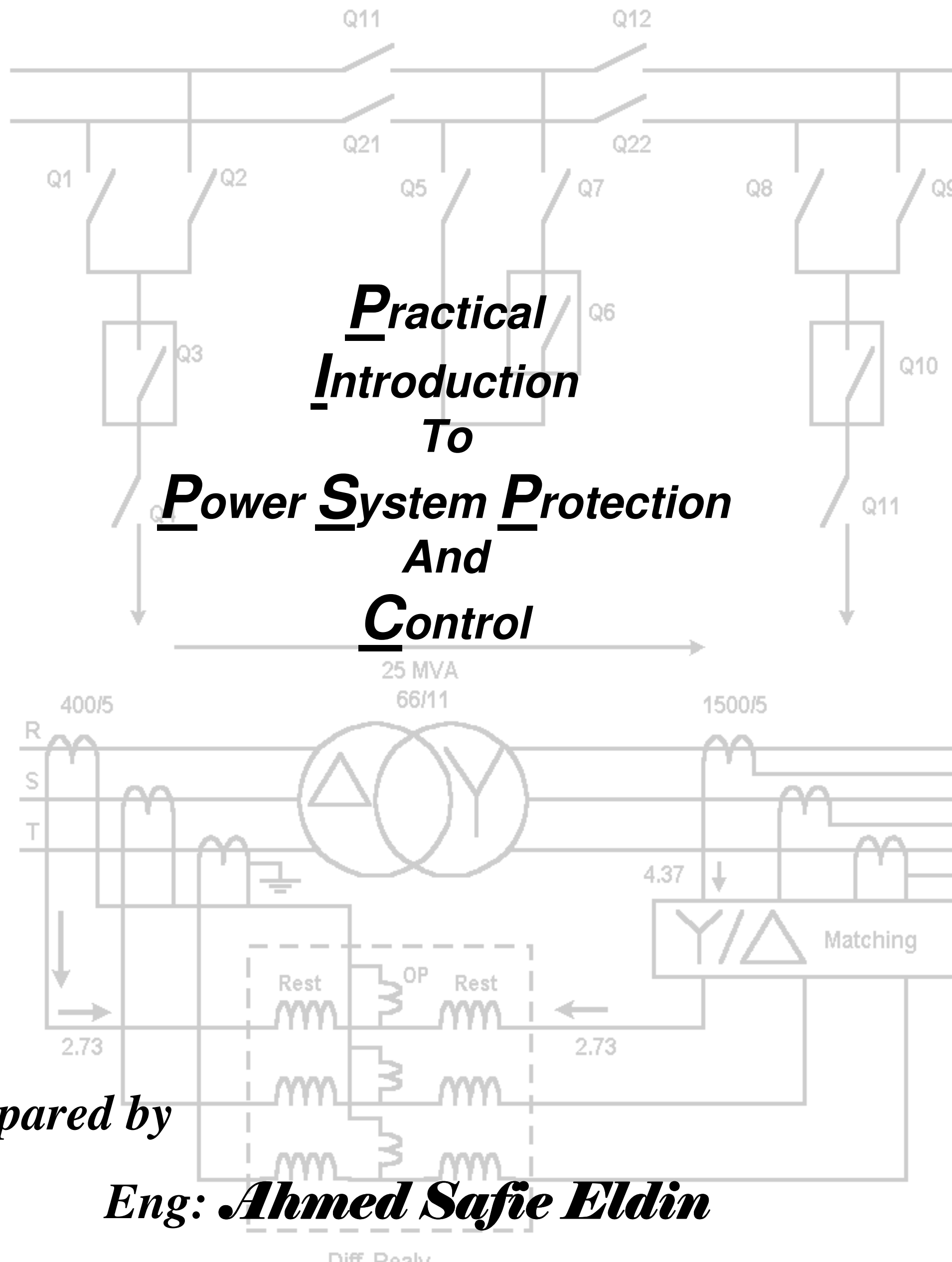
# PIPSPC

Practical Introduction Power System Protection Control




## ***P***ractical ***I***ntroduction ***To*** ***P***ower ***S***ystem ***P***rotection ***And*** ***C***ontrol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**POWER SYSTEMS PRINCIPALS**

In general, the definition of an electric power system includes some stages. Firstly, Power Plants as a source of power. Then, high voltage transmission lines are used to transfer power from power plants to power substations. power substations with their step down transformers are installed for reducing the voltage to suitable levels to be distributed. As a last stage, Distribution systems are used to give the costumer his need of electricity. All these stages are as shown in figure (1).

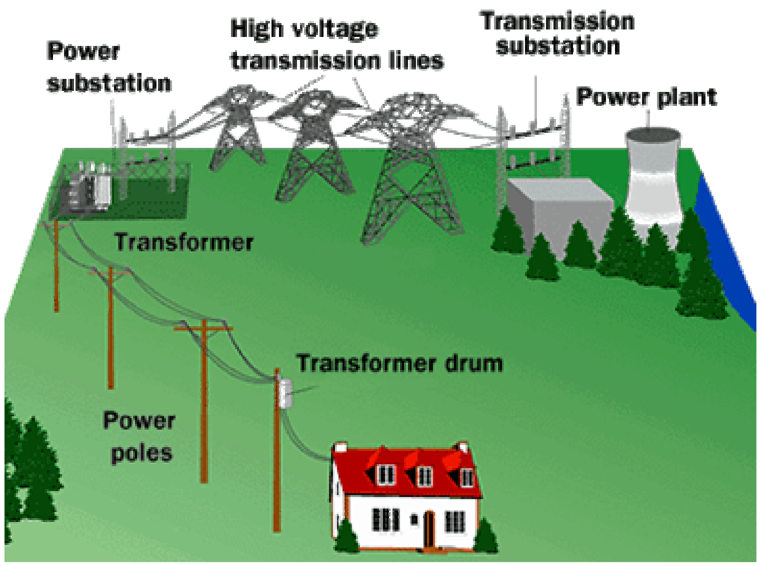



**Figure 1 Complete Power System**

**( Generation, Transmission, and Distribution )**

# POWER SYSTEM FAULTS

Power substations as a target of study consists of some elements which must be protected against different types of fault. These elements are Transmission Lines, Bus Bars, Power Transformers, Outgoing Feeders, and Bus Couplers. Before we go through different functions of protection relays, some of fault causes, fault effects, and fault types must be considered.

## Fault Causes

1- Fault Current

Healthy insulation in the equipment subjected to either transient over voltages of small time duration due to switching and lightning strokes, direct or indirect. Failure of insulation may be happened, resulting in very high fault current. This current may be more than 10 times the rated or nominal current of the equipment.

2- Insulation Aging

Aging of power equipments may cause breakdown of it even at normal power frequency voltage.

3- External Causes

External object such as bird, kite string, or tree branch are considered as external cause of fault. These objects may span one conductor and ground causing single line to ground fault (phase-earth) or span two conductors causing phase-phase fault

**Fault Effects**

The fault must be cleared as fast as possible. Many equipments may be destroyed if the fault is not cleared rapidly. The dangerous of the faults depends on the type of the fault, as example the three phase short circuit is the most dangerous fault because the short circuit current is maximum. Some of the effects of short circuit current are listed here under.

1- Due to overheating and the mechanical forces developed by faults, electrical equipments such as bus bars, generators, transformers will be damaged
2- Negative sequence current arises from unsymmetrical faults will lead to overheating.
3- Voltage profiles may be reduced to unacceptable limits as a result of faults. A frequency drop may lead to instability

**Fault Types**

The fault can be classified due to the NATURE of the fault to

1- Permanent
2- Transient

Or due to PARTICIPATED PHASES as

1- Phase-Earth
2- Phase-Phase
3- Phase-Phase-Earth
4- Three-Phase or Three-Phase-Earth

## Symmetrical Components and Fault Types

Every type of fault contains different components, Table1 below shows some of these types:-

**Table1 Symmetrical Components and Fault Types**

| Type | Positive | Negative | Zero |
|---|---|---|---|
| Healthy | | | |
| Phase-Earth | | | |
| Phase-Phase | | | |
| Phase-Phase-Earth | | | |
| Three Phase | | | |
| Three Phase-Earth | | | |

## INSTRUMENT TRANSFORMER

High voltage network components are subject to high voltage magnitudes (220 kV, 66 kV or at least 11 kV) and hundreds of amperes are passing through them. Instrument transformers are used to reduce the values of volts and current to standard secondary values which are (100 v or 110 v) and (1 or 5) amperes. These values are suitable for protection and measuring relays. Advantage of using instrument transformers is isolating the current and voltage coils of relays from high voltages of the power system.

## Basic Idea of Instrument Transformer

Instrument transformer is similar to power transformer in the idea of work which depends on, when alternating current (AC) follow through primary winding of the transformer, this currents creates a magne-motive force (M.M.F.) causing an alternating flux in the core, which is translated as a current in the secondary winding of the transformer. This study is concentrated on the practical view of current transformer, differential between metering and protection cores of current transformer, stare and open delta of Voltage transformer.

**Current Transformer**

Current transformer consists at least of two secondary cores. The first core is usually designed for measuring, the second (and third…if exist) is (are) used for protection. The secondary of current transformers are almost connected in star.

The stare point of each secondary core must be earthed. All relays of each core are connected in series. Figure (2) shows the secondary connection of one secondary core of a current transformer and the relays connected with it.

<u>Note:</u> Due to capacitance between primary and secondary winding of current transformer, high voltage may be induced on the secondary winding. So, the secondary core must be earthed to prevent secondary leads and relays from high voltage.

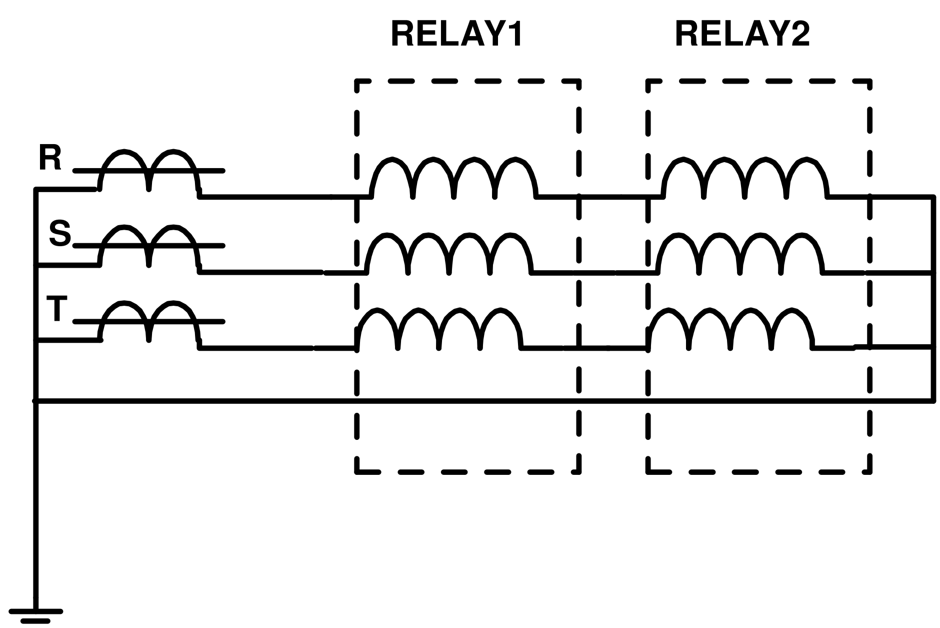



**Figure 2: Two relays connected in series at the same core**

## Measuring And Protection Cores

The measuring core of current transformer is connected to current coils of Ammeters, Wattmeters, Watt-hour meters, Var-Meters, and Var-Hour-Metes. The zone of work of all these relays below the rated of secondary of current transformer.

The measuring cores must have high to accurate monitor of the system quantities accuracy in the range of load levels. In fault conditions, Current is very high and may reach 20 times the rated value, So measuring core must be saturated to avoid the damage of measuring instruments.

Protection cores are designed to work at high levels of current (at fault). The accuracy of these cores may be less comparing with measuring cores. The saturation level of these cores are very higher than measuring cores. Magnetization curve of current transformer with measuring and protection cores is shown in figure (3), and different regions of magnetization curve is shown in figure (4).

<u>Note :</u> The knee point can be defined as the point at which a 10% increase flux density causes 50% increase in exciting ampere -turns.

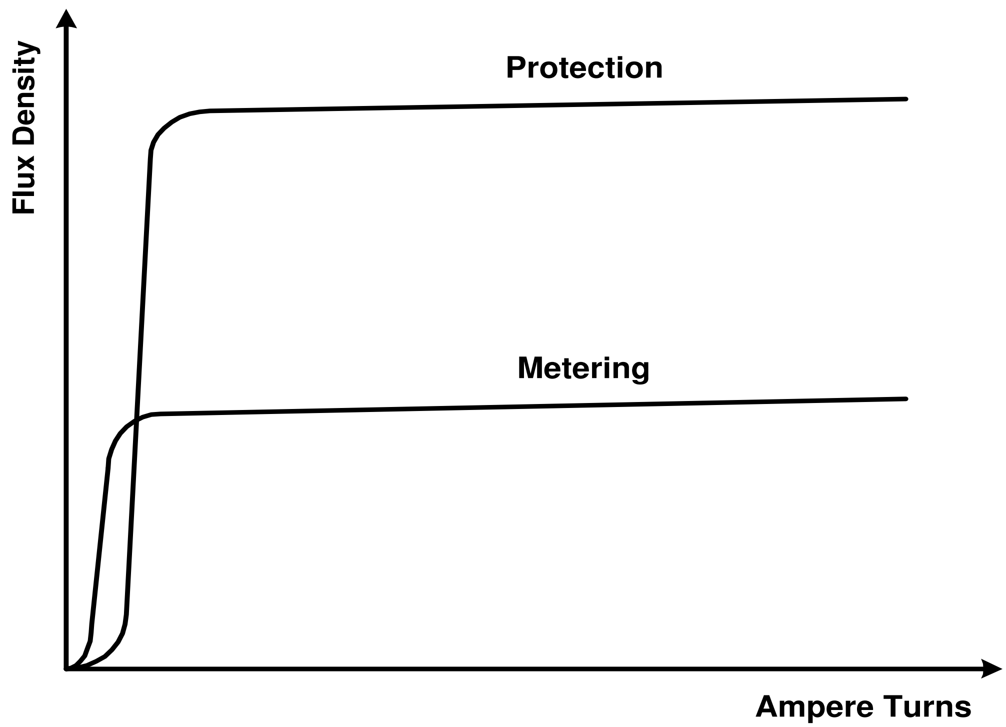



**Figure 3: Protection and Metering Cores**

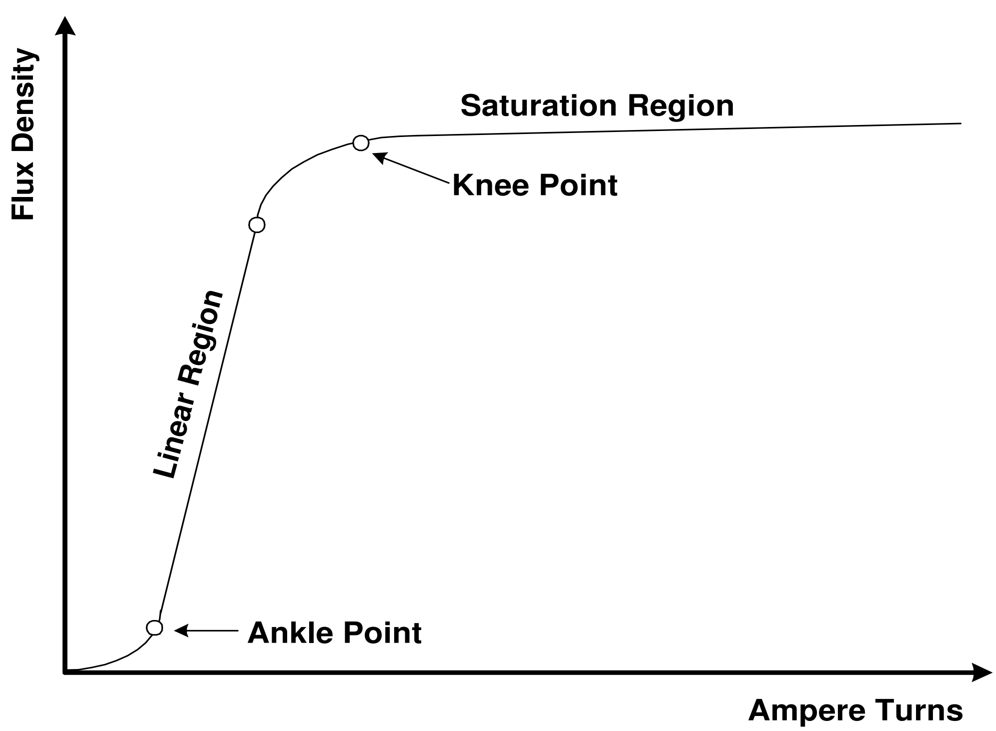



**Figure 4: Different Regions of Magnetization Curve**

## Open Circuit Current Transformer

If by mistake, secondary is open circuited. The voltage across the secondary rises to very high level. The process results in zero secondary current, hence reduced back E.M.F. The working flux Φ increase and core gets saturated the secondary E.M.F. Increase due to increased flux some problems rises from the open circuit of current transformer is:

- The primary winding and the core are over heated. This heat may be sufficient to damage the current transformer.
- High voltage induced between secondary terminals of current transformer is very dangers on the persons and the relays connected with it.

Note: Dangerous of open circuit depends on some factors, load current at which the current transformer is opened, and the material of core and winding.

**Voltage Transformer**

Voltage transformer is often consists of to cores. The first core is connected in star, and the stare point must be earthed. The second core is connected as open delta. Voltage coils of protection relays and measuring meters are connected in parallel with the star core. Open delta core is used fore directional earth fault relay. Connection of stare and open delta core with protection relays and measuring meters are shown in figure (5), and figure (6) respectively.

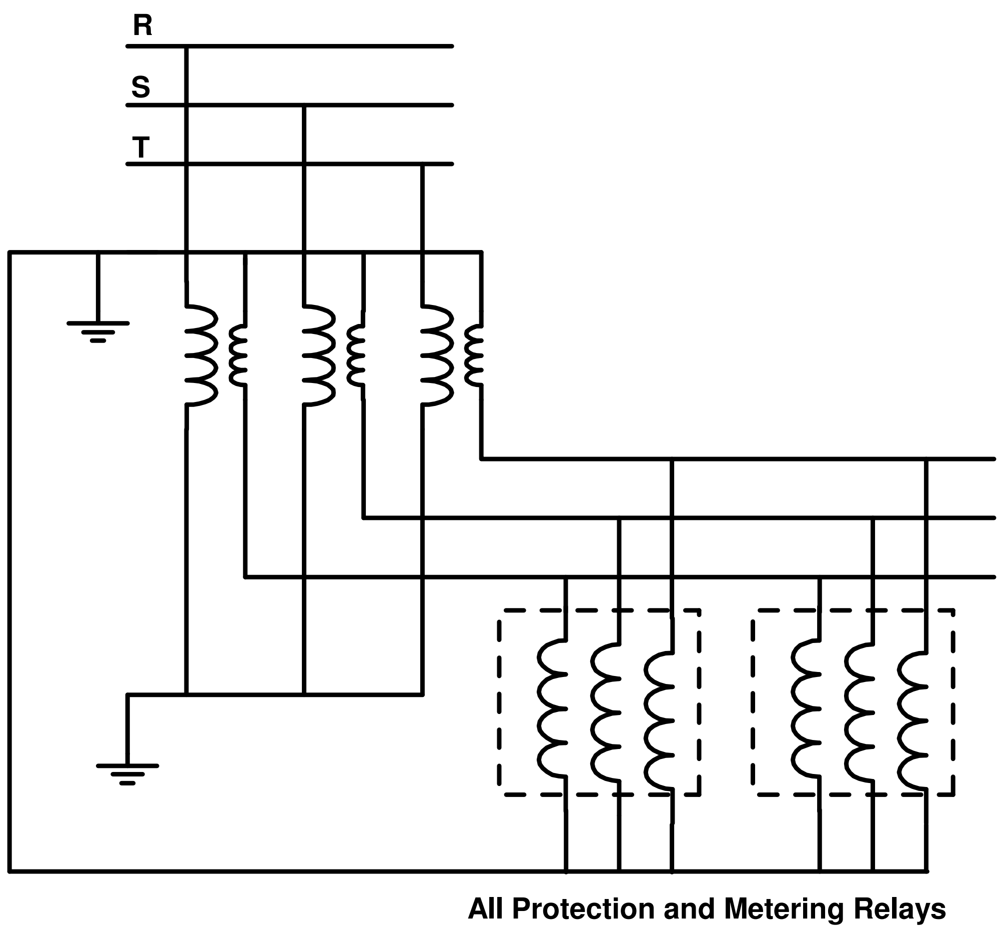



**Figure 5: Star Connection of Voltage Transformer**

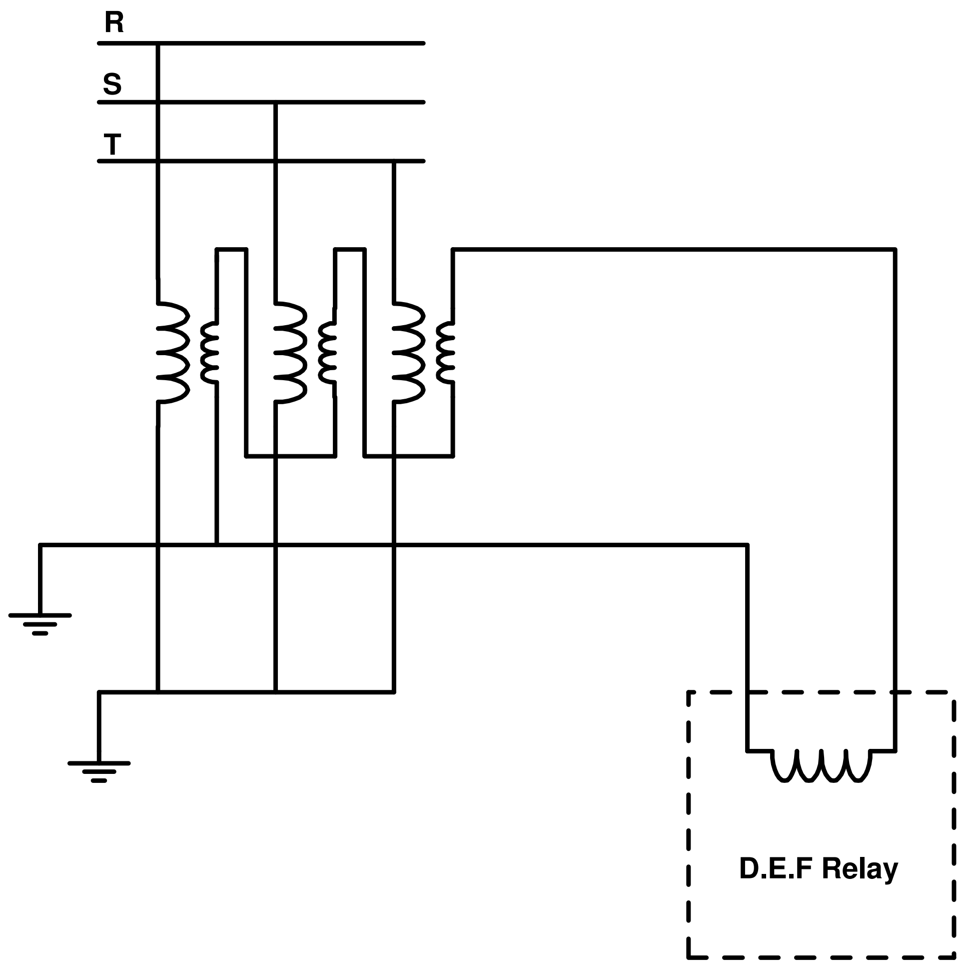



**Figure 6: Open Delta Connection of Voltage Transformer**

**DC System**

Because protective equipment must be ready to clear faults all times. The reliability will not achieve without an absolutely reliable source of supply to operate the trip coils of circuit breakers and all auxiliary relays participation in the tripping process.

To reach this reliability, Battery with nominal voltage of (110 or 220) V is installed. This battery is charged by one of two charges. One of the two charges is connected to the battery and the other is stand by to be connected if the first charger is disconnected. The load is connected to battery and the charger by dc buses. In this situation, the charger acts as a source of dc to feed the load and charge the battery. If the AC supply of the charger is switched, then the charger is out of service and the battery acts as a source of DC to feed the DC load. Connection of charger, battery, and loads as shown in figure (7).

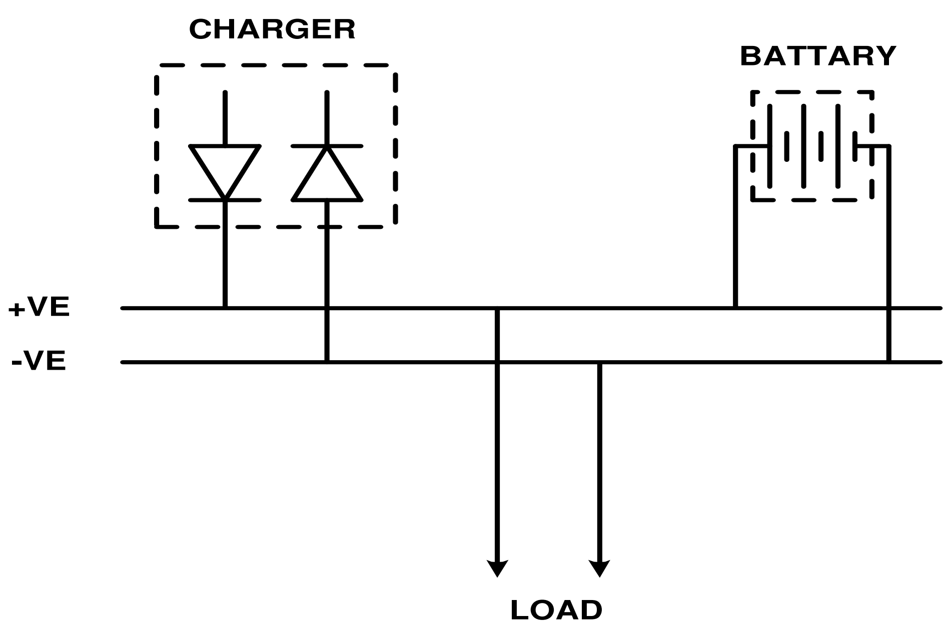



**Figure 7: DC System of a Substation**

**DC-Earth Fault Alarm Device**

Three resistor are used in this device as shown in figure (8). R1,R2 can be replaced by two lamps (L1,L2 ). If there is an earth leakage on the positive side then light of **L1** will be decreased according to the resistance of earth path and will be off in the case of soil earth path . In the opposite, the light of L2 will be increased .

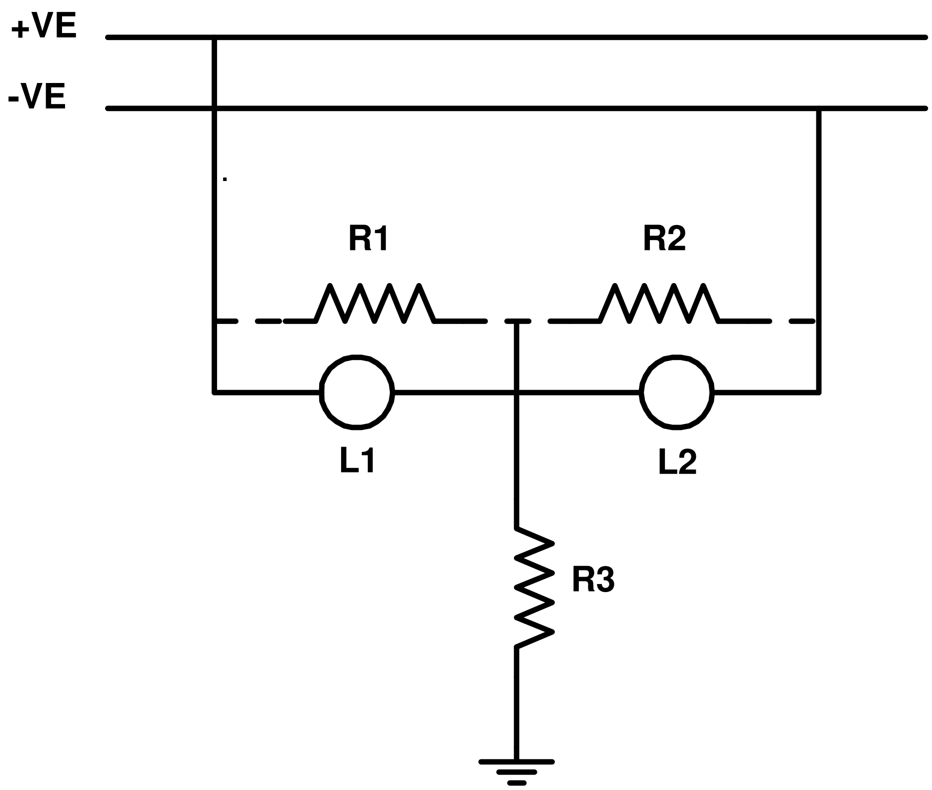



**Figure 8: DC-Earth Fault Alarm Device**

## PROTECTION RELAYS

There are different function of protection relays, Each one of these relays are able to deal with certain type of faults. Every equipment needs different type of protection relays. As example, Distance relays are suitable for transmission lines, and differential relays for power transformers and bus bars. Before go through protection relays, let us list different types of protection relays by its function and ANSI code as shown in table (2).

**Table2 ANSI Code and Relay Function**

| ANSI Number | DESPRIPTION |
|---|---|
| 2 | Time-delay |
| 21 | Distance |
| 25 | Synchronism-check |
| 27 | Undervoltage |
| 30 | Annunciator |
| 32 | Directional power |
| 37 | Undercurrent or underpower |
| 38 | Bearing |
| 40 | Field |
| 46 | Reverse-phase |
| 47 | Phase-sequence voltage |
| 49 | Thermal |
| 50 | Instantaneous overcurrent |
| 51 | AC time overcurrent |
| 59 | Overvoltage |
| 60 | Voltage balance |
| 63 | Pressure |
| 64 | Apparatus ground |
| 67 | AC directional overcurrent |
| 68 | Blocking |
| 69 | Permissive |
| 74 | Alarm |
| 76 | DC overcurrent |
| 78 | Out-of-step |
| 79 | AC reclosing |
| 81 | Frequency |
| 85 | Carrier or pilot-wire |
| 86 | Lock out |
| 87 | Differential |
| 94 | Tripping |

## Over Current Protection

Over current protection is practical application of magnitude relays since it picks up when the magnitude of current exceeds some value (setting value ). There are four types of over current relays.

## Instantaneous Over Current Relay

Instantaneous over current. Relays which operation criteria is only current magnitude (without time delay) as shown in figure (9). This type is applied to the out going feeders. The connection diagram of instantaneous over current relay is shown in figure (10).

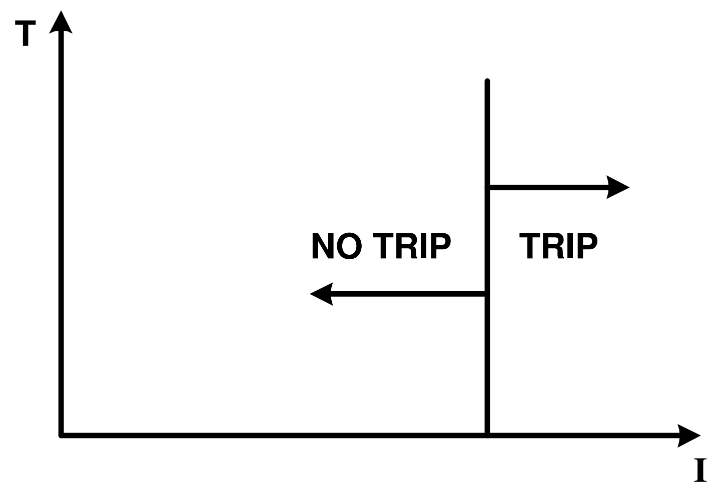



**Figure 9: Tripping Characteristics of Instantaneous Over Current Relay**

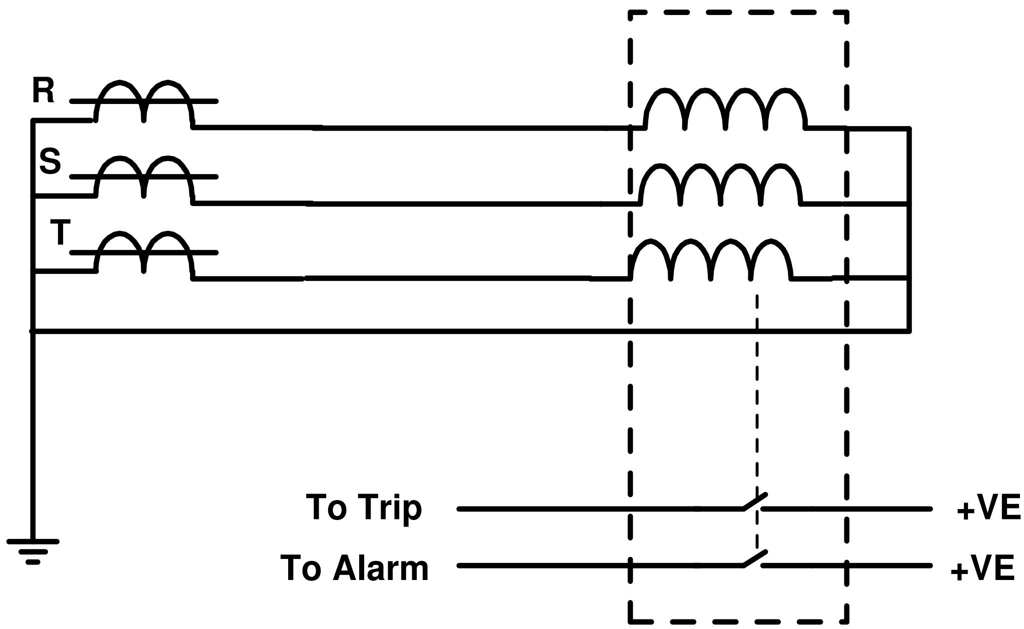



**Figure 10: Connection Diagram of Instantaneous Over Current Relays**

**Definite Time Over Current Relay**

In this type, Two conditions must be satisfied for operation (tripping), Current must exceed the setting value and the fault must be continuous at least for a time equal to time setting of the relay. Modern relays may contain more than one stage of protection each stage includes each own current and time setting. Figure (11) shows a multi stage over current relay.

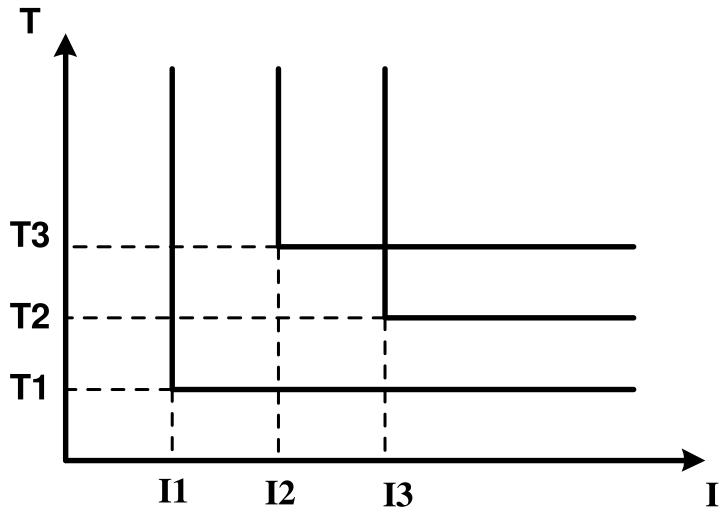



**Figure 11 Tripping Characteristics of**
Multi-Stage Definite Time Over Current Relay

The connection diagram of definite time over current relays with internal and external timers are as shown in figure (12), and figure (13) respectively.

Definite time over current relay is the most applied type of over current. It is used as :

1- Backup protection of distance relay of transmission line with time delay equal to fourth stage of distance relay which is 2.5 second in 220 kV lines, and 1.5 second in 66 kV lines
2- Backup protection to differential relay of power transformer with time delay equal to 2.0 second in 220/66 kV transformers, and 1.1 second in the 66/11 kV transformers

3- Main protection to out going feeders and bus couplers with adjustable time delay setting.

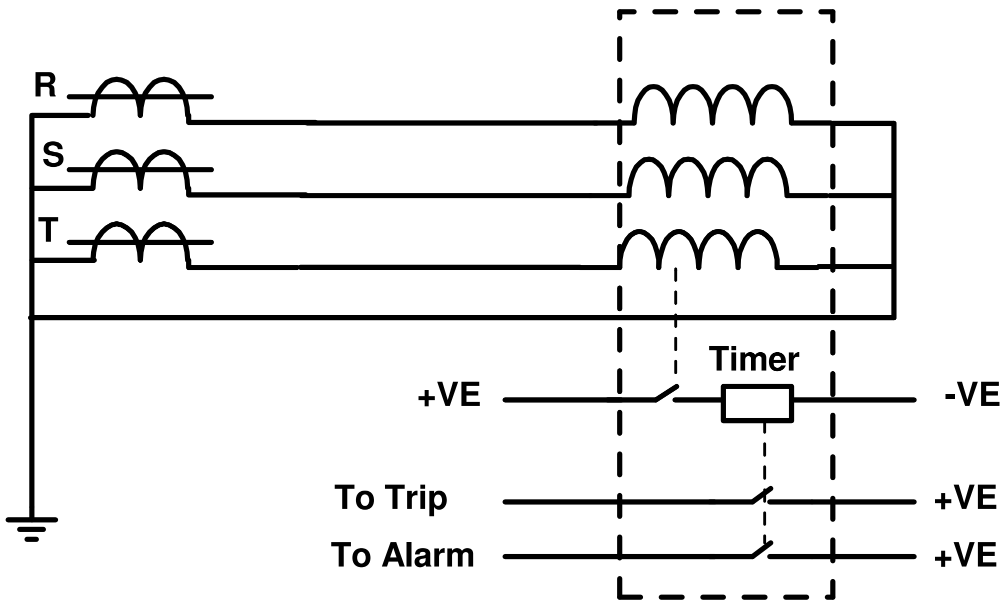



**Figure 12: Definite Time Over Current Relay with Internal Timer**

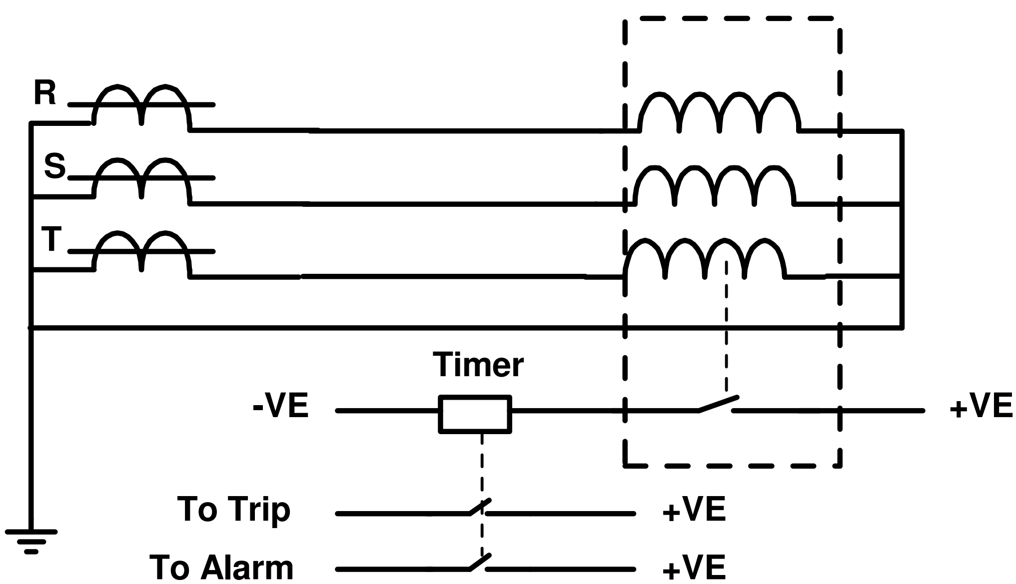


**Figure 13: Definite Time Over Current Relay with External Timer**

### Inverse Time Over Current Relay

In this tape of relays, operating time is inversely changed with current. So, high currents will operate over current relay faster than lower ones. Different currents of inverse time type are defined as standard inverse, very inverse , extremely inverse all these types are shown in figure (14).

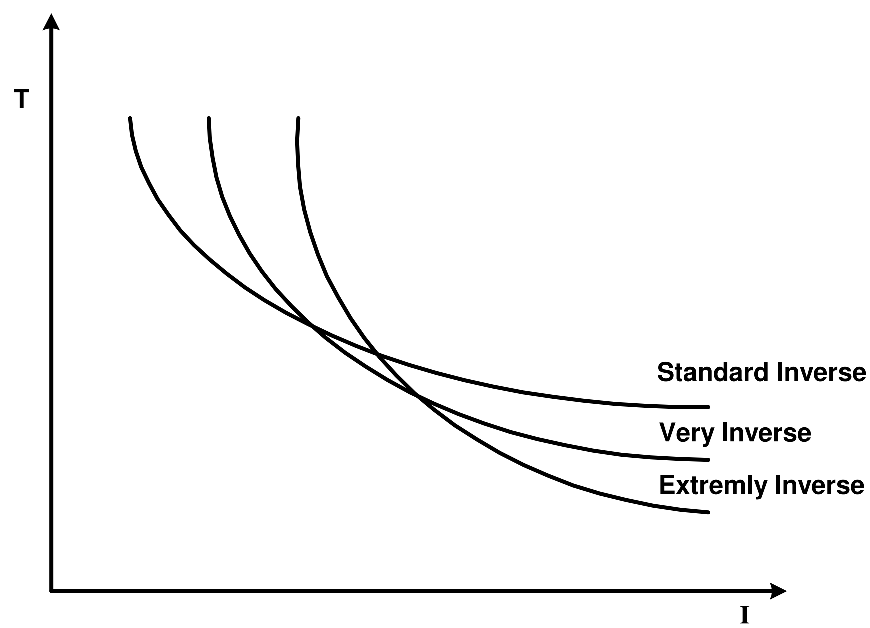



**Figure 14: Tripping Characteristics of Inverse Time Over Current Relays**

### Direction Over Current Relay

The directional over current relay is an over current relay operates in on direction of current flow and blocks in the opposite direction. Three condition must be satisfied for operation the previous two conditions which are current magnitude and time delay must be considered and the third condition which is added in this type is the directionality. The directionality of current flow is identified using voltage as a reference of direction. The connection diagram of current circuit and voltage circuit of directional over current. relays are as shown in figure (15). Almost, this type is installed on the low side of power transformer

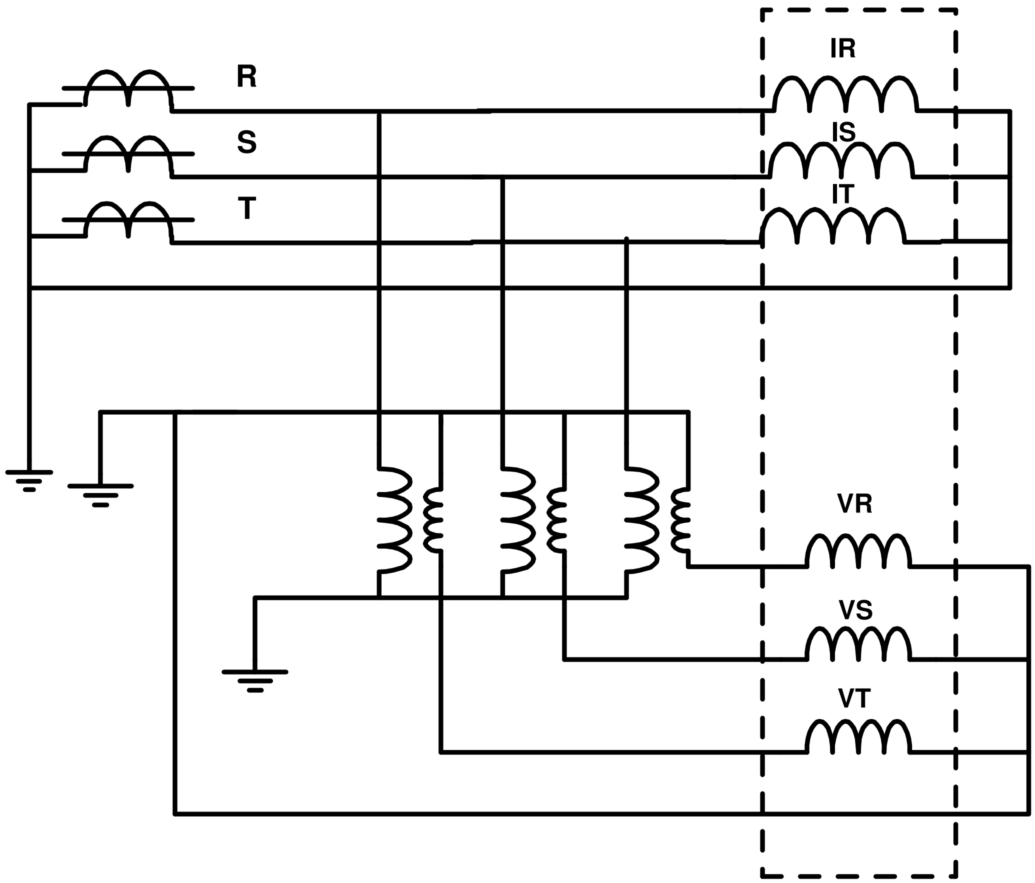



**Figure 15: Connection Diagram of Directional Over Current Relay**

## Earth Fault Relay

Types of earth fault relays are similar to over current relays but with only one coil for current in the case of instantaneous, definite time, or inverse time earth fault types. One voltage coil is added in the case of directional earth fault relays.

## Instantaneous, Definite Time, and Inverse Time Types

Tripping characteristics instantaneous Earth Fault, definite time earth fault, or inverse time earth fault relays are similar to the case of over current type. Different connection of current circuits are exist .

- Current coil may be connected to return path (neutral) of a current transformer as shown in figure (16).
- Current coil may be connected to the secondary of current transformer which is installed at the stare point of power transformer as shown in figure (17) .
- Current coil may be connected to secondary of ring type current transformer installed at power cables as shown in figure (18).

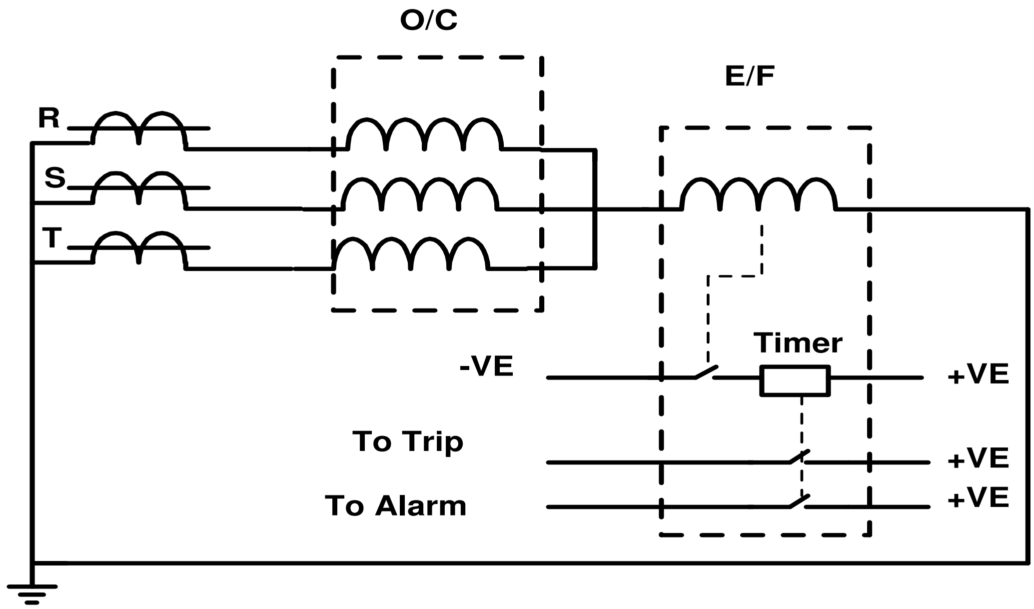



Figure 16: Earth Fault Relay connected at

The Neutral Point of Current Transformer

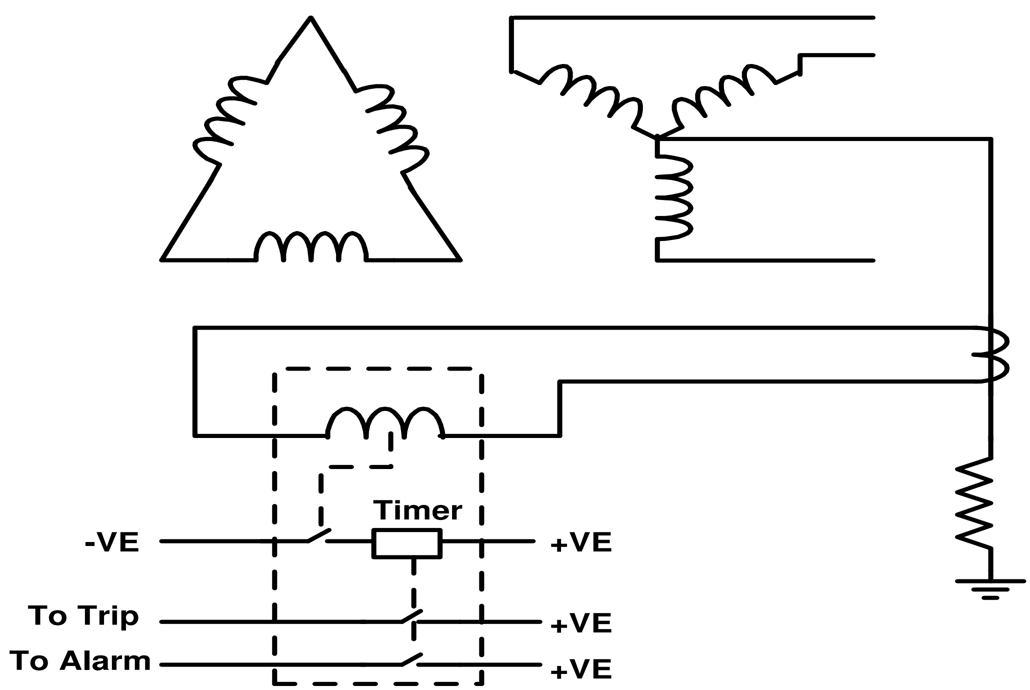



**Figure 17: Earth Fault Relay connected Star Point of**

Power Transformer

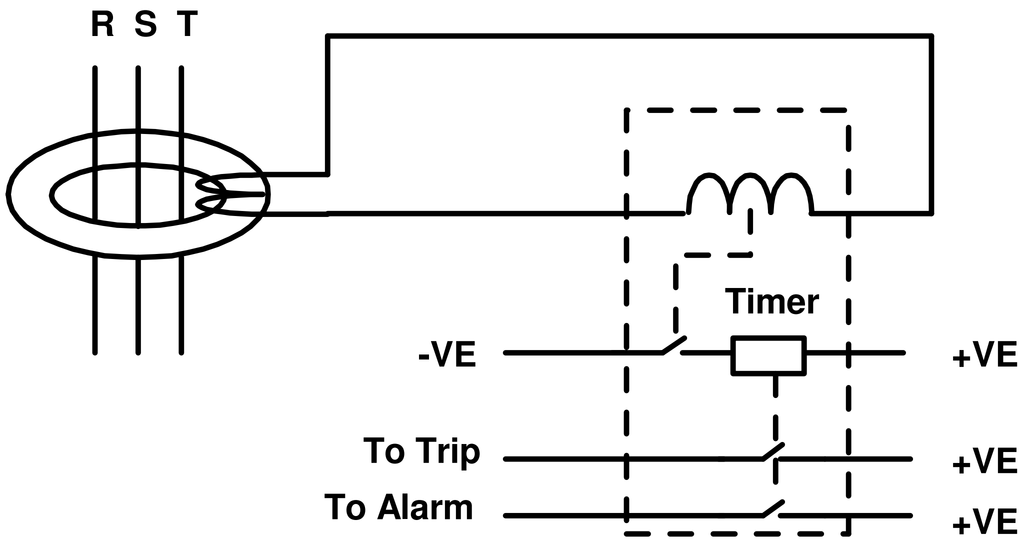



**Figure18: Earth Fault Relay connected to Ring Type Current Transformer**

### Directional Earth Fault Relay

Directional earth fault relay consists of one current coil feed by current of neutral path of current transformer , and voltage coil feed by open delta core of voltage transformer. Figure (19) shows a connection diagram of directional earth fault relay.

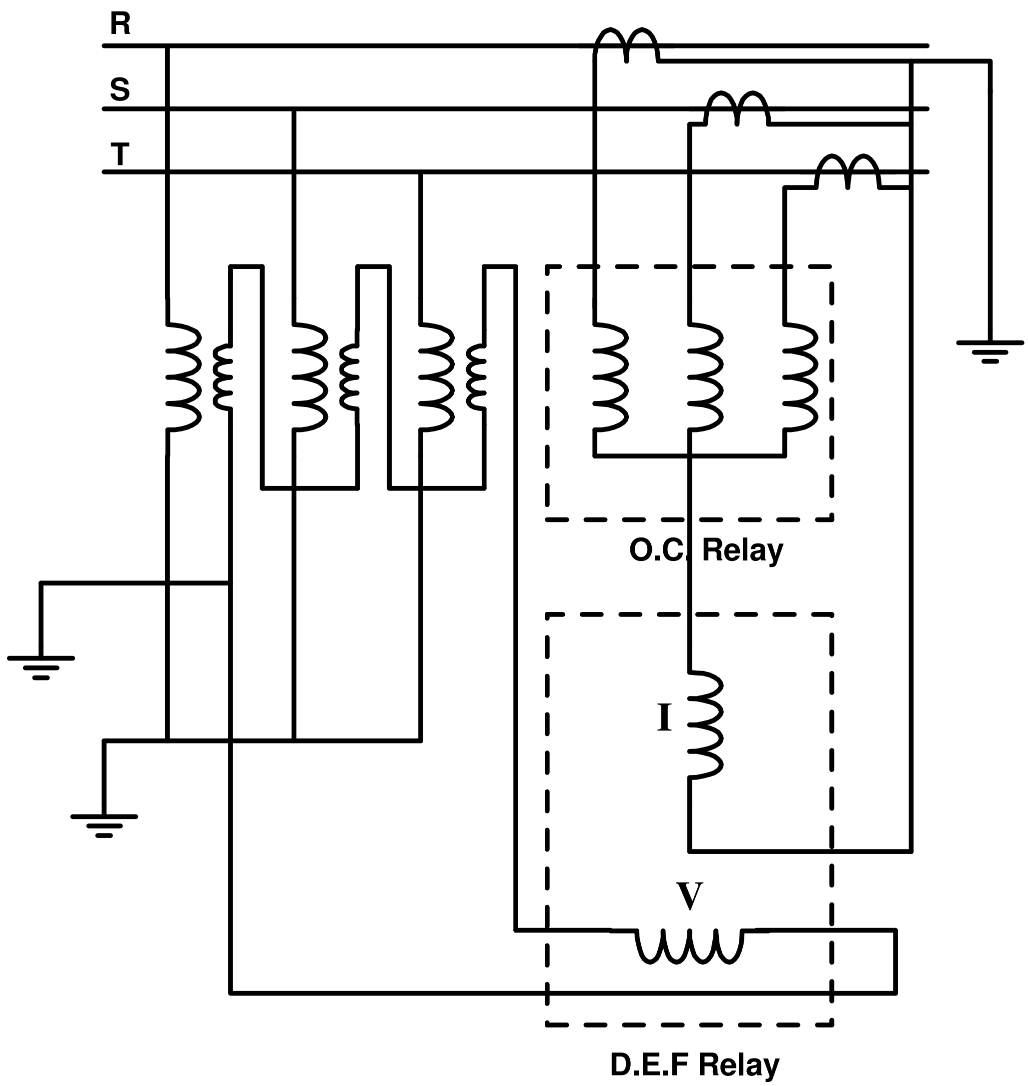



**Figure 19 : Connection Diagram of Directional Earth Fault Relay**

**Transmission Line Protection**

Firstly, Let us assume the following example as shown in figure (20)

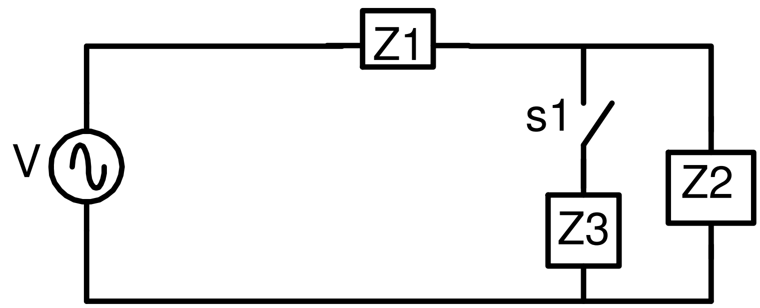



**Figure 20: Simple Circuit for a Transmission Line**

Let

$Z_3$ approximately equal 0.1 $Z_1$

$Z_2$ approximately equal 100 $Z_1$

Case 1

Normally current flow (I ) can be calculated from the relation

$$I = V / ( Z_1 + Z_2 )$$

$$= V / 101 Z_1$$

from the above equation it seems that load current (I ) is absolutely low.

Case 2

When $s_1$ is switched on then equivalent impedance of $Z_2$, and $Z_3$ is equal to $Z_2$ parallel with $Z_3$ approximately equal to $Z_3$ , and in this case current ($I_f$ ) can be calculated from the formula

$$I_f = V / ( Z_1 + Z_3 )$$

$= V / 1.1\ Z_1$

Which is very high compared with the current obtained from case 1

Transmission line healthy and faulted cases is similar to the above cases.

Where

$I$ The normal (load ) current

$I_f$ The fault current

More details are given in the next example which is shown in figure (21).

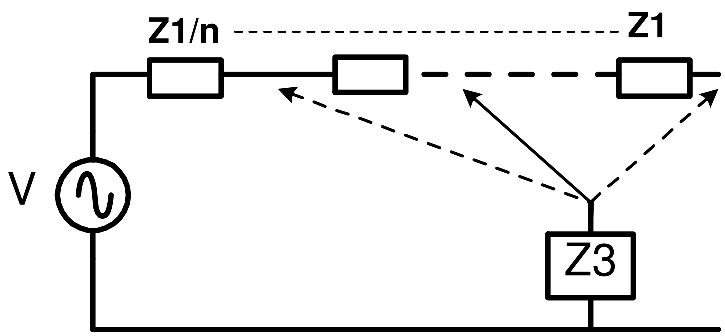



**Figure 21: Different Faults at Different Locations**

For a transmission line let the series impedance $Z_1$ is divided into n equal segments and the switch $S_1$ can be switched into any segment which is an indication of fault location

***For near faults***

Total impedance ($Z_T$) can be calculated from the formula

$$Z_T = Z_3 = \mathbf{0.1\ Z_1}$$

***Fault in mid point of Transmission Line***

$$Z_T = Z_3 + Z_1 / 2 = \mathbf{0.6\ Z_1}$$

***Fault at Line End***

$$Z_T = Z_3 + Z_1 = \mathbf{1.1\ Z_1}$$

From the previous cases, the total impedance ($Z_T$) is proportional to location (distance ) of fault

$$Z_T \propto \text{distance}$$

Which is the idea of working distance relays.

**Distance Relays**

Faults on transmission lines are associated with increasing of current and decreasing of voltage which yields decreasing the value of Z. The idea of distance relays are based on the fact that

- On normal condition, The value of Z is very high so the distance relay does not operate .

- On fault condition, The value of Z is decreased and distance relay will operate. figure (22) shown the change from health condition ( $Z_1$ ) to fault condition ($Z_2$) in the impedance relay characteristics.

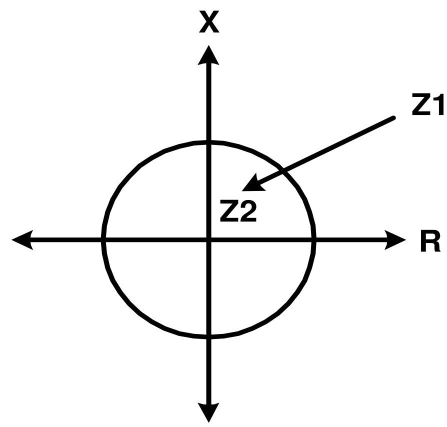



**Figure 22: From Healthy to Faulted**

### Directional Impedance Relay Characteristics

Adding the directionality criteria to the previous situation, Then the characteristic of operation and blocking of the distance relay is as shown in figure (23).

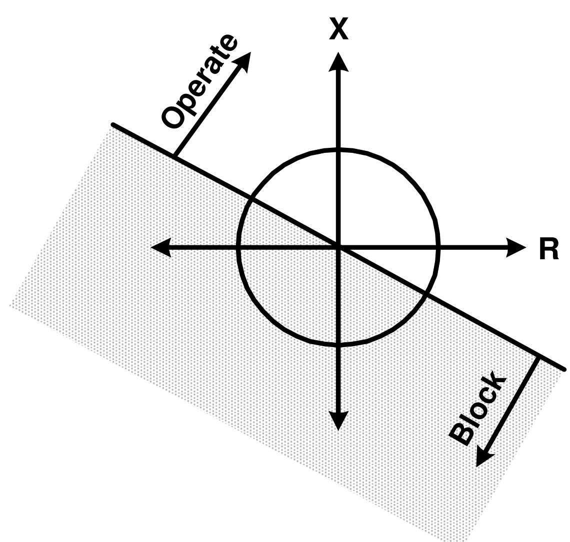



**Figure 23: Operate and Block Regions of Directional Impedance Relay**

**Mho Characteristic**

In this case, most of the circle is in the forward direction. Figure (24) shows the characteristics curve of shifted mho distance relay. Shifted Mho distance relay characteristics can be obtained when the curve is shifted such that, the curve does not pass through the origin.

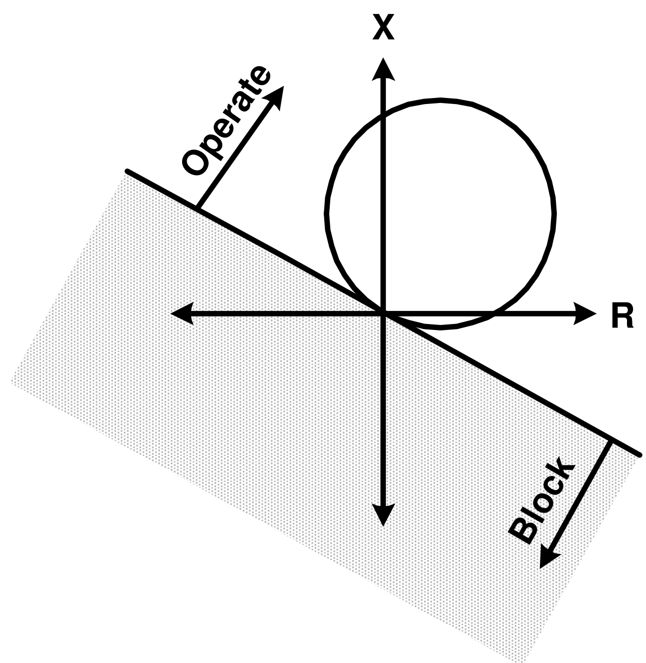



**Figure 24: Mho Distance Relay**

**Multi-Stage Distance Relay**

All previous cases assumes one stage of operation. For more security, Equipments must be protected by more than one relay. So, distance relay can be applied as main protection only for one stage (first stage) with zero time delay, and as a backup protection to another transmission lines ($2^{nd}$ ,$3^{rd}$,………stages). Figure (25) shows the characteristic curve for four stage distance relay.

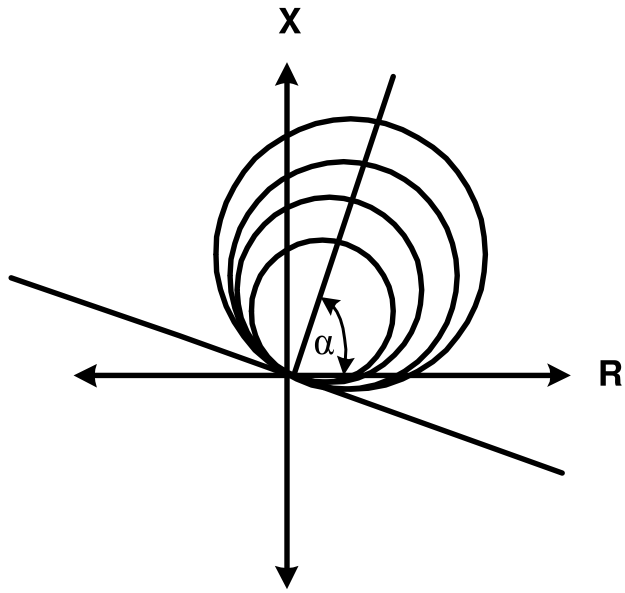



**Figure 25: Four Stages Mho Distance Relay**

## Quadrilateral Characteristics

Mho characteristics is good for phase-phase faults but it is not suitable for phase-earth fault and specially with high fault resistance and arcing resistance.

Quadrilateral characteristics with their availabilities to be increased only in one direction (R or X) is used to over come the problem of high resistance fault. For each stage of distance relay the characteristics can be extended only in R direction with fixed X setting. Figure (26) shows a four stage quadrilateral distance relay characteristics. For that relay zones 1, 2, and 3 are in the forward direction and zone 4 in the reverse direction.

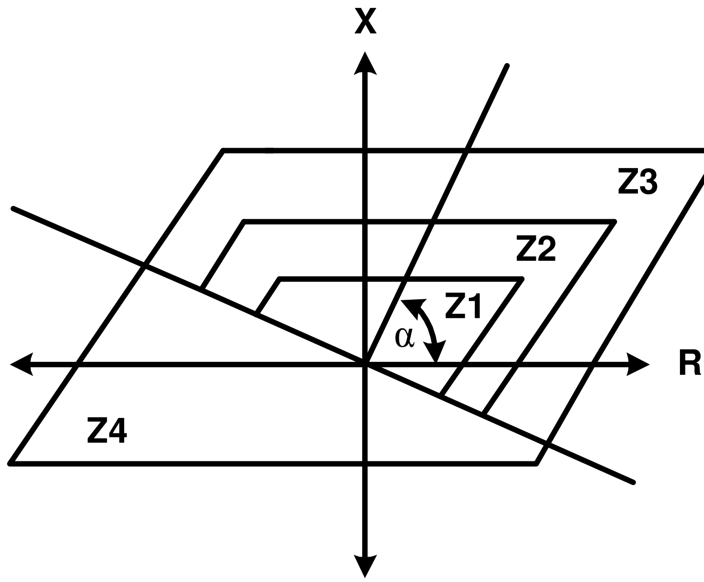



**Figure 26: Four Stages Quadrilateral Characteristics Distance Relay**

### Under Reach

A distance relays is said to under-reach when the impedance presented to it is greater than the apparent impedance to the fault. This may happen when two lines are connected in parallel and a faults occurs as shown in figure (27).

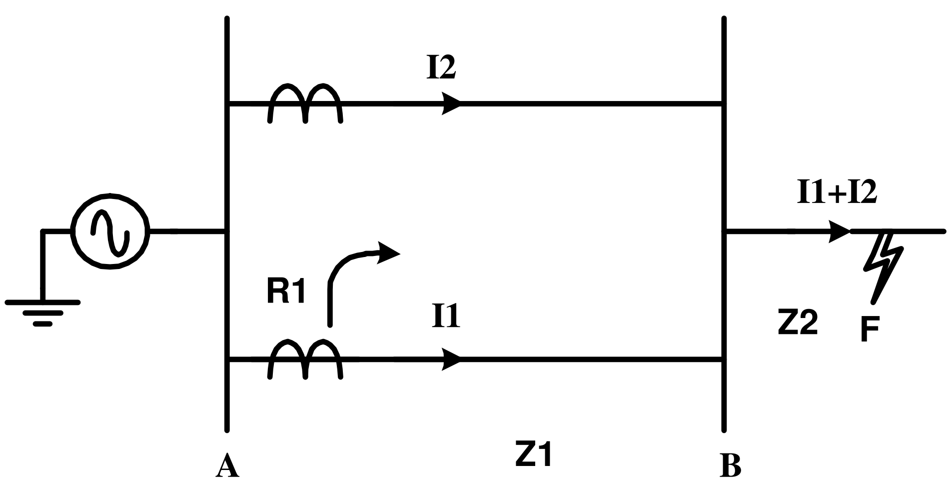



**Figure 27: Under Reach of Distance Relay**

For the fault F with respect to distance relay R1, The expected Values of current, impedance, and voltage are as follows (Assuming one line, no parallel lines).

- Current = $I_1$
- Impedance =$Z_1+Z_2$
- Volt (V) = $I_1(Z_1+Z_2)$

Actually, due to the $I_2$ feed

$$V = I_1(Z_1) + \overline{Z_2}\ (I_1+I_2)$$

Then, the effective reach of the distance relay is changed to be $Z_1+\overline{Z_2}$

To overcome this problem, and due to the fact that V, and $I_1$ are constants

$$I_1(Z_1+Z_2) = I_1(Z_1) + \overline{Z_2}\ (I_1+I_2)$$

Or

$$I_1 Z_2 = \overline{Z_2}\ (I_1+I_2)$$

Then the setting must be increased by a factor equal to $\left( \frac{I_1+I_2}{I_1} \right)$

So, the Setting to be installed on the relay must be equal to

$$Z_1+Z_2\left( \frac{I_1+I_2}{I_1} \right)$$

**Over Reach**

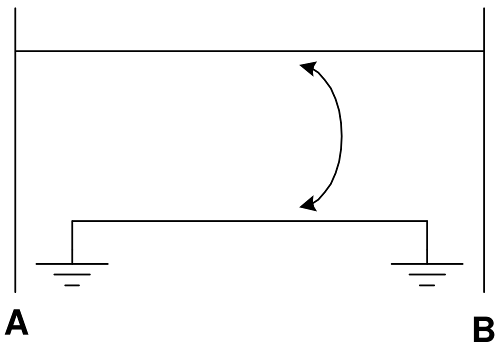



**Figure 28: Over Reach of Distance Relay**

A distance relay is said to be over reach when the impedance presented to the relay less than the apparent a impedance to the fault. Over reach will happen when two transmission lines are connected in parallel, and when one of them is disconnected and earthed from the two ends as shown in figure (28). Mutual coupling between line causes the relay for the line in service to over reach. To over come this problem. Setting impedance of phase-Earth relay must be reduced to nearly (0.65% to 80%) from its original setting.

**Ground Faults and Compensation Factor**

In phase to ground faults, the setting is increased by a factor of $k_0 * Z_1$ to be $Z_1(1+ k_0)$

$k_0 = (Z_0- Z_1 )/3Z_1$

Where:

$k_0$ = Compensation Factor For Ground Faults

$Z_0$ = Zero Sequence Impedance

$Z_1$ = Positive Sequence Impedance

**Distance Protection Schemes**

Here, some of the distance protection schemes are described. The system used is consists of Four substations (Station A, Station B, Station C, and Station D)

T_L_BC: Transmission Line between Station B and Station C starting at Station B and ends at Station C

T_L_CB : Transmission Line between Station C, and Station B starting at Station C and ends at Station B

T_L_BC_T1: First Stage of Distance Relay installed at station B to protect line BC with time delay T1

T_L_BC_T2: Second Stage of Distance Relay installed at station B to protect line BC with time delay T2

T_L_BC_T3: Third Stage of Distance Relay installed at station B to protect line BC with time delay T3

T_L_CB_T1: First Stage of Distance Relay installed at station C to protect line CB with time delay T1

T_L_CB_T2: Second Stage of Distance Relay installed at station C to protect line CB with time delay T2

T_L_CB_T3: Third Stage of Distance Relay installed at station C to protect line CB with time delay T3

The first example of distance schemes is shown in figure (29). It shows a transmission line BC, and this transmission line is protected by two distance relays (one at each end). Every relay consists of three stages in the forward direction with three different time delays T1, T2, and T3.

The second example figure (30) shows a fault nearly at the mid point of the transmission line BC. This fault is classified by both relays as a first stage fault ( fault at Zone1). The two circuit breakers associated with the two relays will be tripped by a time delay equal to T1 (almost T1 is zero).

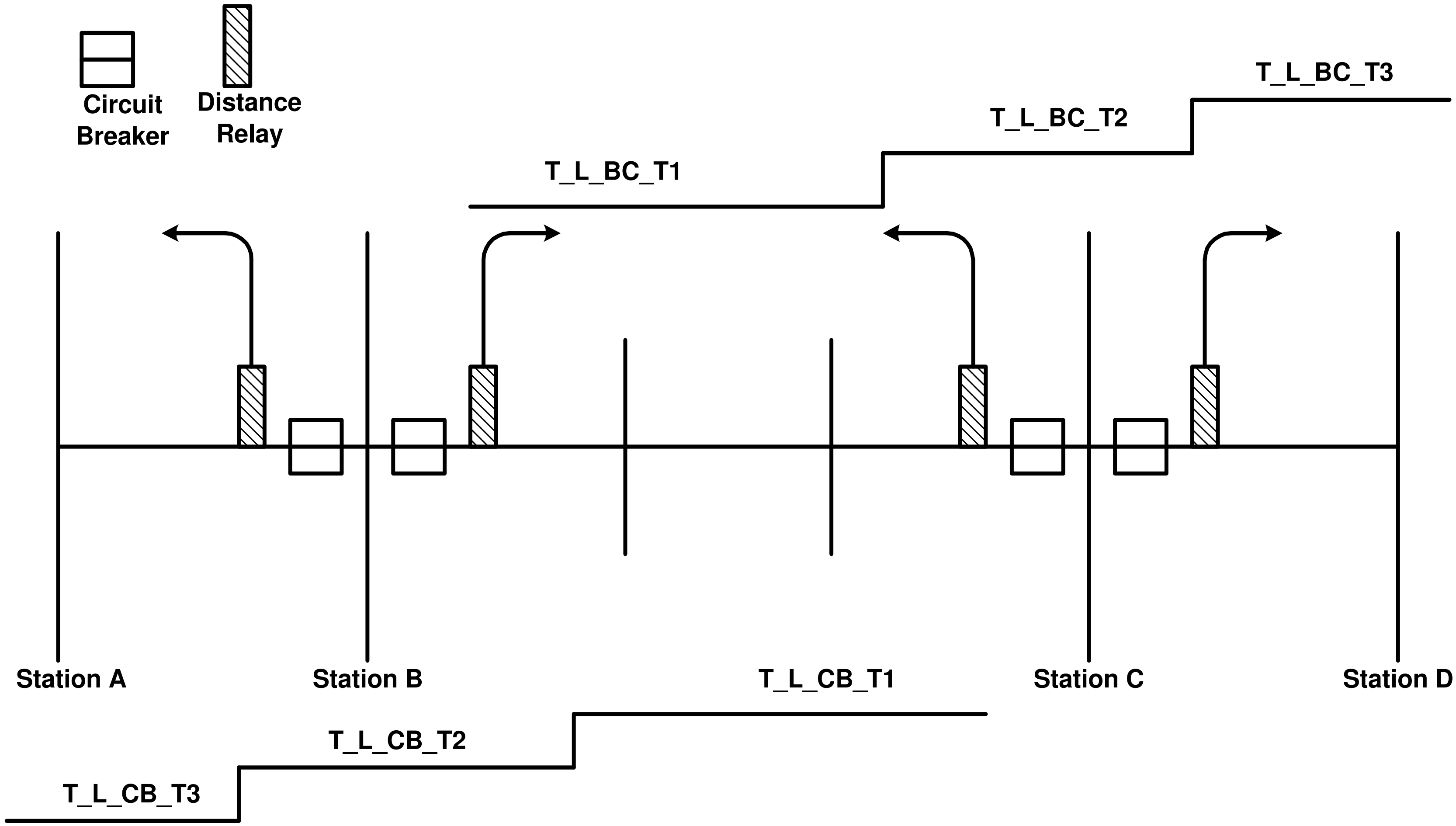
The third example figure (31) shows a fault near to substation C. This fault is classified by relay C as a first stage fault (fault at Zone1), and by relay B as a second stage fault (fault at Zone2). Relay C will operate by a time delay equal to T1, and the fault is still feed by station B which will operate by a time delay equal to T2 (almost T2 = 0.45 : 0.5 second).

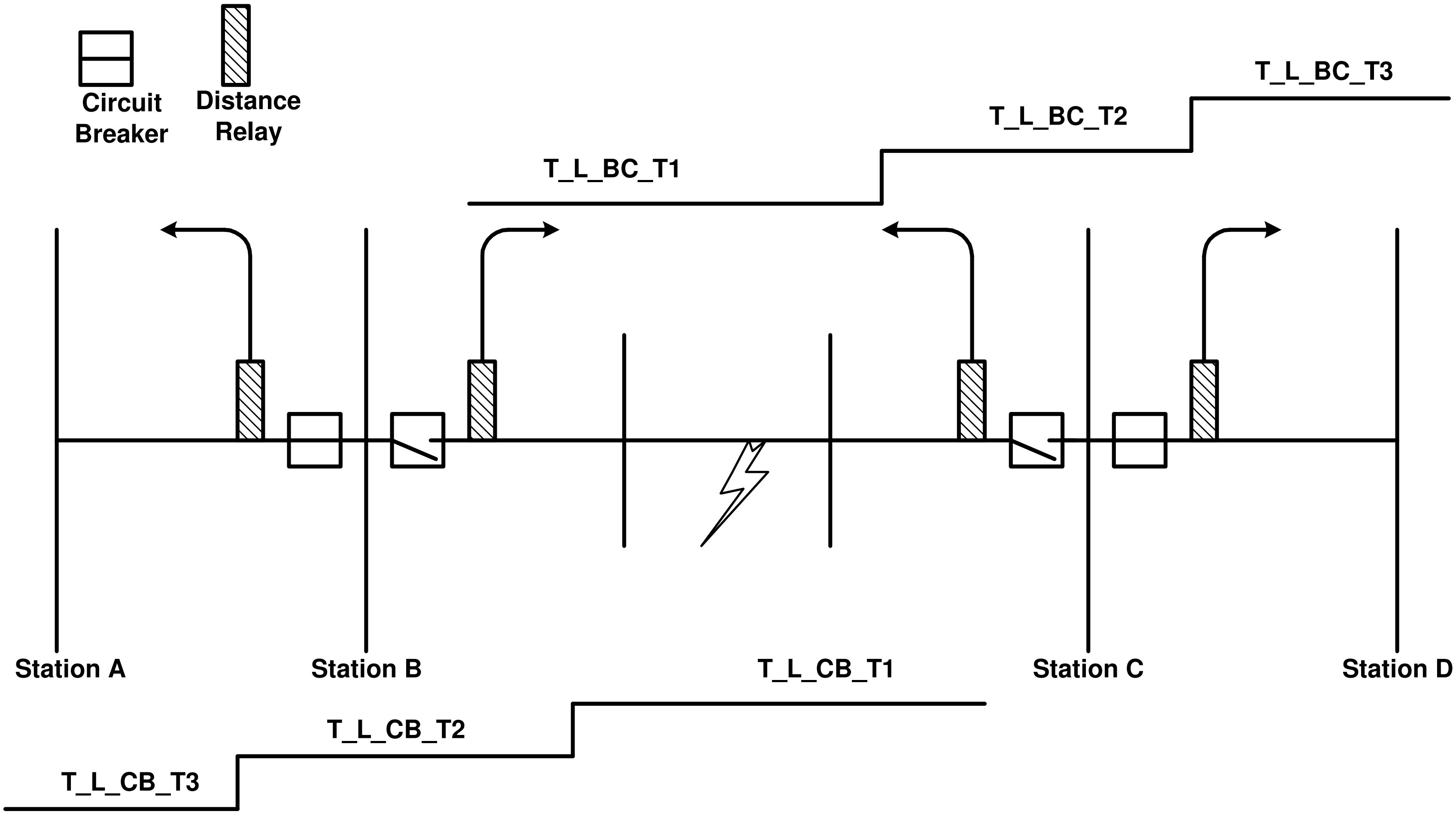
The fourth example figure (32) shows a fault like to the previous example but with applying the under reach scheme. In this example the circuit breaker at station C will be tripped with a time delay equal to T1. In this case, the operation of relay B depends on two condition

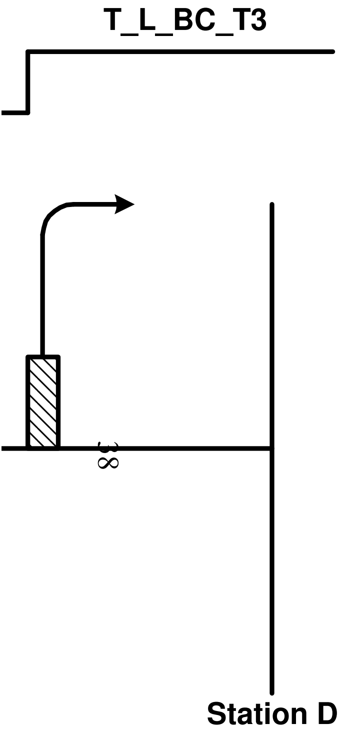
1- Starting Zone2 of relay B

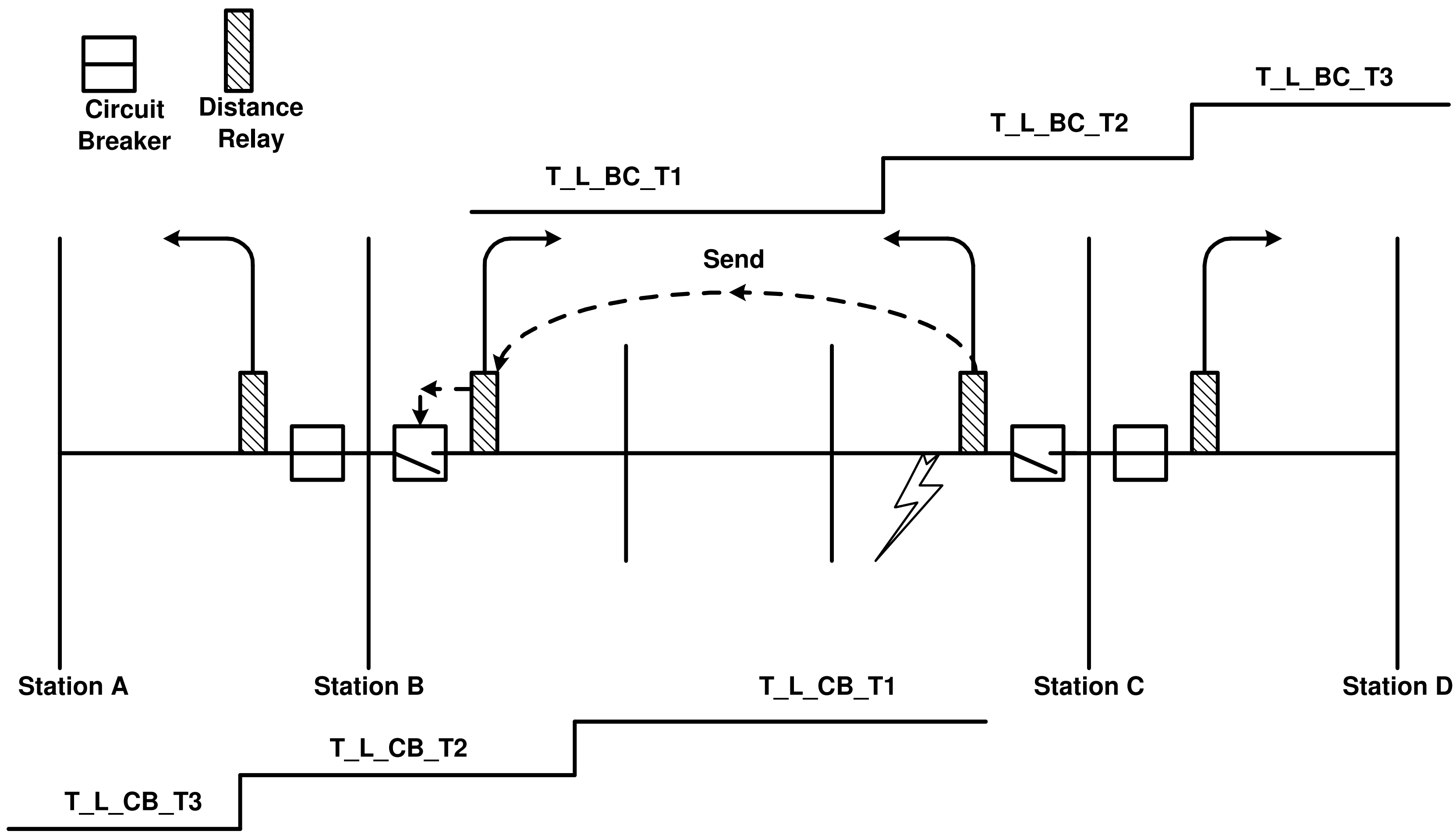
2- Receive signal from relay C ( due to first stage tripping )

The previous two condition will lead relay B to operate without the time delay T2.


Circuit Breaker
Distance Relay
T_L_BC_T3
T_L_BC_T2
T_L_BC_T1
Station A
Station B
T_L_CB_T1
Station C
Station D
T_L_CB_T2
T_L_CB_T3


Circuit
Breaker
Distance
Relay
T_L_BC_T3
T_L_BC_T2
T_L_BC_T1
Station A
Station B
T_L_CB_T1
Station C
Station D
T_L_CB_T2
T_L_CB_T3


T_L_BC_T3
38
Station D


Circuit Breaker
Distance Relay
T_L_BC_T3
T_L_BC_T2
T_L_BC_T1
Send
Station A
Station B
T_L_CB_T1
Station C
Station D
T_L_CB_T2
T_L_CB_T3

**Power Swing**

Some of the faults are transient and there is no need to operate the distance relays or to trip circuit breakers. These transients are classified as power swing as shown in figure (33). Some conditions must be verified to detect power swing which are listed below:

- No earth fault detection (absence of zero sequence current)
- No phase-phase fault (absence of negative sequence current)
- Change in impedance with time is three-phase and less than some setting value (ΔR, and ΔX).

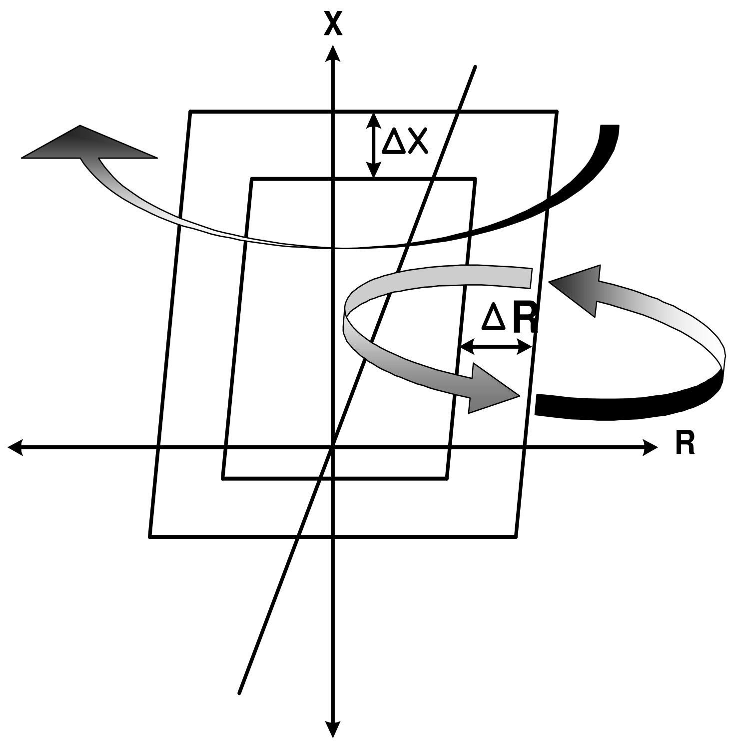



**Figure 33: Power Swing**

**Differential Relays**

Different relay is that relay which checks the different between the input and output currents for a power system current. The difference between the currents may be in magnitude or in phase angle or in both. For healthy operation, magnitude and angle differences must be zero. If there is a difference and that difference exceeds some value (setting valued, the relay will operate and associated circuit breaker will trip .

**Principles of differential relay**

Let us assume a simple example of a power transformer with transformation ratio 1:1 and (Y / Y) connection and the CT1 and CT2 have the same transformation ratio as shown in figure (35). The current flow in the primary and secondary sides of power transformer are identical, assuming ideal transformer. The secondary current $I_1$, and $I_2$ are equal in magnitude and opposite in direction. So, the net current in the differential coil is zero at load condition (without fault), and the relay will not operate .

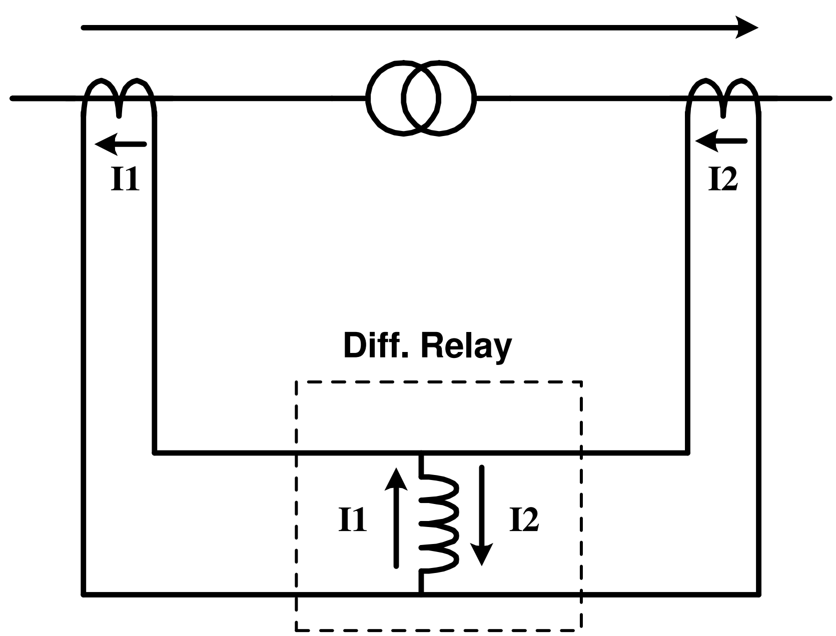



**Figure 35: Differential Relay at Healthy Transformer**

**External Fault Condition**

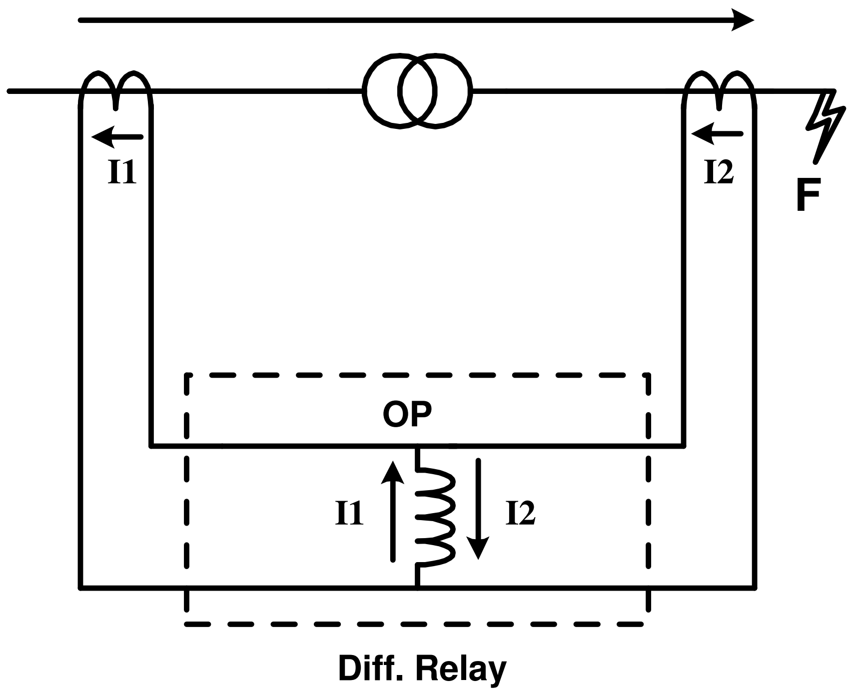



**Figure 36: Differential Relay at External Fault**

Assuming the previous power transformer with an external fault F as shown in figure (36). In this case the two currents $I_1$, and $I_2$ will increase to very high magnitudes values but there is no change in phase angle. So, the net current in the differential coil is still zero and the relay will not operate.

**Internal Fault Condition**

For an internal fault F as shown in figure (37). Here, there are two expected situation :

- There is another source to feed the fault so $I_{2P}$ has a nonzero value $I_{diff} = I_{1S} + I_{2S}$ which will be very high and sufficient to operate the diff relay.

- Redial system , $I_{2P} = 0$. So, $I_{diff} = I_{1S}$ and also the relay will operate and trip the circuit breaker.

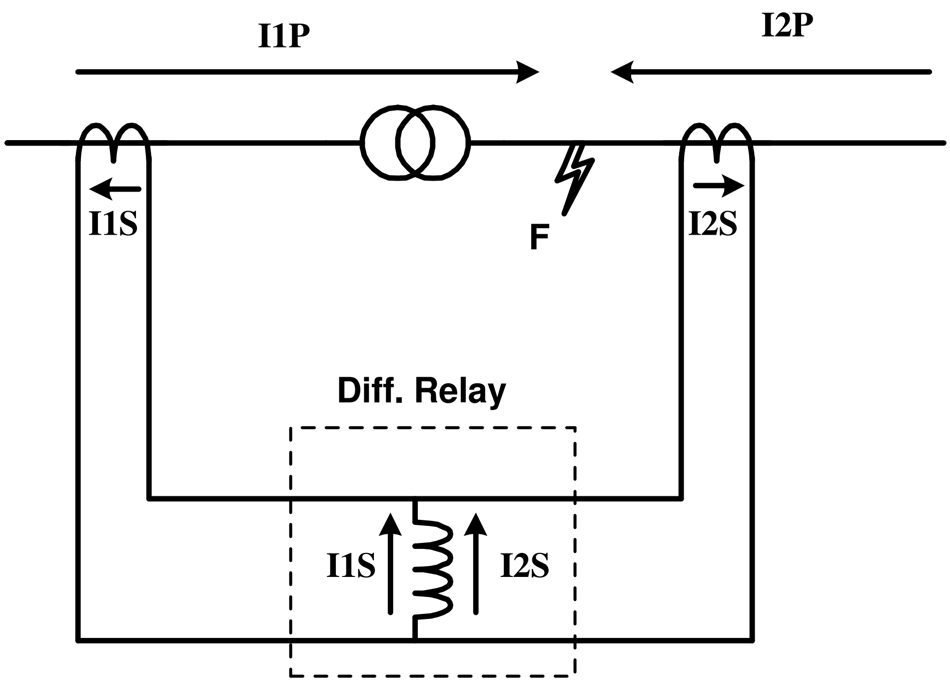



**Figure 37: Differential Relay at Internal Fault**

**Biased differential relay**

Large external fault may cause false operation of simple differential relay. To make the differential relay more stable to external faults and improve relay quality, its respectively to operation was increased by inserting restraining coils. Two restraining (Biasing) coils and one operating are used as shown in figure (38). Restraining coils will opposite the operation of operating coil. The relay will operate only when the operating force is higher than restraining force.

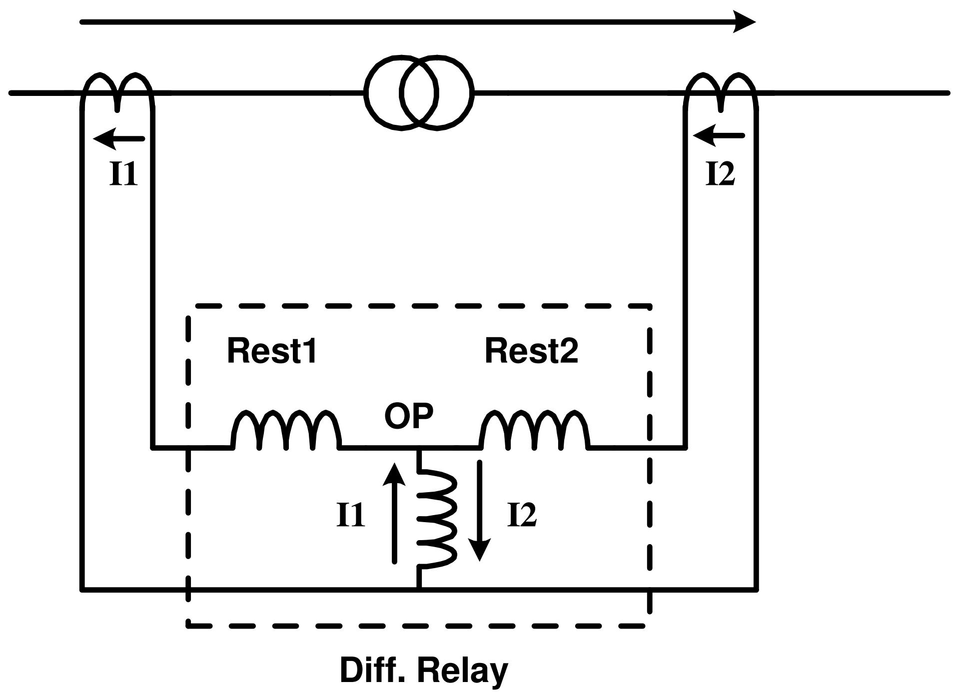



**Figure 38: Biased Differential Relay**

**Practical Example of Differential Relay**

The previous example assume 1:1 transformation ratio of power transformer, Y/Y connection , and equal current transformation ratio. Practically, all these may be changed. Assume a power transformer as shown in figure (39) with the following data:-

25 MVA 66/11 KV ΔY11

C.T.R. (66 KV Side) = 400/5

C.T.R. (11 KV Side) = 1500/5

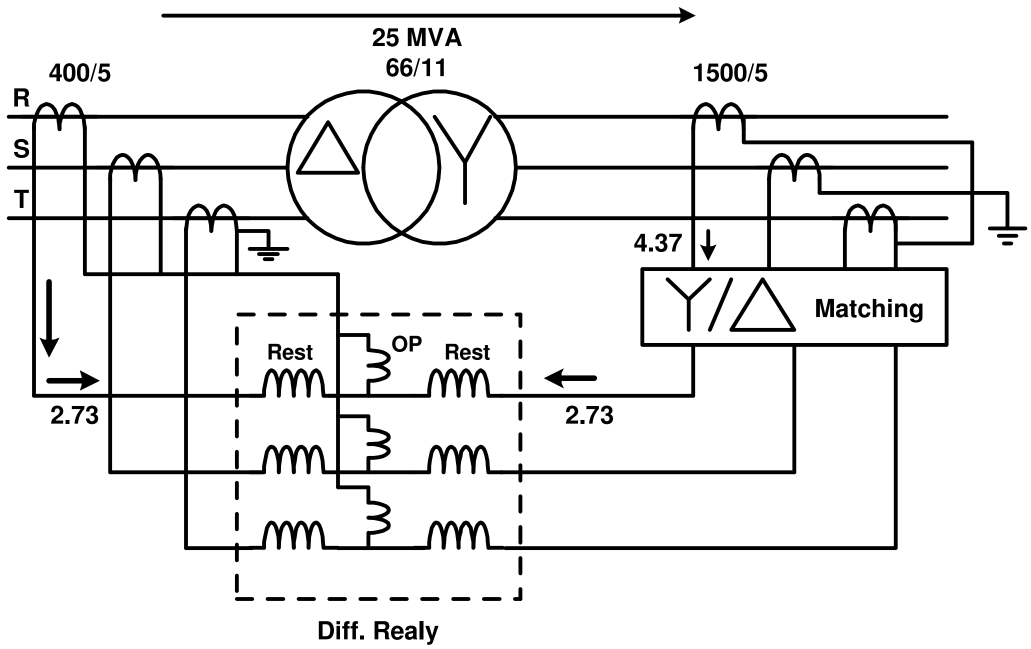



**Figure 39: Practical Example of Differential Relay**

For the ΔY transformer, There is a phase angle difference between primary and secondary equal to -30°. So, an aux current transformer (matching) is installed in the secondary circuit of 11 kV current transformer side to compensate the magnitude and phase.

$$P = \sqrt{3}\ V\ I$$

$$I_{66P} = \frac{25*10^6}{\sqrt{3}*66*10^3} = 218.69\ A$$

$$I_{66S} = \frac{I_{66P}}{(400/5)} = 2.73\ A$$

$$I_{11P} = \frac{25*10^6}{11*10^3*\sqrt{3}} = 1312.2$$

$$I_{11S} = \frac{I_{11P}}{(1500/5)} = 4.37$$ ( Input to differences matching circuit )

For equilibrium of differential relay:-

Current of 11 kV of differential relay must be equal to current of 66kv side of differential relay = 2.73

But, Input current of matching = $I_{11S}$ = 4.37

Out put current of matching (input relay to diff relay) must be equal to $I_{66S}$ = 2.73

<u>Note</u>: Matching connection must be Y / Δ to compensate the original angle of power transformer ( $I_{S\_Matching} = I_{Line} / \sqrt{3}$ )

$$\frac{I_{P\_Matching}}{I_{S\_Matching}} = \frac{4.37}{2.73/\sqrt{3}} = \frac{4.37}{1.579}$$

$$\frac{N_{P\_Matching}}{N_{S\_Matching}} = \frac{1.579}{4.37} \cong 0.36$$

**Tripping Characteristics and Harmonic Restrain**

Differential current must exceed a pre set value to trip the associated circuit breaker(s). this value is the min value to operate the relay . In this case the expected tripping characteristic is as shown in figure (40)

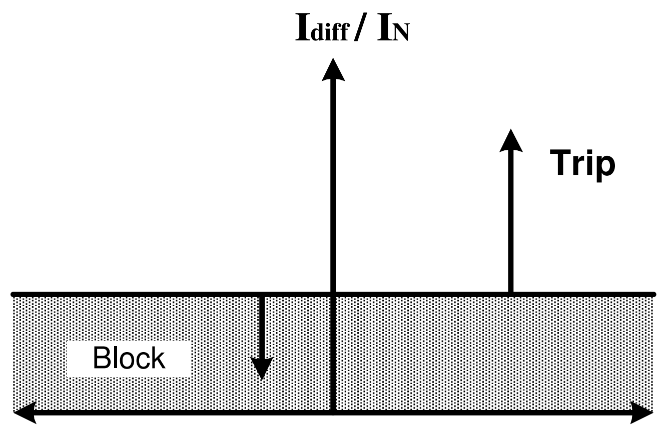



**Figure 40 : Tripping Characteristics of Simple Differential Relay**

If there is a ratio mismatch in current transformers ratio, In this case there will be a small differential current in the load condition. This value is not sufficient to operate the differential relay but in the case of external fault condition this value may exceed the setting value and this leads to false operation of the relay .

To prevent the false operation of directional relays due to external false , stabilizing current is used to resist the operation of the directional relay. figure (41) shows a more stable characteristics.

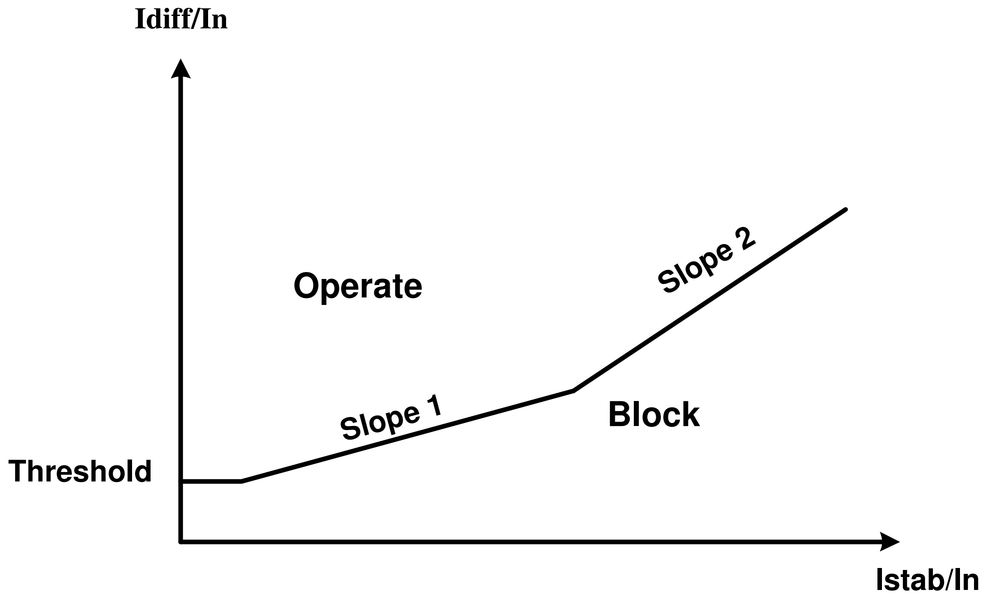



**Figure 41 : Tripping Characteristics of Biased Differential Relay with Two Stages (Two Slops)**

This characteristics consists of two regions with two slaps .In this characteristics when , the stabilizing current increases , the differential current needed for operation will be very high .

Note :

$$I_{diff} = \left| I_1 + I_2 \right|$$

$$I_{stab} = \left| I_1 \right| + \left| I_2 \right|$$

**Differential Relays And Inrush Current**

When a power transformer is re-energized after along time of de-energizing and when the primary side circuit breaker is switched on, Inrush current will be only in the primary side of power transformer. This current may lead to relay operation and circuit breaker tripping .In fact, the inrush current is a current with a frequency equal to twice the normal frequency (second harmonic). This current is separated from the fundamental current and used to resist the operation of the differential relay. figure (42) shows a second harmonic blocking diagram .

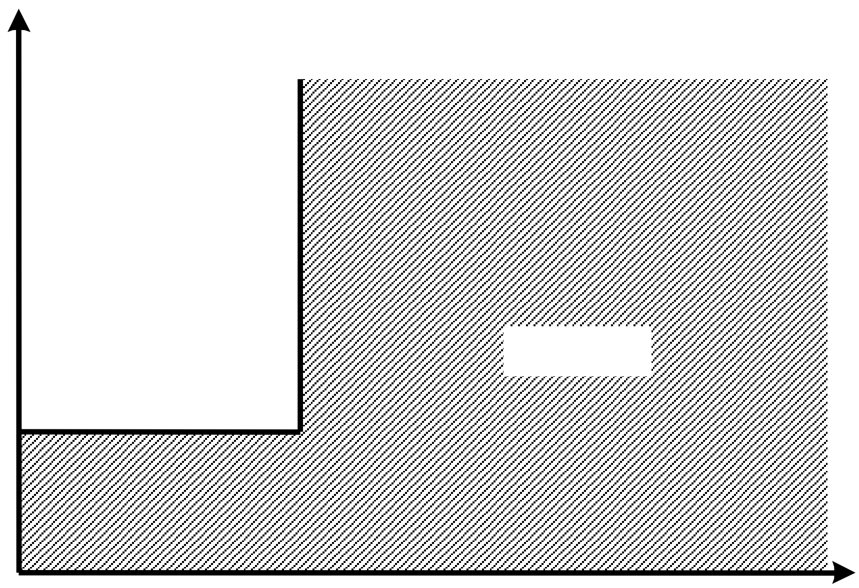


**Figure 42 : Tripping and Blocking Characteristics due to Second Harmonics**

$I_N$= Rated current of power transformer.

$I_{FN}$=Rated frequency current.

$I_{100}$=Second harmonic current.

**Restricted Earth Fault**

Restricted earth fault relay is that relay which can be defined as half differential relay. Figure (43) Shows a connection diagram for the restricted earth fault relay.

This definition is due to its connection. This is relay compare the current flow in :

1- The neutral path of current transformer connected on the star side of power transformer:

2- Current flow in the current transformer connected on the star point of the power transformer.

- For internal faults ( between the two current transformers), There is differential current which is transformed to volt by a very high shunt resister (metrosil) and this value of volt is sufficient for operation of the relay.

- For external faults (as example: outgoing feeders faults), the differential current in this case is zero and the relay will not operate, and no tripping for circuit breakers will occur.

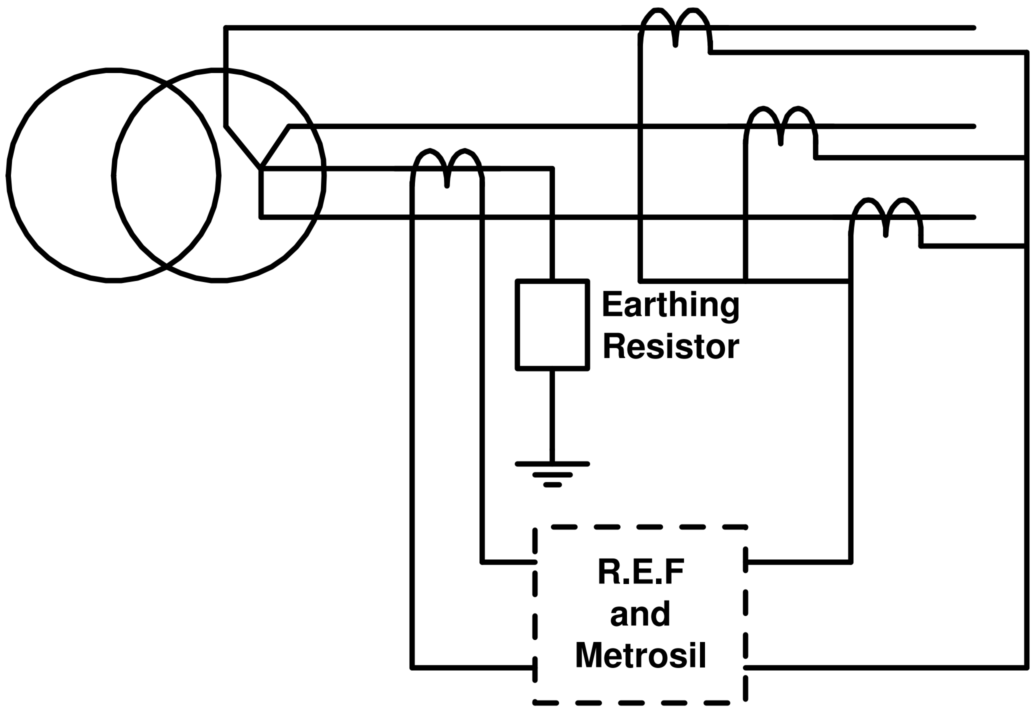



**Figure 43: Restricted Earth Fault Relay**

## Mechanical Protection

There are several mechanical protection relays installed on the power transformer, Almost the operation of these relays is instantaneously (no time delay). As a target of this study, buchholz relay, winding temperature indicator, oil temperature indicator, and pressure relief are explained by their mechanical operation, and electrical circuit needed for alarm and tripping circuits.

## Buchholz Relays

A buchholz relay is a protection device for monitoring the gas and oil movements in oil immersed transformers. It is used on practically all power transformers with the exception of small distribution sizes. In practice it has proved to be the only protective device that can clear certain types of faults. The buchholz relay relies on the principle that during fault conditions, gas is generated inside the transformer tank from the insulating oil. An example of a buchholz relay device is shown in figure (44).

**Figure 44: Buchholz Relay**

The buchholz relay is sited in the pipe work between the transformer and its conservator as illustrated in figure (45), and is filled with oil during normal transformer operation.

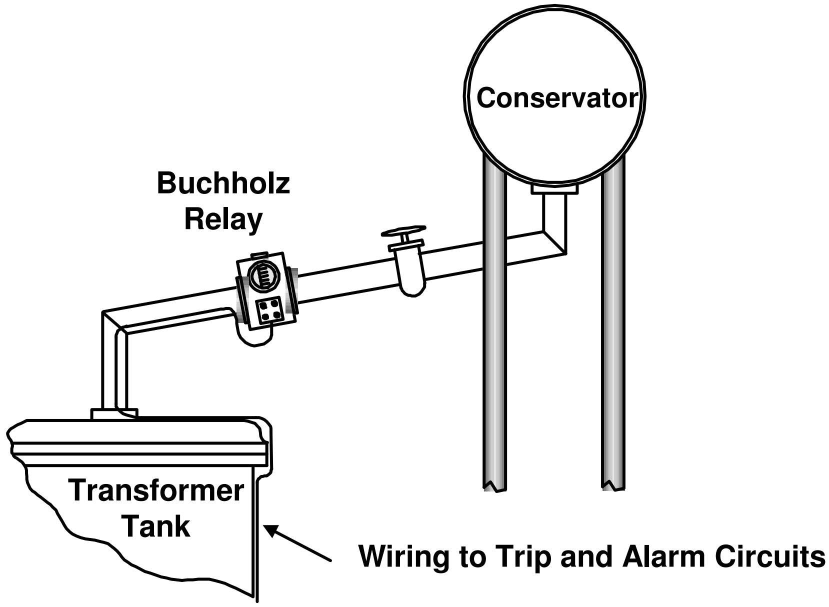



**Figure 45: Location of the buchholz relay on the transformer**

The internal mechanism of a buchholz relay mainly comprises two floats and is illustrated in figure (46). During normal operation, the relay is completely filled with oil keeping the floats in their top limit or rest position. The contact mechanisms in the relays respond to:

- Slight faults causing a slow evolution of gas in the transformer (e.g. overheating)
- Serious faults creating an immediate surge of oil (e.g. short-circuits etc.)
- Oil leakage

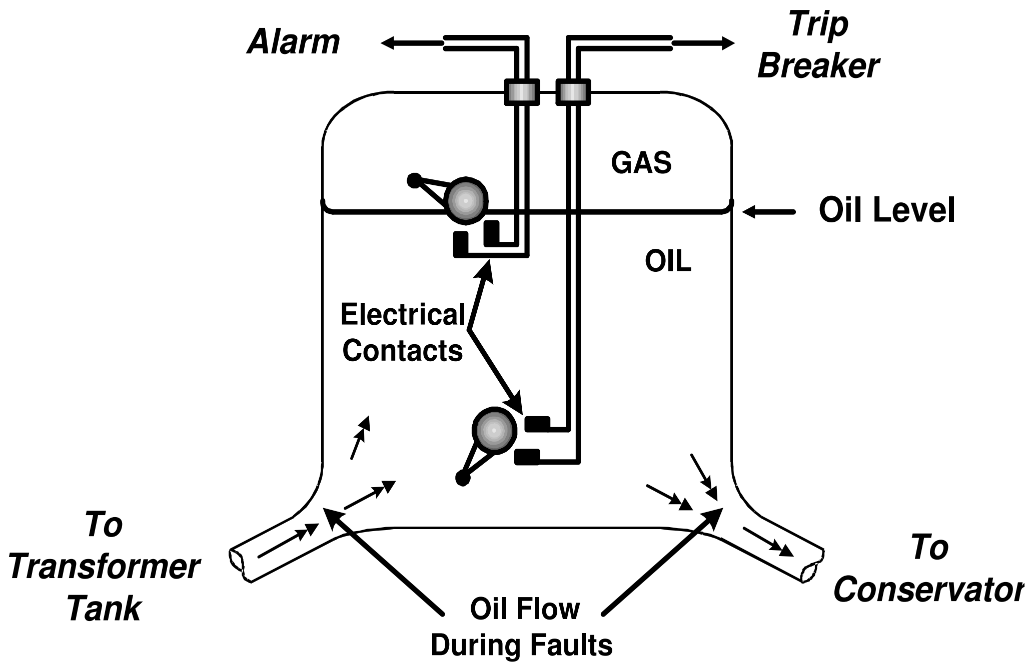



**Figure 46: Schematic Diagram of a Buchholz Relay Arrangement**

### Buchholz Relay Operation

When a slight fault occurs in the transformer, the small bubbles of gas which pass upwards towards the oil conservator tank are trapped in the relay housing this causing its oil level to fall. As a result, the upper float drops and activates the external alarm switch. If gas continues to be generated then the second float operates the second switch that is normally used to isolate (trip) the transformer.

### Winding Temperature Indicator

By making a "Thermal Image" of the winding the Winding Temperature Indicator, simulates the winding temperature. The temperature of the winding depends on the transformer load (i.e. the current through the winding) and the temperature of the cooling medium (the oil). These two parameters are measured and made to interact in the instrument. The oil temperature is measured as usual with a bulb in a pocket. The measuring system also has a specially designed heating element, to measure the transformer load. This heating element is a thermal model of the winding. The heating element is connected to the current transformer (CT) via a Matching Resistance or a Matching Unit, to allow setting the correct winding temperature gradient.

**Figure 47: Winding Temperature Indicator**

The winding temperature indicator shown in figure (47) is consists of four contacts which are normally open and closes in series according to pre set closing value(temperature). These contacts can be assigned as follows:-

1- The first contact is used for automatic operation of first fan group
2- The second contact is used for automatic operation of second fan group, this value is almost higher than the

first contact setting

3- If the cooling fans are not sufficient to retain the transformer temperature to its normal value, the third contact is applied to feed alarm circuit.

4- As a last step, the fourth contact is applied for tripping to prevent the transformer from high temperatures.

Note: These values can be chosen as (55,65,80,90) respectively.

**Oil Temperature Indicator**

Oil temperature indicator is similar to winding temperature indicator except that it depends only on the temperature transferred by the bulb (no current transformer is used). This consists only of two contacts. These contacts are similar to the third and the fourth contacts of the winding temperature indicator but with pre set values less than winding temperature indicator by approximately 5 degrees.

Note: These values can be chosen as (75,85) respectively.

**Pressure relief**

A pressure relief valve is a device designed to protect a power transformers during overpressure event. An overpressure event refers to any condition which could cause pressure in the transformer to increase beyond the specified design pressure.

During internal faults of a power transformer, there will be an increase of temperature associated with impurities in oil and some increase in pressure. This pressure is sufficient to damage the transformer. The pressure relief device is applied to prevent the transformer from this dangerous

The pressure relief device consists of a spring which normally is uncompressed an when the pressure increased in the transformer, the spring is get compressed and give a path of gases to go out of the transformer. Compressing the spring may close an electrical contact, and this contact will give trip to circuit breakers associated with alarm. Figure (48) shows the pressure relief device in the normal condition (before the fault occurrence), while figure (49) shows the fault condition at which the compressed gases are get out from the transformer.

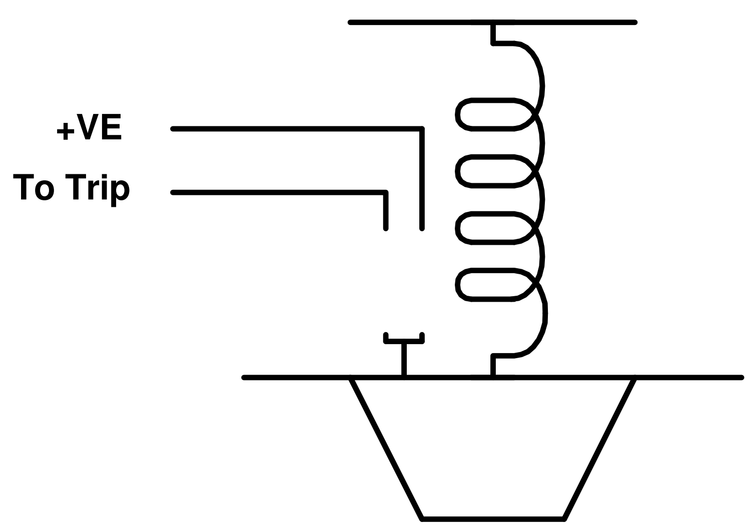



**Figure 48: Pressure Relief Before Fault Occurrence**

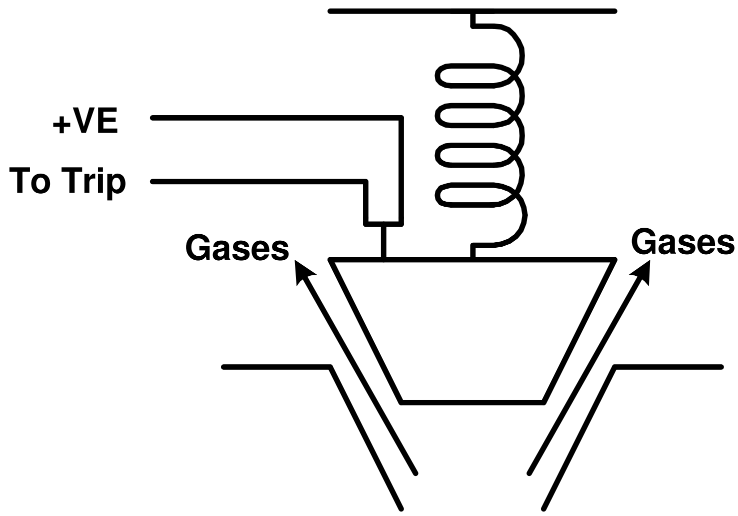



**Figure 49: Pressure Relief Durring Fault**

## Bus Bar Protection

Bus bar protection relays depends mainly on khirchoff's current low, which states that the sum of current inter to any node must be equal to the sum of the currents leaving it.

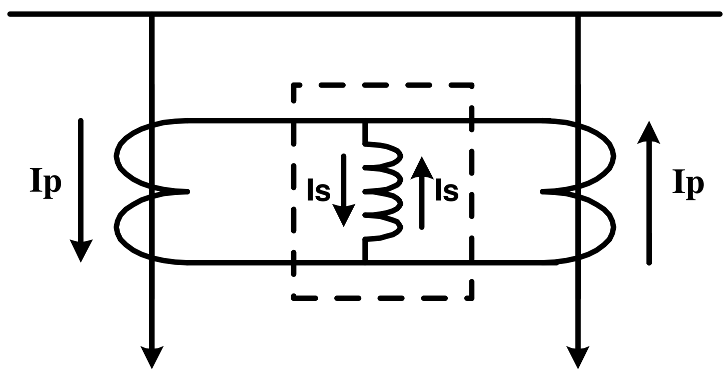



**Figure 50: Simple Bus Bar Protection Relay with Two Equipments**

Figure (50) shows current direction of two equipments connected to the same bus bar in the normal condition (without faults), In this example one of the equipments acts as a source to the bus and the other is a load and they have equal current magnitude and opposite in direction. In this case, the differential current through the differential relay is zero and the relay is stable and dose not operate.

**External Faults**

This case is similar to the pervious healthy case in that the two current will increase to very high values but still equal in magnitude and opposite in direction and the relay will not operate due to the zero current in the differential relay coil as shown in figure (51).

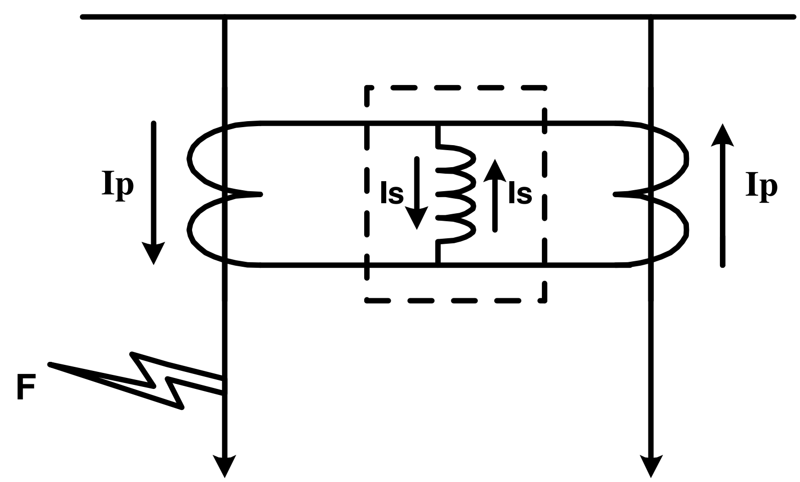



Figure **51: Bus Bar Protection Relay at External Fault**

**Internal Fault**

In the internal fault case shown in figure (52), There are two expected situation:

1- Non redial system, then $I_{2P}$ has a non zero value. In this case the differential current is equal to ($i_{1S}$+$i_{2S}$) and this value is sufficient to operate the relay and trip all the equipments connected.

2- Redial system, then $I_{2P}$= 0.0

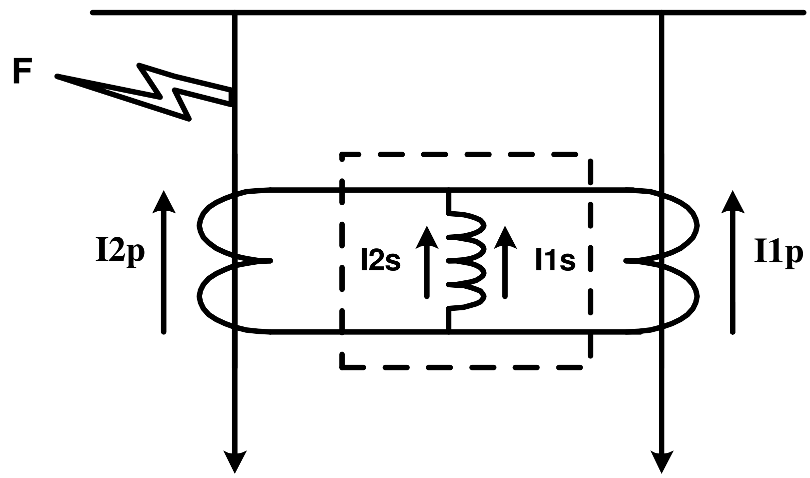



**Figure 52: Bus Bar Protection Relay at Internal Fault**

In this case the differential current is equal to $i_{1S}$ and this value is also sufficient to operate the relay and trip all equipments connected to the bus bar.

Note:- All equipment's current transformers must have the same transformer ratio, if different ratios are exist Aux current transformers (matching current transformers) must be used to compensate these difference. These matching may be internally in the relay (Taps) or externally by separate matching current transformers.

There are different types of bus differential protection relays. Low impedance and high impedance relays may be considered there is some difference between them, but it is not considered in this study.

**Practical Example Of Bus Bar Protection**

Assume the following system shown in figure (53) which consists of two bus bars and four equipments two on each bus and a bus coupler between the two buses.

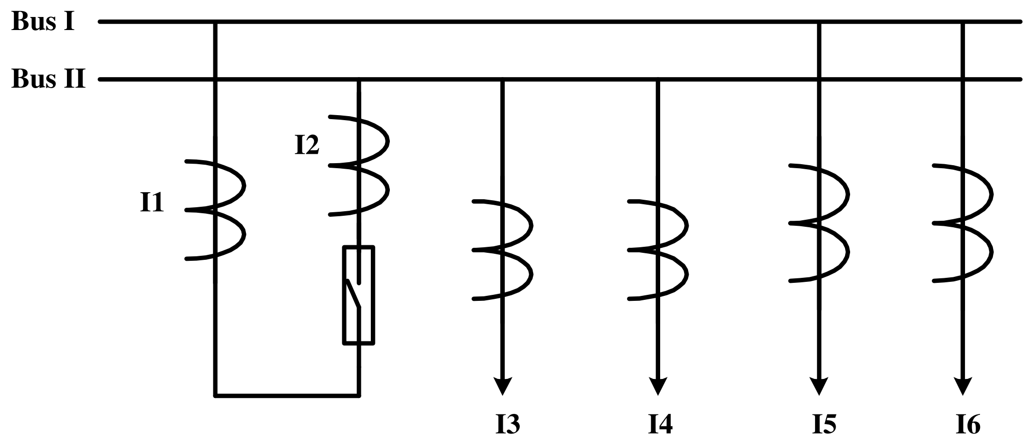



**Figure 53: Simple Two Bus Bar System**

- Each equipment contains one current transformer. Connected on it except the bus coupler which contains two current transformers one on each side of the circuit breaker. For equilibrium, each bus is stable in load condition (without faults).

There are two cases:-

1- Case bus coupler is disconnected:-

$I_3 + I_4 = 0$

$I_5 + I_6 = 0$

2- Case2 bus coupler is connected

$I_1 + I_3 + I_4 = 0$

$I_2 + I_5 + I_6 = 0$

Note: CT1 (of the coupler) is connected between circuit breaker and bus1 and for equilibrium it is added to CT3, and Ct4 which are connected to bus2, and CT2 (of the coupler) is connected between circuit breaker and bus2 and for equilibrium it is connected to CT5, CT6 which are connected to bus1. The advantage of these connections is to protect the zone between circuit breaker and current transformer of the coupler. If one CT is installed for the coupler, the zone between circuit breaker and current transformer is not protected by bus protection.

## Tripping Circuit of Bus Bar Protection

A simple description of the tripping circuit and a connection diagram of it is shown in figure (54). C3, and C4 are n.o. contacts. contact from bus isolator2 of equipment's 3, and 4 respectively, connected on bus 2 so contacts C3, C4 are closed and ready to transfer trip to trip coils of associated circuit breakers if differential coil is operated by differential current. The tripping process is executed through Aux contacts of isolators.

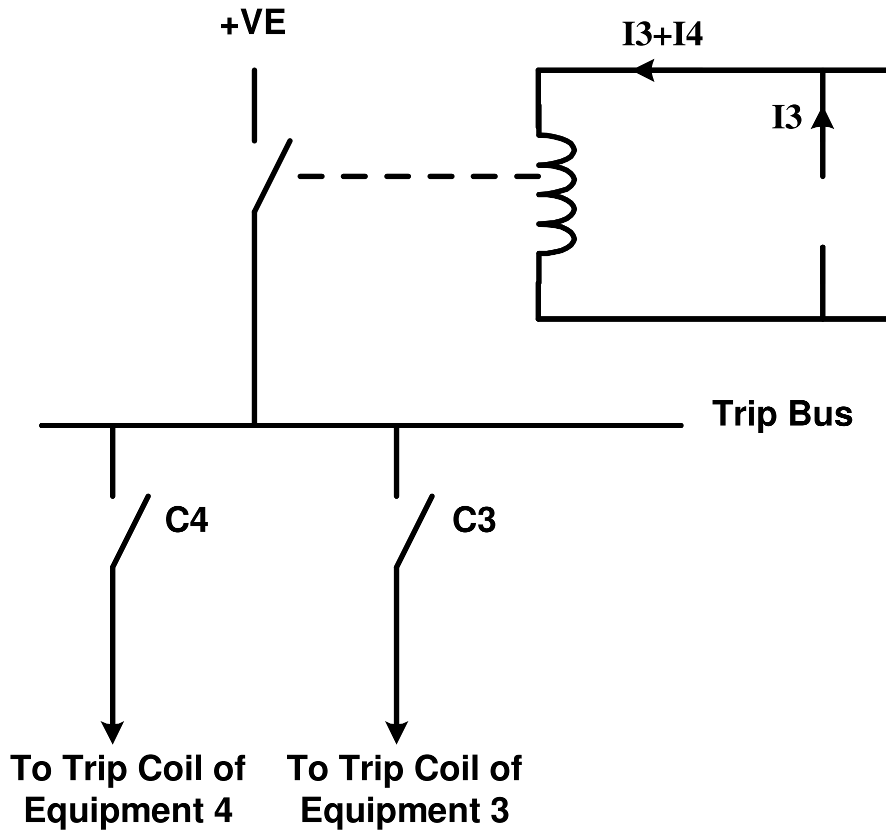



**Figure 54: Tripping Circuit of Bus Bar Protection**

At fault $I_3+I_4 \neq 0$, so the differential coil will operate and transfer a trip signal to a trip bus and so to trip coils of equipments connected to the same bus.

A similar circuit for bus1 (equipment 5,and 6) is exist .

Note:- The previous examples assumes that the coupler is not connected . If the coupler is connected before fault occurrence, the circuit breaker of it is disconnected at the beginning of the fault to isolate bus1 From Bus2 and then identify which bus from1 and 2 is faulted and then trip all equipment's connected to it and leave the healthy bus as it is.

**Breaker Failure**

Breaker failure relays are called back-up protection devices are applied as back-up protection relays for the main relays. As example Breaker failure relay is used as a back up device for differential relay of a power Transformer and also for distance relay of a Transmission line .

**Why Breaker Failure**

In the fault condition of any equipment it is expected that the circuit breaker of this equipment will be tripped by main protection relays of such equipment if there is a failure in the tripping circuit of the circuit breaker or in the circuit breaker it self . in this case the circuit breaker will not tripped and so, to isolate this fault ,the bus bar at which this equipment is connected must by completely isolated by tripping all the equipment connected to it by a delayed time .then , the only connected equipment to this bus bar is the faulted one. In this case , the faulted equipment has no current passing through it so , it is can be disconnected manly by isolates.

### How Breaker Failure Operate

There are three conditions must be satisfied For operation of breaker failure relay which are

- Tripping signal from any main protection relay of the faulted equipment is exist.
- Circuit breaker of the faulted equipment is still connect (n.o. auxiliary contact from circuit breaker is used).
- There is current passing through this equipment even if it is value is very small.

Although one of the second and third condition is sufficient for healthy operation of breaker failure relay, it is preferable to use both for more security. Figure (55) shows wiring diagram of breaker failure circuit. Tripping circuit of breaker failure relay is similar to tripping circuit of bus bar protection relay. In general breaker failure relay may use the same tripping circuit of bus bar protection relay.

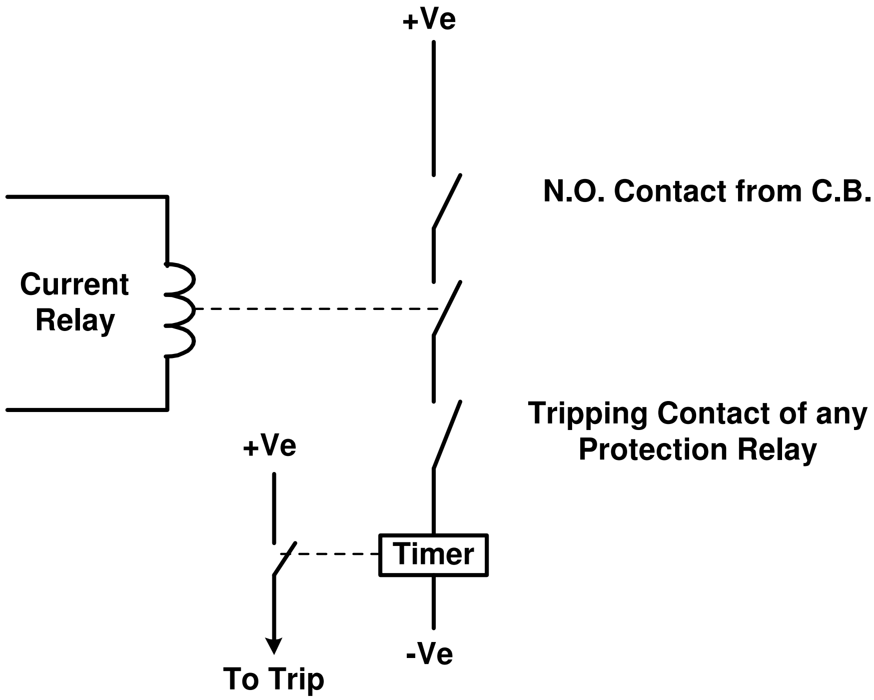



**Figure 55:  Wiring Diagram Of Breaker Failure Circuit**

## CONTROL AND INTERLOCKING

The word control here means the process of switching on and switching off of an equipment (circuit breaker or an isolator). The interlocking are the conditions which must be satisfied to complete the control process, and this can be classified into three main items as follows:-

1. Local/ Remote Switch

This switch must be on the right position to complete the switching on or switching off process. This position must be associated with the location of switching process, location may be control room, marshalling box , or the equipment itself

2. Internal lock

This means the conditions inside the equipment itself, and for example for a circuit breaker these conditions can be listed as follows:

   a. Aux contacts of the circuit breaker
   b. Limit switch of the spring
   c. Low pressure of Sf6 gas

3. External lock

This interlock is associated with another equipments. As example of this type, the isolator of an equipment must be connected before its circuit breaker and inversely, the circuit breaker must be switched off before the isolator.

Some of the previous interlocking are graphed and explained, and the symbols are listed hereunder.

| | |
|---|---|
| M | Motor |
| Y1 | ON Coil |
| Y2 | OFF Coil |
| K1 | Antipumping Relay |
| K2 | Auxiliary Relay to block ON and OFF processes if the Pressure is not sufficient |
| PS | Pressure Switch (SF6) |
| S1 | Auxiliary Switches from Circuit Breaker |
| S2 | Limit Switch from the Spring |

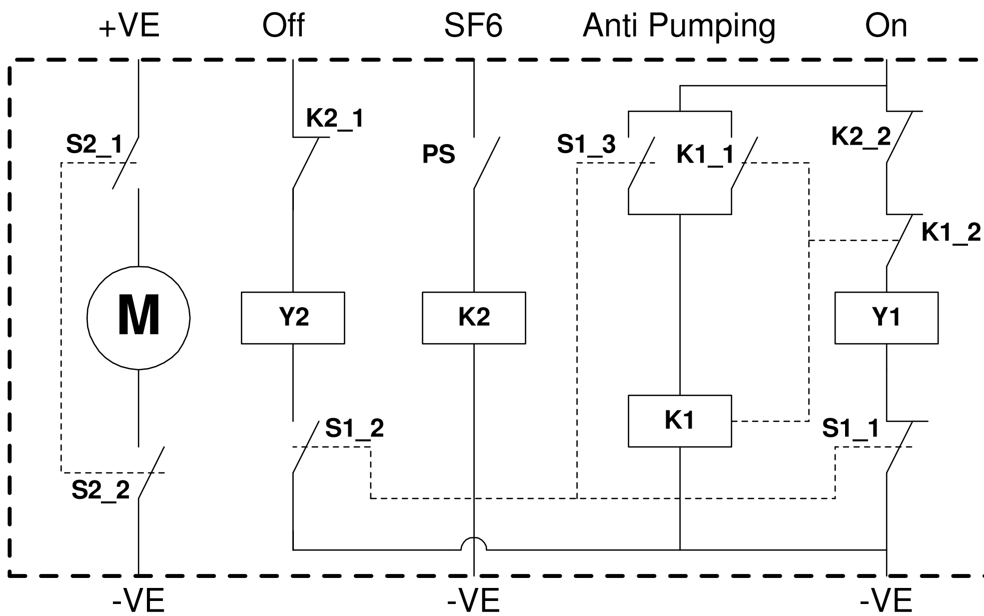



**Figure 56: Original Situation of Circuit Breaker**

- Circuit Breaker OFF
- DC ON
- Spring Charged (S2 Opened)
- Gas Pressure Sufficient for ON/OFF operations (PS is Opened)
- Circuit Breaker ready for ON

There are be five cases will be studied with different conditions of spring, pressure of SF6 gas, and circuit breaker states(on/off).

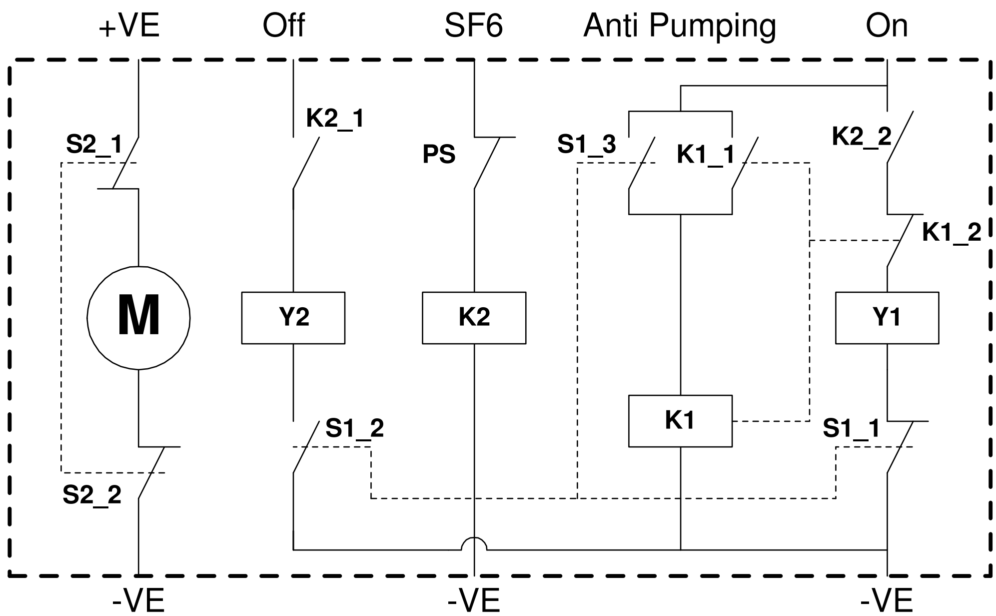



**Figure 57: Case1(Spring Uncharged and Gas Pressure Insufficient)**

- Circuit Breaker OFF
    1- S1_1 Closed
    2- S1_2 Opened
    3- S1_3 Opened
- DC ON
- Spring Uncharged
    1- S2_1 Closed
    2- S2_2 Closed
- Gas Pressure Insufficient for ON/OFF operations
    1- PS Closed
    2- K2 Energized
- Circuit Breaker is not ready for ON

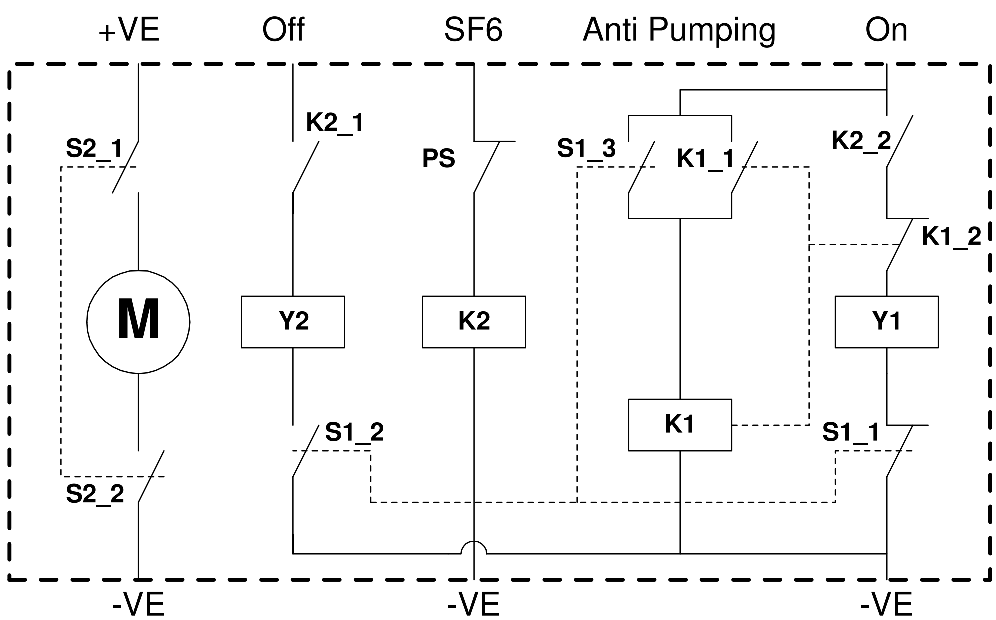



**Figure 58: Case2 (Spring Charged and Gas Pressure Insufficient)**

- Circuit Breaker OFF
  1- S1_1 Closed
  2- S1_2 Opened
  3- S1_3 Opened
- DC ON
- Spring Charged
  1- S2_1 Opened
  2- S2_2 Opened
- Gas Pressure Insufficient for ON/OFF operations
  1- PS Closed
  2- K2 Energized
- Circuit Breaker is not ready for ON

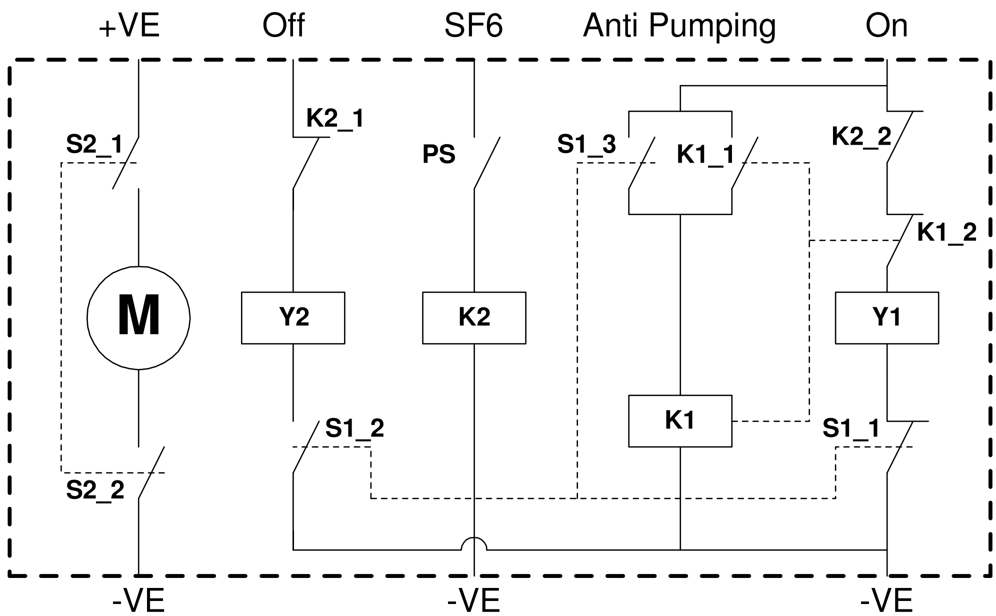



**Figure 59: Case3(Spring Charged and Gas Pressure Sufficient)**

- Circuit Breaker OFF
    1- S1_1 Closed
    2- S1_2 Opened
    3- S1_3 Opened
- DC ON
- Spring Charged
    1- S2_1 Opened
    2- S2_2 Opened
- Gas Pressure Sufficient for ON/OFF operations
    1- PS Opened
    2- K2 De-energized
- Circuit Breaker is ready for ON

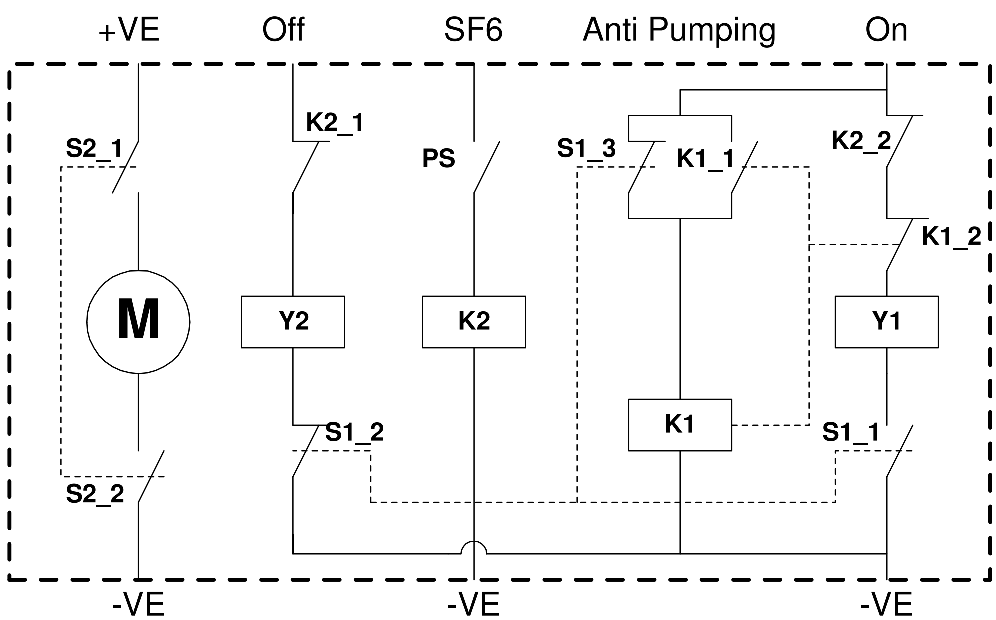



**Figure 60: Case4 (Circuit Breaker ON)**

- Circuit Breaker ON
  1- S1_1 Opened
  2- S1_2 Closed
  3- S1_3 Closed
- DC ON
- Spring Charged
  1- S2_1 Opened
  2- S2_2 Opened
- Gas Pressure Sufficient for ON/OFF operations
  1- PS Opened
  2- K2 De-energized

Circuit Breaker is ready for OFF

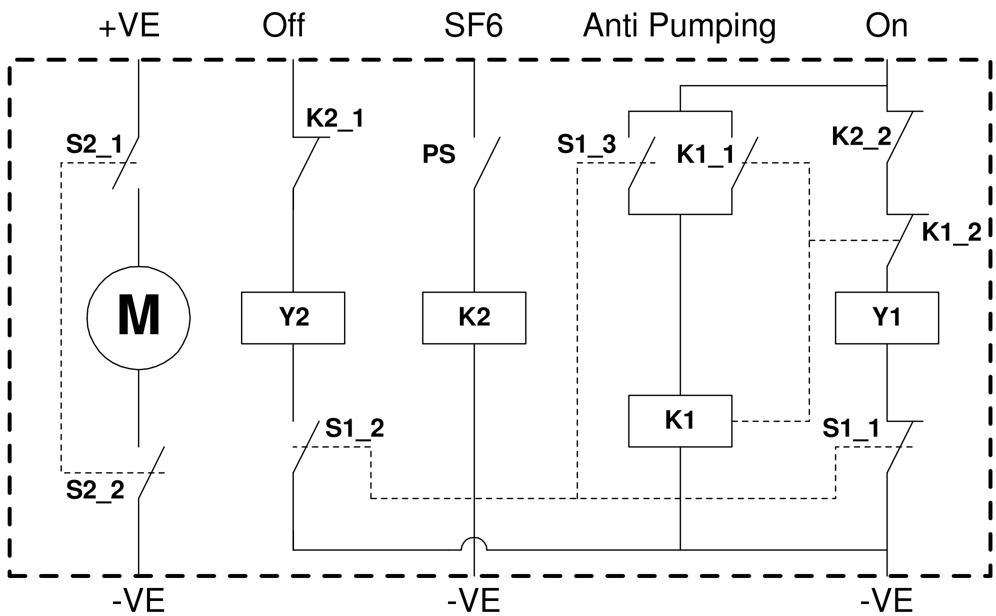



**Figure 61: Case5 (Circuit Breaker OFF)**

- Circuit Breaker OFF
  1- S1_1 Closed
  2- S1_2 Opened
  3- S1_3 Opened
- DC ON
- Spring Charged
  1- S2_1 Opened
  2- S2_2 Opened
- Gas Pressure Sufficient for ON/OFF operations
  1- PS Opened
  2- K2 De-energized

Circuit Breaker is ready for ON Again

Anti-Pumping

When the circuit breaker is closed, the auxiliary contact S1_1 is changed from the closed to the open position to prevent the ON coil from damage if the pulse is still exist after the circuit breaker state is changed to the ON state.

If We try to close the circuit breaker and there was a fault still exist on the equipment (outgoing feeder as example), the following stages explained what will happen:

- The state of the circuit breaker is changed from the off position to the on position, and S1_1 is changed from the closed to the open position
- Due to fault, the circuit will tripped by protection relays.
- If the ON pulse is still exist( due to error ON bush button or any other reason), the circuit breaker will be closed
- These stages will be repeated, and the circuit breaker may be get damaged due to the repeating of ON/OFF operations.

To prevent the circuit breaker from this dangerous, Anti Pumping Relay (K1) is used as shown in figure (62), and figure (63).

The circuit breaker is switched ON

- S1_1 Opened
- S1_3 Closed

K1 is Energized

- K1_1 Closed (Self Hold for K1 Coil)
- K1_2 Opened (Opens the ON Circuit)

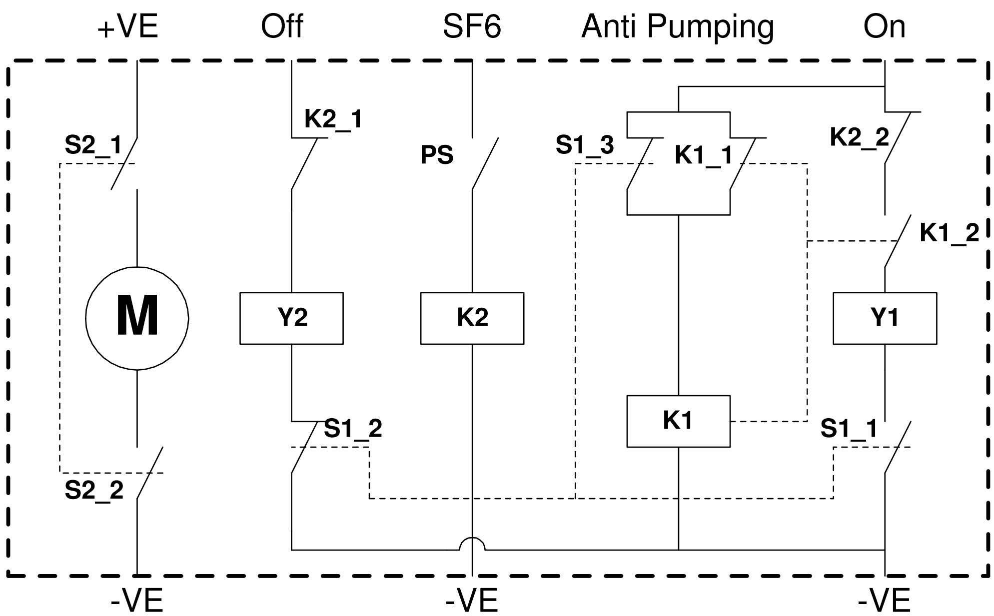



**Figure 62: Anti Pumping Relay while the Circuit Breaker is ON**

The circuit breaker is switched OFF (By Protection Relays)

- S1_1 Closed
- S1_3 Opened

K1 is still Energized

- K1_1 Closed (Self Hold for K1 Coil)
- K1_2 Opened (Opens the ON Circuit)

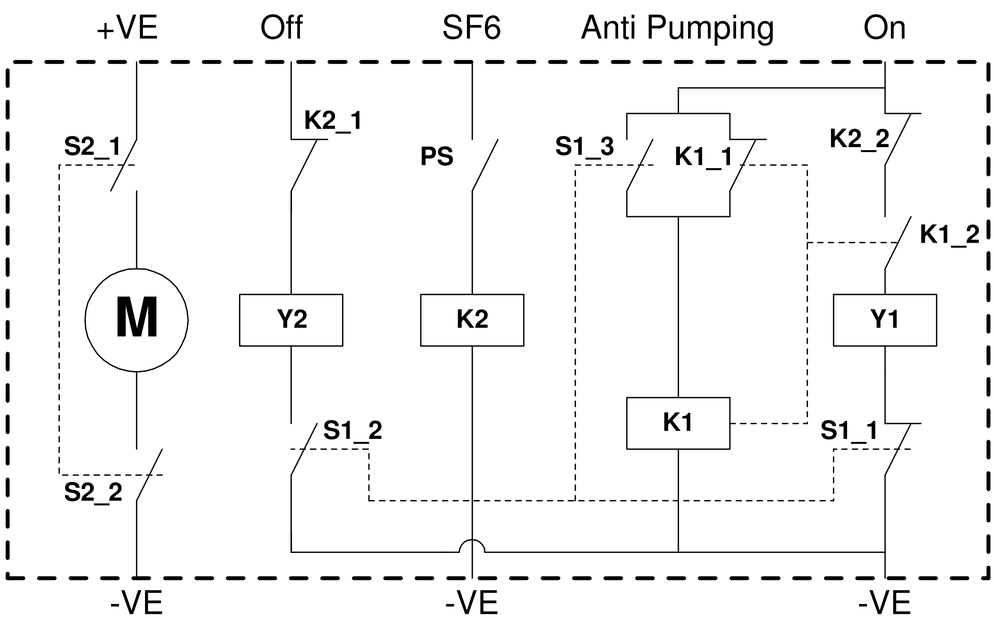



**Figure 63: Anti Pumping Relay while the Circuit Breaker is OFF**

### External Interlocking

Assume the following simple example as shown in figure (64), which is consists of two transmission lines, a bus coupler with two transverse isolators, and two bus bars with four longitudinal isolators.

- Transmission line 1 consists of two bus isolators (Q1, and Q2), Circuit Breaker (Q3), and a line isolator (Q4)
- Transmission line 2 consists of two bus isolators (Q8, and Q9), Circuit Breaker (Q10), and a line isolator (Q11)
- Bus Coupler consists of two transverse isolators (Q5, and Q7), Circuit Breaker (Q6)
- Bus Bars consists of four quarters and four longitudinal isolators (Q11,Q12,Q21,Q22)

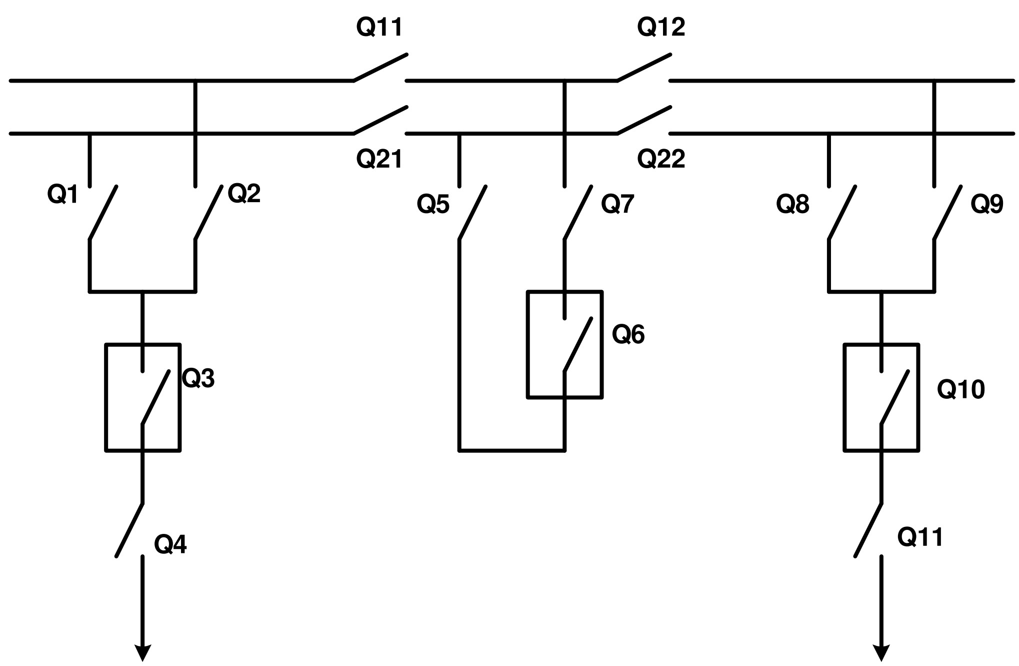



**Figure 64: Interlocking between Equipments**

To Close or Open Q1

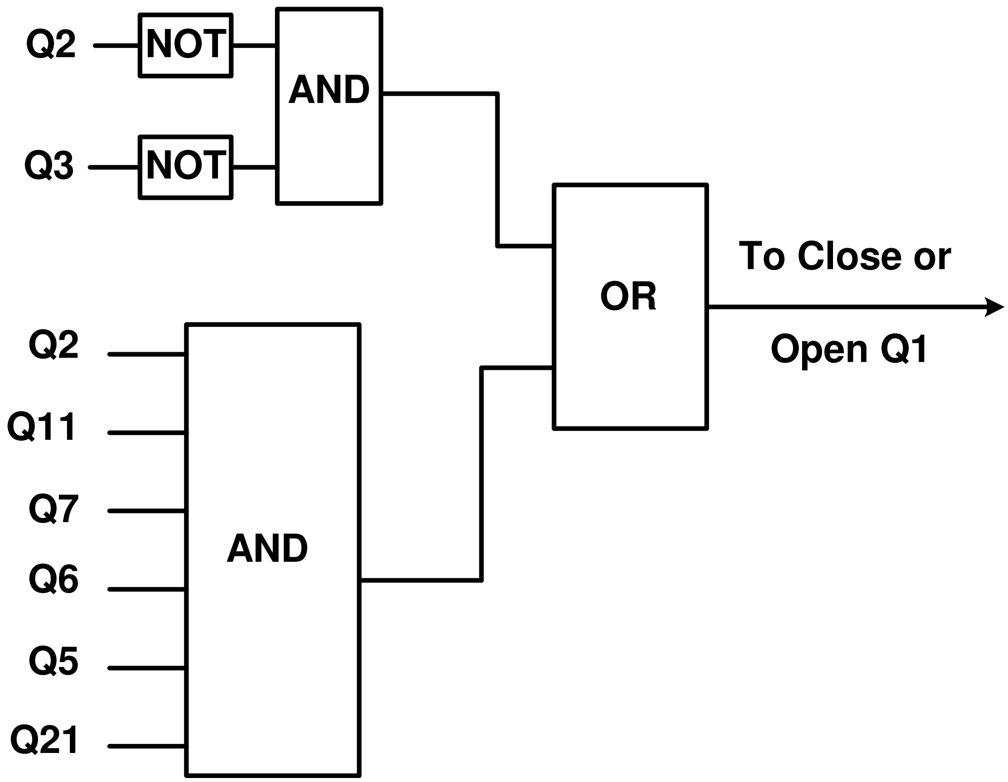



**Figure 65: Closing & Opening Q1**

To Close or Open Q3

- Q1 is completely ON or completely OFF
- Q2 is completely ON or completely OFF
- Q4 is completely ON or completely OFF

To Close or Open Q9

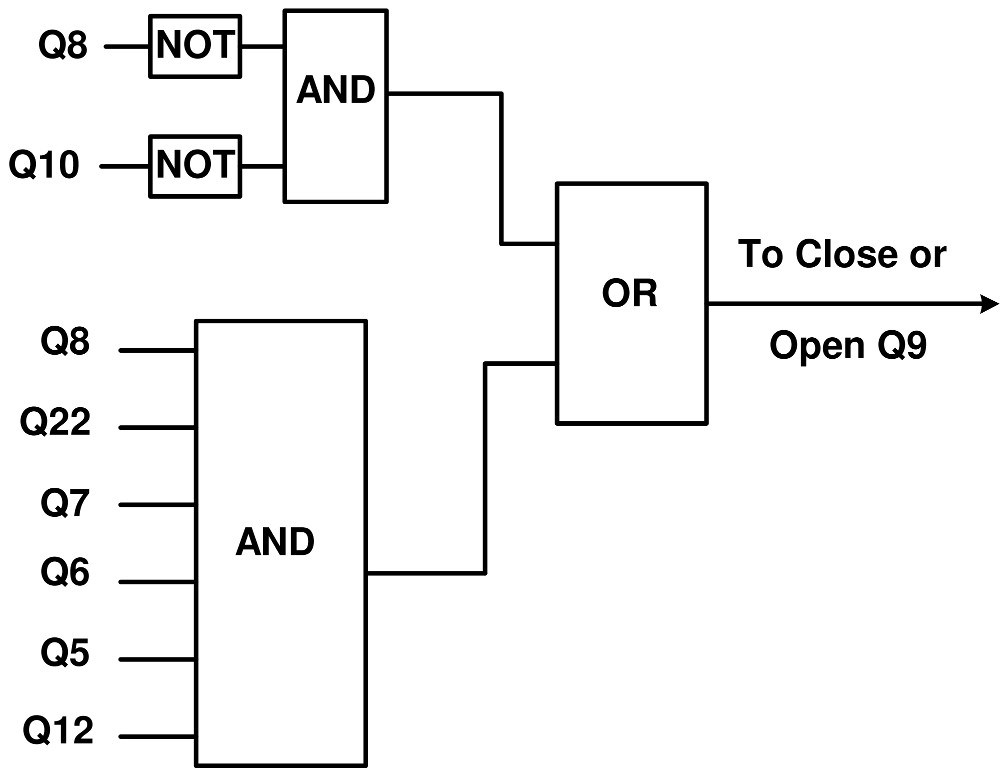



**Figure 66: Closing & Opening Q9**

To Close or Open Q10

- Q8 is completely ON or completely OFF
- Q9 is completely ON or completely OFF
- Q11 is completely ON or completely OFF

To Close or Open Q11

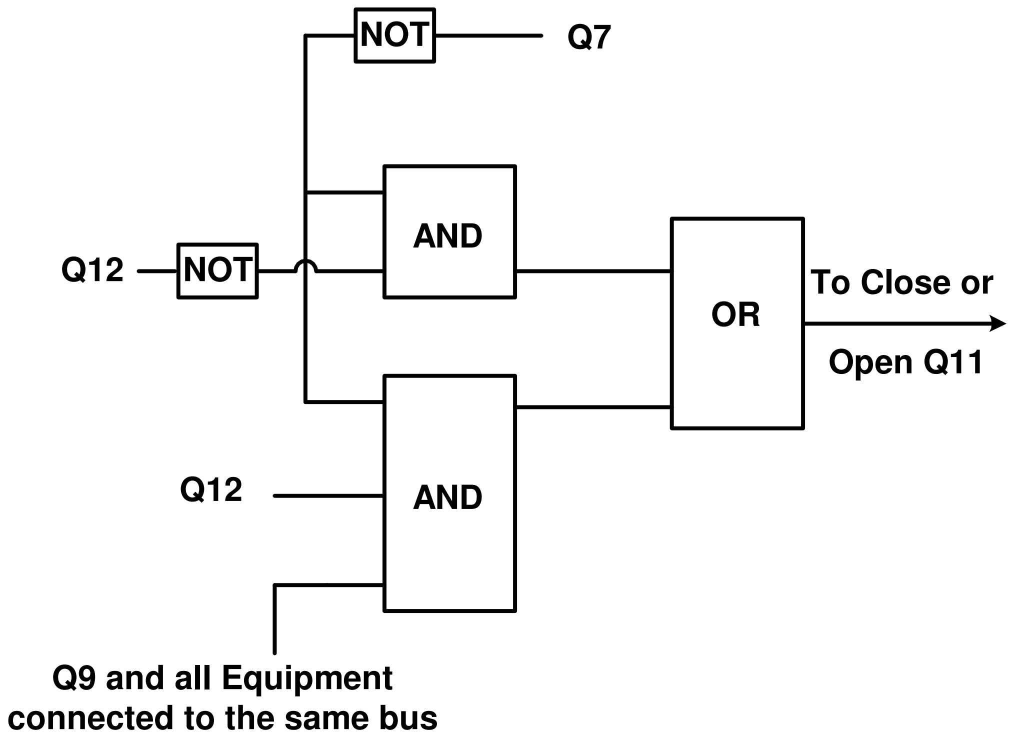



**Figure 67: Closing & Opening Q11**

To Close or Open Q5

- Q6 must be Open

To Close Q6

- Q11 is completely ON or completely OFF
- Q12 is completely ON or completely OFF
- Q21 is completely ON or completely OFF
- Q22 is completely ON or completely OFF
- Q5 is completely ON or completely OFF
- Q7 is completely ON or completely OFF

To Open Q6

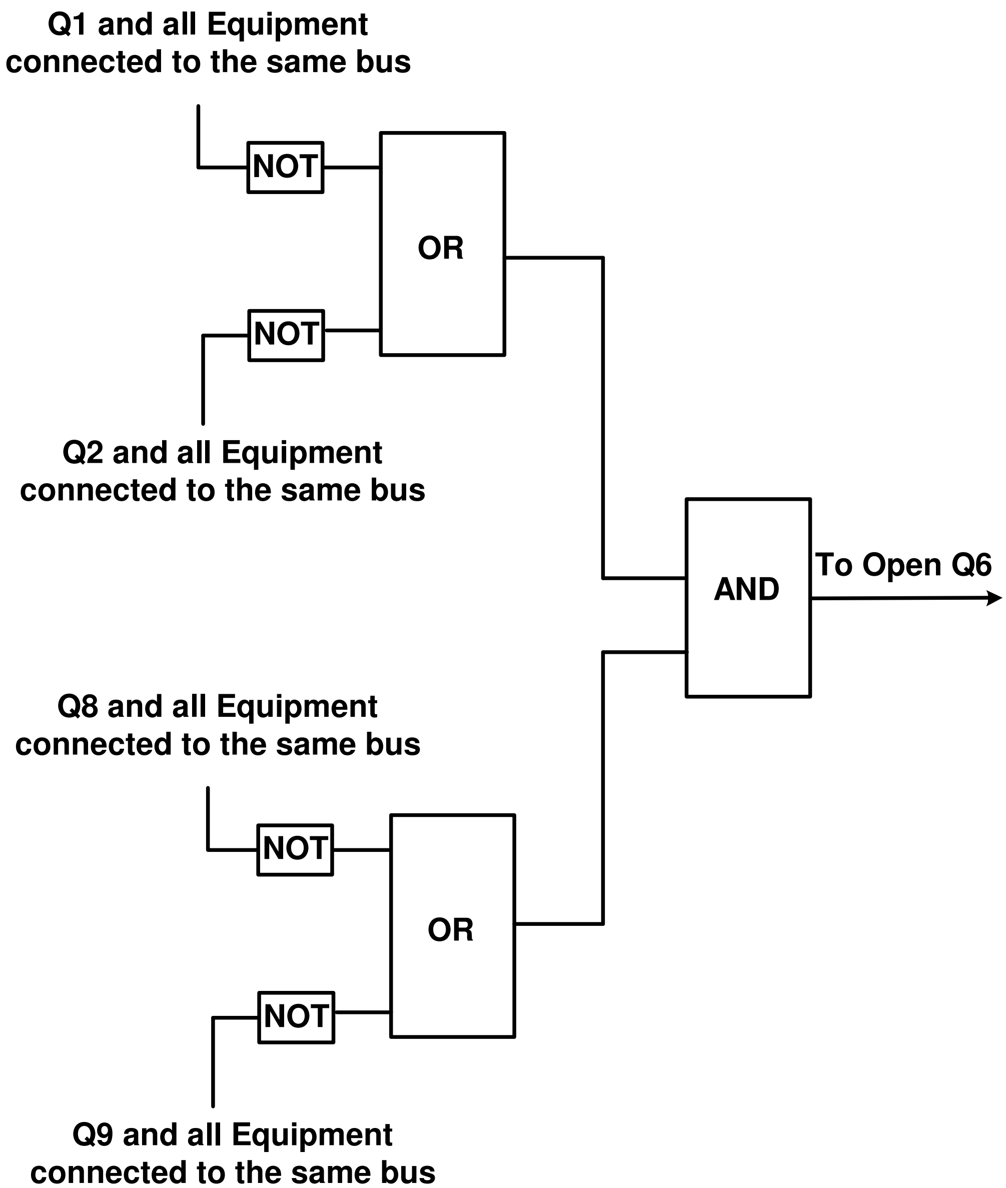



**Figure 68: Opening Q6**

## PARALLEL OPERATION OF POWER TRANSFORMERS

Some of disadvantages of parallel operation of power transformers are

1- High short circuit current levels. The main reason of these high currents is the low impedance of parallel connection ( impedances in parallel).
2- In the fault condition, all parallel transformers may be to tripped due to a single fault

Although there are some advantages of parallel operation of power transformers, in some cases there is a need for this parallel operation. Some conditions must be satisfied for the parallel operation which can be listed as follows:

1- The same frequency
2- The primary and the secondary rated voltages must be the same
3- Vector group is the same in all parallel transformers
4- Equal impedance voltage (% impedances)

Practically, condition 1 must be satisfied but in the case of small difference in one of the conditions 2, 3, or 4 parallel operation may be possible. Parallel operation with these differences will be explained hereunder.

## Parallel operation of transformers with different voltage ratios

When power transformers with different voltage ratios are connected in parallel, the difference will appear as circulating current between transformers in the case of no load. At load condition, the power transformers will be differently loaded due to the difference in voltage ratio. Assume two power transformers with different voltage ratios ( the same primary voltage and different secondary voltage). In this case the circulating current can be obtained from the following equation

$$I_{CIR} = \frac{\Delta K}{\frac{Z_1\%}{I_{S1}} + \frac{Z_2\%}{I_{S2}}}$$

$$\Delta K = \frac{K_2 - K_1}{K} \qquad , \quad K = \sqrt{K_1\, K_2}$$

Where:

| | |
|---|---|
| $K_1$, $K_2$ | Transformation ratios of transformers 1, and 2 respectively |
| $Z_1\%$, $Z_2\%$ | Percentage impedances of transformers 1, and 2 respectively |
| $I_{S1}$, $I_{S2}$ | Rated secondary current of transformers 1, and 2 respectively |

Circulating current is usually expressed as percentage of the rated current of transformer. Taking transformer 1 as a reference

$$I_{CIR} = \frac{\Delta K * 100}{Z_1\% + Z_2\% \frac{I_{S1}}{I_{S2}}}$$

Parallel operation of transformers with different vector group

Different cases of parallel operation of different vector groups power transformers are listed in the following table

**Table 3 Parallel operation of transformers with different vector group**

| Vector Group | For parallel operation | |
|---|---|---|
| | High Voltage Side | Low Voltage Side |
| 1 | RST | rst |
| 5 | RST<br>STR | trs<br>rst |
| 1 | RST | rst |
| 7 | RTS<br>TSR<br>SRT | srt<br>rts<br>tsr |
| 1 | RST | rst |
| 11 | RTS<br>TSR<br>SRT | rts<br>tsr<br>srt |
| 5 | RST | rst |
| 7 | RTS<br>TSR<br>SRT | rts<br>tsr<br>srt |
| 5 | RST | rst |
| 11 | RTS<br>TSR<br>SRT | tsr<br>srt<br>rts |
| 7 | RST | rst |
| 11 | RST<br>STR | trs<br>rst |

**Parallel operation of transformers with different % impedances**

Let us assume the example of three power transformers T1, T2, and T3 with the following data

$P_1^{max} = 100$ MVA $\quad Z_1\% = 10$

$P_2^{max} = 150$ MVA $\quad Z_2\% = 9$

$P_3^{max} = 150$ MVA $\quad Z_3\% = 8$

From the previous data, the expected maximum power available is

$$\mathbf{P_1^{max} + P_1^{max} + P_3^{max} = 100 + 150 + 150 = 400}$$

Actually:

$$P_1 : P_2 : P_3 = \frac{1}{Z_1\%} : \frac{1}{Z_2\%} : \frac{1}{Z_3\%}$$

Assume the total required load to be 400 MVA. The participation of each transformer can be calculated from the formula

$$P_i = \frac{P_t}{\sum_{i=1}^{3} \frac{P_i}{Z_i\%}} * \frac{P_i}{Z_i\%}$$

Where:

$P_i$ Power taken from transformer no. ( i )

$P_t$ Total required power

Then $P_1$ can be calculated as

$$P_1 = \frac{400}{\frac{100}{10} + \frac{150}{9} + \frac{150}{8}} * \frac{100}{10} = 88.073$$

Similarly

$P_2 = 146.7889$

$P_3 = 165.137$ ( overloaded )

But, $P_3$ must not exceed 150 MVA

So, let $P_3 = 150$ MVA

According to the new value of $P_3$ , new values of $P_1$, and $P_2$ can be calculated from the formula

$$\frac{P_1^{old}}{P_1^{new}} = \frac{P_2^{old}}{P_2^{new}} = \frac{P_3^{old}}{P_3^{new}}$$

For $P_1$

$$\frac{88.073}{P_1^{new}} = \frac{165.137}{150.0}$$

So, $P_1^{new} = 80$ MVA

For $P_2$

$$\frac{146.7889}{P_2^{new}} = \frac{165.137}{150.0}$$

$$\text{So, } P_2^{new} = 133.3 \text{ MVA}$$

In this case, the maximum available power from the three transformers is equal to

$$80 + 133.3 + 150 = 363.3 \text{ MVA}$$

Comparing this value with the total required power ( 400 MVA ). The available power in this case is only ( 90.8% ) from the required power.

Note : For high differences between percentage impedances of power transformers, the ratio between the available power to the summation of the total MVA of the transformers will decrease to very small values. So, the differences between percentages impedances of transformers connected in parallel must not exceed 10% from the mean value of them.