Fundamentals of Power System Protection

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Electrical Energy System

The purpose of the electric energy system is to generate electric energy in sufficient quantities to the load centers, and then distribute it to the individual customers in proper form and quality and that the lowest possible ecological and economic price

(Electric Energy Systems Theory: An Introduction, Olle Elgerd, McGraw-Hill, Electrical and Electronic Engineering Series, 1971)

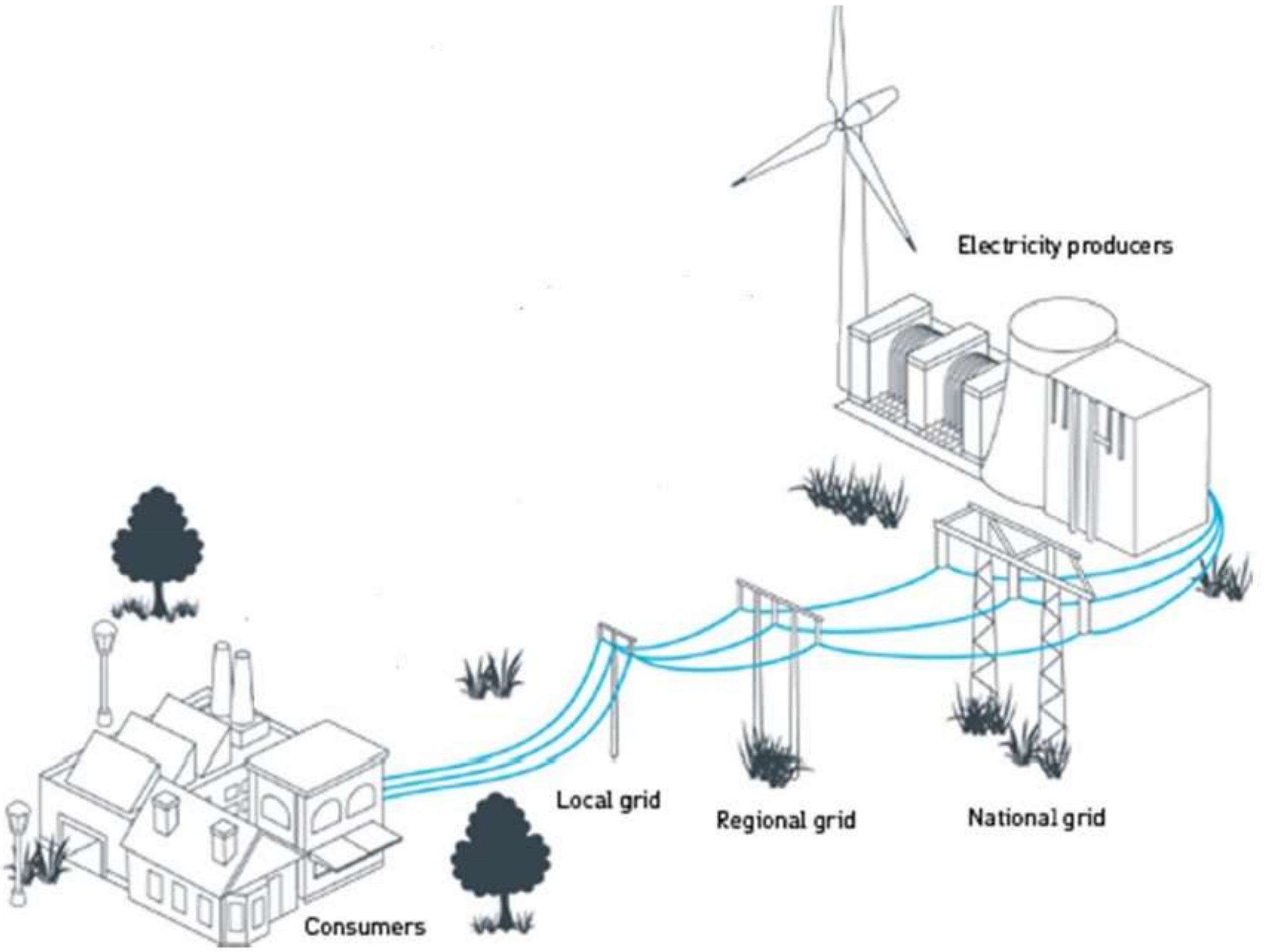
Electrical Energy System

- Electric power systems may vary in size and structure, but they have the same basic characteristics:
  - They are three-phase AC systems operating at essentially constant voltage levels
  - The electric power is mainly produced by synchronous machines
  - The power is transmitted over significant distances to consumers spread over a wide area
- It is common practice to classify the transmission network into the following subsystems:
  - Transmission system
  - Sub-transmission system
  - Distribution system

Electrical Energy System

- The transmission system (typically 230kV and above) interconnects all major generating stations and main load centers in the system
- The sub-transmission system (typically 69kV to 138kV) transmits power in smaller quantities from the transmission substations to the distribution substations
- The distribution system represents the final stage in the transfer of power to the individual customers.
- This system has to be protected from abnormalities which is the task of protection system

Electrical Energy System



Why do we need Protection?

- Electrical apparatus used may be enclosed (e.g., motors) or placed in open (e.g., transmission lines). All such equipment undergo abnormalities in their life time due to various reasons.
- For example,
  - a worn out bearing may cause overloading of a motor.
  - A tree falling or touching an overhead line may cause a fault.
  - A lightning strike (classified as an act of God!) can cause insulation failure.
  - Pollution may result in degradation in performance of insulators which may lead to breakdown.
  - Under frequency or over frequency of a generator may result in mechanical damage to it's turbine requiring tripping of an alternator.
  - Even otherwise, low frequency operation will reduce the life of a turbine and hence it should be avoided.

Consequences of Faults

1. A great reduction of the line voltage over a major part of the power system. This will lead to the breakdown of the electrical supply to the consumer and may produce wastage in production.
2. Damage caused to the elements of the system by the electrical arc which almost always accompanies a short circuit.
3. Damage to other apparatus in the system due to overheating and due to abnormal mechanical forces set-up.
4. Disturbances to the stability of the electrical system and this may even lead to a complete shutdown of the power system.
5. A marked reduction in the voltage which may sometimes be so great that relays having pressure coils tend to fail.
6. Considerable reduction in the voltage on healthy feeders connected to the system having fault. This may cause either an abnormally high current being drawn by the motors or the operation of no-voltage coils of the motors. In the latter case considerable loss of industrial production may result as the motors will have to be restarted.

Frequency of Fault Occurrence

Equipment	% of total
O.H lines	50
Cables	10
Switchgear	15
Transformers	12
CTs and PTs	2
Control Equipment	3
Miscellaneous	8

L – G	85%
L – L	8%
L – L – G	5%
L – L – L	2% of less

Why do we need Protection?

- **Required:** avoid abnormal operating regions for equipment safety. Even more important is safety of the human personnel which may be endangered due to exposure to live parts under fault or abnormal operating conditions.
  - Small current of the order of 50 mA is sufficient to be fatal!
- Whenever human security is sacrificed or there exists possibility of equipment damage, it is necessary to isolate and de-energize the equipment.
- To conclude, every electrical equipment has to be monitored to protect it and provide human safety under abnormal operating conditions.
- Electrical protection systems should protect apparatus and system.

Fundamental of protection

- Objectives of protection
  - Remove faults as quickly as possible while leaving much of the system intact as possible
- Impacts of protection on power systems
  - Local protection
    - Protection of immediate equipment
    - Minimize disruption of loads
    - Reduce duration when interrupted
  - Larger system issues
    - Impacts of stability
  - Power quality
    - Impacts on supply interruptions (e.g., longer or shorter interruptions)
    - Impacts on voltage dips (e.g., longer or shorter dips)

Fundamental of protection

- Protection system
  - Current and voltage transformers
  - Relay
  - Circuit breaker
  - Communication system
  - Coordination with other relays, active controls
- Relay or Protective Relay
  - Piece of equipment whose function is to:
    - Detect defective or abnormal system conditions
    - Initiate proper control responses
  - Common responses
    - Trips circuit breakers
    - In some cases, closes circuit breakers
    - In some cases, only issues alarms

Fundamental of protection

- Sequence of events when a fault occurs
  - Fault occurs somewhere on the system, changing the system currents and voltages
  - Current transformers (CTs) and voltage transformers (VTs) (sensors) detect the change in currents/voltages
  - Relays use sensors' inputs to determine if a fault has occurred
  - If the fault occurs, relays send trip signal to open circuit breakers to isolate the fault

Apparatus protection

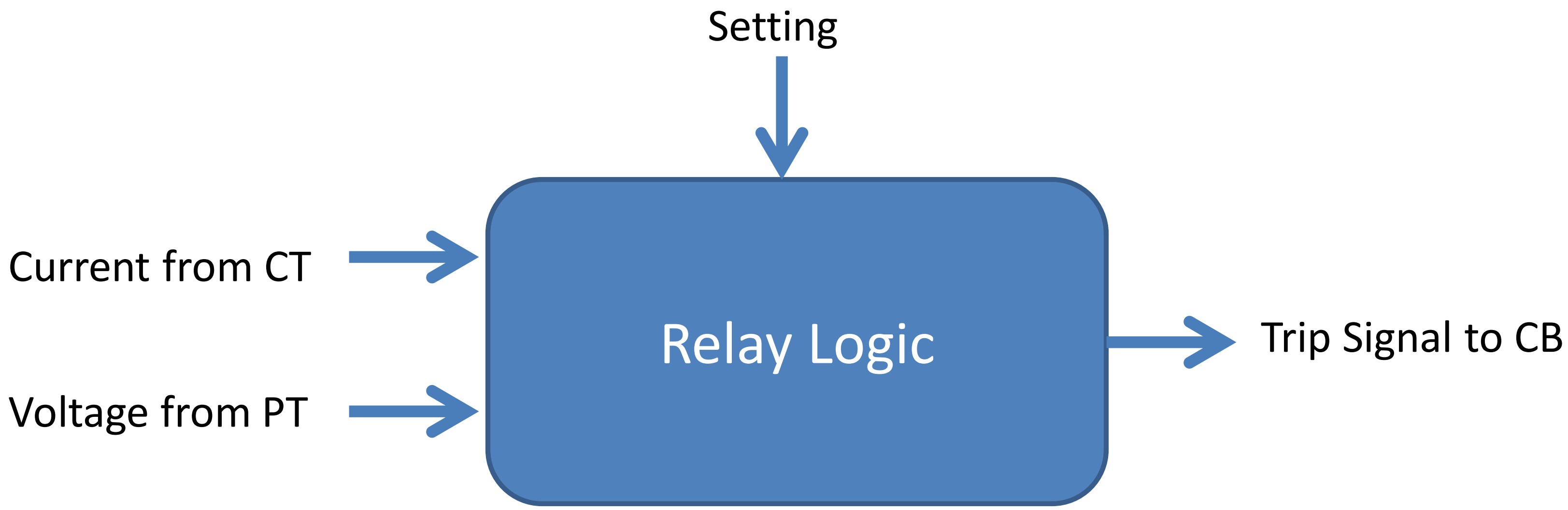
- Detects fault in the apparatus and consequent protection. Apparatus protection can be classified into following:
  - Transmission Line Protection and feeder protection
  - Transformer Protection
  - Generator Protection
  - Motor Protection
  - Busbar Protection

System Protection

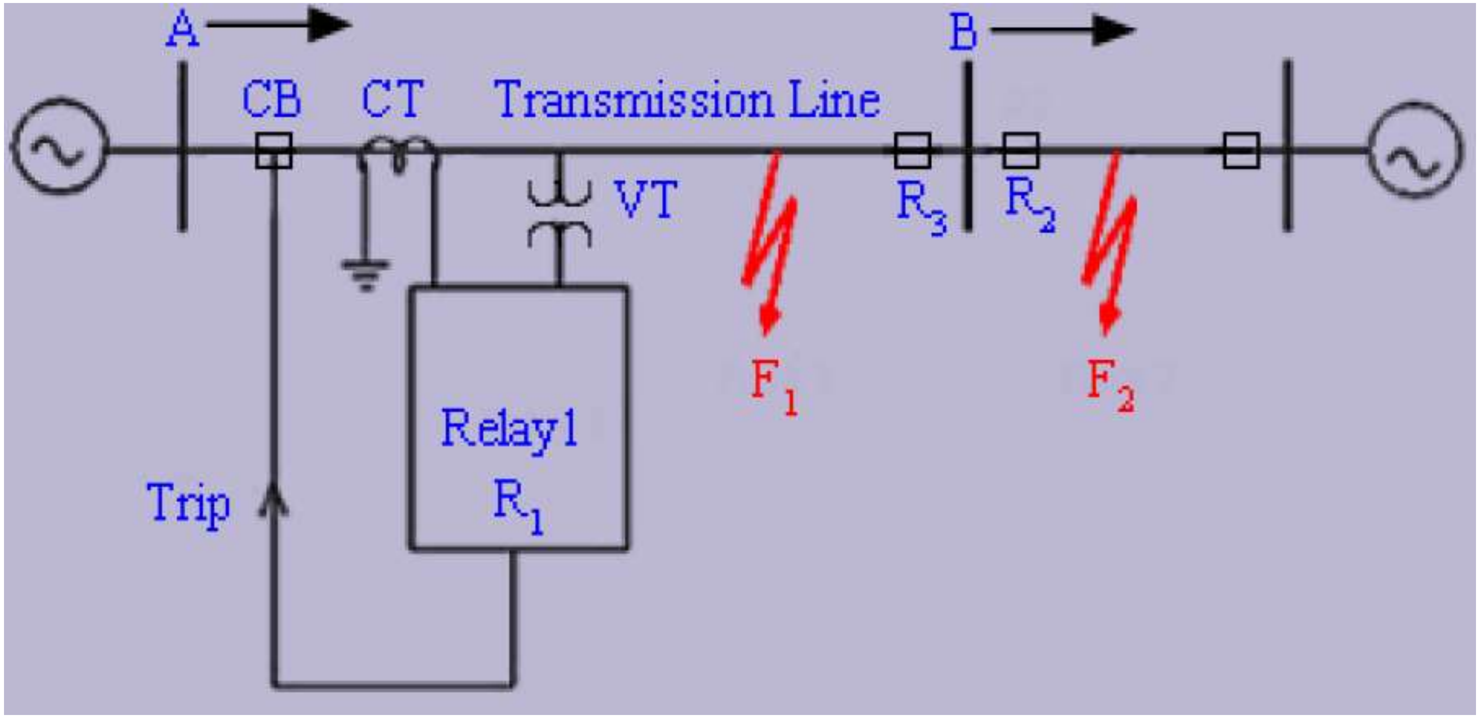
- Detects the situation that can lead the system to unstable operating region and consequently takes control actions to restore stable operating point and/or prevent damage to equipment's.
- If proper action is not taken, the system instability can lead to partial or complete system blackouts.
  – Under-frequency relays, out of- step protection, islanding systems, rate of change of frequency relays, reverse power flow relays, voltage surge relays etc. are used for system protection.
- Control actions associated with system protection may be classified into preventive or emergency control actions.

Relays

- Relay is a logical element which processes the inputs (mostly voltages and currents) from the system/apparatus and issues a trip decision if a fault within the relay's jurisdiction is detected



Relay operation



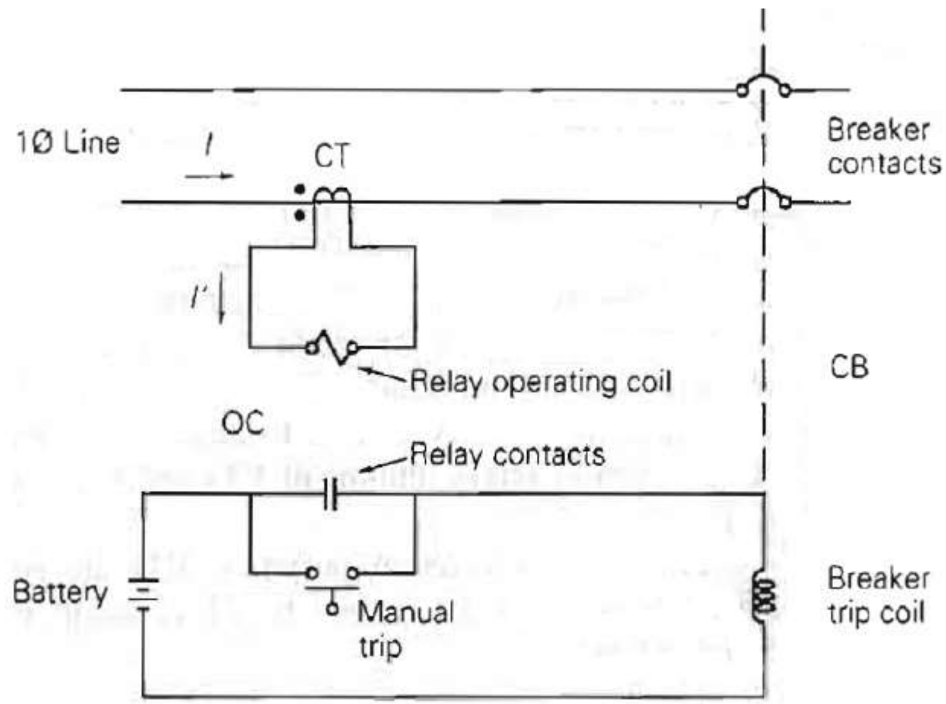
During Fault F1, relays R1 & R3 are used to protect the transmission line by opening the circuit breaker from each ends.

Relay Operation

- To monitor the health of the apparatus, relay senses current through a current transformer (CT), voltage through a voltage transformer (VT). VT is also known as Potential Transformer (PT).
- The relay element analyzes these inputs and decides whether there is a fault and whether it is within jurisdiction of the relay. The jurisdiction of relay R1 is restricted to bus B where the transmission line terminates. If the fault is in it's jurisdiction, relay sends a tripping signal to circuit breaker(CB) which opens the circuit.
- R1 can sense the change in power flow due to fault F1 or F2, but will operate only for F1; if it is F2 than it is in the jurisdiction of R2. R1 should act for fault F2, if and only if, R2 fails to act. We say that relay R1 backs up relay R2. Standard way to obtain backup action is to use time discrimination i.e., delay operation of relay R1 in case of doubt to provide R2 first chance to clear the fault.

Why using CTs and VTs?

- Safety for personnel: electrical isolation from the power systems
- Economy: low-level relay inputs enable relays to be small, simple, less expensive
- Accuracy: CTs and VTs accurately reproduce power system currents and voltages



Types of Relays

Relays can be categorized in three types:

1. Electromechanical Relays
2. Solid State Relays
3. Numerical Relays

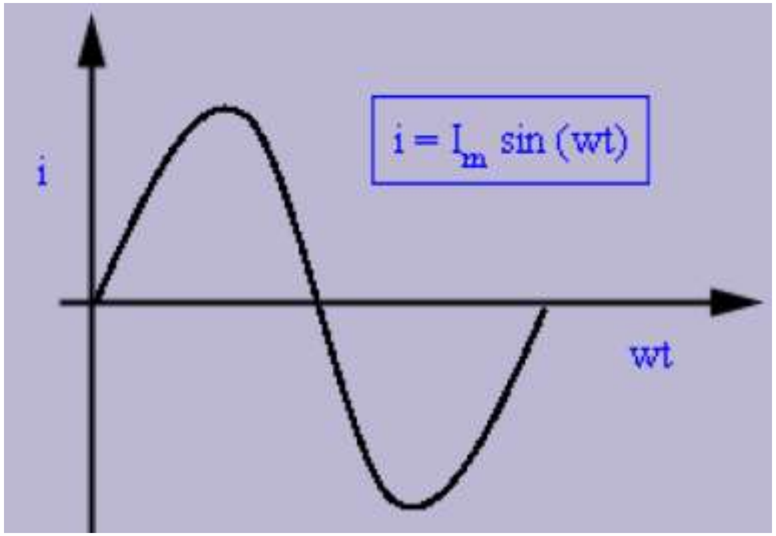
Electromechanical Relays

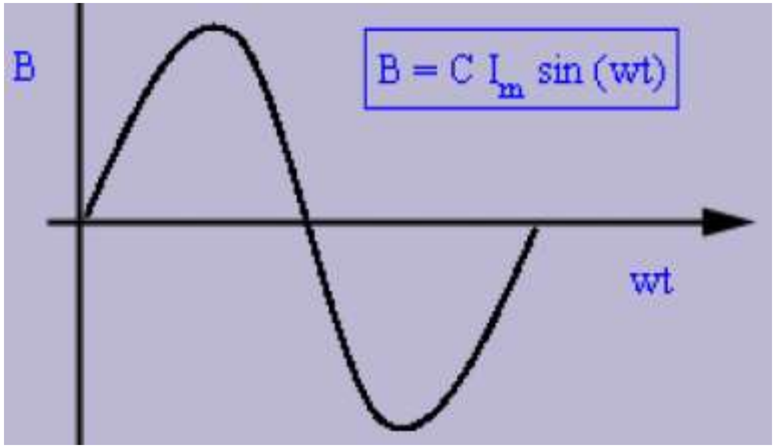
- Represent first generation of relays.
- Based on the principle of electromechanical energy conversion in decision making, for an over current relay, which issues a trip signal if current in the apparatus is above a reference value.
  - By proper geometrical placement of current carrying conductor in the magnetic field, Lorentz force ($F=BIL \sin\Theta$) is produced in the operating coil creating operating torque.
  - If constant 'B' is used (for example by a permanent magnet), then the instantaneous torque produced is proportional to instantaneous value of the current. Since the instantaneous current is sinusoidal, the instantaneous torque is also sinusoidal which has a zero average value. Thus, no net deflection of operating coil is perceived.

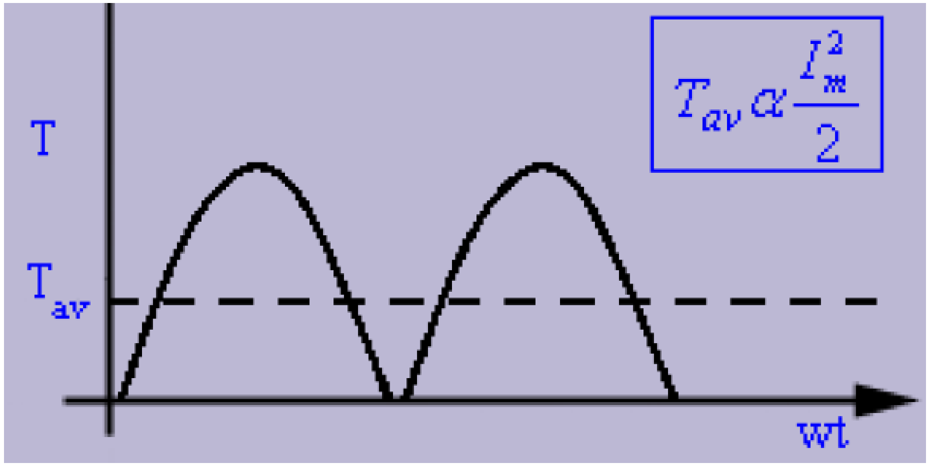
Electromechanical Relays

- If B is also made proportional to the instantaneous value of the current, then the instantaneous torque will be proportional to square of the instantaneous current (non-negative quantity). The average torque will be proportional to square of the rms current.
- Movement of the relay contact caused by the operating torque may be restrained by a spring in the overcurrent relay. If the spring has a spring constant 'k', then the deflection is proportional to the operating torque.
- When the deflection exceeds a preset value, the relay contacts closes and a trip decision is issued.
- Electromechanical relays are known for their ruggedness and immunity to Electromagnetic Interference (EMI).

Electromechanical Relays







Operating principle of an electromechanical time-delay OC relay

AC input current to the relay operating coil:

→ magnetic field perpendicular to the conducting aluminum disc

- The disc can rotate and is restrained by a spiral spring

→ current induced in the disc interacts with the magnetic field → TORQUE

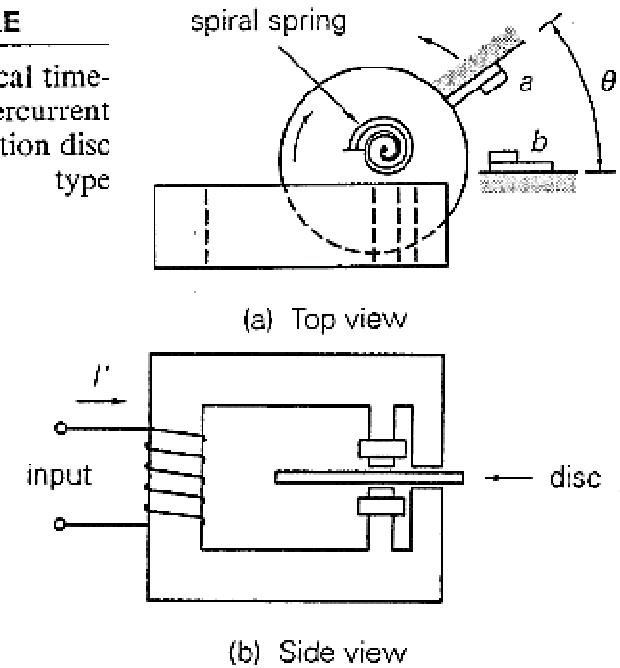
- If $I_{input} > I_{pickup}$ → disc rotates θ → close contacts

  larger I_{input} → larger torque, faster closing

- If $I_{input} < I_{pickup}$ (fault cleared) → spring provides reset to contacts

FIGURE

Electromechanical time-delay overcurrent relay—induction disc type



Solid State Relays

- Developed with the advent of transistors, operational amplifiers etc. using various operations like comparators etc. and therefore provides more flexibility and have less power consumption than their electromechanical counterpart.
- **Advantage**
  - ability to provide self checking facility i.e. the relays can monitor their own health and raise a flag or alarm if its own component fails.
  - low burden, improved dynamic performance characteristics, high seismic withstand capacity and reduced panel space.

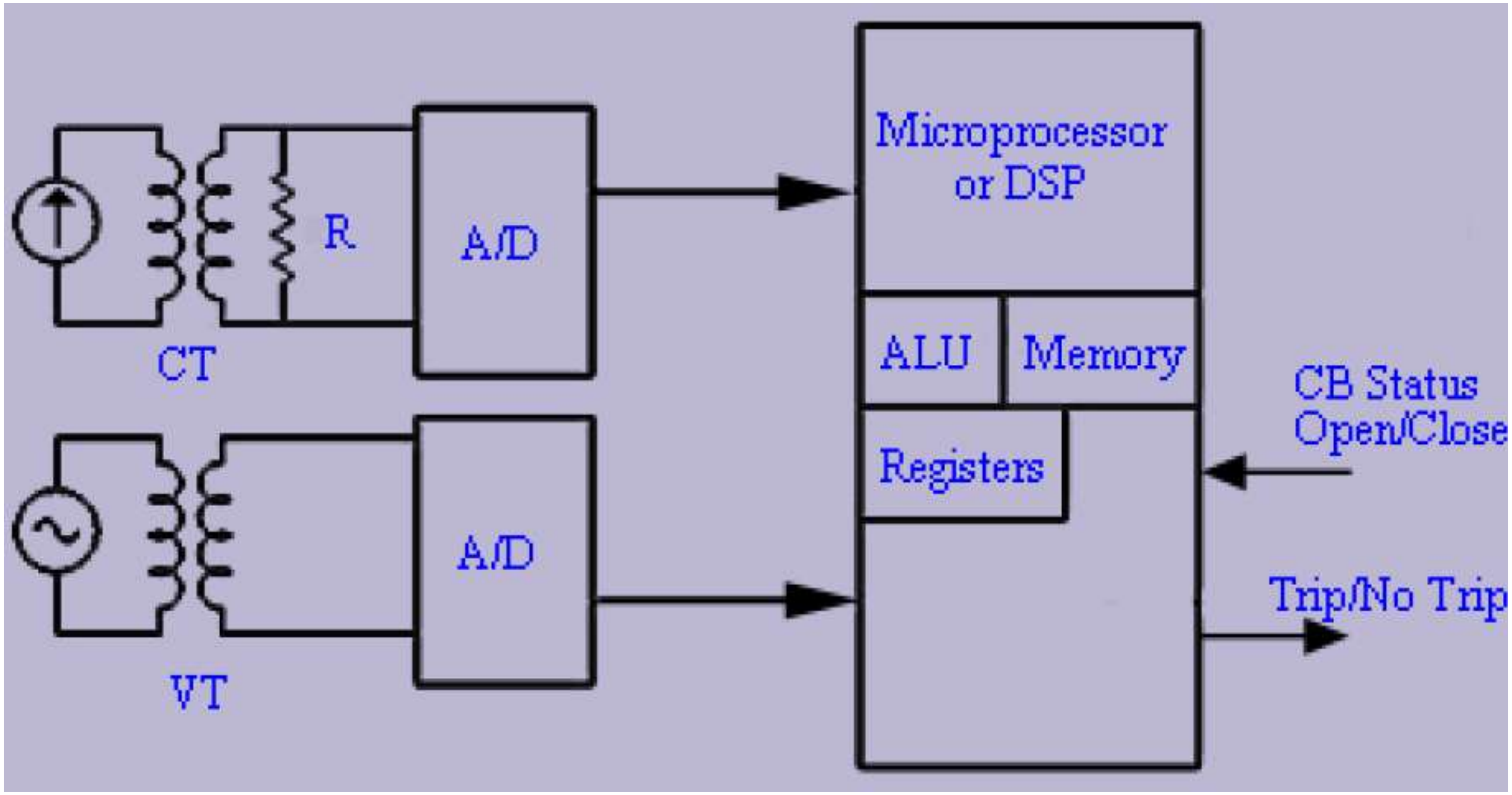
Solid State Relays

- Relay burden refers to the amount of volt amperes (VA) consumed by the relay. Higher is this value, more is the corresponding loading on the current and voltage sensors i.e. current transformers (CT) and voltage transformers (VT) which energizes these relays. Higher loading of the sensors lead to deterioration in their performance.
- A performance of CT or VT is gauged by the quality of the replication of the corresponding primary waveform signal. Higher burden leads to problem of CT saturation and inaccuracies in measurements. Thus it is desirable to keep CT/VT burdens as low as possible.
- These relays have been now superseded by the microprocessor based relays or numerical relays.

Numerical Relays

- Involves analog to digital (A/D) conversion of analog voltage and currents obtained from secondary of CTs and VTs.
- These current and voltage samples are fed to the microprocessor or Digital Signal Processors (DSPs) where the protection algorithms or programs process the signals and decide whether a fault exists in the apparatus under consideration or not.
- In case, a fault is diagnosed, a trip decision is issued.
- Numerical relays provide maximum flexibility in defining relaying logic.

Numerical Relays



Numerical Relays

- Hardware can be made scalable i.e., the maximum number of V and I input signals can be scaled up easily.
- Generic hardware board can be developed to provide multiple functionality
  - Changing the relaying functionality is achieved by simply changing the relaying program or software.
  - Also, various relaying functionalities can be multiplexed in a single relay.

Numerical Relays

- Numerical Relays has all the advantages of solid state relays like self checking etc.
  - Enabled with communication facility, it can be treated as an Intelligent Electronic Device (IED) which can perform both control and protection functionality.
- Relay can be made adaptive i.e. it can adjust to changing apparatus or system conditions.
  - For example, a differential protection scheme can adapt to transformer tap changes. An overcurrent relay can adapt to different loading conditions.
- Numerical relays are both "the present and the future".

Circuit Breaker

- A switch used to interrupt the flow of current upon relay command initiating mechanical separation of the contacts.
- Complex element because it has to handle large voltages (few to hundreds of kV's) and currents (in kA's) and therefore Interrupting capacity is expressed in MVA.
- During faults, the X/R ratio of lines is usually much greater than unity and thus the current cannot change instantaneously.

Circuit Breaker

- The abrupt change in current, if it happens due to switch opening, will result in infinite di/dt and hence will induce infinite voltage. Even with finite di/dt, the induced voltages will be quite high. The high induced voltage developed across the CB will ionize the dielectric between its terminals resulting in arcing.

- When current in CB goes through the natural zero, the arc can be extinguished (quenched). However, if the interrupting medium has not regained its dielectric properties then the arc can be re-struck. The arcing currents reduce with passage of time and after a few cycles the current is finally interrupted.

Circuit Breaker

- Usually CB opening time lies in the 2-6 cycles range. CBs are categorized by the interrupting medium used.
  - Minimum oil, air blast, vacuum arc and SF6 CBs are some of the common examples.
- CB opening mechanism requires much larger power input than what logical element relay can provide. Hence, when relay issues a trip command, it closes a switch that energizes the CB opening mechanism powered by a separate dc source (station battery).
- The arc struck in a CB produces large amount of heat which also has to be dissipated.

Protection design criteria

- Reliability:
  - Operate dependably when fault occurs, even after remaining idle for months or years
  - Failure to do so may result in costly damage
- Selectivity:
  - Ability to distinguishes between those conditions for which it is intended to operate and those for which it must not operate avoid unnecessary, false trips
- Speed:
  - Operate rapidly to minimize fault duration and equipment damage
    - Neither too slow (damage) nor too fast (undesired trip for transient faults)
  - Speed of protection (fault clearing time) has direct effects on transient angular stability of a power system
    - Shorter fault clearing time more load can be transfer without loss of synchronism

Protection design criteria

- Simplicity: minimize protection equipment and circuitry
- Economy: maximum protection at minimum cost
- It is impossible to satisfy all criteria compromised solution is often the case
- Protection is not needed when system is operating normally protection is a form of ”insurance” against failures in the system:
  - Premium: capital and maintenance cost
  - Return: possible prevention of loss of stability and damages

Protection design criteria

- In general, cost of protection is very small compared to the cost of equipment protected
- In designing power system protection systems, two main types of power systems that need to be considered:
  - Radial: single source power flows in a single direction easiest from the protection point of view
  - Networked: power can flow in either direction more difficult to design

Primary and Backup protection

- Protection systems must be designed with both primary protection and backup protection in case primary protection fails (concept of protection zones)
  - Primary protection:
    - expected to operate for fault in the protected zone
  - Backup protection:
    - Intended to supplement the primary
    - Backup can be located on another element to avoid simultaneous failure (remote backup)
    - Slower
    - Disconnect greater portion of the load

Fundamentals of Power System Protection

PROTECTION PARADIGMS - APPARATUS PROTECTION

Types of Protection

- Over current (OC) protection
  - Mainly used in distribution system
  - Radial system: inverse-time OC relay
  - Two-source system: directional OC relay
- Differential protection
  - Protect geographically local devices: buses, transformers, generators
- Distance protection
  - Used in HV transmission lines

Overcurrent Protection

- This scheme is used in radial distribution system to protect apparatus during faults, typically short circuits, that lead to currents much above the load current.
- Over current relaying and fuse protection uses the principle that when the current exceeds a predetermined value, it indicates presence of a fault (short circuit).

Overcurrent Protection

Radial distribution system with a single source

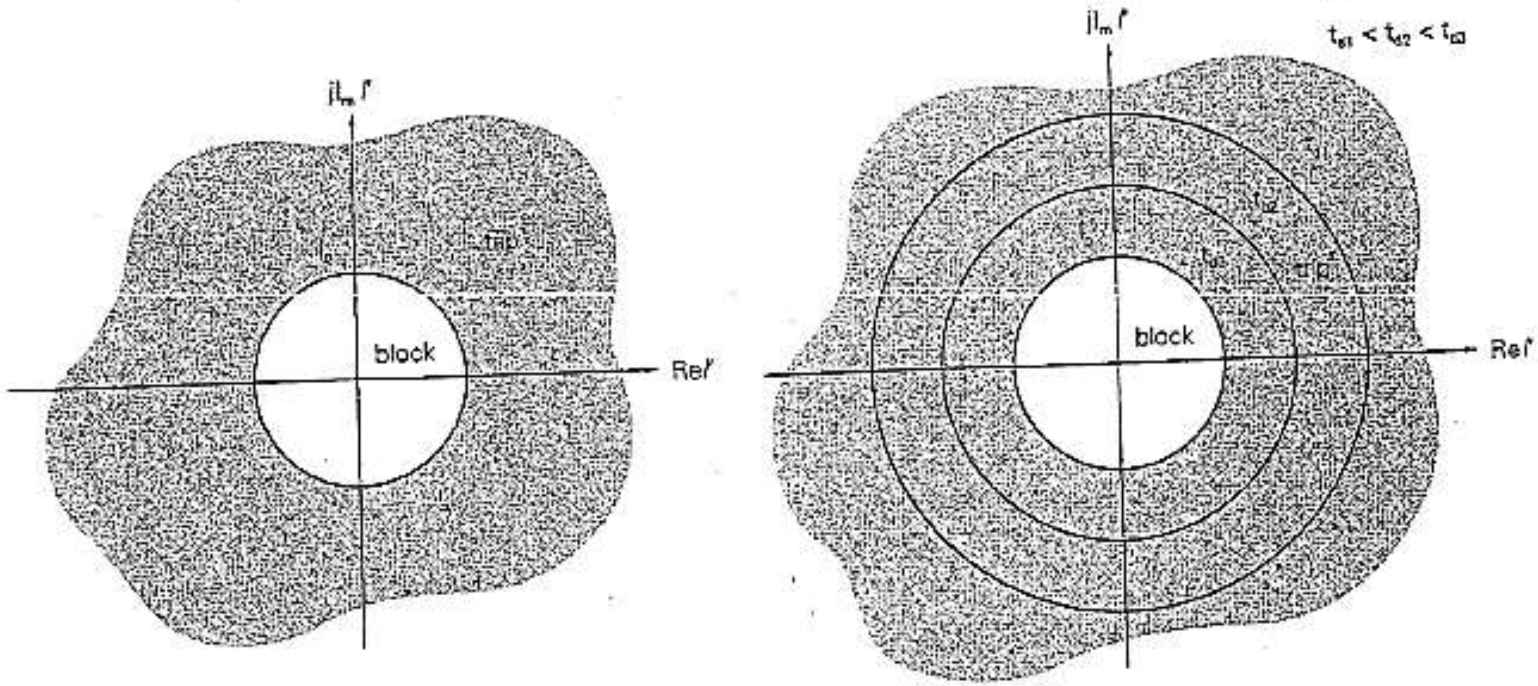
- To relay R1, both downstream faults F1 and F2 are visible i.e. IF1 as well as IF2 pass through CT of R1.
- To relay R2, fault F1, an upstream fault is not seen, only F2 is seen. This is because no component of IF1 passes through CT of R2. Thus, selectivity is achieved naturally.

Relaying decision is based solely on the magnitude of fault current. Such a protection scheme is said to be non-directional.

Overcurrent Protection

a) Instantaneous OC: reponses to input current ($I>I_{pickup}$) instantaneously

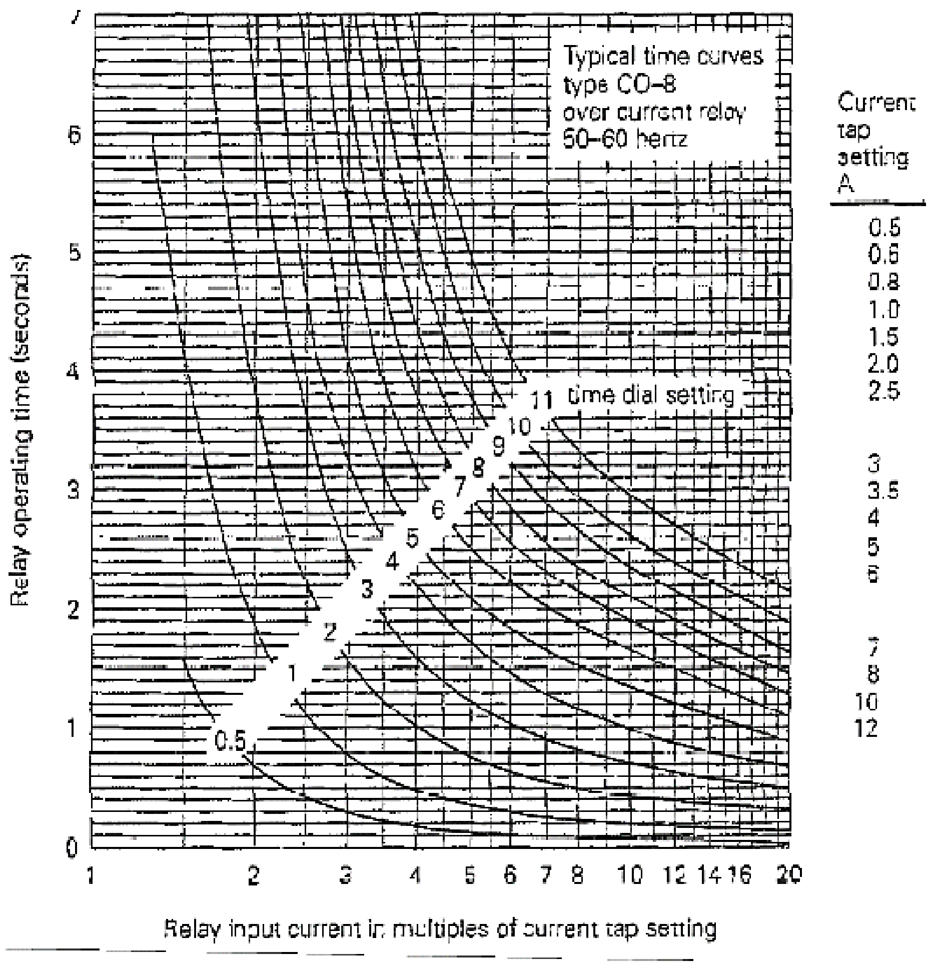
b) Time-delay OC: responses with an intentional time delay



a) b)

Overcurrent Protection

- Current tap setting: the pickup current in amperes
- Time-dial setting: adjustable amount of time delay:
  - Inverse-time delay characteristic
- Why time delay? → COORDINATION PURPOSE



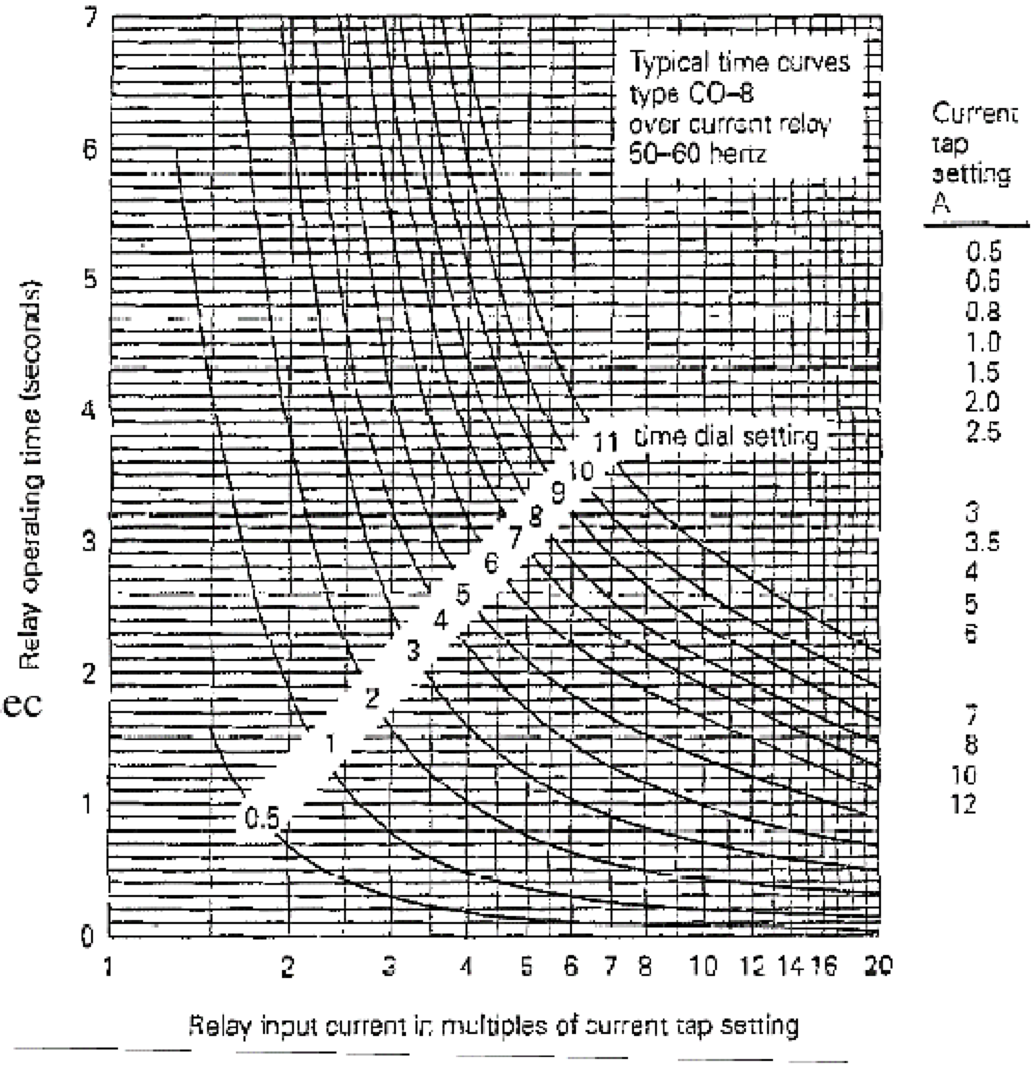
Relay settings: example

- Relay CO-8:
  - Ip= 6A (tap setting)
  - Time-dial curve 1

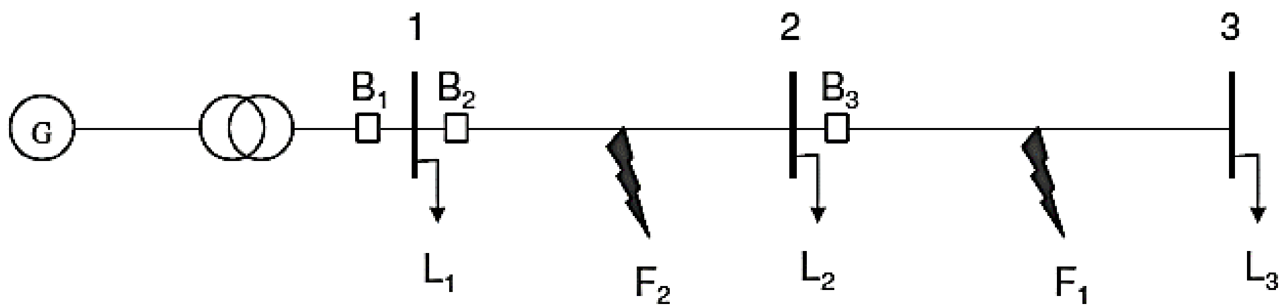
$$I' = 5A \rightarrow \frac{I'}{I_p} = \frac{5}{6} = 0.83 \rightarrow \text{No operation}$$

$$I' = 8A \rightarrow \frac{I'}{I_p} = \frac{8}{6} = 1.33 \rightarrow t_{operating} = 6\,\text{sec}$$

$$I' = 15A \rightarrow \frac{I'}{I_p} = \frac{15}{6} = 2.5 \rightarrow t_{operating} = 1.2\,\text{sec}$$



Radial System Protection by OC relay

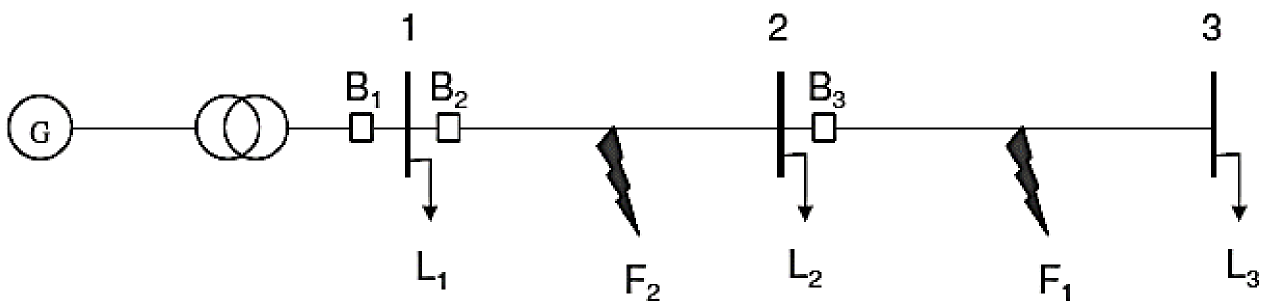


<u>Protection criteria:</u>

1. Normal: B1, B2, B3 closed
2. Fault:
   - Only breaker closest to the left of the fault should operate
   - Other upstream breaker with larger time delays remain closed

   → interrupt minimum load during faults
3. If the closest breaker fails to operate, the next breaker closer to the source should operate → backup protection

Radial System Protection by OC relay



<u>Relay coordination:</u>

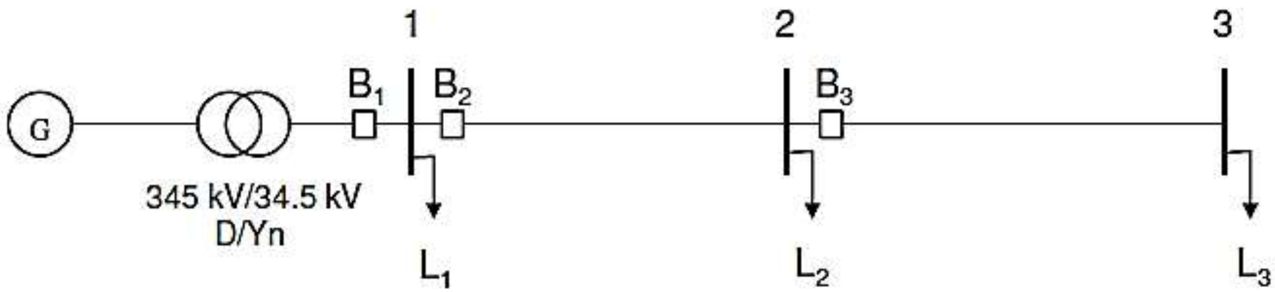
- Fault at F1:
  - B3 opens while B2 (and B1) closes → only load L3 is disconnected
  - Select longer time delay for relay at B2 so that B3 operates first (B3 primary, B2 backup)
- Fault at F2:
  - B2 opens while B1 closes
  - Fault closer to source → higher fault current than fault at F1 → B2 operates more rapidly
  - Select time delay for B1 longer than that of B2 so that B2 opens first
    - B2 primary, B1 backup (for B3 as well)

Coordinating time-delay OC relays

- Coordination time interval (CTI) is the time interval between primary and remote backup, i.e., the difference between the time that backup relay operates and the time that the circuit breaker clears the faults under primary relaying
  - Typical value of CTI = 0.2 – 0.5 sec
- Coordination of relays:
  - From fault current information (calculated), chose:
    - Current tap setting
    - Time-dial setting
    - Taking into account the CTI

Coordinating time-delay OC relays

- Example: Consider the system



- The system data is given

Bus	Max load S (MVA)	Lagging p.f.
1	11.0	0.95
2	4.0	0.95
3	6.0	0.95

Bus	Max fault current (bolted three-phase) A
1	3000
2	2000
3	1000

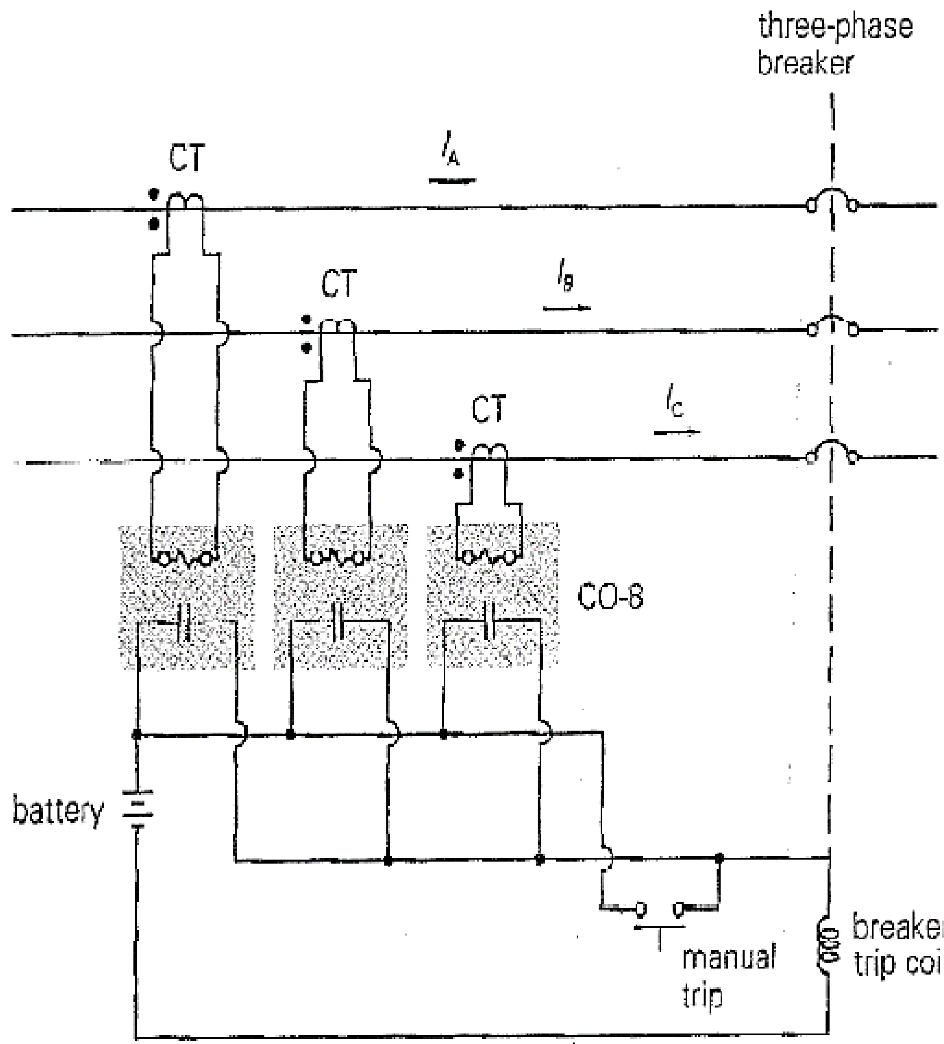
Breaker	Breaker operating time	CT ratio	Relay
B1	5 cycles	400:5	CO-8
B2	5 cycles	200:5	CO-8
B3	5 cycles	200:5	CO-8

Coordinating time-delay OC relays

- Assume using CO-8 relays (characteristics given), CTI = 0.3 sec.
- Relay are connected such that all three phases of the breakers open when a fault is detected on any phase.

Tasks:

- Select the current tap settings (TS) and time-dial settings (TDS) to protect the system from faults.



Example: solution

1) Select the TSs such that relays do not operate for max load currents

At B3, max load current: $\left|I_{L_3}\right| = \dfrac{\left|S_{L_3}\right|}{\sqrt{3}\left|V_3\right|} = \dfrac{6\,MVA}{\sqrt{3} * 34.5\,\text{kV}} = 100.4\,(A)$

Secondary current of CT: $\left|I'_{L_3}\right| = \dfrac{\left|I_{L_3}\right|}{CT_{ratio-3}} = \dfrac{100.4}{200/5} = 2.51\,(A)$

From the relay characteristics, select for B3 relay a 3A tap setting (TS3) which is the lowest TS above 2.51 A

identical p.f.

At B2:

$$\left|I_{L_2}\right| = \frac{\left|S_{L_2} + S_{L_3}\right|}{\sqrt{3}\left|V_2\right|} = \frac{\left|S_{L_2}\right| + \left|S_{L_3}\right|}{\sqrt{3}\left|V_2\right|} = \frac{(4+6)\,MVA}{\sqrt{3} * 34.5\,\text{kV}} = 167.3\,(A)$$

$$\left|I'_{L_2}\right| = \frac{\left|I_{L_2}\right|}{CT_{ratio-2}} = \frac{167.3}{200/5} = 4.18\,(A)$$

From the relay characteristics, select for B2 relay a 5A tap setting (TS2) which is the lowest TS above 4.18 A

Example: solution

<u>At B1</u>:

$$\left|I_{L_1}\right| = \frac{\left|S_{L_1}\right| + \left|S_{L_2}\right| + \left|S_{L_3}\right|}{\sqrt{3}\left|V_1\right|} = \frac{(11+4+6)\,MVA}{\sqrt{3} * 34.5\text{ kV}} = 351.4\,(A)$$

$$\left|I'_{L_1}\right| = \frac{\left|I_{L_1}\right|}{CT_{ratio-1}} = \frac{351.4}{400/5} = 4.39\,(A)$$

From the relay characteristics, select for B1 relay a 5A tap setting (TS1) which is the lowest TS above 4.39 A

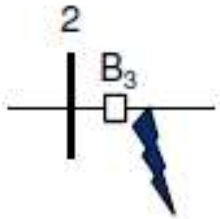
2) Select the Time-dial settings

Relays are coordinated for max fault currents, start with relay furthest from the source

So, start with B3:

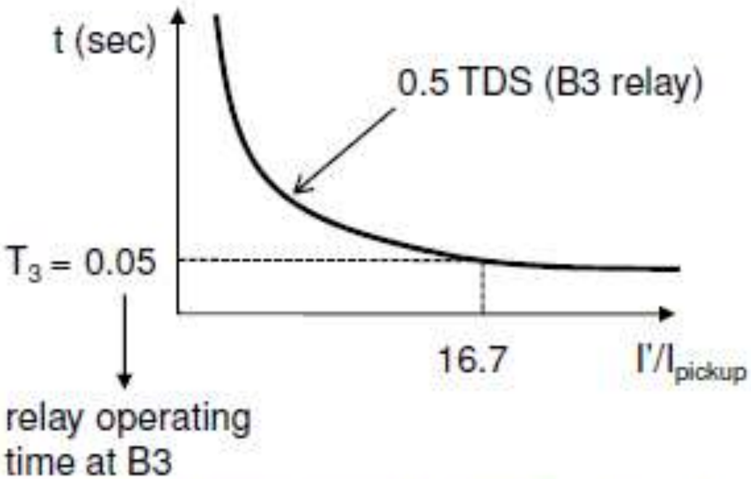
Largest fault current through B3 is 2000A (fault at bus 2, just to the right of B3).

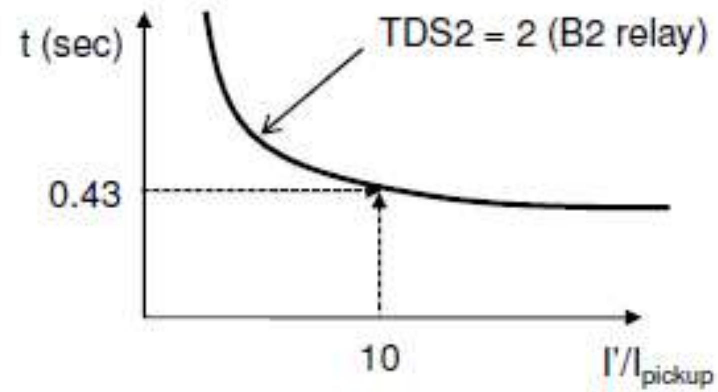
$$\underbrace{\frac{I'_{3fault}}{I_{3pickup}}}_{\text{fault-to-pickup ratio}} = \frac{I'_{3fault}}{TS3} = \frac{2000/(200/5)}{3} = 16.7$$



Example: solution

Since there is no down-stream breaker after B3, the fault should be cleared as fast as possible → Select a 0.5 TDS for B3 relay.





Primary protection clears fault after: $T_3 + T_{breaker} = 0.05 + 5$ cycles (@60Hz) = 0.133 sec

For this same fault, the current seen by B2 is: $\frac{I'_{2fault}}{I_{2pickup}} = \frac{I'_{2fault}}{TS2} = \frac{2000/(200/5)}{5} = 10$

For B2 to be backup of B3, B2 relay should have the operating time:

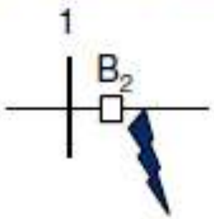
$T_2 = T_3 + T_{breaker} + CTI = 0.05 + 0.083 + 0.3 = 0.43$ sec

→ From the relay characteristics, TDS for B2 = TDS2 = 2.

Example: solution

Now select the TDS for B1 relay

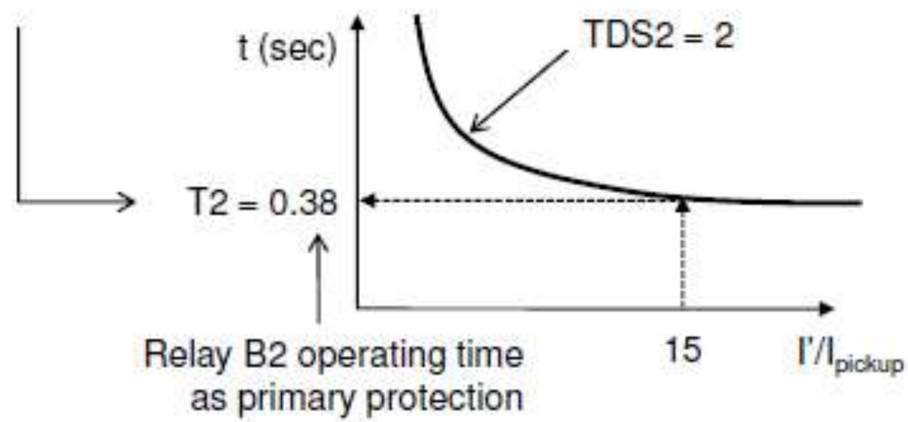
B1 should function as backup for B2. Largest fault current through B2 is 3000 A for a fault at bus 1, just to the right of B2)



$$\frac{I'_{2\,fault}}{I_{2\,pickup}} = \frac{I'_{2\,fault}}{TS2} = \frac{3000/(200/5)}{5} = 15$$

For this same fault, the current seen by B1:

$$\frac{I'_{1\,fault}}{I_{1\,pickup}} = \frac{I'_{1\,fault}}{TS1} = \frac{3000/(400/5)}{5} = 7.5$$



Example: solution

B1 relay should operate after:

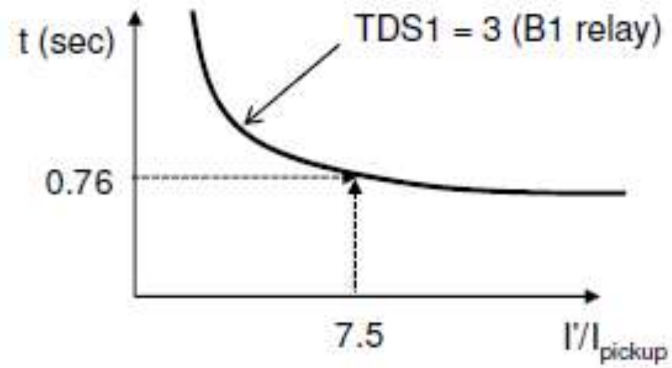
$T_1 = T_2 + T_{breaker} + CTI = 0.38 + 0.083 + 0.3 = 0.76$ sec

→ From the relay characteristics,

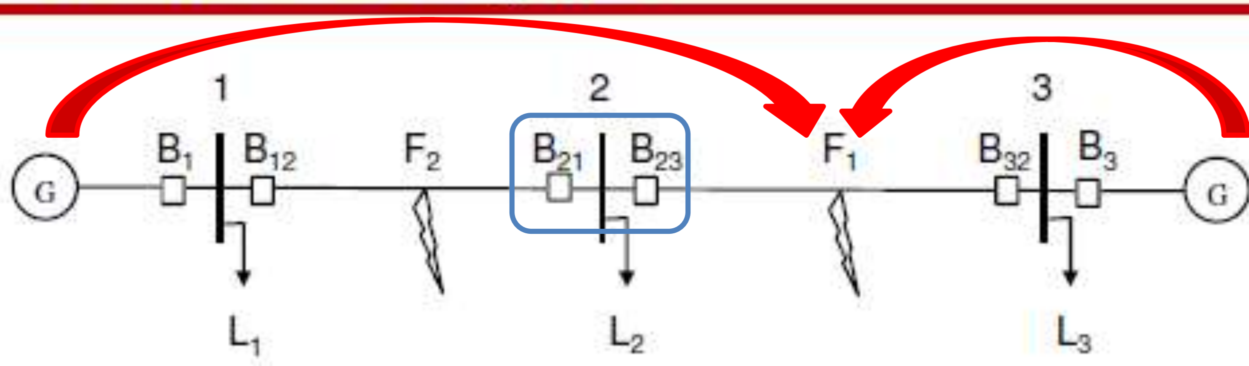
TDS for B1 = TDS1 = 3.

Summary of the result

Breaker	Relay	TS	TDS
B1	CO-8	5	3
B2	CO-8	5	2
B3	CO-8	3	0.5



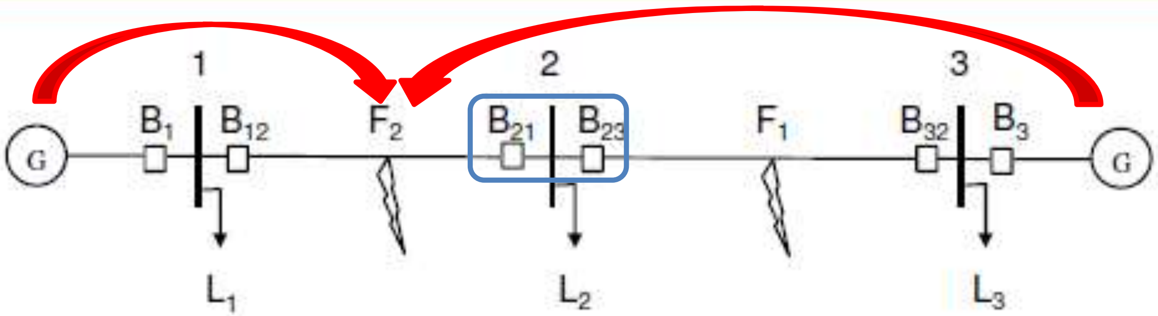
Protection of two-source system



- Fault at F1: B23 and B32 should clear the fault, L1-L3 not interrupted
  - Using the time-delay OC relays, we could set B23 relay faster than B21 relay.
- Now if the fault is at F2 instead: B23 acts before B21 does → L2 is interrupted

→ When a fault can be fed from both sides, the OC relays cannot be coordinated → Using OC relay combined with directional relay.

Protection of two-source system



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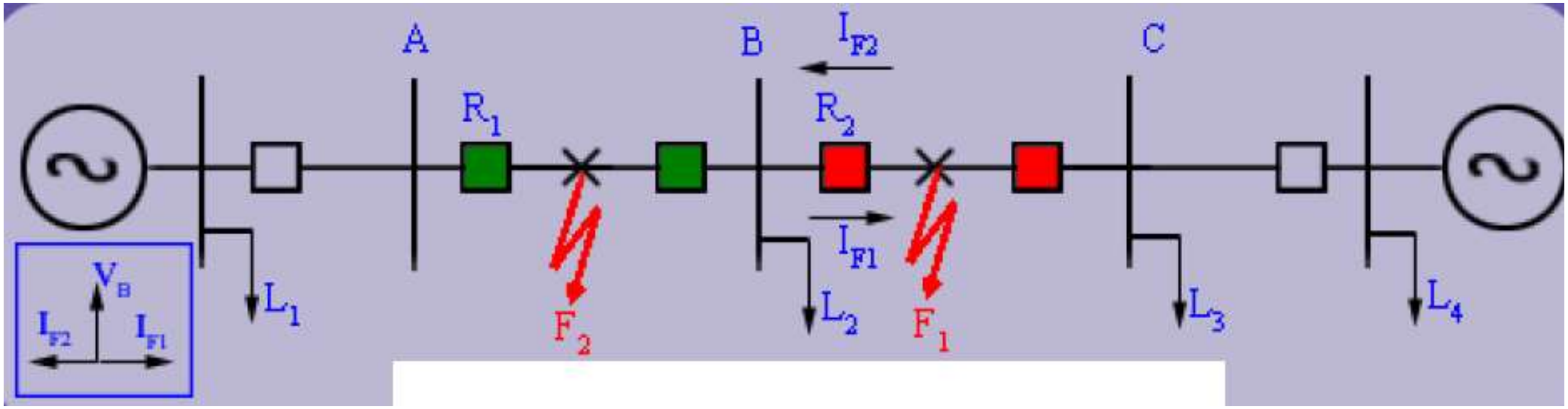
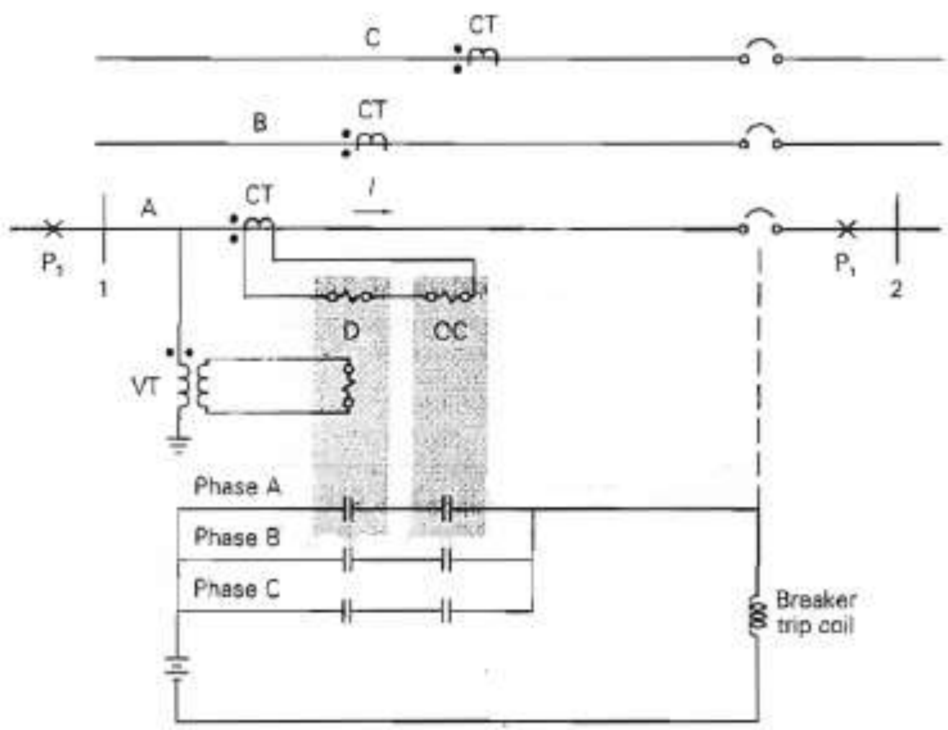
Directional Overcurrent Protection



- The scheme is used in situations for the purpose of **selectivity**,
- For a radial system with source at both ends the relays at both ends of the feeder are required along with phase angle information to interrupt the fault current,.
- For R2, it is not possible to distinguish whether the fault is in the section AB or BC. Since faults in section AB are not in its jurisdiction, it should not trip.
- To obtain selectivity, a directional overcurrent relay is required that uses both magnitude of current and phase angle information for decision making. It is commonly used in sub-transmission networks where ring mains are used.

Directional relay

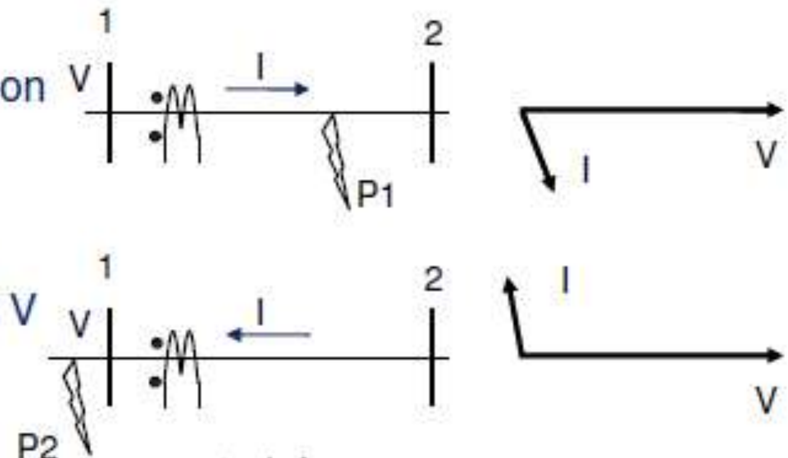
- To operate for fault currents in only one direction
- Combined with OC relays to protect line with two sources



Directional relay in series with over current relay

Directional relay: Operating principle

- Measures both V and I
- Fault at P1 (right of CT): fault current direction from 1→2, current lags bus voltage V by approx. 90^0 (due to line reactance).
  - Fault current in the "forward" direction
- Fault at P2 (left of CT): Fault current I leads V by approx. 90^0
  - Fault current in the reverse direction

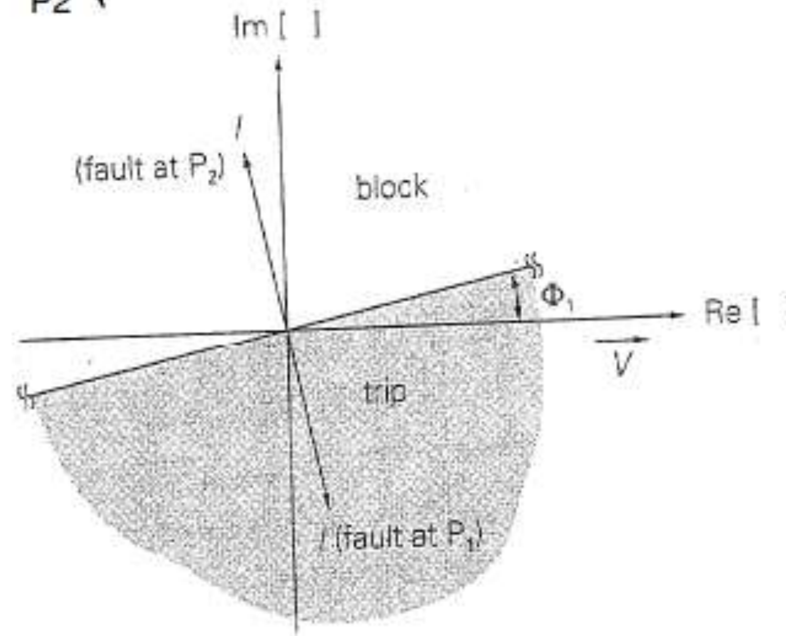


- Inputs of Directional relay (D-relay):
  - The reference voltage $V = V\angle 0^0$ and the current $I = I\angle\phi$
- The relay trip and block regions:

$-180^0 < (\phi-\phi_1) < 0^0$ TRIP

Otherwise BLOCK

where ϕ is the angle of the current with respect to the voltage, and ϕ_1 is typically between 2^0 to 8^0



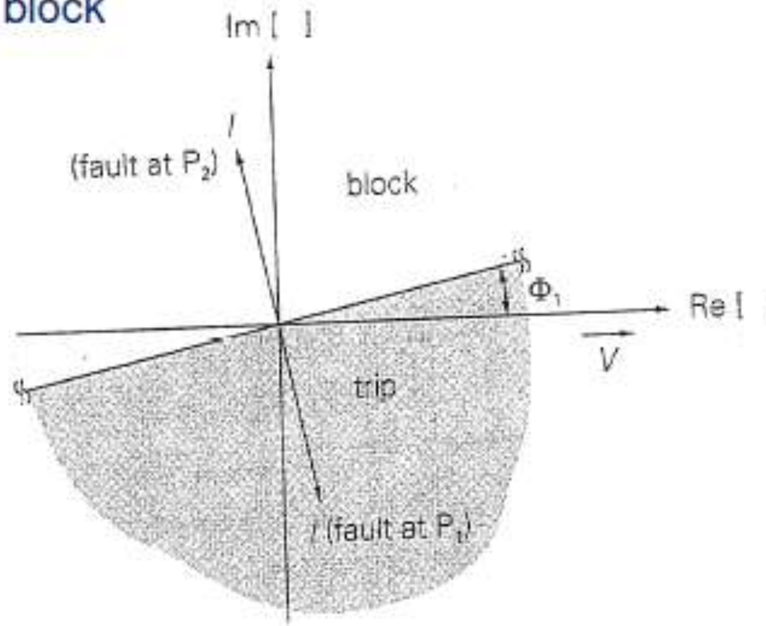
Directional relay: Operating principle

- Torque = k $|V||I|\sin(\phi_1-\phi)$
- For a fault in "forward" direction: $\phi_1-\phi \cong 90^0$ ($\phi<0^0$)

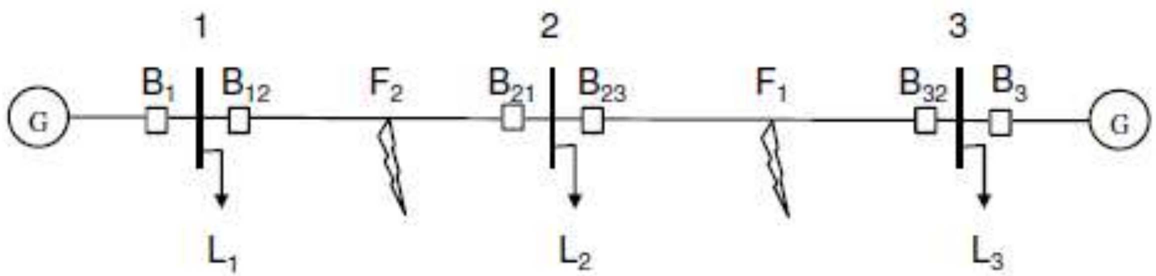
  +Torque → max → close contacts

  Since the contacts of D-relay and OC relay are connected in series → trip coil is energized only when CT secondary current 1) exceeds the OC relay pickup value and 2) is in the forward direction
- For a fault in reverse direction: $\phi_1-\phi \cong -90^0$ ($\phi>0^0$)

  - Torque → max → rotate backward → block



Directional relay coordination



- B12, B21, B23, B32: used with D-relay
- B1, B3: OC relay only. D-relay not required (only one direction of fault current through them)
- Fault at F1:
  - B21 should not operate
  - B12 should coordinate with B23 such that B23 operates before B12 (and B1)
  - B32 should coordinate with B3 such that B32 operates before B3.
- Fault at F2:
  - B23 should not operate
  - B21 should coordinate with B32 such that B21 operates before B32 (and B3)
  - B12 should coordinate with B1 such that B12 operates before B1.

Line protection with impedance (distance) relay

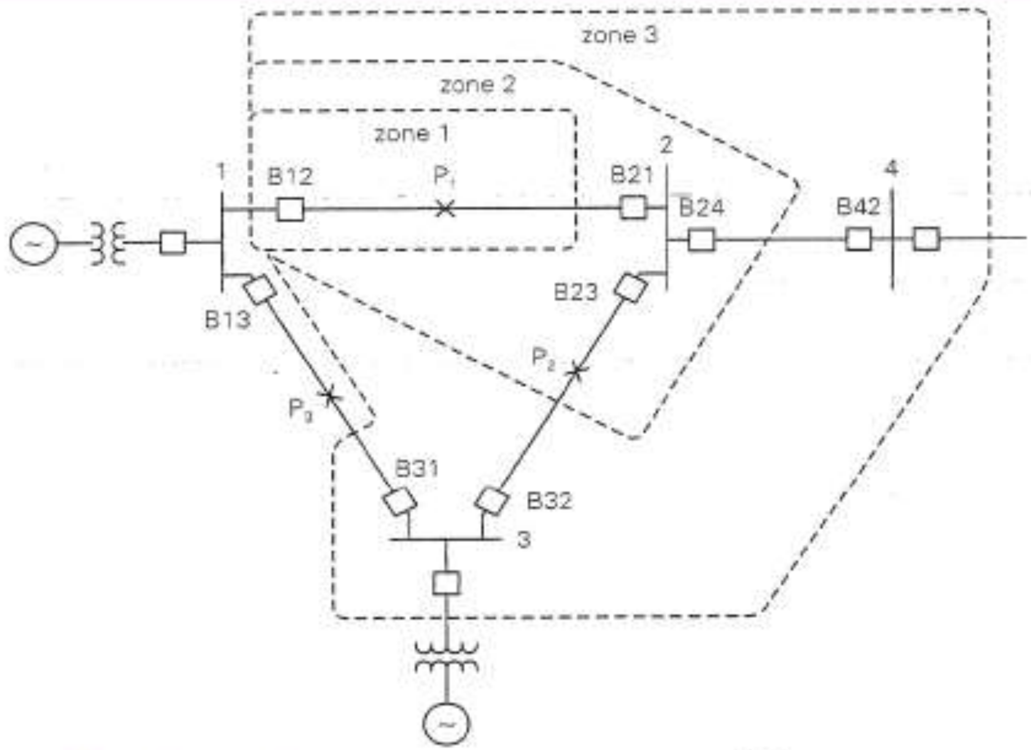
- If there are too many lines and buses to be protected by OC relays, the time delay for the breaker closest to the source becomes excessive.
  - dangerous for the equipment since the fault level at or near the source is very high
- Directional over current relays are difficult to coordinate in transmssion loops with multiple sources.
- Proper coordination becomes difficult

→ Relays use voltage-to-current ratio as input

(voltage-to-current: Impedance, a.k.a. distance or ratio relay)

At fault: $|I| \uparrow$, $|V| \downarrow$ $\Rightarrow \frac{|V|}{|I|} \Downarrow$

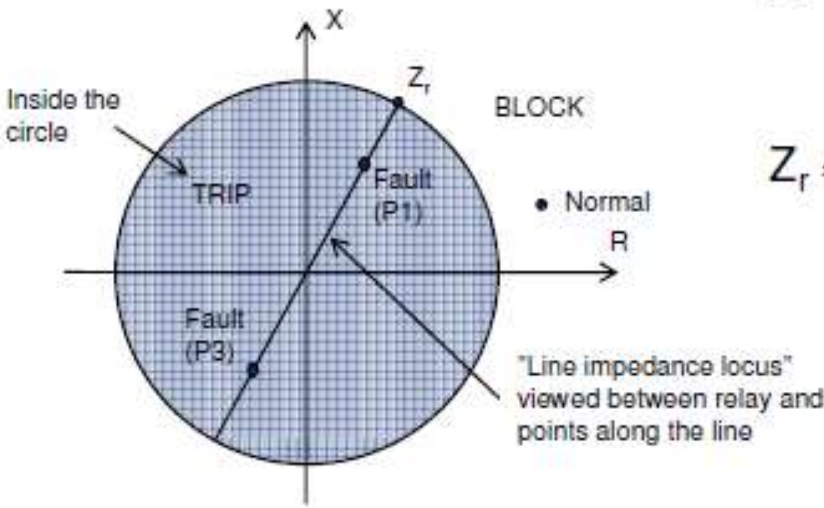
The transmission loop



- Fault at P1: B21<B32 (operating time)
- Fault at P2: B32<B13
- Fault at P3: B13<B21

Not possible in the loop

Block and trip regions



Z = voltage-to-current ratio at relay position

$$Z = \frac{V}{I} \text{ (phasor)}$$

Z_r = adjustable relay setting

TRIP: $|Z| < |Z_r|$

BLOCK: $|Z| > |Z_r|$

Impedance relay for breaker B12: $Z = \frac{V_1}{I_{12}}$

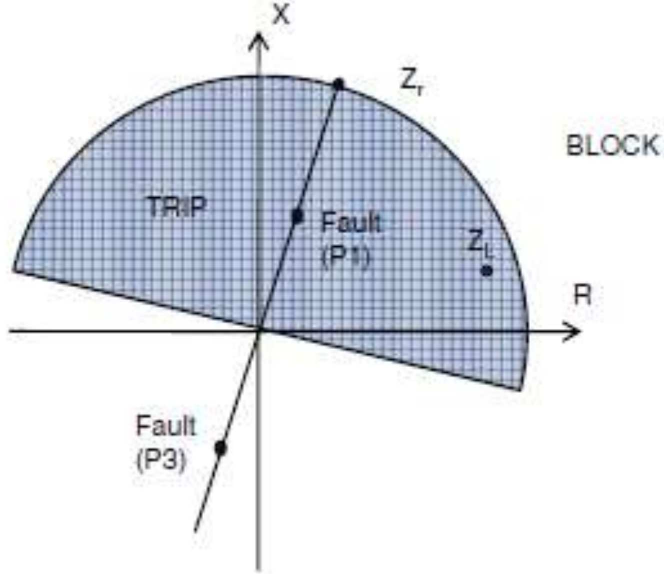
Normal operation: $|Z| >> |Z_r|$ → block

Fault at P1: $|Z| < |Z_r|$ → trip
↓
Z of line from relay to fault position

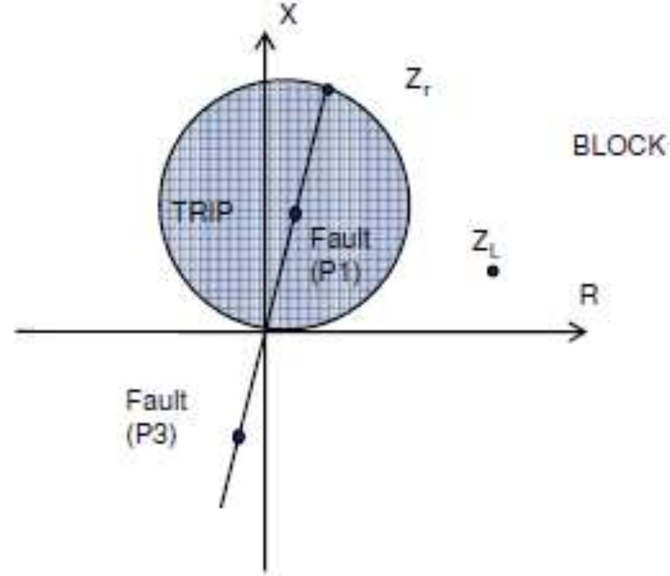
Fault at P3: $|Z| < |Z_r|$ → trip
↓
Negative of Z of line from relay to fault position

Impedance relay not directional → MODIFIED

Impedance relay with directional capability



Impedance relay with
directional restraint



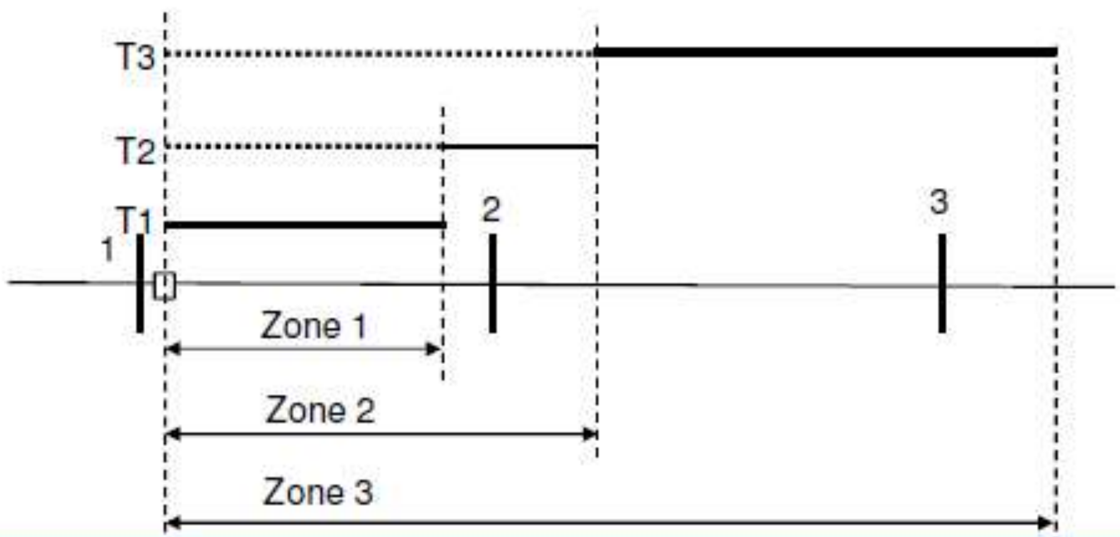
Modified impedance relay

better than direction restraint in
selectivity for high power factor load

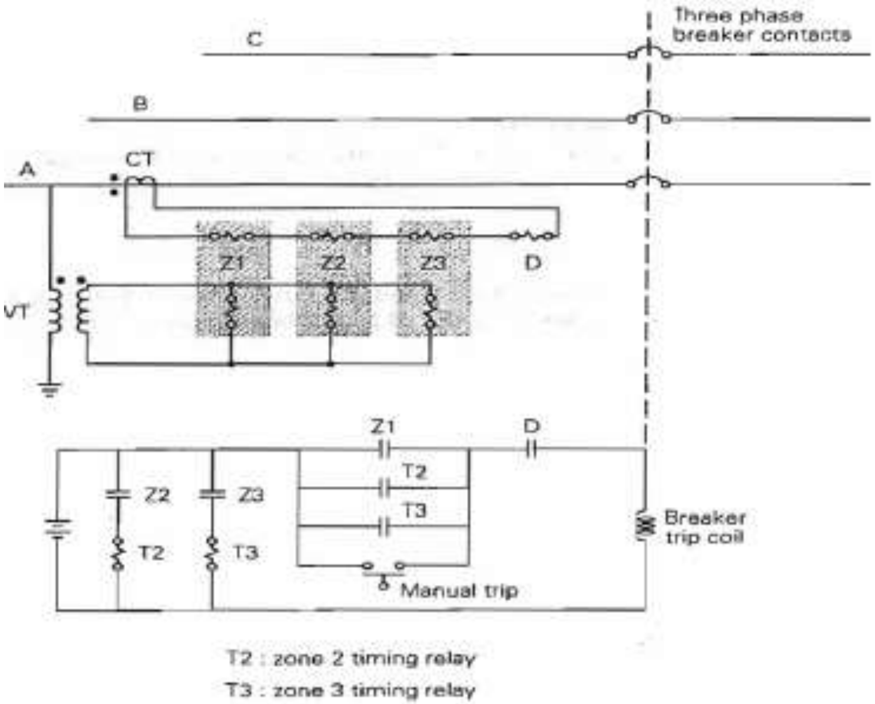
Reach of relay

Reach = How far down the line the relay can detect the faults
→ Typically 80% of line length

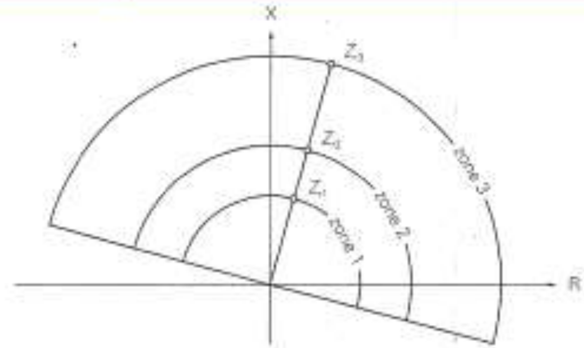
- Zones of protection: 3 zones with increasing reaches and longer time delays, provided by 3 directional impedance relays per phase:
- The setting of reach can vary, some typical settings are:
  - Zone-1: 80% reach, instantaneous operation (primary, no time delay)
    - 80%: to avoid trippiping of the fault near the other end of the line
  - Zone-2: 120% reach, 0.2 to 0.3 sec time delay
    - primary for the remaining 20% of the line (with time delay) and backup for the part of the next line.
  - Zone-3: 100% reach + 120% of the next line, 1 sec time delay, provides backup for the next lines



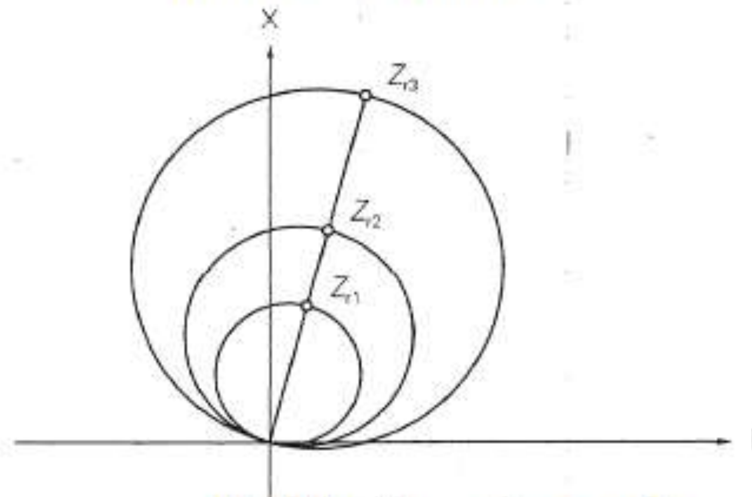
Three zone directional distance relay



Relay connections



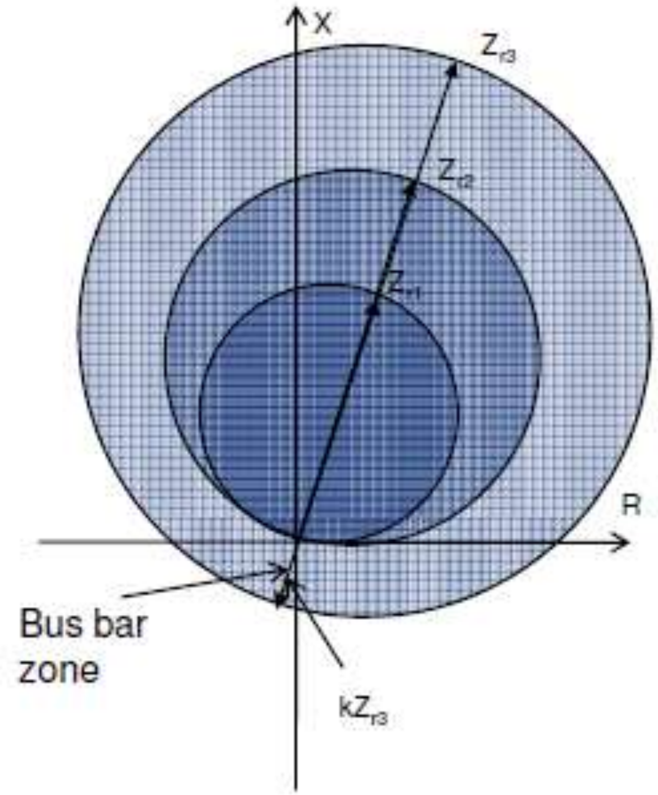
Impedance relay with directional restraint



Modified impedance relay

Setting for reverse reach

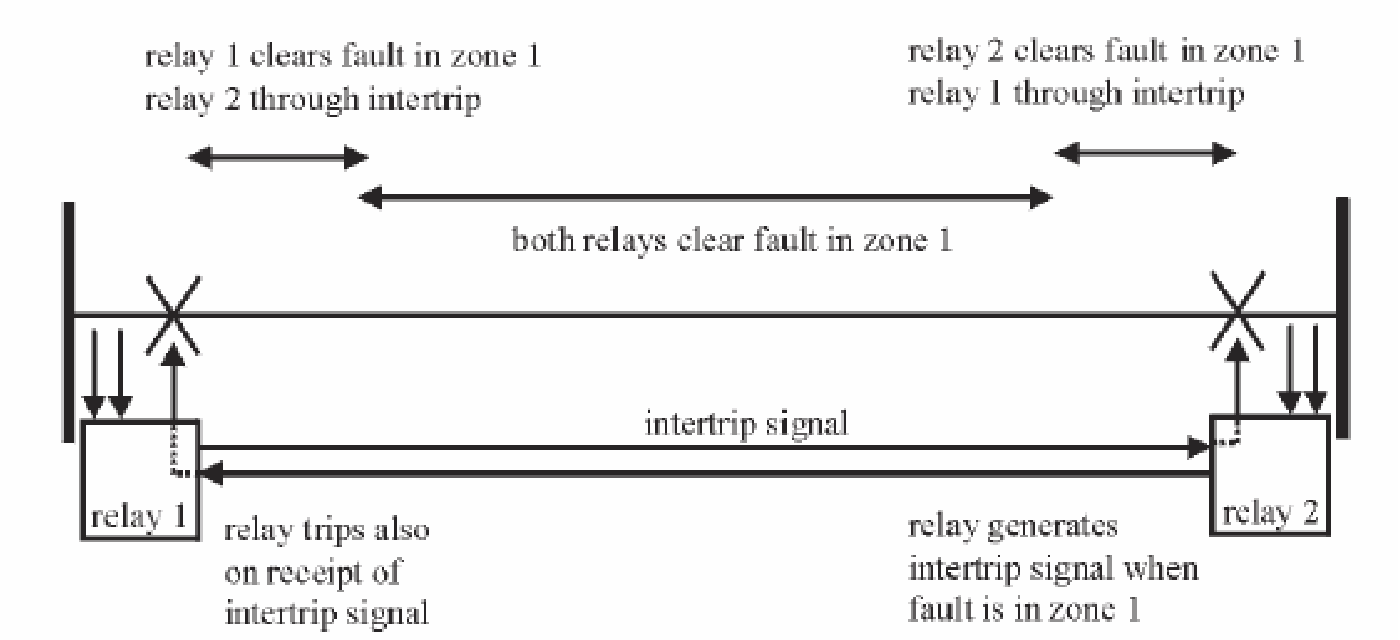
- The aim is to provide backup protection of the local bus-bar
- One of the forward looking zone (typically zone 3) could be set with a small reverse off-set reach from the origin of the X-R diagram, in addition to its forward reach setting
  - Forward reach Z_{r3}
  - Backward reach kZ_{r3}



Communication between relays: Increase speed

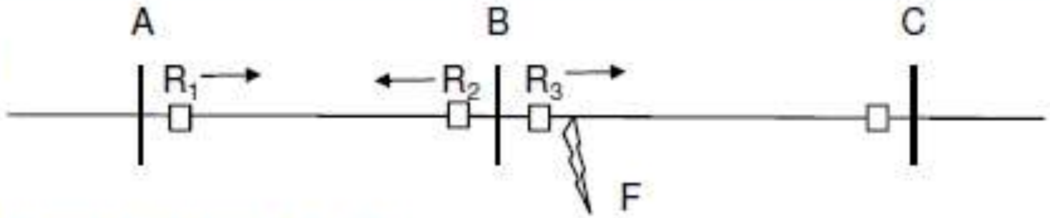
1. **Intertripping**

- Speeds up the clearing of faults towards the remote line terminal
- When one of the two relays detects a fault in its zone 1, it generates a trip signal for the local circuit breakers and a so-called intertrip signal to the remote breakers.
- Failures of communications: revert to the original scheme (i.e. each relay trips in the zone it sees the fault)



Communication between relays: Increase speed

2. Blocking over-reach



R1: Over-reach:

Zone 1 has a reach longer than the line A-B

- Fast tripping for the entire line AB
- Problem when fault is outside A-B

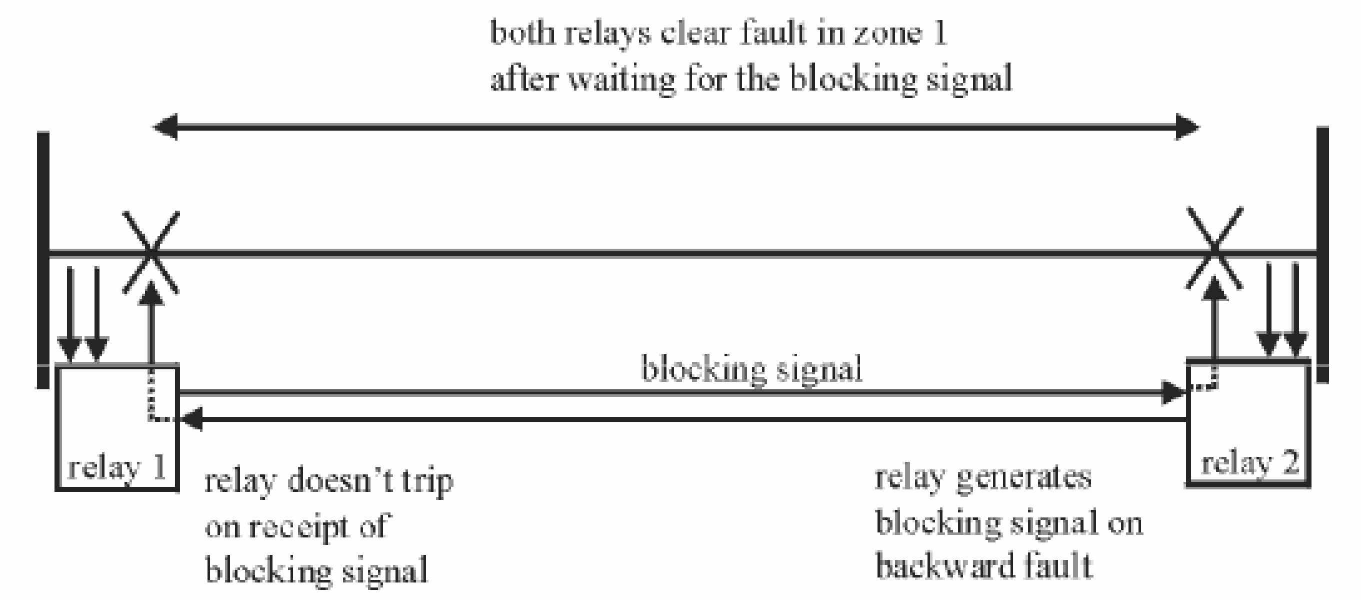
For a fault at F: both R1 and R3 trips in Zone 1. Both A-B and B-C are out!

Solutions:

- R2 is bi-direction (with reverse reach) → R2 senses fault in B-C (backward fault).
- R2 does not trip, but sends blocking signal to R1, so only R3 trips
- R1 will send the trip signal when no blocking signal is received after a certain time delay (depending on speed of fault detection and communication)
- If communication fails → R1 will trip: False but safe.

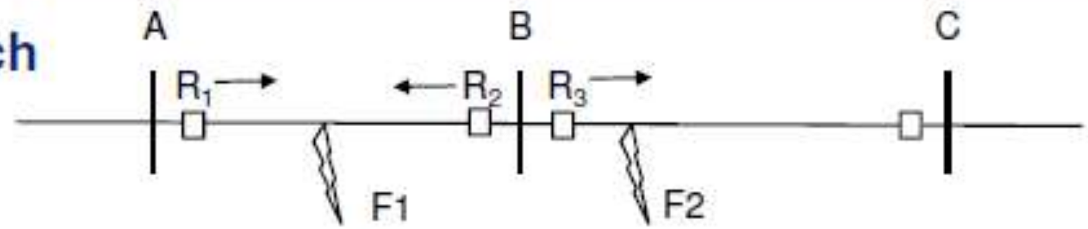
Communication between relays: Increase speed

2. Blocking over-reach



Communication between relays: Increase speed

3. Permissive over-reach

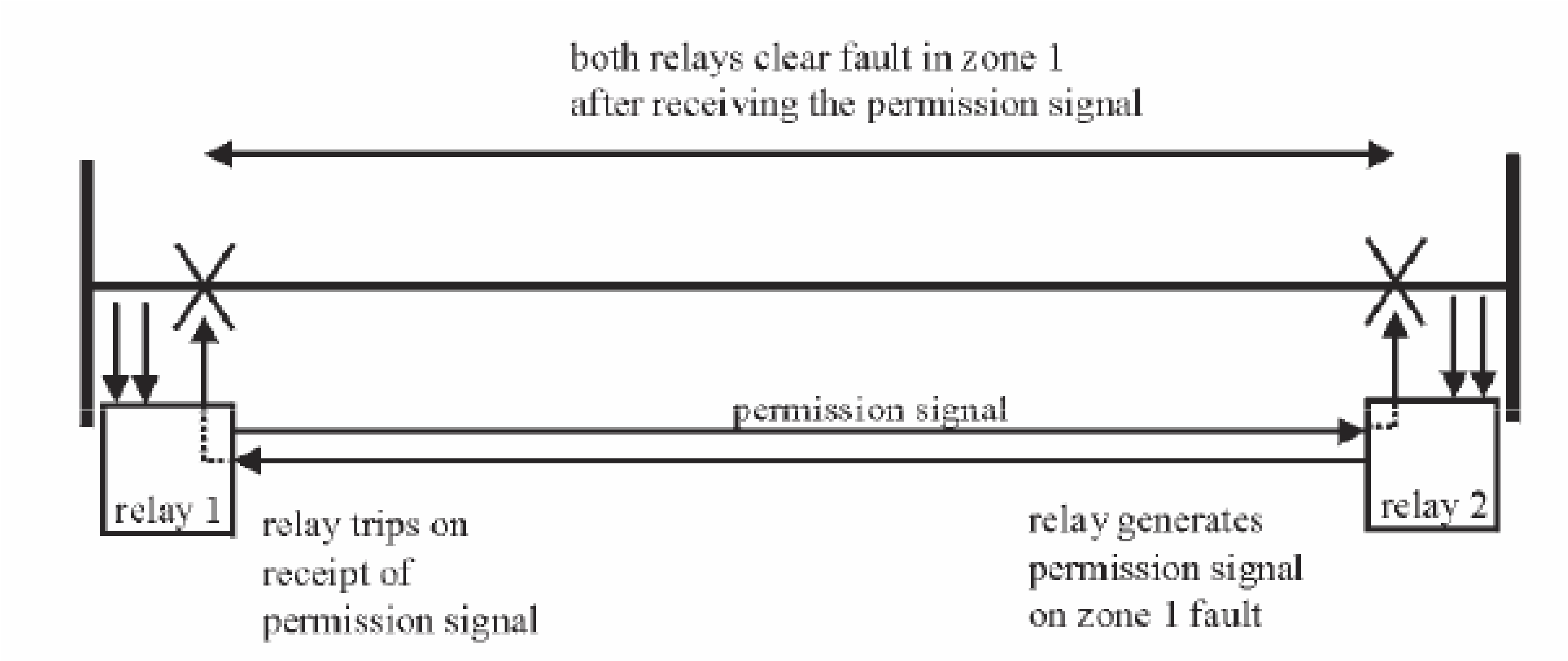


Similar to blocking over-reach, but:

- Fault at F1:
  - R1 and R2 trip after receiving permission signals from R2 and R1, respectively.
- Fault at F2:
  - R2 does not send trip signal to R1 → R1 does not trip
  - R3 trips in Zone 1
- Communication fails for fault at F1, R1 and R2 do not trip → Problem!
  - Redundancy in communication
  - Built-in logic: if permission is not received and fault persists → Trip after some delay.

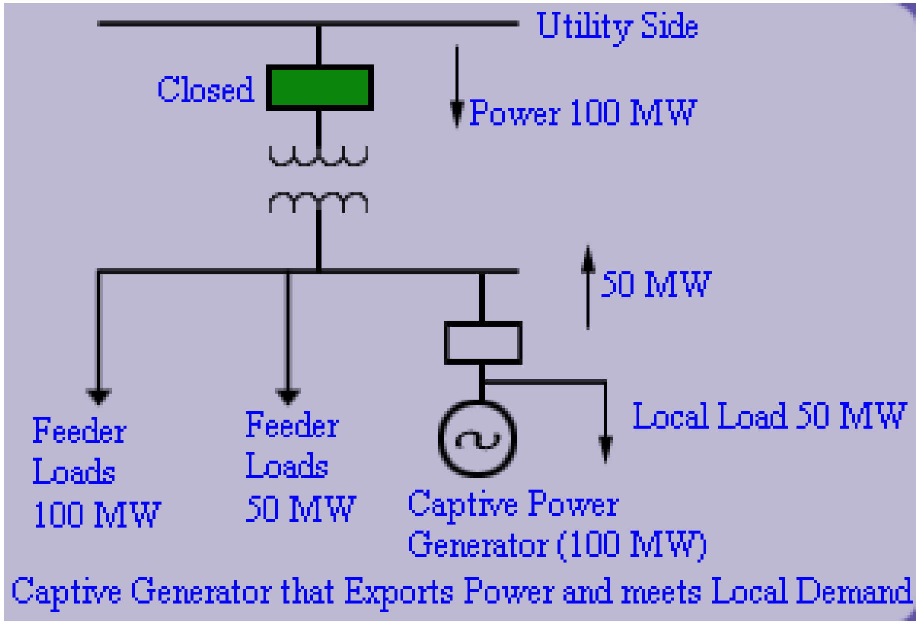
Communication between relays: Increase speed

3. Permissive over-reach



SYSTEM PROTECTION

System Protection Relays



Medium voltage distribution system having local generation (e.g., captive power generation) which is also synchronized with the grid. During grid disturbance, if plant generators are not successfully isolated from the grid, they also sink with the grid, resulting in significant loss in production and damage to process equipment.

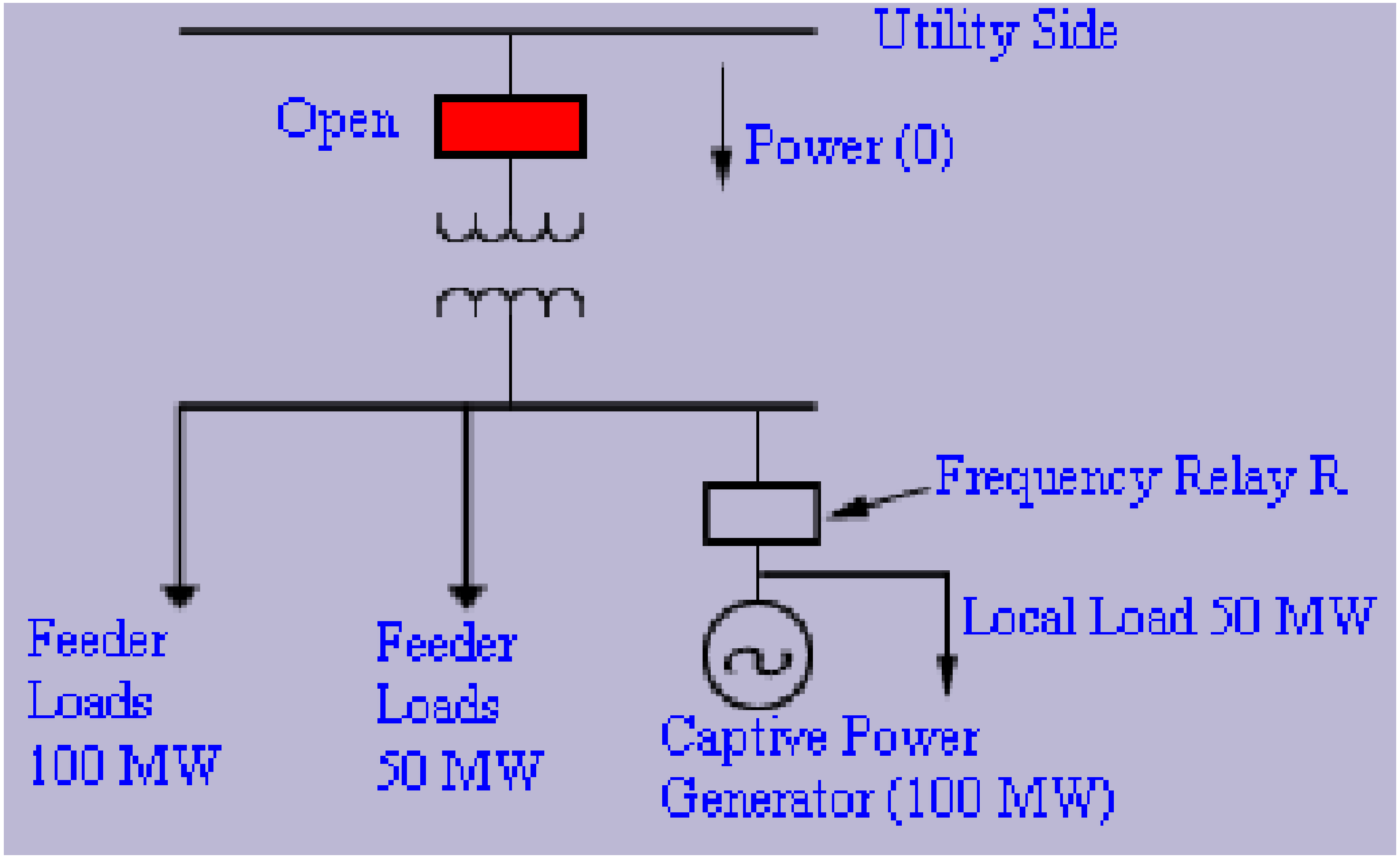
The following relays are used to detect such disturbances, its severity and isolate the in plant system from the grid.

- Under frequency and over frequency relays.
- Rate of change of frequency relays.
- Under voltage relays.
- Reverse power flow relays

System Protection Relays

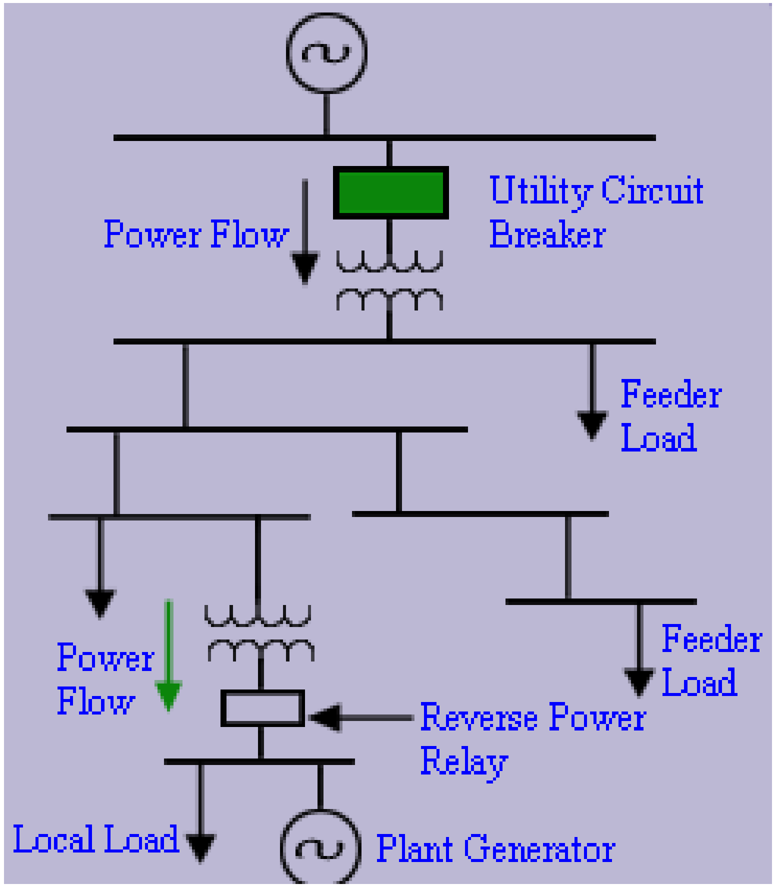
- Under-frequency Relay and Rate of Change of Frequency Relay
  - In case of a grid failure, captive generators tend to supply power to other consumers connected to the substation. The load-generation imbalance leads to fall in frequency.
  - The under-frequency relay R detects this drop and isolates local generation from the grid by tripping breaker at the point of common coupling.
  - After disconnection from the grid, it has to be ascertained that there is load-generation balance in the islanded system. Because of the inertia of the machines, frequency drops gradually. To speed up the islanding decision, rate of change of frequency relays are used.

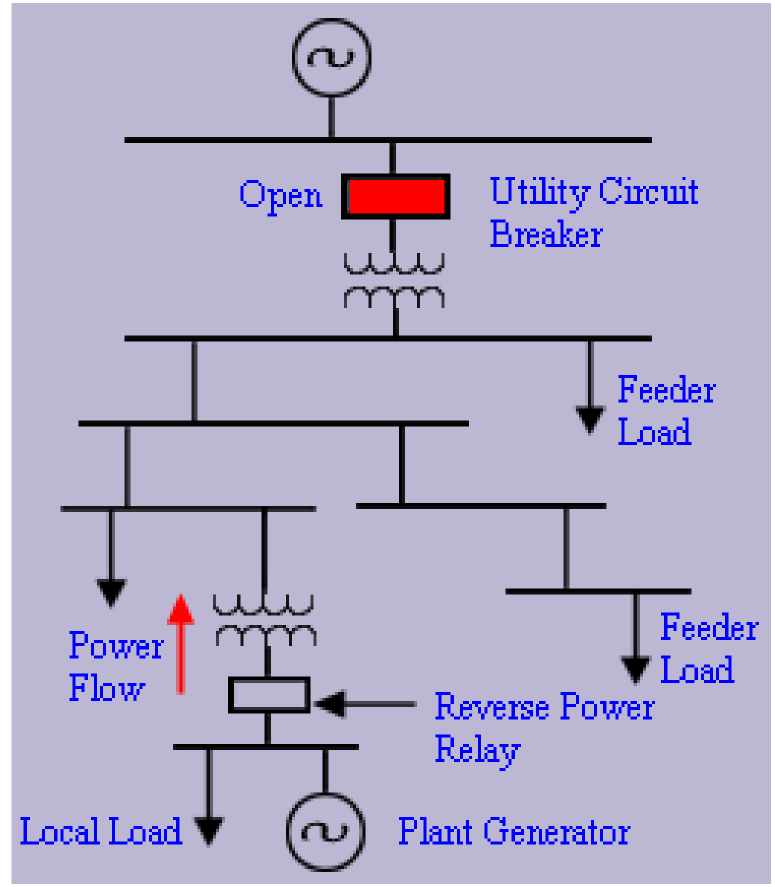
Under-frequency Relay and Rate of Change of Frequency Relay



System Protection Relays

- Under-voltage Relay
  - Whenever there is an un-cleared fault on the grid close to the plant, the plant generators tend to feed the fault, and the voltages at the supply point drops. This can be used as a signal for isolating from the grid.
- Reverse Power Relay
  - Distribution systems are radial in nature. If there is a fault on the utility's distribution system, it may trip a breaker thereby isolating plant from the grid. This plant may still remain connected with downstream loads as shown in figures.





Consequently, power will flow from the plant generator to these loads. If in the pre-fault state, power was being fed to the plant, then this reversal of power flow can be used to island the plant generation and load from the remaining system. This approach is useful to detect loss of grid supply whenever the difference between load and available generation is not sufficient to obtain an appreciable rate of change of frequency but the active power continues to flow into the grid to feed the external loads.

System Protection Relays

- Lightning Protection
  - Many line outages result from lightning strokes that hit overhead transmission lines.
  - Lightning discharges normally produce overvoltage surges which may last for a fraction of second and are extremely harmful.
  - The line outages can be reduced to an acceptable level by protection schemes like installation of earth wires and earthing of the towers
- Classification of Lightning over-voltages
  - Induced over-voltages which occur when lightning strokes reach the ground near the line.
  - Over-voltages due to shielding failures that occur when lightning strokes reach the phase conductors.
  - Over-voltages by back flashovers that occur when lightning stroke reaches the tower or the shield wire.

System Protection Relays

- **<u>Protection against lightning surges</u>**:
  - Shielding by earth wires: Normally, transmission lines are equipped with earth wires to shield against lightning discharges. The earth wires are placed above the line conductor at such a position that the lightning strokes are intercepted by them. In addition to this, earthing of tower is also essential.
  - Lightning Arrestors: An alternative to the use of earth wire for protection of conductors against direct lightning strokes is to use lightning arrestors in parallel to insulator strings. Use of lightning arrestors is more economical also. ZnO varistor is commonly used as lightning arrestor because of its peculiar resistance characteristic. Its resistance varies with applied voltage, i.e, its resistance is a nonlinear inverse function of applied voltage. At normal voltage its resistance is high. But when high voltage surges like lightning strokes appear across the varistor, its resistance decreases drastically to a very low value and the energy is dissipated in it, giving protection against lightning.