A protective zone is the separate zone which is established around each system element. The significance of such a protective zone is that any fault occurring within cause the tripping of relays which causes opening of all the circuit breakers within that zone.

The circuit breakers are placed at the appropriate points such that any element of the entire power system can be disconnected for repairing work, usual operation and maintenance requirements and also under abnormal conditions like short circuits. Thus a protective covering is provided around rich element of the system.

The various components which are provided with the protective zone are generators, transformers, transmission lines, bus bars, cables, capacitors etc. No part of the system is left unprotected. The figure below shows the various protective zones used in a system.

1.6.1Various protective zones

The boundaries of protective zones are decided by the locations of the current transformer. In practice, various protective zones are overlapped.

The overlapping of protective zones is done to ensure complete safety of each and every element of the system. The zone which is unprotected is called dead spot. The zones are overlapped and hence there is no chance of existence of a dead spot in a system. For the failures within the region where two adjacent protective zones are overlapped, more circuit breakers get tripped than minimum necessary to disconnect the faulty element.

If there are no overlaps, then dead spot may exist, means the circuit breakers lying within the zone may not trip even though the fault occurs. This may cause damage to the healthy system.

The extent of overlapping of protective zones is relatively small. The probability of the failures in the overlapped regions is very low; consequently the tripping of the too many circuit breakers will be frequent. The figure shows the overlapping of protective zones in primary relaying.

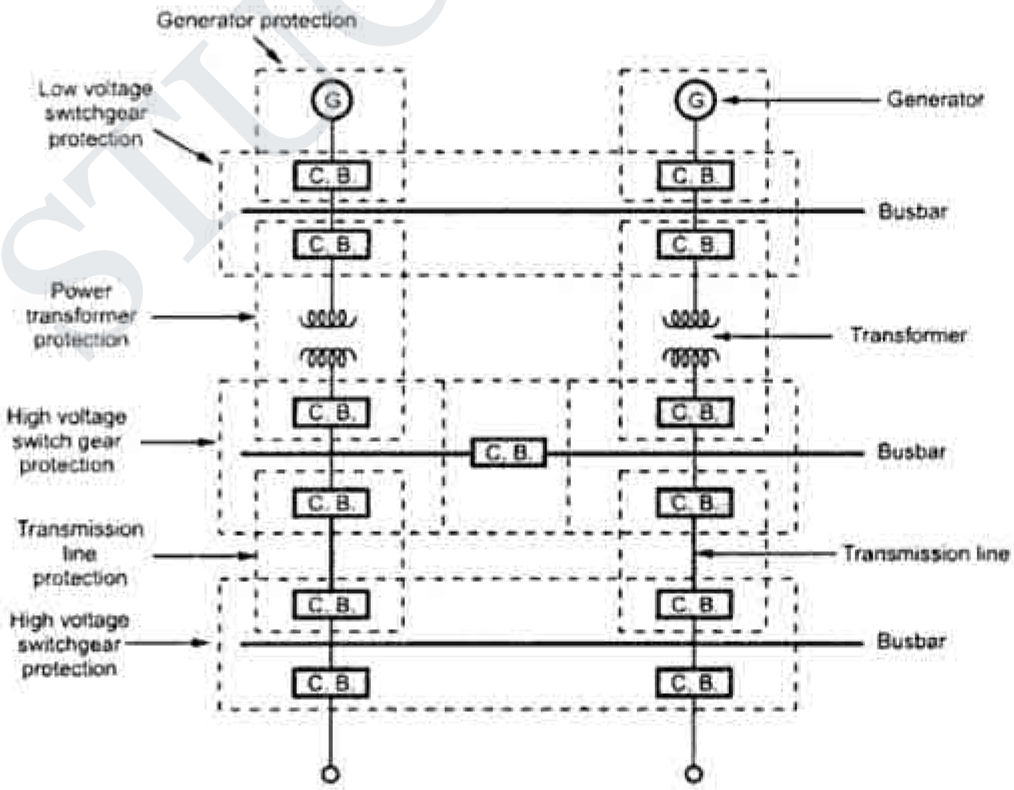


Figure shows Overlapping zones in primary relaying. It can be seen from the figure that the circuit breakers are located in the connections to each power system element. This provision makes it possible to disconnect only the faulty element from the system.

Occasionally for economy in the number of circuit breakers, a breaker between the two adjacent sections may be omitted but in that case both the power system are required to be disconnected for the failure in either of the two. Each protective zone has certain protective scheme and each scheme has number of protective systems.

1.6.2Primary and Back up protection

Primary Protection

The primary protection scheme ensures fast and selective clearing of any fault within the boundaries of the circuit element, that the zone is required to protect. Primary Protection as a rule is provided for each section of an electrical installation. However, the primary protection may fail. The primary causes of failure of the Primary Protection system are enumerated below.

1. Current or voltage supply to the relay.
2. D.C. tripping voltage supply
3. Protective relays
4. Tripping circuit
5. Circuit Breaker

Back-up Protection

Back-up protection is the name given to a protection which backs the primary protection whenever the later fails in operation. The back-up protection by definition is slower than the primary protection system. The design of the back-up protection needs to be coordinated with the design of the primary protection and essentially it is the second line of defence after the primary protection system.

1.6.3Concept of back up relay

The backup relaying schemes provide this extra reliability to the system. Backup relays are extra relaying schemes attached to the equipment or part of the network with their own relaying system. The main function of backup relay, to operate in any failure of tripping of circuit_breaker due to main relays. The relay attached to the system may fail due to

- Mechanical defect of moving parts of the main relay,
- Failure of DC supply to the relay,
- Failure of tripping pulse to the breaker from relay,
- Failure of current or voltage to the relay from CT or PT circuits etc.

In this typical situation there should be another line of protection called back up relaying. Hence, back up relaying essentially have everything separate from main relaying scheme. This is because backup relay must not fail to operate in the event of failure of main relays.

There are some situations when we have to disconnect main relays from the system for preventive maintenance or trouble shootings. In those cases due to presence of back up relays, we do not have to interrupt the equipment or circuit. During this time back up protection scheme takes care of the protection of the system. As the back relaying is second line of protection it must be slow in action than main relay so that it can only be operated when the main relaying scheme of the system/equipment fails.

1.6.4 Methods of Back up protection

The methods of back-up protection can be classified as follows :

1. Relay Back-up
2. Breaker Back-up
3. Remote back-up
4. Centrally Coordinated Back-up

Relay Back-up

Same breaker is used by both main and back-up protection, but the protective systems are different. Separate trip coils may be provided for the same breaker.

Breaker Back-up

Different breakers are provided for main and back-up protection, both the breakers being in the same station

Remote back-up

The main and back-up protections provided at different stations and are completely independent.

Centrally Coordinated Back-up

The system having central control can be provided with centrally controlled back-up. Central control continuously supervises the load flow and frequency in the system. The information about load flow and frequency is assessed continuously. If one of the components in any part of the-system fails, (e.g. a fault on a transformer, in some station) the load flow in the system is affected. The central coordinating station receives information about the abnormal condition through high frequency carrier signals. The stored programme in the digital computer determines the correct switching operation, as regards severity of fault, system stability,

1.7. Essential qualities of protection

The essential qualities of protection are

1. Reliability
2. Selectivity and Discrimination
3. Speed and Time
4. Sensitivity
5. Stability
6. Adequateness
7. Simplicity and Economy

1. Reliability

A protective relaying should be reliable is its basic quality. It indicates the ability of the relay system to operate under the predetermined conditions. There are various components which go into the operation before a relay operates. Therefore every component and circuit which is involved in the operation of a relay plays an important role. The reliability of a protection system depends on the reliability of various components like circuit breakers, relays, current transformers (C.T.s), potential transformers (P.T.s), cables, trip circuits etc. The proper maintenance also plays an important role in improving the reliable operation of the system. The reliability cannot be expressed in the mathematical expressions but can be adjusted from the statistical data. The statistical survey and records give good idea about the reliability of the protective system. The inherent reliability is based on the design which is based on the long experience. This can be achieved by the factors like,

i) Simplicity ii) Robustness
iii) High contact pressure iv) Dust free enclosure
iv) Good contact material vi) Good workmanship and
vii) Careful Maintenance

2 Selectivity and Discrimination

The selectivity id the ability of the protective system to identify the faulty part correctly and disconnect that part without affecting the rest of the healthy part of system. The discrimination means to distinguish between. The discrimination quality of the protective system is the ability to distinguish between normal condition and abnormal condition and also between abnormal condition within protective zone and elsewhere. The protective system should operate only at the time of abnormal condition and not at the time of normal condition. Hence it must clearly discriminate between normal and abnormal condition. Thus the protective system should select the fault part and disconnect only the faulty part without disturbing the healthy part of the system.

The protective system should not operate for the faults beyond its protective zone. For example, consider the portion of a typical power system shown in the Fig. 1.

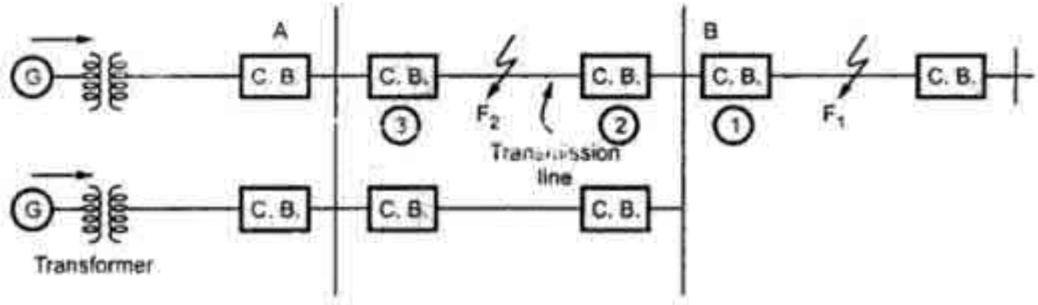


Fig. 1

It is clear from the Fig. 1 that if fault F_2 occurs on transmission line then the circuit breakers 2 and 3 should operate and disconnect the line from the remaining system. The protective system should be selective in selecting faulty transmission line only for the fault and it should isolate it without tripping the adjacent transmission line breakers or the transformer.

If the protective system is not selective then it operates for the fault beyond its protective zones and unnecessary the large part of the system gets isolated. This causes a lot of inconvenience to the supplier and users.

3 Speed and Time

A protective system must disconnect the faulty system as fast as possible. If the faulty system is not disconnect for a long time then,

1. The devices carrying fault currents may get damaged.
2. The failure leads to the reduction in system voltage. Such low voltage may affect the motors and generators running on the consumer sude.
3. If fault persists for long time, then subsequently other faults may get generated.

The high speed protective system avoids the possibility of such undesirable effects.

The total time required between the instant of fault and the instant of final arc interruption in the circuit breaker is called fault clearing time. It is the sum of relay time and circuit breaker time. The relay time is the time between the instant of fault occurrence and the instant of closure of relay contacts. The circuit breaker times is the time taken by the circuit breaker to operate to open the contacts and to extinguish the arc completely. The fault clearing time should be as small as possible to have high speed operation of the protective system.

Though the small fault clearing time is preferred, in practice certain time lag is provided. This is because,

1. To have clear discrimination between primary and backup protection
2. To prevent unnecessary operation of relay under the conditions such as transient, starting inrush of current etc.

Thus fast protective system is an important quality which minimises the damage and it improves the overall stability of the power system.

4 Sensitivity

The protective system should be sufficiently sensitive so that it can operate reliably when required. The sensitivity of the system is the ability of the relay system to operate with low value of actuating quantity.

It indicates the smallest value of the actuating quantity at which the protection starts operating in relation with the minimum value of the fault current in the protected zone.

The relay sensitivity is the function of the volt-amperes input to the relay coil necessary to cause its operation. Smaller the value of volt-ampere input, more sensitive is the relay. Thus 1 VA input relay is more sensitive than the 5VA input relay.

Mathematically the sensitivity is expressed by a factor called sensitivity factor . It is the ratio of minimum short circuit current in the protected zone to the minimum operating current required for the protection to start.

$$K_s = I_s/I_o$$

where K_s = sensitivity factor

I_s = minimum short circuit current in the zone

I_o = minimum operating current for the protection

5 Stability

The stability is the quality of the protective system due to which the system remains inoperative and stable under certain specified conditions such as transients, disturbance, through faults etc. For providing the stability, certain modifications are required in the system design. In most of the cases time delays, filter circuits, mechanical and electrical bias are provided to achieve stable operation during the disturbances.

6 Adequateness

There are variety of faults and disturbance those may practically exists in a power system. It is impossible to provide protection against each and every abnormal condition which may exist in practice, due to economical reasons. But the protective system must provide adequate protection for any element of the system. The adequateness of the system can be assessed by considering following factors,

1. Ratings of various equipments
2. Cost of the equipments
3. Locations of the equipments
4. Probability of abnormal condition due to internal and external causes.
5. Discontinuity of supply due to the failure of the equipment

7 Simplicity and Economy

In addition to all the important qualities, it is necessary that the cost of the system should be well within limits. In practice sometimes it is not necessary to use ideal protection scheme which is economically unjustified. In such cases compromise is done. As a rule, the protection cost should not be more than 5% of the total cost. But if the equipments to be protected are very important, the economic constrains can be relaxed.

The protective system should be as simple as possible so that it can be easily maintained. The complex systems are difficult from the maintenance point of view. The simplicity and reliability are closely related to each other. The simpler system are always more reliable.

1.8.Protection schemes

The various protection schemes are

(i)OverCurrent Protection
(ii)Distance Protection
(iii)Carrier current Protection
(iv)Differential protection

(i)OverCurrent Protection

An overcurrent exists when current exceeds the rating of conductors or equipment. It can result from overload, short circuit, or ground fault.

- An *overload* is a condition in which equipment or conductors carry current exceeding their rated ampacity. An example is plugging two 12.5A (1,500W) hair dryers into a 20A branch circuit.
- A *short circuit* is the unintentional electrical connection between any two normally current-carrying conductors of a circuit (line-to-line or line-to-neutral).

.A *ground fault* is an unintentional, electrically conducting connection between an ungrounded conductor of a circuit and the equipment grounding conductor, metallic enclosures, metallic raceways, metallic equipment, or earth. During a ground fault, dangerous voltages and abnormally large currents exist.

(ii)Distance protection

Distance protection relay is the name given to the protection, whose action depends on the distance of the feeding point to the fault. The time of operation of such protection is a function of the ratio of voltage and current, i.e., impedance. This impedance between the relay and the fault depends on the electrical distance between them. The principal type of distance relays is impedance relays, reactance relays, and the reactance relays.

Distance protection relay principle differs from other forms of protection because their performance does not depend on the magnitude of the current or voltage in the protective circuit but it depends on the ratio of these two quantities. It is a double actuating quantity relay with one of their coil is energized by voltage and the other coil is energized by the current. The current element produces a positive or pick-up torque while the voltages element has caused a negative and reset torque.

The relay operates only when the ratio of voltage and current falls below a set value. During the fault the magnitude of current increases and the voltage at the fault point decreases. The ratio of the current and voltage is measured at the point of the current and potential transformer. The voltage at potential transformer region depends on the distance between the PT and the fault.

If the fault is nearer, measured voltage is lesser, and if the fault is farther, measured voltage is more. Hence, assuming constant fault impedance each value of the ratio of voltage and current measured from relay location comparable to the distance between the relaying point and fault point along the line. Hence such protection is called the distance protection or impedance protection.

Distance zone is non-unit protection, i.e., the protection zone is not exact. The distance protection is high-speed protection and is simply to apply. It can be employed as a primary as well as backup protection. It is very commonly used in the protection of transmission lines.

Distance relays are used for both phase fault and ground fault protection, and they provide higher speed for clearing the fault. It is also independent of changes in the magnitude of the short circuits, current and hence they are not much affected by the change in the generation capacity and the system configuration. Thus, they eliminate long clearing times for the fault near the power sources required by overcurrent relay if used for the purpose.

(iii)Carrier current protection

Carrier current protection scheme is mainly used for the protection of the long transmission line. In the carrier, current protection schemes, the phase angle of the current at the two phases of the line are compared instead of the actual current. And then the phase angle of the line decides whether the fault is internal and external. The main elements of the carrier channel are a transmitter, receiver, coupling equipment, and line trap.

The carrier current receiver receives the carrier current from the transmitter at the distant end of the line. The receiver converts the received carrier current into a DC voltage that can be used in a relay or other circuit that performs any desired function. The voltage is zero when the carrier current, is not being received.

Line trap is inserted between the bus-bar and connection of coupling capacitor to the line. It is a parallel LC network tuned to resonance at the high frequency. The traps restrict the carrier current to the unprotected section so as to avoid interference from the with or the other adjacent carrier current channels. It also avoids the loss of the carrier current signal to the adjoining power circuit.

The coupling capacitor connects the high-frequency equipment to one of the line conductors and simultaneously separate the power equipment from the high power line voltage. The normal current will be able to flow only through the line conductor, while the high current carrier current will circulate over the line conductor fitted with the high-frequency traps, through the trap capacitor and the ground.
The different methods of current carrier protection and the basic form of the carrier current protection are

1. Directional Comparison protection
2. Phase Comparison Protection

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These types are explained below in details

1. Directional Comparison Protection

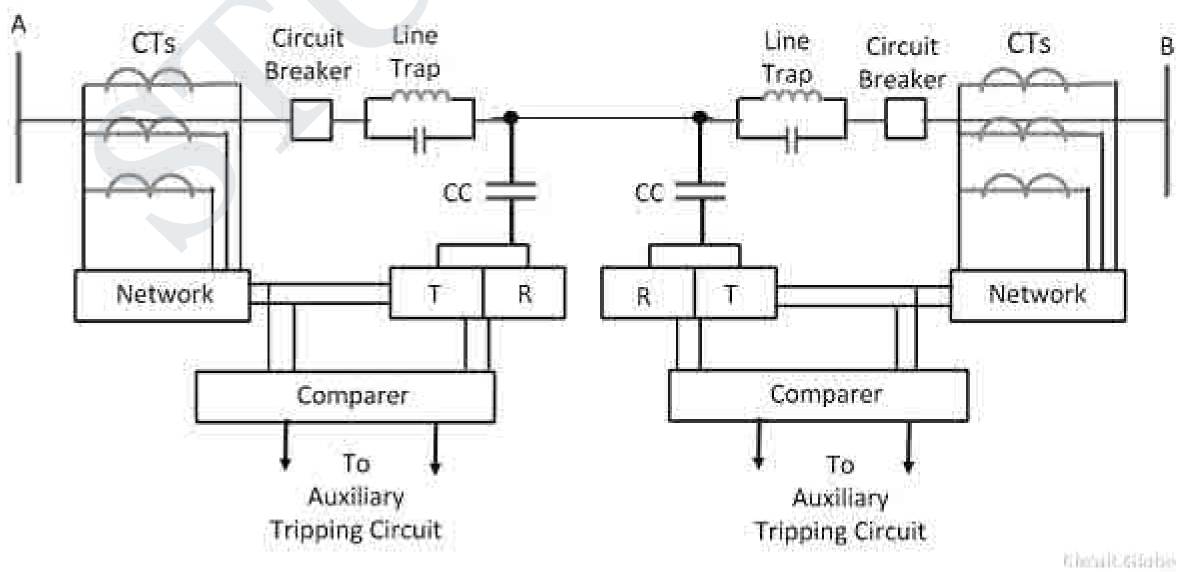
In this protection schemes, the protection can be done by the comparison of a fault of the power flow direction at the two ends of the line. The operation takes place only when the power at both the end of the line is on the bus to a line direction. After the direction comparison, the carrier pilot relay informs the equipment how a directional relay behaves at the other end to a short circuit.

The relay at both the end removes the fault from the bus. If the fault is in protection section the power flows in the protective direction and for the external fault power will flow in the opposite direction. During the fault, a simple signal through carrier pilot is transmitted from one end to the other. The pilot protection relaying schemes used for the protection of transmission are mainly classified into two types. They are

- *Carrier Blocking Protection Scheme* – The carrier blocking protection scheme restricts the operation of the relay. It blocks the fault before entering into the protected section of the system. It is one of the most reliable protecting schemes because it protects the system equipment from damage.
- *Carrier Permitting Blocking Scheme* – The carrier, protective schemes allows the fault current to enter into the protected section of the system.

2. Phase Comparison Carrier Protection

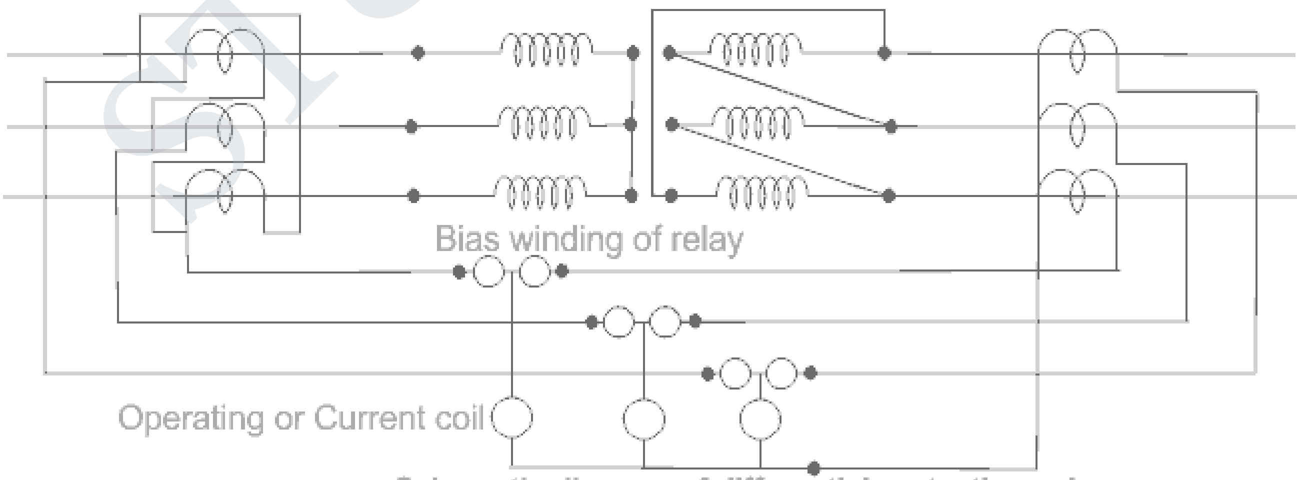
This system compares the phase relation between the current enter into the pilot zone and the current leaving the protected zone. The current magnitudes are not compared. It provided only main or primary protection and backup protection must be provided also.



The transmission line CTs feeds a network that transforms the CTs output current into a single phase sinusoidal output voltage. This voltage is applied to the carrier current transmitter and the comparer. The output of the carrier current receiver is also applied to the comparer. The comparer regulates the working of an auxiliary relay for tripping the transmission line circuit breaker.

(iv)Differential protection

Principle of Differential Protection scheme is one simple conceptual technique. The differential actually compares between primary current and secondary current of power transformer, if any unbalance found in between primary and secondary currents the relay will actuate and inter trip both the primary and secondary circuit breaker of the transformer. Suppose you have one transformer which has primary rated current I_p and secondary current I_s. If you install CT of ratio I_p/1A at the primary side and similarly, CT of ratio I_s/1A at the secondary side of the transformer. The secondaries of these both CTs are connected together in such a manner that secondary currents of both CTs will oppose each other. In other words, the secondaries of both CTs should be connected to the same current coil of a differential relay in such an opposite manner that there will be no resultant current in that coil in a normal working condition of the transformer. But if any major fault occurs inside the transformer due to which the normal ratio of the transformer disturbed then the secondary current of both transformers will not remain the same and one resultant current will flow through the current coil of the differential relay, which will actuate the relay and inter trip both the primary and secondary circuit breakers. To correct phase shift of current because of star-delta connection of transformer winding in the case of three-phase transformer, the current transformer secondary's should be connected in delta and star as shown here.



Schematic diagram of differential protection scheme

At maximum through fault current, the spill output produced by the small percentage unbalance may be substantial. Therefore, differential protection of transformer should be provided with a proportional bias of an amount which exceeds in effect the maximum ratio deviation.

Unit II

ELECTROMAGNETIC RELAYS

Operating principles of relays - the Universal relay – Torque equation – R-X diagram - Electromagnetic Relays Overcurrent, Directional, Distance, Differential, Negative sequence and Under frequency relays.

2.1. Operating principles of relays

2.1.1 Principles

A relay is automatic device which senses an abnormal condition of electrical circuit and closes its contacts. These contacts in turns close and complete the circuit breaker trip coil circuit hence make the circuit breaker tripped for disconnecting the faulty portion of the electrical circuit from rest of the healthy circuit.

Pickup Level of Actuating Signal: The value of actuating quantity (voltage or current) which is on threshold above which the relay initiates to be operated.If the value of actuating quantity is increased, the electromagnetic effect of the relay coil is increased and above a certain level of actuating quantity the moving mechanism of the relay just starts to move.

Reset Level: The value of current or voltage below which a relay opens its contacts and comes in original position.

Operating Time of Relay: Just after exceeding pickup level of actuating quantity the moving mechanism (for example rotating disc) of relay starts moving and it ultimately close the relay contacts at the end of its journey. The time which elapses between the instant when actuating quantity exceeds the pickup value to the instant when the relay contacts close.

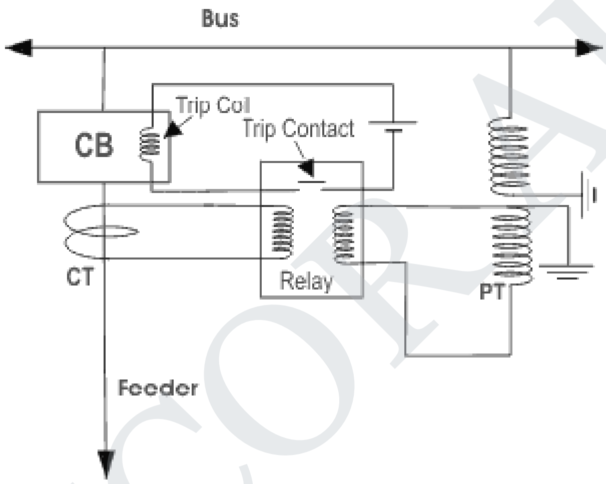
Reset Time of Relay: The time which elapses between the instant when the actuating quantity becomes less than the reset value to the instant when the relay contacts returns to its normal position.

Reach of Relay: A distance relay operates whenever the distance seen by the relay is less than the pre-specified impedance. The actuating impedance in the relay is the function of distance in a distance protection relay. This impedance or corresponding distance is called reach of the relay.

2.1.2Definition

A relay is automatic device which senses an abnormal condition of electrical circuit and closes its contacts. These contacts in turns close and complete the circuit breaker trip coil circuit hence make the circuit breaker tripped for disconnecting the faulty portion of the electrical circuit from rest of the healthy circuit.

2.1.3Relay Circuit



Basic connection diagram of protection relay

The basic connection of protection relay has been shown. It is quite simple. The secondary of current transformer is connected to the current coil of relay. And secondary of voltage transformer is connected to the voltage coil of the relay. Whenever any fault occurs in the feeder circuit, proportionate secondary current of the CT will flow through the current coil of the relay due to which mmf of that coil is increased. This increased mmf is sufficient to mechanically close the normally open contact of the relay. This relay contact actually closes and completes the DC trip coil circuit and hence the trip coil is energized. The mmf of the trip coil initiates the mechanical movement of the tripping mechanism of the circuit breaker and ultimately the circuit breaker is tripped to isolate the fault.

2.1.4Types of relays

Types of protection relays are mainly based on their characteristic, logic, on actuating parameter and operation mechanism.

Based on operation mechanism protection relay can be categorized as

- Electromagnetic relay,
- static relay and
- mechanical relay.

Based on Characteristic the protection relay can be categorized as-

1. Definite time relays
2. Inverse time relays with definite minimum time(IDMT)
3. Instantaneous relays.
4. IDMT with inst.
5. Stepped characteristic.
6. Programmed switches.
7. Voltage restraint over current relay.

Based on of logic the protection relay can be categorized as-

1. Differential.
2. Unbalance.
3. Neutral displacement.
4. Directional.
5. Restricted earth fault.
6. Over fluxing.
7. Distance schemes.
8. Bus bar protection.
9. Reverse power relays.
10. Loss of excitation.
11. Negative phase sequence relays etc.

Based on actuating parameter the protection relay can be categorized as-

1. Current relays.
2. Voltage relays.
3. Frequency relays.
4. Power relays etc.

Based on application the protection relay can be categorized as-

1. Primary relay.
2. Backup relay.

2.1.5 Universal relay

Universal **relay** is an electrically operated switch. Many relays use an electromagnet to mechanically operate a switch, but other operating principles are also used, such as solid-state relays. Relays are used where it is necessary to control a circuit by a separate low-power signal, or where several circuits must be controlled by one signal. The first relays were used in long distance telegraph circuits as amplifiers: they repeated the signal coming in from one circuit and re-transmitted it on another circuit. Relays were used extensively in telephone exchanges and early computers to perform logical operations.

A type of relay that can handle the high power required to directly control an electric motor or other loads is called a contactor. Solid-state relays control power circuits with no moving parts, instead using a semiconductor device to perform switching. Relays with calibrated operating characteristics and sometimes multiple operating coils are used to protect electrical circuits from overload or faults; in modern electric power systems these functions are performed by digital instruments still called "protective relays".

Magnetic latching relays require one pulse of coil power to move their contacts in one direction, and another, redirected pulse to move them back. Repeated pulses from the same input have no effect. Magnetic latching relays are useful in applications where interrupted power should not be able to transition the contacts.

Magnetic latching relays can have either single or dual coils. On a single coil device, the relay will operate in one direction when power is applied with one polarity, and will reset when the polarity is reversed. On a dual coil device, when polarized voltage is applied to the reset coil the contacts will transition. AC controlled magnetic latch relays have single coils that employ steering diodes to differentiate between operate and reset commands.

The Universal Torque Equation is a equation which governs the application of all types of relays. The equation has variables and constants which can be ignored for specific functions.

$$T = K_1 I^2 + K_2 V^2 + K_3 VI\cos(\theta - \tau) + K$$

This equation can be used to describe the operation of any Electrical Relay by changing the signs of some of the terms or ignoring them entirely.

For example, to describe the overcurrent relay, K2 and K3 can be considered zero while K will be negative as it is used to describe the restraining torque.

The Equation will then become

$T=K_1I^2-K$

In the case of a directional power relay, K1 and K2 can be considered to be zero while K can be considered to be negative.

2.2 Electromagnetic Relay

Electromagnetic relays are those relays which are operated by electromagnetic action.Modern electrical protection relays are mainly micro processor based, but still electromagneticrelay holds its place. It will take much longer time to be replaced the all electromagnetic relaysby micro processor based static relays.

2.2.1Operating principle

The flow of current through an electrical conductor causes a magnetic field at right angles to the current flow direction. If this conductor is wrapped to form a coil, then the magnetic field produced gets oriented along the length of the coil. If the current flowing through the conductor increases, then the magnetic field strength also increases (and vice-versa).

The magnetic field produced by passing current through coil can be used for various purposes such as inductors, construction of transformer using two inductor coils with an iron core. But, in electromechanical relay construction the magnetic field produced in coil is used to exert mechanical force on magnetic objects. This is similar to permanent magnets used to attract magnetic objects, but here the magnetic field can be turned on or off by regulating current flow through the coil. Thus, we can say that the electromechanical relay operation is dependent on the current flowing through the coil.

Practically all the relaying device are based on either one or more of the following types

1. Magnitude measurement,
2. Comparison,
3. Ratio measurement.

<u>2.2.2Types</u>

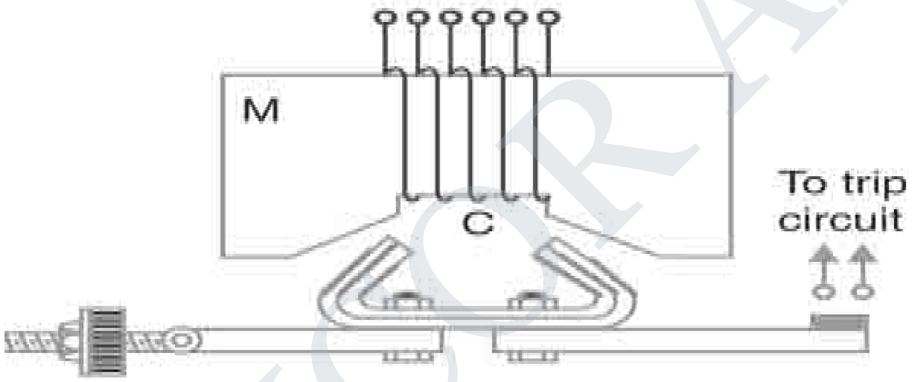
Depending upon workingprinciple the these can be divided into following types of electromagnetic relays.

1. Attracted Armature type relay,
2. Solenoid type relay
3. Balanced Beam type relay,
4. Moving coil type relay,

5. Polarized Moving Iron type relay.

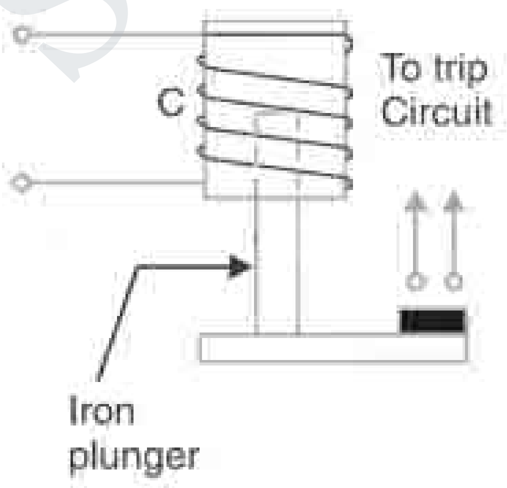
Attraction Armature Type Relay

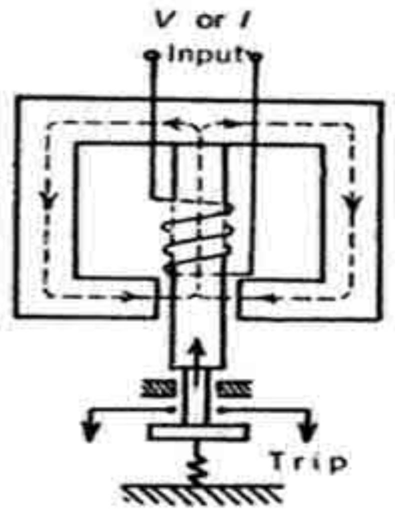
It consists of a laminated electromagnet M carrying a coil C and a pivoted laminated armature. The armature is balanced by a counterweight and carries a pair of spring contact fingers at its free end. Under normal operating conditions, the current through the relay coil C is such that counterweight holds the armature in the position shown. However, when a short-circuit occurs, the current through the relay coil increases sufficiently and the relay armature is attracted upwards. The contacts on the relay armature bridge a pair of stationary contacts attached to the relay frame. This completes the trip circuit which results in the opening of the circuit breaker and, therefore, in the disconnection of the faulty circuit.The minimum current at which the relay armature is attracted to close the trip circuit is called pickup current. It is a usual practice to provide a number of tappings on the relay coil so that the number of turns in use and hence the setting value at which the relay operates can be varied.



<u>Solenoid type relay & working</u>

It consists of a solenoid and movable iron plunger arranged as shown. Under normal operating conditions, the current through the relay coil C is such that it holds the plunger by gravity or spring in the position shown.



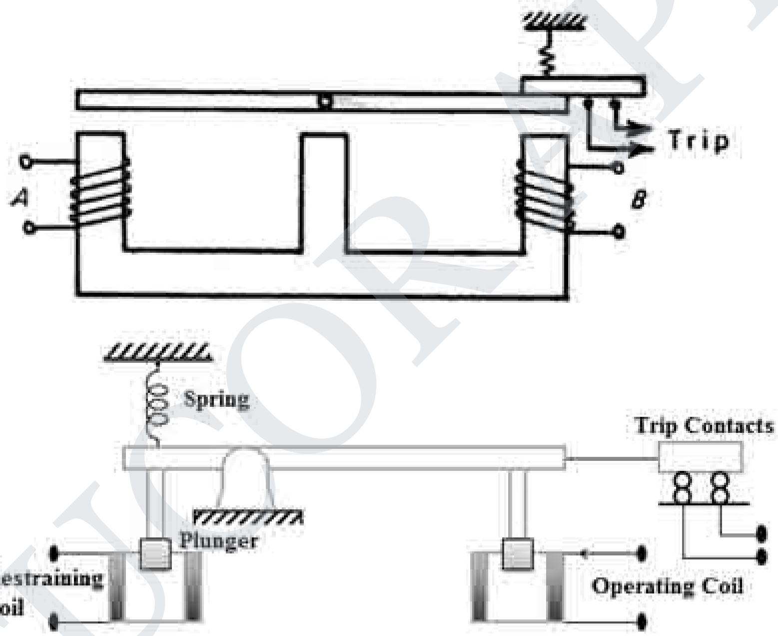


However, on the occurrence of a fault, the current through the relay coil becomes more than the pickup value, causing the plunger to be attracted to the solenoid. The upward movement of the plunger closes the trip circuit, thus opening the circuit breaker and disconnecting the faulty circuit

Balanced Beam Relay

It consists of an iron armature fastened to a balance beam. Under normal operating conditions, the current through the relay coil is such that the beam is held in the horizontal position by the spring.

However, when a fault occurs, the current through the relay coil becomes greater than the pickup value and the beam is attracted to close the trip circuit. This causes the opening of the circuit breaker to isolate the faulty circuit.



All these relays have the same principle. That is electromagnetic force produced by the magnetic flux which in turn is produced by the operating quantity. The force exerted on the moving element is proportional to the square of the flux in the air gap or square of the current. In DC electromagnetic relays this force is constant. If this force exceeds the restraining force, the relay operates.

$$F \propto \Phi^2 \text{ (AC)}, F = K \text{ (DC)}$$

This type of balanced beam relay has a fixed beam and an electromagnet (EM) as shown in the figure. The EM has two windings, one is energized by the voltage and the other energized by the current. Under normal conditions, the pull due to the voltage (restraint quantity) will be high and hence the contact remains open. When a fault occurs, the current increases, the pull due to current will be more than the pull due to voltage. This closes the contacts of the trip circuit.

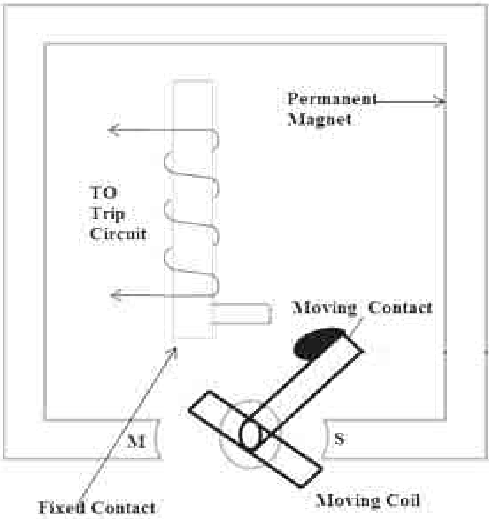
This balanced beam type relay shown in the figure consists of a horizontal beam pivoted centrally, with one armature attached to either side. There are two coils, one on each side. The beam remains horizontal till the operating force becomes greater than the restraining force. Current in coil gives the operating force and in the other, the restraining force. When the operating force or torque increases, the beam tilts and then the contact closes. The relay then actuates the tripping mechanism of the circuit breaker controlling the line / equipment.

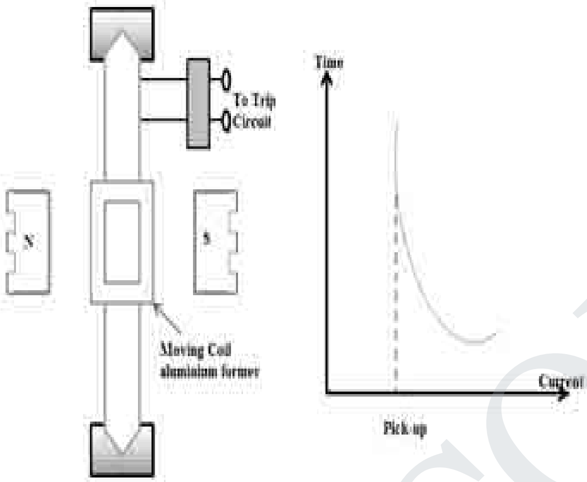
Moving Coil Type Relay

It consists of a permanent magnet coil wound on a non-magnetic former, spring, spindle etc. as shown in the fig. The coil is energised by the fault current. Due to the interaction of the permanent magnetic field and the field due to the coil, moving torque is developed. Due to this the spindle rotates and closes the trip circuits. It has negative time-current characteristics as shown in the figure. It has high torque / weight ration.

$$F \alpha NHIL$$

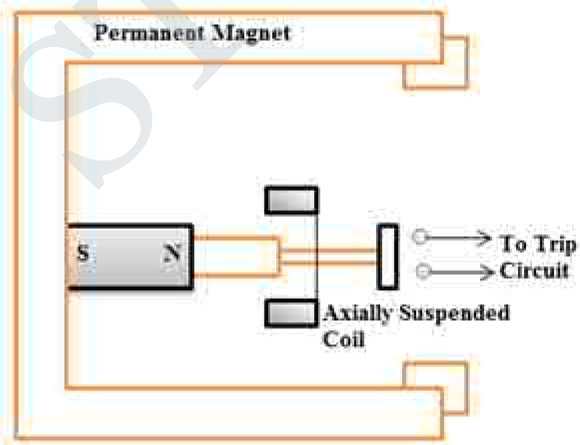
Where F = Force, N= No. of turns, H=Magnetic Field, I=Current in the coil, L=Length of coil





Axial Moving Coil Relay

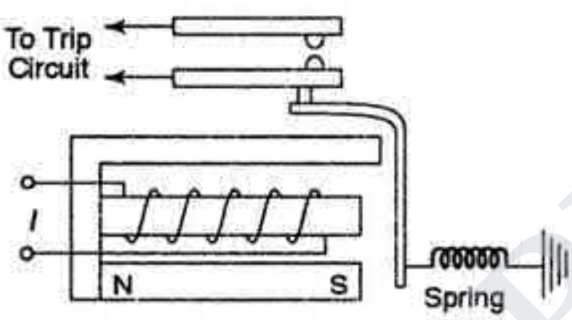
It has axially suspended coil wound on a former. The coil has only axial movement. When the coil is energized by the current, magnetic field is developed and this magnetic field is repelled by the already existing permanent magnet. Due to this, contacts get closed.



This relay is more sensitive and faster than the rotary moving coil relay. This relay has inverse operating time-current characteristics.

Polarized Moving Iron type relay.

These relays contain a permanent magnet that supplements the magnetic flux of the coil. The permanent magnet supplies flux to either of two permeable paths than can be completed by an armature. To transfer the armature and its associated contacts from one position to the other requires energizing current through the electromagnetic coil using the correct polarity.



These relays contain a permanent magnet that supplements the magnetic flux of the coil. The permanent magnet supplies flux to either of two permeable paths than can be completed by an armature. To transfer the armature and its associated contacts from one position to the other requires energizing current through the electromagnetic coil using the correct polarity.

2.2.3Advantages and Disadvantages

Advantages or merits

- Electromagnetic relays have fast operation and fast reset
- They can be used for both ac and dc systems for protection of ac and dc equipments
- Electromagnetic relays operating speeds which has the ability to operate in milliseconds are also can be possible
- They have the properties such as simple, robust, compact and most reliable
- These relays are almost instantaneous. Though instantaneous the operating time of the relay varies with the current. With extra arrangements like dashpot, copper rings etc. slow operating times and reset can be possible

Disadvantages or demerits:

- High burden level instrument transformers are required (CTs and PTs of high burden is required for operating the electromagnetic relays compared to static relays)
- The directional feature is absent in electromagnetic relays
- Requires periodic maintenance and testing unlike static relays

- Relay operation can be affected due to ageing of the components and dust, pollution resulting in spurious trips
- Operation speed for an electromagnetic relays is limited by the mechanical inertia of the component

2.3.Overcurrent Relay

In an over current relay or o/c relay the actuating quantity is only current. There is only one current operated element in the relay, no voltage coil etc. are required to construct this protective relay.

2.3.1Principle

In an over current relay, there would be essentially a current coil. When normal current flows through this coil, the magnetic effect generated by the coil is not sufficient to move the moving element of the relay, as in this condition the restraining force is greater than deflecting force. But when the current through the coil increased, the magnetic effect increases, and after certain level of current, the deflecting force generated by the magnetic effect of the coil, crosses the restraining force, as a result, the moving element starts moving to change the contact position in the relay.

Although there are different types of over current relays but basic working principle of over current relay is more or less same for all.

2.3.2Types of Over Current Relay

Depending upon time of operation, there are various types of Over Current relays, such as,

1. Instantaneous over current relay.
2. Definite time over current relay.
3. Inverse time over current relay.

Inverse time over current relay or simply inverse OC relay is again subdivided as inverse definite minimum time (IDMT), very inverse time, extremely inverse time over current relay or OC relay.

Instantaneous Over Current Relay

Here generally a magnetic core is wound by current coil. A piece of iron is so fitted by hinge support and restraining spring in the relay, that when there is not sufficient current in the coil, the NO contacts remain open. When current in the coil crosses a present value, the attractive force becomes sufficient to pull the iron piece towards the magnetic core and consequently the no contacts are closed.The preset value of current in the relay coil is referred as pick up setting current. This relay is referred as instantaneous over current relay, as ideally, the relay operates as soon as the current in the coil gets higher than pick up setting current. There is no intentional time delay applied. But there is always an inherent time delay which can not be avoided practically. In practice the operating time of an instantaneous relay is of the order of a few milliseconds.

Definite Time Over Current Relay

This relay is created by applying intentional time delay after crossing pick up value of the current. A definite time over current relay can be adjusted to issue a trip output at definite amount of time after it picks up. Thus, it has a time setting adjustment and pick up adjustment.

Inverse Time Over Current Relay

Inverse time is a natural character of any induction type rotating device. This means the speed of rotation of rotating art of the device is faster if input current is increased. In other words, time of operation inversely varies with input current. This natural characteristic of electromechanical induction disc relay in very suitable for over current protection. This is because, in this relay, if fault is more severe, it would be cleared more faster. Although time inverse characteristic is inherent to electromechanical induction disc relay, but the same characteristic can be achieved in microprocessor based relay also by proper programming.

Inverse Definite Minimum Time Over Current Relay or IDMT O/C Relay

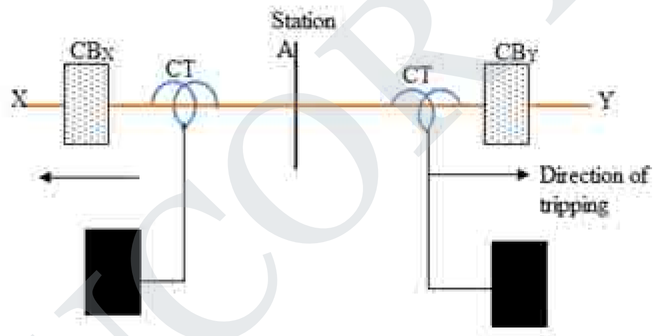
Ideal inverse time characteristics cannot be achieved, in an over current relay. As the current in the system increases, the secondary current of the current transformer is increased proportionally. The secondary current is fed to the relay current coil. But when the CT becomes saturated, there would not be further proportional increase of CT secondary current with increased system current. From this phenomenon it is clear that from trick value to certain range of faulty level, an inverse time relay shows exact inverse characteristic. But after this level of fault, the CT becomes saturated and relay current does not increase further with increasing faulty level of the system. As the relay current is not increased further, there would not be any further reduction in time of operation in the relay. This time is referred as minimum time of operation. Hence, the characteristic is inverse in the initial part, which tends to a definite minimum operating time as the current becomes very high. That is why the relay is referred as inverse definite minimum time over current relay or simply IDMT relay.

2.4.Directional Relay

2.4.1Principle

This is also a special type of over current relay with a directional features. This directional over current relay employs the principle of actuation of the relay, when the fault current flows into the relay in a particular direction. If the power flow is in the opposite direction, the relay will not operate. Normally, the conventional over current relay (non-direction) will act for fault current in any direction.

The directional over current relay recognizes the direction in which fault occurs, relative to the location of the relay. The principle of directional protection is as under:



directional over current relay

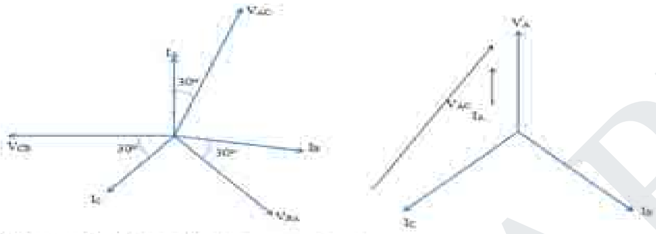
Consider a feeder XY, passing through station A. The circuit breaker in feeder AY is provided with a directional relay R, which will trip the breaker CB_y, if the fault power flow is in the direction AY alone. Therefore, for faults in feeder AX, the circuit breaker CB_y, does not trip unnecessarily. However, for faults in feeder AY, the circuit Breaker CB_y trips, due to direction feature of the relays, set to act in the direction AY. This type of relay is also called reverse power relay, So far as the direction of fault current (power) flow is concerned.Reverse power flow relays with directional features, not only senses the direction flow, but also measures magnitude of power flow.

2.4.2Construction and Operation

Whenever a near or close-up fault occurs, the voltage becomes low and the directional relay may not develop sufficient torque for its operation. To get sufficient torque during all types faults, irrespective of locations with respect to relays, the relays connections are to be modified. Each relay is energized by current from its respective phase and voltage. One of the methods of such connections is 30° connection and other is 90° connection.

30° Connection phasor Diagram

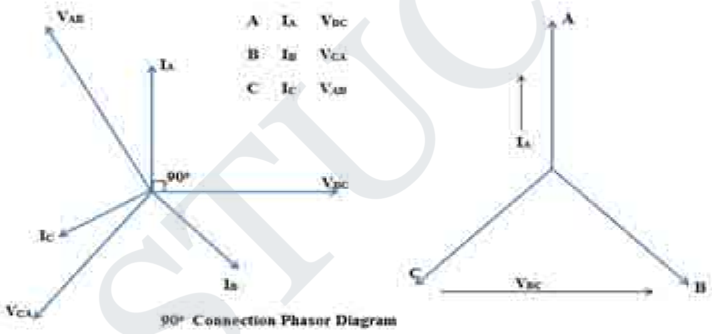
In this type of 30° connections, the current coil of the current coil of the relay of phase A is energized by phasor current I_A and the line voltage V_{AC}. Similarly, the relay in phase B by I_B and V_{BA} and in phase C by I_C and V_{CB}. The relay will develop maximum torque when its current and voltage are in phase.



30° connection phasor diagram

90° Connection Phasor Diagram

In the 90° connection, relay in phase A is energized by I_A and V_{BC}, relay in phase B, by I_B and V_{CA} and the relay in phase C by I_C and V_{AB}. The relay is designated to develop maximum torque when the relay current leads the voltage by 45°.

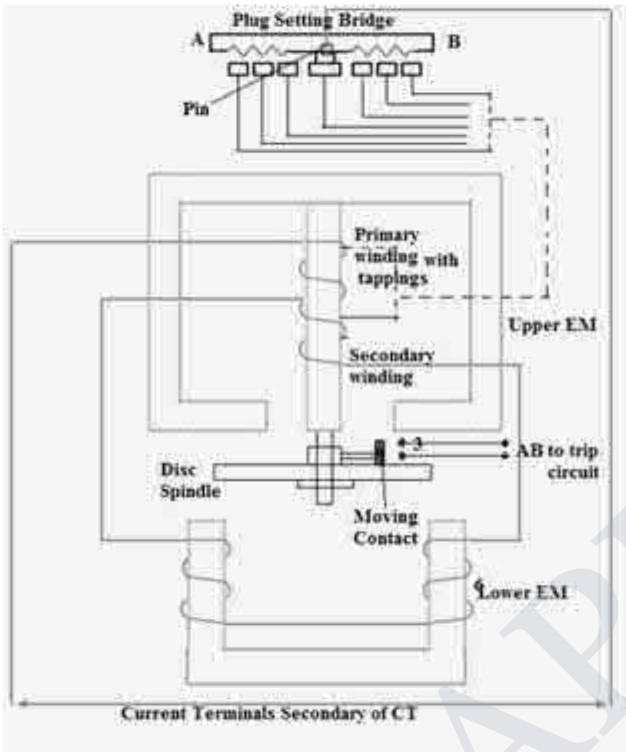


90° Connection Phasor Diagram

Construction

It has a metallic disc free to rotate between the poles of two electromagnets (EM).

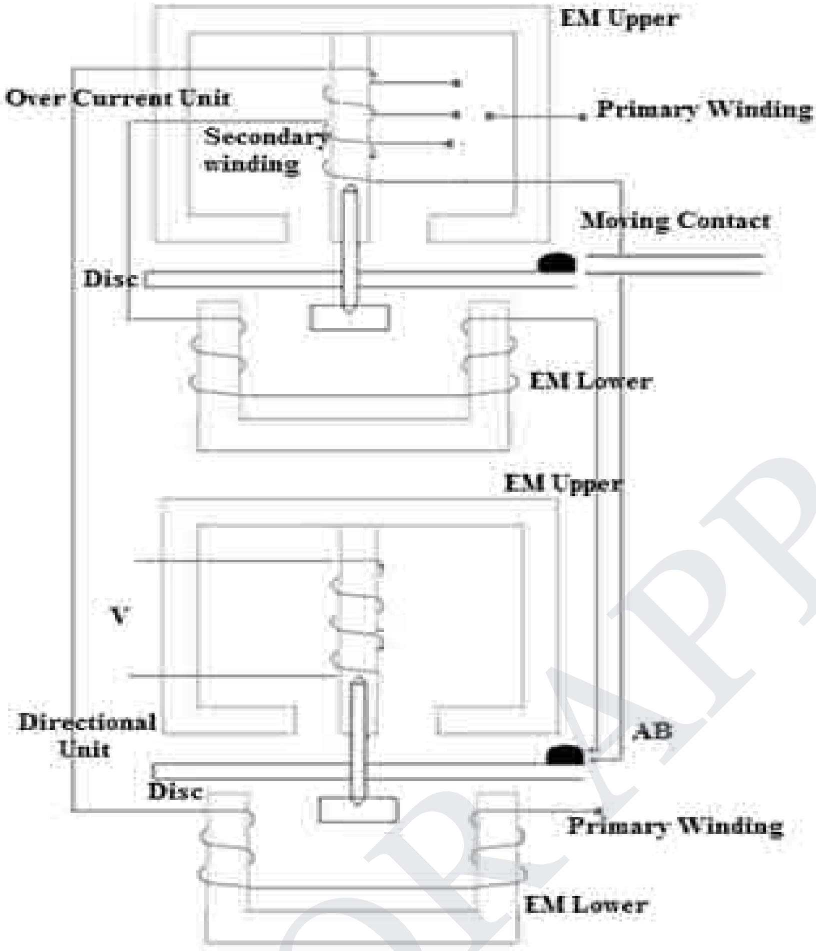
The spindle of this disc carries a moving contact which bridges two fixed contacts when the disc rotates through an angle, which is adjustable between 0° to 360°. By adjusting this angle, the travel of moving contact can be adjusted so that the relay can be given any desired time setting which is indicated by a pointer, The dial is calibrated from 0-1. The relay time from name plate curve is to be multiplied by time multiplier setting.



The upper magnet has two windings. The primary coil is connected to the secondary of CT through tapping in it. Theses tapings are connected to plug setting bridge. The secondary is connected to the lower electro magnet; the torque exerted on the disc is due to the interaction of eddy currents produced therein by the flux from the upper EM and the lower EM. The relay setting is 50% to 200% in steps of 25%.

<u>Constructional Details and Operation of Directional Over Current Relay (Wattmeter Type)</u>

A directional over current relay operates when the current exceeds a specified value in a specified direction. It contains two relaying units, over current units and the other a directional unit. For directional unit, the secondary winding of the over current (relay) unit is kept open (AB). When the directional unit operates, it closes the open contacts of the secondary winding of the relay may be either wattmeter or shaded pole type.



Under normal operating conditions, power flows in the normal direction in the circuit, protected by the relay and therefore, the directional unit does not operate. When a short circuit occurs, there is a tendency for the current or power to flow in the reverse direction. In such a case, the disc of the directional unit rotates to bridge he fixed contacts A and B, completing the circuit for the over current unit. The disc of the over current unit rotates consequently and the moving contacts attached to it closes the trip circuit. This operates the circuit breaker which isolates the faulty section.

The directional unit is made very sensitive so that with the lowest value of voltage which may be anticipated under severe fault conditions, sufficient torque is produced by the current to complete the operation and allow its contacts to close.

2.5 Distance Relay

Distance protection is a widely used protective scheme for the protection of high or an extra high voltage transmission lines. The operation of the conventional over current relays either direction or non directional, depend on the magnitude of current or

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power in the protected circuit, where as the distance protection relay operate on the principle of the ratio of applied voltage to current in that circuit. This ratio is proportional to the distance along the line, and the relay that measures the distance is called distance protection relay. It is not unit system of protection. A single scheme provides both primary and backup protections.

2.5.1Principle

The working principle of distance relay **or** impedance relay is very simple. There is one voltage element from potential transformer and an current element fed from current transformer of the system. The deflecting torque is produced by secondary current of CT and restoring torque is produced by voltage of potential transformer.

In normal operating condition, restoring torque is more than deflecting torque. Hence relay will not operate. But in faulty condition, the current becomes quite large whereas voltage becomes less. Consequently, deflecting torque becomes more than restoring torque and dynamic parts of the relay starts moving which ultimately close the No contact of relay. Hence clearly operation or working principle of distance relay, depends upon the ratio of system voltage and current. As the ratio of voltage to current is nothing but impedance a distance relay is also known as impedance relay.

The operation of such relay depends upon the predetermined value of voltage to current ratio. This ratio is nothing but impedance. The relay will only operate when this voltage to current ratio becomes less than its predetermined value. Hence, it can be said that the relay will only operate when the impedance of the line becomes less than predetermined impedance (voltage / current). As the impedance of a transmission line is directly proportional to its length, it can easily be concluded that a distance relay can only operate if fault is occurred within a predetermined distance or length of line.

2.5.2Torque equation

The impedance relay is a double actuating relay and essentially consists of two elements operated voltage element and the current operated element. The current operated elements produce a positive (pick up torque) while the voltage elements develop a negative or reset torque. Taking spring control effects as $-K_3$, the torque equation of the relay is

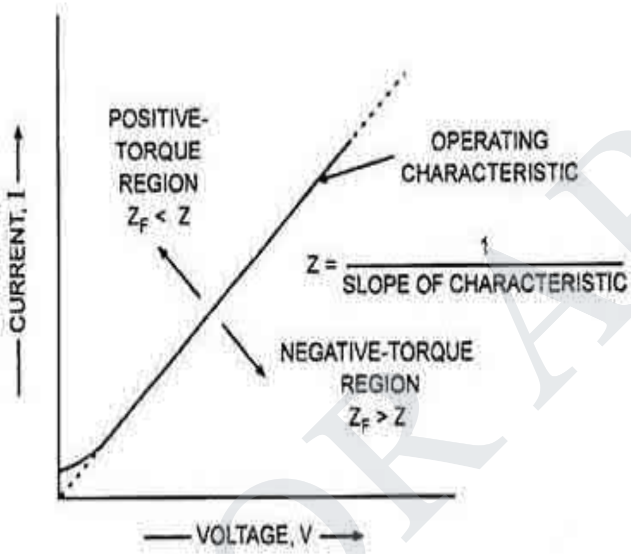
$$T = k_1 I^2 - k_2 V^2 - k_3$$

where V and I are the RMS value of voltage and current respectively. At balance point, when the relay is on the extreme of operating the net torque is zero, and

$$k_2 V^2 = k_1 I^2 - k_3$$

The effect of control spring magnitude is negligible. Its effect is noticeable only at current, magnitude well below those normally encountered. Hence, taking $K_3 = 0$ the relay torque equation becomes

$$Z = \sqrt{\frac{k_1}{k_2}} = Constant$$



The operating characteristic regarding voltages V and current I is shown in the figure, causing a notable bend in the characteristic only at the current low end. The dashed line represents an operating characteristic which represents a constant value of Z, may be considered as operating characteristic.

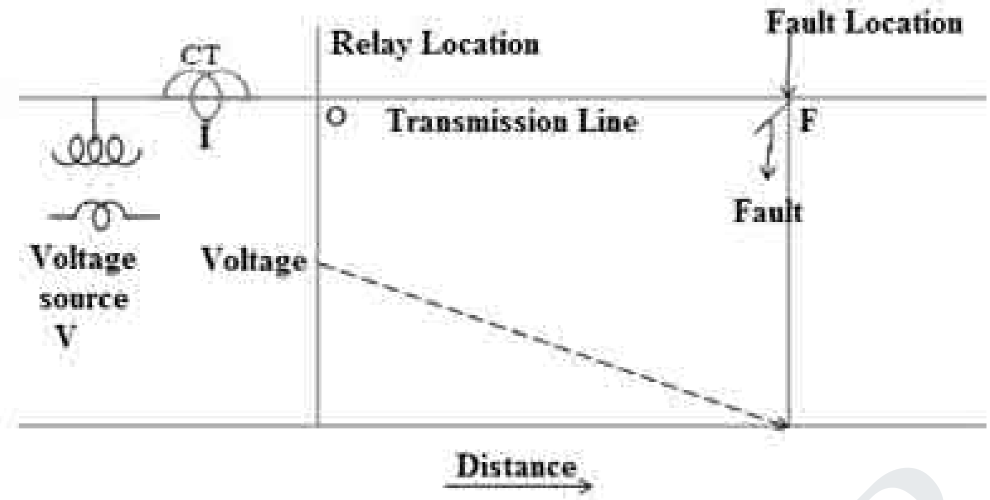
2.5.3Types of Distance Protection Relay

The distance protection relay family consists of the following types of Relays:

1. Impedance Relays
2. Reactance Relays
3. MHO Relays or Admittance Relays.

Impedance Relay

An impedance relay measures the impedance of the line at the relay location. When a fault occurs in the protected line section the measured impedance is the impedance of the line section between the relay location and the point of fault. It is proportional to the length of the line and hence to the distance along the line as shown below.

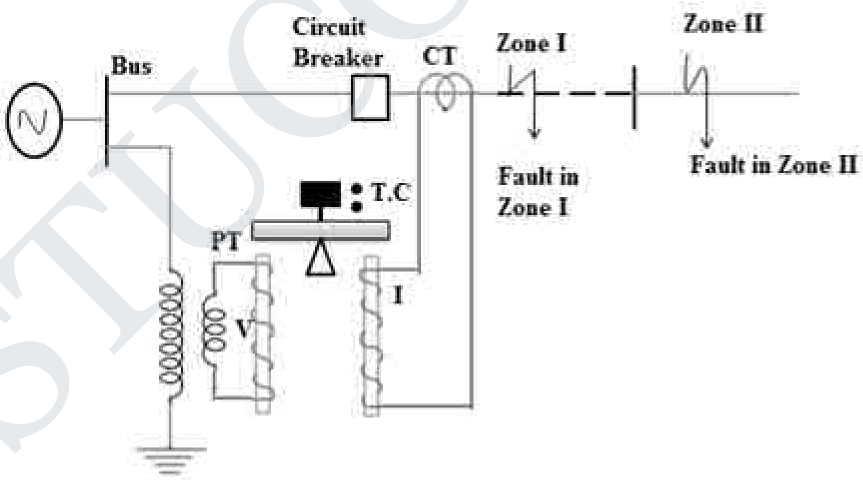


OF is the distance along the line between the relay location and the fault location, The voltage drop along OF and the current I flowing in the line are taken for measurement by the relay and the ratio of the both quantities is nothing but impedance.

Construction of Impedance Relay

The figure shows the simple arrangement of impedance relay operates based on the distance of the fault.

Here, balanced beam type EM relay is used as impedance relay. The CT and PT are energized by the current and voltage of the circuit which is to be protected.



Operating Principle of Impedance Relay

A simple form of EM balanced beam impedance relay is shown in the fig. It has a fixed beam and two electromagnets (EM). One EM is energized by voltage of the zone through PT and the other EM is energized by current of the zone through CT.Under no fault condition, the pull due to voltage element will be more than the pull due to current element and the trip circuit (TC) remains open.Since this type of relay operates based on the impedance of the circuit which in turn depends upon the distance of the fault from the relay location, it is called distance relay.In operating characteristics of an impedance of the circuit is compared with voltage at relay location. The current produces a positive torque, called Operating Torque and the voltage produces a negative torque called Restraining Torque. This equation for the operating torque of an electromagnetic relay is:

$$T = K_1 I^2 - K_2V^2 - K_3$$

Where K_1, K_2, K_3 are constants, K_3 being the torque due to control spring effect.

Neglecting the effect of the spring used, which is very small, the torque equation can be written as:

$$T = K_1 I^2 - K_2V^2$$

For the operation of the relay, the following condition should be satisfied.

$$K_1I^2 > K_2V^2 \text{ or } K_2V^2 < K_1I^2$$

$$V_2/I^2 < K_1/K_2$$

V/I < K where K is a constant.

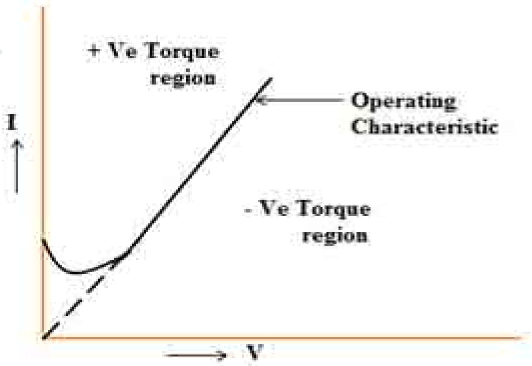
as V/I is Z, Z<K.

The above expression explains that the relay is on the verge of operation when the ratio of V to I i.e., the measured value of line impedance is equal to a given constant. The relay operates, if the measured Z is less than the given constant. This given constant, is a design value depending on the total length of the HT / EHT feeder to be protected.

A distance relay can also be called as an Ohmmeter, measuring the impedance of the line in ohms.

Operating Characteristic of an Impedance Relay (V-I and R-X Diagram)

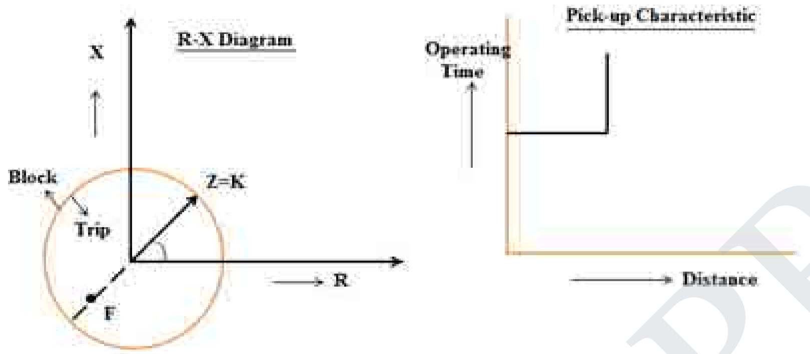
V-I Diagram



The above figure shows the operating characteristic of impedance relay in terms of voltage and current. Hence the above is termed as V-I diagram. The operating characteristic is slightly bent near the origin due to the effect of the control spring. If the relay is of static relay type, the characteristic would have been a straight line, as there is no control spring in the relay. The positive torque region is the relay operating zone (above the characteristic curve) and the negative torque region below the curve is the relay non-operating zone.

R-X Diagram

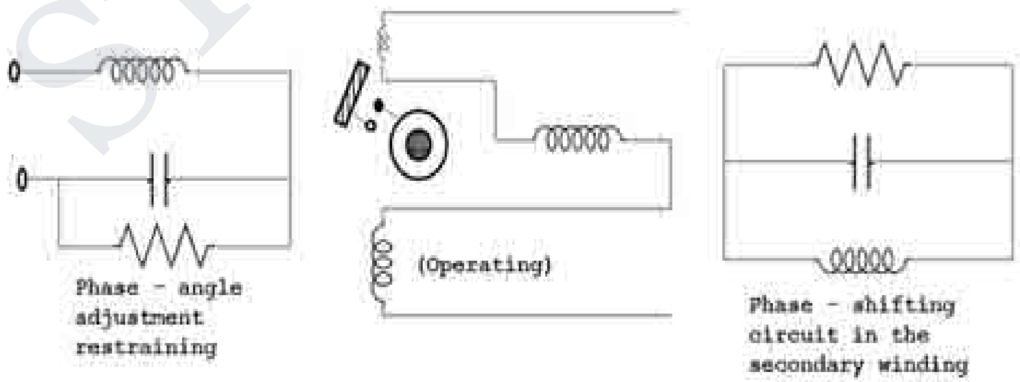
Another and more useful way of representing the operating characteristic of the relay is an R-X diagram as shown below:



Z = K = radius of the circle. When Z, i.e., the impedance of the line up to fault location measured from the relay location is less than K, the relay will operate i.e., the fault location lies inside the circle. If it is outside the circle, the relay will not sense it and hence, that zone is theBlocking zone. The operations of the relay depends upon the magnitude of Z and not on angle Φ, as Z is the radius of the circle, having equal magnitude along the circumference of the circle, from the centre. It is also seen that the impedance relay, basically a non-directional relay, as it operates on the magnitude of the operating quantity and not on its direction of flow, The figure indicates that the operating time of this relay is constant irrespective of the distance within the protective zone.

Reactance relay

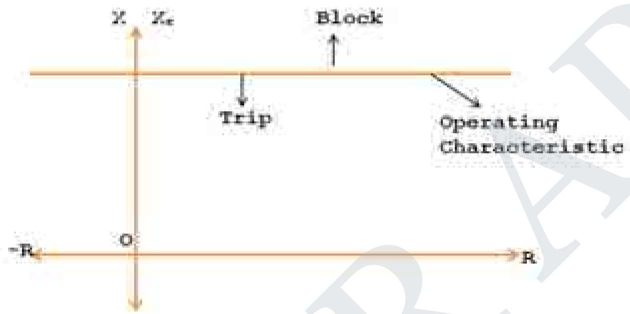
A simplest form of electromagnetic induction type reactance relay (Induction Cup) is shown in the figure.



The current is the operating quantity. It produces flux in the upper, lower and right hand side poles. The right hand side pole flux is out of phase with the flux in the lower and upper poles because of the secondary winding which is closed by a phase shifting circuit and is placed on the right hand side pole. The polarizing flux and the right hand side pole flux interacts to produce the operating torque K_1I^2. The interaction of left hand side pole flux and the polarizing flux produces the restraining torque. The phase angle adjustment circuit is connected in series with the voltage coil.

A reactance relay measures the reactance of the line at the relay location. This induction type reactance relay performance is not affected by arc resistance during the occurrence of the fault. In case of a fault, the relay measures the reactance of the line up to the fault point from the relay location.

The relays operating characteristic on R-X diagram, is a straight line parallel to X axis as indicated below in figure.



The operating torque is by current and the Restraining torque is by current–voltage directional element. The Reactance relay may also be called as over current relay with directional restraint. The directional element is arranged to develop maximum negative torque, when thecurrent lags its voltage by 90°. If the spring control effect is K_3, the torque T is given by:

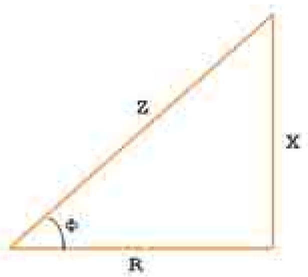
$T = K_1I^2 - K_2VI \sin \Phi - K_3$ where $\sin \Phi = \cos (90 - \Phi)$

As the value of K_3 is very small, it can be neglected.

$T = K_1I^2 - K_2VI \sin \Phi$.

$VI\sin\Phi$ indicates reactive voltamperes.

As the start of relay operation,



$K_1I^2 = K_2VI\sin\Phi$

$K_1I = K_2 V \sin\Phi$

$(V/I) = K_1 / K_2 \sin\Phi$

$Z \sin\Phi = K_1/K_2 = X = \text{Constant}$

Operating torque will be more than the Restraining torque for relay operation. In other words the Restraining torque should be less than the operating torque.

i.e., $K_2 VI\sin\Phi < K_1I^2$

$K_2V\sin\Phi < K_1I$

$V/I \sin\Phi < K_1/K_2 < K$, a constant

$X < K$, as $X = Z \sin\Phi$ and $Z = V/I$

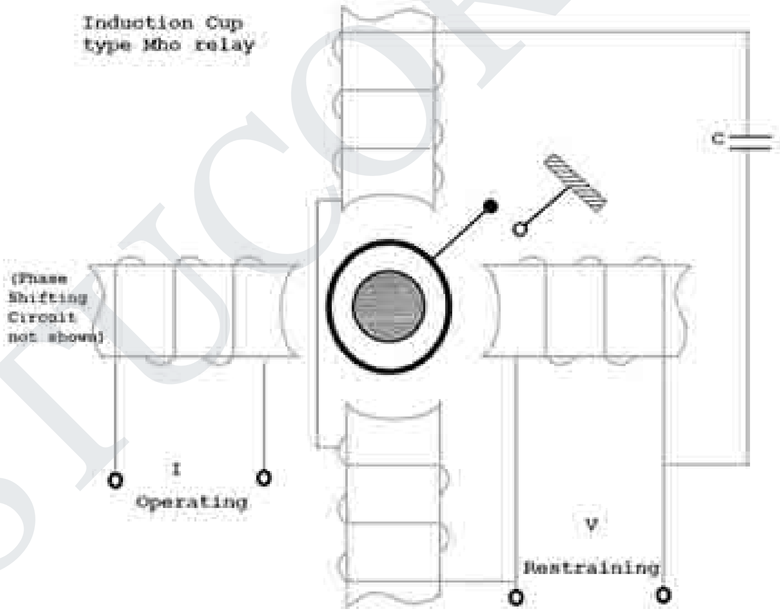
The reactance relay will operate, when the measured value of the reactance is less than the predetermined or design value of K.

The directional unit used with the reactance relay is not the same as the one used with theimpedance type relay because the reactance relay will trip under normal load conditions when the power factor of the load is unity or near zero. This is because; the restraining reactive volt-ampere at U.P.F or near U.P.F will be near zero. Therefore, we must have directional unit is called Mho unit or Mho relay, having a circular characteristic.

Reactance relay are used for protection of short lines having fault currents less than 20 KA. In such lines, the effect of fault resistance or arc resistance is predominant.

Mho relay

A simple form of Mho relay | Admittance or angle admittance relay shown in the figure below:

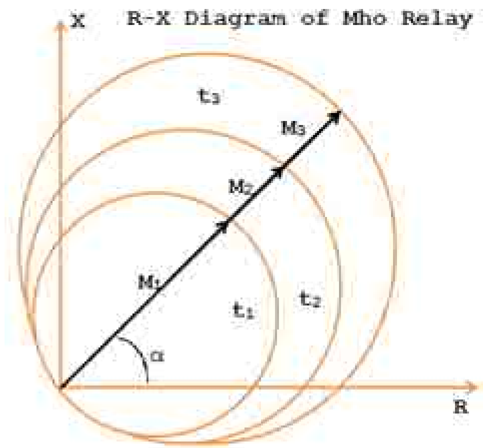


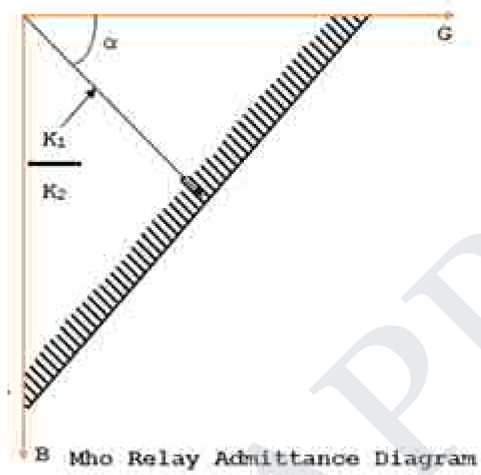
It is an electromagnetic induction cup type mho relay.

The torque equation is given by $T = K_1 VI (\Phi - \alpha) - K_2V^2 - K_3$

The upper and lower poles are energized by a voltage V to produce a polarizing flux. The capacitor connected in series provides memory action. The left is energized by a current is the operating quantity. The left pole due to current I interacts with the polarized flux due to V produce the operating torque $K_1VI \cos(\Phi - \alpha)$.

The angle α can be varied by adjusting the resistance in the phase shifting circuit provided on the left pole. The right hand side pole is energized by the voltage and the flux produced by it interacts with the polarizing flux for producing the restraining torque, K_2V^2.





A Mho relay measures a component of admittance $|Y| \angle\theta$. But its characteristic when plotted on the impedance diagram (i.e., R-X diagram) is a circle passing thro' the origin shown in the fig. It is inherently a directional relay as it detects the fault only in the forward direction. The relay is called Mho relay because its characteristic is a straight line, when plotted on an admittance diagram (G-B axes i.e., conductance – susceptance axes) as in the figure.

The operating torque for a Mho relay is by V-I element and restraining torque is by voltage element.Therefore, a Mho relay can be called as a voltage restrained directional relay.

$T = K_1\ VI \cos(\Phi - \alpha) - K_2V^2$, neglecting the effect of the spring.

$K_2V^2 < K_1VI \cos(\Phi - \alpha)$

$K_2V < K_1I \cos(\Phi - \alpha)$

$(V/I \cos(\Phi - \alpha)) < K_1/K_2$ or $(V/I) < (K_1/K_2) \cos(\Phi - \alpha)$ or $Z < (K_1/K_2)\cos(\Phi - \alpha)$

At balance conditions, the operating torque is equal to restraining torque.

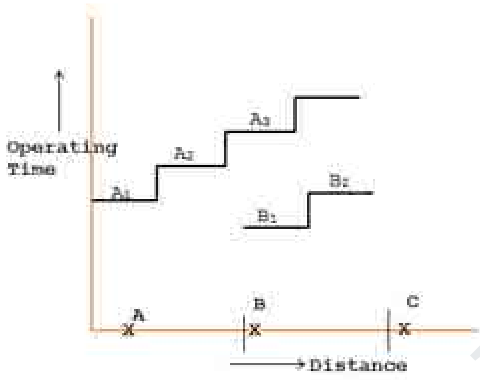
i.e., $K_1VI\cos(\Phi - \alpha) = K_2V^2$

$(I/V)\cos(\Phi - \alpha) = (K_2K_1) = K$

$(1/Z) = (K / \cos(\Phi - \alpha)) = Y$

$Y = K / \cos(\Phi - \alpha)$ = admittance in mho.

There units of mho relays are used for the protection of a section of the line. I unit is a high speed unit to protect 80% to 90% of the line section. The II unit protects the rest of the line section and its reach extends up to 50% of the adjacent line section. The III unit is meant for backup protection of the adjacent line section. The II and III units operate with a preset time delay, usually 0.2 sec to 0.5 sec and 0.4 sec to 1sec respectively. The time distance characteristic is a stepped one as shown in figure.



2.5.4Comparisions of distance relay

S. No	Type of Relay	Operating Torque Element	Restraining Torque Element	Used for Protection
1	Impedance Relay (Z)	Current (I)	Voltage (V)	Phase faults in medium length lines
2	Reactance Relay (X)	Current (I2)	Voltage – Current SinΦ (V – I sin Φ)	Ground faults in short lines
3	Admittance Relay (Y)	VI Cos (Φ – α)	V	Phase faults in long Lines

2.6.Differential Relay

2.6.1Definition

A differential relay is defined as the relay that operates when the phase difference of two or more identical electrical quantities exceeds a predetermined amount.

From the definition the following aspects are known; -

1- The differential relay has at least two actuating quantities say I_1, I_2

2- The two or more quantities should be similar i.e. current/current.

3- The relay responds to the vector difference between the tow i.e. to I_1-I_2, which includes magnitude and/or phase angle difference.

Differential protection is generally unit protection. The protected zone is exactly determined by location of CT's and VT's. The vector difference is achieved by suitable connections of current transformer or voltage transformer secondaries.

2.6.2Types

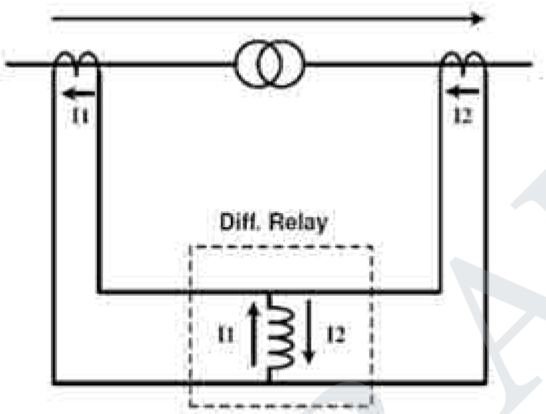
1.Current Differential Relay

2.Merz Price or Biased or Percentage Differential Relay

3.Voltage Balance Differential Relay

Current Differential Relay

Principle Operation of differential relay

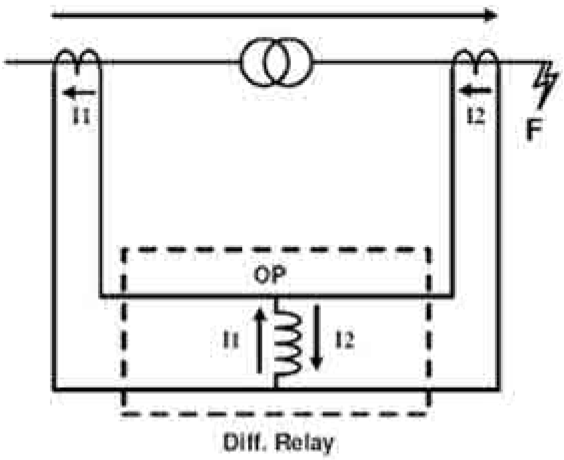


Differential Relay at Normal Condition

Let assume an power transformer with transformation magnitude (ratio) relation 1:1 and (Y/Y) connection and therefore the CT1 and CT2 ensure a similar transformation magnitude relation as shown. The current flows within the primary side and secondary side of power transformer are equal, presumptuous ideal power transformer. The secondary current I1 and I2 are same in magnitude and reverse in direction. Therefore, the net current within the differential coil is nil at load situation (without any fault), and therefore the relay won't operate.

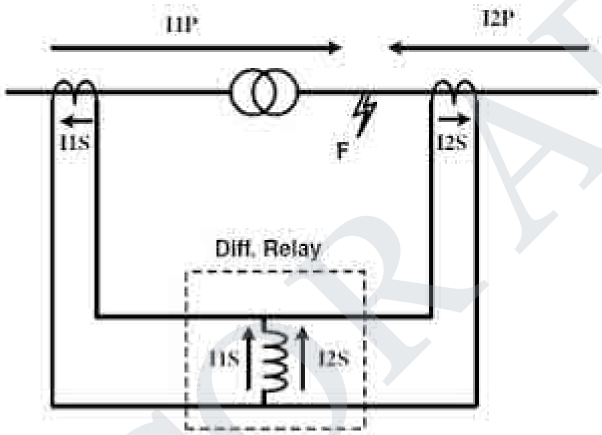
External Fault Condition in Differential Relay

Assigning the previous one the power transformer with an external fault F is shown in figure. During this case the 2 currents I1, and I2 can increase to terribly high magnitudes values however there's no modification in phase angle. Hence, net current within the differential coil continues to be zero and therefore the relay won't operate.



Differential Relay External Fault condition

Internal Fault Condition in Differential Relay



Differetial Relay With Internal Fault Condition

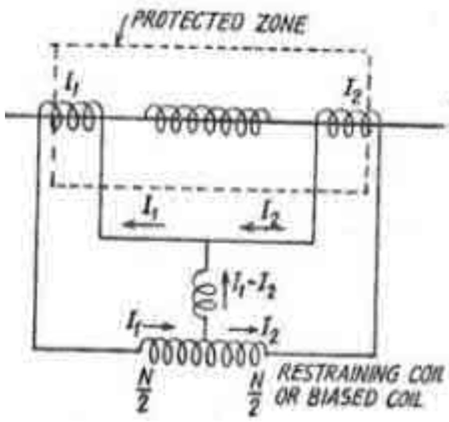
An internal fault F is shown in this figure. Now, there are 2 anticipated conditions:

There's other supply to feed the fault thus I2P includes a nonzero value Idiff = I1S + I2S which can be terribly high and sufficient to function the differential relay.

Radial system, I2P = 0. So, Idiff = I1S and additionally the relay can work and disconnect the breaker.

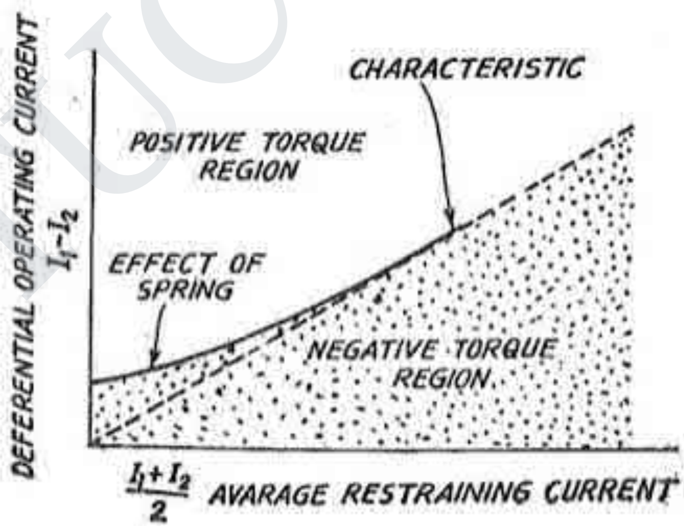
2.6.3Merz –price protection

The reason for using this modification is circulating current current differential relay is to overcome the trouble arising out of differences in CT ratios for high values of external short circuit currents.



The percentage differential relay has an additional restraining coil connected in the pilot wire as shown in In this relay the operating coil is connected to the mid-point of the restraining coil becomes the sum of ampere turns in its tow halves, i.e (I_1N/2) + (I_2N/2) which gives the average restraining current of ($I_1 + I_2$)/2 in N turns. For external faults both I_1 and I_2 increase and thereby the restraining torque increases which prevents the mal-operation.

In this relay the operating coil is connected to the mid-point of the restraining coil becomes the sum of ampere turns in its tow halves, i.e (I_1N/2) + (I_2N/2) which gives the average restraining current of ($I_1 + I_2$)/2 in N turns. For external faults both I_1 and I_2 increase and thereby the restraining torque increases which prevents the mal-operation.



The ratio of differential operating current to average restraining current is Fixed percentage.Hence the relay is called 'percentage differential relay'.

The relay is so called 'Based differential relay' because the restraining coil is also called a biased coil as it provides additional flux.

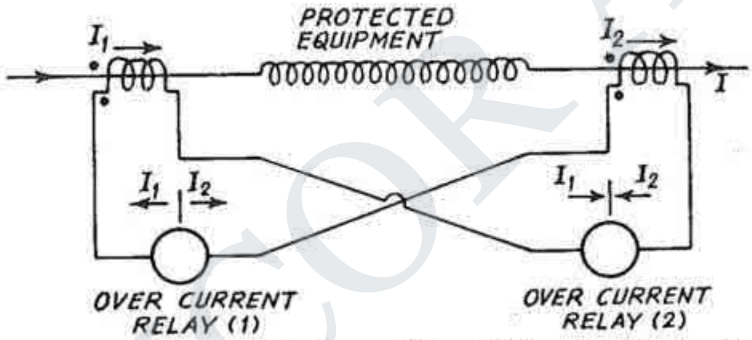
The percentage of biased differential relay has a rising single pick up characteristic. As the magnitude of through current increases, the restraining current decreases.

2.6.4Balanced voltage differential relay

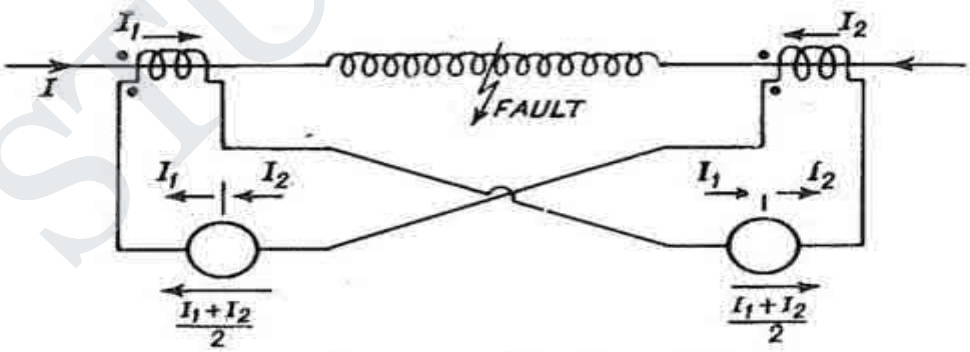
The relays are connected in series with the pilot wires, one at each end. The relative polarity of the current transformers is such that there is no current through the relay under normal operating conditions and under fault conditions

In this the secondaries of CT's are connected such that for normal conditions and through fault conditions, the secondary current of CT's on tow sides opposes each other and their voltage are balanced During internal fault, the condition changes as an equivalent current $(I_1 + I_2)/2$ flows through relay coils at each end.

The current transformer used in such protection is with air gap core so that the core does not get saturated and overvoltages are not produced during zero secondary current under working normal condition.



Through fault condition Differential Protection based on balanced voltage principle.



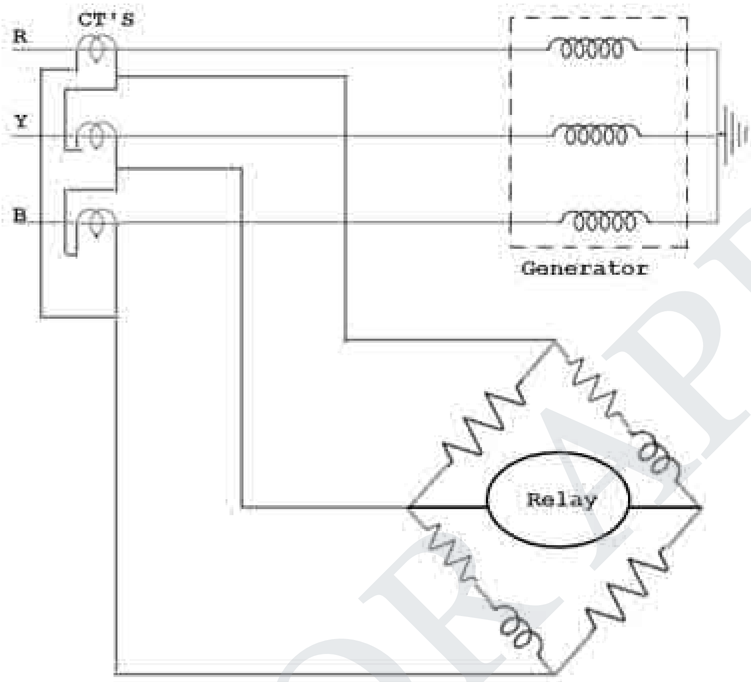
2.7Negative sequence relay and Under frequency relays.

Negative sequence relay

2.7.1Principle

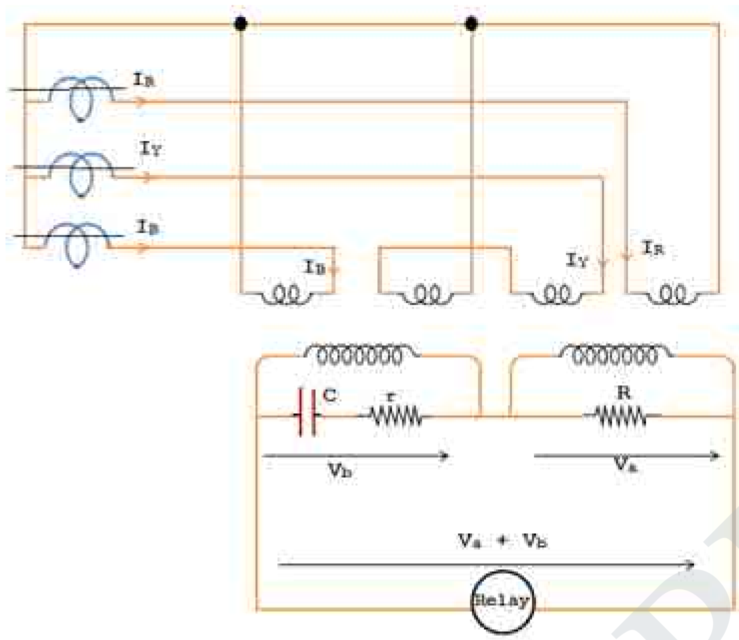
Negative sequence relays are used to protect electrical machines against overheating due to unbalance currents in stator. These unbalance currents cause heating of rotor and damage it. Unbalance three-phase currents have negative sequence components. These components rotate at synchronous speed in a direction opposite to the direction of rotation of rotor, including double frequency currents in the rotor.

2.7.2Construction and Operation

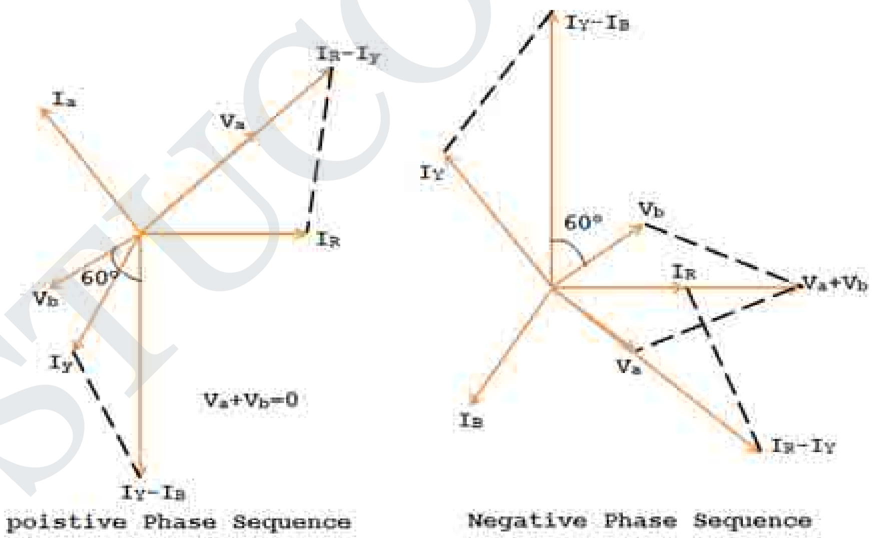


The arrangement of negative sequence relay connection is shown in the figure. The relay is connected in parallel across the current transformer secondaries. Under normal conditions, as equal current flows in all the three phases, their algebraic sum is zero. Hence no current flows through the relay. But, if unbalancing occurs, the secondary currents will be different and the resultants current flows through the relay and the operation of the relay trips the circuit breaker to disconnect the generator from the system.

For unbalanced conditions or unsymmetrical faults, negative phase sequence network are used as shown in the figure below.



The values of c and r are such as to give a phase shift 60°. It can be seen from the vector diagrams that for the positive sequence currents the output voltage $V_a + V_b$ applied to the relay is zero shown in fig-a below where for the negative sequence currents, the output voltage $V_a + V_b$ is of considerable magnitude to operate the relay shown in fig-b.

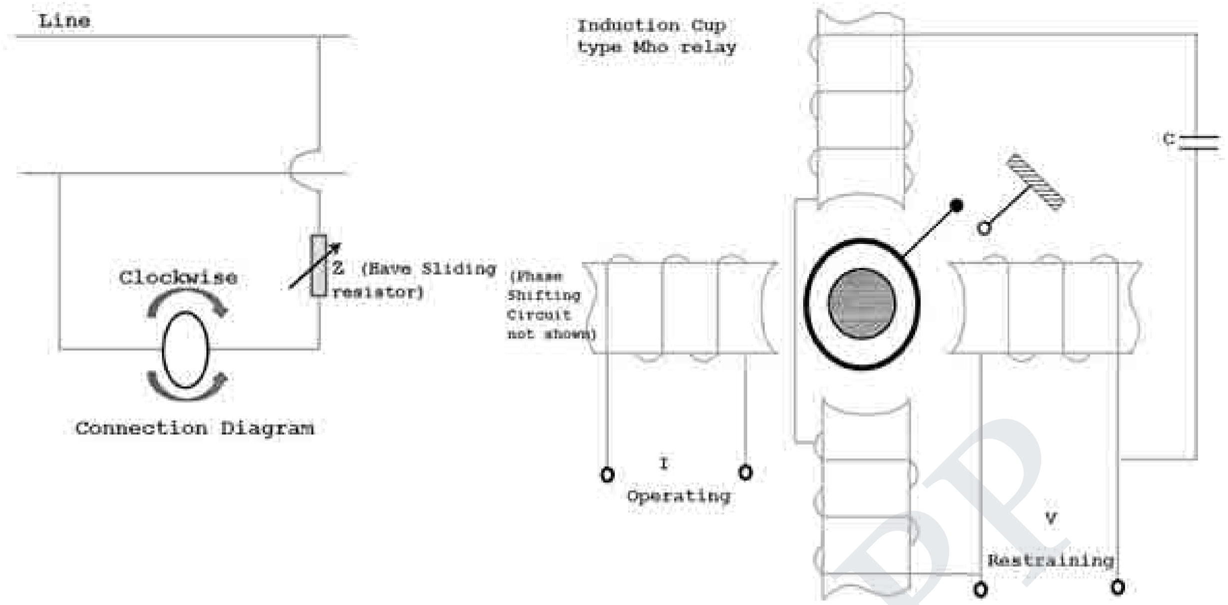


The negative sequence relay has the inverse square law characteristic. i.e., $I_2^2 t = K$, a constant. I_2 is the negative sequence component of the current.

$$t = K / I_2^2 \text{ i.e., } t \propto 1/I_2^2.$$

Under Frequency Relay Or Over Frequency Relay.

The frequency relays are normally used in generator protection and for load-frequency control.



The frequency of induced e.m.f. of synchronous generator is maintained constant by constant speed. Over speeding of the generator occurs due to loss of load and under speeding occurs due to increase in load. In both the cases, the frequency varies from normal value. In order to avoid damage to the generator under the above two conditions, frequency relays are used.Under frequency relay trips the feeder on load at set value of frequency, so as to give relief to the generator, thereby saving the unit. Under frequency relay thus aids load shedding programme to save the grid.

Unit IV

STATIC RELAYS AND NUMERICAL PROTECTION

Static relays – Phase, Amplitude Comparators – Synthesis of various relays using Static comparators– Block diagram of Numerical relays – Overcurrent protection, transformer differential protection,distant protection of transmission lines.

4.1. Static relays

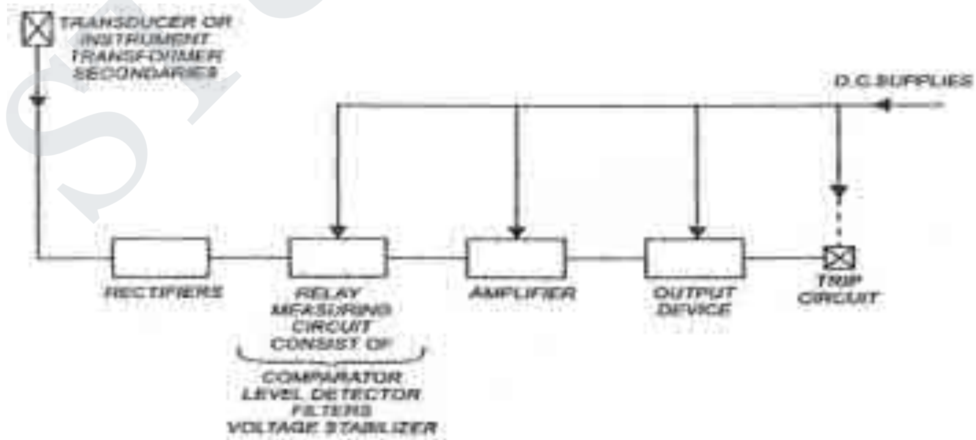
A static relay is a type of relay, an electrically operated switch, that has no moving partsStatic relays are contrasted with electromechanical relays, which use moving parts to create a switching action. Both types of relay control electrical circuits through a switch that is open or closed depending upon an electrical input.Static relays have been designed to perform similar functions with the use of electronic circuit control as an electromechanical relay performs with the use of moving parts or elements.

Static relays may be based on analog solid state circuits, digital logic circuits, or microprocessor-based designs

4.1.1Components

A static relay consists of

- An input circuit that measures the value of desired property
- A comparator circuit that compares the measured value to a preset threshold
- An optional time delay circuit that controls the timing of the switch action after the input has reached the threshold
- A power supply for the static relay circuits



The output of CT's or PT's or transducers is rectified in rectifier. The rectified output is fed to the measuring unit. The measuring unit comprises comparators, level detectors, filters, logic circuits. The output is initiated when input reaches the threshold value.

The output of measuring unit is amplified by Amplifier. The amplified output is given to the output unit which energizes the trip coil only when relay operates.

In conventional electromagnetic the measurement is carried out by comparing operating torque/force with restraining torque/force. The electro-mechanical relay operates when operating torque/fence exceeds the restraining torque/force. The pick-up of relay is obtained by movement of movable element in the relay. In a static relay the measurement is performed by static circuits.

A simplified block diagram of single input static relay is given in the above figure. In individual relays there is a wide variation. The quantities: voltage, current. etc. is rectified and measured. When the quantity to be measured reaches certain well defined value, the output device is triggered. Thereby current flows in the trip circuit of the circuit-breaker.

4.1.2Merits and demerits

Advantages of Static Relay

- The power consumption of the static relay is much lower and thereby decreases the burden on the instrument transformer and increased its accuracy.
- The static relay has the quick response, long life, shockproof, fewer problems of maintenance, high reliability and a high degree of accuracy.
- Quick reset action, a high reset value and the absence of overshoot can be easily achieved because of the absence of thermal storage.
- Ease of providing amplification enables greater sensitivity to be obtained.
- The risk of unwanted tripping is less with static relays.
- Static relays are quite suitable for earthquakes prone areas, ships, vehicles, airplanes, etc., This is because of high resistance to shock variation.
- A static protection control and monitoring system can perform several functions such as protection, monitoring, data acquisition measurement, memory, indication, etc.,

Limitations of Static Relay

- Some components are sensitive to electrostatic discharges.Even small charges can damage the components, and therefore precautions are necessary for the manufacturing of static relays to avoid components failures due to electrostatic discharges.
- Static relays are sensitive to voltage spikes or voltage transients. Special measures are taken to avoid such problems.
- The reliability of the system depends on a large number of small components and their electrical components.
- The static relay has low short-time overload capacity as compared to electromagnetic relays.

- Static relays are costlier, for simple and single function than their equivalent electromechanical counterparts. But for multi-functional protection, static relay proves economical.
- Highly trained personnel are required for their servicing.
- Static relays are not very robust in construction and easily affected by surrounding interference.

4.1.3Types of static relays

- Analog Relay
- Digital Relay
- Numerical /Microprocessor Relay

4.2. Comparators

Comparator is a part of **static relay**, which receives two or more inputs to be compared and gives output based on the comparison.

The various *types of comparators* are;

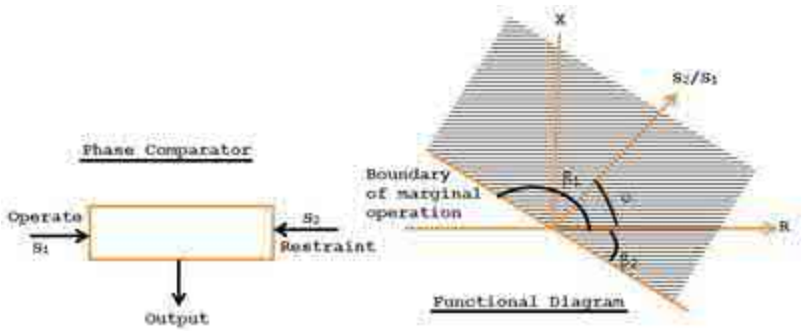
1. Amplitude Comparator
2. Phase Comparator
3. Hybrid Comparator

4.2.1Phase Comparator

Phase comparison technique is the most widely used one for all practical directional, distance, differential and carrier relays.

If the two input signals are S_1 and S_2 the output occurs when the inputs have phase relationship lying within the specified limits.

Both the input must exist for an output to occur. The operation is independent of their magnitudes and is dependent only on their **phase relationship**. The figures below show that the phase comparator is simple form. The function is defined by the boundary of marginal operation and represented by the straight lines from the origin of the S-plane.



The condition of operation is $\beta_1 < \theta < \beta_2$.θ is the angle by which S_2 lands S_1. If $\beta_1 = \beta_2 = 90^o$, the comparator is called **cosine comparator** and if $\beta_1=0$ and $\beta_2=180^o$, it is a **sine comparator**.

In short, **a phase comparator compares two input quantities in phase angle** (vertically) irrespective of the magnitude and operates if the phase angle between them is $< 90^o$.

There are two **types of phase comparators**:

1. Vector product comparator
2. Coincidence type phase comparator.

Vector Product comparator

This comparator recognizes the vector product or division between the two or more quantities. Thus, the output is A, B or A/B

Coincidence Comparator

Consider two signals S_1 and S_2. The period of Coincidence of S_1 and S_2 will depend on the phase difference between S_1 and S_2. The fig below shows the coincidence of S_1 and S_2 when S_2 lags S_1 by less than $\pi/2$ ie., θ.

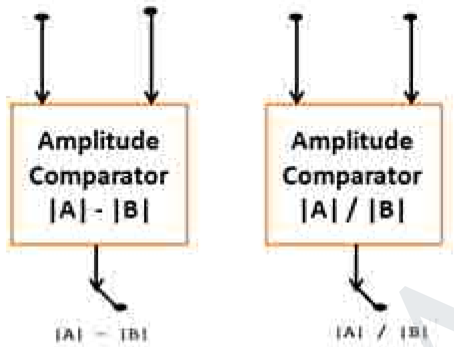
The period of coincidence of S_1 and S_2 with a phase difference of θ is $\Psi = 180^o - \theta$. Different techniques are used to measure the period of coincidence.

Two of the important types are

1. **Bloke Spike Method (Direct Phase Comparison)** and
2. **Coincidence type – Integrating phase comparator.**

4.2.2 Amplitude Comparator

An **amplitude comparator** compares the magnitude of two input quantities irrespective of the angle between them. One of the inputs is the operating quantity and the other a restraining quantity.When the amplitude of the operating quantity exceeds that of restraining quantity, the relaysends a tripping signal to the circuit breaker.



- The Amplitude comparator compares two vector, |A| and |B|

- Gives an output: the algebraic difference between the magnitudes |A| and |B|

- Output is +ve, if |A| > |B|

- Output is –ve, if |A| < |B|

- Output is zero, if |A| = |B|

Comparison by ratio:

- Output is >1, if |A| > |B|

- Output <1, if |A| < |B|

- Output is Zero, if |A| is zero.

Amplitude types of comparator.

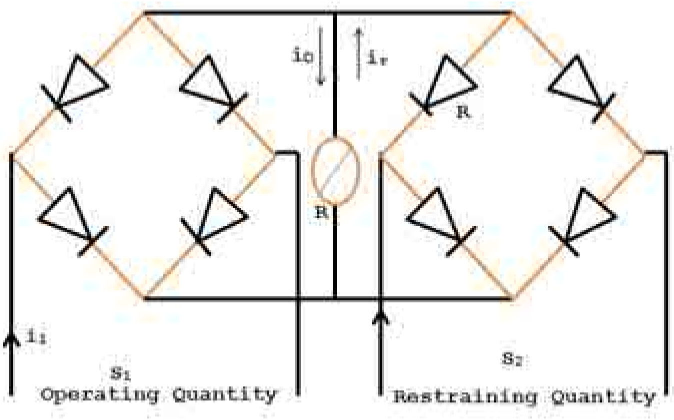
1. Integrating comparator
2. Instantaneous comparator
3. Sampling Comparator

Integrating Comparator

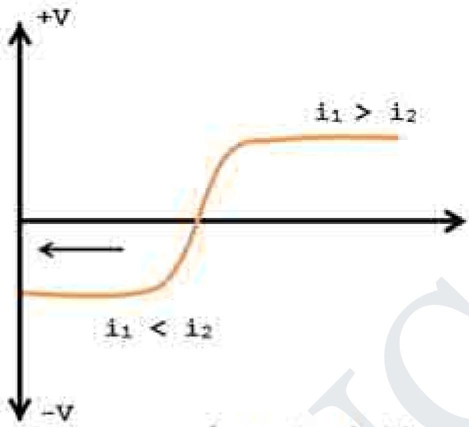
- Circulating Current Type

- Opposed Voltage Type

Circulating Current Type



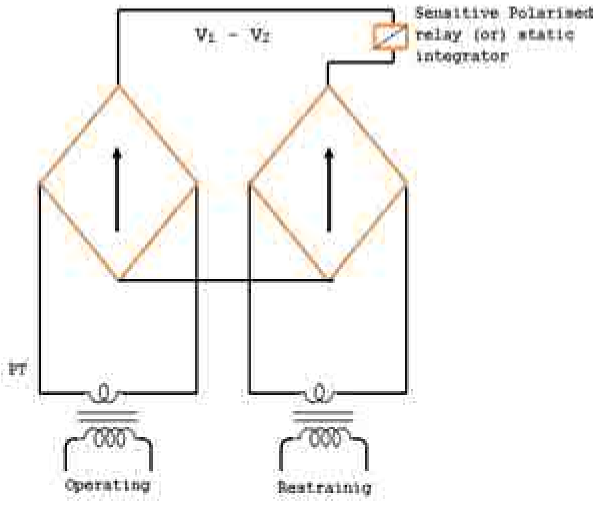
Circulating Current Type



V-I Characteristic

It can also be used as impedance relay. Two rectifier bridges can be arranged in such a manner as shown in the figure below, to function as amplitude comparator circulating type. The polarized relay operates when $S_1>S_2$ where $S_1=K_1i_1$ and $S_2 = K_2i_2$. This arrangement gives a sensitive relay whose voltage may be represented in the VI characteristic of the figure.

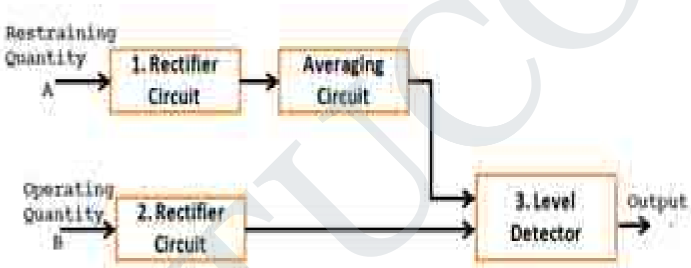
Opposed Voltage type



Opposed Voltage Type

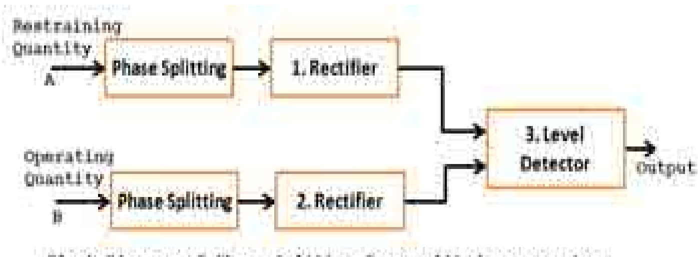
This type works with voltage input signals derived from PTs. The operation depends on the difference of the average **rectified voltage** (V1-V2).Here the rectifiers are not protected against higher currents. The relay operates when V1 >V2.

Instantaneous Comparator (Directing Amplitude Comparator) – Averaging Type



Here the restraining signal is rectified and smoothed completely in order to provide a level restraint.

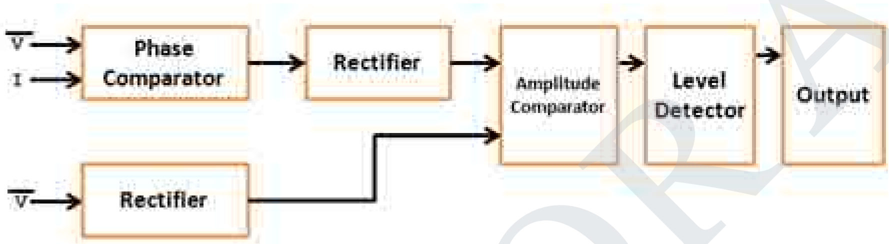
This is then compared with the peak value of operating signal, which may or may not be rectified but is smoothened. The tripping signal is provided if the operating signal exceeds the level of the restraint. The block diagram is shown in the fig above. Since this method involves smoothening, the operation is slow. A faster method is phase splitting the wave shapes of instantaneous amplitude comparator are shown in fig below before rectification and the averaging circuit can be eliminated.



Block Diagram of Phase Spliting for amplitude comparator

Hybrid Comparator

This kind of comparator compares both magnitude and phase of the input quantities. Hence this type is of mixed version.In the **hybrid comparator**, both amplitude and phase comparators are used. Inputs are given to a phase comparator. The output of the phase comparator is given to amplitude comparator.

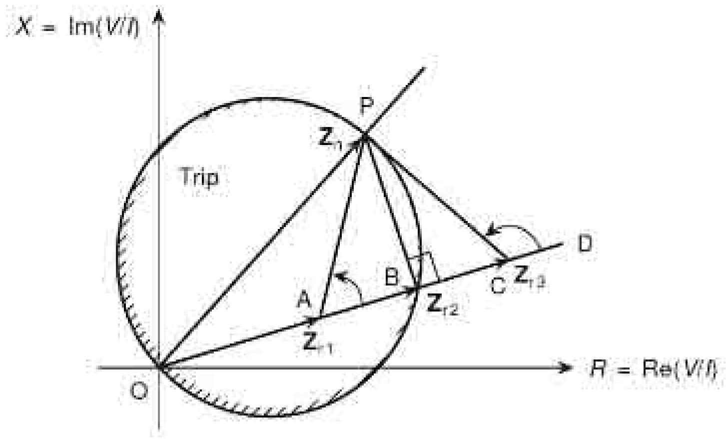


Static impedance relays comparing V and I are generally of Hybrid Comparator.

4.3.Synthesis of various relays using Static comparators

4.3.1MHO relay

Using Phase comparators



$OA = \lvert Z_{r1}\rvert \rightarrow$ Trip	$AP = \lvert Z_n - Z_{r1}\rvert$
$OB = \lvert Z_{r2}\rvert \rightarrow$ Threshold	$BP = \lvert Z_n - Z_{r2}\rvert$
$OC = \lvert Z_{r3}\rvert \rightarrow$ Restrain	$CP = \lvert Z_n - Z_{r3}\rvert$

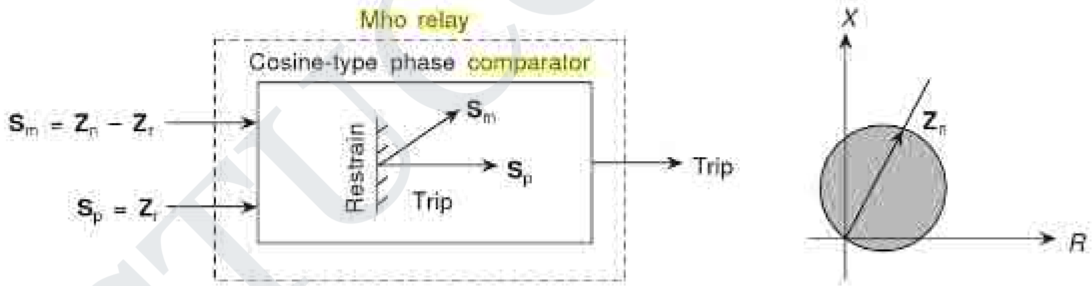
$$\text{Arg}\ \frac{|Z_n - Z_{r1}|}{|Z_{r1}|} = \angle BAP < 90^\circ \quad \Rightarrow \quad \text{Trip}$$

$$\text{Arg}\ \frac{|Z_n - Z_{r2}|}{|Z_{r2}|} = \angle CBP = 90^\circ \quad \Rightarrow \quad \text{Threshold}$$

$$\text{Arg}\ \frac{|Z_n - Z_{r3}|}{|Z_{r3}|} = \angle DCP > 90^\circ \quad \Rightarrow \quad \text{Restrain}$$

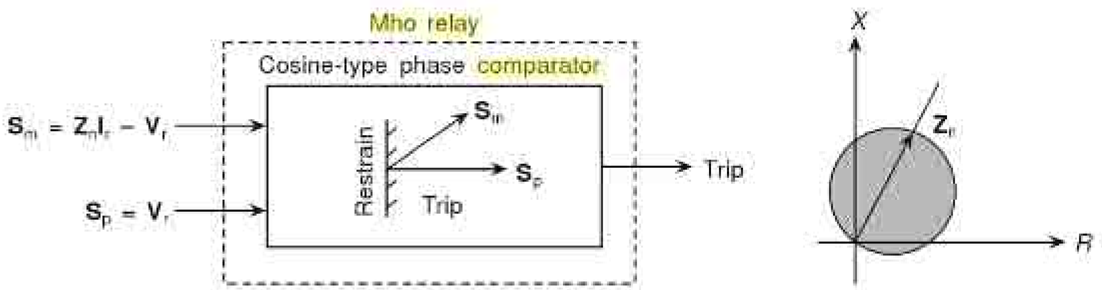
Trip law:

$$\text{If} \quad \text{Arg}\ \frac{|Z_n - Z_r|}{|Z_r|} < 90^\circ, \quad \text{then trip}$$

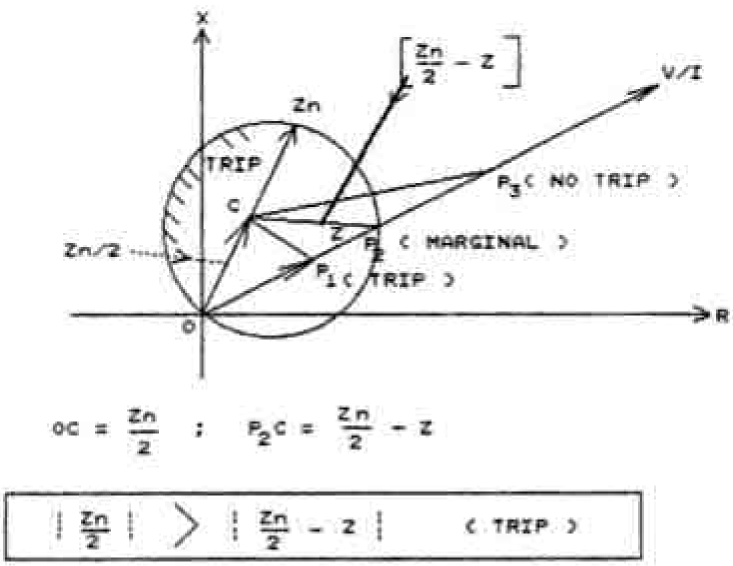


$$(Z_n - Z_r)I_r = Z_nI_r - V_r = S_m$$

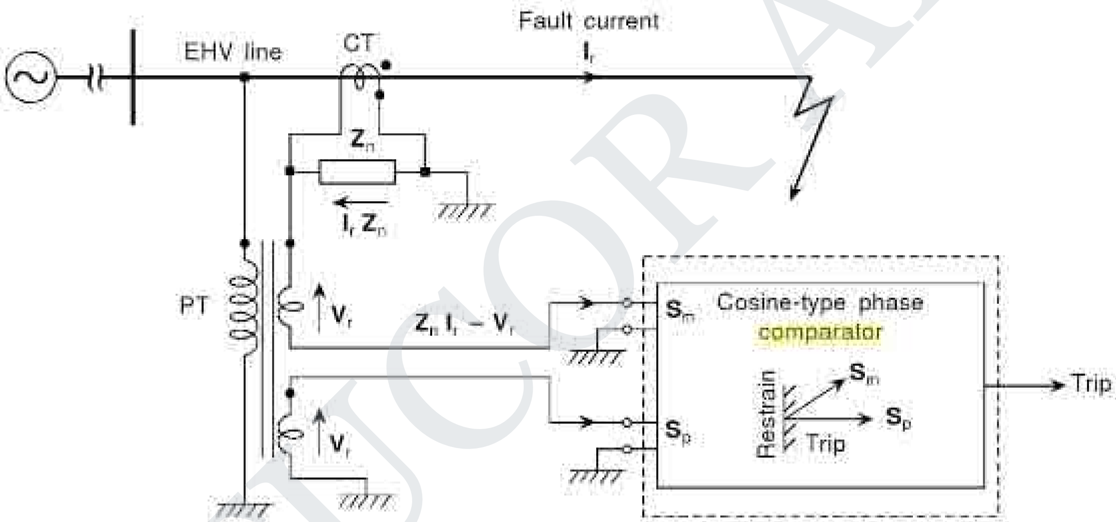
$$Z_rI_r = V_r = S_p$$



<u>Using amplitude comparators</u>

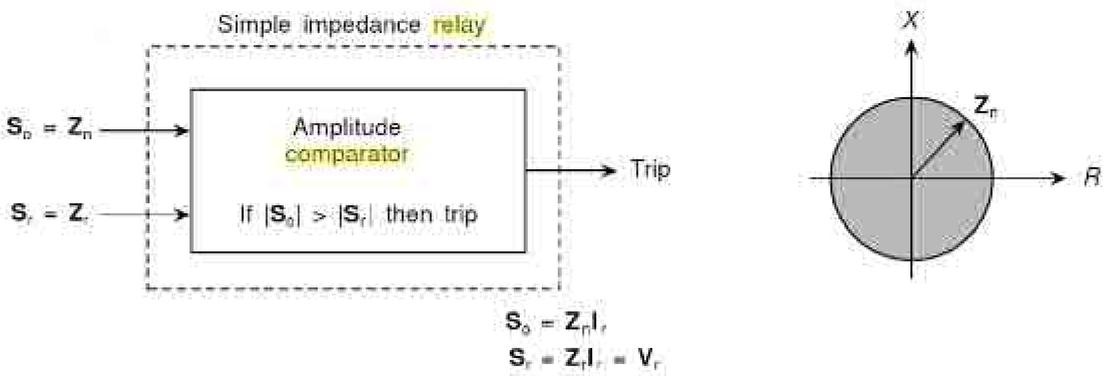


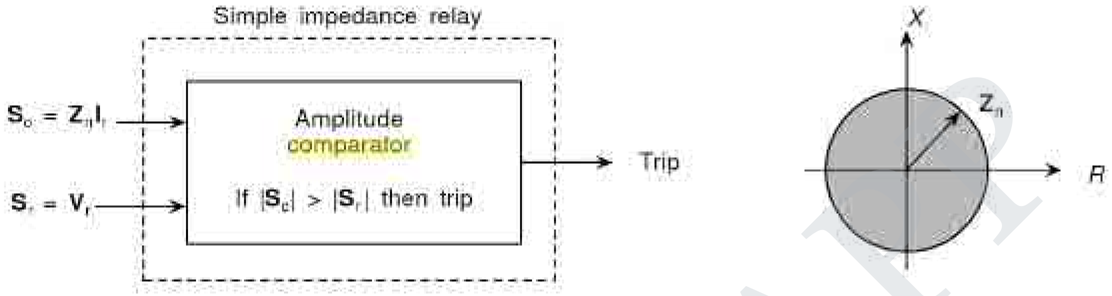
4.3.2Reactance relay



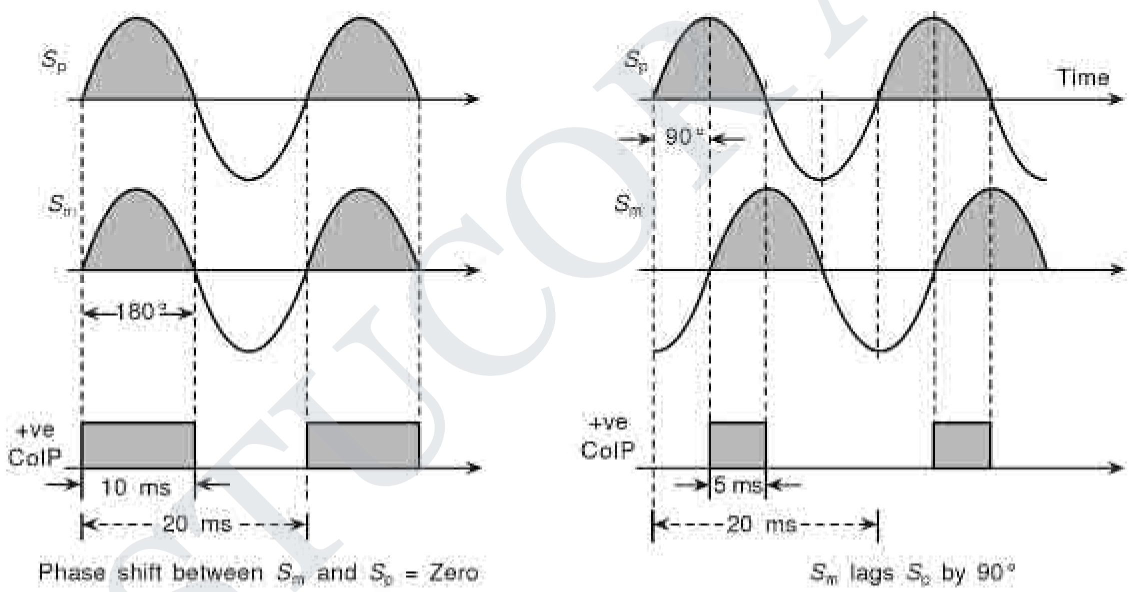
If Sn< sp then trips

4.3.3Impedance relay



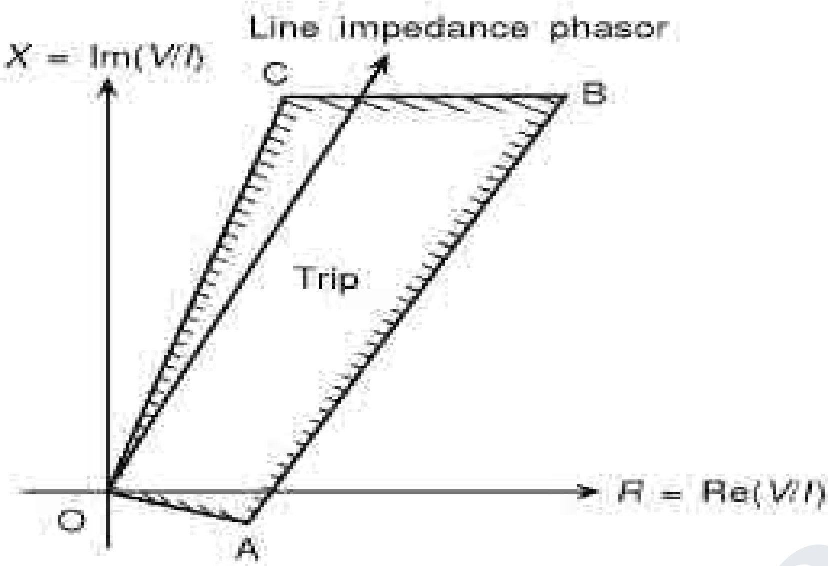


Coincidence period for phase shift

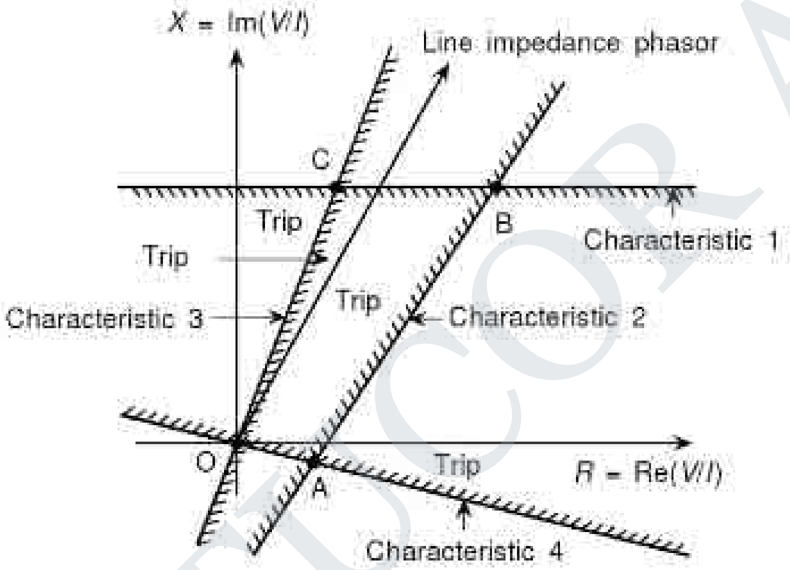


4.3.4Distance relay

Characteristics of distance relay

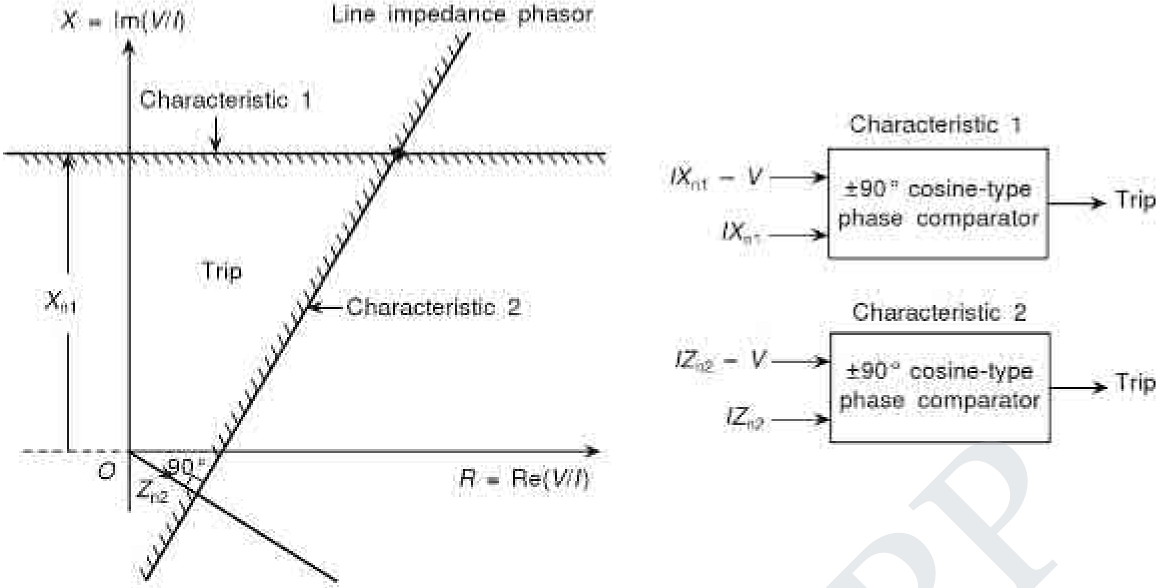


Four characteristics synthesis of distance relay

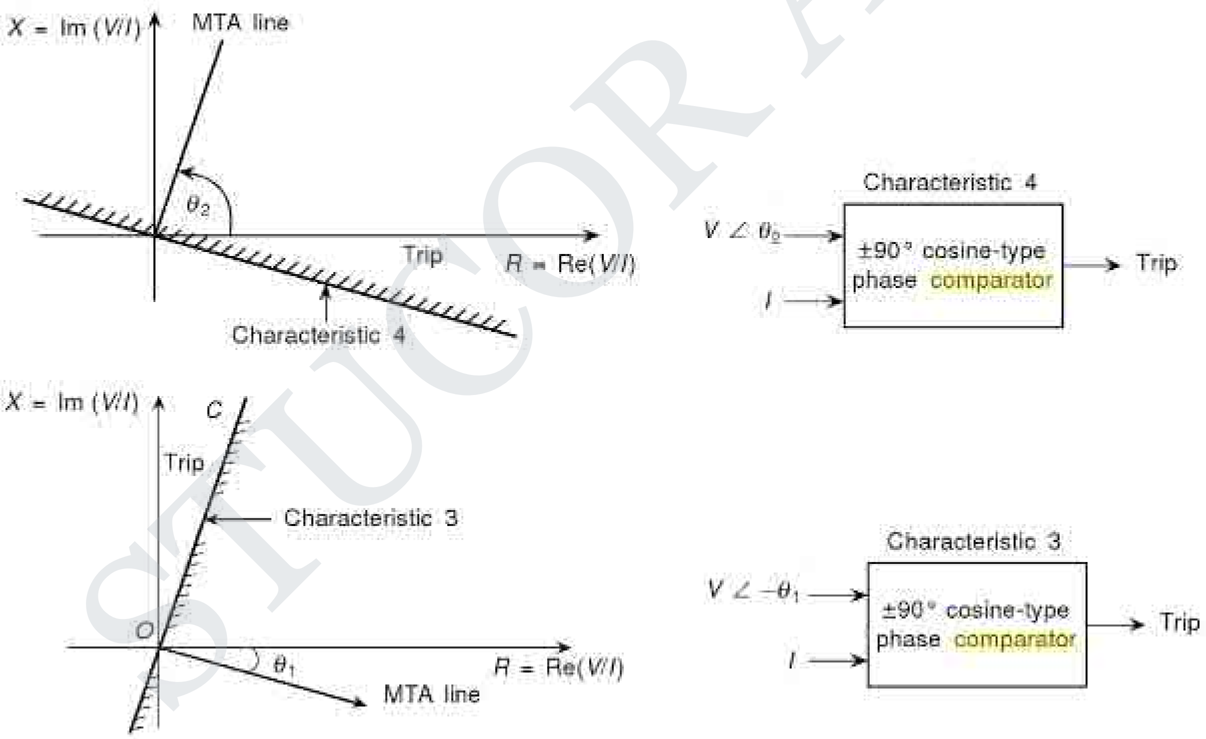


Characteristic	*Polarizing qty.*	*Measured qty.*
Reactance	$IX_{n1} - V$	IX_{n1}
Angle impedance	$IZ_{n2} - V$	IZ_{n2}
Directional with MTA = θ_1	$V \angle -\theta_1$	I
Directional with MTA = $-\theta_2$	$V \angle \theta_2$	I

Synthesis of reactance and impedence



Synthesis of directional characteristics



4.4.Numerical relays

4.4.1Definition

Numeric relays are programmable relays where the characteristics and behavior can be programmed. Most numerical relays are also multifunctional.

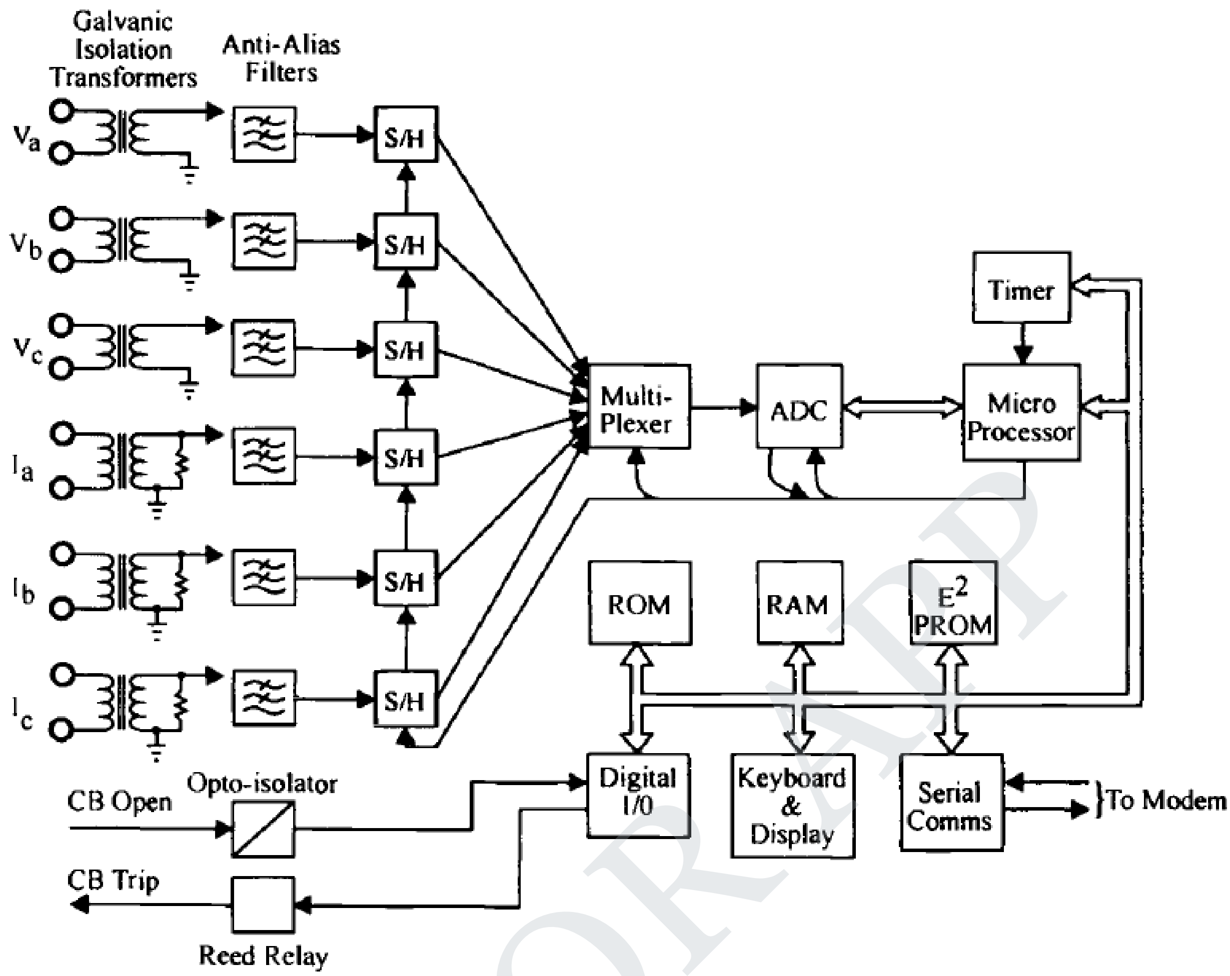
4.4.2Characteristics

Compact design and lower cost due to integration of manyfunctions into one relay

- High availability even with less maintenance due to integral self-monitoring
- No drift (aging) of measuring characteristics due to fully numerical processing
- High measuring accuracy due to digital filtering and optimized measuring algorithms
- Many integrated add-on functions, for example, for load monitoring and event/fault recording
- Local operation keypad and display designed to modern ergonomic criteria (Menu-driven human interfaces)

4.4.3Block diagram & description

The general hardware outline of a numericprotection relay is shown below. Relaying voltages at 110 V or 50 V and currents, at 5 A or 1 A,are first passed through isolation transformers. Since analogue to digitalconversion is usually performed on voltages, the current signals are convertedto representative voltage signals by, for example, passing the current througha known resistance value. All the signals are then filtered using very simpleanalogue anti-aliasing filters.Since ADCs are expensive it iscommon to find only one used in a digital relay, thus an analogue multiplexer,under microprocessor control, is used sequentially to select the required signalinto the ADC. Because the ADC takes a finite conversion time, typically 25s, it is necessary to hold the incoming signal for the duration of the conversion;this is achieved with the sample and hold amplifier. Having been converted bythe ADC, the signals can now be manipulated by the microprocessor. It iscommon to find more than one microprocessor used, e.g. a TMS320 forexecuting the relay algorithm and a 80186 for the scheme logic. The relayingprogram will be located in the read only memory (ROM), and the randomaccess memory (RAM) will be used for storing sampled quantities andintermediate products in the relaying algorithm. Relay settings are stored inthe electrically erasable programmable read only memory (E-PROM).

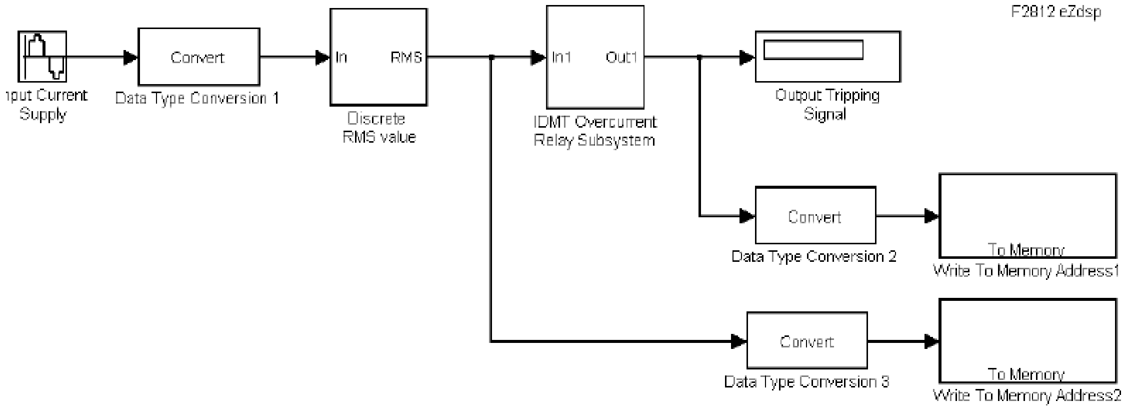


Relays are powered from the station batteries which are typically 50 V. Sincethe battery voltage is prone to variation depending on its state of charge, apower supply is incorporated in the relay to provide regulated, constant powerrails for the relay electronics. These are typically ±5V and ±12V. Switched modepower supplies are normally used in relays since they are more efficient,dissipating less power, and can work with a wider variation in supply voltagethan more conventional series regulator types. In addition, switched modepower supplies also allow isolation between the station batteries and the relayelectronics.

4.5.Numerical Overcurrent protection

Overcurrent relays are the least complex type of relay to be implemented by numeric means. Due to the relative slow operation of an overcurrent relay compared with, say, a distance relay, there is litde performance benefit to be gained from a numeric implementation. The main benefit of numeric overcurrent relays is lower cost and the ability to provide a full range of characteristics in one product, the required characteristic being selected by switches on the relay front panel.

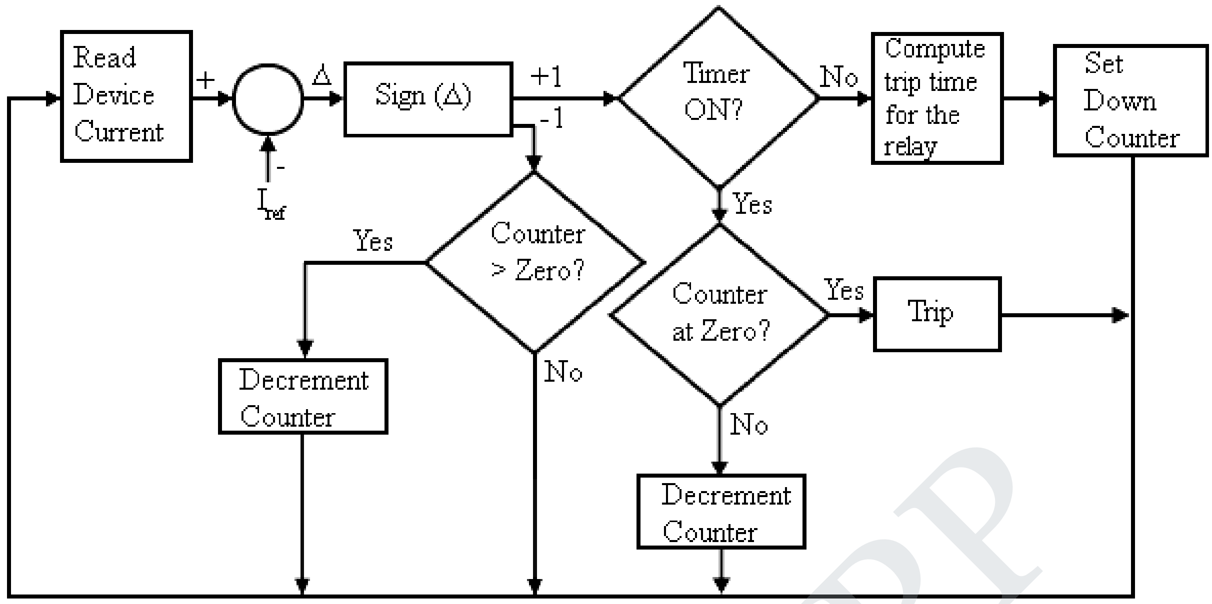
4.5.1Block diagram



4.5.2Agorithm and Flow chart

It should be realized, that there is an implicit upper limit on current which is considered healthy. Typically, this reference is the maximum load current that an equipment can endure during continuous operation. Also, faults (short circuits), lead to overcurrents. Thus, a simple protection philosophy that could be easily implemented by a microcontroller or microprocessor would be as follows:

▪	Set reference or threshold for discriminating overcurrent I_{ref}.
▪	Measure the device current I. This may correspond to the rms value of the fundamental component of the current.
▪	Compute ratio abs(I / I_{ref}).
	Since currents are measured through current transformer, both I_{ref} and I should be referred to either primary or secondary of the CT. This ratio abs(I / I_{ref}) is called the Plug Setting Multiplier (PSM). The value of PSM indicates the severity of the fault as seen by the relay.
▪	Trip the device, if PSM is above the threshold. The threshold should be strictly greater than 1,



4.5.3Operation

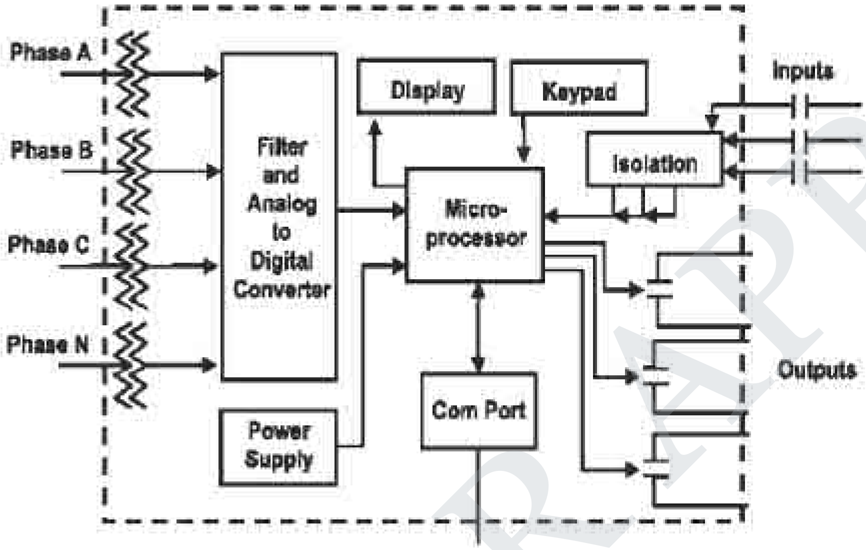
The current into the relay is firstly rectified and then passed through a resistor network, selected by switches on the front panel, to provide a voltage proportional to the incoming current. The switches are the equivalent of the plug setting multiplier found in electromechanical overcurrent relays and serve to scale the input current. The scaling is such that, irrespective of the current setting, input current at the setting level will produce the same internal voltage in the relay. This voltage is then digitised by an analogue to digital converter. Sequential samples are then compared to find the peak values of the rectified sine wave. These peak values are stored in peak registers within the microprocessor; four peak registers are used to store the preceding four peak values. Every time a new peak value is added, all the peak registers are compared to find the highest peak valueover the last four peaks. The highest peak value to then referred to a look-up table (a table of coefficients stored in memory) which produces an increment number.

4.6. Transformer differential protection

Many digital algorithms have been used so far after the invention of the computer. These algorithms do the same job with different accuracy and speed. The acceptable speed according to IEEE standard for transformer protection is 100 msec. All modern algorithms are faster than this IEEE standard. Nowadays, there are some algorithms performs their function in less than 10 msec. In this chapter, a fast algorithm is introduced. Its speed is in the range of 1 to 15 msec. This algorithm is based on the Fast Fourier algorithm (FFT). This algorithm is not new, however, significant changes has been introduced to make it much faster.

This algorithm is built on the principle of harmonic-current restraint, where the magnetizing-inrush current is characterized by large harmonic components content that are not noticeably present in fault currents. Due to the saturated condition of the transformer iron, the waveform of the inrush current is highly distorted. The amplitude of the harmonics, compared with the fundamental is somewhere between 30% to 60% and the third harmonic 10% to 30%.

4.6.1Block diagram



4.6.2Agorithm and Flow chart

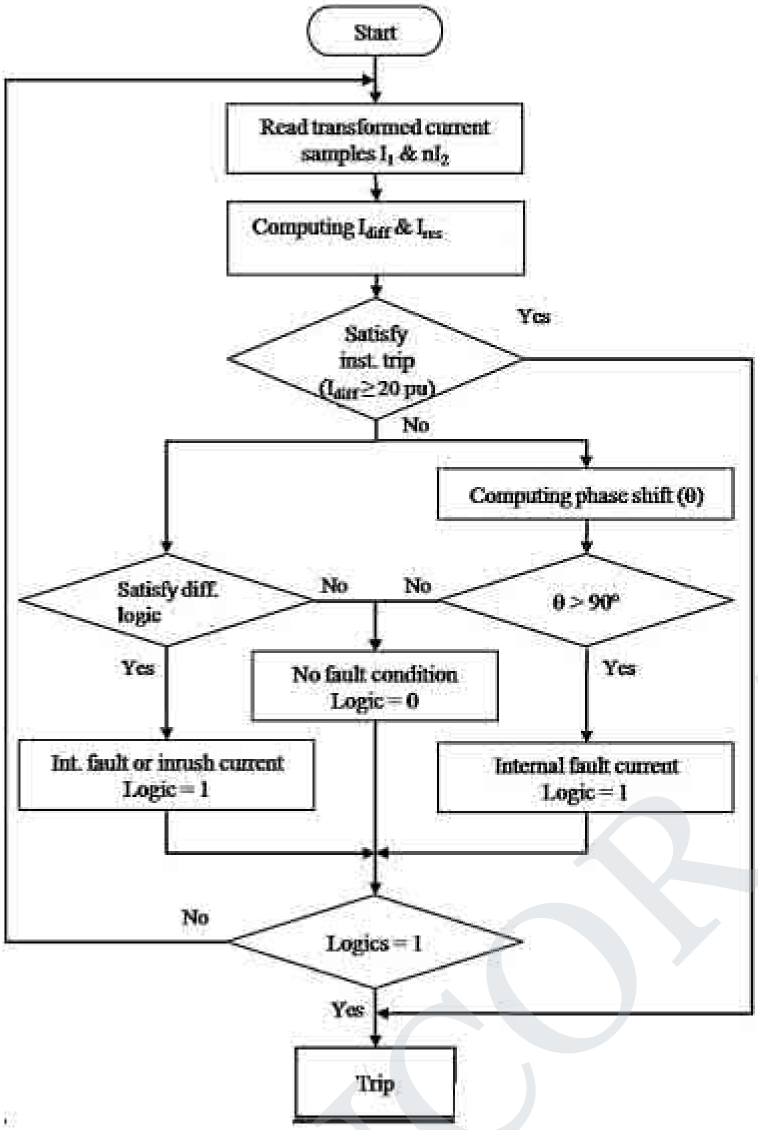
Step 1. Reading data from the CTs

Step 2. Data calculation, which is given as follows;

For the amplitude calculation, if the absolute difference between the CT,output currents is greater than zero the logic (1) takes place, which indicates the case of an inrush current or an internal fault. Otherwise, the logic (0) takes place, which indicates a detection of an external fault.

Step 3. Taking the final decision:

If the logic cases received from both cases in step two are both (1), that indicates adetection of an internal fault. Then a trip signal is released to stop the simulation.For the other logic options of (0,1) means an external fault, (1,0) means an inrush current, or(0,0) indicate an occurrence of an inrush current or an external fault, and the simulation goesback to step two to start the calculation again for the next sample.



4.6.3Operation

In this algorithm the output currents of the CTsundergo over two analysis processes, amplitude comparison process and harmonic content calculation process. The amplitude comparison between the RMSvalues of the CTsoutput currents (|Id1 — Id2|) is in the left hand side of the flowchart, and the harmonic calculation is in the right hand side of the flowchart.

The software is implemented according to the following steps

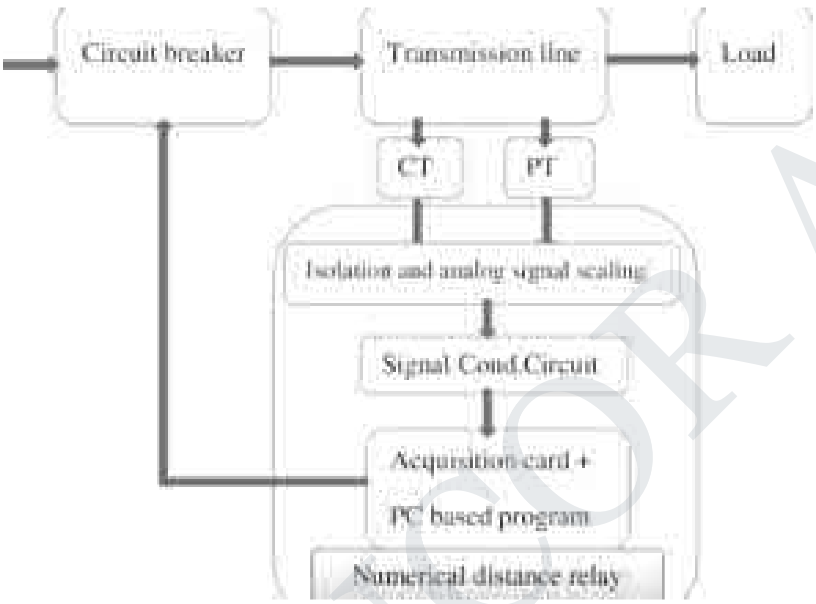
1. Reading data from theCTs.
2. Data calculation, which is given as follows;

For the amplitude calculation, if the absolute difference (|Id1 — Id2|) between the CTsoutput currents is greater than zero the logic (1) takes place, which indicates the case of an inrush current or an internal fault. Otherwise, the logic (0) takes place, which indicates a detection of an external fault.

4.7.Distant Protection of transmission lines.

Distance relays were one of the first protective devices to be considered fornumeric implementation yet, ironically, they are currently the least mature ofall numeric relay types in terms of commercial development, with productsonly recently emerging into the market place. The most probable reason forthis is the relative complexity of a numeric distance relay when compared withother types described in this book. Thus the recent arrival of powerfulmicroprocessors to enable practical commercial designs was instrumental tothis progress.

4.7.1Block diagram



4.7.2Operation

Numeric distance relays differ from more conventional static types in thatthey calculate an actual numeric value for the apparent impedance at therelaying point. This impedance is subsequently compared against animpedance plane-based characteristic in order to make a relaying decision. Instatic distance protection, e.g. by using a block-average comparator, the relayfunctions by directly combining the voltage and current inputs in thecomparator to form the relaying decision.Although the end result is the same in either case, the following advantagesapply to the numeric relay:

(a) Since both the phase and amplitude information of the input signalsare used, the security of the relay is higher than if only, say, the phaseinformation is used;

(b) Any shape of characteristic can be easily programmed into the relay;

(c) Zones of protection are easily incorporated since, once the impedancehas been calculated, extra zones may be added with little processingpenalty;

(d) The characteristic may be set with ohmic values, not Kvalues, thussimplifying commissioning.

Many different approaches to impedance measurement have been attempted.One approach is an algorithm based upon Fourier techniques. For example, if the discrete Fourier transform (DFT) is applied to the voltage and currentsamples, the resulting phasors can be combined by complex division to formresistance and reactance quantifies. The large majority of algorithms, however,are based upon solving the first order differential equation of the line; suchalgorithms assume a series resistance and inductance model of the line – shuntcapacitance is neglected. Since algorithms of this nature assume that the inputsignals are sinusoidal, it is necessary to prefilter the signals with a digital filterto ensure that only the power system frequency component is processed. Bycomparison, algorithms using DVI" techniques do not need pre-filtering sincethe DFT has an inherent filtering property.

UNIT-5
CIRCUIT BREAKERS

Physics of arcing phenomenon and arc interruption - DC and AC circuit breaking – re-striking voltage and recovery voltage - rate of rise of recovery voltage - resistance switching - current chopping - interruption of capacitive current - Types of circuit breakers – air blast, air break, oil, SF6 and vacuum circuit breakers – comparison of different circuit breakers – Rating and selection of Circuit breakers.

5.1. Physics of arcing phenomenon

When a short-circuit occurs, a heavy current flows through the contacts of the *circuit breaker beforethey are opened by the protective system. At the instant when the contacts begin to separate, thecontact area decreases rapidly and large fault current causes increased current density and hence risein temperature. The heat produced in the medium between contacts (usually the medium is oil or air)is sufficient to ionise the air or vaporise and ionise the oil. The ionised air or vapour acts as conductorand an arc is struck between the contacts. The potential difference between the contacts is quite small and is justsufficient to maintain the arc. The arc provides a low resistance path and consequently the current inthe circuit remains uninterrupted so long as the arc persists.During the arcing period, the current flowing between the contacts depends upon the arc resistance.The greater the arc resistance, the smaller the current that flows between the contacts. The arcresistance depends upon the following factors:

(*i*) *Degree of ionisation*— the arc resistance increases with the decrease in the number of ionised particles between the contacts.

(*ii*) *Length of the arc*— the arc resistance increases with the length of the arc *i.e.*, separation of contacts.

(*iii*) *Cross-section of arc*— the arc resistance increases with the decrease in area of X-section of the arc.

5.1.1Initiation of arc

The electric arc is a type of electric discharge between the contacts of the circuit breaker. Arc plays an important role in the behavior of an electric circuit breaker. A circuit breaker should be capable of extinguishing the arc without getting damaged.

As the contacts of a circuit breaker begin to separate, the voltage is appreciable and the distance of separation is very small. Therefore, a large voltage gradient occurs at the contact surface. When the voltage gradient attains a sufficiently high value (10^6 V/cm) electrons are dragged out of the surface causing ionization of the particles between the contacts. The emission of electrons because of the high value of voltage gradient is known as field emission.

Although this high voltage gradient exist only for a fraction of micro-seconds, but a large number of electrons are liberated from the cathode because of this. These electrons move towards the positive contact i.e. anode at a very rapid pace. On their way to anode, these electrons collide with the atoms and molecules of the gases and vapour existing between the contacts. Hence, each liberated electron tends to create other electrons. If the current is high, which is certainly in case of an electric fault, the discharge attains the form of an arc.

The temperature of arc is high enough and causes thermal ionization. The liberation of electrons because of high temperature is calledthermal emission. Thus, in an electric circuit breaker, an arc is initiated because of field emission but is maintained due to thermal ionization.

5.1.2Maintenance of arc

The factors responsible forthe maintenance of arc between the contacts. These are:

(*i*) p.d. between the contacts

(*ii*) Ionised particles between contacts

Taking these in turn,

(*i*) When the contacts have a small separation, the p.d. between them is sufficient to maintainthe arc. One way to extinguish the arc is to separate the contacts to such a distance that p.d.becomes inadequate to maintain the arc. However, this method is impracticable in highvoltage system where a separation of many metres may be required.

(*ii*) The ionised particles between the contacts tend to maintain the arc. If the arc path is deionised,the arc extinction will be facilitated. This may be achieved by cooling the arc or by bodilyremoving the ionised particles from the space between the contacts.

5.1.3Electric arc

An electric arc or arc discharge is an electrical breakdown of a gas that produces an ongoing electrical discharge. The current through a normally nonconductive medium such as air produces a plasma; the plasma may produce visible light. An arc discharge is characterized by a lower voltage than a glow discharge, and it relies on thermionic emission of electrons from the electrodes supporting the arc. An archaic term is voltaic arc, as used in the phrase "voltaic arc lamp".

An electric arc is the form of electric discharge with the highest current density. The maximum current through an arc is limited only by the external circuit, not by the arc itself.

An arc between two electrodes can be initiated by ionization and glow discharge, as the current through the electrodes is increased. The breakdown voltage of the electrode gap is a function of the pressure, distance between electrodes and type of gas surrounding the electrodes. When an arc starts, its terminal voltage is much less than a glow discharge, and current is higher. An arc in gases near atmospheric pressure is characterized by visible light emission, high current density, and high temperature. An arc is distinguished from a glow discharge partly by the approximately equal effective temperatures of both electrons and positive ions; in a glow discharge, ions have much less thermal energy than the electrons.

A drawn arc can be initiated by two electrodes initially in contact and drawn apart; this can initiate an arc without the high-voltage glow discharge. This is the way a welder starts to weld a joint, momentarily touching the welding electrode against the workpiece then withdrawing it till a stable arc is formed. Another example is separation of electrical contacts in switches, relays and circuit breakers; in high-energy circuits arc suppression may be required to prevent damage to contacts

Electrical resistance along the continuous electric arc creates heat, which ionizes more gas molecules (where degree of ionization is determined by temperature), and as per this sequence: solid-liquid-gas-plasma; the gas is gradually turned into thermal plasma. A thermalplasma is in thermal equilibrium; the temperature is relatively homogeneous throughout the atoms, molecules, ions and electrons. The energy given to electrons is dispersed rapidly to the heavier particles by elastic collisions, due to their great mobility and large numbers.

Current in the arc is sustained by thermionic emission and field emission of electrons at the cathode. The current may be concentrated in a very small hot spot on the cathode; current densities on the order of one million amperes per square centimetre can be found. Unlike a glow discharge, an arc has little discernible structure, since the positive column is quite bright and extends nearly to the electrodes on both ends. The cathode fall and anode fall of a few volts occurs within a fraction of a millimetre of each electrode. The positive column has a lower voltage gradient and may be absent in very short arcs.[9]

A low-frequency (less than 100 Hz) alternating current arc resembles a direct current arc; on each cycle, the arc is initiated by breakdown, and the electrodes interchange roles as anode and cathode as current reverses. As the frequency of the current increases, there is not enough time for all ionization to disperse on each half cycle and the breakdown is no longer needed to sustain the arc; the voltage vs. current characteristic becomes more nearly ohmic

5.2.Arc interruption

The insulating material (may be fluid or air) used in circuit breaker should serve two important functions. They are written as follows:

- It should provide sufficient insulation between the contacts when circuit breaker opens.
- It should extinguish the arc occurring between the contacts when circuit breaker opens.

The second point needs more explanation. To understand this point let us consider a situation if there is some fault or short circuit in the system, the relay provides desired signals to the circuit breaker so as to prevent system from ongoing fault. Now when circuit breaker opens its contacts, due to this an arc is drawn. The arc is interrupted by suitable insulator and technique.

5.2.1Theroies of arc interruption

There are two theories which explains the phenomenon of arc extinction:

1. Energy balance theory,
2. Voltage race theory.

Energy Balance Theory

When the contact of circuit breaker are about to open, restriking voltage is zero, hence generated heat would be zero and when the contacts are fully open there is infinite resistance this again make no production of heat. We can conclude from this that the maximum generated heat is lying between these two cases and can be approximated, now this theory is based on the fact that the rate of generation of heat between the contacts of circuit breaker is lower than the rate at which heat between the contact is dissipated. Thus if it is possible to remove the generated heat by cooling, lengthening and splitting the arc at a high rate the generation, arc can be extinguished.

Voltage Race Theory

The arc is due to the ionization of the gap between the contact of the circuit breaker. Thus the resistance at the initial stage is very small i.e. when the contacts are closed and as the contact separates the resistance starts increasing. If we remove ions at the initial stage either by recombining them into neutral molecules or inserting insulation at a rate faster than the rate of ionization, the arc can be interrupted. The ionization at zero current depends on the voltage known as restriking voltage.

Let us define an expression for restriking voltage. For loss-less or ideal system we have,

$$v = V\left[1 - cos\left(\frac{t}{\sqrt{LC}}\right)\right]$$

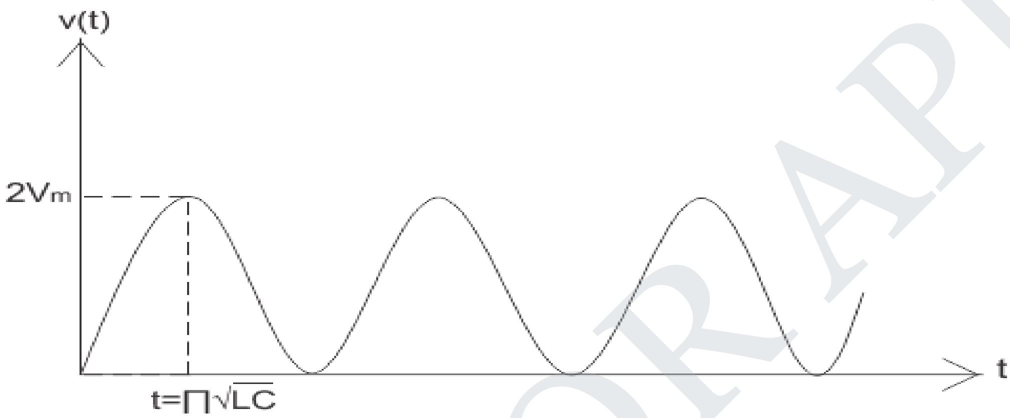
Here v = restriking voltage.

V = value of voltage at the instant of interruption.

L and C are series inductor and shunt capacitance up to fault point.

Thus from above equation we can see that lower the value of product of L and C, higher the value of restriking voltage.

The variation of v versus time is plotted below:



5.2.2Modes of arc interruption

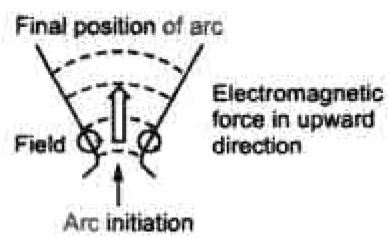
There are two methods of extinguishing the arc in circuit breakers

1. High resistance method. **2.** Low resistance or current zero method

1. High resistance method. In this method, arc resistance is made to increase with time sothat current is reduced to a value insufficient to maintain the arc. Consequently, the current is interruptedor the arc is extinguished. The principal disadvantage of this method is that enormous energyis dissipated in the arc. Therefore, it is employed only in d.c. circuit breakers and low-capacity a.c.circuit breakers.

The resistance of the arc may be increased by:

(i) Lengthening the arc. The resistance of the arc is directly proportional to its length. Thelength of the arc can be increased by increasing the gap between contacts.

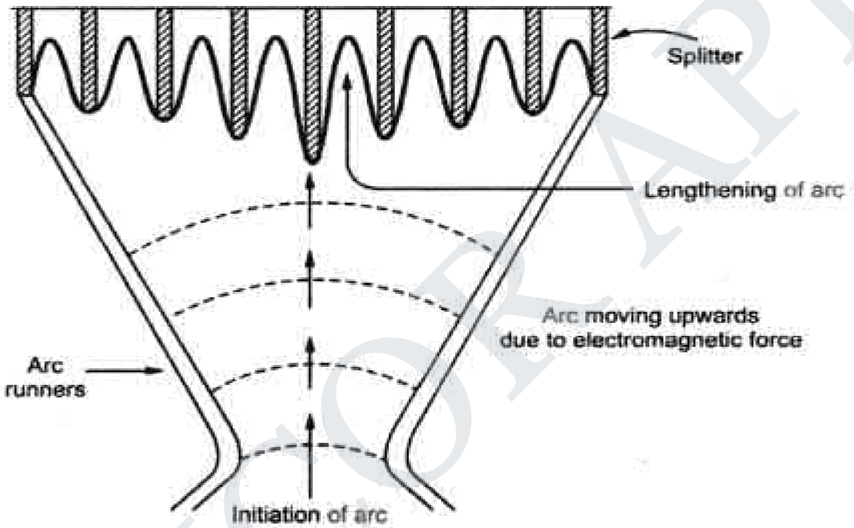


(ii) Cooling the arc. Cooling helps in the deionisation of the medium between the contacts.

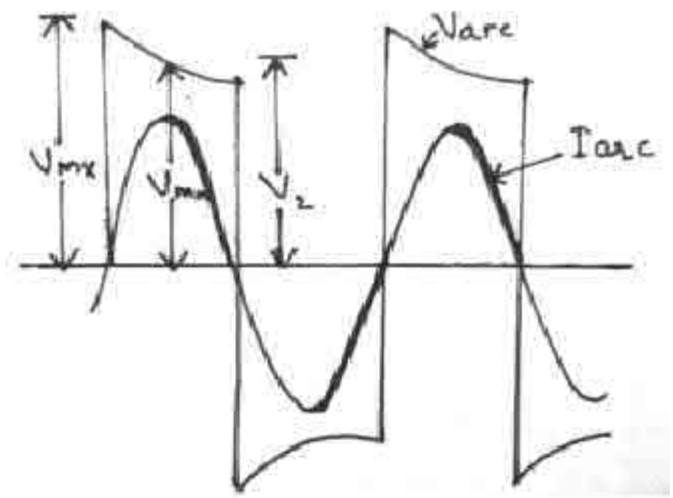
This increases the arc resistance. Efficient cooling may be obtained by a gas blast directed along the arc.

(iii) Reducing X-section of the arc. If the area of X-section of the arc is reduced, the voltagenecessary to maintain the arc is increased. In other words, the resistance of the arc path isincreased. The cross-section of the arc can be reduced by letting the arc pass through anarrow opening or by having smaller area of contacts.

(iv) Splitting the arc. The resistance of the arc can be increased by splitting the arc into anumber of smaller arcs in series. Each one of these arcs experiences the effect of lengtheningand cooling. The arc may be split by introducing some conducting plates between the contacts.



2. Low resistance or Current zero method. This method is employed for arc extinction in a.c. circuits only. In this method, arc resistance is kept low until current is zero where the arc extinguishes naturally and is prevented from restrikinginspite of the rising voltage across the contacts. All modern high power a.c. circuit breakers employ this method for arc extinction.



In an a.c. system, current drops to zero after every half-cycle. At every current zero, the arcextinguishes for a brief moment. Now the medium between the contacts contains ions and electronsso that it has small dielectric strength and can be easily broken down by the rising contact voltageknown as restriking voltage. If such a breakdown does occur, the arc will persist for another half cycle.If immediately after current zero, the dielectric strength of the medium between contacts isbuilt up more rapidly than the voltage across the contacts, the arc fails to restrike and the current willbe interrupted. The rapid increase of dielectric strength of the medium near current zero can beachieved by :

(a) Causing the ionised particles in the space between contacts to recombine into neutralmolecules.

(b) Sweeping the ionised particles away and replacing them by un-ionised particlesTherefore, the real problem in a.c. arc interruption is to rapidly deionise the medium betweencontacts as soon as the current becomes zero so that the rising contact voltage or restriking voltagecannot breakdown the space between contacts.

The de-ionisation of the medium can be achieved by:

(i) Lengthening of the gap. The dielectric strength of the medium is proportional to the lengthof the gap between contacts. Therefore, by opening the contacts rapidly, higher dielectricstrength of the medium can be achieved.

(ii) High pressure. If the pressure in the vicinity of the arc is increased, the density of theparticles constituting the discharge also increases. The increased density of particles causeshigher rate of de-ionisation and consequently the dielectric strength of the medium betweencontacts is increased.

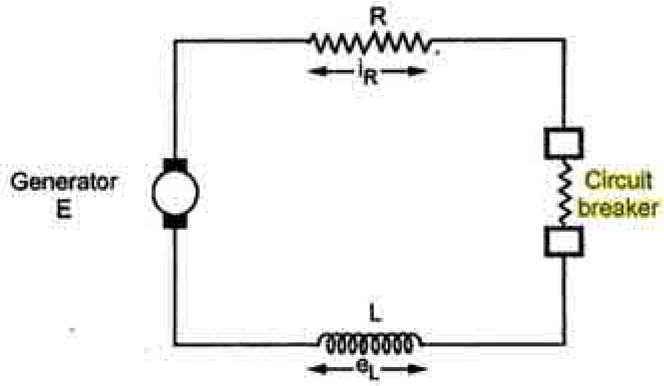
(iii) Cooling. Natural combination of ionised particles takes place more rapidly if they are allowedto cool. Therefore, dielectric strength of the medium between the contacts can beincreased by cooling the arc.

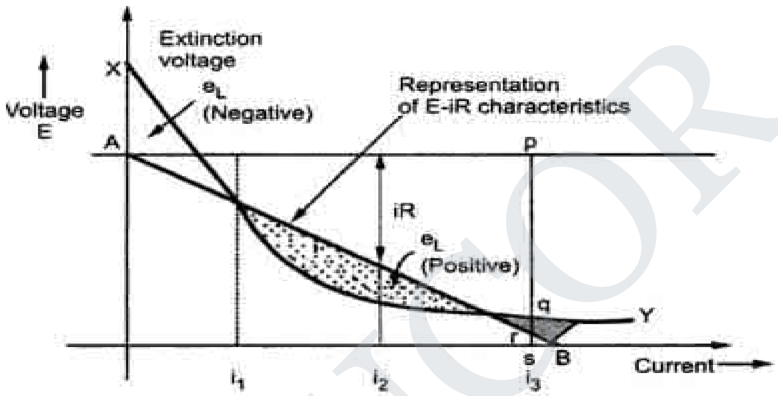
(iv) Blast effect. If the ionised particles between the contacts are swept away and replaced by unionisedparticles, the dielectric strength of the medium can be increased considerably. Thismay be achieved by a gas blast directed along the discharge or by forcing oil into the contactspace.

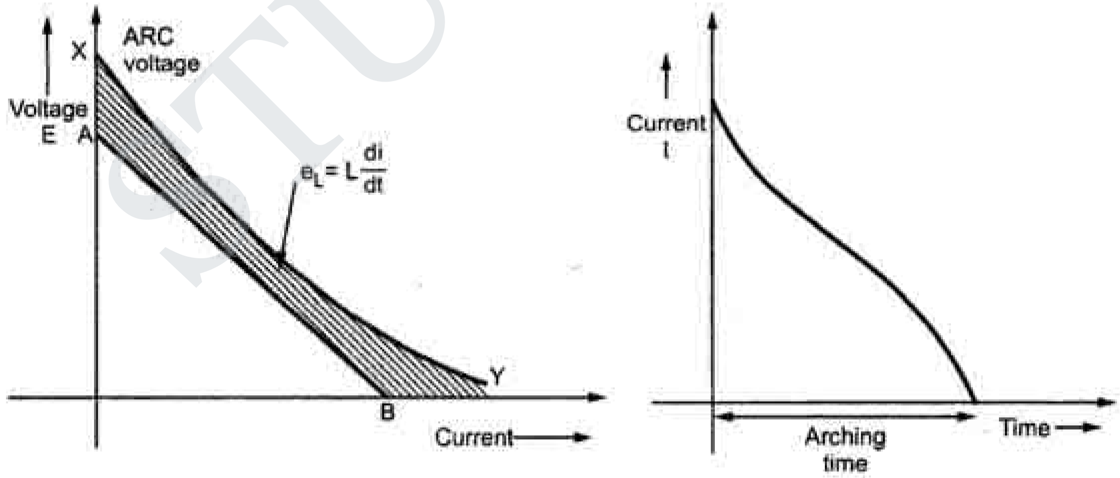
5.3.DC and AC circuit breaking

DC circuit breaking

It can be explained by considering the generator arrangement as shown below



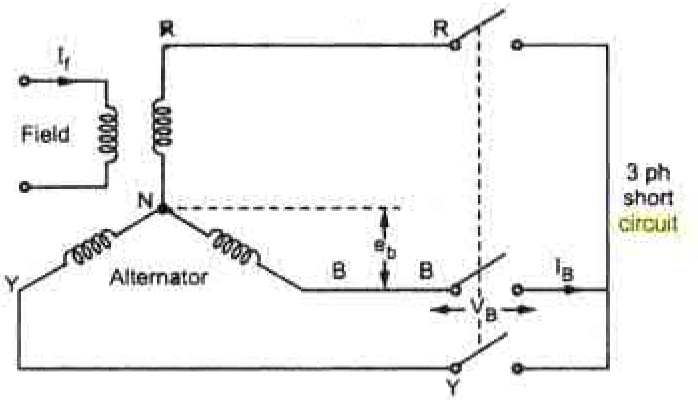




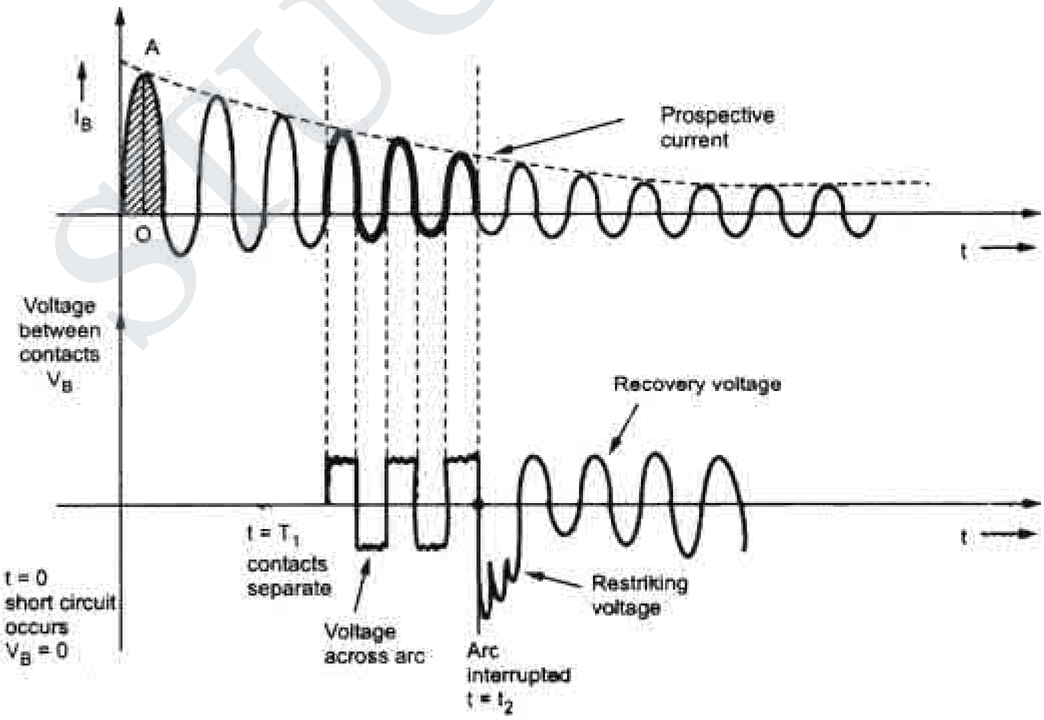
- When the circuit breaker starts opening it carries the load current I=E/R.The current is shown to be reduced to i1,i2 and i3respectively
- Pr portion represents voltage drop i3R
- Qs represents arc voltage which is greater than available voltage

- The arc becomes unstable and the difference in voltage is supplied by inductance L across which the voltage is e_L=Ldi/dt.
- For decreasing values of currents this voltage is negative so it maintains the arc

AC Circuit breaking



The circuit breaker is open condition with its other side short circuited.When phase B voltage with respect to neutral is zero, the circuit breaker is closed.Under this condition the phase B current will have maximum D.C component and its current waveform will be unsymmetrical about normal zero axis.The short circuit making capacity of circuit breaker is expressed in peak value not in rms value like breaking capacity.Theoretically at the instant of fault occurrence in a system, the fault current can rise to twice of its symmetrical fault level. At the instant ofswitching on a circuit breaker in faulty condition, of system, the short circuit portion of the system connected to the source.



The first cycle of the current during a circuit is closed by circuit breaker, has maximum amplitude. This is about twice of the amplitude of symmetrical fault current waveform. The breaker's contacts have to withstand this highest value of current during the first cycle of waveform when breaker is closed under fault. On the basis of this above mentioned phenomenon, a selected breaker should be rated with short circuit making capacity. As the rated**short circuit making current of circuit breaker**is expressed in maximum peak value, it is always more than rated short circuit breaking current of circuit breaker. Normally value of short circuit making current is 2.5 times more than short circuit breaking current.

This is the maximum short circuit current which a circuit breaker can withstand before it, finally cleared by opening its contacts. When a short circuit flows through a circuit breaker, there would be thermal and mechanical stresses in the current carrying parts of the breaker. If the contact area and cross-section of the conducting parts of the circuit breaker are not sufficiently large, there may be a chance of permanent damage in insulation as well as conducting parts of the CBHence short circuit breaking capacity or **short circuit breaking current of circuit breaker** is defined as maximum current can flow through the breaker from time of occurring short circuit to the time of clearing the short circuit without any permanent damage in the CB. The value of short circuit breaking current is expressed in RMS

The voltage that appears across the contacts of the circuit breaker after final arc extinction is called as recovery voltage

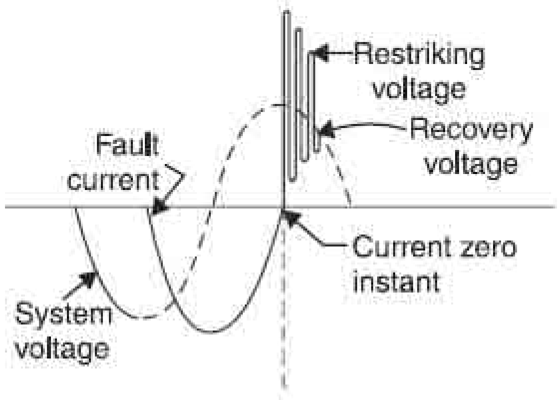
At current zero, a high-frequency transient voltage appearsacross the contacts called as restriking voltage

5.4. Re-striking voltage and Recovery voltage

5.4.1Definition

Restriking voltage.

It is the transient voltage that appears across the contacts at or nearcurrent zero during arcing period.At current zero, a high-frequency transient voltage appearsacross the contacts and is caused by the rapid distributionof energy between the magnetic and electric fields associatedwith the plant and transmission lines of the system. Thistransient voltage is known as restriking voltage. The current interruption in the circuit depends upon this voltage.If the restriking voltage rises more rapidly than the dielectricstrength of the medium between the contacts, the arcwill persist for another half-cycle. On the other hand, if thedielectric strength of the medium builds up more rapidly thanthe restriking voltage, the arc fails to restrike and the current will be interrupted



Recovery voltage.

It is the normal frequency (50 Hz) r.m.s. voltage that appears across the contacts of the circuit breaker after final arc extinction. It is approximately equal to the system voltage.When contacts of circuit breaker are opened, current drops to zero after every half cycle. Atsome current zero, the contacts are separated sufficiently apart and dielectric strength of the mediumbetween the contacts attains a high value due to the removal of ionised particles. At such an instant,the medium between the contacts is strong enough to prevent the breakdown by the restriking voltage.Consequently, the final arc extinction takes place and circuit current is interrupted. Immediately afterfinal current interruption, the voltage that appears across the contacts has a transient part. However, these transient oscillations subside rapidly due to the damping effect of systemresistance and normal circuit voltage appears across the contacts. The voltage across the contacts isof normal frequency and is known as recovery voltage.

5.4.2Factros

The active recovery voltage depends upon the following factors

(i)Effect of power factor

(ii)Effect of armature reaction

(iii)Effect of circuit conditions

5.4.3Transient recovery voltage

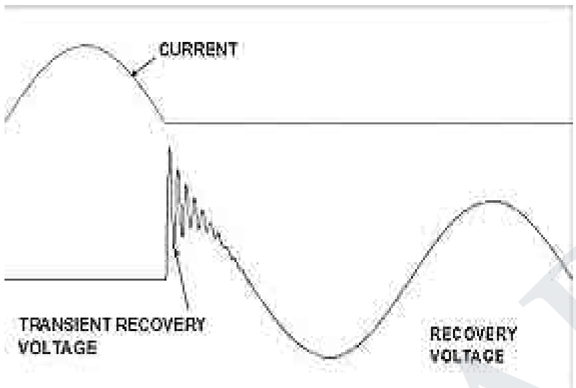
A transient recovery voltage (or TRV) for high-voltage circuit breakers is the voltage that appears across the terminals after current interruption. It is a critical parameter for faultinterruption by a high-voltage circuit breaker; its characteristics (amplitude, rate of rise) can lead either to a successful current interruption or to a failure (called reignition or restrike).

The TRV is dependent on the characteristics of the system connected on both terminals of the circuit-breaker, and on the type of fault that this circuit breaker has to interrupt (single, double or three-phase faults, grounded or ungrounded fault).

Characteristics of the system include:

- type of neutral (effectively grounded, ungrounded, solidly grounded ..)
- type of load (capacitive, inductive, resistive)
- type of connection: cable connected, line connected..

The most severe TRV is applied on the first pole of a circuit-breaker that interrupts current (called the first-pole-to-clear in a three-phase system).



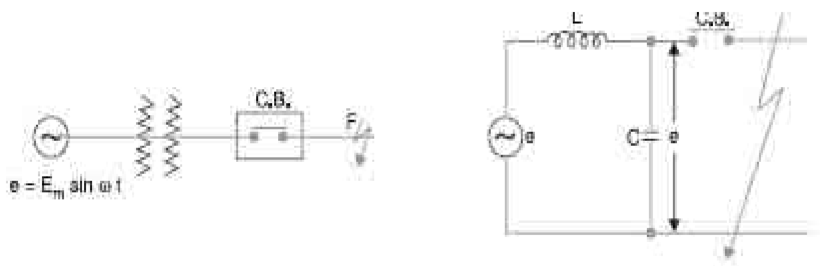
A terminal fault is a fault that occurs at the circuit breaker terminals. The circuit breaker interrupts a short-circuit at current zero, at this instant the supply voltage is maximum and the recovery voltage tends to reach the supply voltage with a high frequency transient. The normalized value of the overshoot or amplitude factor is 1.4.

5.5. Rate of rise of recovery voltage

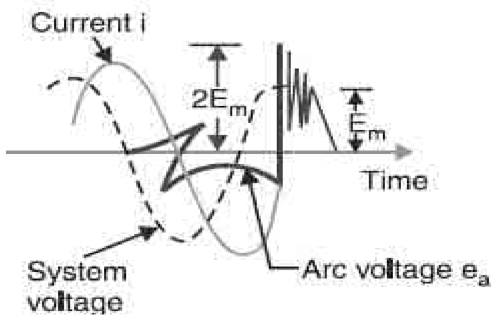
When a fault occurs, the energy stored in the system can be considerable. Interruption of fault current by a circuit breaker will result in most of the stored energy dissipated within the circuit breaker, the remainder being dissipated during oscillatory surges in the system. The oscillatory surges are undesirable and, therefore, the circuit breaker must be designed to dissipate as much of the stored energy as possible. Equivalent circuit where *L* is the inductance per phase of the system upto the point of fault and *C* is the capacitance per phase of the system. The resistance of the system is neglected as it is generally small.

It is the rate of increase of re-striking voltage and is abbreviated by R.R.R.V. usually; the voltage is in kV and time in microseconds so that R.R.R.V. is in kV/µ sec.

Consider the opening of a circuit breaker under fault conditions shown in simplified form in Fig.



(i) (ii)



Before currentinterruption, the capacitance *C* is short-circuited by the faultand the short-circuit current through the breaker is limited by inductance*L* of the system only. Consequently, the short-circuit currentwill lag the voltage by 90º as shown in Fig., where *i*represents the short-circuit current and *ea* represents the arc volt- age. It may be seen that in this condition, the entire generator voltage appears across inductance *L*.When the contacts are opened and the arc finally extinguishes at some current zero, the generatorvoltage *e* is suddenly applied to the inductance and capacitance in series. This *L*–*C* combinationforms an oscillatory circuit and produces a transient of frequency:

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

Which appears across the capacitor *C* and hence across the contacts of the circuit breaker. Thistransient voltage, as already noted, is known as re-striking voltage and may reach an instantaneous peak value twice the peak phase-neutral voltage *i.e.* 2 *Em*. The system losses cause the oscillations to decay fairly rapidly but the initial overshoot increases the possibility of re-striking the arc. It is the rate of rise of re-striking voltage (R.R.R.V.) which decides whether the arc will re-strike or not. If R.R.R.V. is greater than the rate of rise of dielectric strength between the contacts, the arc will re-strike. However, the arc will fail to re-strike if R.R.R.V. is less than the rate of increase of dielectric strength between the contacts of the breaker. The value of R.R.R.V. depends upon:

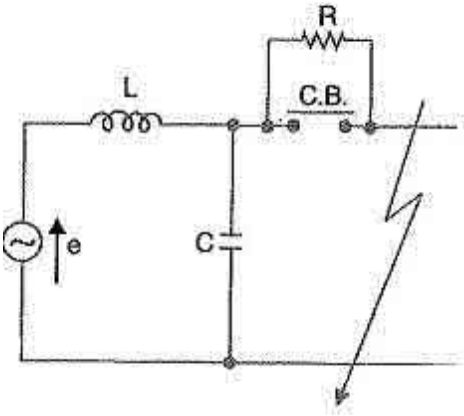
(*a*) Recovery voltage

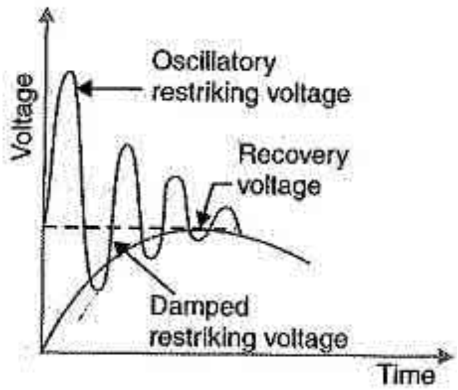
(*b*) Natural frequency of oscillations

For a short-circuit occurring near the power station bus-bars, *C* being small, the natural frequency

5.6.Resistance switching

The excessive voltage surges during circuit interruption can be preventedby the use of shunt resistance *R* connected across the circuit breaker contacts as shown in below figure

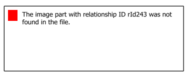




When a fault occurs, the contacts of the circuit breaker are opened and anarc is struck between the contacts. Since the contacts are shunted by resistance *R*, a part of arc currentflows through this resistance. This results in the decrease of arc current and an increase in the rate ofde-ionisation of the arc path. Consequently, the arc resistance is increased. The increased arc resistanceleads to a further increase in current through shunt resistance. This process continues until thearc current becomes so small that it fails to maintain the arc. Now, the arc is extinguished and circuitcurrent is interrupted.The shunt resistor also helps in limiting the oscillatory growth of re-striking voltage. It can beproved mathematically that natural frequency of oscillations of the circuit isgiven by :

$$f_n = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{1}{4R^2C^2}}$$

The effect of shunt resistance *R* is to prevent the oscillatory growth of re-striking voltage andcause it to grow exponentially upto recovery voltage. This is being most effective when the value of*R* is so chosen that the circuit is critically damped. The value of *R* required for critical damping is



To sum up, resistors across breaker contacts may be used to perform one or more of the followingfunctions:

(*i*) To reduce the rate of rise of re-striking voltage and the peak value of re-striking voltage.

(*ii*) To reduce the voltage surges due to current chopping and capacitive current breaking

(*iii*) To ensure even sharing of re-striking voltage transient across the various breaks in multibreakcircuit breakers.

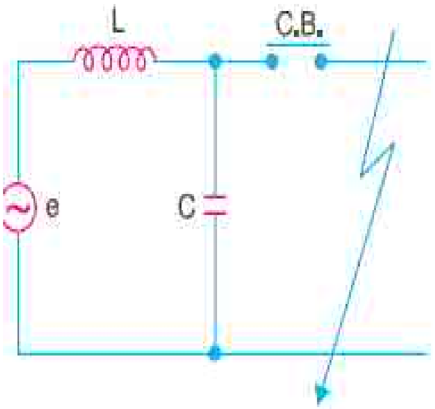
It may be noted that value of resistance required to perform each function is usually different.However, it is often necessary to compromise and make one resistor do more than one of thesefunctions.

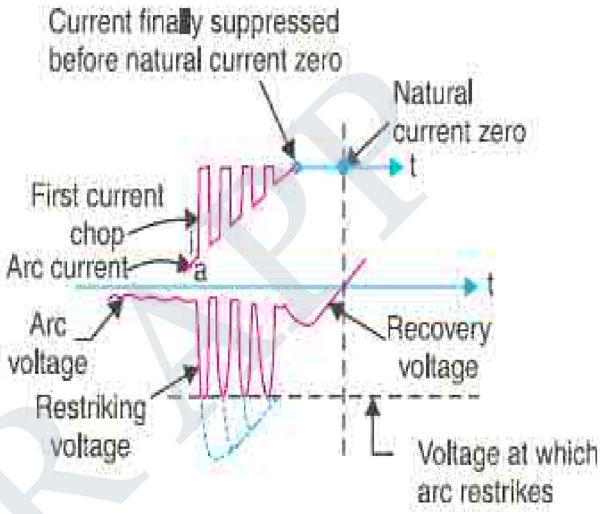
5.7. Current chopping andinterruption of capacitive current

Current chopping

It is the phenomenon of current interruption before the natural currentzero is reached.

Current chopping mainly occurs in air-blast circuit breakers because they retain the sameextinguishing power irrespective of the magnitude of the current to be interrupted. When breakinglow currents (*e.g.*, transformer magnetising current) with such breakers, the powerful de-ionisingeffect of air-blast causes the current to fall abruptly to zero well before the natural current zero isreached. This phenomenon is known as current chopping and results in the production of high voltagetransient across the contacts of the circuit breaker





Suppose the arc current is $i$when it ischopped down to zero value as shown by point $a$in Fig As the chop occurs at current i,therefore, the energy stored in inductance is L i2/2. This energy will be transferred to the capacitance$C$, charging the latter to a prospective voltage e given by :

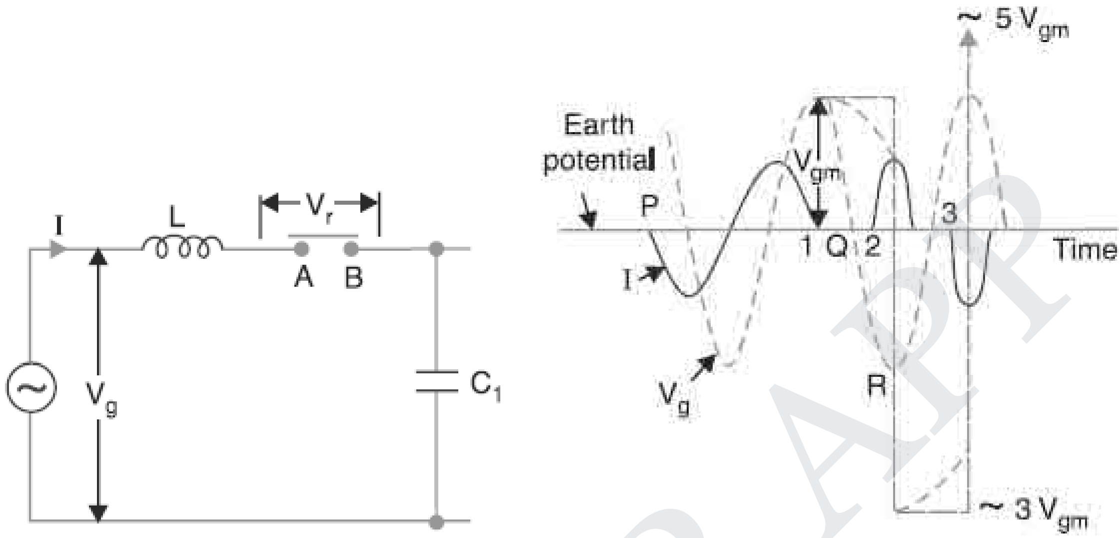
$$\frac{1}{2} L i^2 = \frac{C e^2}{2}$$

$$e = i \sqrt{\frac{L}{C}} \text{ volts}$$

The prospective voltage e is very high as compared to the dielectric strength gained by thegap so that the breaker restrikes. As the de-ionising force is still in action, therefore, chop occursagain but the arc current this time is smaller than the previous case. This induces a lower prospectivevoltage to re-ignite the arc. In fact, several chops may occur until a low enough current is interruptedwhich produces insufficient induced voltage to re-strike across the breaker gap. Consequently, thefinal interruption of current takes place.Excessive voltage surges due to current chopping are prevented by shunting the contacts of thebreaker with a resistor (*resistance switching*) such that reignition is unlikely to occur.

Interruption of capacitive current

Another cause of excessivevoltage surges in the circuit breakers is the interruptionof capacitive currents. Examples of such instances are openingof an unloaded long transmission line, disconnecting a capacitorbank used for power factor improvement etc.



Such a line, although unloaded in the normal sense, willactually carry a capacitive current *I* on account of appreciableamount of capacitance *C* between the line and the earth.Let us suppose that the line is opened by the circuit breakerat the instant when line capacitive current is zero. At this instant, the generatorvoltage *Vg* will be maximum (*i.e.*, *Vgm*) lagging behind the current by 90º. The opening of the lineleaves a standing charge on it (*i.e.*, end *B* of the line)and the capacitor *C*1 is charged to *Vgm*. However, thegenerator end of the line (*i.e.*, end *A* of the line) continuesits normal sinusoidal variations. The voltage *Vr*across the circuit breaker will be the difference betweenthe voltages on the respective sides. Its initial value iszero (point 1) and increases slowly in the beginning.But half a cycle later, the potentialof the circuit breaker contact '*A*' becomes maximumnegative which causes the voltage across the breaker (*Vr*)to become 2 *Vgm*. This voltage may be sufficient to restrikethe arc. The two previously separated parts of thecircuit will now be joined by an arc of very low resistance.The line capacitance discharges at once to reducethe voltage across the circuit breaker, thus setting up high frequency transient. The peak valueof the initial transient will be twice the voltage at that instant i.e., − 4 Vgm. This will cause thetransmission voltage to swing to − 4 Vgmto + Vgm i.e., −3Vgm.The re-strike arc current quickly reaches its first zero as it varies at natural frequency. Thevoltage on the line is now −3Vgm and once again the two halves of the circuit are separated and the lineis isolated at this potential. After about half a cycle further, the aforesaid events are repeated even onmore formidable scale and the line may be left with a potential of 5Vgm above earth potential. Theoretically,this phenomenon may proceed infinitely increasing the voltage by successive increment of2 times Vgm.While the above description relates to the worst possible conditions, it is obvious that if the gapbreakdown strength does not increase rapidly enough, successive re-strikes can build up a dangerousvoltage in the open circuit line. However, due to leakage and corona loss, the maximum voltage onthe line in such cases is limited to 5 Vgm.

5.8.Types of circuit breakers

(i) Air-blast circuit breakers

(ii) Oil circuit breakers

(iii) Sulphur hexafluoride circuit breaker

(iv) Vacuum circuit breakers

5.8.1Air blast CB

These breakers employ a high pressure air-blast as an arc quenching medium. The contacts areopened in a flow of air-blast established by the opening of blast valve. The air-blast cools the arc andsweeps away the arcing products to the atmosphere. This rapidly increases the dielectric strength ofthe medium between contacts and prevents from re-establishing the arc. Consequently, the arc isextinguished and flow of current is interrupted.

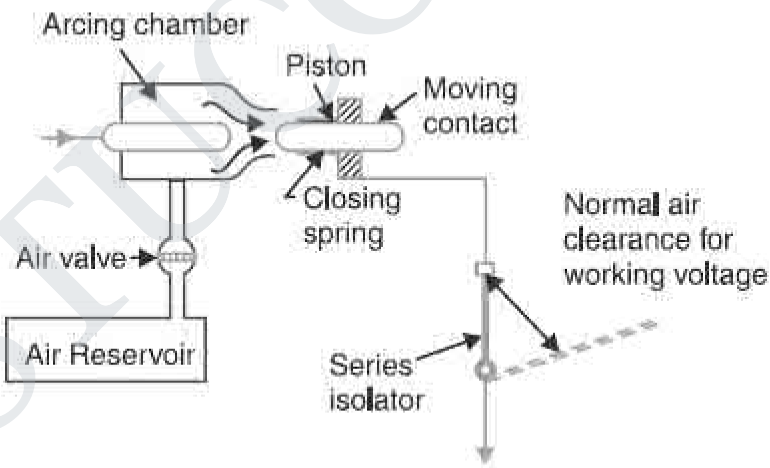
Types of Air-Blast Circuit Breakers

(i) Axial-blast type

(ii) Cross-blast type

(iii) Radial-blast type

Axial-blast air circuit breaker



The fixed and moving contacts are held in the closed position byspring pressure under normal conditions. The air reservoir is connected to the arcing chamberthrough an air valve. This valve remains closed under normal conditions but opensautomatically by the tripping impulse when a fault occurs on the system.

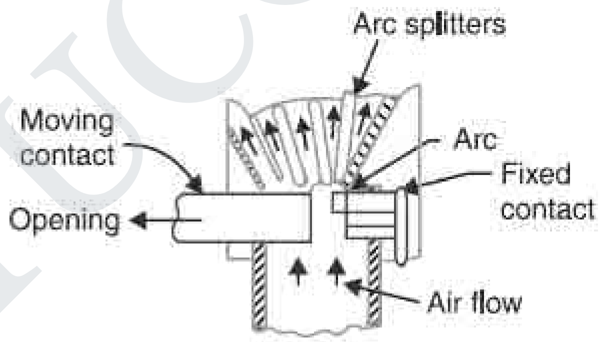
When a fault occurs, the tripping impulse causes opening of the air valve which connects thecircuit breaker reservoir to the arcing chamber. The high pressure air entering the arcing chamberpushes away the moving contact against spring pressure. The moving contact is separated and an arcis struck. At the same time, high pressure air blast flows along the arc and takes away the ionisedgases along with it. Consequently, the arc is extinguished and current flow is interrupted.

It may be noted that in such circuit breakers, the contact separation required for interruption isgenerally small (1·75 cm or so). Such a small gap may constitute inadequate clearance for the normalservice voltage. Therefore, an isolating switch is incorporated as a part of this type of circuit breaker.

Cross-blast air breaker.

In this type of circuit breaker, an air-blast is directed at rightangles to the arc. The cross-blast lengthens and forces the arc into a suitable chute for arcextinction

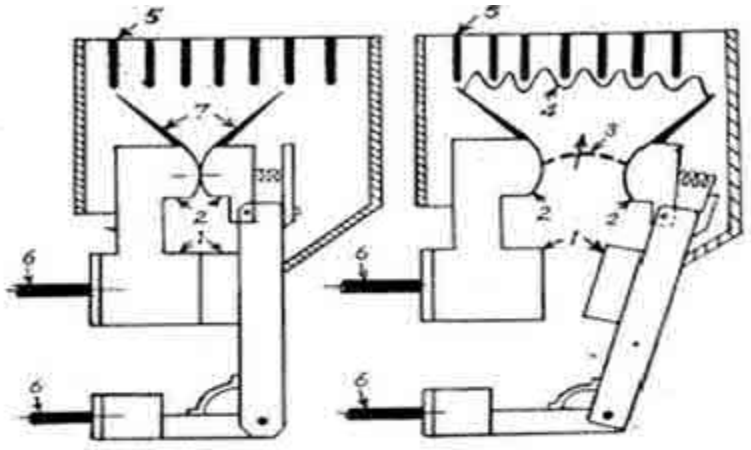
Whenthe moving contact is withdrawn, an arc is struckbetween the fixed and moving contacts. The highpressure cross-blast forces the arc into a chute consistingof arc splitters and baffles. The splittersserve to increase the length of the arc and bafflesgive improved cooling. The result is that arc isextinguished and flow of current is interrupted.Since blast pressure is same for all currents, theinefficiency at low currents is eliminated. The final gap for interruption is great enough togive normal insulation clearance so that a series isolating switch is not necessary.



5.8.2 Air break CB

In air break circuit breaker the arc is initiated and extinguish in substantially static air in which the arc moves. Such breakers are used for low voltages, generally up to 15KV and rupturing capacities of 500MVA. Air circuit breaker has several advantages over the oil, as an arc quenching medium. These are

- Elimination of risk and maintenance associated with the use of oil.
- The absence of mechanical stress that is set up by gas pressure and oil movement.
- Elimination of the cost of regular oil replacement that arises due to deterioration of oil with the successive breaking operation.



(I) Contacts Closed (II) Contacts Open
Principle of air-break circuit-breaker

1. Main contacts
2. Arcing contacts
3. Arc rising in the direction of the arrow
4. Arc getting split
5. Arc splitter plates
6. Current carrying termina
7. Arc runners

In the air break, circuit breaker the contact separation and arc extinction take place in air at atmospheric pressure. In air break circuit breaker high resistance principle is employed. In this circuit breaker arc is expanded by the mean of arc runners, arc chutes, and arc resistance is increased by splitting, cooling and lengthening.

The arc resistance is increased to such an extent that the voltage drop across the arc becomes more than the system voltage, and the arc gets extinguished at the current zero of AC wave.

Air break circuit breakers are employed in DC circuits and Ac circuits up to 12,000 voltages. Such breakers are usually of indoor type and installed on vertical panels or indoor draw out switch gear. AC circuit breakers are widely employed indoor medium voltage and low voltage switchgear.

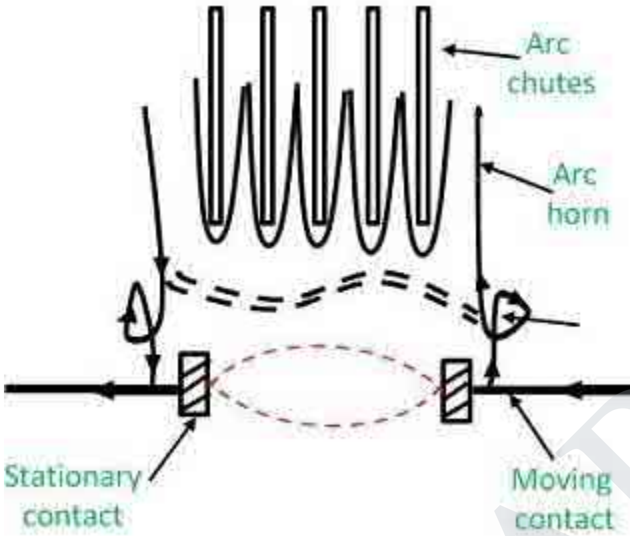
Plain Break Type Air Break Circuit Breaker

It is the simplest one in which contacts are made in the shape of two horns. The air initially strikes across the shortest distance between the horns and is driven steadily upwards by the convection currents caused by heating of air during arcing and the interaction of the magnetic and the electric fields. The arc extends from one tip to the other when the horns are fully separated resulting in lengthening and cooling arc.The relative slowness of the process and the possibility of arc spreading of adjacent metal works limits the application of about 500V and too low power circuits.

Magnetic Blow-Out Type Air Break Circuit Breaker

Some air circuit breakers are used in the circuits having voltage up to 11 KV, the arc extinction is accomplished using magnetic field provided by the current in blowout coils connected in series with the circuit being interrupted. Such coils are called blow out the coil.

The magnetic field itself does not extinguish the arc. It simply moves the arc into chutes where the arc is lengthened, cooled and extinguished. The arc shields prevent arc spreading to an adjacent network.



It is important to connect the coils at correct polarity so that the arc is directed upwards. As the breaking action becomes more effective with large currents, this principle has resulted in increasing the rupturing capacities of such breakers to higher values.

Arc chute is an efficient device for arc extinction in air and performs the following three interrelated functions

- It confines the arc within a restricted space.
- It provides magnetic control over the arc movement so as to make arc extinction within the devices.
- It provides for the rapid cooling of arc gasses to ensures arc extinction by deionization.

<u>Air Chute Air Break Circuit Breaker</u>

The normal arrangement of air-chute air break circuit breaker employed for low and medium voltage circuits is shown in the figure below. There are two sets of contacts called the main contacts and arcing or auxiliary contacts. Main contacts are usually of copper and conduct the current in the closed position of the breakers. They have low contact resistance and are silver plated.

The arcing contacts are hard, heat resistant and usually of copper alloy. Arcing contacts are used to relieve the main contacts from damage due to arcing. The arcing contacts are easily renewable when required. The auxiliary and arcing contacts close before and open after the main contacts during the operation.

Here the blowouts consist of a steel insert in the arcing chutes. These are so arranged that the magnetic field induced in them by the current in the arc moves it upwards still faster. The steel plates divide the arc into a number of arcs in the series.

The distribution of voltage along the arc length is not linear, but it is accompanied by a rather large anode and cathode drops. In case the total sum of anode and drops of all the short arcs in series exceeds the system voltage, conditions for the quick extinction of the arc are automatically established.

When the contact has come in contact with the relatively cool surfaces of the steel plants gets rapidly and effectively cooled. The movement of the arc may be naturally or aided by a magnetic blowout. Thus, the arc is extinguished by lightening and increasing the power loss of the arc.

Working Principle Air Break Circuit Breaker

When the fault occurs, the main contacts are separate first, and the current is shifted to the arcing contacts. Now the arcing contacts are separate, and the arc is drawn between them. This arc is forced upwards by the electromagnetic forces and thermal action. The arc ends travel along the arc runner. The arc moves upward and is split by the arc splitter plates. The arc is extinguished by lengthening, cooling, splitting, etc.

Applications of Air Break Circuit Breaker

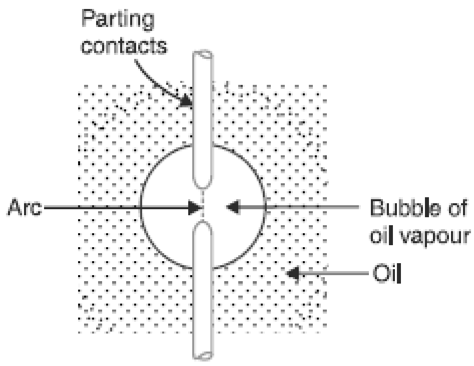
Air break circuit breaker is suitable for the control of power station auxiliaries and industrial plants. They do not require any additional equipment such as compressors, etc. They are mainly used in a place where there are possibilities of fire or explosion hazards. Air break principle of lengthening of the arc, arc runners magnetic blow-up is employed for DC circuit breakers up to 15 KV.

Drawback of Air Break Circuit Breaker

A drawback of arc chute principle is its inefficiency at low currents where the electromagnetic fields are weak. The chute itself is not necessarily less efficient in its lengthening and deionizing action than at high currents, but the arc movement into the chute tends to become slower, and high-speed interruption is not necessarily obtained

5.8.3.Oil CB

In such circuit breakers, some insulating oil (*e.g.*, transformeroil) is used as an arc quenching medium. The contactsare opened under oil and an arc is struck betweenthem. The heat of the arc evaporates the surrounding oiland dissociates it into a substantial volume of gaseous hydrogenat high pressure. The hydrogen gas occupies avolume about one thousand times that of the oil decomposed.The oil is, therefore, pushed away from the arc andan expanding hydrogen gas bubble surrounds the arc regionand adjacent portions of the contacts.



The arc extinction is facilitated mainly by two processes.Firstly, the hydrogen gas has high heat conductivity andcools the arc, thus aiding the de-ionisation of the medium between the contacts. Secondly, the gassets up turbulence in the oil and forces it into the space between contacts, thus eliminating the arcingproducts from the arc path. The result is that arc is extinguished and circuit current †interrupted.

Advantages.

The advantages of oil as an arc quenching medium are :

(*i*) It absorbs the arc energy to decompose the oil into gases which have excellent cooling properties.

(*ii*) It acts as an insulator and permits smaller clearance between live conductors and earthed components.

(*iii*) The surrounding oil presents cooling surface in close proximity to the arc.

Disadvantages.

The disadvantages of oil as an arc quenching medium are:

(*i*) It is inflammable and there is a risk of a fire.

(*ii*) It may form an explosive mixture with air

(*iii*) The arcing products (*e.g.,* carbon) remain in the oil and its quality deteriorates with successive operations. This necessitates periodic checking and replacement of oil.

Types of Oil Circuit Breakers

The oil circuit breakers find extensive use in the power system. These can be classified into thefollowing types:

(*i*) *Bulk oil circuit breakers*which use a large quantity of oil. The oil has to serve two purposes.

Firstly, it extinguishes the arc during opening of contacts and secondly, it insulates the currentconducting parts from one another and from the earthed tank. Such circuit breakersmay be classified into :

(*a*) Plain break oil circuit breakers

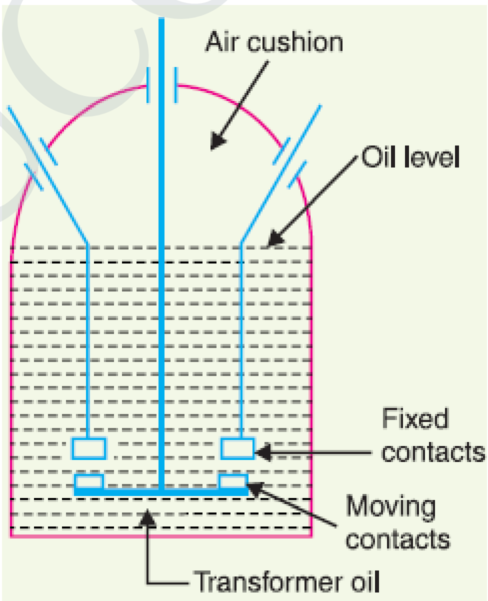
(*b*) Arc control oil circuit breakers.

In the former type, no special means is available for controlling the arc and the contacts aredirectly exposed to the whole of the oil in the tank. However, in the latter type, special arc controldevices are employed to get the beneficial action of the arc as efficiently as possible.

(*ii*) *Low oil circuit breakers*which use minimum amount of oil. In such circuit breakers, oil isused *only* for arc extinction; the current conducting parts are insulated by air or porcelain or organic insulating material.

Plain Break Oil Circuit Breakers

A plain-break oil circuit breaker involves the simple process of separating the contacts under thewhole of the oil in the tank. There is no special system for arc control other than the increase in lengthcaused by the separation of contacts. The arc extinction occurs when a certain critical gap betweenthe contacts is reached.The plain-break oil circuit breaker is the earliest type fromwhich all other circuit breakers have developed. It has a verysimple construction.



It consists of fixed and moving contactsenclosed in a strong weather-tight earthed tank containing oil uptoa certain level and an air cushion above the oil level. The aircushion provides sufficient room to allow for the reception of thearc gases without the generation of unsafe pressure in the domeof the circuit breaker. It also absorbs the mechanical shock ofthe upward oil movement. It is called a double break because it providestwo breaks in series.Under normal operating conditions, the fixed and movingcontacts remain closed and the breaker carries the normal circuitcurrent. When a fault occurs, the moving contacts are pulleddown by the protective system and an arc is struck whichvaporises the oil mainly into hydrogen gas. The arc extinctionis facilitated by the following processes:

(*i*) The hydrogen gas bubble generated around the arc cools the arc column and aids the deionisationof the medium between the contacts.

(*ii*) The gas sets up turbulence in the oil and helps in eliminating the arcing products from thearc path.

(*iii*) As the arc lengthens due to the separating contacts, the dielectric strength of the medium isincreased.The result of these actions is that at some critical gap length, the arc is extinguished and thecircuit current is interrupted.

Disadvantages

(*i*) There is no special control over the arc other than the increase in length by separating themoving contacts. Therefore, for successful interruption, long arc length is necessary.

(*ii*) These breakers have long and inconsistent arcing times.

(*iii*) These breakers do not permit high speed interruption.

Due to these disadvantages, plain-break oil circuit breakers are used only for low-voltage applicationswhere high breaking-capacities are not important. It is a usual practice to use such breakersfor low capacity installations for voltages not exceeding †11 kV.

Arc Control Oil Circuit Breakers

In case of plain-break oil circuit breaker discussed above, there is very little artificial control over thearc. Therefore, comparatively long arc length is essential in order that turbulence in the oil caused bythe gas may assist in quenching it. However, it is necessary and desirable that final arc extinctionshould occur while the contact gap is still short. For this purpose, some arc control is incorporatedand the breakers are then called arc control circuit breakers. There are two types of such breakers,namely :

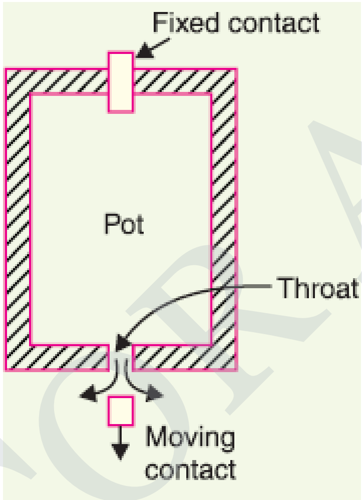
(*i*) *Self-blast oil circuit breakers*— in which arc control is provided by internal means *i.e.* the arc itself is employed for its own extinction efficiently.

(*ii*) *Forced-blast oil circuit breakers*— in which arc control is provided by mechanical meansexternal to the circuit breaker.

(*i*) Self-blast oil circuit breakers.

In this type of circuit breaker, the gases produced duringarcing are confined to a small volume by the use of an insulating rigid pressure chamber or potsurrounding the contacts. Since the space available for the arc gases is restricted by the chamber, avery high pressure is developed to force the oil and gas through or around the arc to extinguish it. Themagnitude of pressure developed depends upon the value of fault current to be interrupted. As thepressure is generated by the arc itself, therefore, such breakers are sometimescalled self-generated pressure oil circuit breakers.The pressure chamber is relatively cheap to make and gives reducedfinal arc extinction gap length and arcing time as against the plain-breakoil circuit breaker. Several designs of pressure chambers (sometimes calledexplosion pots) have been developed and a few of them are describedbelow :

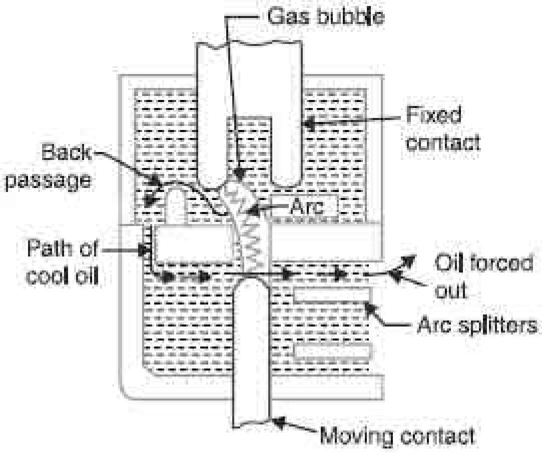
(a) Plain explosion pot.It is a rigid cylinder of insulating materialand encloses the fixed and moving contacts. The movingcontact is a cylindrical rod passing through a restricted opening (calledthroat) at the bottom.



When a fault occurs, the contacts get separated andan arc is struck between them. The heat of the arc decomposes oil into agas at very high pressure in the pot. This high pressure forces the oil andgas through and round the arc to extinguish it. If the final arc extinction does not take place while themoving contact is still within the pot, it occurs immediately after the moving contact leaves the pot. Itis because emergence of the moving contact from the pot is followed by a violent rush of gas and oilthrough the throat producing rapid extinction.The principal limitation of this type of pot is that it cannot be used for very low or for very highfault currents. With low fault currents, the pressure developed is small, thereby increasing the arcingtime. On the other hand, with high fault currents, the gas is produced so rapidly that explosion pot isliable to burst due to high pressure. For this reason, plain explosion pot operates well on moderateshort-circuit currents only where the rate of gas evolution is moderate.

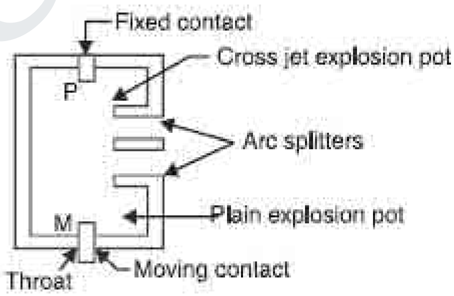
Cross jet explosion pot.

This type of pot is just a modification of plain explosion pot andis illustrated in Fig.



It is made of insulating material and has channels on one side which act asarc splitters. The arc splitters help in increasing the arc length, thus facilitating arc extinction. Whena fault occurs, the moving contact of the circuit breaker begins to separate. As the moving contact iswithdrawn, the arc is initially struck in the top of the pot. The gas generated by the arc exerts pressureon the oil in the back passage. When the moving contact uncovers the arc splitter ducts, fresh oil isforced *across* the arc path. The arc is, therefore, driven sideways into the "arc splitters" whichincrease the arc length, causing arc extinction.Thecross-jet explosion pot is quite efficient for interrupting heavy fault currents. However, forlow fault currents, the gas pressure is †small and consequently the pot does not give a satisfactoryoperation.

(*c*) Self-compensated explosion pot. This type of pot is essentially a combination of plainexplosion pot and cross jet explosion pot. Therefore, it can interrupt low as well as heavy shortcircuit currents with reasonable accuracy.



It consists of two chambers; the upper chamber is the cross-jet explosion pot with two arc splitter ducts while the lowerone is the plain explosion pot. When the short-circuit current is heavy, the rate of generation of gas isvery high and the device behaves as a cross-jet explosion pot. The arc extinction takes place when themoving contact uncovers the first or second arc splitter duct. However, on low short-circuit currents,the rate of gas generation is small and the tip of the moving contact has the time to reach the lowerchamber. During this time, the gas builds up sufficient pressure as there is very little leakage througharc splitter ducts due to the obstruction offered by the arc path and right angle bends. When themoving contact comes out of the throat, the arc is extinguished by plain pot action.It may be noted that as the severity of the short-circuit current increases, the device operates lessand less as a plain explosion pot and more and more as a cross-jet explosion pot. Thus the tendencyis to make the control self-compensating over the full range of fault currents to be interrupted.

(*ii*) Forced-blast oil circuit breakers.

In the self-blast oil circuit breakers discussed above, thearc itself generates the necessary pressure to force the oil across the arc path. The major limitation ofsuch breakers is that arcing times tend to be long and inconsistent when operating against currentsconsiderably less than the rated currents. It is because the gas generated is much reduced at lowvalues of fault currents. This difficulty is overcome in forced-blast oil circuit breakers in which thenecessary pressure is generated by external mechanical means independent of the fault currents to bebroken.In a forced -blast oil circuit breaker, oil pressure is created by the piston-cylinder arrangement.The movement of the piston is mechanically coupled to the moving contact. When a fault occurs, thecontacts get separated by the protective system and an arc is struck between the contacts. The pistonforces a jet of oil towards the contact gap to extinguish the arc. It may be noted that necessary oilpressure produced does not in any way depend upon the fault current to be broken.

Advantages

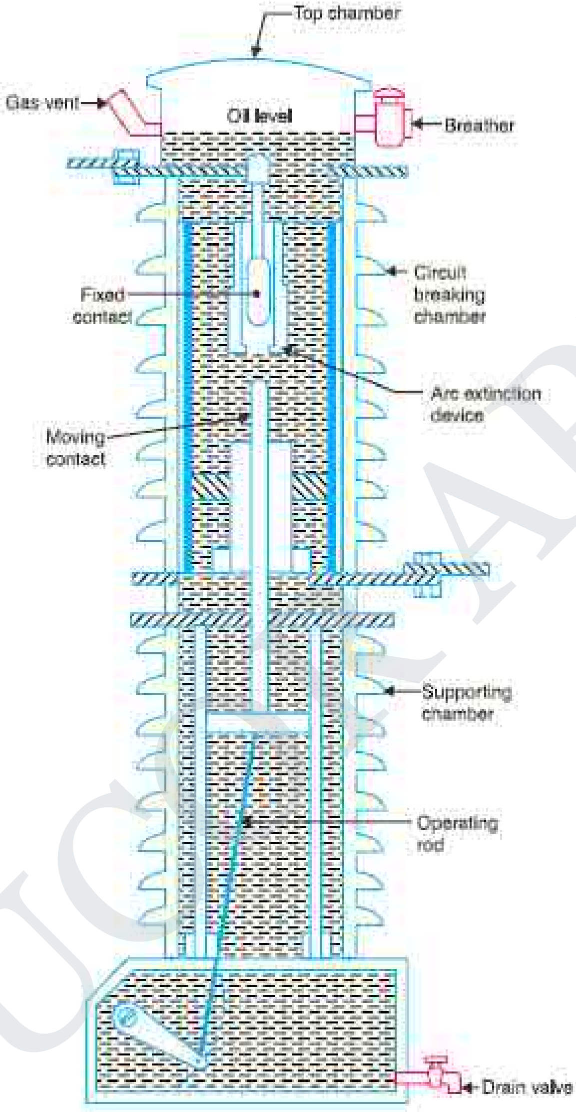
(*a*) Since oil pressure developed is independent of the fault current to be interrupted, the performanceat low currents is more consistent than with self-blast oil circuit breakers.

(*b*) The quantity of oil required is reduced considerably.

Low Oil Circuit Breakers

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

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



Construction.

Thereare two compartments separated from each other but both filled with oil. The upper chamber is thecircuit breaking chamber while the lower one is the supporting chamber. The two chambers areseparated by a partition and oil from one chamber is prevented from mixing with the other chamber.This arrangement permits two advantages. Firstly, the circuit breaking chamber requires a smallvolume of oil which is just enough for arc extinction. Secondly, the amount of oil to be replaced isreduced as the oil in the supporting chamber does not get contaminated by the arc.

(*i*) *Supporting chamber.*

It is a porcelain chamber mounted on a metal chamber. It is filled withoil which is physically separated from the oil in the circuit breaking compartment. The oilinside the supporting chamber and the annular space formed between the porcelain insulationand bakelised paper is employed for insulation purposes only.

(*ii*) *Circuit-breaking chamber.*

It is a porcelain enclosure mounted on the top of the supportingcompartment. It is filled with oil and has the following parts :

(*a*) upper and lower fixed contacts

(*b*) moving contact

(*c*) turbulator

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

(*iii*) *Top chamber.*

It is a metal chamber and is mouted on the circuit-breaking chamber. Itprovides expansion space for the oil in the circuit breaking compartment. The top chamberis also provided with a separator which prevents any loss of oil by centrifugal action causedby circuit breaker operation during fault conditions.

<u>Operation.</u>

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

<u>Advantages.</u>

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

(*i*) It requires lesser quantity of oil.

(*ii*) It requires smaller space.

(*iii*) There is reduced risk of fire.

(*iv*) Maintenance problems are reduced.

Disadvantages.

A low oil circuit breaker has the following disadvantages as compared to a bulkoil circuit breaker:

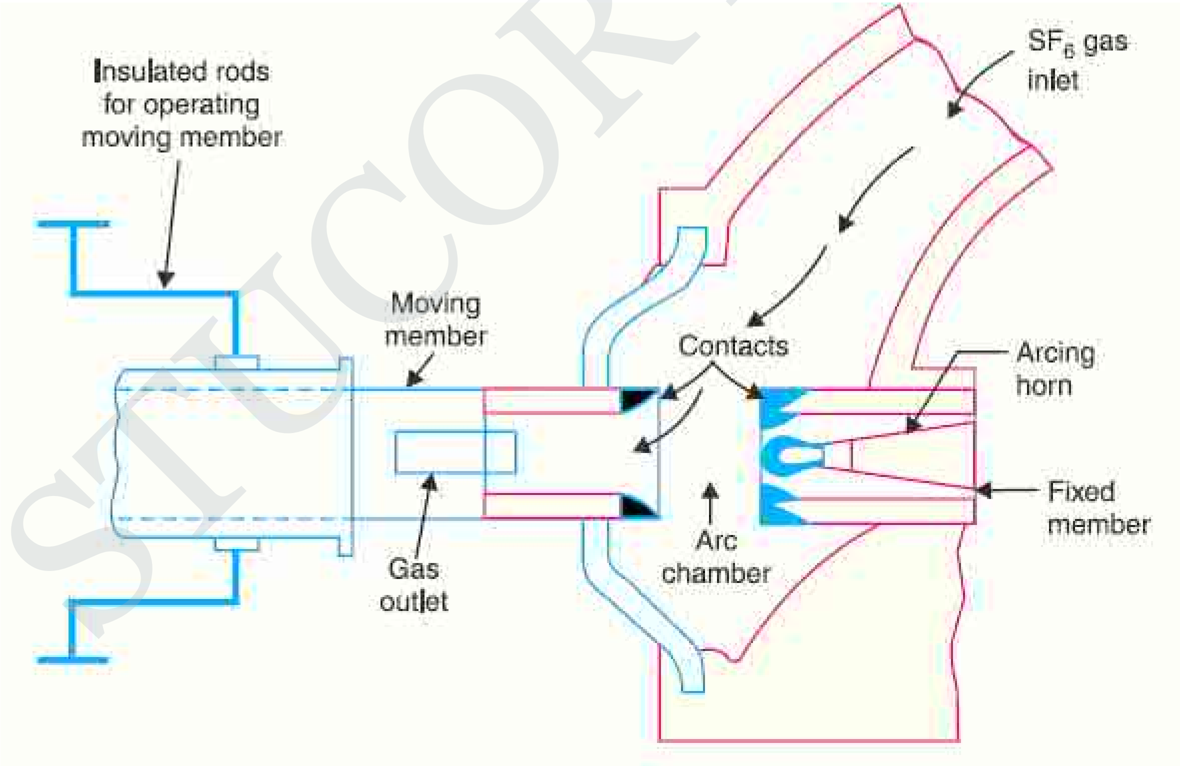
(*i*) Due to smaller quantity of oil, the degree of carbonisation is increased.

(*ii*) There is a difficulty of removing the gases from the contact space in time.

(*iii*) The dielectric strength of the oil deteriorates rapidly due to high degree of carbonisation.

5.8.4SF6 CB

In such circuit breakers, sulphur hexaflouride (SF6) gas is used as the arc quenching medium. TheSF6 is an electro-negative gas and has a strong tendency to absorb free electrons. The contacts of thebreaker are opened in a high pressure flow of SF6 gas and an arc is struck between them. Theconducting free electrons in the arc are rapidly captured by the gas to form relatively immobilenegative ions. This loss of conducting electrons in the arc quickly builds up enough insulation strengthto extinguish the arc. The SF6 circuit breakers have been found to be very effective for high powerand high voltage service.



Construction

It consists of fixedand moving contacts enclosed in a chamber (called arc interruption chamber) containing SF6 gas.This chamber is connected to SF6 gas reservoir. When the contacts of breaker are opened, the valvemechanism permits a high pressure SF6 gas from the reservoir to flow towards the arc interruptionchamber. The fixed contact is a hollow cylindrical current carrying contact fitted with an arc horn.The moving contact is also a hollow cylinder with rectangular holes in the sides to permit the SF6 gasto let out through these holes after flowing along and across the arc. The tips of fixed contact, movingcontact and arcing horn are coated with copper-tungsten arc resistant material. Since SF6 gas iscostly, it is reconditioned and reclaimed by suitable auxiliary system after each operation of the breaker.

Working

In the closed position of the breaker, the contacts remain surrounded by SF6 gas at apressure of about 2·8 kg/cm2. When the breaker operates, the moving contact is pulled apart and anarc is struck between the contacts. The movement of the moving contact is synchronised with theopening of a valve which permits SF6 gas at 14 kg/cm2 pressure from the reservoir to the arc interruptionchamber. The high pressure flow of SF6 rapidly absorbs the free electrons in the arc path to formimmobile negative ions which are ineffective as charge carriers. The result is that the medium betweenthe contacts quickly builds up high dielectric strength and causes the extinction of the arc.After the breaker operation (*i.e.*, after arc extinction), the valve is closed by the action of a set ofsprings.

Advantages.

Due to the superior arc quenching properties of SF6 gas, the SF6 circuit breakershave many advantages over oil or air circuit breakers. Some of them are listed below :

(*i*) Due to the superior arc quenching property of SF6, such circuit breakers have very shortarcing time.

(*ii*) Since the dielectric strength of SF6 gas is 2 to 3 times that of air, such breakers can interruptmuch larger currents.

(*iii*) The SF6 circuit breaker gives noiselss operation due to its closed gas circuit and no exhaust

to atmosphere unlike the air blast circuit breaker.

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

(*v*) There is no risk of fire in such breakers because SF6 gas is non-inflammable.

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

(*vii*) The SF6 breakers have low maintenance cost, light foundation requirements and minimumauxiliary equipment.

(*viii*) Since SF6 breakers are totally enclosed and sealed from atmosphere, they are particularlysuitable where explosion hazard exists *e.g.*, coal mines.

Disadvantages

(*i*) SF6 breakers are costly due to the high cost of SF6.

(*ii*) Since SF6 gas has to be reconditioned after every operation of the breaker, additional equipmentis required for this purpose.

Applications.

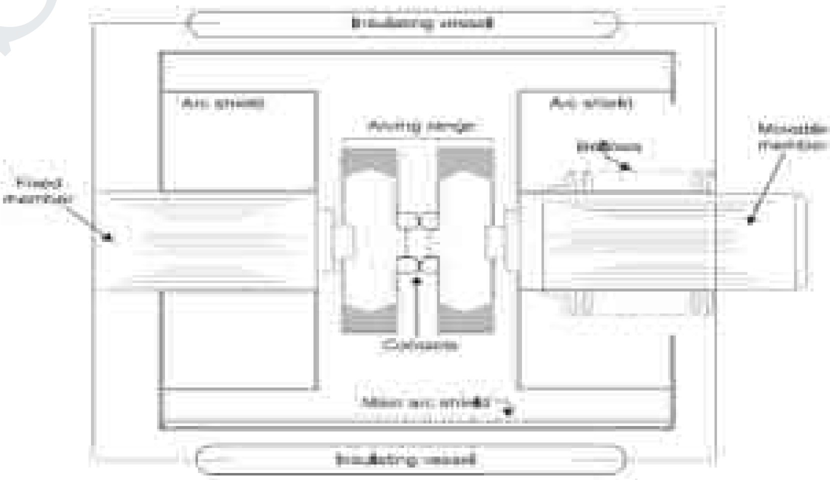
A typical SF6 circuit breaker consists of interrupter units each capable of dealingwith currents upto 60 kA and voltages in the range of 50—80 kV. A number of units are connected inseries according to the system voltage. SF6 circuit breakers have been developed for voltages 115 kVto 230 kV, power ratings 10 MVA to 20 MVA and interrupting time less than 3 cycles.

5.8.5Vaccum CB

In such breakers, vacuum (degree of vacuum being in the range from 10−7 to 10−5 torr) is used as the arc quenching medium. Since vacuum offers the highest insulating strength, it has far superior arc quenching properties than any other medium. For example, when contacts of a breaker are opened in vacuum, the interruption occurs at first current zero with dielectric strength between the contacts building up at a rate thousands of times higher than that obtained with other circuit breakers.

Principle

The production of arc in a vacuum circuit breaker and its extinction can be explainedas follows: When the contacts of the breaker are opened in vacuum (10−7 to 10−5 torr), an arc is produced between the contacts by the ionisation of metal vapours of contacts. However, the arc isquickly extinguished because the metallic vapours, electrons and ions produced during arc rapidlycondense on the surfaces of the circuit breaker contacts, resulting in quick recovery of dielectricstrength. The reader may note the salient feature of vacuum as an arc quenching medium. As soon asthe arc is produced in vacuum, it is quickly extinguished due to the fast rate of recovery of dielectricstrength in vacuum.



Construction.

It consists of fixed contact, moving contact and arc shield mounted inside a vacuum chamber. The movable member is connected to the control mechanism by stainless steel bellows. This enables the permanent sealing of the vacuum chamber so as to eliminate the possibility of leak. A glass vessel or ceramic vessel is used as the outer insulating body. The arc shield prevents the deterioration of the internal dielectric strength by preventing metallic vapours falling on the inside surface of the outer insulating cover.

Working

When the breaker operates, the moving contact separates from the fixed contact andan arc is struck between the contacts. The production of arc is due to the ionisation of metal ions anddepends very much upon the material of contacts. The arc is quickly extinguished because the metallicvapours, electrons and ions produced during arc are diffused in a short time and seized by thesurfaces of moving and fixed members and shields. Since vacuum has very fast rate of recovery ofdielectric strength, the arc extinction in a vacuum breaker occurs with a short contact separation (say0·625 cm).

Advantages

Vacuum circuit breakers have the following advantages:

(i) They are compact, reliable and have longer life.

(ii) There are no fire hazards.

(iii) There is no generation of gas during and after operation.

(iv) They can interrupt any fault current.

(v) They require little maintenance and are quiet in operation.

(vi) They can successfully withstand lightning surges.

(vii) They have low arc energy.

(viii) They have low inertia and hence require smaller power for control mechanism.

Applications

For a country like India, where distances are quite large and accessibility toremote areas difficult, the installation of such outdoor, maintenance free circuit breakers should provea definite advantage. Vacuum circuit breakers are being employed for outdoor applications rangingfrom 22 kV to 66 kV. Even with limited rating of say 60 to 100 MVA, they are suitable for a majorityof applications in rural areas.

5.8.6Comparision

	SF6 Circuit Breakers		Vacuum Circuit Breakers
Criteria	Puffer Circuit Breaker	Self-pressuring circuit-breaker	Contact material-Chrome-Copper

Operating energy requirements	Operating Energy requirements are high, because the mechanism must supply the energy needed to compress the gas.	Operating Energy requirements are low, because the mechanism must move only relatively small masses at moderate speed, over short distances. The mechanism does not have to provide the energy to create the gas flow	Operating energy requirements are low, because the mechanism must move only relatively small masses at moderate speed, over very short distances.
Arc Energy	Because of the high conductivity of the arc in the SF6 gas, the arc energy is low. (arc voltage is between 150 and 200V.)		Because of the very low voltage across the metal vapour arc, energy is very low. (Arc voltage is between 50 and 100V.)
Contact Erosion	Due to the low energy the contact erosion is small.		Due to the very low arc energy, the rapid movement of the arc root over the contact and to the fact that most of the metal vapour re-condenses on the contact, contact erosion is extremely small.
Arc extinguishing media	The gaseous medium SF6 possesses excellent dielectric and arc quenching properties. After arc extinction, the dissociated gas molecules recombine almost completely to reform SF6. This means that practically no loss/consumption of the quenching medium occurs. The gas pressure can be very simply and permanently supervised. This function is not needed where the interrupters are sealed for life.		No additional extinguishing medium is required. A vacuum at a pressure of 10-7 bar or less is an almost ideal extinguishing medium. The interrupters are 'sealed for life' so that supervision of the vacuum is not required.
Switching behavior in relation to current chopping	The pressure build-up and therefore the flow of gas is independent of the value of the current. Large or small currents are cooled with the same intensity. Only small values of high frequency, transient currents, if any, will be interrupted. The de-ionization of the contact gap proceeds very rapidly, due to the electro-negative characteristic of the SF6 gas and the arc products.	The pressure build-up and therefore the flow of gas is dependent upon the value of the current to be interrupted. Large currents are cooled intensely, small currents gently. High frequency transient currents will not, in general, be interrupted. The de-ionization of the contact gap proceeds very rapidly due to the electro-negative characteristic of the SF6 gas and the products.	No flow of an 'extinguishing' medium needed to extinguish the vacuum arc. An extremely rapid de-ionization of the contact gap, ensures the interruption of all currents whether large or small. High frequency transient currents can be interrupted. The value of the chopped current is determined by the type of contact material used. The presence of chrome in the contact alloy with vacuum also.

No. of short-circuit operation	10—50	10—50	30—100
No. full load operation	5000—10000	5000—10000	10000—20000
No. of mechanical operation	5000—20000	5000—20000	10000—30000

5.8.7Rating and selection of Circuit breakers

The rating of circuit breaker is given according to the duties that are performed by it. For complete specifications, standard rating and various tests of switches and circuit breakers IS 375/1951 may be consulted. A circuit breaker is required to perform the following three major duties.

1. It must be capable of opening the faulty circuit and breaking the fault current. This is described as breaking capacity of a circuit breaker
2. It must be capable of being closed on to a fault. This refers to making capacity of a circuit breaker
3. It must be capable of carrying fault current for a short time while another circuit breaker is clearing the fault. This refers to short time capacity of the circuit breaker.

In addition to the above ratings, a circuit breaker should be specified in terms of

- *Rated voltage:* the rated maximum voltage of a circuit breaker is the highest rms voltage, above nominal system voltage ,for which circuit breaker is designed and is the upper limit for operation. The rated voltage is expressed in kVrms and refer phase to phase voltage for three phase circuit.
- *Rated current:* the rated normal current of a circuit breaker is the rms value of the current which the circuit breaker shall be able to carry at rated frequency and at the rated voltage continuously, under specified condition.
- *Rated frequency:* the rated frequency of a circuit breaker is the frequency at which it is designed to operate.
- *Operating Duty*: the operating duty of a circuit breaker consist of the prescribed number of unit operations at stated intervals.

Breaking capacity:

Breaking current is the RMS value of current that a circuit breaker is required to break at the instant of contact separation. The symmetrical breaking current is the RMS value of its symmetrical component. If however, at the instant of contact separation, the wave is still asymmetrical it is known as the asymmetrical breaking current.

Breaking capacity (MVA) = Rated symmetrical breaking current (kA) × Rated service voltage (kV) × √3

Making capacity:

A circuit breaker may complete a full short circuit on being closed. This is known as making capacity.

Making capacity = 1.8 × √2 × Symmetrical breaking capacity.

Short time rating:

Circuit breaker should be capable of carrying high currents safely and without showing undue stress for a specified short period in a closed position. This is known as short time rating. This happens in case of momentary fault like bird age on the transmission lines and the fault is automatically cleared and persists only for 1 or 2 seconds. For this reason the circuit breakers are short time rated and they trip only when the fault persists for a duration longer than the specified time limit.