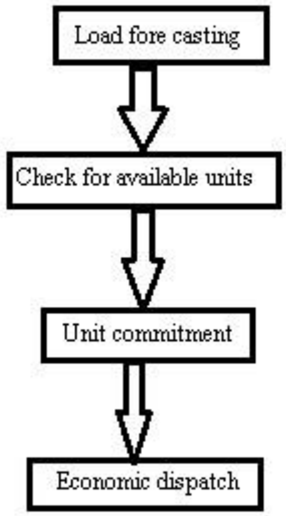
ECONOMIC LOAD DISPATCH

The power output of a base load power plant is constant. Nuclear power plants work as base power plants as it is very difficult to control the output power of nuclear power plants. Hydro power plants, the fuel cost for the generation of power is almost zero. So the power from hydro power plants will be utilized without considering economic load dispatch. The steps involved in electronic load dispatch:



The previous day load curve is the base for load forecasting. Generally we will do economic load dispatch under plant level. According to the available units, we will get per unit cost of the generation. The unit commitment decides how many units must be on and which unit must be on (unit selected which have less per unit cost). The unit commitment gives the commitment status of all the units. In economic dispatch the power demand is distributed among the selected units in unit commitment based on the fuel cost of the unit. The units which have less fuel cost, more power is taken from that unit. The final solution is the power output of all the committed units.

Unit commitment problem:

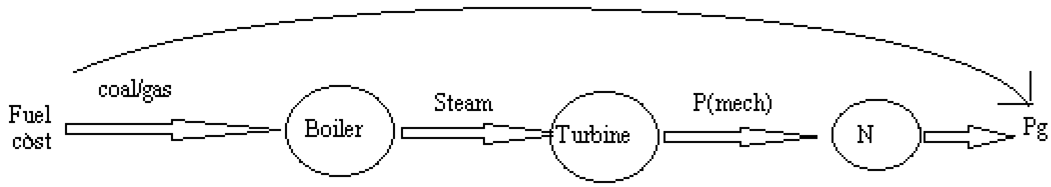
The main objective of unit commitment problem is to minimize the fuel cost of thermal generating units and to decide the commitment status of all the units which are participated in economic dispatch

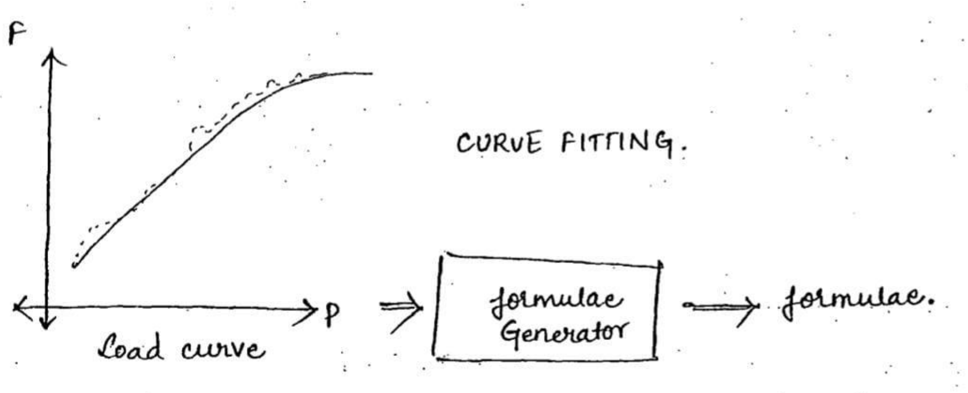
Economic dispatch problem

Main objective of the economic dispatch problem is to minimize the fuel cost of thermal generating units and to decide the power output of all the units.

NOTE:

The assumption for solving the economic dispatch problem is “all the units which are given are continuously ON”.





Fuel cost equation of a thermal power plant

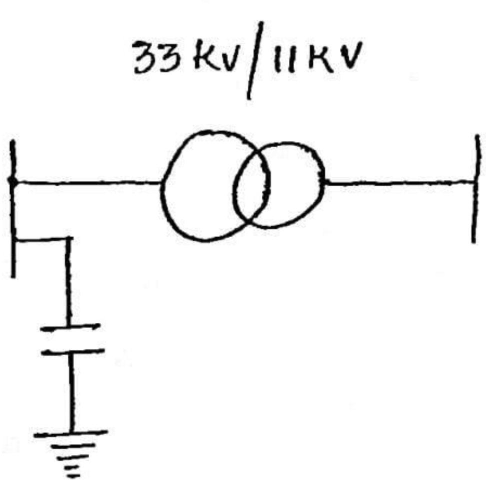
It gives the relation between fuel cost of the unit with respect to power generation; it is an empirical formula.

$F_i = \frac{1}{2} a_i {P_i}^2 + b_i P_i + c_i$ Rs/hr

Where a_i, b_i, c_i are cost coefficients of i^{th}unit

$P_i$is the power output of i^{th}unit in MW.

Generally capacitor banks are connected on the high voltage side as more reactive power is generated.



$$Q_{gen} = \frac{V^2}{X_c}$$

As $P = \sqrt{3} V_L I_L pf$

If P $\uparrow, I_L \uparrow, {I_L}^2 R \uparrow, heat\ generation \uparrow$

If change in temperature is more than the condition is undesirable for operation and insulation so in order to controlΔT, heat generation is controlled and P has to be controlled so the power output is always limited to P_{imax}. The P_{imax} is decided by the Thermodynamics constraints of the boiler or fixed due to boiler unstability. Generally to switch on a plant it requires a minimum time of 6-8 hours.

Checklist to ensure turn on of plant(some are given)

- Verify the coal storage level in the coal handling plant. It should be more than the dead storage.
- Temperature of the boiler from ambient temperature to require temperature (temperature greater than critical temperature)
- Synchronize generator with grid (voltage frequency, voltage phase, voltage value).
  In order to ensure a temperature greater than critical temperature always, $P_{imin}$is to be maintained even for proper synchronisation of generators. To operate the boiler in a stable zone critical temperature is maintained in the boiler. With respect to critical temperature in the boiler there is a minimum mechanical input to the generator, so there is a minimum electrical output.

Incremental fuel cost of thermal power plant

Mathematically it is defined as

$I_{ci} = \frac{\partial F_i}{\partial P_i}$ Rs/MWhr

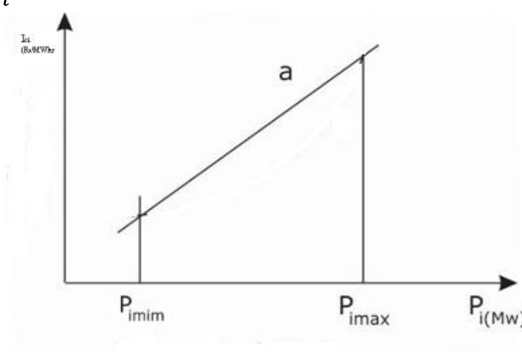
$F_i = \frac{1}{2} a_i P_i^2 + b_i P_i + c_i$ Rs/hr

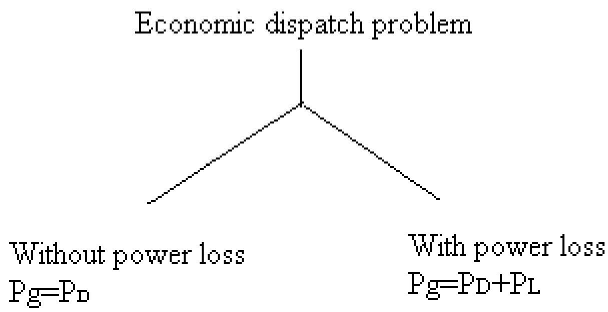
$I_{ci} = a_i P_i + b_i \ Rs/MWhr$ incremental cost of i^{th} unit

If Power output should be more, then incremental cost of the unit is more.

Incremental cost curve

It is the curve between I_c Vs $P_i$of the unit.





Where Pg is power generated and PD is power demand.

Optimization problem

1. Objective function

It refers to either minimization problem or maximization problem. min{f(x)=$x_1{}^2 + x_2{}^2$}
In power system, objective function is min{$F_T = F_1 + F_2 + F_3 + \ldots.. F_N$
Other examples: maximize the power transfer, minimise the distribution losses.

2. Constraints

It is the equation representation of requirements.
equality constraints: =
inequality constraints: >,< etc
Eg; $x_1 + x_2 = 5$: equality constraints
$0 \leq x_1 \leq 2$: inequality constraints

3. Optimization methods

Eg: $[x_1 \;\; x_2] = [\;\;]$
The solution can be,

1. Valid solution vector : satisfies all constraints
2. invalid solution vector : if even one constraint not satisfied
3. final solution vector : it is valid solution vector and it should give minimum value

If a solution vector satisfies all the constraints of an Optimisation problem then it is a valid solution vector. If a solution vector is not satisfied by even one constraint of an optimization problem then it is called invalid solution vector. The final solution vector should be a valid solution vector and it has to give minimum value for or objective function for a minimization problem or maximum value for an objective function for maximization problem.

ECONOMIC DISPATCH WITHOUT POWER LOSS

Objective:

Minimize the total fuel cost of thermal generating units.

$\min\{F_T = F_1 + F_2 + F_3 + \ldots\ldots F_N\} = \min\{F_T = \sum_{i=1}^{N} F_i\}$

Constraints:

(i) Equality constraints

Total power generation=total power demand

$P_g = P_D$

$P_1 + P_2 + P_3 + \ldots.. P_N = P_D$

$P_D - \sum_{i=1}^{N} P_i = 0$

(ii)Inequality constraints

- Limits on active power generated by the unit: $P_{imin} \leq P_i \leq P_{imax}$, i=1 to N
- Limits on reactive power generation : $Q_{imin} \leq Q_i \leq Q_{imax}$
- Limits on busbar voltages: $V_{jmin} \leq V_j \leq V_{jmax}$

(iii) $P_D = 150MW$

$P_1 = 63.64MW$,$P_2 = 86.36MW$, $I_{C1} = 26.3636Rs/MWh$, $I_{C2} = 26.3636Rs/MWh$, $\lambda^s =$ I_{C1}=I_{C2}=26.3636 Rs/MWh

(iv)$P_{Dmin} = P_{1min} + P_{2min} + \ldots\ldots P_{Nmin} = 20 + 20 = 40MW$

Ex: $I_{C1} = 0.15P_1 + 15$, $I_{C2} = 0.12P_2 + 10$, $I_{C3} = 0.1P_3 + 20$ All are Rs/MWh

P_1 in between 15MW and 150MW,

P_2 in between 10MW and 100MW

P_3 in between 25MW and 250MW

$$P_D = 50MW$$

$P_1 + P_2 + P_3 = 50MW$,

$P_1 = 15MW$,$P_2 = 10MW$,$P_3 = 25MW$

Note: If the demand given in the problem is P_{Dmin},then solution for economic dispatch problem is,

$P_1 = P_{1min}$,$P_2 = P_{2min}$,$P_3 = P_{3min}$ and so on.

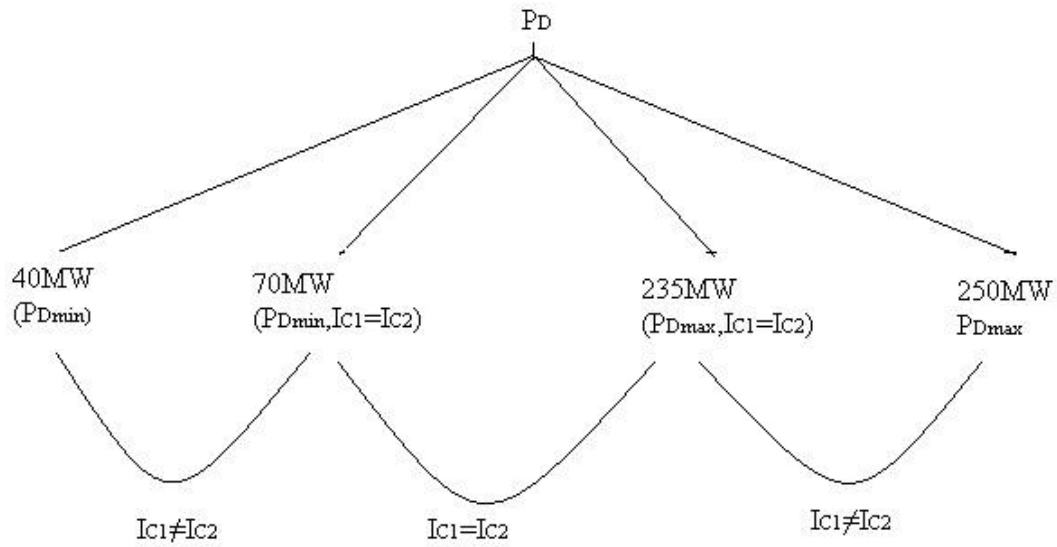
Solving for P_{Dmin} with $I_{C1} = I_{C2}$

1. Calculate P_{Dmin}
2. If $P_D = P_{Dmin}$, Calculate $P_1, P_2, P_3 \ldots\ldots P_N$, Calculate $I_{C1}, I_{C2}, I_{C3} \ldots\ldots I_{CN}$
3. Calculate $I_{Cmax} = max\{I_{C1}, I_{C2}, I_{C3} \ldots\ldots I_{CN}\}$
4. $I_{C1} = I_{Cmax} \Rightarrow P_1$,$I_{C2} = I_{Cmax} \Rightarrow P_2$,$I_{C3} = I_{Cmax} \Rightarrow P_3$ and so on.
5. $P_{Dmin}(I_{C1} = I_{C2}) = \sum P_i$

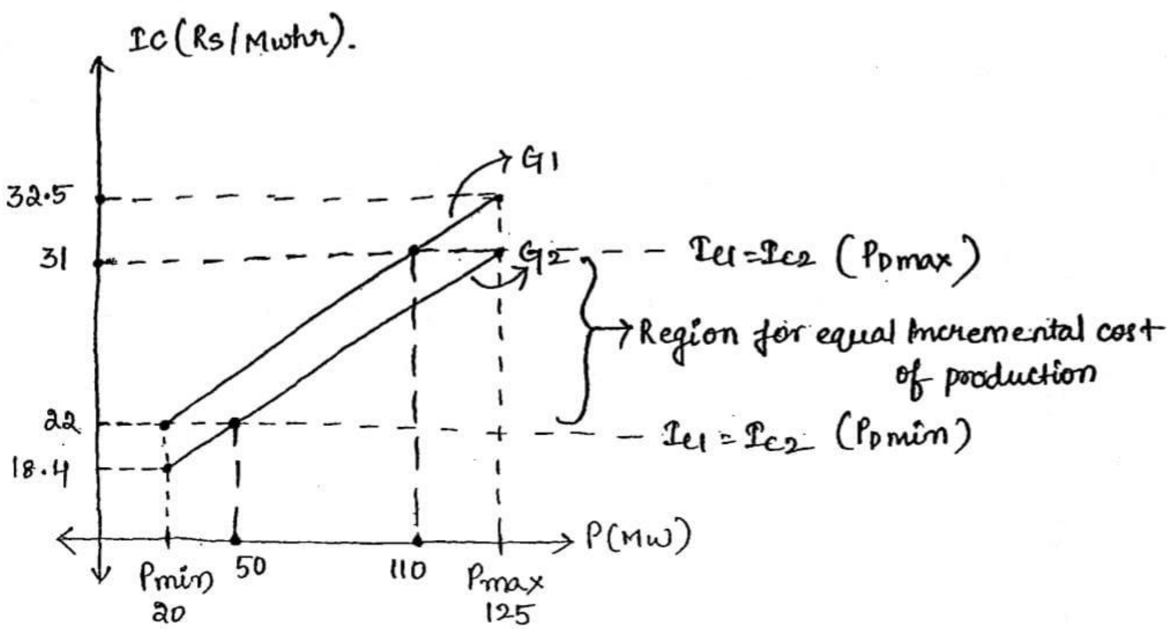
Solving for P_{Dmax} with $I_{C1} = I_{C2}$

1. Calculate P_{Dmax}
2. If $P_D = P_{Dmax}$, Calculate $P_1, P_2, P_3 \ldots\ldots P_N$, Calculate $I_{C1}, I_{C2}, I_{C3} \ldots\ldots I_{CN}$
3. Calculate $I_{Cmin} = min\{I_{C1}, I_{C2}, I_{C3} \ldots\ldots I_{CN}\}$

4. $I_{C1} = I_{Cmin} \Rightarrow P_1, I_{C2} = I_{Cmin} \Rightarrow P_2, I_{C3} = I_{Cmin} \Rightarrow P_3$ and so on.
5. $P_{Dmax}(I_{C1} = I_{C2}) = \sum P_i$



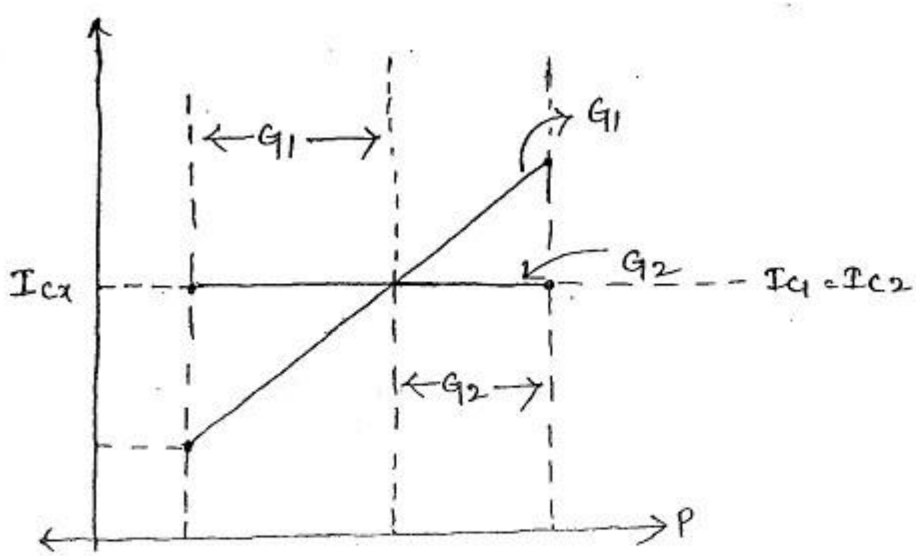
Case 1:



Conclusion 1:

- ★ There exists a region for equal incremental cost of production.
- ★ Generator 2 is the minimum cost generator throughout the operating region.
- ★ For any given demand, P2>P1 (Except P_{Dmin} and P_{Dmax})

Case 2:



- ➢ Limits on power flow through the transmission line, $|S_k|<|S|_{kmax}$
- ➢ Limits on ramp up price
- ➢ Ramp down rate
- ➢ Security constraints

Optimisation method:

Using Lagranzian method, In 1971 by Khuntucker.

$\min\{\alpha = F_T + \lambda(P_D - \sum_{i=1}^{N} \quad P_i\}$

α is Lagranzian function or fitness function or Augmented cost function

λ is Lagranzian coefficient or Lagranzian multiplier

$$\frac{\partial \alpha}{\partial P_i} = 0 \Rightarrow 0 = \frac{\partial F_T}{\partial P_i} + \lambda(0-1)$$

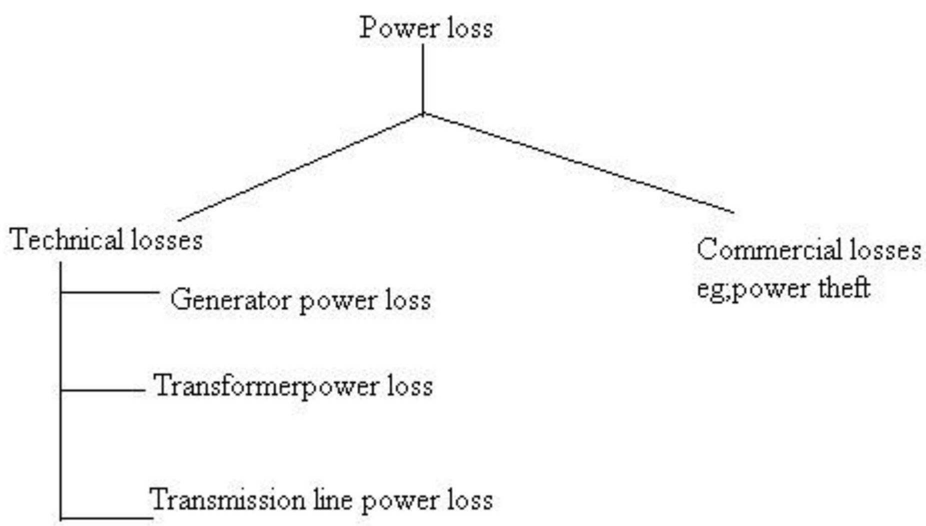
$0 = I_{ci} - \lambda, \lambda = I_{ci}$Rs/MWh

$\frac{\partial \alpha}{\partial P_1} = 0 \Rightarrow \lambda = I_{c1}, \frac{\partial \alpha}{\partial P_2} = 0 \Rightarrow \lambda = I_{c2} \ldots\ldots\ldots \frac{\partial \alpha}{\partial P_N} = 0 \Rightarrow \lambda = I_{cN}$

$\lambda = I_{c1} + I_{c2} = \ldots\ldots\ldots I_{cN}$: Condition for minimum fuel cost solution or coordination equation or Khuntucker equation.

To get the minimum fuel cost solution for the economic dispatch problem without power loss the incremental fuel cost of all the generating units should be equal.

ECONOMIC POWER DISPATCH WITH POWER LOSS



Examples for generator power losses: core loss, copper loss, mechanical loss etc
Examples for T/F power losses: core loss, copper loss etc(neglected)
Examples for T/L power losses: copper loss
In Indian power system,

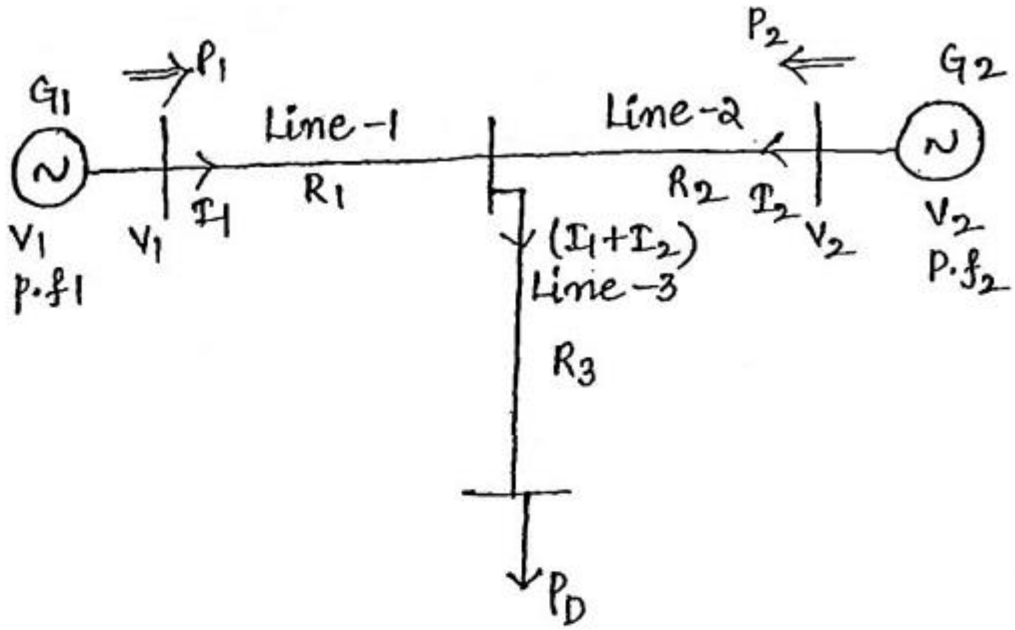
- Primary transmission: 220kV/400kV (generating station to grid)
- Secondary transmission: 132kV/220kV/110kV (grid to load)
- Interconnected transmission: 400kV/765kV (grid to grid)

Highest Generating voltage: 25kV.
NTPC Ramagundam: 25kV, 500 MVA
Highest transmission voltage: 765kV
Highest HVDC link: $\pm$500kV, $\pm$800kV(under construction)
Biswanath chariali to Agra: 2600MW.
Substation with least voltage transformer: 33kV/11kV

TRANSMISSION LOSS FORMULA

$$P_L = f(P_1, P_2, P_3, \ldots\ldots. P_N)$$

Consider two generators,



Considering a balanced system, $P_L = 3{I_1}^2R_1 + 3{I_2}^2R_2 + 3(I_1 + I_2)^2R_3$

$$P_L = 3({I_1}^2R_1 + {I_2}^2R_2 + (I_1 + I_2)^2R_3 = 3({I_1}^2(R_1 + R_3) + {I_2}^2(R_2 + R_3) + 2I_1I_2R_3$$

$P_1 = \sqrt{3}V_1I_1pf_1,\ P_2 = \sqrt{3}V_2I_2pf_2$

$I_1 = \frac{P_1}{\sqrt{3}V_1pf_1},\ I_2 = \frac{P_2}{\sqrt{3}V_2pf_2}$

Substituting current values in power equations, $P_L = B_{11}{P_1}^2 + B_{22}{P_2}^2 + 2B_{12}B_{21}P_1P_2$

Loss coefficients in MW^{-1},

$B_{11} = \frac{R_1+R_3}{(V_1pf_1)^2} \Rightarrow \alpha\ \ R_1 + R_3$

$$B_{22} = \frac{R_2 + R_3}{(V_2pf_2)^2} \Rightarrow \alpha\ \ R_2 + R_3$$

$$B_{12} = B_{21} = \frac{R_3}{V_1V_2pf_1pf_2} \Rightarrow \alpha\ \ R_3$$

$$P_L = \begin{bmatrix} P_1 & P_2 \\ & \end{bmatrix} \begin{bmatrix} B_11 & B_12 \\ B_21 & B_22 \end{bmatrix} \begin{bmatrix} P_1 & \\ P_2 & \end{bmatrix}$$

Loss coefficient matrix in MW^{-1}

For N generators, $P_L = \sum_{i=1}^{N} \quad \sum_{j=1}^{N} \quad P_iB_{ij}P_j$ MW. Always $B_{ij} = B_{ji}$

Objective: $\min\{F_T = \sum_{i=1}^{N} \quad F_i\}$

Constraints: $P_g = P_D + P_L = \sum_{i=1}^{N} \quad P_i \Rightarrow P_D + P_L - \sum_{i=1}^{N} \quad P_i = 0$

$$P_{imin} \leq P_i \leq P_{imax}$$

Using Langrangian method:

$\min\{L = F_T + \lambda(P_D + P_L - \sum_{i=1}^{N} \quad P_i)\}$ $\lambda$is the Lagrangian coefficient

$$\frac{\partial L}{\partial P_i} = 0 = \frac{\partial F_T}{\partial P_i} + \lambda(0 + \frac{\partial P_L}{\partial P_i} - 1) = \frac{\partial F_T}{\partial P_i} - \lambda(1 - \frac{\partial P_L}{\partial P_i})$$

The first term is the incremental cost of the i-th unit (I_{ci})and the second derivative term is incremental transmission loss of the i-th unit(ITL_i).

$ITL_i = \frac{\partial P_L}{\partial P_i}$ (MW/MW so unitless)

$= 2\sum_{i=1}^{N} B_{ij}P_j$

$0 = I_{ci} - \lambda(1 - ITL_i)$

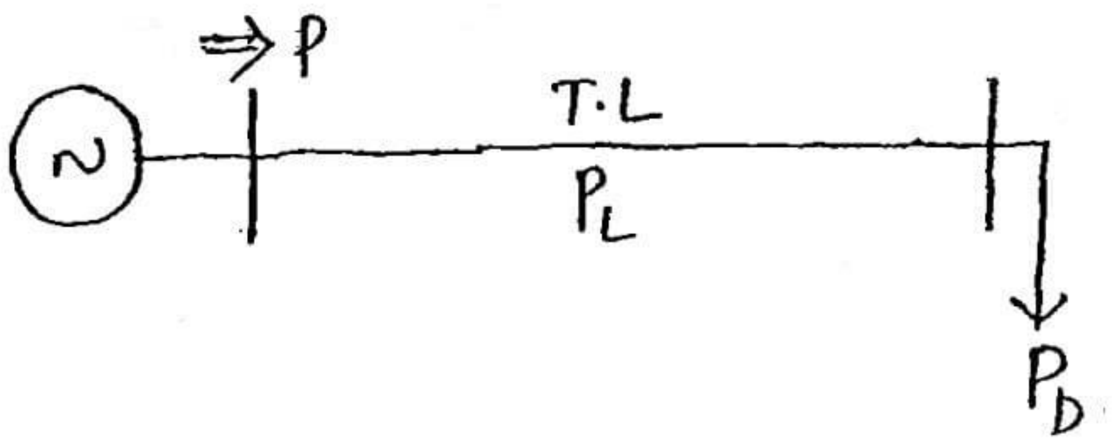
From this, $\lambda = I_{ci}L_i$Rs/MWhr where, $L_i = \frac{1}{1-ITL_i}$is the penalty factor of i-th unit

$\lambda = I_{c1}L_1 = I_{c2}L_2 = I_{c3}L_3 = I_{cN}L_N$: condition food minimum fuel cost solution or coordination equation or Khuntucker equation.

To get the minimum fuel cost solution for economic dispatch with power loss, the product of penalty factor and incremental cost of all the units must be equal.

Importance of penalty factor

- As L.IC=constant, If L increases, IC decreases.
  $F = \frac{1}{2}aP^2 + bP + C, IC = aP + b, P = \frac{IC-b}{a}$ So, power decreases as IC decreases.
- $P = P_D + P_L$,

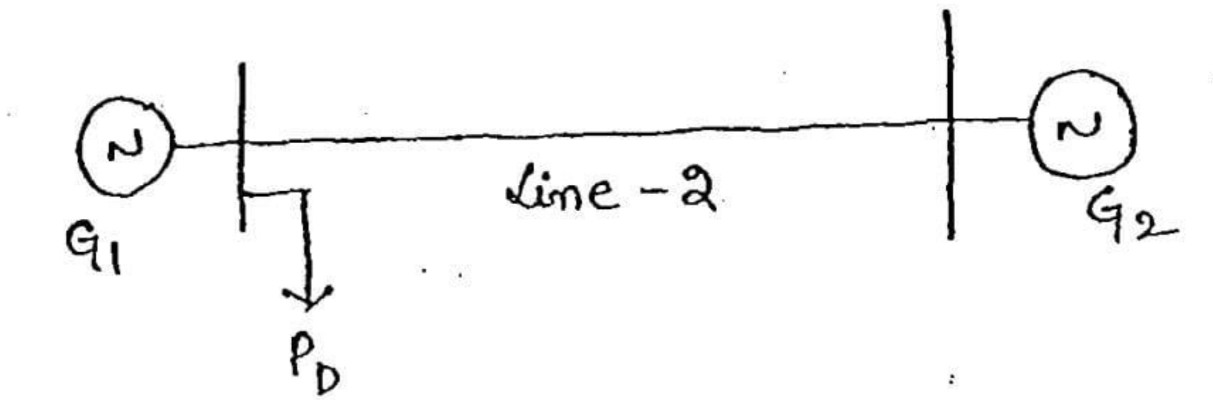


$ITL = \frac{P_L}{P}, 0 \le P_L \le P$

- $L = \frac{1}{1-ITL}$ if it increases, L decreases.
- $L \ge 1, L_{min} = 1$: if load centre directly connected to generator terminal then L=1, It represents there is no penalty on corresponding unit
- For a fixed power generation:
  L increases if ITL increase, $ITL = \frac{P_L}{P}$
  ITL increases if $P_L$increase, $P_L = I^2R$
  $P_L$increases, if R increase, $R = \frac{\rho l}{A}$
  R increases , if l increase
  Length of TL increases, if distance between load centre and generating station increases.

Penalty factor is a physical parameter which mainly depends on distance between generating station and load centre.

CASE 1: Load units is located at unit-1



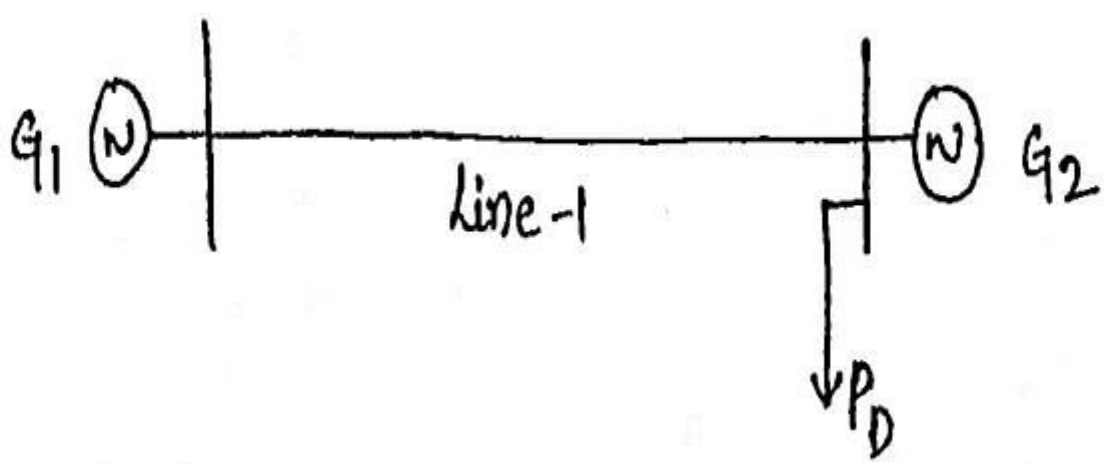
$$R_1 = 0; R_2 \neq 0, R_3 = 0$$
$$B_{11}\alpha\ (R_1 + R_3) \Rightarrow B_{11} = 0$$
$$B_{22}\alpha\ (R_2 + R_3) \Rightarrow B_{22} \neq 0$$
$$B_{12} = B_{21}\alpha\ R_3 \Rightarrow B_{12} = 0$$

$P_L = B_{11}{P_1}^2 + B_{22}{P_2}^2 + 2B_{12}B_{21}P_1P_2 = B_{22}{P_2}^2$ MW

$\frac{\partial P_L}{\partial P_1} = 0,\ L_1 = \frac{1}{1-\frac{\partial P_L}{\partial P_1}} = \frac{1}{1-0} = 1$

$\frac{\partial P_L}{\partial P_2} = 2B_{22}P_2\ \ ,\ L_2 = \frac{1}{1-\frac{\partial P_L}{\partial P_2}} = \frac{1}{1-2B_{22}P_2} > 1$

CASE 2: Load units is located at unit-2



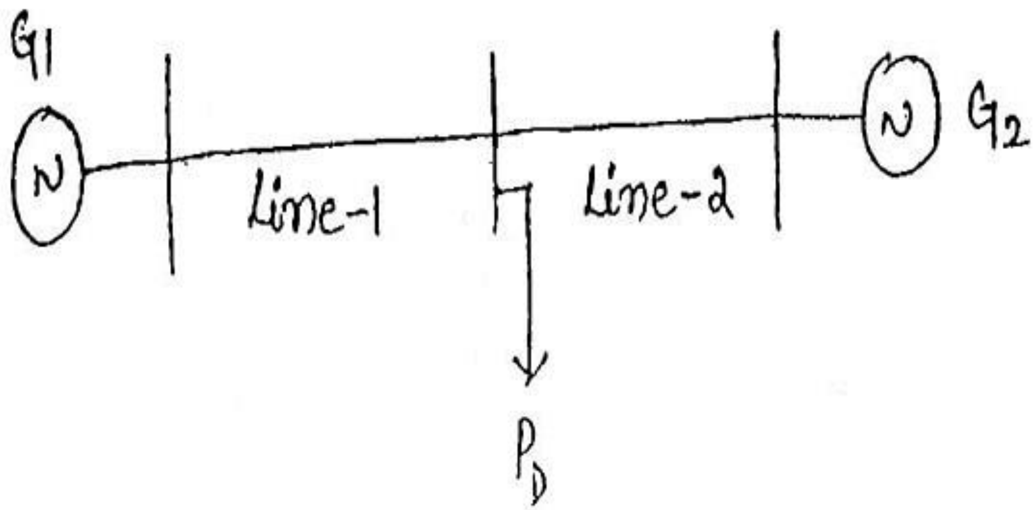
$$R_1 \neq 0; R_2 = 0, R_3 = 0$$
$$B_{11}\alpha\ (R_1 + R_3) \Rightarrow B_{11} \neq 0$$
$$B_{22}\alpha\ (R_2 + R_3) \Rightarrow B_{22} = 0$$
$$B_{12} = B_{21}\alpha\ R_3 \Rightarrow B_{12} = 0$$

$P_L = B_{11}{P_1}^2 + B_{22}{P_2}^2 + 2B_{12}B_{21}P_1P_2 = B_{11}{P_1}^2$ MW

$\frac{\partial P_L}{\partial P_1} = 2B_{11}P_1\ \ ,\ L_1 = \frac{1}{1-\frac{\partial P_L}{\partial P_1}} = \frac{1}{1-2B_{11}P_1} > 1$

$\frac{\partial P_L}{\partial P_2} = 0, L_2 = \frac{1}{1-\frac{\partial P_L}{\partial P_2}} = \frac{1}{1-0} = 1$

CASE : Load units is located at equidistant from both units



$$R_1 \neq 0; R_2 \neq 0, R_3 = 0$$
$$B_{11} \alpha \ (R_1 + R_3) \Rightarrow B_{11} \neq 0$$
$$B_{22} \alpha \ (R_2 + R_3) \Rightarrow B_{22} \neq 0$$
$$B_{12} = B_{21} \alpha \ R_3 \Rightarrow B_{12} = 0$$

$P_L = B_{11}{P_1}^2 + B_{22}{P_2}^2 + 2B_{12}B_{21}P_1P_2 = B_{11}{P_1}^2 + B_{22}{P_2}^2$ MW

$\frac{\partial P_L}{\partial P_1} = 2B_{11}P_1 \quad , L_1 = \frac{1}{1-\frac{\partial P_L}{\partial P_1}} = \frac{1}{1-2B_{11}P_1} > 1$

$\frac{\partial P_L}{\partial P_2} = 2B_{22}P_2 \quad , L_2 = \frac{1}{1-\frac{\partial P_L}{\partial P_2}} = \frac{1}{1-2B_{22}P_2} > 1$

If load information is specified (loss Coefficient will be given/ loss formula will be given/ hints for calculation of loss coefficients)

$$P_g = P_L + P_D, \lambda = L_1 I_{c1} = L_2 I_{c2} = L_2 I_{c2} = \ldots\ldots\ldots = L_N I_{cN}$$

Not given : economic dispatch without power loss

$P_g = P_D, \ \lambda = I_{c1} = I_{c2} = I_{c2} = \ldots\ldots\ldots = I_{cN}$

If the question asked like,

(i) Solve for ED if loss are included and coordinated

$P_g = P_L + P_D, \lambda = L_1 I_{c1} = L_2 I_{c2} = L_2 I_{c2} = \ldots\ldots\ldots = L_N I_{cN}$

(ii)Solve for ED if losses are included but not coordinated

$P_g = P_L + P_D, \lambda = I_{c1} = I_{c2} = I_{c2} = \ldots\ldots\ldots = I_{cN}$

Overall losses will be increased compared to coordinated, and take less simulation time.

NOTE: method 2 gives more fuel cost and less simulation time solution compared to method 1.

(iii) Solve for ED if losses are not included but coordinated

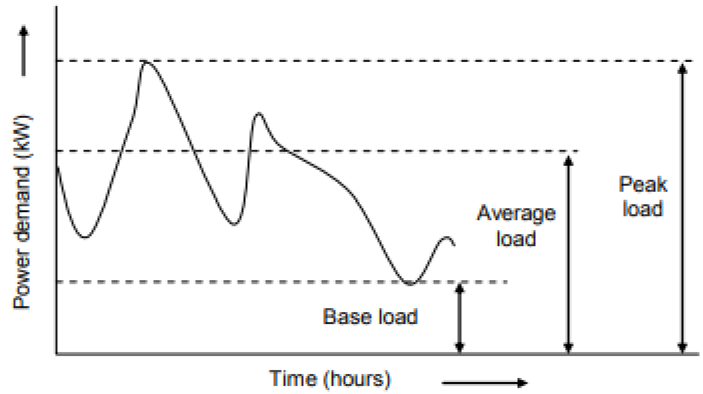
No practical importance

(iv) Solve for ED if losses are not included and not coordinated

$P_g = P_D, \ \lambda = I_{c1} = I_{c2} = I_{c2} = \ldots\ldots\ldots = I_{cN}$

ED without power loss.

Economic power generation



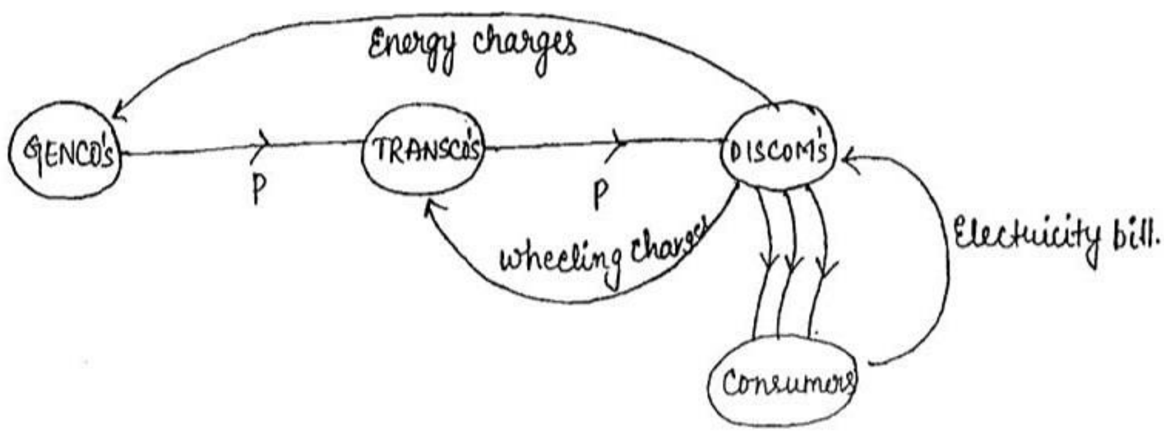
Load curve: it is a curve between demand in KW Vs time operation in hours. The load curve gives the variation of demand on the power system with respect to time. The area under the load curve gives the total number of units generated or consumed in a given time. Always load curve presented as kilowatt vs hours since one unit is equal to 1 kilowatt hour.

Three Types of load

- Daily load curve: controlling of power system
- Monthly load curve: billing power system
- Yearly load curve: planning of power system

PPA: power purchase agreement: It decides the unit cost. According to this, GENCO'S will evaluate the power to distribution companies. Distribution companies will pay to generation companies in terms of energy charges.

Before electricity act 2003, all GENCO,TRANSCO, DISCOMS were used to work under one unit, ie State Electricity Board(SEB). The distribution companies also paid to transmission companies in terms of wheeling charges based on length of the line and voltage.



Information is obtained from load curve

- Number of units consumed or generated in a given period = area under the load curve in a given period.
- Maximum demand on the power system and its occurring time. It is the greatest of all the demands which are occurring in the power system.
- Minimum demand on the power system and its occurring time.
- Average demand on the power system,
  Average demand (in kW)=Number of units consumed or generated per total number of hours
  Average demand =Area under the load curve per total number of hours
- Base load on the power system (from yearly load curve)

Characteristics of a base load power plant

- Base load plant should be capable of supplying the energy throughout the year without any disturbance.
- It should supply the energy Atlas course, hydro power plants are the best to select as base load power plants.

Order of preference of base load power plants:

1. Hydroelectric power plants with ample capacity of water.
2. Nuclear power plants
3. Thermal power plants

Characteristics of peak load power plants

- It should be able to control the power output of the unit.
- It should have a quick starting nature.(on time should be minimum)

Order of preference of peak load power plants:

1. Pumped storage hydroelectric power plants.
2. Diesel power plants.
3. Gas power plants.

Pumped storage power plant

Pump storage power plant having three modes of operation

- Generating mode: during peak load period
- Motoring mode: during off peak period
- Synchronous condenser: depending on the requirement of the grid.

Connected load

It is the sum of continuous ratings of all the equipment which are connected to the power system.

generating capacity (GC) < connected load(CL)

generation capacity > maximum demand (MD)

Demand factor(DF)

It is defined as the ratio of maximum demand to the connected load.

$DF = \frac{MD}{CL}$, MD<CL; DF<1 always

Load factor

It is defined as the ratio of average demand to maximum limit.

$LF = \frac{AD}{MD}$, AD<MD; LF<1

Generally the ROI (return of investment) is the final parameter to be considered while deciding the plant capacity.

Eg; PC=100MW, MD=80MW, Number of units=AD.T

LF is directly proportional to AD.

The revenue status of the power system depends on load factor. So the load factor should be as high as possible.

Conclusion:

- In a practical power system, load factor should be as high as possible (near to Unity).
- Load factor mainly affects the revenue of the power plant or power system.
- If the load factor increases revenue of the power plant or power system increases.

Diversity factor

It is defined as the ratio of sum of individual maximum demand to the coincidence maximum demand on the power system.

Div.F=Sum of individual maximum demand/coincidence maximum demand

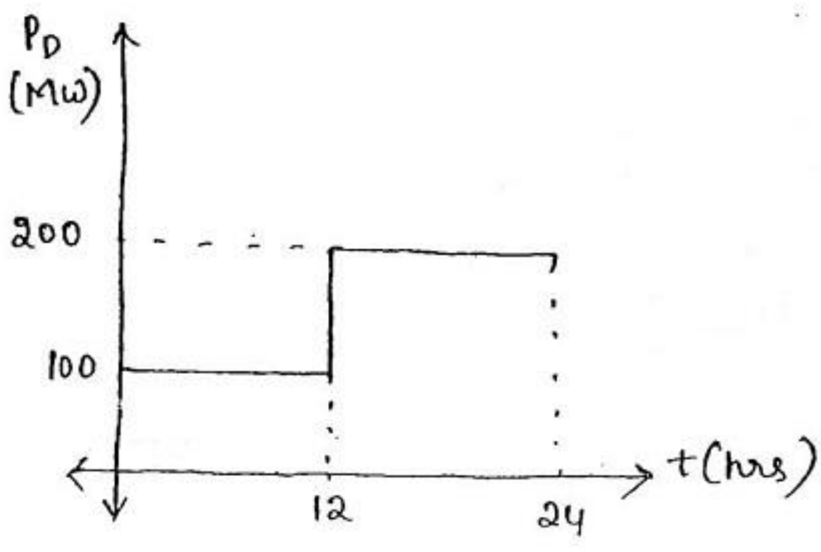
It's always greater than or equal to 1.

- domestic Loads
- commercial loads
- industrial loads
- Municipal loads
- traction loads
- agricultural loads

Eg;Case 1:

	MD	t-op
A	100MW	0-12h

B 200MW 12-24hr



Div.F=(100+200)/200=1.5
Plant capacity=250MW
AD=$\frac{100\times12+200\times12}{24} = 150MW,$
LF=AD/MD=150/200=0.75
Case 2: MD t-op
A 100MW 0-14h
B 200MW 12-24hr
MD=300MW
Div.F=(100+200)/300=1, Plant capacity=350MW
AD=$\frac{100\times12+300\times2+200\times10}{24} = 158.33MW$
LF=AD/MD=158.33/300=0.527
The plant capacity decides the fixed cost of the power system. If maximum demand ie; coincidence maximum demand is less than the Div.F is more the power plant capacity will be less. So the operating condition of the power system in case-1 is more reliable than in case 2.

- Diversity factor is always greater than 1.
- Diversity factor should be as high as possible.
- Diversity factor mainly affects the fixed cost of the power system (plant capacity) or investment decisions.
- If the diversity factor increases the fixed cost of the power system decreases.

Coincidence factor

CF=1/Div.F

Plant utilisation factor(PUF)

It is defined as the ratio of maximum demand to the plant capacity.
PUF=MD/PC ; MD≤PC; PUF≤1

Plant capacity factor(PCF)

It is defined as the ratio of average demand to the plant capacity.
PCF=AD/PC; AD<PC;PCF<1

- Plant capacity factor should be as high as possible(near to Unity)
- It mainly affects the revenue of the power plant.
- If pcf increases, the revenue of the power plant increases.
- LF≥PCF
- PCF=LF×PUF

Reserve capacity(RC)

It is the difference between plant capacity and maximum demand.
RC=PC-MD =PC(1-MD/PC))=PC(1-PUF)=AD$(\frac{1}{PCF}-\frac{1}{LF})$
Spinning revenue is contributed by the unit which is connected to the grid which is producing the power.

- The default reserve is a spinning reserve.
- Spinning reserve is always contributed by the unit which is connected to the grid.

Cold reserve

It is the generation capacity which is available for service but not in operation.
Cold reserve=PC
Cold reserve conditions:

- $N_r = 0$
- Boiler is off
- Boiler temperature greater than 100 degree Celsius.
- Excitation is off

Cold start time :6-8hrs

Hot reserve

It is the generation capacity which is in Operation but not in service.
Hot reserve=PC
Hot reserve conditions:

- Boiler is on
- Boiler temperature greater than 120 degree Celsius but less than Tc
- Excitation is off
- $\frac{1}{5}N_s < N_r < N_s$

Hot start time :120mnt to 140mnt.

Service factor(SF)

It is defined as the ratio of the actual number of hours the plant is in operation (service hours) to the total number of hours in a given period.
SF=Service hrs/Total number of hrs=sh/T
sh≤T, SF≤1
Base load power plants have a very good service factor compared to peak load power plants.

Plant use factor(P.Use.F)

It is defined as the ratio of the actual number of units generated by the plant to the maximum number of units that should have been generated.

P.Use.F=number of units generated/maximum number of units=No.of units/(PCXsh)

=(AD/PC)(T/sh)=PCF/SF

P.Use.F≥PCF, LF≥ PCF

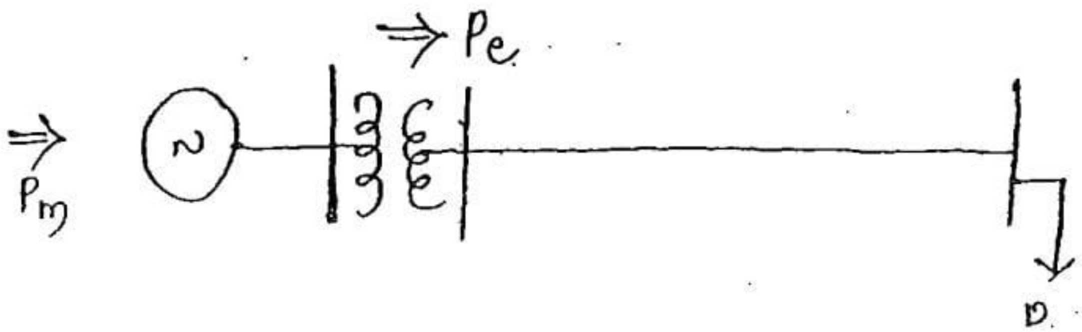
If the power plant is running throughout the time

sh=T, SF= 1, P.Use.F=PCF

If the power plant is running throughout the time with MD=PC

PUF= 1, LF=PCF=P.Use.F, RC=0

Transient behaviour of generator in practical power system



At t=0- (System is under steady state)

$P_D = P_{D0}; P_e = P_{e0}; P_m = P_{m0};$

In loss free system, $P_{m0} = P_{D0} = P_{e0}$

$N_r = N_s \Rightarrow \omega_{rm} = \omega_{sm} \Rightarrow KE = KE_s$

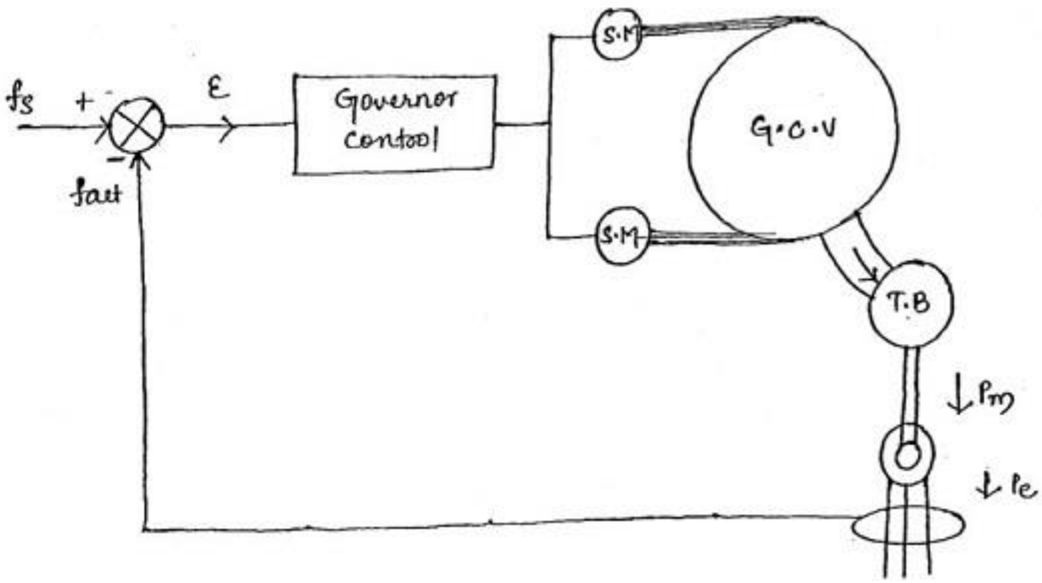
$f = f_s, \delta = \delta_0$

$P_e = \frac{EV}{X_s} sin\delta = P_{max} sin\delta = P_{e0}$

$\delta = sin^{-1}(\frac{P_{e0}}{P_{ma}}) = \delta_0$

At t=0 (Load on the system is suddenly increased)

$P_D = P_{D0} + \triangle P_D, P_e = P_{e0} + \Delta P_e; P_m = P_{m0}$



ΔP_e comes from KE stored in rotating parts of a synchronous machine.

$KE = \frac{1}{2}\tau\omega_{rm}^2$; $\omega_{rm} = \frac{2\pi N_r}{60}$

Net KE decreases,

KE=$KE_s + \Delta KE$

ΔKE is negative.

$$KE\alpha N_r^2 \quad N_r < N_s$$

As KE decreases, N_r decreases, δ decreases

The time taken to become to steadystate:

t= $5\tau_m$ τ_m is the time constant of GCS

$P_m = P_{m0} + \Delta P_m$; ΔP_m will restore KE back.

$$N_r = N_s \Rightarrow \omega_{rm} = \omega_{sm} \Rightarrow KE = KE_s$$

$f = f_s, \delta = \delta_0 + \Delta\delta, \Delta P_m = \Delta P_{e0} = \Delta P_0$

$P_e = P_{e0} + \Delta P_e$

$\delta = sin^{-1}(\frac{P_{e0}+\Delta P_e}{P_{ma}})$; $\delta_{max} = \pi - \delta$

δ Corresponds to New steady state of reading point if the system is stable.

During a sudden rise in Lord on the grid, the generators which are connected directly to the grid are affected more and among them the generator which is having poor regulation will be affected more.

ENTRI

PROTECTION SYSTEMS

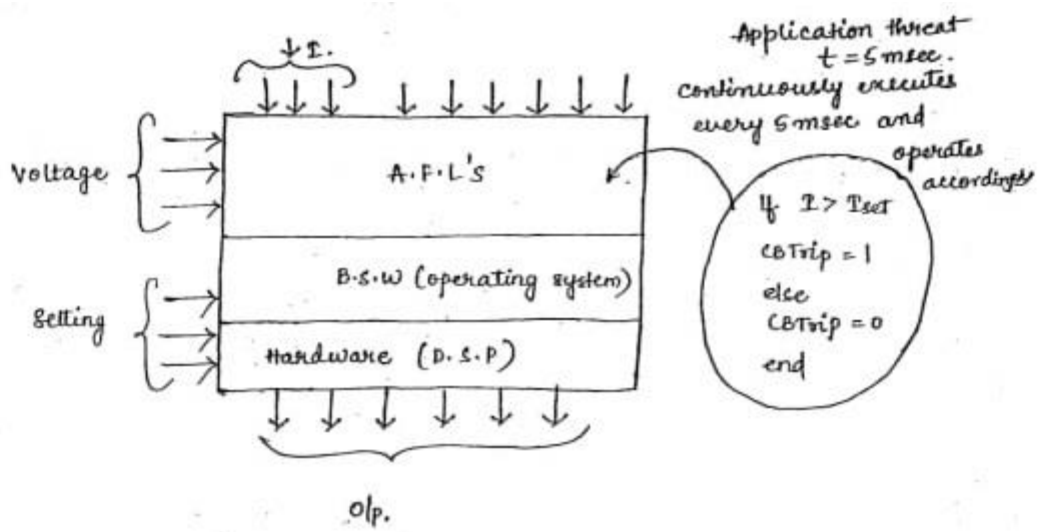
Philosophies of protection:

- Over current
- Directional
- Distance
- Differential

Types

- Circuit breakers
- Relays
    - Mechanical
        - Attraction
        - Induction
    - Static
    - Digital
    - Numerical

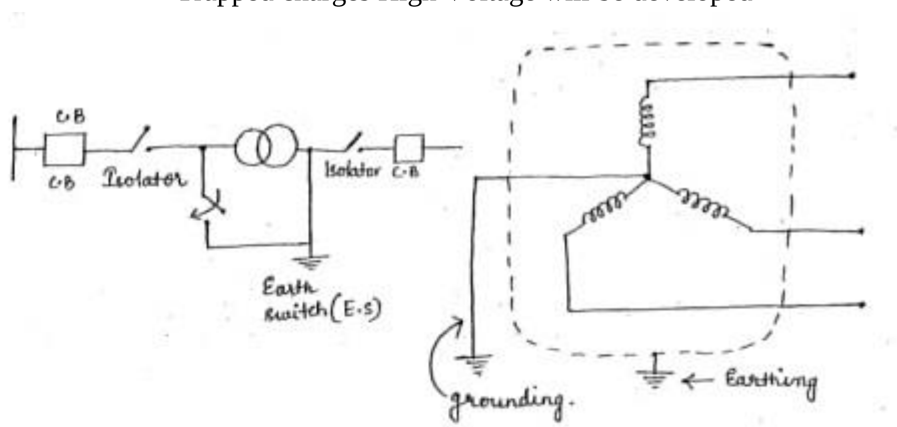
The basic building block of numerical relays is is intensive explosive device(IED)
IED: Intelligent electronic device
AFL: application function libraries(protection functionalities)



➔ Loss of excitation: induction generator
➔ loss of prime mover: synchronous motor
➔ loss of prime mover Input and loss of excitation: induction motor
➔ loss of synchronisation: RL load

Causes of abnormal conditions

- ❖ Natural events
  - ➢ Lightning
  - ➢ Wind
  - ➢ Snow, ice, rain
  - ➢ Fire, explosion
  - ➢ Earthquake
  - ➢ Flying objects
- ❖ Physical accidents
  - ➢ Animals or operators coming in contact with the live objects, contractors digging underground cable .
  - ➢ Vehicle crashing transmission pole
- ❖ Equipment failure
  - ➢ Breakdown of conducting path or breakdown of oc fault
  - ➢ Breakdown of insulation of electrical equipment
- ❖ Miss-operation
  - ➢ Never open in isolator prior to CB opening
  - ➢ Trapped charges High Voltage will be developed



Sequence during closing:

- Open ES
- Close isolator
- Close circuit breaker

Sequence during opening(before going to maintenance)

- Open CB
- Open isolator
- Close ES

Interlocking is provided for avoiding LLLG fault. To avoid miss operation, the system must be provided with the proper interlocking but it is not employed in all systems due to cost of installation. In general, the distribution system cannot have an interlocking system.

Abnormal conditions: series fault(open circuit fault) and shunt fault(short circuit fault)

Series fault

If there is a breakdown of the conducting path then it leads to serious fault. Causes;

- Mal operation of CB
- breakdown of jumpers
- Broken conductive in electrical machine

Open circuit faults are characterized by decrease in current and increase in voltage. The over voltage induced due to the false is always transient in nature. Because $\frac{1}{2}CV^2$goes through R,$\frac{1}{2}LI^2\downarrow$,$\frac{1}{2}CV^2\uparrow$ $, So\ V\uparrow$ So negative I flow.

Problems due to OC Faults

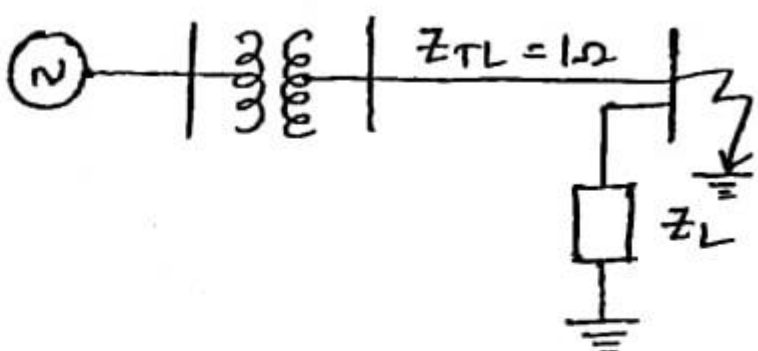
- Outage to consumers and causes loss of revenue to Supply Companies
- If the over Voltage in power system is very high then it may lead to breakdown of insulation of electrical equipments
- Due to single phase or two phase OC fault the power system is experienced with unbalanced operation
- If the disturbance created by the OC fault is very high then it may lead to grid instability.

Shunt fault

Causes: mainly due to breakdown of insulation of electrical equipment in the below cases,

- Overvoltage caused by lightning for switching
- Aging effect
- Impurities in insulation for manufacturing defects
- Atmospheric factors
- Temperature rise

If there is fault on any part of the power system, the magnitude of fault current is very high(2 to 10 times of full load current) and fault current is flowing through faulty sections as well as healthy sections of the systems.



During normal operation:

$I = \frac{V}{Z_{TL}+Z_L} = \frac{V}{101}A$

For 400 KV system, V=$\frac{400kV}{\sqrt{3}}$; Then I=$\frac{4kA}{\sqrt{3}}$

During fault;

$I_f = \frac{V}{Z_{TL}+Z_f} = \frac{V}{1}A$

The sources for the circulation of fault currents are synchronous generators and synchronous Motors.
NOTE: During fault induction m/c will also contribute to fault current for a very short duration. So for all theoretical calculations the fault current contributed by induction m/c is neglected.

the magnitude of fault current depends on

- Type of fault
- Location of Fault
- Value of fault impedance
- Number of sources available to feed the fault

Fault statistics

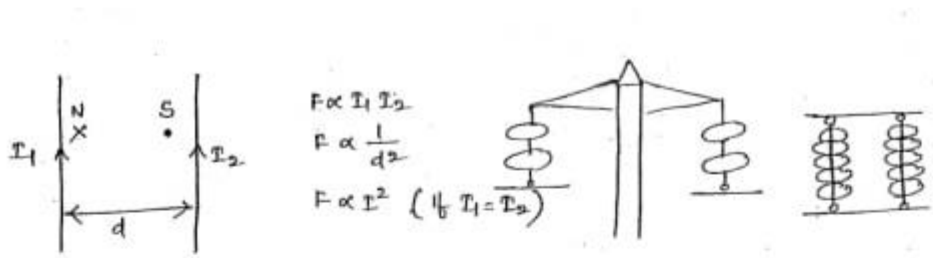
transmission line: 50 %
underground cables:8%
Transformers: 9%
generators:12%
CT and PT and control circuits: 11%
relays and circuit breakers:10%

Short circuit faults are characterized by current increase and voltage decrease.

thermal stresses
mechanical stress
heat energy=$I_f{}^2Rt$
I_f: fault current =10 to 20 times normal current
t: fault duration
if fault is not cleared, HE increase, due to this

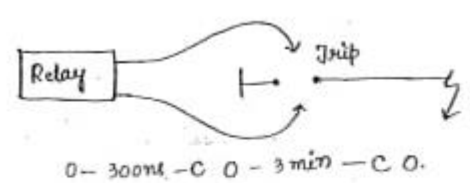
- Insulation get deteriorated
- conductors get melted
- fire hazards

MECHANICAL STRESS



Depending on duration of fault on the wisdom

- Transient fault:80%
- Sustained or steady-state fault: 20%



Protection system

Protection system is designed for continuous monitoring of the power system and it should be maximum continuous with the meaning of damage to life equipment and property. it should provide maximum continuity of service. the objectives of power system is

- Speed of operation
- Sensitivity
- Selectivity
- Reliability
- Simplicity
- Economical

Speed of operation

The protection system should ensure our minimum fault duration and consequent equipment damage. If the fault clearing is delayed the healthy equipment of the power system may damage due to excessive thermal and mechanical stresses. So the protection system should operate as quickly as possible.
Actuating quantity: it is a parameter of the power system which undergoes variation with respect to abnormal conditions in the power system. Actuating quantity the relay continuously monitors the power system.
Threshold quantity: it is the value of activating quantity which is on threshold above which relay operates.

Sensitivity

The relay system should be able to detect even the smallest possible value of fault current in the protection zone.

Selectivity

System has to ensure maximum monitoring of the system with minimum system interruption during fault. Effective protection protection system has to be insured with a minimum of two protection systems. The unit system of protection does not have a backup protection. the system should provide maximum continuity of service with minimum system introduction during the fault. selectivity is also called as discrimination. the relay should properly disconnect between the false which are inside the zone of protection or outside the zone of protection. Selectivity is achieved by unit system of protection or non-unit system of protection.
UNIT SYSTEM OF PROTECTION: Here relay detects the fault which is inside the zone of protection. if the fault is outside the zone of protection it will detect as the normal operation.
NON-UNIT SYSTEM OF PROTECTION:Here relay detects the point which is inside the zone of protection and outside the zone of protection. insta fault is inside the zone of protection the relay provides primer protection. If the fault is outside the zone of protection, the relay provides backup protection.
Note: In system protection backup protection is not possible. there are two types of backup protections

- Local backup
- Remote backup(commonly preferred)

Local backup: backup relay is located in the same substation where primary relay is located. The backup release duplication of primary relay this scheme requires an extra investment. If primary protection fails backup protection will be operated but the same number of consumers are affected.
Remote backup: Backup relay is located in the remote substation upstream. The main objective of the backup relay is to provide the primary protection for another transmission line. so this scheme requires no extra investment. If primary protection fails then backup protection will operate but it will interrupt the maximum number of consumers.

Reliability

The protection system should perform 100% correctly. reliability having two aspects,

- Dependability: it should operate when it is required
- Security: it should not operate when it is not required

Simplicity

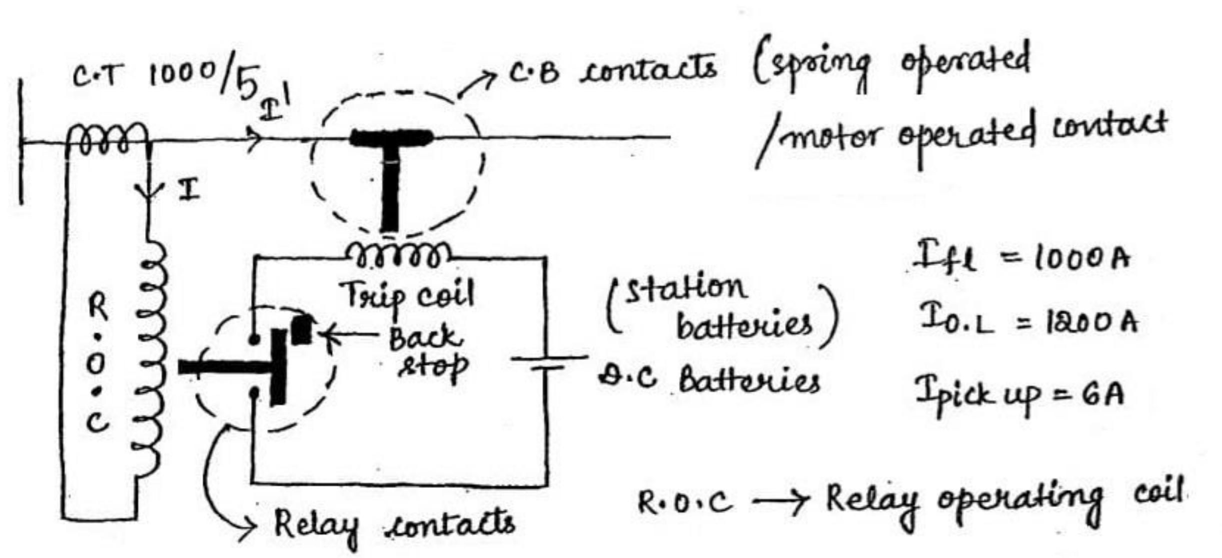
The relaying system should have a minimum number of components and associated circuitry to achieve protection objectives.

Economical

Relay system must provide maximum protection at minimum cost.

Components of system protection

Overload current is 120 to 150% of the full load current.



Primary relaying equipment: If the ROC is directly connected in the circuit to be protected then it is called the primary relay in equipment .

Secondary relaying equipment: if the ROC is connected to the circuit to be protected through CT,PT or both CT and PT, then it is called secondary relaying Equipment.

Purpose of CT

CT Is considered the father of the protection system.

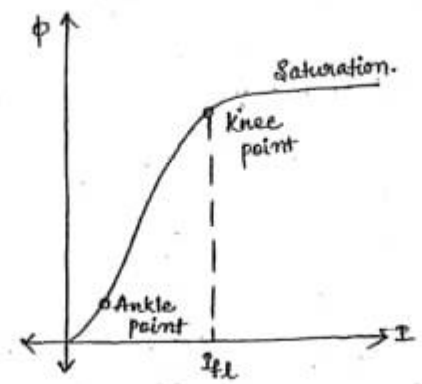
1. Measurement or metering: it should be encouraged for 10 to 120% of full load current.
2. Relaying or protection: it should be accurate for all the possible fault current.

Measuring CT

Reluctance of air, $R_{eA} = \frac{l}{\mu_0 A}$

Reluctance of magnetic material, $R_e = \frac{l}{\mu_0 \mu_r A}$ $\mu_r = 1500\ to\ 20000$

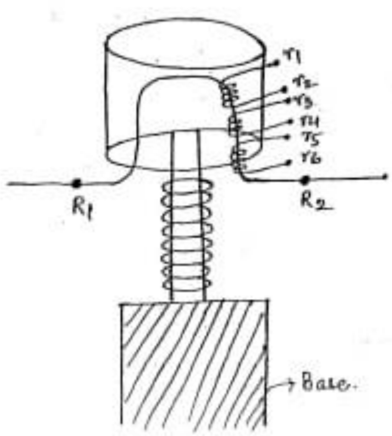
The flux will always be retained in the Corps itself as reluctance of air is very very greater than that of magnetic material.

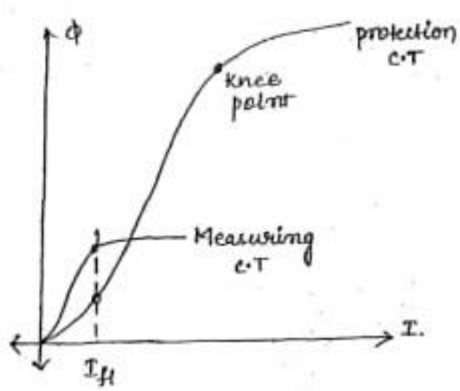


After the knee point even though the current increases the flux will be increased as it is operating in saturation. So even if the current is more, the equipment connected in the secondary will not be affected by a high-current in primary. The measuring CT is designed to operate at knee point.

Protection CT

Protection CT is designed to operate at angle point. Protection CT requires more cores compared to measuring CT.





The torque produced by ROC,

$$T_{op}\ \alpha\ \phi I$$

$\phi = NI/R_e; \phi\ \alpha\ I$

Then $T_{op} \alpha\ I^2$ $T_{op} = K_1\ I^2$

Every relay circuit is provided with restraining torque(this will pull the plunger in the opposite direction of the pull due to operating torque.

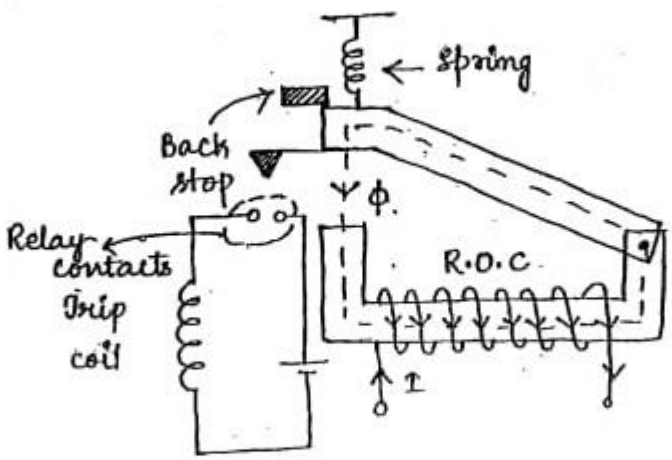
$T_{res} = T_{op}$ T_{res}: restraining torque

T_{res} can be achieved by using spring.

$$T_{res} = K_1 I_{pickup}{}^2 = K$$

Net torque, T=$T_{op} - T_{res}$
If $T_{op} > T_{res}$: T>0: Plunger moves left side and relay operates.
If $T_{op} = T_{res}$: T=0: Relay is on threshold.
If $T_{op} < T_{res}$(normal operation): T<0: Plunger moves right side and relay does not operate.
During normal operation, the plunger moves in the opposite direction. To avoid this, the relay circuit is provided with back stops. The position of the backstop is adjustable so that the relay operating time is controlled.

MECHANICAL RELAYS



The force is always created in such a way that the flux occupies a low reactance path.
For DC application:

$$I = I_{DC}$$

$I_{rms} = \frac{I_m}{\sqrt{2}}$ ${I_{rms}}^2 = \frac{{I_m}^2}{2}$

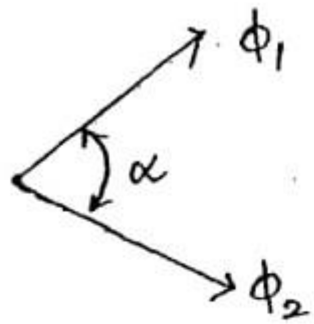
$$T_{op} = K_1 {I_m}^2 sin^2\omega t - K_1 {T_m}^2 (1 - cos2\omega t)$$

$$T_{op} = K_1 \frac{{I_m}^2}{2} - K_1 \frac{{I_m}^2}{2} cos2\omega t = T_{op1} - T_{op2}$$

T_{op1}:unidirectional torque
T_{op2}:pulsating torque
If $I_{rms} > I_{pickup}$
Unidirectional torque > restraining torque
The average of pulsating torque is zero. But due to pulsating torque, The plunge will be vibrating when it touches the relay contacts. So contacts will be damaged. So it requires more maintenance compared to DC application.Electromagnetic attraction principle is applicable for both AC as well as DC system protection. The electromagnetic attraction principle has Limited applications for AC protection because pulsating torque produced in AC applications may damage relay contacts (requires more maintenance).
Induction principle:

1. Induction Disc type construction
2. Induction Cup type construction

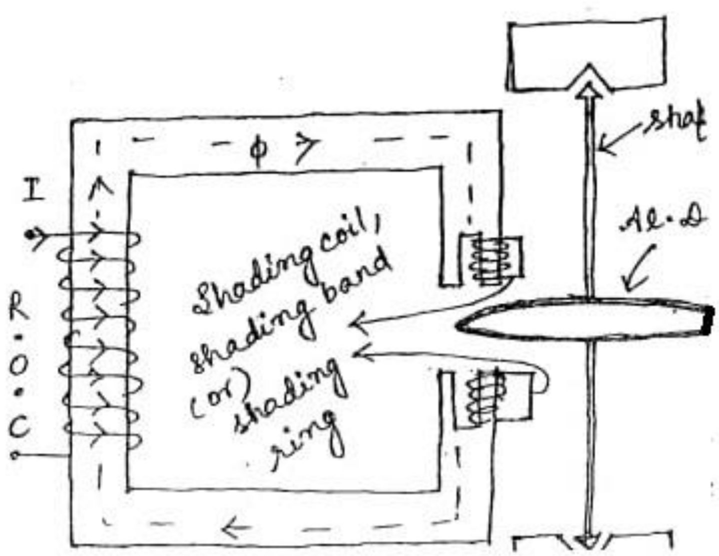
Induction principle is not applicable for DC system protection because in a DC system it is not possible to create electrical phase displacement between any two electrical quantities. It is applicable only for AC system applications.



$$T_{op} \alpha\ \phi_1 \phi_2 sin\alpha$$

If $\alpha = 0, T_{op} = 0$
If $\alpha = 90, T_{op} = maximum$

Induction Disc type construction



Shaded pole structure: As current is time varying, the flux produced is also time varying. The time-varying flux will link with the stationary shading coil and EMF will be induced.

Flux produced by ROC, $\phi \ = \frac{NI}{R_e}$

EMF induced in the shading coil, $E_{sh} = -N_{sh}\frac{d\phi}{dt}$

N_{sh}: total number of turns in the shading coil.

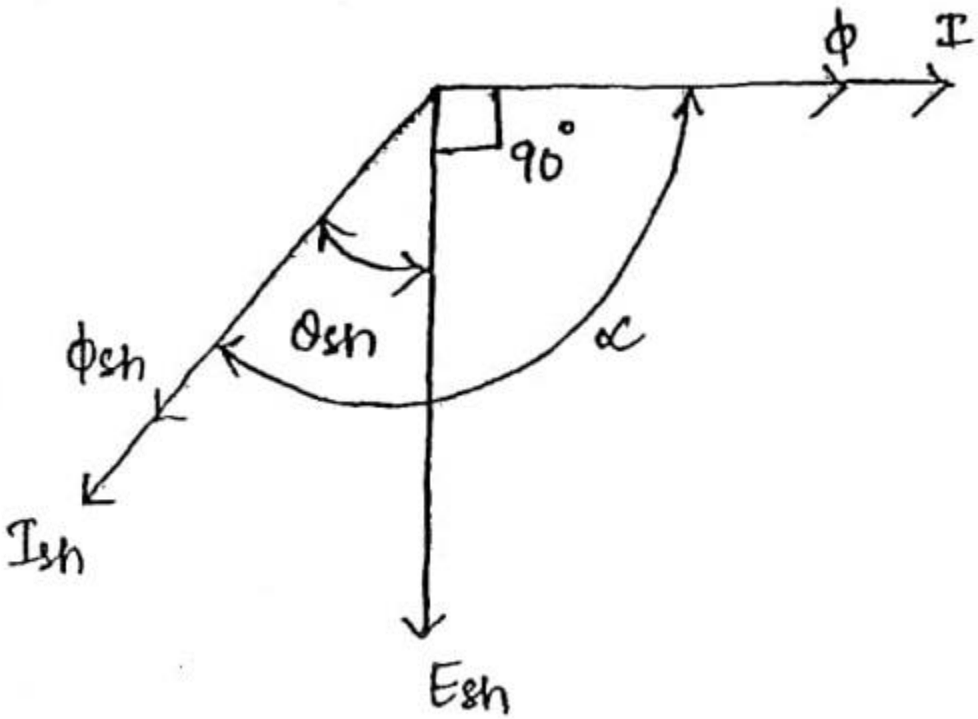
Current flowing through shading coil, $I_{sh} = \frac{E_{sh}}{Z_{sh}}$

Z_{sh}: impedance of shading coil

$$Z_{sh} = R_{sh} + jX_{sh} = |Z_{sh}|\theta_{sh}$$
$$\theta_{sh} = tan^{-1}(\frac{X_{sh}}{R_{sh}})$$

Flux produced by the shading coil, $\phi_{sh} = \frac{N_{sh}I_{sh}}{R_e}$

If there is a phrase angle difference between the two fluxes produced by the Shading coil then only the torque will be produced.



$$T_{op}\alpha\ \phi\phi_{sh}sin\alpha$$
$$T_{op}\alpha\ \phi\phi_{sh}sin(90 + \theta_{sh})$$
$$T_{op}\alpha\ \phi\phi_{sh}cos\theta_{sh}$$

If θ_{sh} <45, then T_{op} >70.7%T_{opmax}

Always the torque produced should be maximum, so that torque weight ratio is maximum and the sensor sensitivity will be more. So it can be used in fast acting systems.

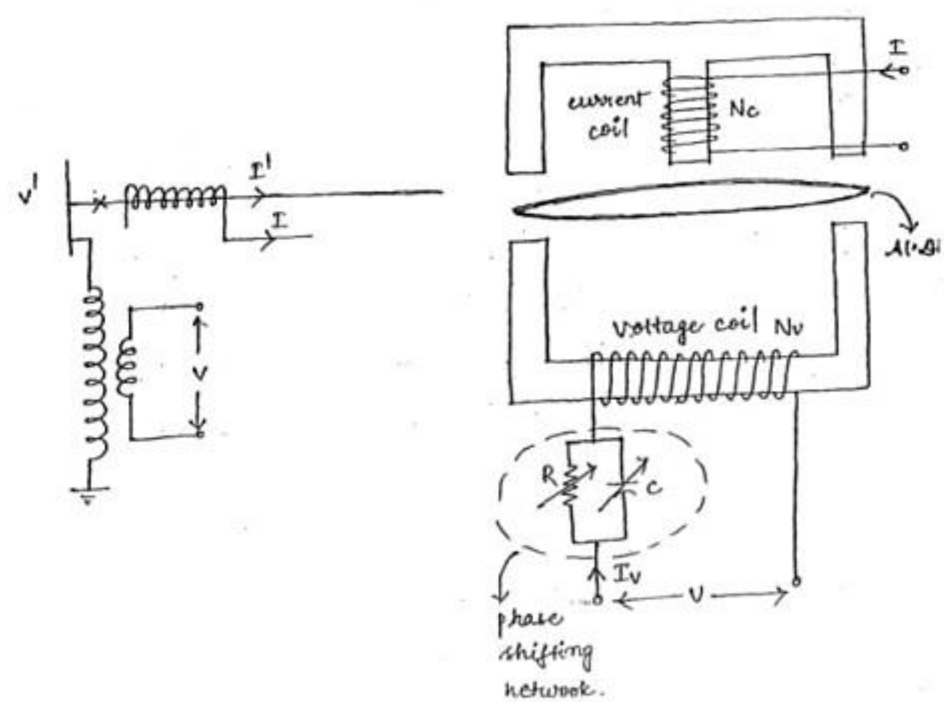
To achieveL_{sh} <45, $X_{sh} < R_{sh}$

$$R_{sh} = \frac{\rho l}{A},\ X_{sh} = \omega L_{sh}, L_{sh} = \frac{{N_{sh}}^2}{Reluctance}$$

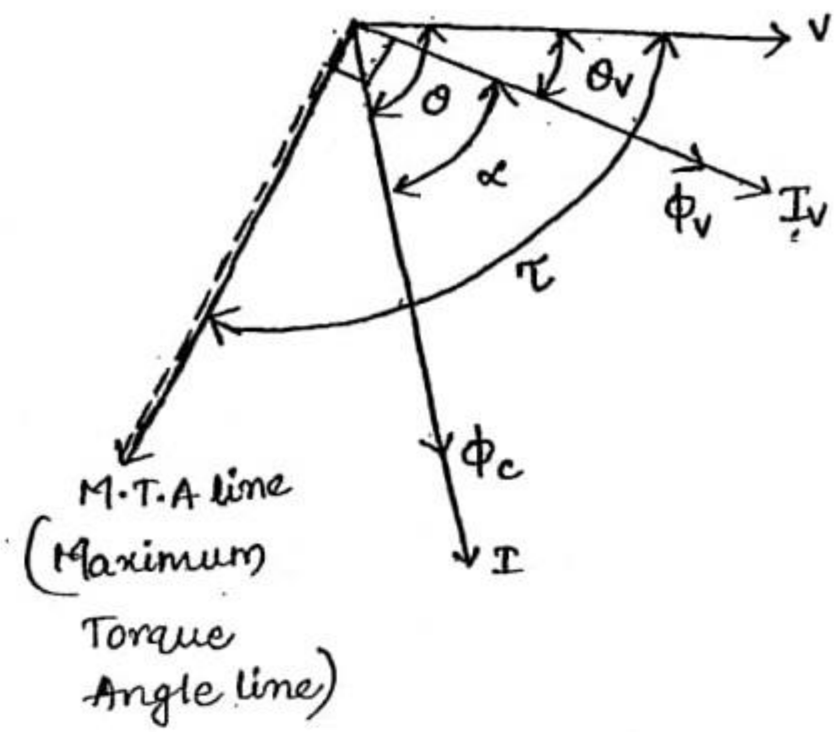
Shading coil is designed with thin wire and with less number of turns. For a relay the coil cannot be changed frequently. So θ_{sh} is constant for a relay.

$T_{op}\alpha\ \phi\phi_{sh}$ $\qquad$ $T_{op}\alpha\ I^2$

Watthour meter



Angle between V’ and I’= Angle between V and I
This angle is called the power factor angle of fault. $\theta \simeq 90^0$ for an ideal system.
Z_v:Sum of impedance of phase shifting network and voltage coil.
The main purpose of phase shifting network is to vary θ_V
$\phi_c = \frac{N_c I}{R_{ec}}$, $\phi_V = \frac{N_V I_V}{R_{ev}}$



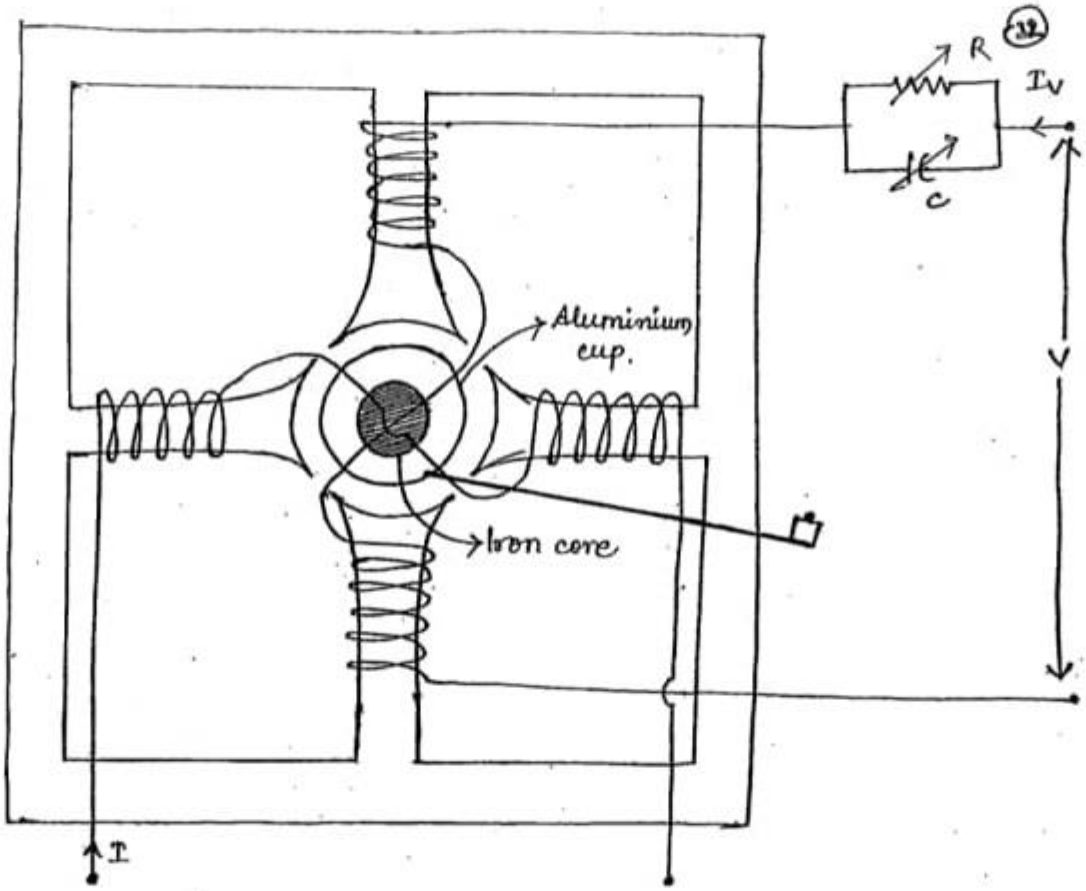
$T_{op}\alpha\ \phi_c\phi_v sin\alpha,$

$$T_{op}\alpha\ VIcos(\theta-\tau)$$

τ: Maximum torque angle
θ_VCan be zero,lagging, leading.

Induction Cup type construction

It consists of 4 Electromagnets and a stationary iron core. Here the cup can constitute the rotating part which is a hollow cylinder and it is free to rotate in between Electromagnets and stationery iron core. The coils of the two opposite electromagnets connected together with series aiding polarity. One such connection is excited by voltage of the power system through PT secondary and other connection is excited from current through CT secondary.
Weight of the moving part of induction cup<Weight of the moving part of watthour meter structure.



Torque by weight ratio of induction cup >Torque by weight ratio of watthour meter

Induction Cup type of relatives are more sensitive than induction Disc type Relays. Induction Cup type relay used in high speed relying application.

Let

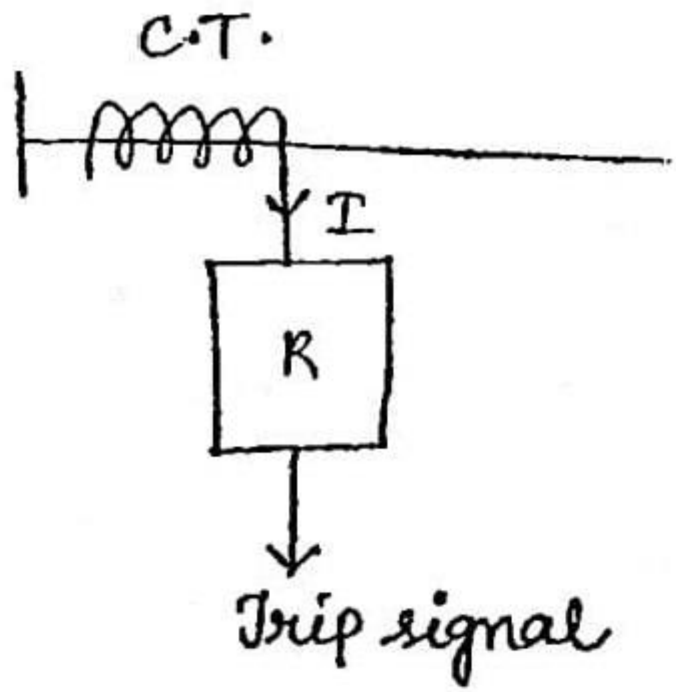
$$I_{pickup} = 100A$$

	Induction principle	Attraction principle
(1) I = 101	Top1	Top 1
Relay (2) I = 101 contacts closed	Top 1	Top 2 (Top 2 > Top 1)
	I = 99 Resets	I = 90 – 95 Resets

- Reset/pickup ratio always <1
- Reset/pickup ratio of induction relay is higher than that of attraction armature relays.
- For induction relay reset by pick up ratio is near to 0.95 and for attracted armature relays it is near to 0.5 to 0.8.

Reason for low reset to pick up ratio of attracted armature relay is the relay operation is affecting the magnetic circuit behavior (because of relay operation reluctance decreases)

Under threshold



$$T=0, T_{op} = T_{res}, K_1 I^2 - |K| = 0,$$

$$I = \sqrt{\frac{|K|}{K_1}} = I_{pickup}$$

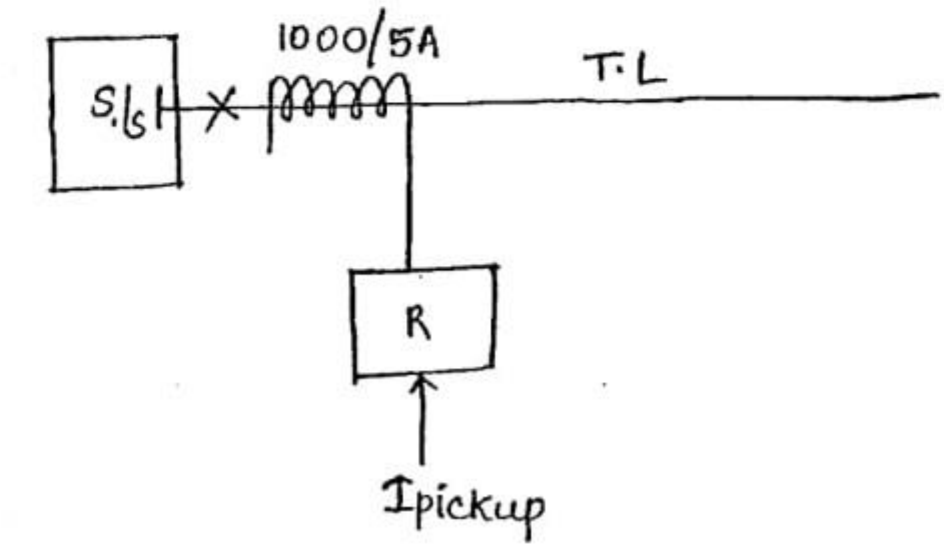
When relay is operating

$$T > 0 , T_{op} > T_{res}, K_1 I^2 > |K|,$$

$$I > \sqrt{\frac{|K|}{K_1}} > I_{pickup}$$

For design of CB: Maximum value of fault current is required.

For design of relay: Minimum value of fault current is required.



$$I_{fmin} = 1400A\ , I_{fmax} = 10000A, I_{pickup} = \frac{5}{1000} \times 1400 = 7A$$

If 5A(indicates that T_{res}has been designed according to 5A;I_{relay}) OC relay taken,

$$T_{res} = T_{op}(I = I_{relay})$$

Current setting: it is defined as the ratio of the pick value of the current to the relay current rating.

CS(%)=$\frac{7A}{5A} \times 100 = 140\%$, $CS(\%) = \frac{I_{pickup}}{I_{relay}} \times 100$

Note: If relay current rating is not given then secondary current of CT is reference for calculation of pick up current.

$$I_{pickup} = current\ setting(A) = Plug\ setting\ (PS(A)) = set\ value\ of\ current$$
$$= Threshold\ value\ of\ current$$

$$I_{pickup} = \frac{CS(\%)}{100} \times I_{relay}$$

$$I_{pickup} \alpha\ I_{relay} CS \alpha \frac{1}{\sqrt{K_1}}$$

$$T_{op} = K_1 I^2 \alpha\ \phi I$$

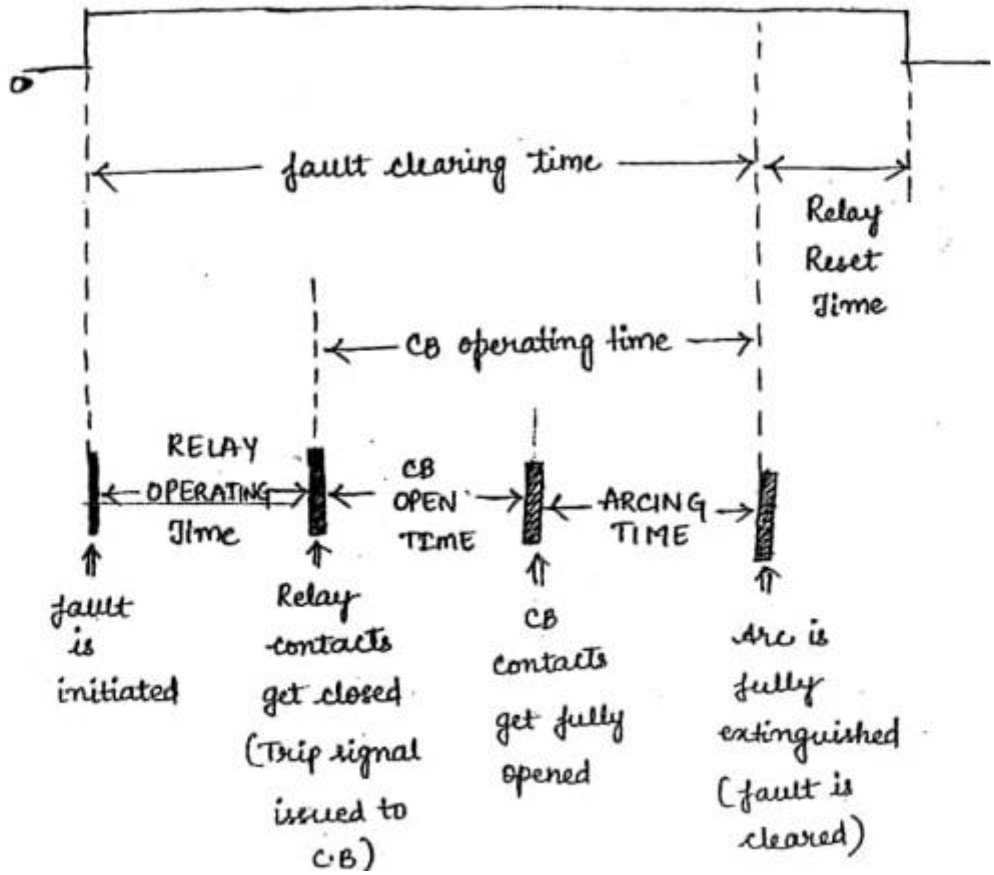
$$T_{op} = C_0\ \phi I$$

$$\phi = \frac{NI}{reluctance},\quad C_1 = \frac{1}{R_e}$$

Operating time

Logic 0 position of relay: spindle rests at backstop position

Logic 1 position of relay :when spindle leaves the backstop position

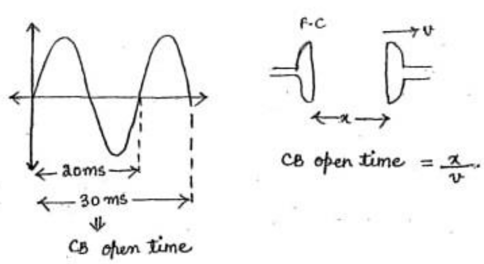


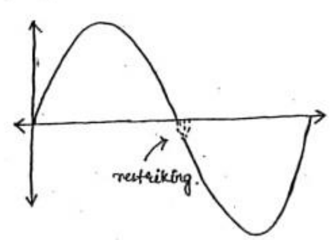
Relay operating time: it is the time elapsed between the instant at which fault is initiated to the instant at which the relay contacts get closed.

Relay reset time: it is the time elapsed between the instant at which fault is cleared to the instant at which relay back to its original position.

Fault clearing time= relay operating time + CB operating time

CB operating time= CB opening time + Arcing time





Arc is always going to be engaged at its natural current zero point.

arcing time less than or equal to 10ms under the assumption of no restrikes.

Universal torque equation

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

Each term represents current unit,voltage unit,directional unit or power unit and spring torque respectively.

Over current relays

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

K_1: positive, $K_2 = 0, K_3 = 0$, K=negative

$T = K_1 I^2 - |K|$

$\phi = C_1 NI$

Then $T_{op} = C_0 C_1 NI^2$

$K_1 = C_0 C_1 N$

$K_1 \alpha\ N$

$CS(\%) \alpha\ I_{pickup} \alpha \frac{1}{\sqrt{N}}$

Eg; A 5A OC relay having 121 turns in its relay operating coil with 100% current setting. If the pickup current is adjusted to 5.5A calculate the number of turns in ROC?

$I_{pickup1} \alpha \frac{1}{\sqrt{N_1}}, 5\alpha\ \frac{1}{11}$

$I_{pickup2} \alpha \frac{1}{\sqrt{N_2}}, 5.5\alpha\ \frac{1}{\sqrt{N_2}}$

$\frac{121}{1.21} = N_2 = 100$turns

Plug setting multiplier(PSM): it is defined as the ratio of secondary fault current of CT to the current rating(A).

PSM=secondary fault current/current rating

PSM=primary fault current/(CT ratio x CS(A))

PSM= $\frac{I_f}{CT\ ratio \times CS(A)}$

If PSM>1: relay operates

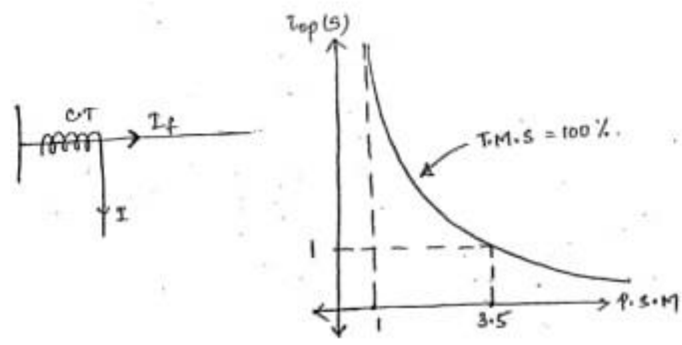
PSM=1;relay is on threshold or virge of operation

PSM<1; relay not operates, $T_{op} = \infty$

PSM is directly proportional to fault current.

Characteristics of an overcurrent relay

It is a curve drawn between PSM Vs T_{op}



$$T_{op} = K_1 I^2 \uparrow, T = T_{op} - T_{res} \uparrow \ speed\ of\ the\ disc \uparrow operating\ time \downarrow.$$

$$T_{op} \alpha \frac{1}{PSM^x}$$

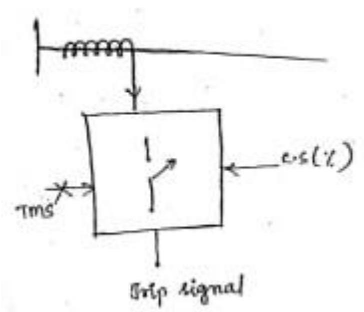
Eg;(above graph)

For $I_f = 5000A$, PSM=$\frac{5000}{7\times1000/5} = 3.57$

Time multiplier setting (TMS)

By adjusting TMS value the actual operating time of the relay can be controlled. TMS is adjusted internally to the relay backstop position.

$$T_{op} = TMS(pu) + t_{op}(TMS = 100\%)$$



Types of overcurrent relays

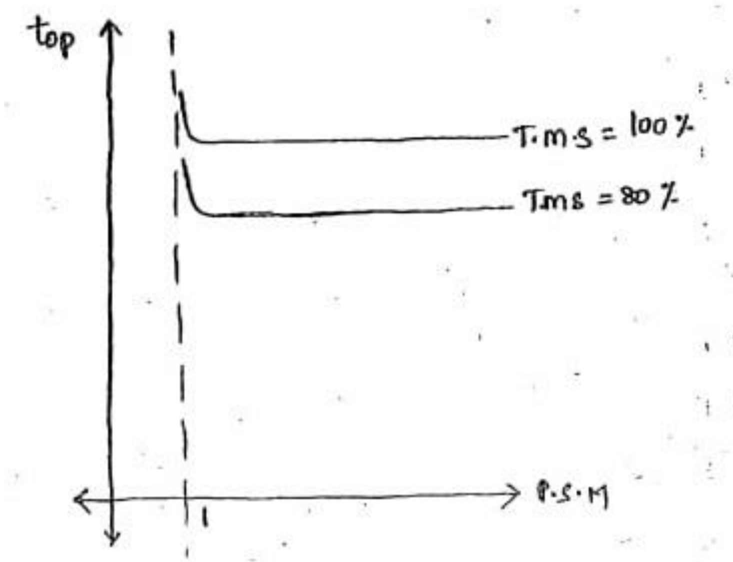
Depending on the characteristics the overcurrent relay is classified as,

- Instantaneous overcurrent relay
- definite time overcurrent relay
- inverse definite minimum time overcurrent relay(IDMT)
- inverse overcurrent relay(very IOCR)
- extremely inverse overcurrent relay

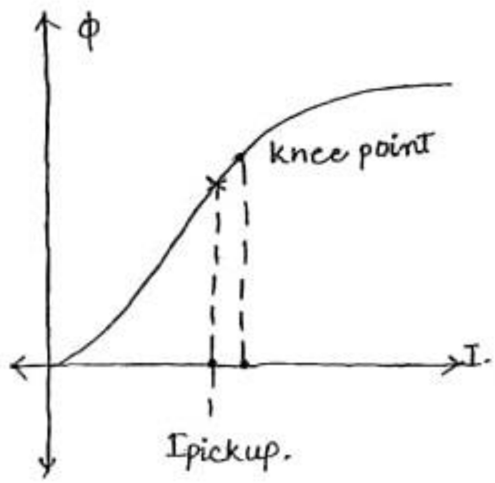
Instantaneous overcurrent relay

- Here the relay operates immediately if the fault current exceeds pickup value or Threshold value. there is no intentional time lag is provided for relay operation
- no provision for TMS
- approximate operating time is 0.1s
- relay operating time is constant throughout working range (PSM>1)

Definite time overcurrent relay

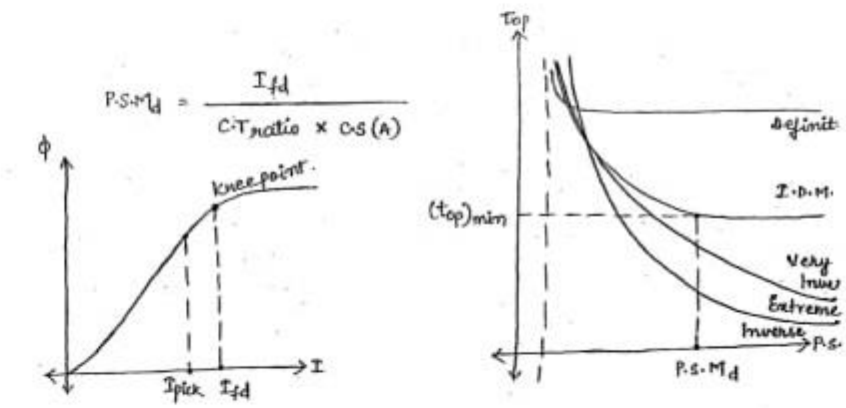


- Relay operates within a definite time if fault current exceeds pickup value
- here operating time of relays constant throughout working range for PSM>1
- The Definite operating time of released adjusted by adjusting psm value



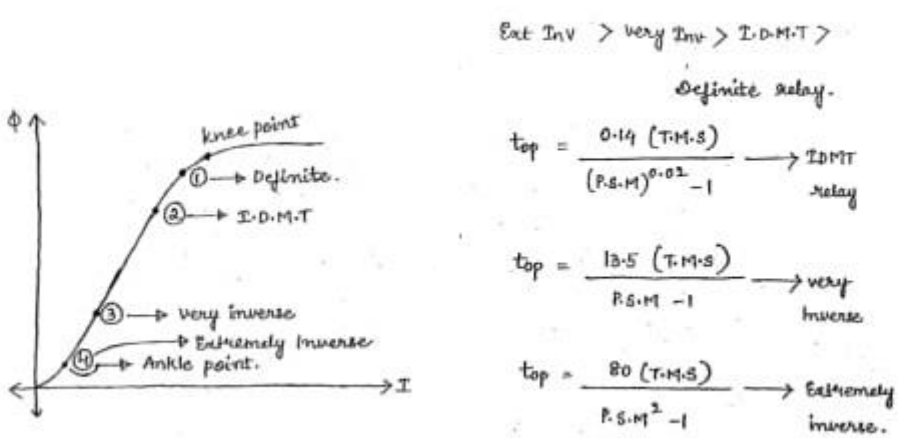
To achieve definite time characteristics, the suitable CT is selected in which Saturation should occur just above the pickup value of the current.

Inverse definite minimum time overcurrent relay (IDMT)



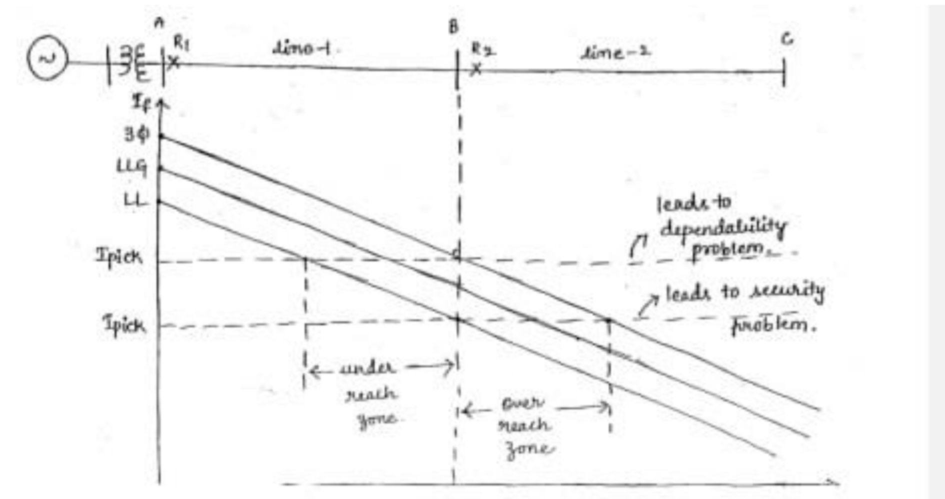
In an IDMT relay the operating time is inversely proportional to fault current near the pickup value and becomes substantially constant through the working range after a certain minimum time is reached. to achieve IDMT characteristics as suitable CT is selected in which saturation should occur about the pickup value of current.

Inverse overcurrent relay (very IOCR)



Applications of overcurrent relays

They are used for the protection of Generator, Motors, Transformers, distribution line, and feeders. Distribution system



In the transmission system LLLG gives maximum fault current and LG gives minimum fault current.
In the distribution system LLLG gives maximum fault current and LL gives minimum fault current.

1. The pickup current of an overcurrent relay selected based on the minimum value of fault current in the protection zone.
2. In Transmission and distribution system, a three phase fault with maximum generation gives the maximum value of fault current in the protection zone.
3. In the transmission system, a LG fault with minimum generation gives the minimum value of fault current in the protection zone.
4. In the distribution system, LL fault with minimum generation gives the minimum value of fault current in the protection zone.

Overreach:

If the relay operates for a point which is outside the zone of protection, then it is called an over reach problem. Due to over-reach, the relays experience security problems. If pickup current is selected based on minimum value of fault current in the protections on, the ove for security problems. So overcurrent relays are not preferred in transmission systems.

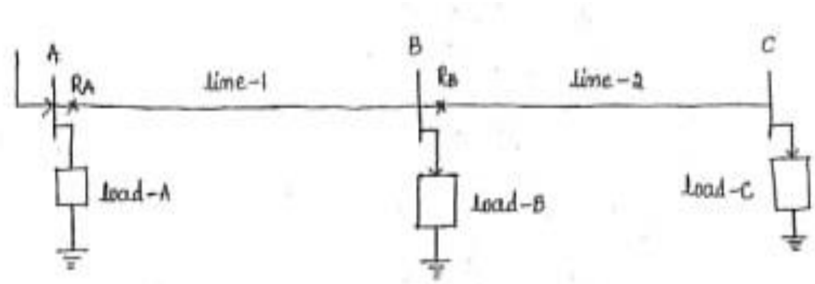
Under reach:

If the relay does not operate for a fault which is inside the zone of protection then it is called under reach. Due to under-reach relays experience with dependability problems. If the pickup current of an overcurrent relay is selected based on maximum value of fault current in the protection zone then the relay experiences an under reach or dependability problem. The dependability is not at all acceptable in the transmission system as well as in the distribution system. Overcurrent relays are preferred in the distribution system but pickup current is selected based on minimum value of fault current in protections on to avoid dependability problems.

To improve the selectivity of overcurrent relays in distribution system

- Time graded scheme
- Current graded scheme
- Time current credit scheme

Time graded scheme



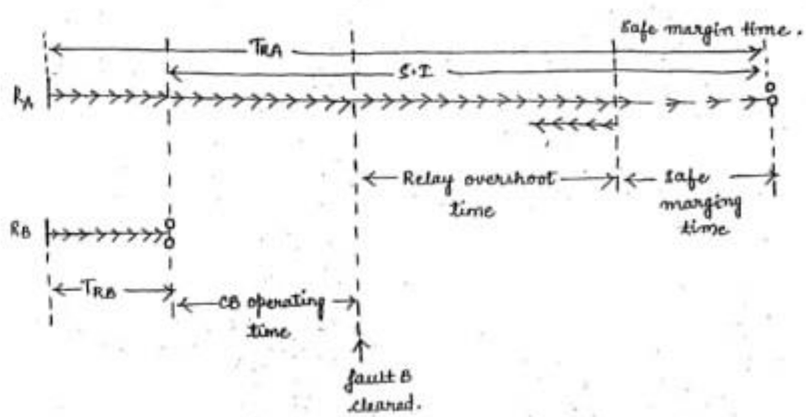
R_A: to provide Primary protection for line 1 and backup protection for Line 2
R_B: To provide primary protection for Line 2
$1.2I_L < I_{set} < I_{fmin}$

Relay R_B:

$1.2I_{LC} < I_{set-RB} < I_{fminC}$
T_{RB}=instantaneous

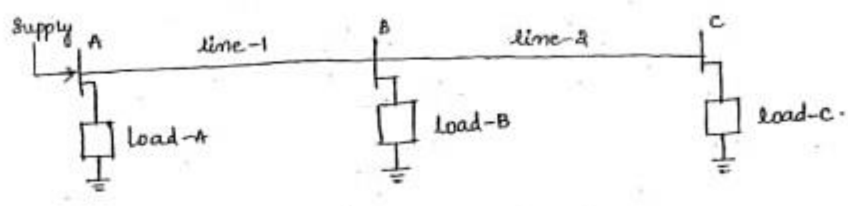
Relay R_A:

$1.2(I_{LC} + I_{LB)} < I_{set-RA} < I_{fminC}$
T_{RA}=$T_{RA} + selective\ interval\ (SI)$
SI=CB operating time+relay overshoot time+safe margin time



In this scheme to achieve the proper selectivity, definite time overcurrent relays are preferred. In a time graded scheme towards the supply the operating time of the relay increases. If there is a fault near the supply system, fault current and fault durations are maximum, which causes damage to substation equipment due to excessive thermal and mechanical stresses. so a time graded scheme alone is not preferred for protection of a practical system if the system consists of more than two lines.
T_{RA}: Definite time overcurrent relay

Current graded scheme

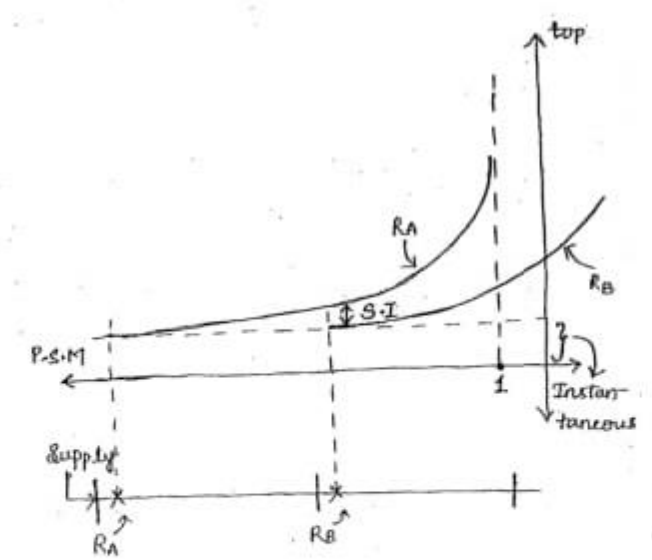


R_A: To provide primary protection for line 1
R_B: To provide primary protection for Line 2

$$1.2I_{LC} < I_{set-RB} < I_{fminC}$$
$$1.2(I_{LC} + I_{LB)} < I_{set-RA} < I_{fminB}$$

- This scheme uses instantaneous overcurrent relays
- Here backup protection not possible
- This scheme mainly suffer with over reached problem
- To provide the practical system protection current graded scheme is not preferred.

Time current credit scheme



This scheme uses IDMT and invest release at the suitable location to achieve the proper selectivity.

<u>DIRECTIONAL RELAYS</u>:-

Universal Torque Equation is

$T = k_1 I^2 + k_2 V^2 + k_3 VIcos(\theta - \tau) + k$

For Directional relay,

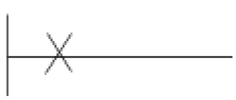
$k_1 = 0, \quad k_2 = 0, \quad k_3 = + Ve, \quad k = - Ve.$

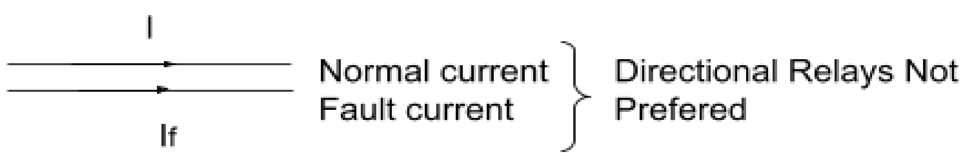
$\therefore T = k_3 \ VIcos\,(\theta - \tau) - |k|$

$\uparrow$ Top $\quad \uparrow$ Tres

<u>Note 1:-</u> In the circuit to be protected, if there is a proper discriminination between the fault current and normal current direction, then directional relays are preferred.

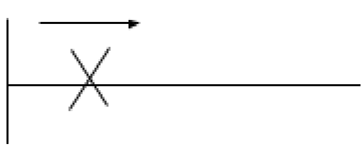
Case 1:

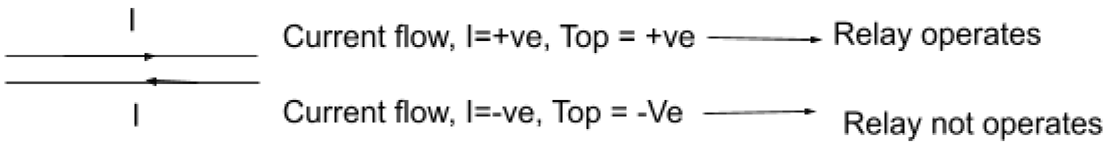




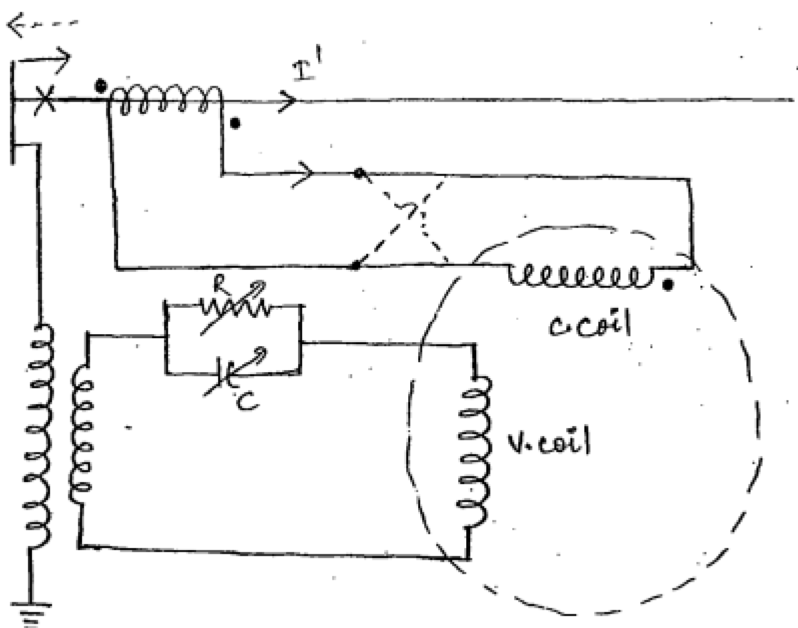
Case 2:

<u>Note 2:</u>- The directional relay in a power system must be indicated with set direction.





The directional relay operates if the current is flowing in the set direction.
The set direction of directional relay is selected based on fault current direction.



Note 3 :- The set direction of directional relay is adjusted by changing current coil terminals.
Note 4 :- The restraining torque ensures that for the operation of directional relay, minimum current is required in the SET direction.

$$I > I_{min} \ in\ set\ direction \rightarrow Relay\ operates$$
$$I < I_{min} \ in\ set\ direction \rightarrow Relay\ not\ operates$$

$$T = k_3 \ VIcos\,(\theta - \tau) - |k|$$

If $(\theta - \tau)$ = Constant;
$\cos(\theta - \tau)$ = Constant

$$k_4 = k_3 \ cos\,(\theta - \tau)$$

$$T = k_4 \ VI - |k|$$

Under Threshold,

$$T = 0,\ T_{op} = T_{res}$$

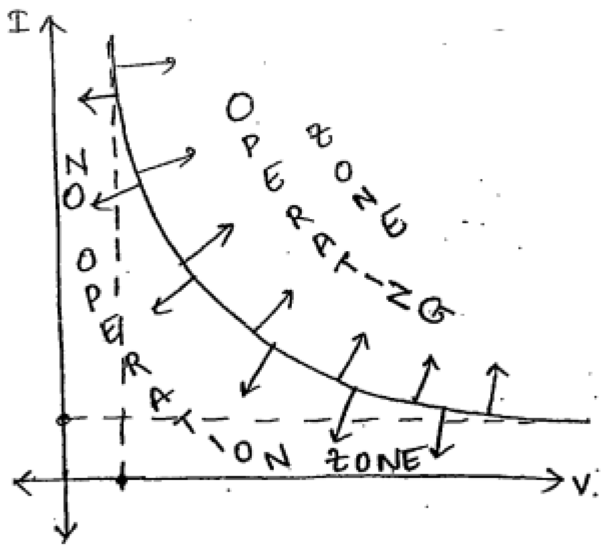
$$k_4 VI - |k| = 0$$

$$VI = \frac{|k|}{k_4}$$

$$\Downarrow$$

Constant product characteristics of Directional relays

When relay is operating,



$$T > 0, \quad T_{op} > Tres$$

$$k_4 VI - |k| > 0$$

$$k_4 VI > |k|$$

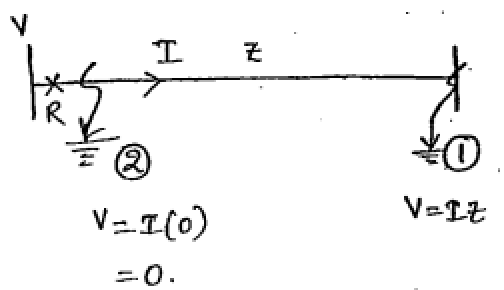
$$VI > \frac{|k|}{k_4}$$

(i) If $I < I_{min} (set\ direction)$

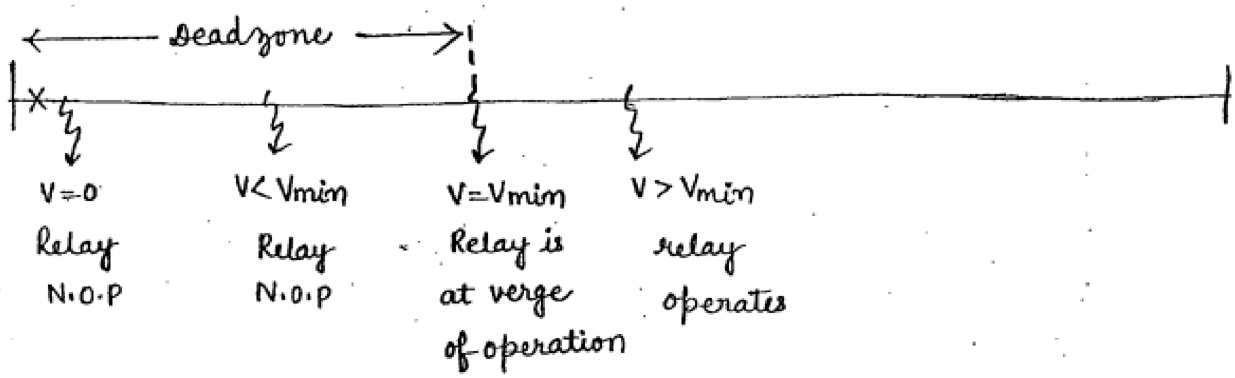
For any value of voltage, relay does not operate.

(ii) If $V < V_{min,}$

For any value of current ($I > I_{min}$)in the set direction, relay is not in operation. So dependability problem occurs.



If the fault is very near to the relay location then voltage fed to the relay is the minimum voltage required for its operation.



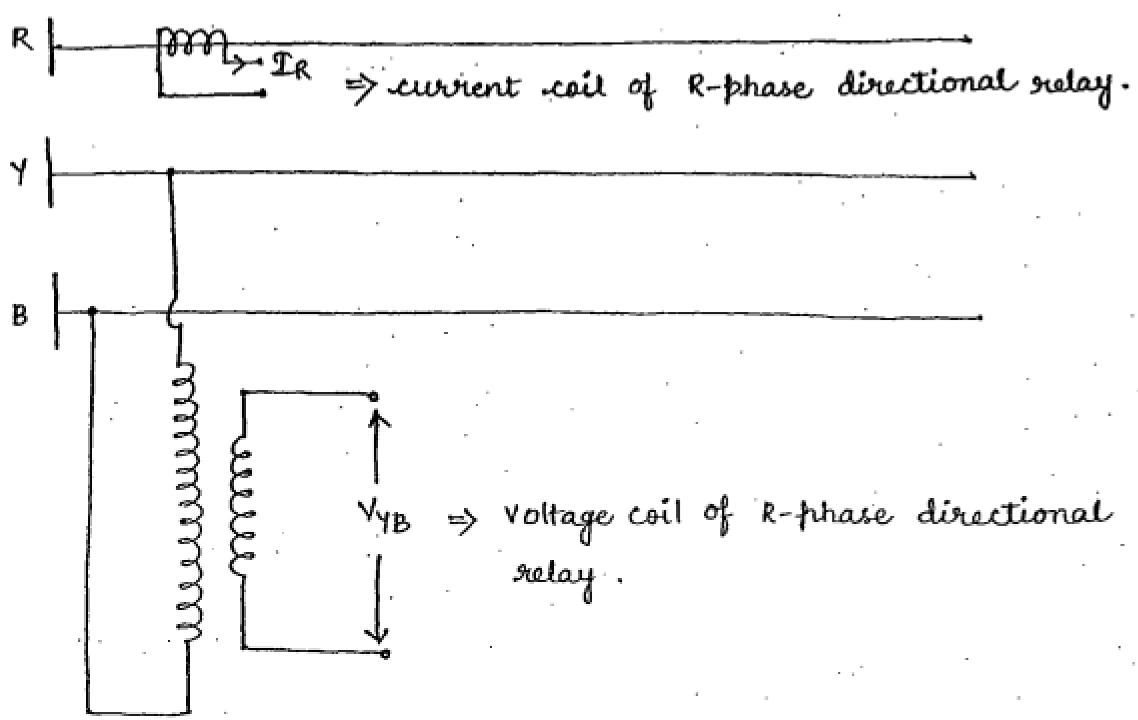
CONNECTIONS OF DIRECTIONAL RELAY:-

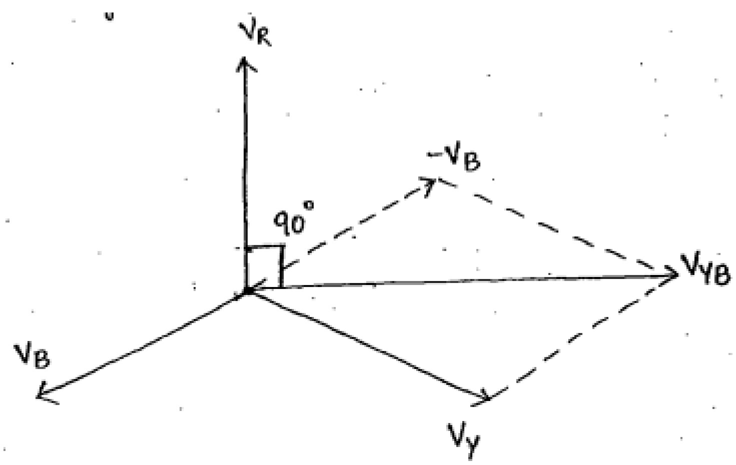
1) $90^{0} connection$
2) $30^{0} connection$
3) $60^{0} connection$

$90^{0} connection$:-

$I = I_R$

$V = V_{YB} = V_Y - V_B$





LG = 85%
LL = 8%
LLG = 5%
3-Phase < 2%

- $90^0 connection$ looses its sensitivity for 3 phase faults.

Type of fault	RG fault	RY fault	RYG fault	RB fault
Voltage Relations	$V_R = 0$, $V_Y \neq 0$, $V_B \neq 0$,	$V_R = V_Y \neq 0$ $V_B \neq 0$, $V_{YB} \neq 0$	$V_R = V_Y = 0$ $V_B \neq 0$, $V_{YB} \neq 0$	$V_R = V_B \neq 0$ $V_Y \neq 0$, $V_{YB} \neq 0$

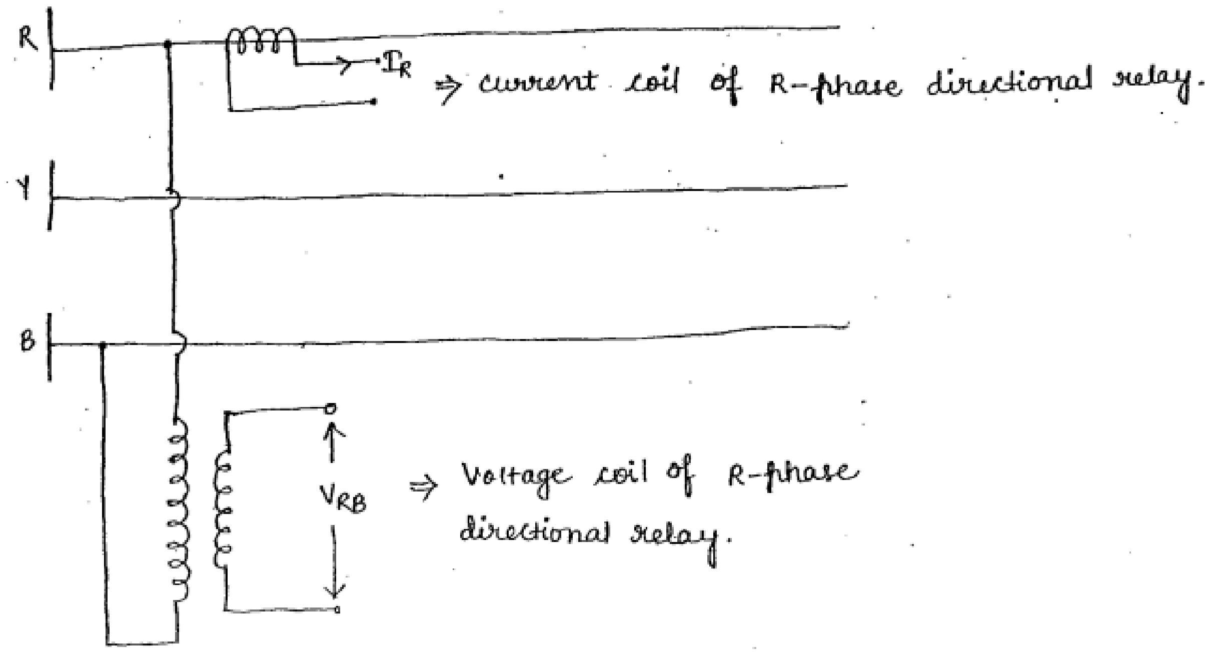
	$V_{YB} \neq 0$			
$0^0 connection$	×	☑	×	☑
$90^0 connection$	☑	☑	☑	☑

Type of fault	RBG Fault	RYB Fault	RYBG Fault	% Failure
Voltage Relations	$V_R = V_B = 0$, $V_Y \neq 0$, $V_{YB} \neq 0$,	$V_R = V_Y = V_B \neq 0$ $V_{YB} = 0$	$V_R = V_Y = V_B = 0$ $V_{YB} = 0$	
$0^0 connection$	×	☑	×	90%
$90^0 connection$	☑	×	×	< 2%

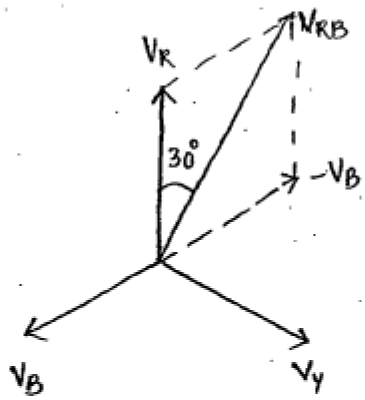
$30^0 connection$:-

$I = I_R$

$V = V_{RB} = V_R - V_B$



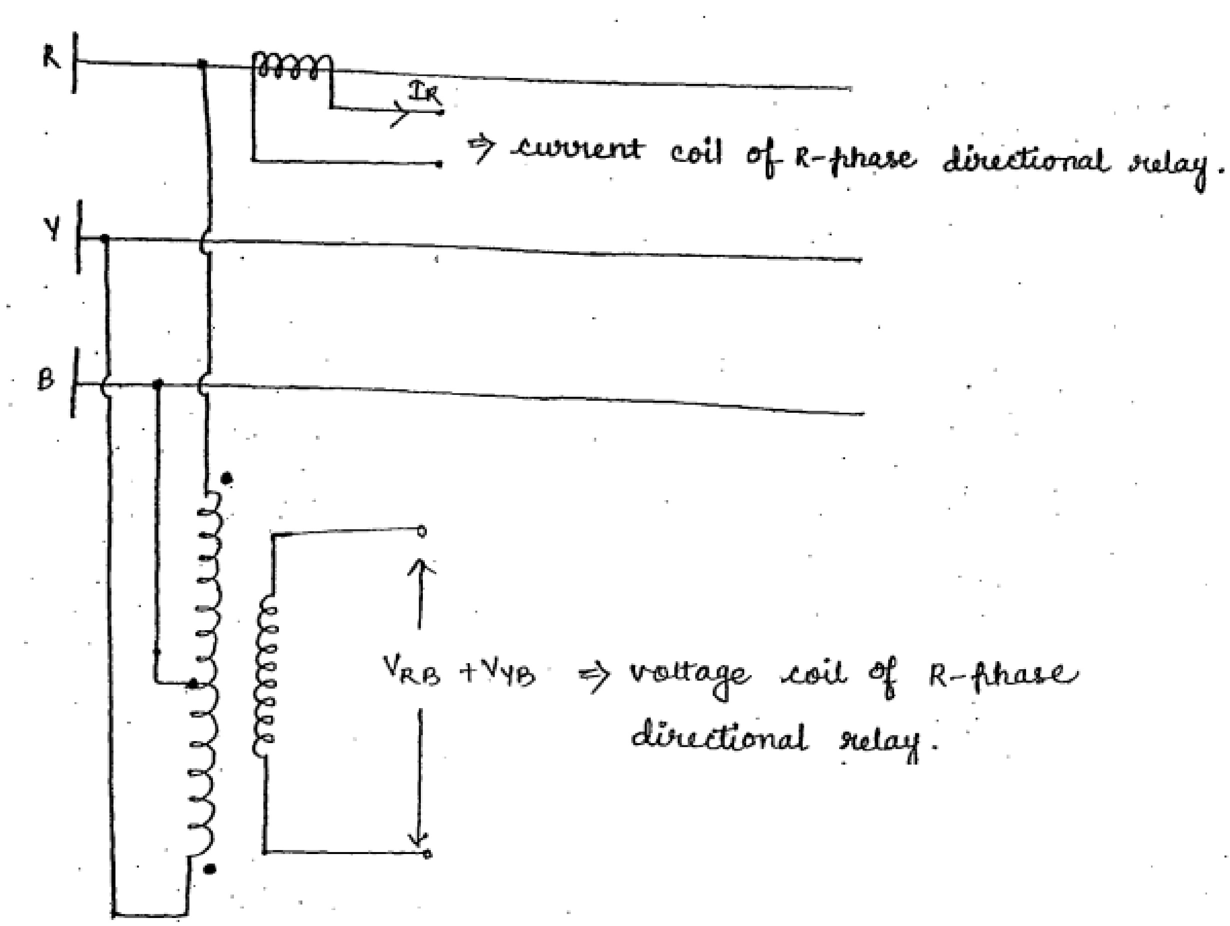
30^0 *connection* loses its sensitivity for 3-phase, LL,LLG faults.

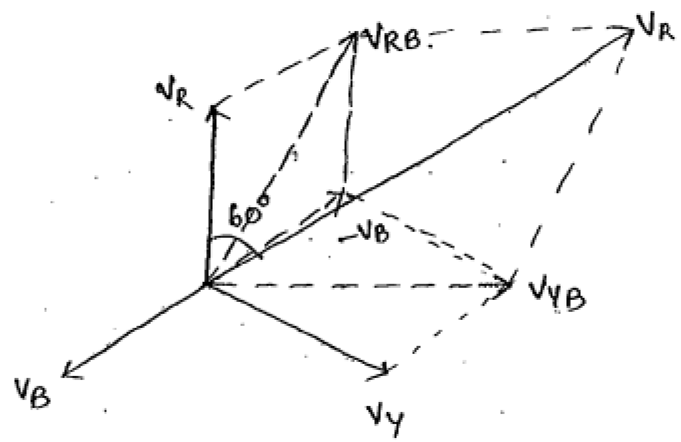


60^0 *connection*:-

$I = I_R$

$V = V_{RB} + V_{YB}$





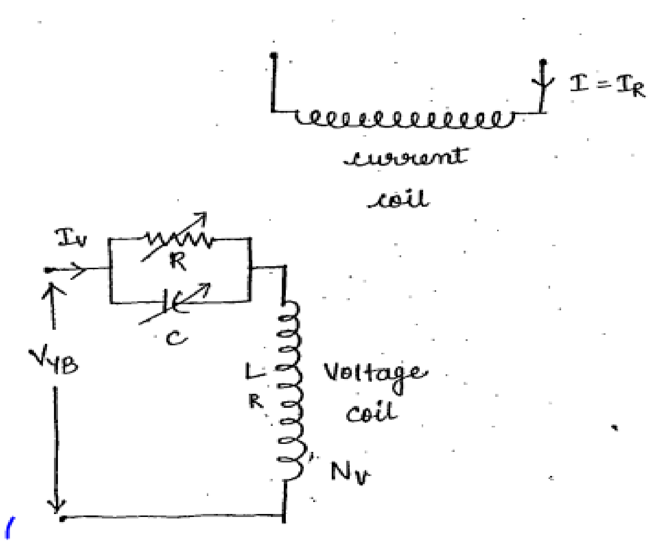
90^0 *connection* is the best connection among the three connections of differential relay.

Type of fault	RG fault	RY fault	RYG fault	RB fault	RBG fault
Voltage Relations	$V_R = 0$ $V_Y \neq 0$	$V_R = V_Y \neq 0$ $V_B \neq 0$	$V_R = V_Y = 0$ $V_B \neq 0$	$V_R = V_B \neq 0$ $V_Y \neq 0$	$V_R = V_B = 0$ $V_Y \neq 0$

	$V_B \neq 0$ $V_{YB} \neq 0$ $V_{RB} \neq 0$	$V_{YB} \neq 0$ $V_{RB} \neq 0$	$V_{YB} \neq 0$ $V_{RB} \neq 0$	$V_{YB} \neq 0$ $V_{RB} = 0$	$V_{YB} \neq 0$ $V_{RB} = 0$
$0^0 connection$	×	☑	×	☑	×
$90^0 connection$	☑	☑	☑	☑	☑
$30^0 connection$	☑	☑	☑	×	×
$60^0 connection$	☑	☑	☑	☑	☑

Directional Relay connections	R-phase		Y-Phase		B-phase	
	Current coil	Voltage coil	Current coil	Voltage coil	Current coil	Voltage coil
$90^0 connection$	I_R	V_{YB}	I_Y	V_{BR}	I_B	V_{RY}
$30^0 connection$	I_R	V_{RB}	I_Y	V_{YR}	I_B	V_{BY}
$60^0 connection$	I_R	$V_{YB}+V_{RB}$	I_Y	$V_{BR} + V_{YR}$	I_B	$V_{BY}+V_{RY}$

PHASOR DIAGRAM OF DIRECTIONAL RELAY:-



$$Top = k_3 \; VIcos\,(\theta - \tau)$$

$$Top \; \alpha \; \phi_c \phi_v sin\alpha$$

$$\phi_c = \frac{N_c I_c}{Re_c}$$

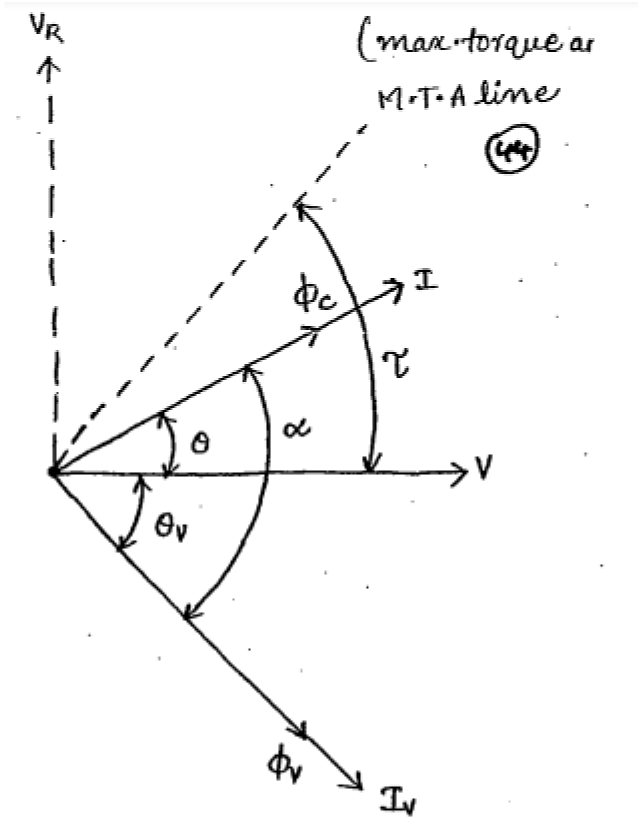
$$\phi_v = \frac{N_v I_v}{Rv}$$

$$I_v = \frac{V}{Z_v}$$

$$Z_v = |Z_v| L\theta_v$$

Power factor angle of fault = (90-θ)

- The MTA line is always in quadrature with voltage coil current and voltage coil flux. By adjusting the angle between voltage coil voltage and voltage coil current (θ_v), it is possible to adjust the maximum torque angle line.



$$\theta_v + \tau = 90^0$$

$$\text{If } \theta_v = 0^0, \tau = 90^0$$

$$\theta_v = 90^0, \tau = 0^0$$

$$\theta_v = 45^0, \tau = 45^0 \rightarrow Best\ range\ of\ values$$

$$\Rightarrow 0^0 < \theta < 90^0$$

For $\tau = 45^0$,

$-45^0 < (\theta - \tau) < 45^0$

$|\theta - \tau| < 45^0$

$cos(\theta - \tau) > \frac{1}{\sqrt{2}}$

$cos(\theta - \tau) > 0.707$

$Top = k_3 VIcos(\theta - \tau)$

Thus $Top >$ 70.7% of Top max→ $(for\ \tau = 45^0)$

POLAR CHARACTERISTICS OF DIRECTIONAL RELAYS :-

(i) $T_{res} = 0$

$T = k_3 VIcos(\theta - \tau)$

If I>0 in set direction, relay operates.

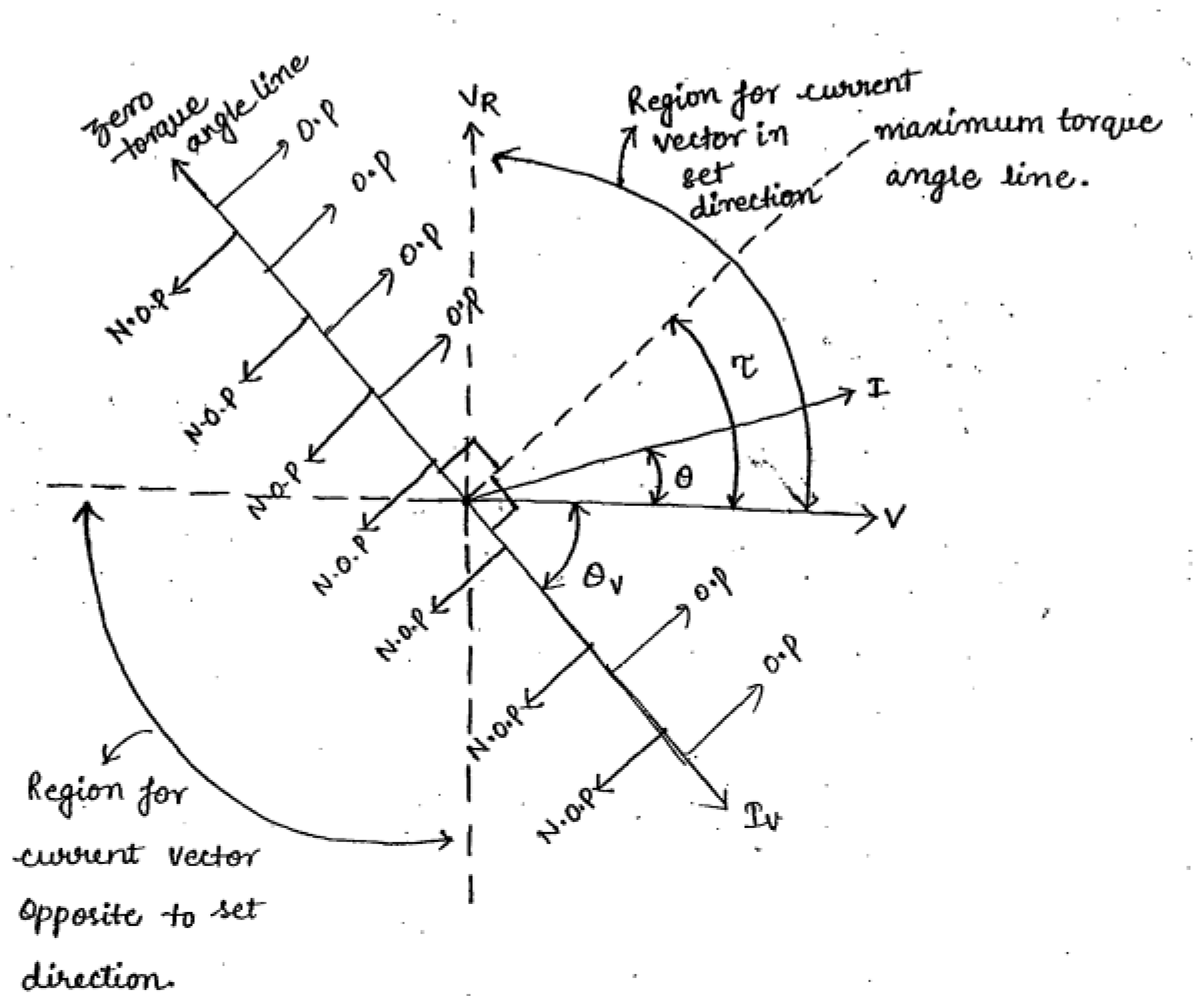
Under threshold: T=0, $T_{op} = T_{res}$

$k_3 VIcos(\theta - \tau)=0$

$cos(\theta - \tau)=0$

$\theta - \tau = \pm \frac{\Pi}{2}$

$\theta = \tau \pm \frac{\Pi}{2}$ ⇒Polar characteristics of directional relay



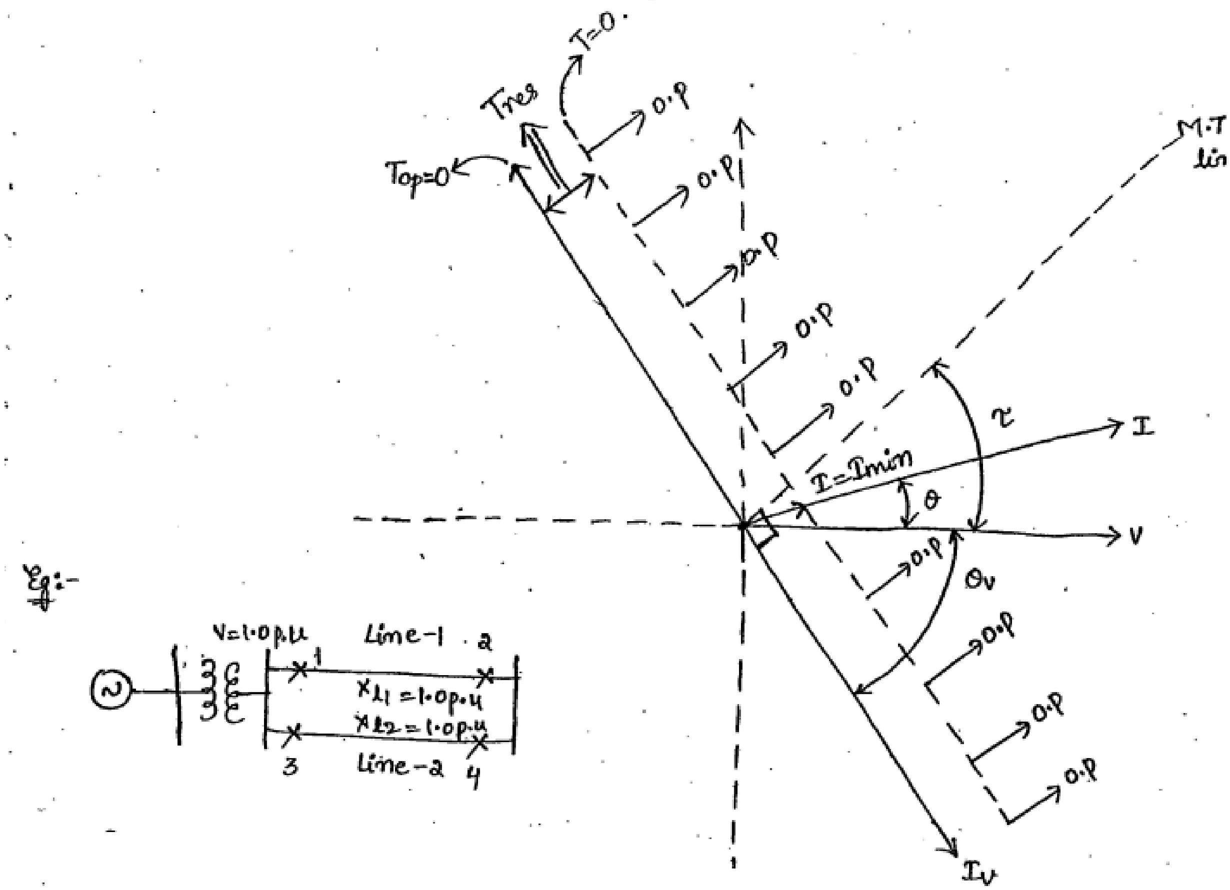
(ii) Tres$\neq$ 0,

$$T = k_3\ VIcos\,(\theta - \tau) - |k|$$

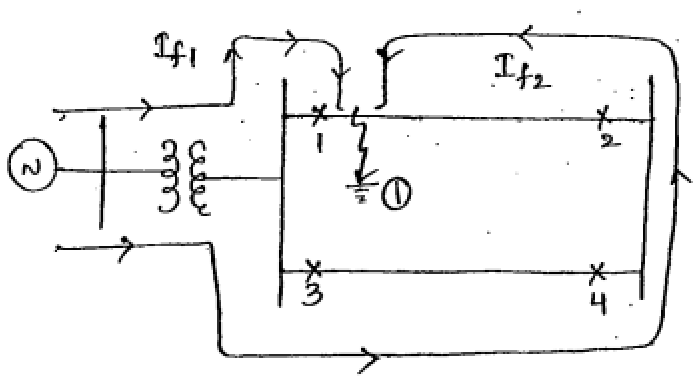
If $I > I_{min}$ in set direction, the relay operates.

APPLICATIONS OF DIRECTIONAL RELAY:-

- Directional relays are used for protection of parallel feeders.
- Used in ring main distribution section.

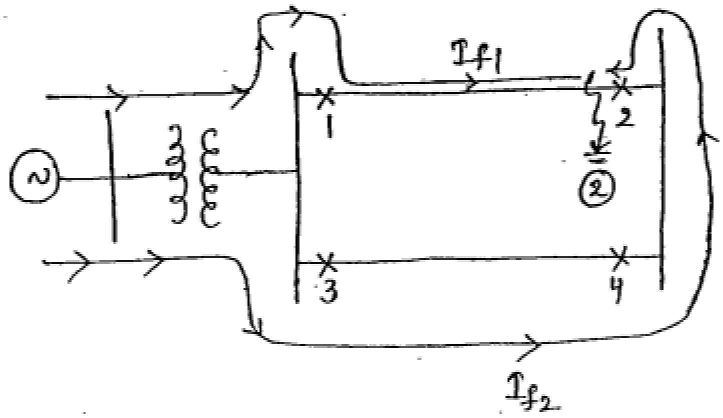


If over current relays are used, the pick up current setting of the relays:



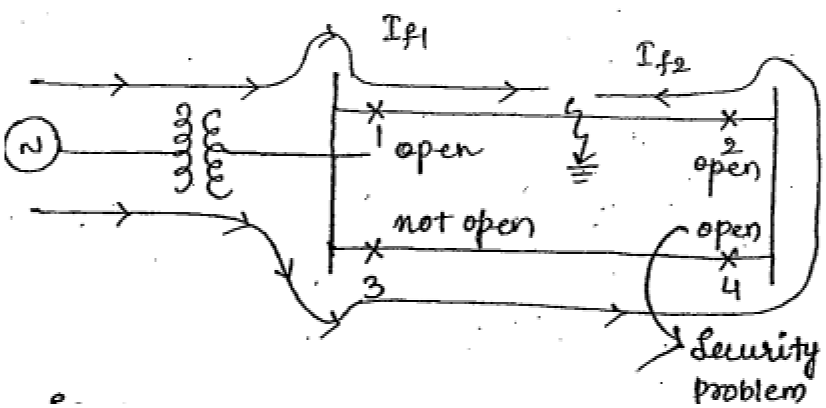
$$I_{f1}=\frac{1}{0}=\infty$$

$$I_{f2}=\frac{1}{1+1}=0.5pu$$



$I_{f1} = \frac{1}{1} = 1p.u$

$I_{f2} = \frac{1}{1} = 1pu$



$I_{f1} = \frac{1}{0.5} = 2p.u$

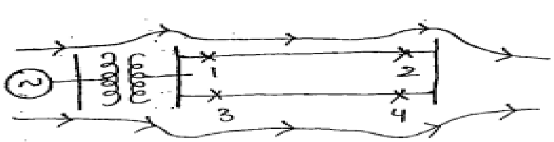
$I_{f2} = \frac{1}{1+0.5} = 0.667pu$

So over current relays does not provide feasible protection.

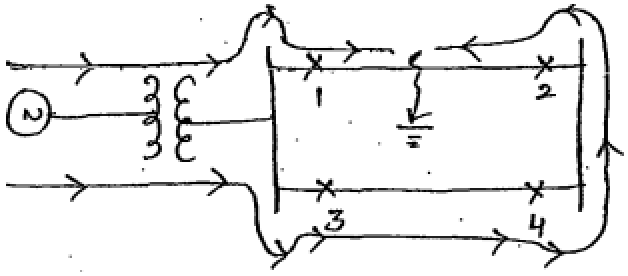
By using directional relays protection can be provided.

PROCEDURE FOR IDENTIFYING DIRECTIONAL RELAY LOCATIONS:-

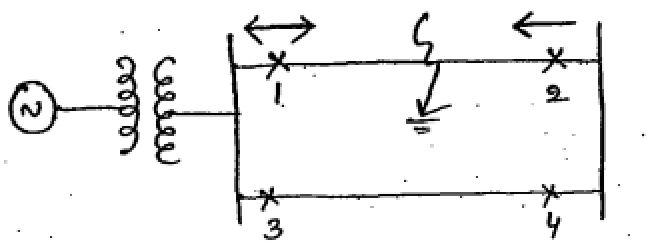
1. Identify the relay location and the purpose of their locations.
2. Mark the normal current direction.



3. Create a fault in one transmission line and observe the fault current direction. (This gives the conclusion about the relays which are monitoring that particular transmission line).



Conclusion 1: If the fault current and the normal current observed by the relay are in same direction, then the relay must be a nondirectional relay.



Conclusion 2: If the fault current and the normal current observed by the relay are in opposite direction, then the relay must be a directional relay.(Set direction must be in fault current direction.)

4. Repeat the procedure for all transmission lines.

DISTANCE RELAYS:-

1. Impedance relays
2. Reactance relays
3. MHO relays

Impedance Relays:-

$T = k_1 I^2 + k_2 V^2 + k_3 VIcos(\theta - \tau) + k$

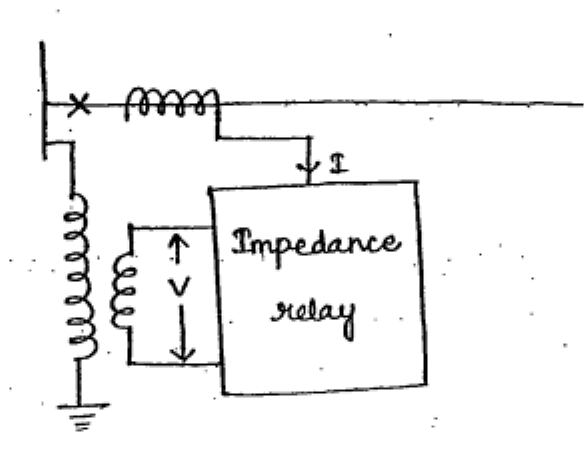
$k_1 = positive, k_2 = negative, k_3 = 0. k = 0$

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

↑ Top ↑ Tres

- Current is providing torque
- Voltage unit is providing restraining torque
- Impedance Relays is also called Voltage restrained over current relay.

Note:- For distance Relays the voltage coil and current coils should be supplied from same phase C.T and P.T.



Under Treshold:-

T=0, Top= Tres

$k_1 I^2 = |k_2| V^2$

$\frac{V^2}{I^2} = \frac{k_1}{|k_2|}$

$\frac{V}{I} = \sqrt{\frac{k_1}{|k_{2|}}}$

$Z = \sqrt{\frac{k_1}{|k_{2|}}}$

$Z_{set} = \sqrt{\frac{k_1}{|k_{2|}}}$

When relay is operating:-

T>0, Top>Tres

$k_1 I^2 > |k_2| V^2$

$\frac{V^2}{I^2} < \frac{k_1}{|k_2|}$

$\frac{V}{I} < \sqrt{\frac{k_1}{|k_{2|}}}$

$Z_{seen} < \sqrt{\frac{k_1}{|k_{2|}}}$

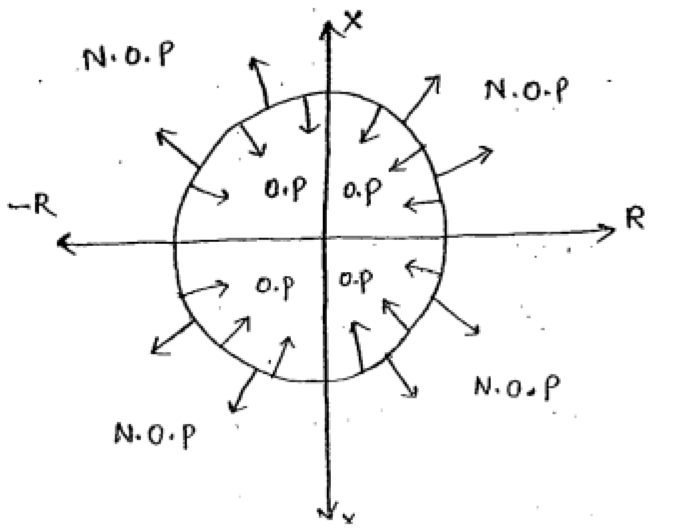
$Z_{seen} < Z_{set} \Rightarrow (eqn\ 2)$

$Z_{set} = \sqrt{\frac{k_1}{|k_{2|}}}$=c

$\sqrt{R_{set}^{\ 2} + Z_{set}^{\ 2}} = c^2 \Rightarrow (eqn\ 3)$

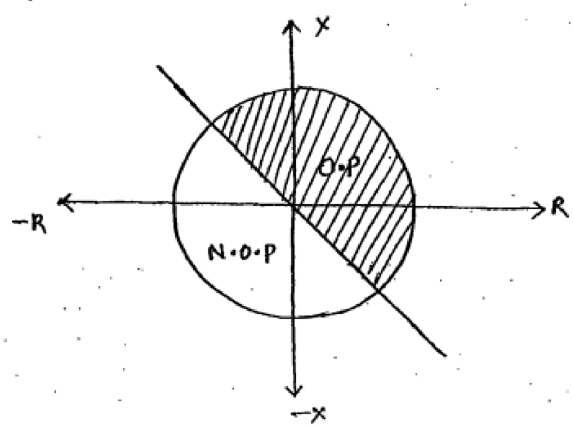
Equation 2 represents region inside the circle

Equation 3 represents a circle with radius c or Z_{set} and centre at origin or RX plane



Conclusion 1:-

- If the impedance seen by the relay< Z_{set}, then the relay operates.
- The operation of the relay depends on both resistance and reactance seen by the relay.
- Impedance relay dont have inherent directional property.
- If external directional properties are added, then the relay characteristic will be as shown below:



REACTANCE RELAY:-

$T = k_1 I^2 + k_2 V^2 + k_3 VIcos(\theta - \tau) + k_T$

For reactance Relays,

$k_1 = positive, k_2 = 0, k_3 = negative, k_T = 0$

$T = k_1 I^2 - |k_3| VIcos(\theta - \tau)$

↑ Top   ↑ Tres

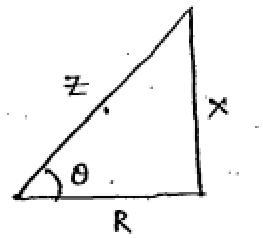
- Current unit is providing operating torque.
- Directional unit is providing restraining torque

- Reactance Relays is also called directional restrained over current relay.

$$\tau = 90^0$$

$$T = k_1 I^2 - |k_3| VI sin(\theta)$$

$$\theta \text{ is power factor angle or impedance angle.}$$



$sin\theta = \frac{X}{Z}$, $cos\ \theta = \frac{R}{Z}$

Under threshold:-

T=0 , Top=Tres.

$k_1 I^2 = |k_3| VI sin(\theta)$

$\frac{VI sin\theta}{I^2} = \frac{k_1}{|k_3|}$

$\frac{V}{I} sin\theta = \frac{k_1}{|k_3|}$

$Z sin\theta = \frac{k_1}{|k_3|}$

$X = \frac{k_1}{|k_3|}$

When Relay is operating:-

T>0,

Top>Tres

$k_1 I^2 > |k_3| VI sin(\theta)$

$\frac{VI sin\theta}{I^2} < \frac{k_1}{|k_3|}$

$\frac{V}{I} sin\theta < \frac{k_1}{|k_3|}$

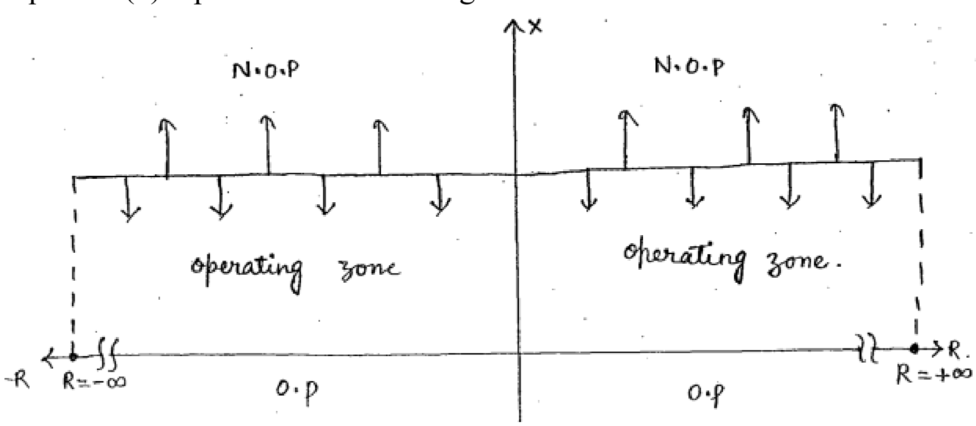
$Z sin\theta < \frac{k_1}{|k_3|}$

$X < \frac{k_1}{|k_3|}$

$X_{set} = \frac{k_1}{|k_3|}$............(1)

$X_{seen} < X_{set}$ ......(2)

Equation (1) represents a straight line parallel to resistance axis on R-X plane.
Equation (2) represents the entire region below the line.



- If the reactance seen by the relay is less than the set value, then the relay operates.
- The operation of relay depends on only reactance seen by the value

- The operation of relay independent on resistance seen by the relay
- Reactance Relay don't have inherent directional properties.

MHO RELAY:-

$T = k_1 I^2 + k_2 V^2 + k_3 VI\cos(\theta - \tau) + k$

For reactance Relays,

$k_1 = 0, k_2 = negative, k_3 = positive,\ k = 0$

$T = k_3 VI\cos(\theta - \tau) - |k_2|V^2$

↑ Top ↑ Tres

- Directional unit is providing operating torque.
- Voltage unit is providing restraining torque
- MHO Relay is also called voltage restrained directional relay.

Under threshold:-

T=0 , Top=Tres.

$k_3 VI\cos(\theta - \tau) = |k_2|V^2$

$\frac{V^2}{VI} = \frac{k_3}{|k_2|}\cos(\theta - \tau)$

$Z = \frac{k_3}{|k_2|}\cos(\theta - \tau)$

$Z_{set} = \frac{k_3}{|k_2|}\cos(\theta - \tau)$......(1)

↓ ↓ ↓

Ω Ω no unit

$Z_{set} = Z\cos(\theta - \tau)$

If Z=$\frac{k_3}{|k_2|}$=c

When Relay is operating:-

T>0,

Top>Tres

$k_3 VI\cos(\theta - \tau) > |k_2|V^2$

$\frac{V^2}{VI} < \frac{k_3}{|k_2|}\cos(\theta - \tau)$

$Z < \frac{k_3}{|k_2|}\cos(\theta - \tau)$

$Z_{seen} < Z_{set}$.......(2)

Equation (1) represents a circle passing through origin on R-X plane.

Equation (2) represents the region inside the circle.

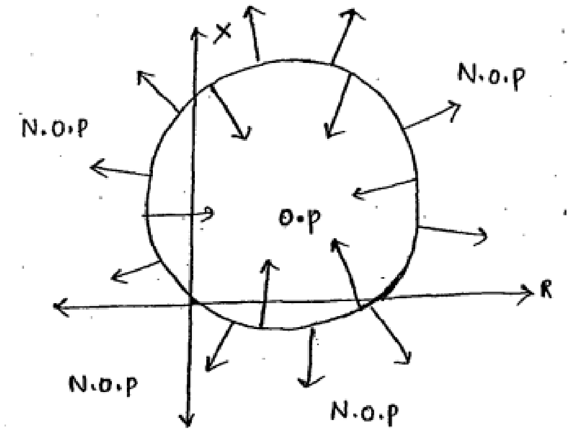
As $Z_{seen} < Z_{set}$

$Y_{seen} > Y_{set}$

↓ ↓

℧ ℧

ENTRI



Conclusion :-

- If the impedance seen by the relay is less than the preset value, then the relay operates.
- The operation of relay depends on both resistance and reactance seen by the relay
- Mho Relay is having inherent directional properties.

Calculation of impedance seen by the relay:

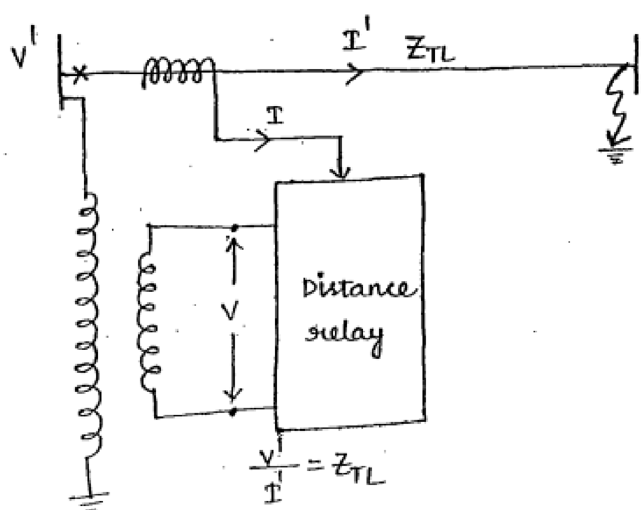
$Z_{seen} = \frac{V}{I}$

$x = CT\ ratio = \frac{I'}{I}$

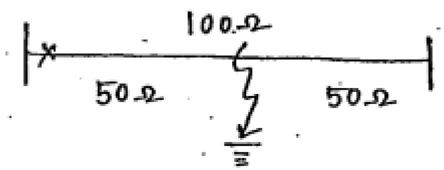
$y = PT\ ratio = \frac{V'}{V}$

$Z_{seen} = \frac{V}{I} = \frac{V'}{y} * \frac{x}{I'}$

$Z_{seen} = \frac{x}{y} * \frac{V'}{I'} = \frac{x}{y} * Z_{TL}$



Eg:-A 3-ϕ, 132KV, 50Hz, Transmission line having an impedance of $100\Omega/phase$. An impedance relay is connected to a transmission line through a C.T of ratio 1000/1A and a P.T of ratio 100KV/50V. A 3-ϕ fault occurred in the middle of the transmission line, calculate the impedance seen by the relay.



Solution:

Z_{TL}=100Ω/*phase*.

$\frac{V'}{I'}$=50Ω/*phase*.

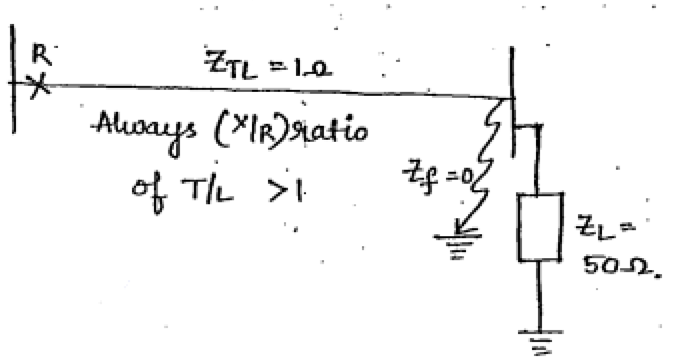
$Z_{seen} = \frac{x}{y} * \frac{V'}{I'}$

$=\frac{1000/1}{100*10^3/50} * 50$

$=\frac{1}{2} * 50$

=25Ω/*phase*.

Calculation of settings for Distance Relays:-



For Transmission Line:

$X_{TL} >> R_{TL}$

For Load

$X_{TL} << R_{TL}$

As for reactive power conpensation, capacitor bamks are introduced at the Load Centres. So it is assumed that the load cunsuming only active power only. Hence

$X_{TL} << R_{TL}$ is valid.

Generally power factor of load =0.8 lag

Power factor= cosθ

$\theta = tan^{-1}(\frac{X_L}{R_L})$

Power factor =cos($tan^{-1}(\frac{X_L}{R_L})$)

$(\frac{X_L}{R_L}) = tan(cos^{-1}(power\ factor))$

=$tan(cos^{-1}(0.8))$
=0.75

Generally generator is considered to be operating at unity power factor as it is considered that it will supply active power.If generator has to supply reactive power then it has to compromise with active power as VA rating of generator

During normal operation,
$V = IZ_{TL} + IZ_L$

$V = I(Z_{TL} + Z_L)$

$\frac{V}{I} = I(Z_{TL} + Z_L)$

$Z_{seen} = (Z_{TL} + Z_L)$

$Z_{seen} = (R_{TL} + R_L) + j(X_{TL} + X_L),$

During fault,
$V \simeq IZ_{TL} + IZ_f$

$V \simeq I(Z_{TL} + Z_f)$

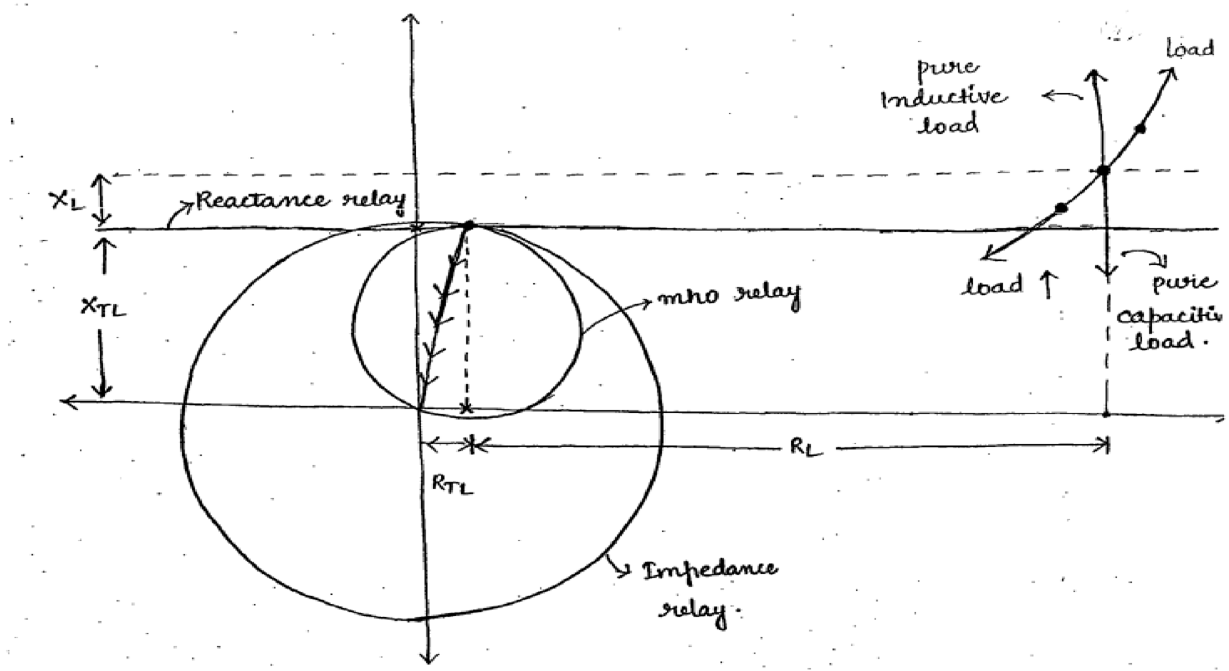
$\frac{V}{I} \simeq (Z_{TL} + Z_f)$

$Z_{seen} \simeq (Z_{TL} + Z_f)$

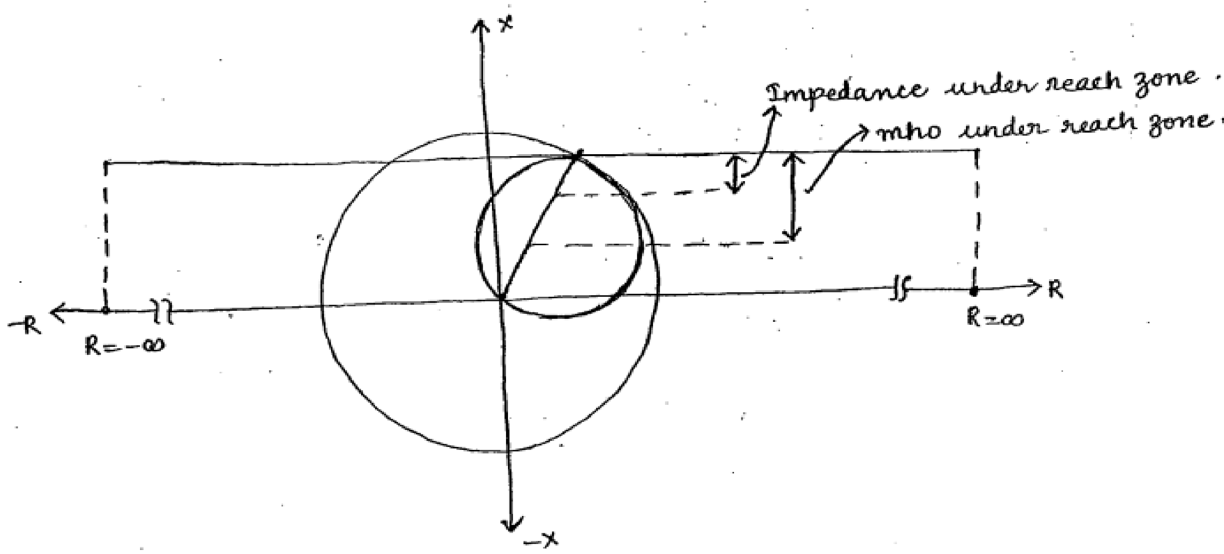
$Z_{seen} \simeq Z_{TL}$ $\qquad As\ I_f = 0$

$Z_{seen} = R_{TL} + jX_{TL}$

Conclusion:
- The setting for the distance relay are calculated based on the Transmission Line impedance
- The Impedance relay and mho relay do not issue any trip signal during normal operation.
- Reactance Relay issues trip signal during normal operation (maloperation). So reactance relay is not alone preferred for practical system protection.

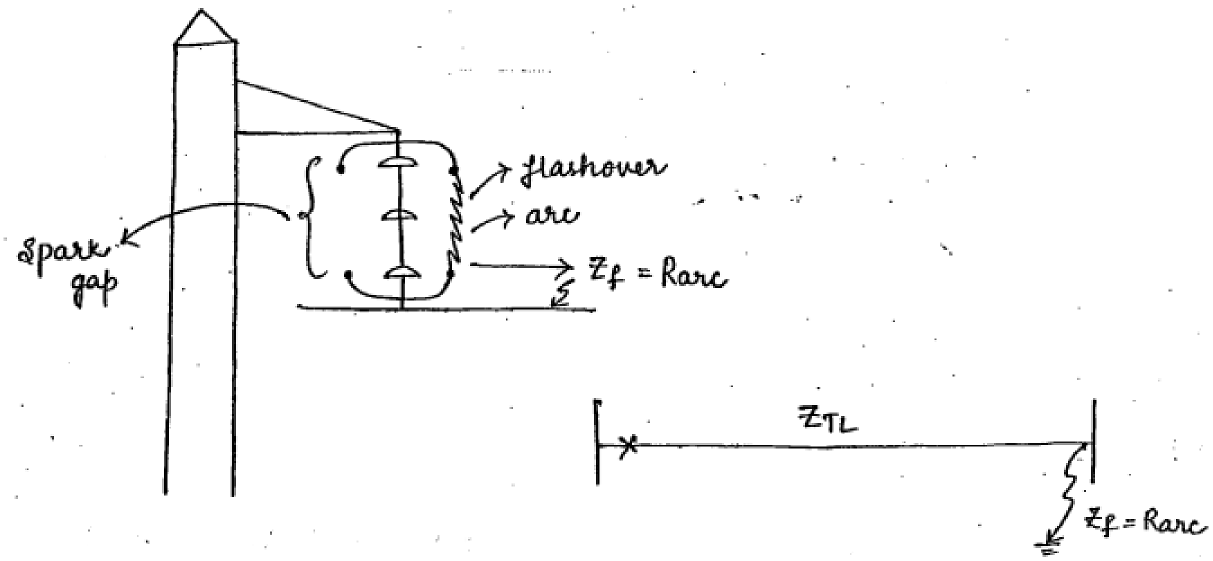


Comparison of Distance Relays:-



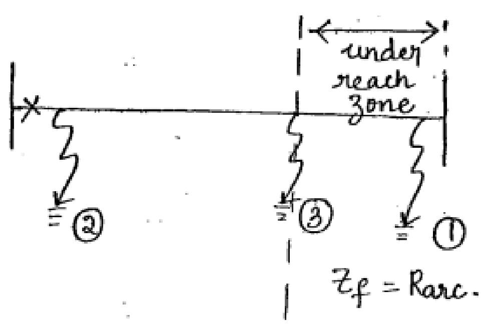
- Reactance relays occupies more space on R-X diagram.
- Impedance relays occupies moderate space on R-X diagram.
- Mho relays occupies least space on R-X diagram.

(2) Effect of Arc resistance:-

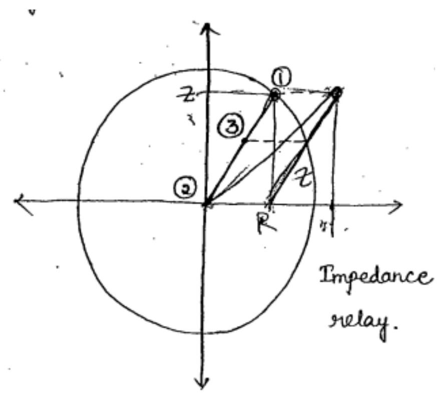


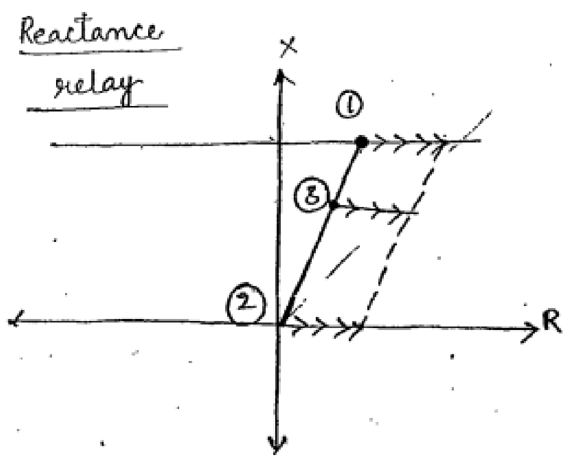
$$Z_{seen} = (Z_{TL} + Z_f)$$
$$Z_{seen} = (R_{TL} + jX_{TL} + R_{arc})$$
$$Z_{seen} = (R_{TL} + R_{arc}) + jX_{TL}$$

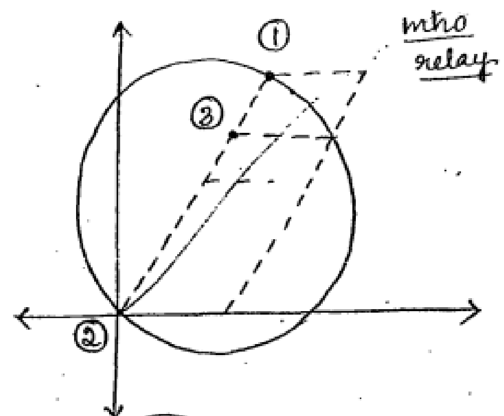
- If there is a flash over across the insulators due to over voltage caused by lightening or switching then fault current flowing through the air is in the form of arc.
- The path of the arc is purely resistive.
- During arc fault the effective impedance seen by the relay increases and operating point shifts horizontally in R-X plane

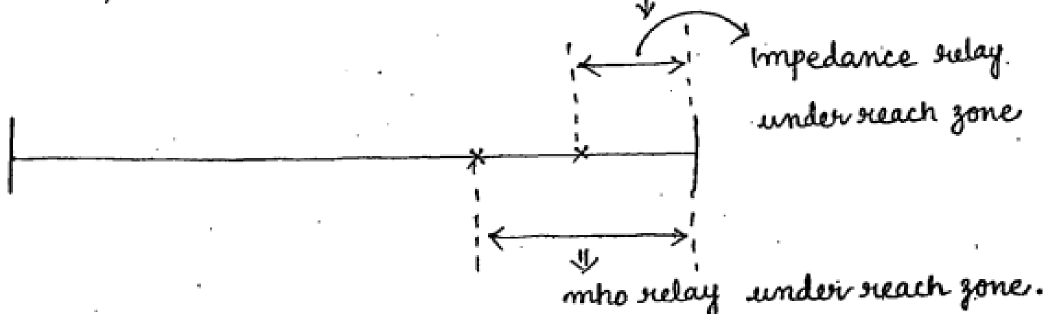


Impedance Relay





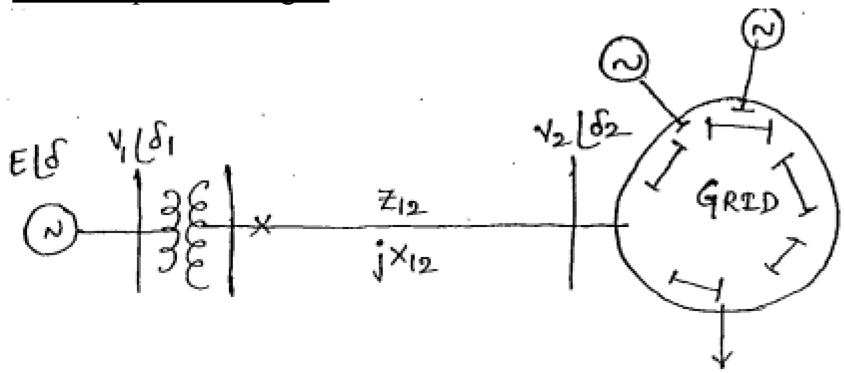




Conclusion:

- The impedance relays and mho relays under reaches during the arc fault.
- The relay which occupies the least space on the arc fault is highly effective due to arc resistance.
- The effect of arc resistance causes dependability problems for impedance relays and mho relays.
- Underreach zone of the impedance relay is less than the undereach zone of the Mho relay.
- Mho relay is highly affected due to arc resistance.
- Impedance relay moderately affected due to arc resistance.
- Reactance relay is not affected due to arc resistance.

(3) Effect of power swings:-

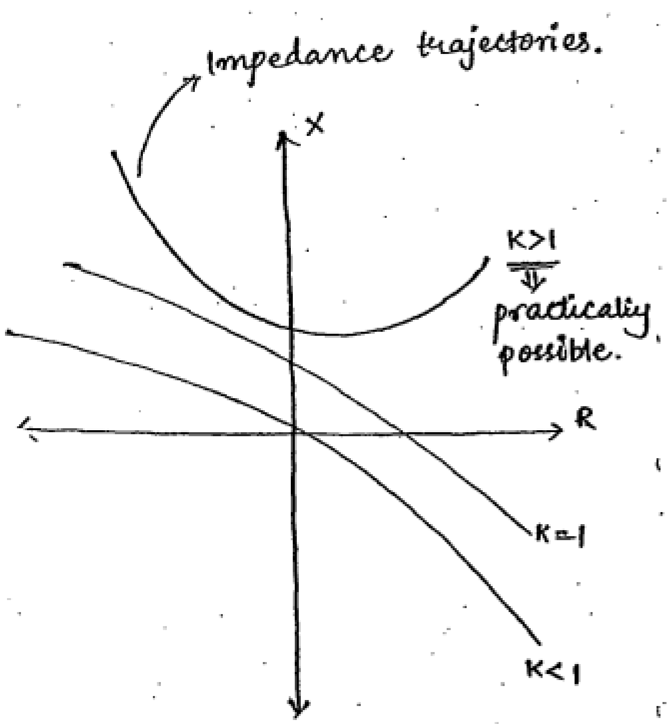


$$P_{12} = \frac{V_1 V_2}{X_{12}} sin(\delta_1 - \delta_2)$$

$$Z_{seen} = \frac{V}{I}$$

$$I = \frac{V_1 \angle \delta_1 - V_2 \angle \delta_2}{Z_{12}}$$

$$k = \frac{V_1}{V_2}$$



POWER SWING:-

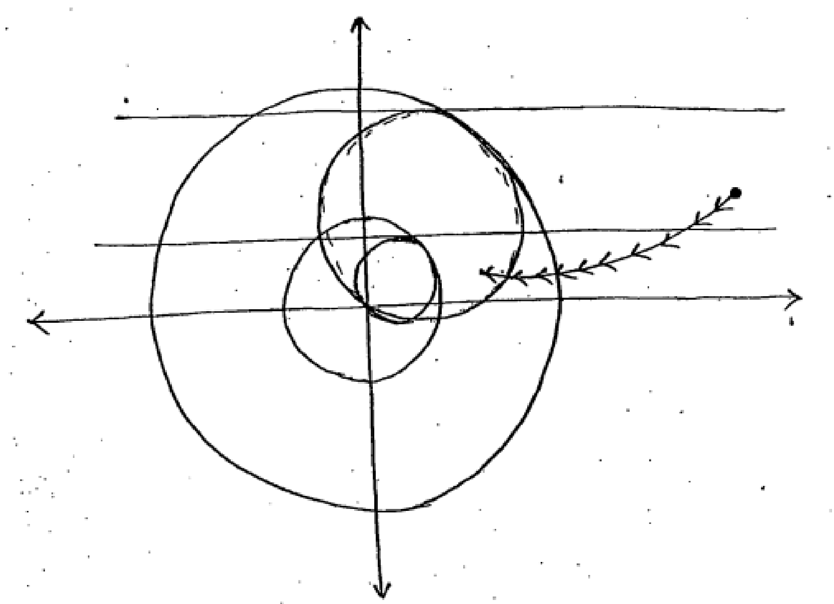
If the power system is experienced with disturbance, the load angle of synchronous machine undergoes huge variations which causes fluctuations in power flow through the transmission lines, this phenomenon is k.

During power swings the impedance seen by the relay highly fluctuates and causes maloperation of distance relays.

- The relay which occupies more space on RX diagram is highly affected due to power swing.
- The effect of power swing causes security problem for all the distance relays.
- Reactance relay is highly affected due to Power swing.
- Impedance relay moderately affected due to Power swing.
- Mho relay is least affected due to Power swing.

(4) Effect of Load encroachment:-

- If the power system is experienced with overloads, then impedance seen by the relay decreases and encroaches into third zone of distance relays. This phenomenon is known as Load encroachment.



- Reactance relay is highly affected due to Load encroachment.
- Impedance relay is moderately affected due to Load encroachment.
- Mho relay is least affected due to Load encroachment.

Distance Relays	Operating Torque	Restraining Torque	Directional-feature	During normal load flow	Space on RX diagram	Effect of Arc resistance	Effect of power swing
Impedance Relay (medium lines)	Current Unit	Voltage Unit	No	Not operates	Moderate Space	Moderately	Moderately

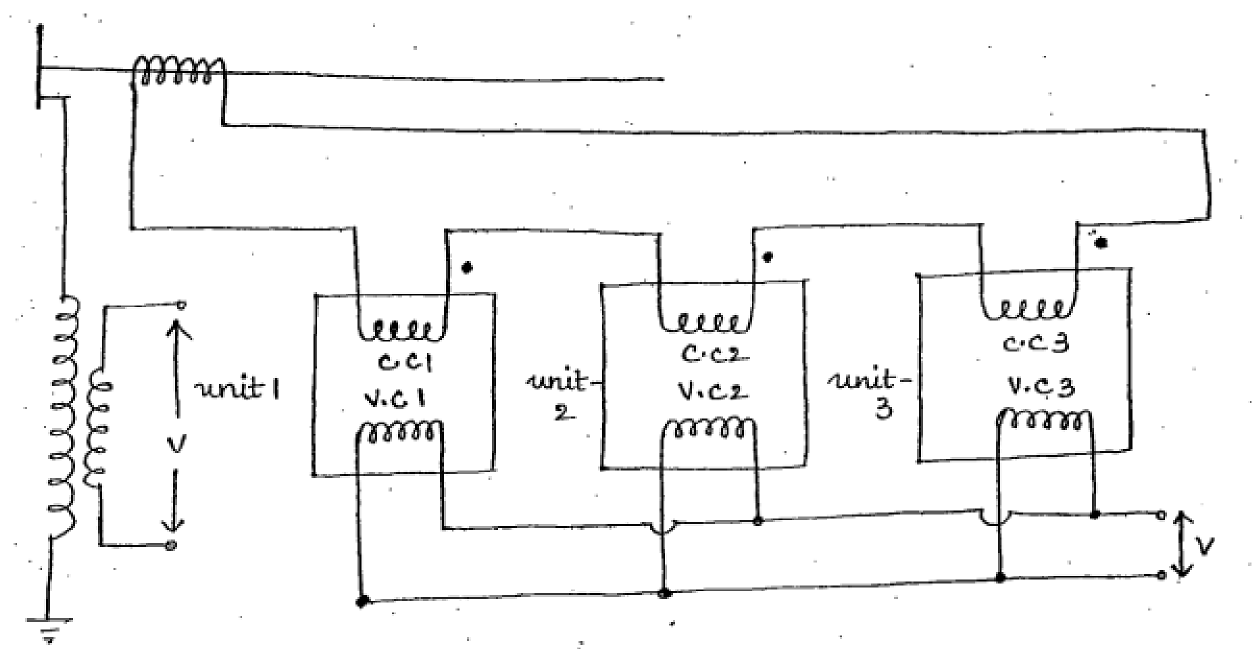
Reactance Relays (Short lines)	Current unit	Directional Unit	No	Operates	More Space	Not affected	Highly
Mho Relays (Long Lines)	Directional unit	Voltage Unit	Yes	Not Operates	Less space	Highly	Least

APPLICATIONS:
The distance relays are used for the protection of transmission line.
(The comparison made by considering the same voltage and same p.u reactance).

	Length	Z(in Ω)	Space on RX	Dominant effect
Short Lines	50km	0.5	Least	Arc resistance
Medium Lines	150km	1.5	Moderate	R arc and powerswings moderate
Long Lines	300km	3	More	Power swings

- For earth fault protection, reactance relay is preferred.

THREE ZONE PROTECTION:-



Ideal System Practical System

Unit 1

$Z_1R_A =$

$T_1R_A = Instantaneous$

(20ms to 40ms)

Unit 2

$Z_2R_A =$

$T_2R_A =$

Unit 3

$Z_3R_A =$

$T_3R_A =$

Zone 1

$Z_1R_A = 10\Omega$

$T_1R_A = Instantaneous$

Zone 2

$Z_2R_A = 20\Omega$

$T_2R_A = T_1R_B + SI$

Zone 1

$Z_1R_A = 8\Omega$

$T_1R_A = Instantaneous$

Zone 2

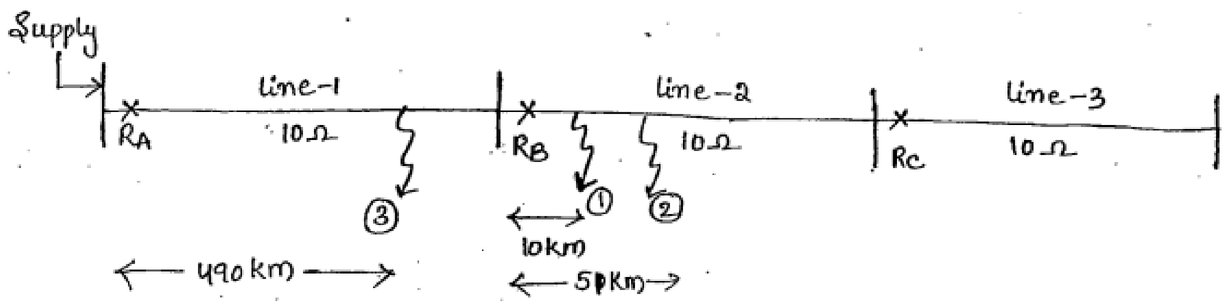
$Z_2R_A = 15\Omega$

$T_2R_A = T_1R_B + SI$

Zone 3

$Z_3R_A = 21 - 22\Omega$

$T_3R_A = T_2R_B + SI$



$Z = \frac{V}{I}$ Consider P.T→ $\pm\ 5\%\ error$

C.T→ $\pm\ 5\%\ error$

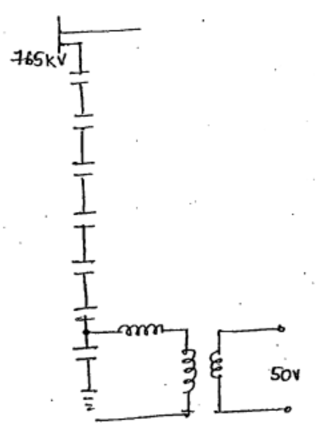
$\frac{V}{I}$→ $\pm\ 5\%\ error$

$\Rightarrow \pm\ 1\Omega\ error$

<u>Purpose of CVT(Capacitive Voltage Transformer):-</u>

In a practical power system, PT is not used since for higher voltages insulation will be a major criteria for the design of P.T. So CVTs are used in place of P.T.

Disadvantage of CVT is it does not allow sudden change in voltages, so it creates an error in reading during fault condition.



Fault at 1:- 10km away from bus-B

500km→10Ω

10km→?

$\Rightarrow \frac{10*10}{500}$

$Z_{seen} R_A = 10.2 \pm 1$

$Z_{seen} R_A$ = 9.2 to 11.2

$Z_{seen} R_A = 9.2$

$Z_{seen} R_A < Z_1 R_A$ (overreach)

- R_B *operates instantaneously*
- R_A *operates instantaneously* (mal operation)
- R_A *facing security problem*

Fault at 2:- 51km away from bus-B

49km

$Z_{seen} R_A = 11.02 \pm 1$

$Z_{seen} R_A$ = 10.02 to 12.02

$Z_{seen} R_A = 10.8 \pm 1$

$\Rightarrow 9.8$ *to* 11.8 (overreach)

$Z_{seen} R_A > Z_1 R_A$ and $Z_{seen} R_A < Z_1 R_A$

- R_B *operates instantaneously*
- R_A *not operates instantaneously*
- R_A *provides proper backup protection*
- Max overreach is 50km

Fault at 3:- 490km away from bus-A

$Z_{seen} R_A = 9.8 \pm 1$

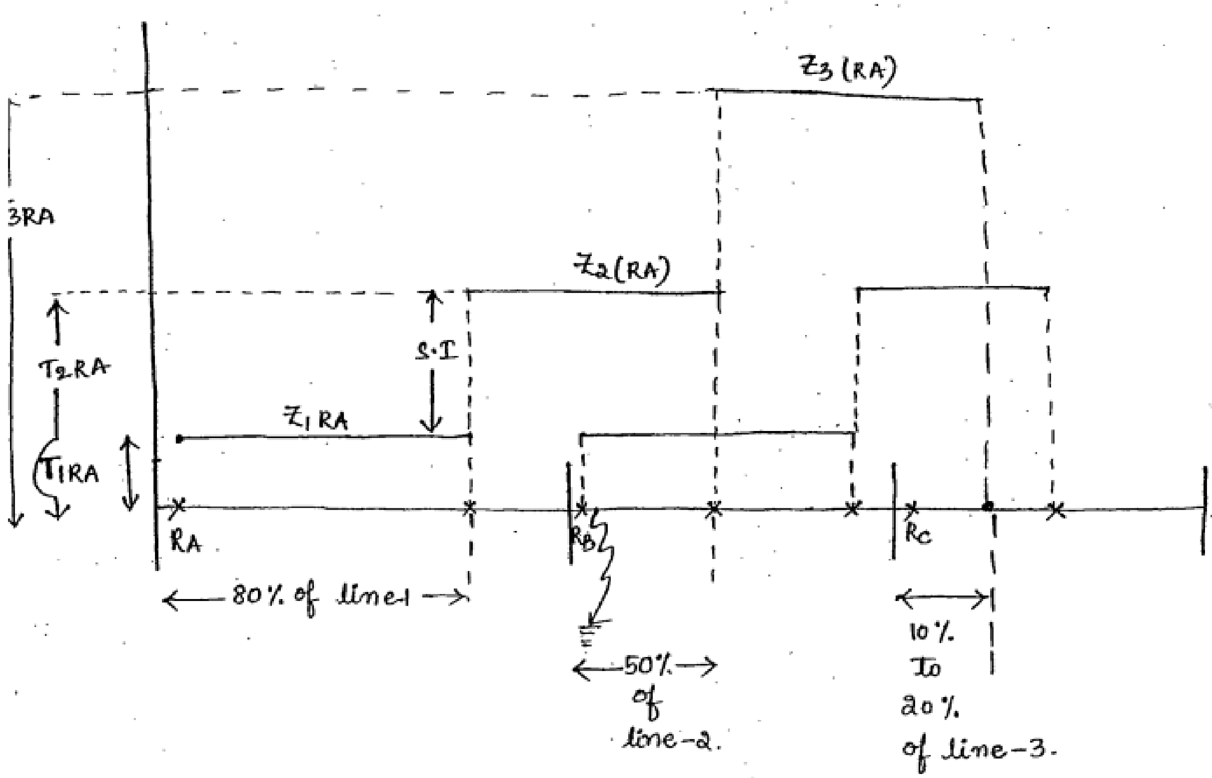
= 8.8 to 10.8

$Z_{seen} R_A = 10.8$

$Z_{seen} R_A > Z_1 R_A$ (under reach) and $Z_{seen} R_A < Z_2 R_A$

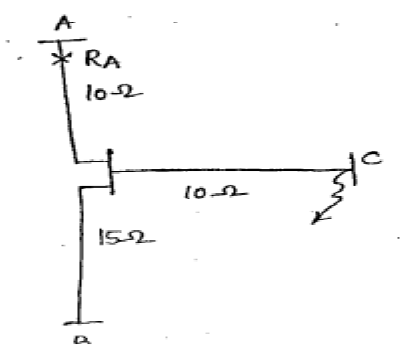
- R_B *not operates*
- R_A *not operates instantaneously*
- R_A *operates after* $T_{1RB} + S.I$ *by unit* 2

By using 3-zone protection,



If the Transmission line is fed from one side then 80% of the line length, high speed protection is possible.
If the Transmission line is fed from both sides then 60% of the line length, high speed protection is possible.

Eg:- A DC power system is shown below, for a fault at location C, the fault current contributed by A and B are 10A, 20A respectively. Calculate the impedance seen by relay A,



$V_A - (10 * 10) - (30 * 10) = 0$

$V_A = 100 + 300$

$= 400V$

$V_B - (15 * 20) - (30 * 10) = 0$

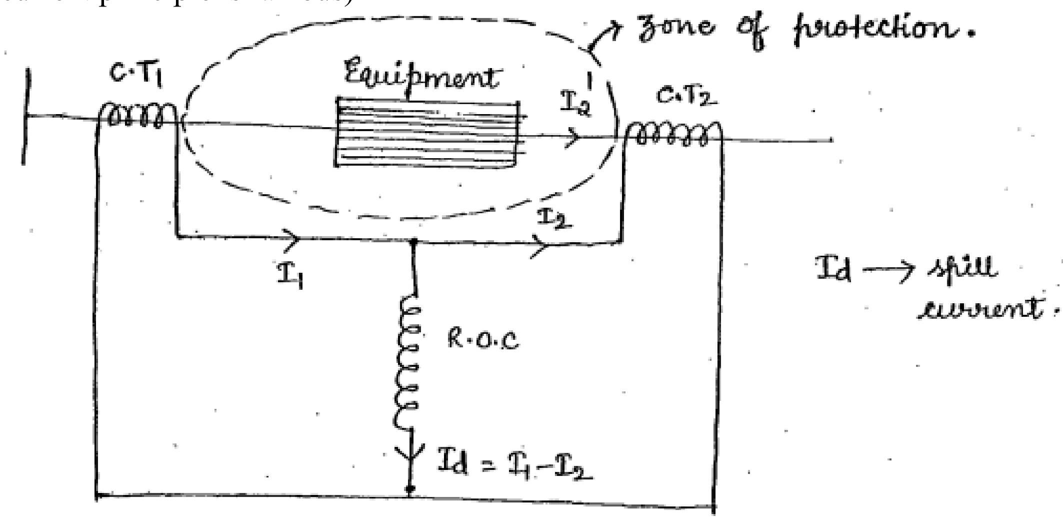
$V_B = 300 + 300$

$= 600V$

$Z_A = \frac{V_A}{I_A} = \frac{400}{10} = 40\Omega$

<u>DIFFERENTIAL RELAY:-</u>

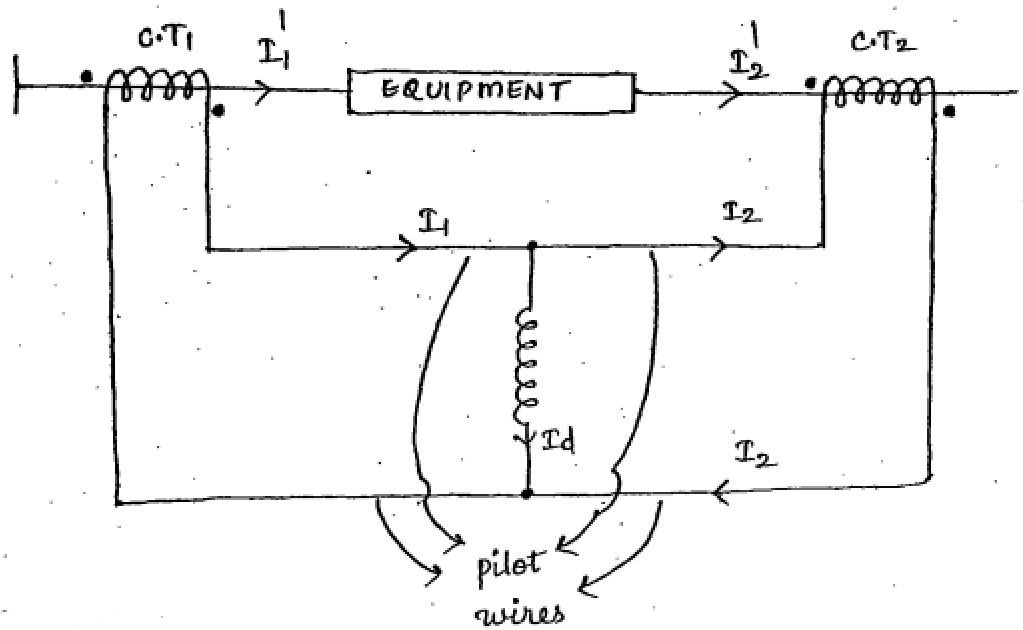
- Also called unit protection.
- Also called mertz-price protection.
- It works on either circulating current principle or voltage balance principle.(Circulating current principle is famous)



<u>Note</u> :- The region between C.T's comes under zone of protection for differential relay.

<u>Requirement For Differential Protection:</u>

- Requires current transformers (≥2 depending in the equipment to be protected)
- For generator protection every phase has 2 C.T's, For two winding transformer protection every phase has 2 C.T's, For three winding transformer protection every phase has 3 C.T's, For busbar protection
  Number of C.Ts = Number of incoming + Number of outgoing
- The CTs must be provided with proper CT ratios (The CT ratios is selected such that even if their primary currents are not same during normal operation their secondary current must be equal.)
- The C.Ts should have equal characteristics.
- The C.Ts must be connected in the circuit with proper polarities.



- Requires pilot wires
- Requires relay operating coil, but it should be connected at equipotential points on the pilot wires.

Note: During normal operation there is a small spill current flowing the relay O.C due to

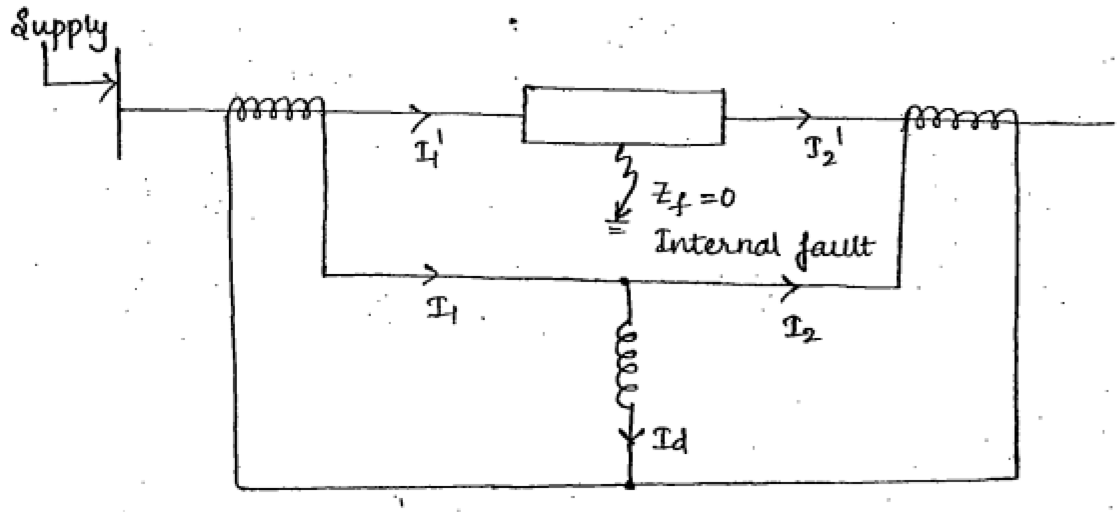
- Little mismatch between CT characteristics
- Shifting of equipotential point from R.O.C (relay operating coil) which causes mal-operation of Differential protection
- To avoid the Maloperation the differential protection is provided with a restraining torque

$$T_{op} = k_1 I_d^2$$
$$T_{res} = k(spring\ torque)$$
$$T = T_{op} - T_{res}$$
$$T = k_1 I_d^2 - k$$

- For relay operation $I_d > I_{min}$. Here I_{min} is fixed by spring torque.

Mode1:- Normal operation,

There is no internal and external fault to the equipment which is monitored by differential protection.



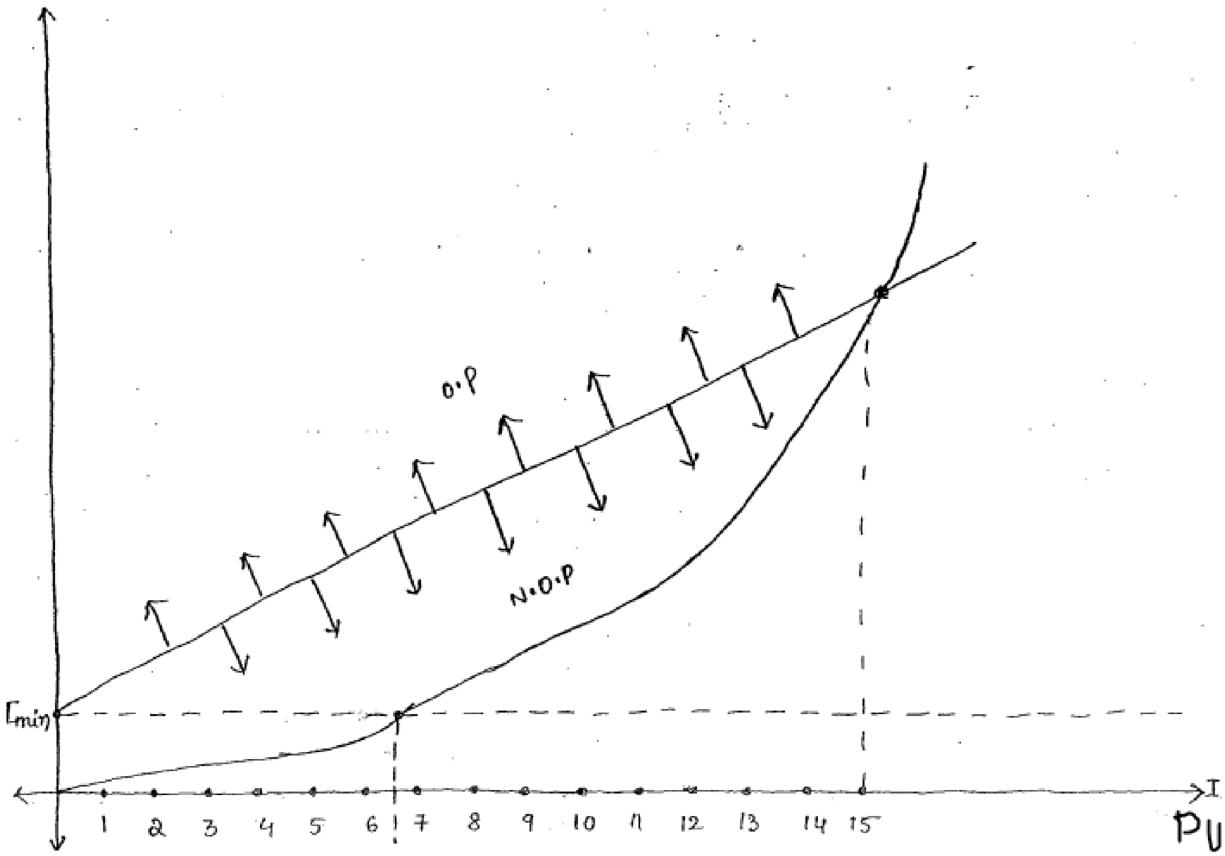
$I_1' = I_2' > 1.2pu$
$I_1 \simeq I_2$
$I_d = I_1 - I_2$
$I_d \simeq 0$
$I_d < I_{min}$
Relay not operates.

Mode 2: Internal faults.
$I_1' = I_{fp}, I_2' = 0$
$I_1 = I_{fs}; I_2 = 0$
$I_d = I_1 - I_2$
$I_d = I_{fs}$
$I_d > I_{min}$

Relay operates.
Mode 3: External faults.
$I_1' = I_2' = 2\ to\ 10\ times\ I_{fl}$
$I_1 \simeq I_2$
$I_d = I_1 - I_2$
$I_d \simeq 0$
$I_d < I_{min}$
If fault current increases, mismatch between C.Ts increases, then Id increases.

If $I_d > I_{min}$

Relay Operates(Maloperation).



Through Fault Stability:
It is defined as the ratio of minimum value of through fault current at which differential protection mal-operates to the minimum internal fault current required for relay operation.

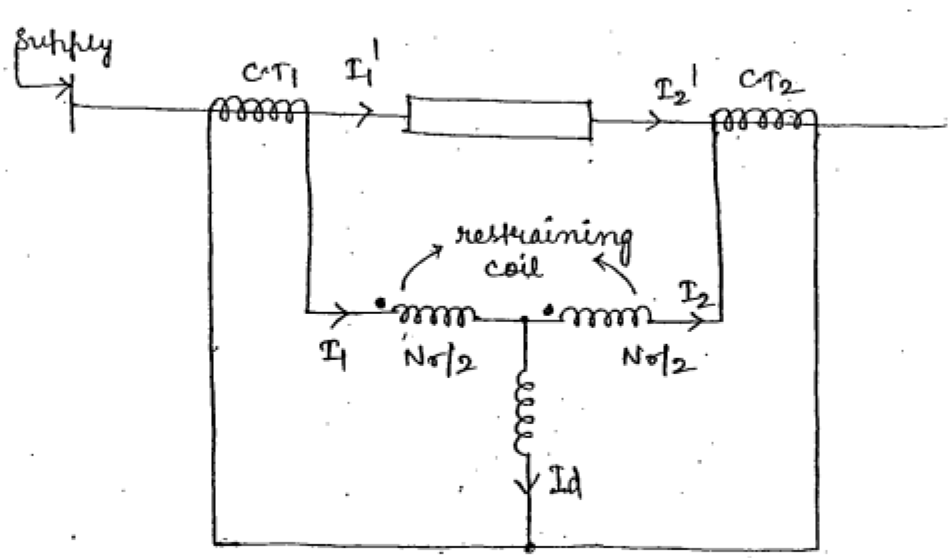
Through Fault Stability=$\frac{I_{fmin}}{I_{min}}$

Through Fault stability should be as high as possible, to achieve this I_{fmin} should be increased without changing I_{min}.

To avoid the maloperation of differential protection during through fault, differential protection is designed with restraining torque which should be increasing with increasing true fault current.

Percentage Differential Protection:

- Also called biased differential protection



$T \propto (M.M.F)^2$

$\propto (A.T)^2$

MMF produced by restraining coil,

$MMF_{res} = \frac{N_r}{2} I_1 + \frac{N_r}{2} I_2$

$MMF_{res} = \frac{N_r(I_1+I_2)}{2}$

$MMF_{res} = N_r I_{avg}$

$T_{res} \propto MMF_{res}^2$

$T_{res} \propto (N_r I_{avg})^2$

$T_{res} = C_0 (N_r I_{avg})^2$

MMF produced by ROC,

$MMF_0 = N_0 I_d$

$T_{op} \propto MMF_0^2$

$T_{op} \propto (N_o I_d)^2$

$T_{op} = C_0 (N_o I_d)^2$

$T = T_{op} - T_{res}$

$T = C_0 (N_o I_d)^2 - C_0 (N_r I_{avg})^2$

Under Threshold:
T=0; $T_{op} = T_{res}$

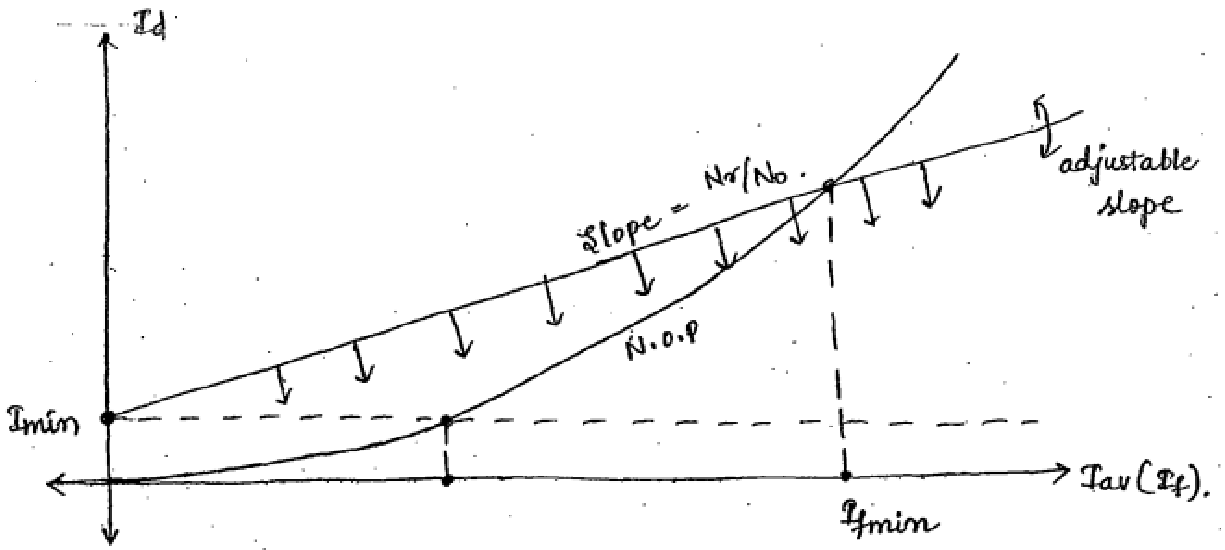
$C_0(N_o I_d)^2 = C_0(N_r I_{avg})^2$

$(N_o I_d) = (N_r I_{avg})$

$\frac{I_d}{I_{avg}} = \frac{N_r}{N_0}$

$I_d = \frac{N_r}{N_0} I_{avg} \Rightarrow without\ spring\ torque$

$I_d = \frac{N_r}{N_0} I_{avg} + I_{min} \Rightarrow with\ spring\ torque$



When relay is operating:-
T>0; $T_{op} > T_{res}$

$C_0(N_o I_d)^2 > C_0(N_r I_{avg})^2$

$(N_o I_d) > (N_r I_{avg})$

$\frac{I_d}{I_{avg}} > \frac{N_r}{N_0}$

$I_d = \frac{N_r}{N_0} I_{avg} \Rightarrow without\ spring\ torque$

$I_d > \frac{N_r}{N_0} I_{avg} + I_{min} \Rightarrow with\ spring\ torque$

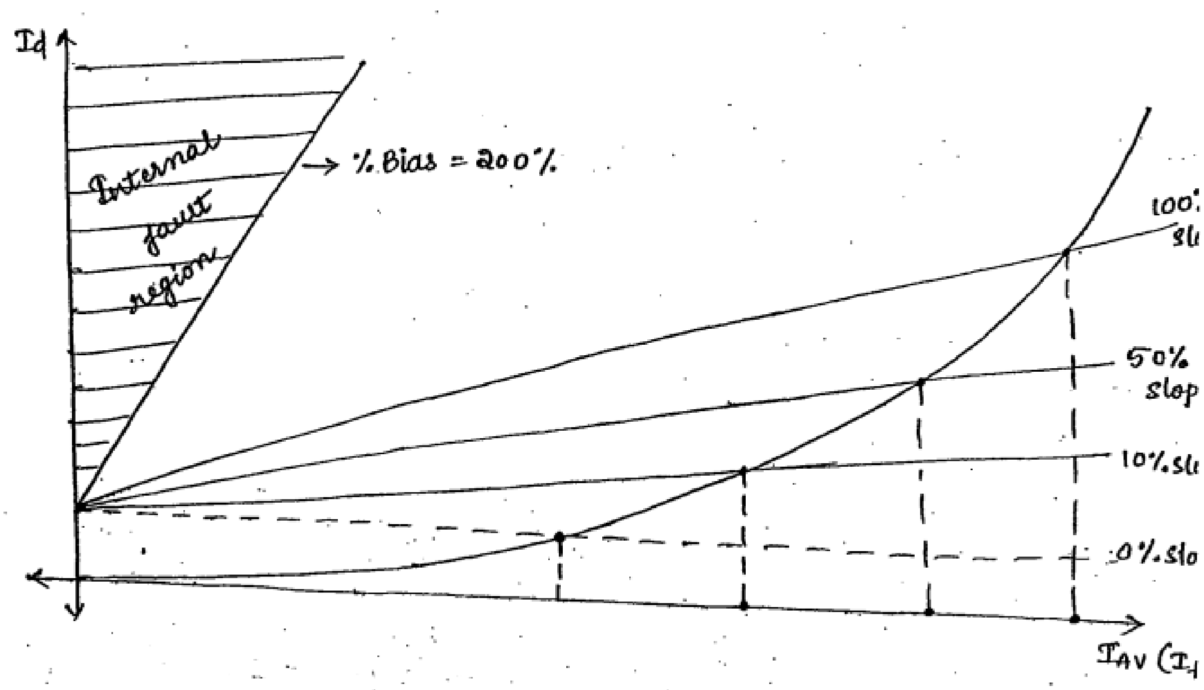
$$\%slope \ = \frac{N_r}{N_0} \times 100$$

$$\% \, bias \ = \frac{I_d}{I_{avg}} \times 100$$

If % bias> % slope , then relay operates.

<u>Conclusion:-</u>

- Slope of the characteristics is adjustable by adjusting the number of turns in restraining coil.
- For generator and Busbar protection the slope is adjusted to 5 -15%
- For transformer protection slope is adjusted to 30-45 %
- By increasing the slope of the characteristics through fault stability can be increased.



During Internal fault,

$$I_1' = I_{fp} \ ; \ I_2' = 0$$

$$I_1 \ = I_{fs} \ ; \ I_2 \ = 0$$

$$I_d = I_1 - I_2 = I_{fs}$$

$$I_{avg} = \frac{I_1 + I_2}{2} = \frac{I_{fs} + 0}{2} = \frac{I_{fs}}{2}$$

$$\% \, bias \ = \frac{I_d}{I_{avg}} \times 100$$

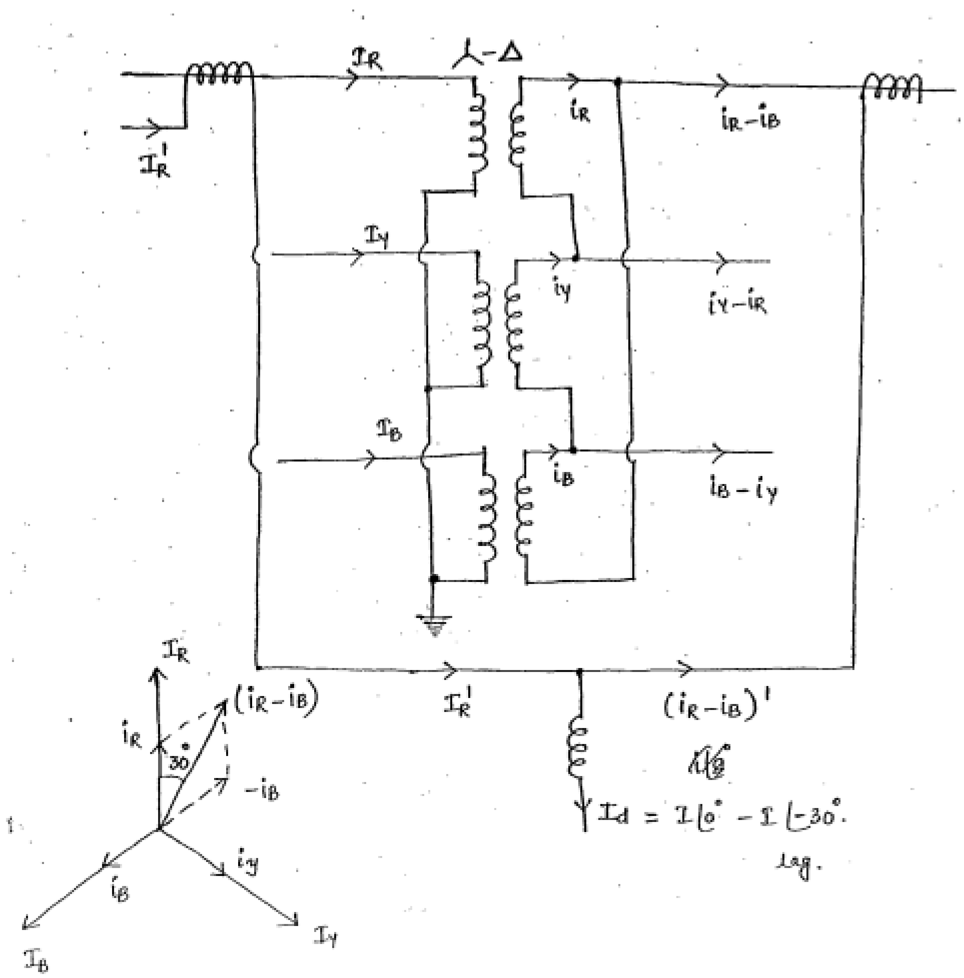
$$\% \, bias = \frac{I_{fs}}{I_{fs}/2} \times 100 = 200\%$$

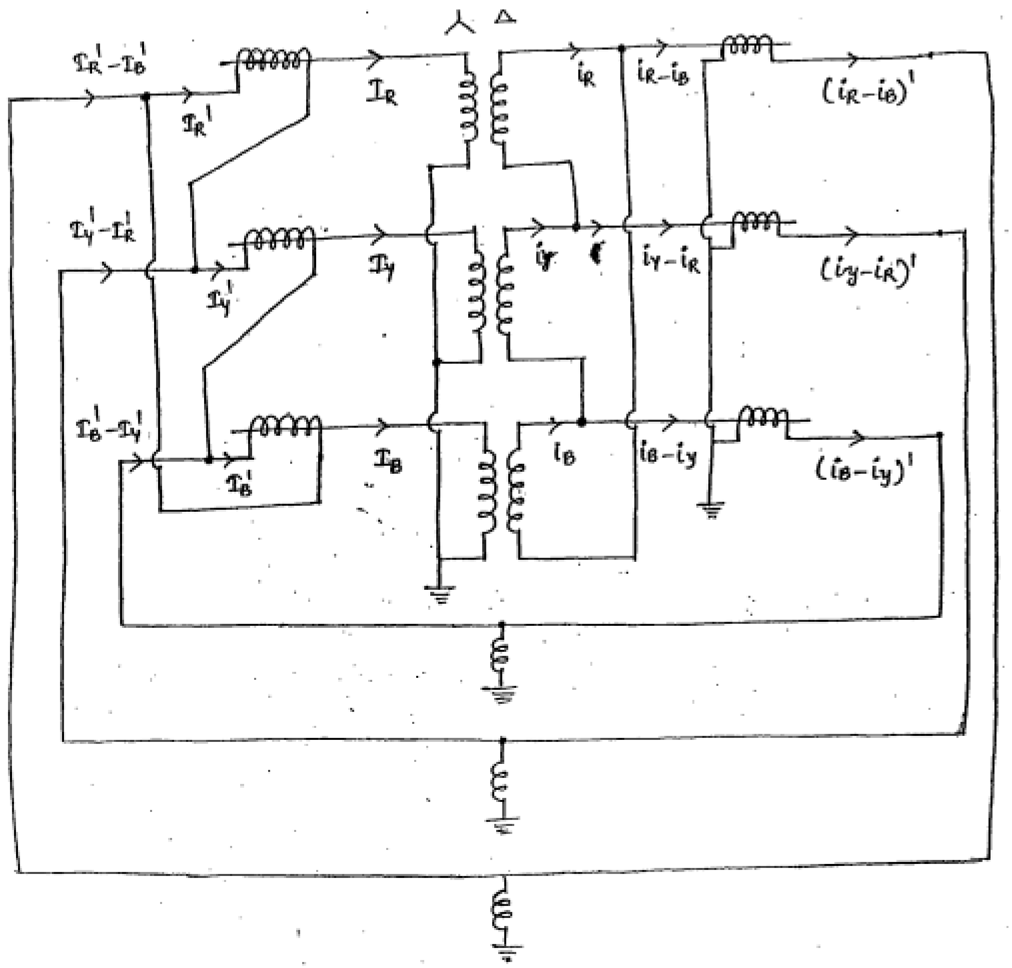
TRANSFORMER DIFFERENTIAL PROTECTION:-

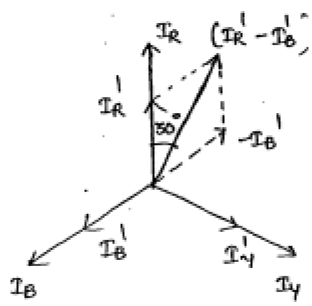
Transformer differential protection may Mal-operate due to

- Phase shift provided by Y-Δ and $\Delta - Y$ Transformer banks.
- Improper CT ratio
- Tap Changers provided for voltage control
- Over excited operation of Transformers
- Magnetic inrush currents.

The phase currents are in phase, i.e phase current of primary is in phase with phase current of secondary provided that they are of same phase.



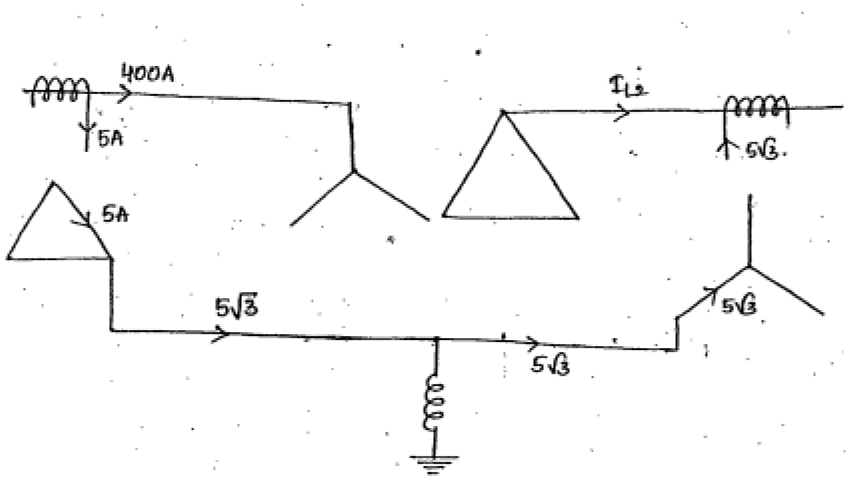




To avoid the Mal operation of Differential protection due to the phase shift provided by Y-Δ and $\Delta - Y$ Transformers, the current Transformers must be connected either in Y or Δ depending on the power transformer connection.

Eg:- A 3-ϕ, 50Hz, 100MVA 132KV/400KV Y-Δ power transformer is protected by Merge-price protection scheme. The C.T on LV side having a ratio of 400/5A. Calculate the C.T ratio connected to the H.V side.

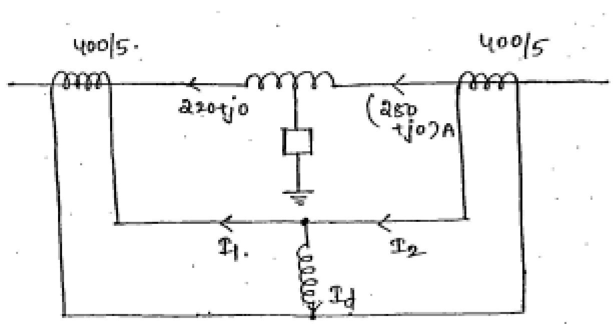
Solution:
132KV/400KV Y-Δ power transformer



$$\sqrt{3}V_{L1}I_{L1} = \sqrt{3}V_{L2}I_{L2}$$

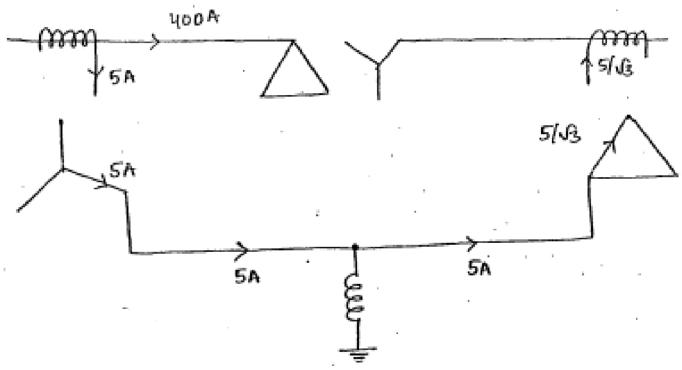
$$V_{L1}I_{L1} = V_{L2}I_{L2}$$
$$132 \times 400 = 400 \times I_{L2}$$
$$I_{L2} = 132A$$

Q9



Solution:-
$Id = I_2 - I_1$
$= 250 \times \frac{5}{400} - 220 \times \frac{5}{400}$
=0.375 A

Q10



Solution:

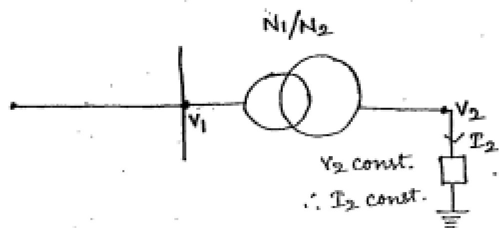
$\sqrt{3}V_{L1}I_{L1} = \sqrt{3}V_{L2}I_{L2}$

$V_{L1}I_{L1} = V_{L2}I_{L2}$

$11 \times 400 = 66 \times I_{L2}$

$I_{L2} = \frac{400}{6}A$

CT ratio = $\frac{400/6}{5/\sqrt{3}} = \frac{40}{\sqrt{3}} = 23$



$\frac{V_2}{V_1} = \frac{N_2}{N_1}$

$V_2 = \frac{N_2}{N_1}V_1$

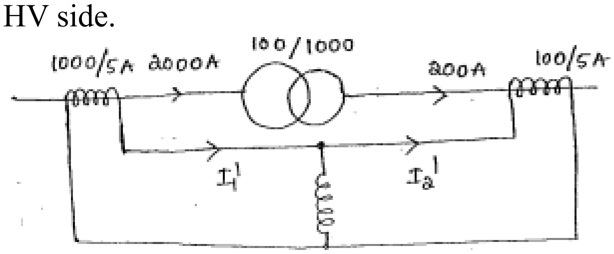
If V_1 is less than rated values, then N_2 must be increased to maintain V_2 $at\ rated\ value.$

N_2 is varied within the limits of $\pm\ 10\%$

EG: If N_2=1000 as per nominal turns

$N_2 \rightarrow 900 - 1100$

Always taps are provided on the HV side in order to smooth variation as current will be less on HV side.



If N_2=900, I_2=200A

$I_2^{'}$=10A

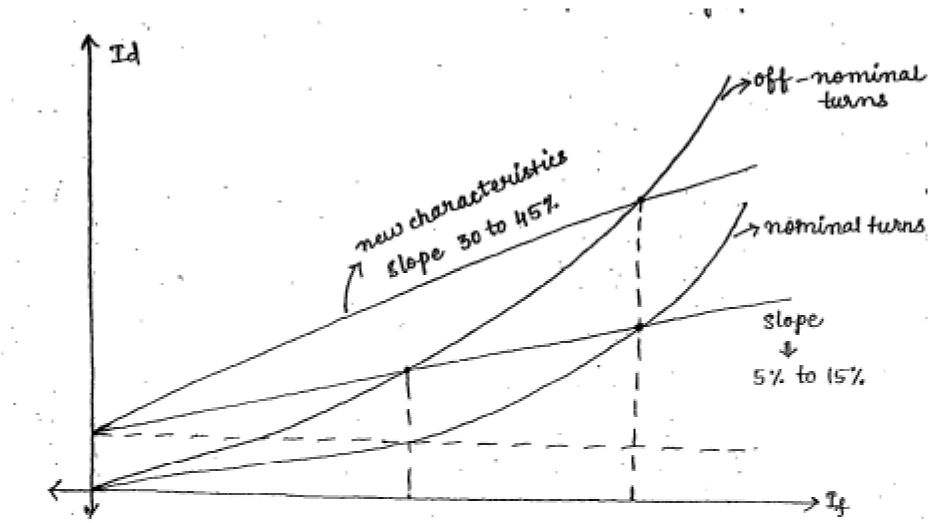
$I_1 = \frac{N_2}{N_1} I_2$

$I_1 = \frac{900}{100} \times 200 = 1800A$

$I_1^{'} = \frac{5}{1000} \times 1800 = 9A$

$|I_d| = 1A$

If turns are nominal turns then relay will not operate but if turns are greater or lesser than nominal turns then $I_d \neq 0$ then relay operates.



If the transformers are provided with tap changers then differential protection mal-operates with respect to off nominal turns ratio. To avoid the maloperation of differential protection % slope must be increased.

<u>Over excitation:</u>

If V increases, or f decreases or $\frac{V}{f}$ increases, then

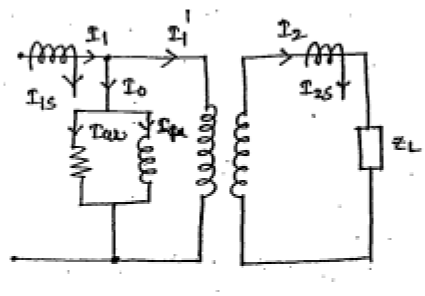
Flux increases as $\phi \propto \frac{V}{f}$

$\phi > \phi_{rated}$

Always transformer is designed to operate at knee point if it is designed to operate in linear region,then core required is more and core losses is also more and thus efficiency reduces.

As $\frac{V}{f}$ increases,

$\phi > \phi_{rated}$.



Transformer enter into saturation and draws more magnetizing current.

$I_1 = I_0 + I_1^{'}$

$I_0 = I_C - jI_\mu$

$I_0 = \sqrt{I_C^{\ 2} + I_\mu^{\ 2}}$

As I_μ increases, I_0 increases, I_1 increases, $I_{1s} increases$

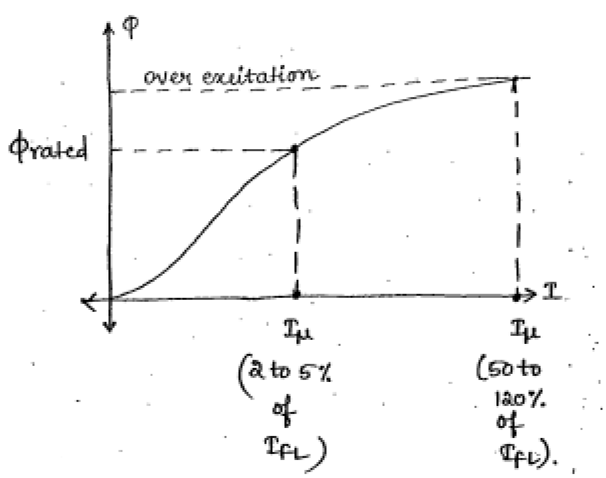
But $I_2 = \ constant,\ I_{2s} = \ constant$

$I_d = I_{1s} - I_{2s}$

If $I_d > I_{dmin}$, differential protection maloperates.

As I_s is constant, restraining torque is constant, but due to over excitation operating torque becomes more than restraining torque and relay maloperates. So in order to avoid that, the restraining Torque of relay has to be increased only at the time of overexcitation. This extra provided restraining torque must be zero under normal condition. The extra restraining torque will be provided by 5th harmonic current. The 5th harmonic current can be obtained by designing a suitable filter.

This protection is not made to obtain from differential protection, as it affects the operation under fault and abnormal conditions.

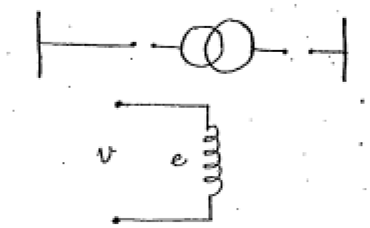


To avoid maloperation of differential protection during over excitation, it is provided with 5th harmonic restraining torque.

Generator transformer is mainly affected by over excited operation. So to provide the protection for generator transformer, a separate the V/f protection is used.

	Normal operation	Over excitation
3rd harmonics	High	Very high
5th harmonics	Very less	Appreciable
7th harmonics	Negligible	Very less

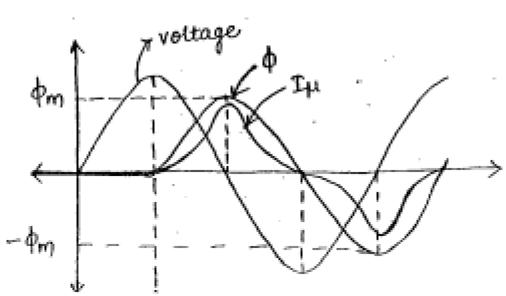
When transformer is disconnected from the load under maximum voltage condition then current is zero ideally, transformer draws only magnetizing current, then current flux is zero and no residual flux will be retained in the transformer.



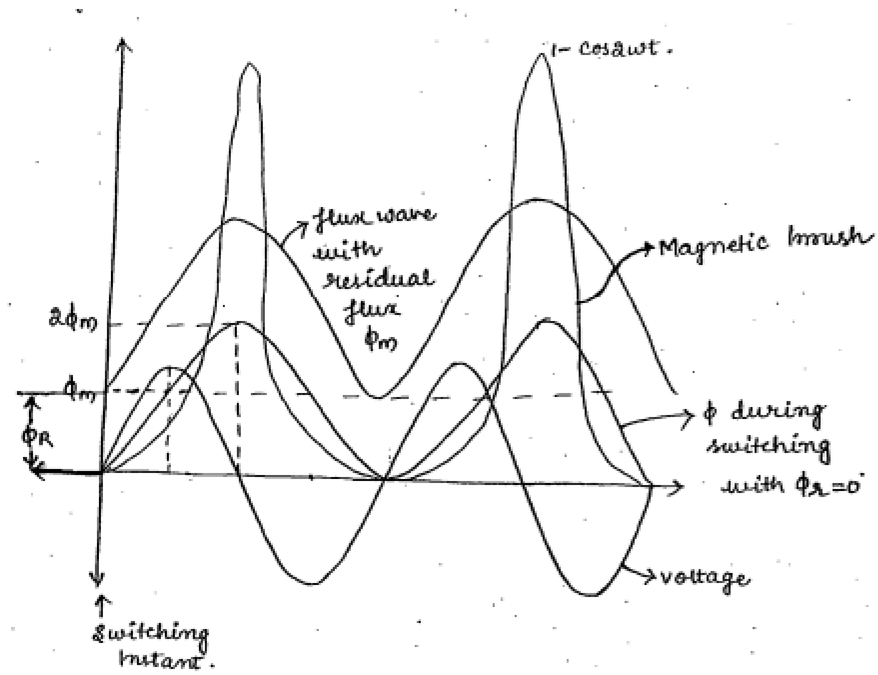
Smooth Switching:

$$e = v = N\frac{d\phi}{dt}$$

$$\phi = \frac{1}{N}\int v dt$$



Worst Switching:

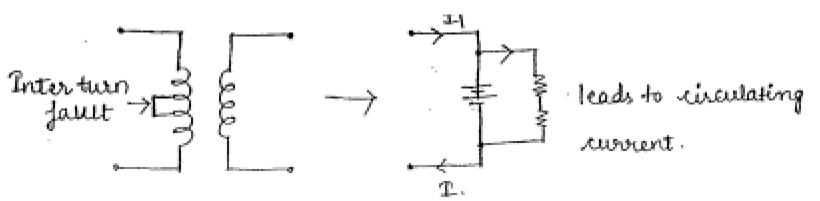


To avoid the mal-operation of differential protection due to magnetic inrush current it is provided with a second harmonic restraining torque.

The differential protection of transformer will operate for:

- Inter turn Faults- insulation breakdown between two or more than two turns of same phase it is an incipient fault.
- Turn to core faults.
- Core faults
- Phase faults
- Tank faults

If incipient fault is recognised at starting then no damage occurs or else it creates a huge damage because of large value of circulating current.



Because of inter turn fault, more heat is generated at small portion so hot spots will be created.

In inter turn faults, ± 10 % of turns will be affected, but the differential protection may not operate as slope is increased to avoid maloperation during tap changing. If the number of turns affected > 10 % ,then differential protection operates.

$$\frac{I_2}{I_1} = \frac{N_1}{N_2}$$

$\downarrow I_2 == \frac{N_1 \downarrow}{N_2} I_1$ So differential protection operates.

Buchholz relay has to be operated but it takes more time to operate (as heat to be generated, gases to be liberated, oil has to move to Conservator tank). So buchholz relay provides backup protection. It takes around 2 to 3 minutes for buchholz relay to operate.

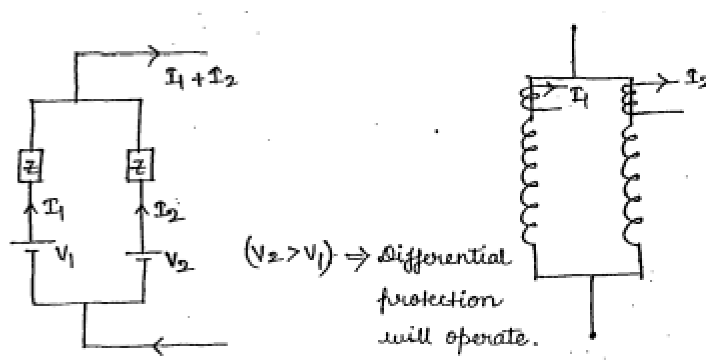
- Inter turn faults are mainly due to breakdown of insulation between two or more than two turns of same phase or same winding.
- The Transformer differential protection will operate for internal fault.
- Internal faults are also called incipient fault.
- If it is tap changing transformer then differential protection may not operate for internal fault due to number of turns effected during internal fault is less than the number of turns available for Tap setting.[-10%]
- If differential protection is failed during internal fault then buchholz relay provides backup protection.
- Due to breakdown of insulation between winding and core, differential protection operates because faltered winding causes heavy current and other winding still carrying normal current.

Because of core faults Eddy current will flow in successive laminations.
Due to breakdown of insulation between core lamination, core fault occurs.

If oil in transformer is reduced, then the uneven insulation and uneven cooling takes place. So some part of the winding has no oil around it. So between winding and tank wall, air will be present and it has very less dielectric strength, so flash over takes place between winding and tank. Tank faults are mainly due to reduction of oil level in the Transformer.

The differential protection will not operate for inter turn fault inside the generator.

To provide the protection against inter turn fault, a split phase scheme or inter turn fault protection is used.



Modern Turbo alternator has only one turn per coil, so there are no inter turn fault in modern Turbo alternator.

CIRCUIT BREAKERS:-

Purpose:-

To break the circuit

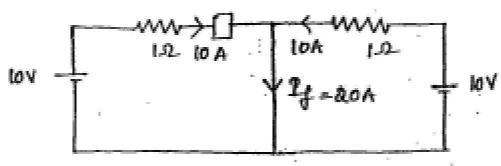
- During fault (relay)
- Under full load for load shedding (operator or scada system)(under frequency relay).

To make the circuit

- Under no load for maintenance (issued by operator)
- During full load
- During fault (for auto recloser operation to know whether the fault is permanent or transient)

Always breaker is designed with respect to Maximum current as, if breaker is able to close at Maximum current or open at Maximum current then the breaker is able to operate at any current. So during fault condition, the current will be maximum and among all the faults, 3-phase fault has more fault current so this current is taken as reference in the design of breaker. (The fault current flowing through the breaker).

Eg:-



Note:-

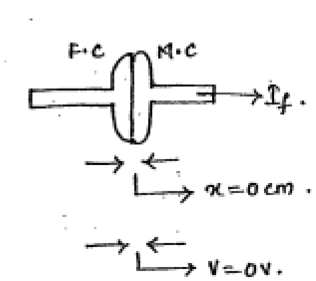
- To design the breaker maximum fault current through it is reference.
- Circuit breaker parameters are calculated based on a 3-phase fault at its terminal.

There are three stages in circuit breaker operation:

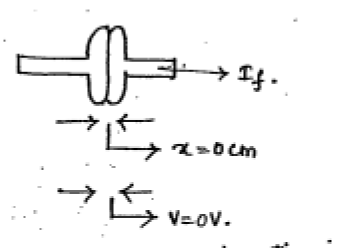
- Arc initiation
- Arc maintenance
- Arc interruption

ARC INITIATION:-

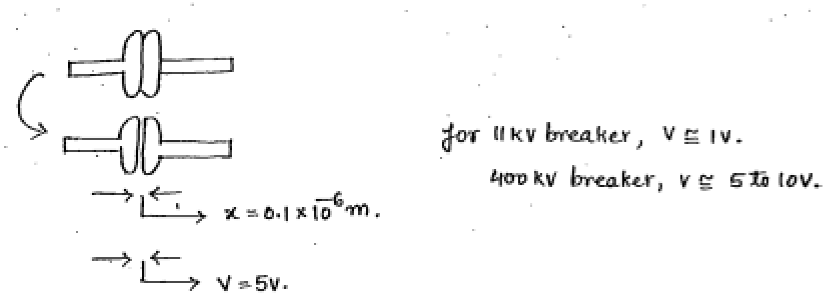
At t= 0^- (no trip signal to breaker)



At t= 0, (CB receives a trip signal from relaying system.)



At t= 0^+ (CB contacts are separating)



Gradient or Electric field Intensity or Stress across the gap:

$$g = \frac{V}{x}$$
$$g = \frac{5}{0.1\times10^{-6}} V/m$$
$$g = 50 \times 10^{6} V/m$$
$$g = 500 kv/cm$$

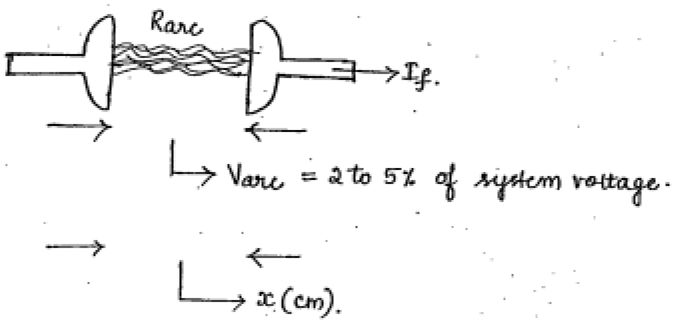
Eg:Air is the medium between contacts, dielectric strength of air, G= 21.1 KV, g>G, medium breakdowns and arc strikes between the contact (As because of high gradient, Arc strikes).

Because of field ionization between the contacts, more free electrons are created between contacts (Avalanche breakdown)

Arc is initiated between the contacts due to field ionisation just after the circuit breaker has received a trip signal from relay.

Eg:- A 100kV, 50Hz, $1\frac{1}{2}$cycles Circuit breaker.
t=30m/s: (C.B contacts get fully opened)

(Vacuum Circuit breakers has lowest spacing between the contacts)



$V_{ARC} = I_f \times R_{ARC}$

$V_{ARC} = \frac{5}{100} \times \frac{100}{\sqrt{3}} kV = \frac{5}{\sqrt{3}} kV$

x=1cm

$g = \frac{V}{x} = \frac{5}{\sqrt{3}} kV/cm$

g<G

Heat Energy $= I_f^2 R_{arc}$

This heat energy is responsible to maintain arc. As insulators have negative temperature Coefficient, as temperature rises, resistance decreases so current continues to flow with high-value.

Arc is maintained between circuit breaker contacts due to thermal ionization because of excessive heat energy released between contacts due to high magnitude fault current.

ARC INTERRUPTION METHODS:-

- High resistance method
- Current zero interruption method

HIGH RESISTANCE METHOD:-

If fault current is reduced to a value which is not sufficient to maintain the arc then Arc extinguishes. For this Arc resistance should be increased sufficiently.

$I_f = \frac{V_{ARC}}{R_{arc}}$

If R_{arc} increases, I_f decreases

Heat energy $\propto I_f^2$

Thus if I_f decreases, Heat energy decreases.

$R_{arc} \propto \frac{1}{Heat\ energy}$

$$Heat\ Energy = \frac{V_{arc}^2}{R_{arc}} t$$

$$R_{arc} = \frac{\rho l}{A}$$

l= length of the arc
A= area of cross section of the arc.

$$R_{arc} \propto \frac{1}{Heat\ energy}$$

Resistance is increased by:

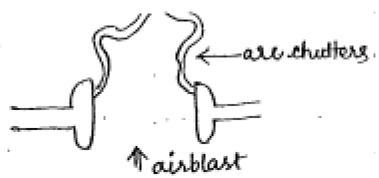
- Cooling the arc

By sending high pressure air of 20 to 30 kg/cm^2 air blast circuit breaker.

But these air blast circuit breaker is not used in small substation where space is small, the hot gases released from a blast circuit breaker may heat up other equipments surrounding it.

In oil circuit breaker, transformer oil is used which has high cooling property. The gases released are mostly hydrogen gases, those also have good cooling property.

- Lengthening the arc
- Decreasing the cross section area of the arc
- Splitting the arc



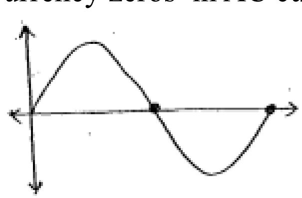
In this method the resistance of the arc is sufficiently increased so fault current decreases to a value which is insufficient to maintain the arc and are will be extinguished.

CURRENT ZERO INTERRUPTION METHOD:

Because of energy conversion from $\frac{1}{2}LI^2$ to $\frac{1}{2}CV^2$, high voltage appears across the circuit breaker contacts.

High resistance method is not used for high current interruption. High resistance method is mainly used for DC circuit interruption.

Current zero interruption method is suitable for AC circuit interruption as there are natural currency zeros in AC current.



one cycle gives two natural currency zeros.

1 second → 100 natural currency zeros.

At current zero point rate of ionization is very minimum.

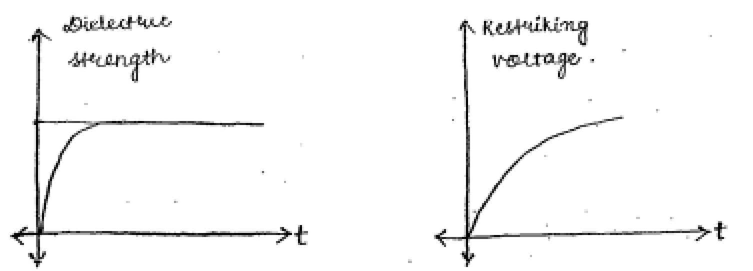
If rate of ionization is less than the rate of charges remove then r will not be sustained.

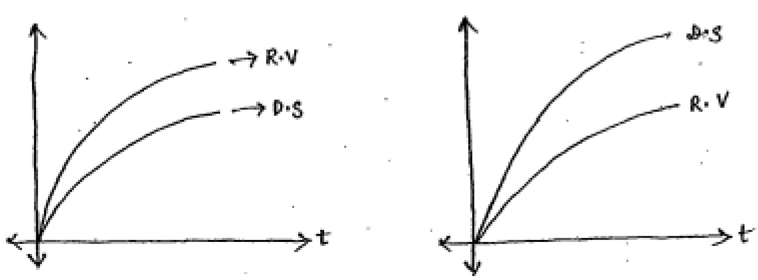
There are two methods to to kill the free electrons

- Reverse rate theory
- Energy balance theory

If rate of rise of dielectric strength is more than rate of rise of voltage across circuit breaker contact then arc extinguishes.

If rate of rise of voltage is more than rate of rise of dielectric strength then arc restrikes.





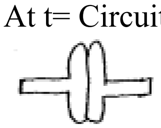
Arc restrikes and continues For next half cycle. Arc completely extinguishes

If Rate of rise of restriking voltage> Rate of rise of dielectric strength
(R.R.R.V) (R.R.D.S)
⇒Arc restrikes.

If Rate of rise of restriking voltage< Rate of rise of dielectric strength
(R.R.R.V) (R.R.D.S)
⇒Arc completely extinguishes.

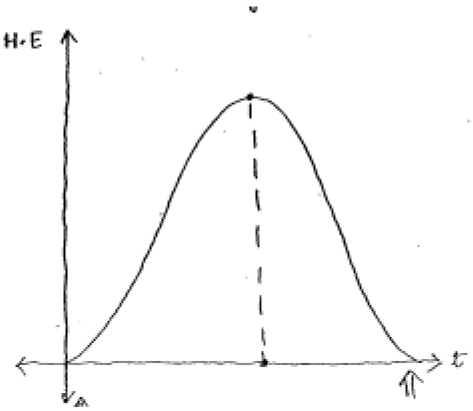
ENERGY BALANCE THEORY:-

.At $t=0^{-}$, Circuit breaker contacts closed.
At t= Circuit breaker operating time arc fully exxtinguishes.



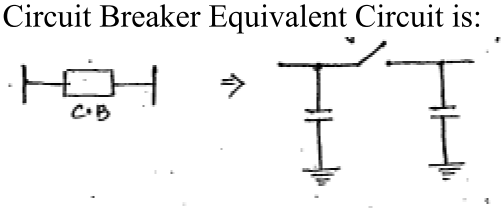
R=0; Heat Energy =0

R=∞; $I_f = 0$,Heat Energy =0

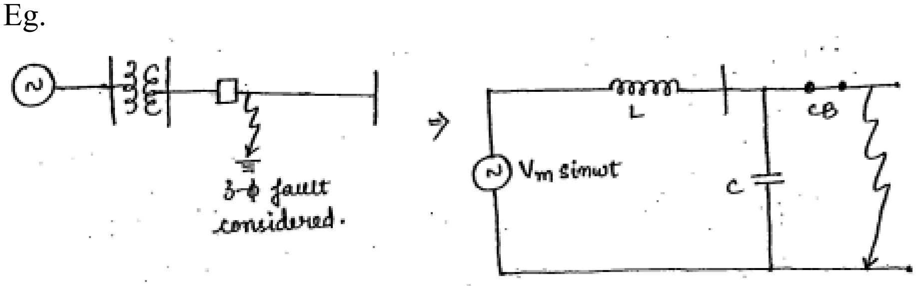


If Rate of Heat generation< Rate of heat dissipation
⇒Arc completely extinguishes.
If Rate of Heat generation> Rate of heat dissipation
⇒Arc will restrike.

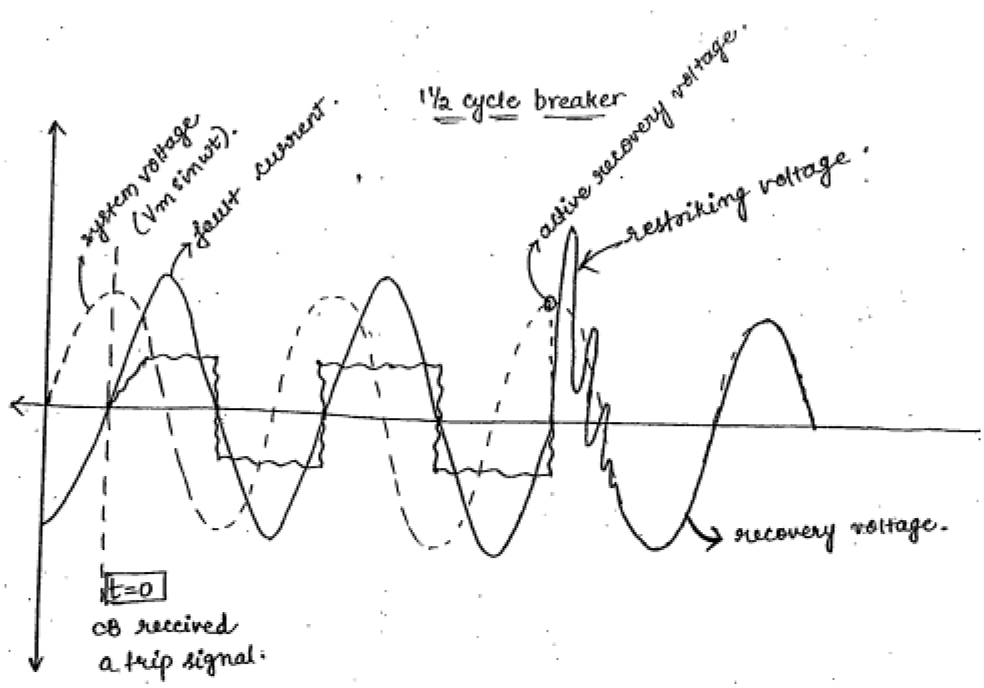
Circuit Breaker Equivalent Circuit is:



Eg.



At $t = 0^{-}$, CB contacts closed, $V_{CB} = 0$
At 0<t<CB operating time ,Arc is present between contacts, $V_{cb} = V_{arc}$
At t= CB operating time, Arc extinguished, $V_{CB} = V_c(t) = V_{res}(t)$
$V_{res}(t)$ is restriking voltage.
Under steady state CB is recovered(i.e arc recovered completely) , V_{CB}=system voltage



ARC VOLTAGE:-

- It is the voltage across circuit breaker during the arcing period.

$V_{arc} = I_f \times R_{arc}$

- Arc voltage and fault current are always in phase.
- Under ideal condition the phase angle between the system voltage and arc voltage is ----.

ARV(Arc Recovery Voltage):-

It is the recovery voltage (instantaneous voltage) across the circuit breaker contacts.at the instant of arc interruption.

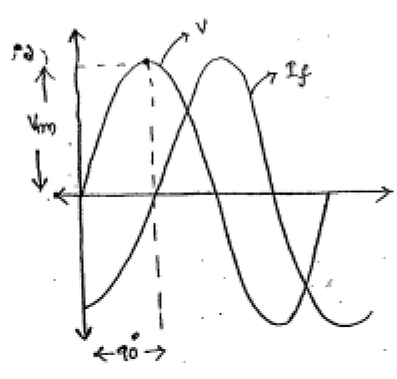
$A.R.V = V_m$

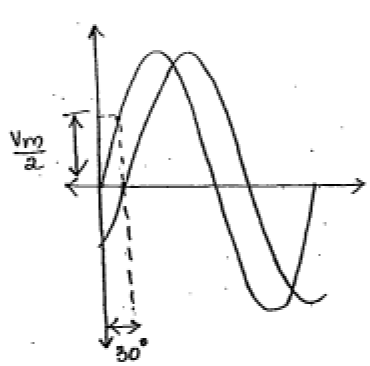
Eg: 132kV ,3-ϕ, 50 Hz circuit breaker

$A.R.V = \frac{132kv}{\sqrt{3}} \times \sqrt{2}$

(i) pf angle of the fault

(ii) Armature reaction of synchronous machine





(i) AR$V = V_m \sin\theta$

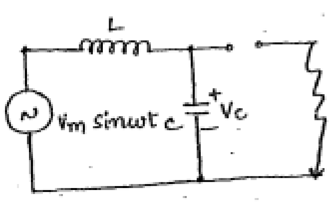
θ= power factor angle of the fault
For pf=0.8 lag
ARV= $V_m \times 0.6$
$A.R.V = \frac{132kv}{\sqrt{3}} \times \sqrt{2} \times 0.6$
(ii)Synchronous generator supplies fault current, Armature reaction is demagnetising, net flux decreases, generated voltage decreases.
ARV $= k_1 V_m \sin \theta$

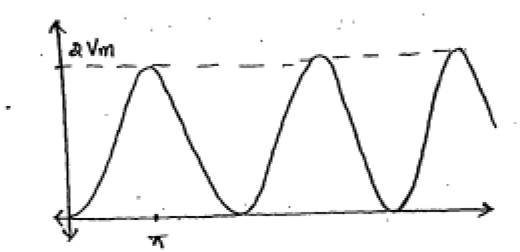
Where k≤ 1
(iii) Circuit conditions→ $System\ grounding$
→ $Grounded\ Fault$(LG, LLG, LLLG faults)
ARV $= k_1 k_2 V_m \sin \theta$

$k_2 = 1$ $when\ system\ must\ be\ grounded$
$k_2 = 1.5$ $in\ case\ of\ fault\ or\ system\ not\ grounded$

Restriking Voltage:-
It is the transient over-voltage across the breaker contacts at the instant of arc interruption.
$V_{res}(t) = V_c(t)$
$= V_m(1 - cos\omega nt)$
$\omega_n = \frac{1}{\sqrt{LC}}$rad/sec

$f_n = \frac{1}{2\pi\sqrt{LC}}$rad/sec
$ARV = V_m$
Maximum value of restriking voltage $= 2V_m$





$\omega_n t_p = \pi$

$t_p = \frac{\pi}{\omega_n} = \pi\sqrt{LC}$

Gradient $g = \frac{2V_m}{x}$

g<G

$\frac{2V_m}{x}$<G

$x > \frac{2V_m}{G}$

Average value of restriking voltage $= \frac{Peak\ Value}{Peak\ Time} = \frac{2V_m}{\pi\sqrt{LC}}$

Rate of rise of restriking voltage (RRRV)$= \frac{dV_{res}(t)}{dt}$

$= \frac{d}{dt}(V_m(1 - cos\omega nt)$

$= V_m \omega n\ sin\omega nt)$

Maximum value of RRRV= $V_m \omega n$

$= \frac{V_m}{\sqrt{LC}}\ KV/\mu sec$

Rate of rise of dielectric strength > Maximum value of RRRV

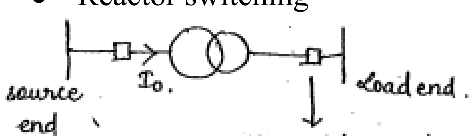
CURRENT CHOPPING:-

If the circuit breaker is interrupting low magnitude inductive currents, the current becomes absolutely zero well before the natural current zero instant.

This phenomenon is known as current chopping.

Low magnitude inductive current interruption takes place in:

- Transformer de-energization
- Reactor switching



Generally circuit breaker at load end is disconnected as circuit breaker at source end has high stress.

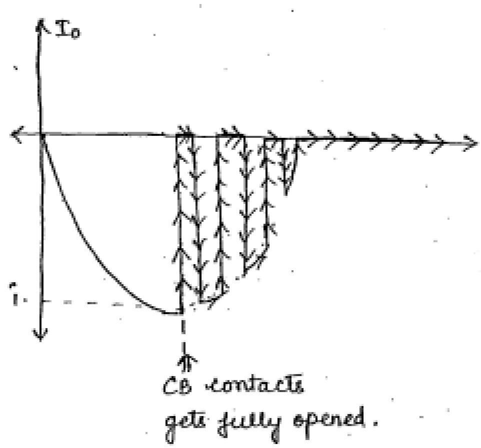
Noload $I_0 = 2 - 5\%\ of\ I_{FL}$

Fault current $I_f = 2\ to\ 10\ times\ of\ I_{FL}$

Eg:I_{FL}=1000,

I_0=20

I_f=10000



Heat energy = $I_0^{\,2}R_t$

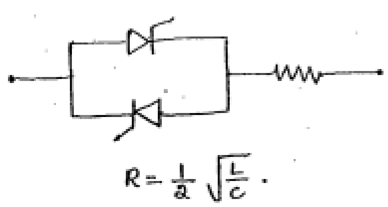
As, I_0 is less, heat produced is also very less.

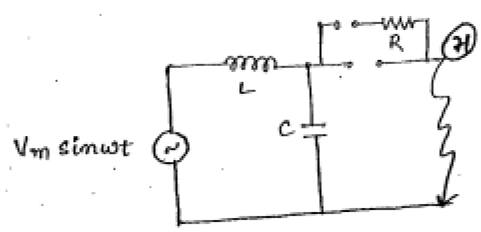
The current chopping is mainly because of insufficient heat energy. The air blast circuit breaker is highly effected due to current chopping and restriking voltage. To reduce the effect of current chopping and restriking voltage, resistance switching is employed.

The restriking of arc is due to transfer of energy from $\frac{1}{2}LI^2$ to $\frac{1}{2}CV^2$.

At this instant $V = i\sqrt{\frac{L}{C}} \rightarrow very\ high\ value.$

RESISTANCE SWITCHING:-





$R = \frac{1}{2}\sqrt{\frac{L}{C}} \rightarrow Critically\ damped$

$R < \frac{1}{2}\sqrt{\frac{L}{C}} \rightarrow Over\ damped$

$R > \frac{1}{2}\sqrt{\frac{L}{C}} \rightarrow Under\ damped$

$R = \infty \rightarrow Undamped$

RATING OF CIRCUIT BREAKER:

Eg: A 3-ϕ, 50 Hz, 1000 A, 132kV, 10000MVA, $1\frac{1}{2}cycle$, SPO/TPO break

↓ ↓ ↓ ↓ ↓ ↓ ↓

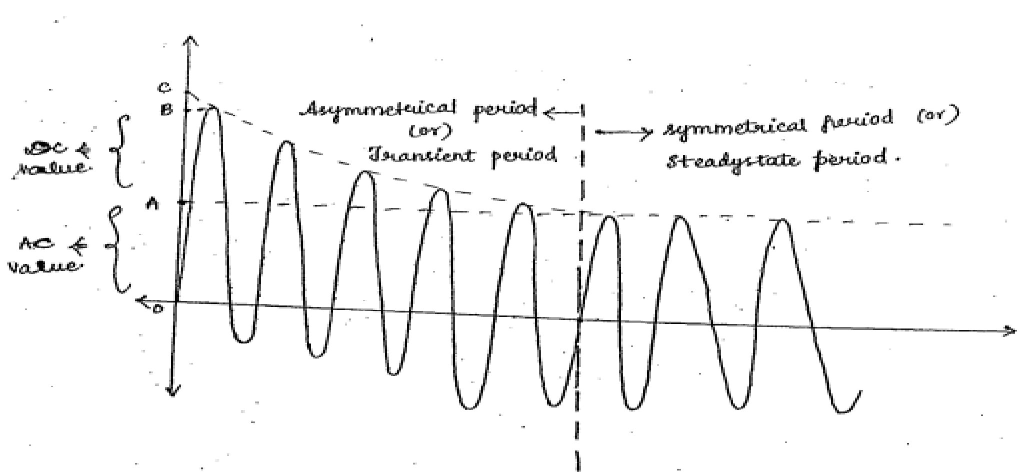
Rated frequency	Continous Current	Rated Line Voltage	symmetrical breaking capacity	CB open time	Single Pole	Triple Pole Operated

Breaking Capacity:

- Symmetrical breaking capacity
- Asymmetrical breaking capacity

Making Capacity:

- In Transmission system CB gets trip signal in transient period.
- In Distribution system CB gets trip signal in steady state period.



⇒Symmetrical breaking Capacity(S.B.C)=

$\sqrt{3} \times rated\ system\ voltage\ \times\ symmetrical\ breaking\ current\{I_{sy}\}$

$I_{sy} = \frac{V_{pre}}{Z_{th}}$ (3 phase fault at breaker location)

$I_{sy} = \frac{0A}{\sqrt{2}}$

S.B.C $= I_f(pu) \times MVA_{base}$

⇒Asymmetrical breaking capacity(A.S.B.C)

$= \sqrt{3} \times rated\ system\ voltage\ \times\ asymmetrical\ breaking\ current\{I_{Asy}\}$

$I_{Asy} = \sqrt{(\frac{OA}{\sqrt{2}})^2 + AB^2}$

$= x \times I_{sy}$

(1.6 for first cycle)

ASBC = x *SBC

$\Rightarrow Making\ Capacity\ (MC)$

$=\sqrt{3} \times rated\ system\ voltage \times making\ current$

Making current = Peak value of 1st cycle current

=OC

$=1.8\times I_{sy} \times \sqrt{2}$

$= 2.55 I_{sy}{}^{*}$

For m phase SBC $=\sqrt{m} \times V_l \times I_L$