Transformer Fault Categories

1. **Winding and terminal faults**
2. **Sustained or uncleared external faults**
3. **Abnormal operating conditions such as overload, overvoltage and overfluxing**
4. **Core faults**

Transformer Protection (1)

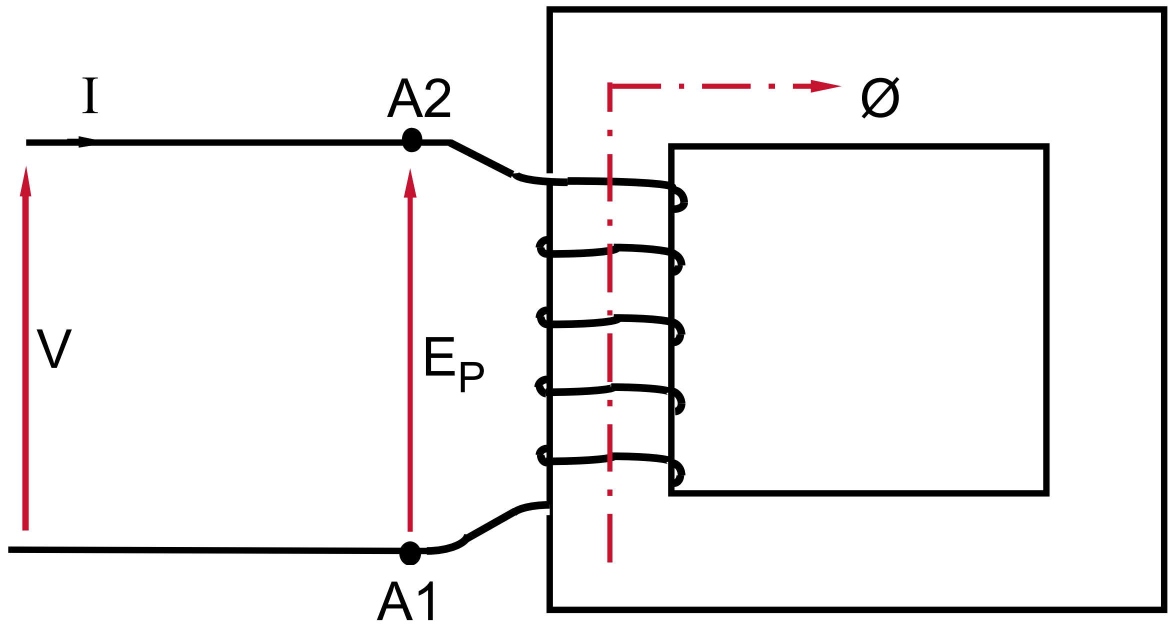
- Transformer Connections
- Overcurrent Protection
- Directional Protection of Parallel Transformers
- Partial Differential Protection of Parallel Transformers
- Earth Faults on Transformer Windings
- Unrestricted Earth Fault Protection
- Restricted Earth Fault Protection
- Biased Differential Protection of 2 and 3 Winding Transformers

Transformer Protection (2)

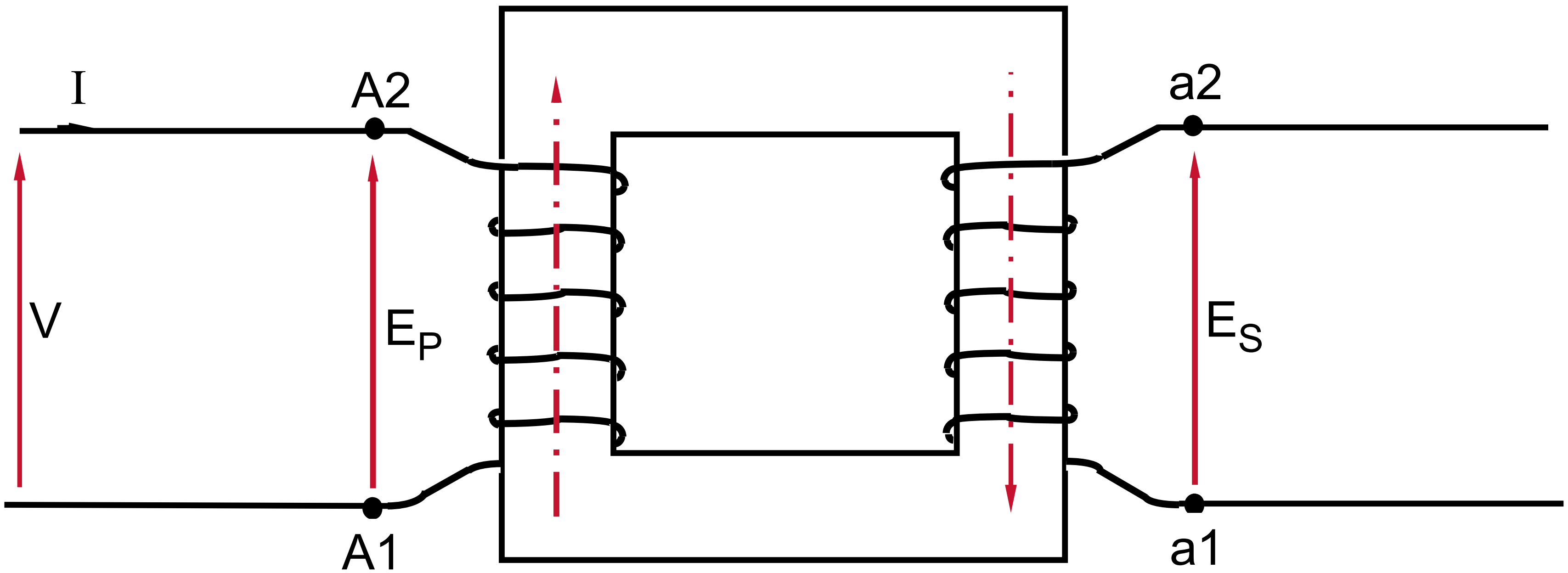
- Combined Differential and Restricted Earth Fault Protection
- Protection of Auto-Transformers
- Inter-Turn Faults and Buchholz Protection
- Overfluxing Protection
- Overload Protection
- Transformer Feeder Protection

Transformer Connections

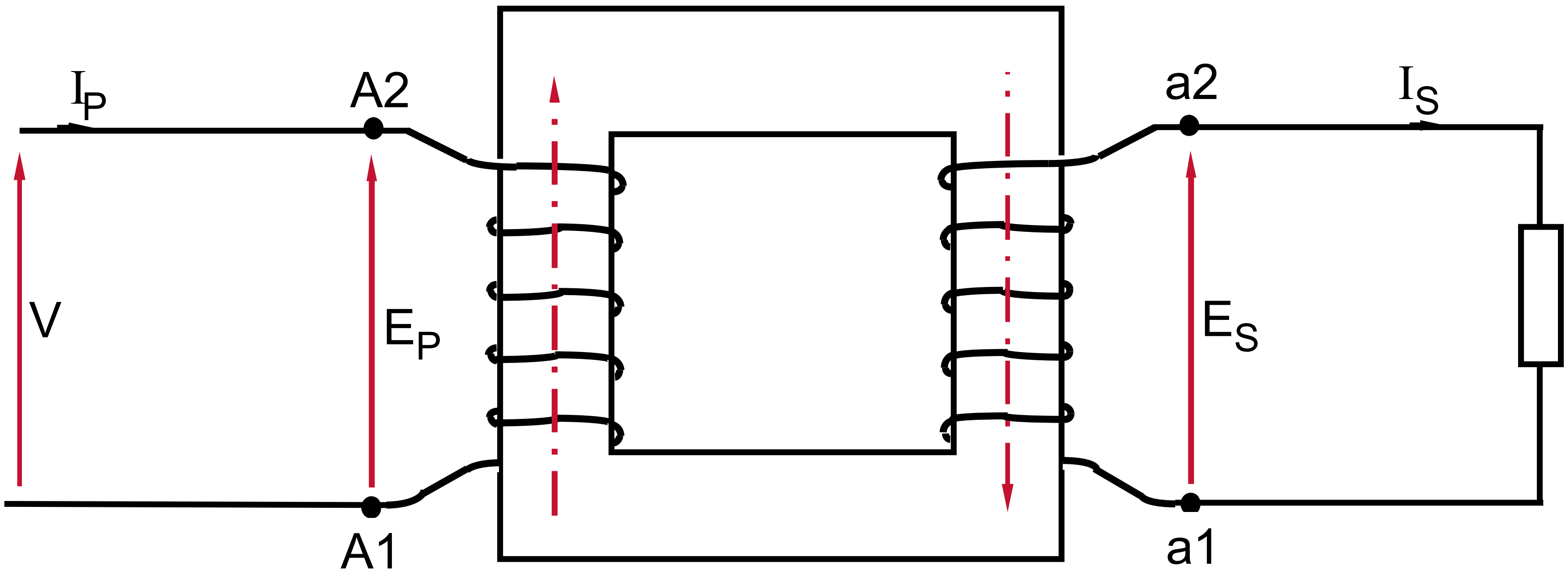
Transformer Protection (3)



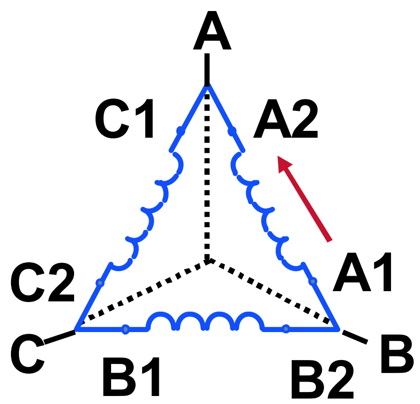
Transformer Protection (4)

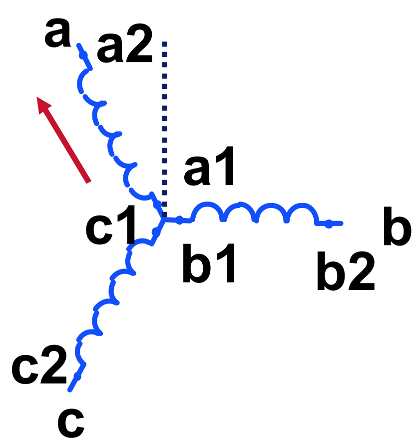


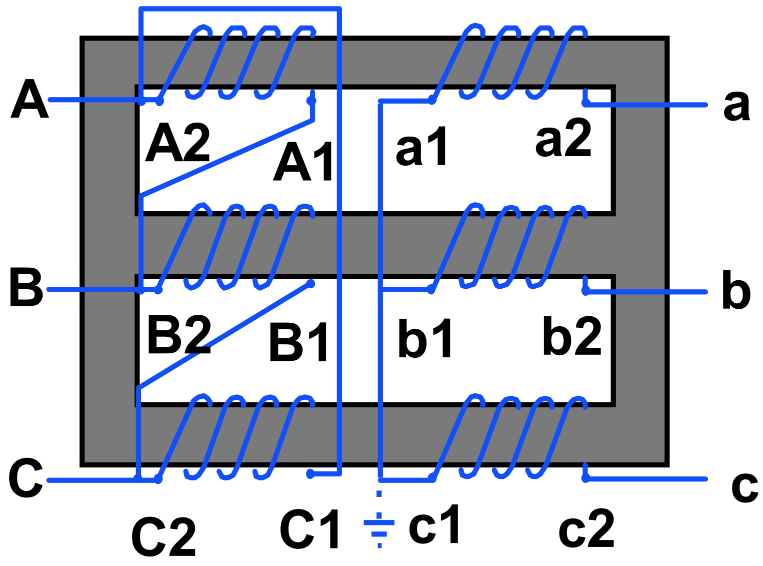
Transformer Protection (5)



Transformer Connections







"Clock face" numbers refer to position of low voltage phase - neutral vector with respect to high voltage phase - neutral vector.

Line connections made to highest numbered winding terminal available.

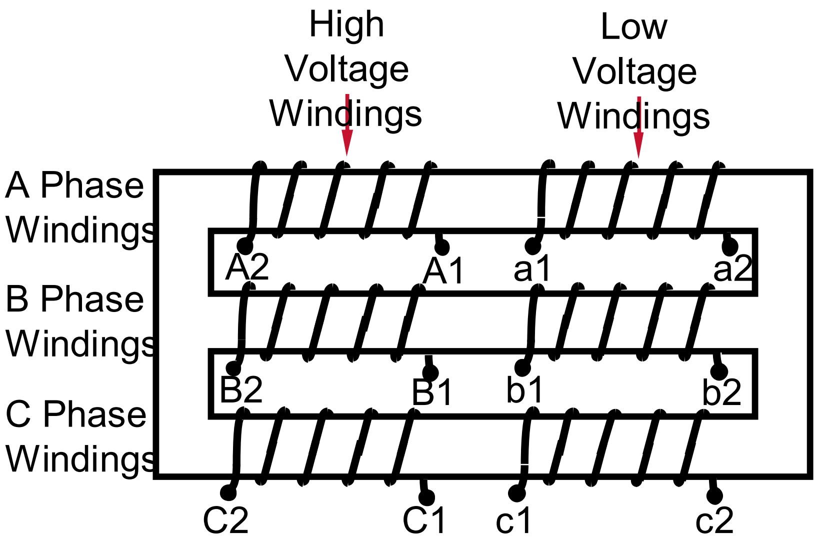
Line phase designation is same as winding.

Transformer Vector Groups

Group 1 0° Phase displacement	Yy0 Dd0 Zd0
Group 2 180° Phase displacement	Yy6 Dd6 Dz6
Group 3 30° Lag phase displacement	Yd1 Dy1 Yz1
Group 4 30° Lead phase displacement	Yd11 Dy11 Yz11

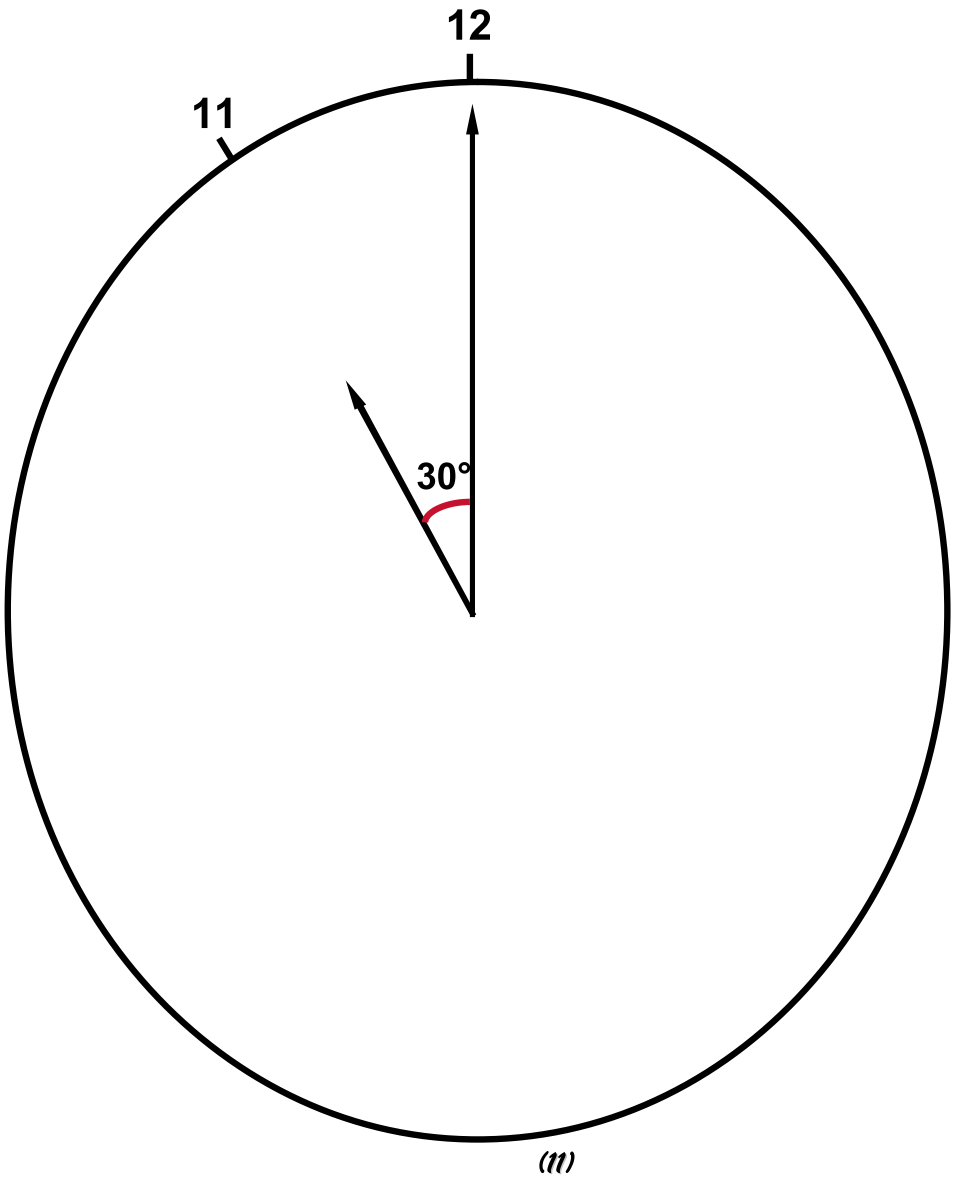
- "Clock Face" numbers refer to position of low voltage phase-neutral vector with respect to high voltage phase neutral vector
- Line connections made to highest numbered winding terminal available
- Line phase designation is same as winding

Example 1 : Dy 11 Transformer

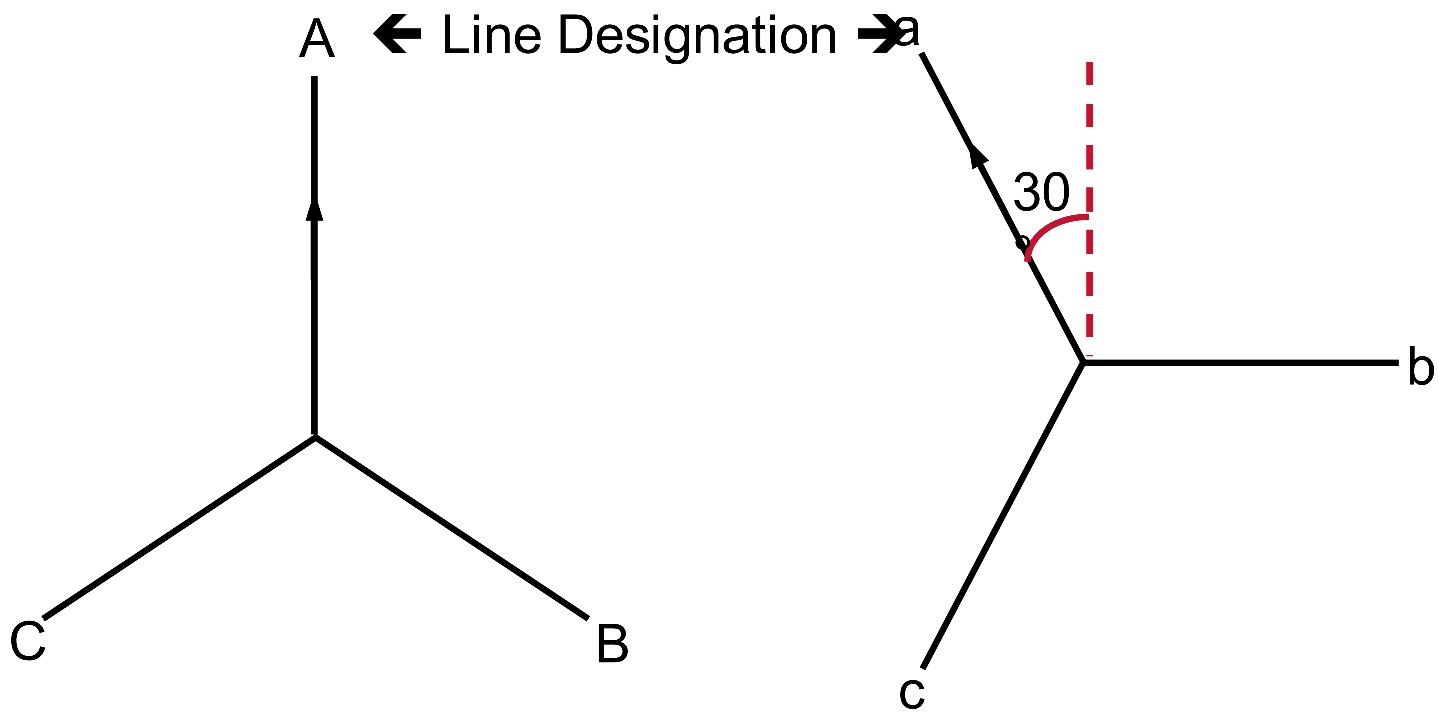


Question : How to connect windings ?

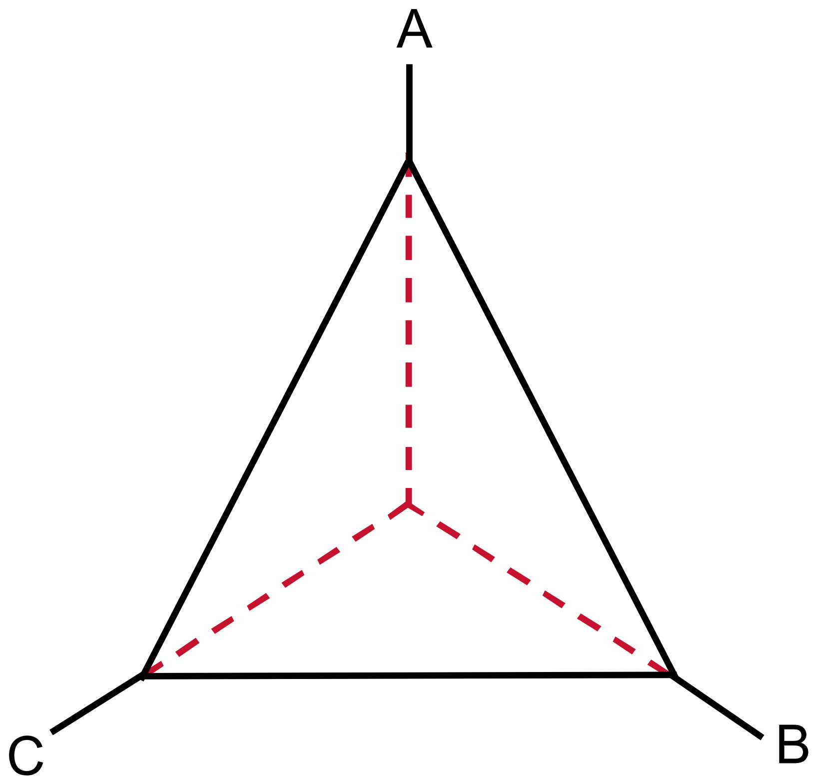
Dy 11

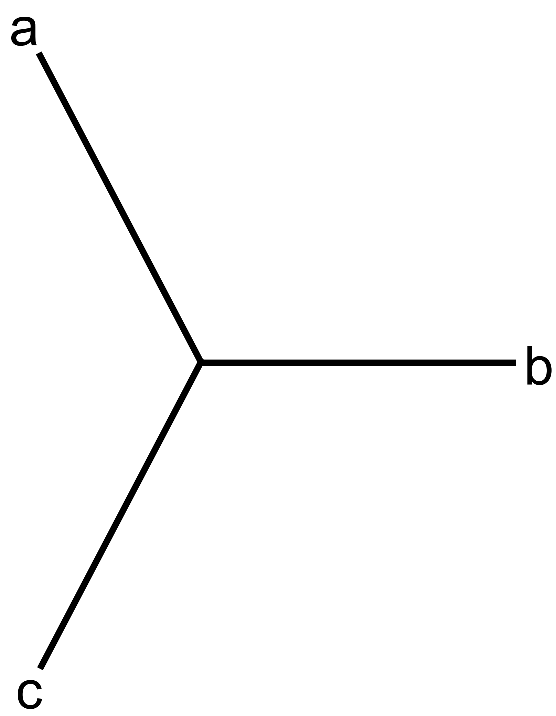


1. Draw Phase-Neutral Voltage Vectors

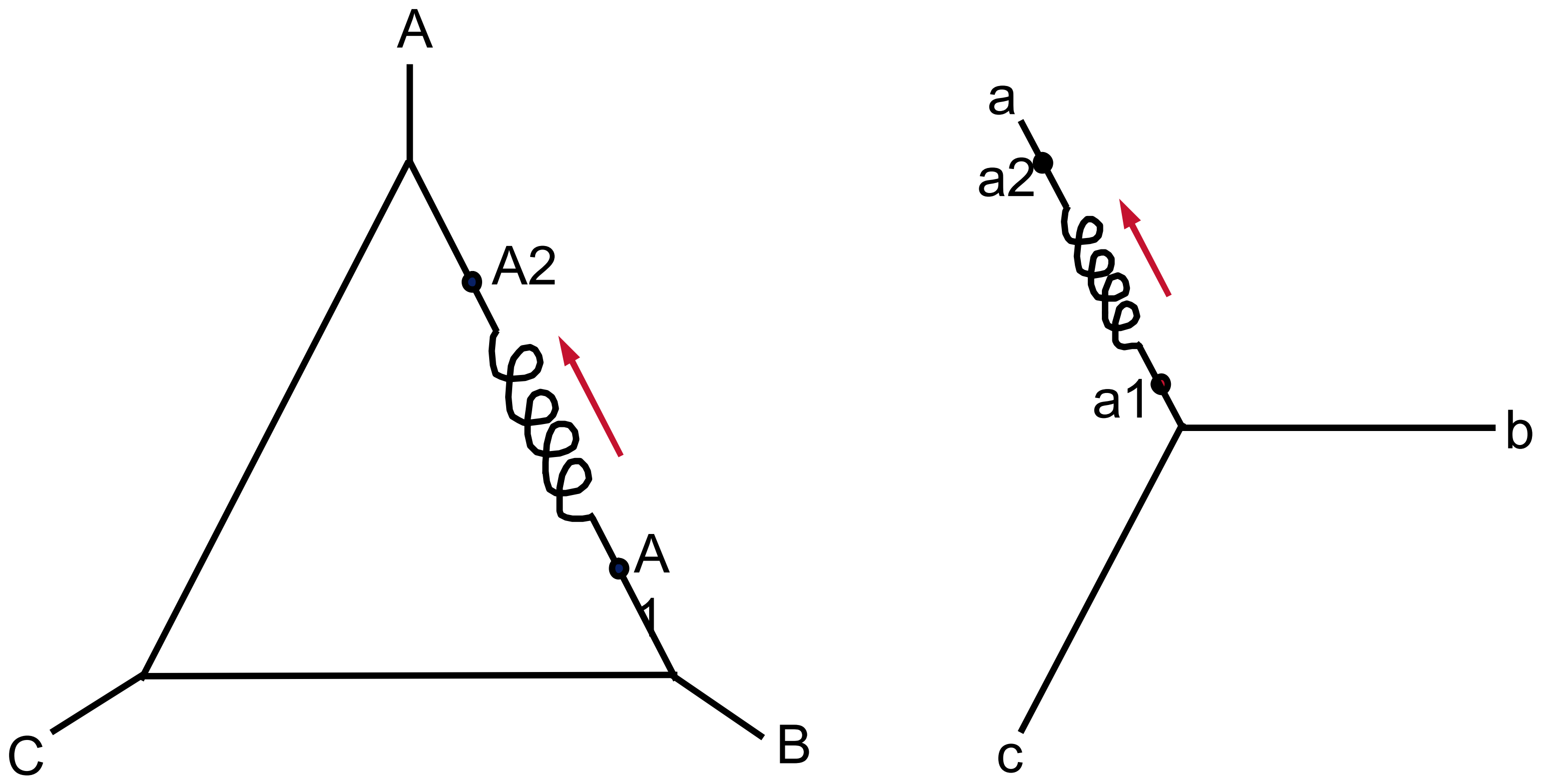


2. Draw Delta Connection

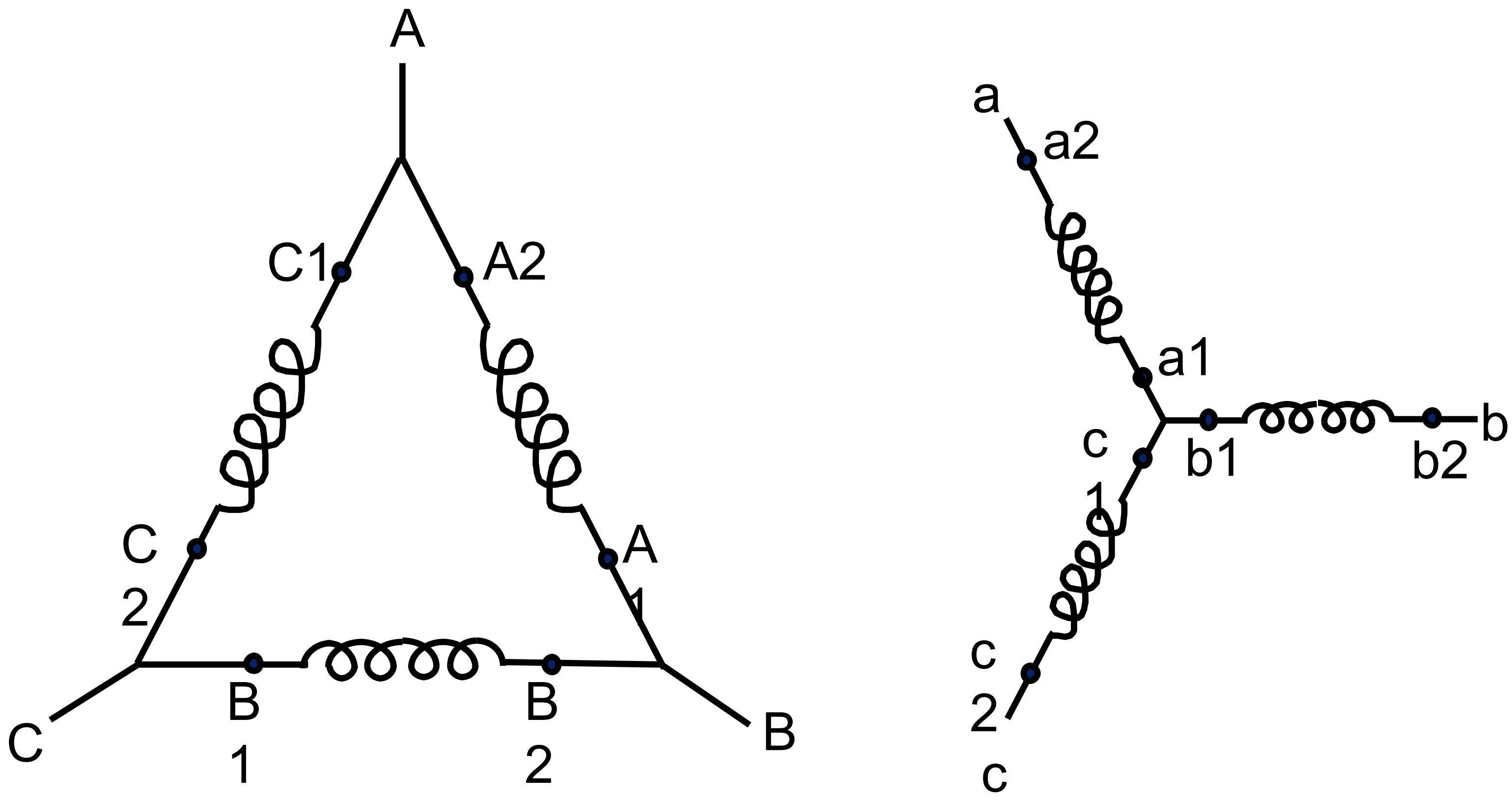




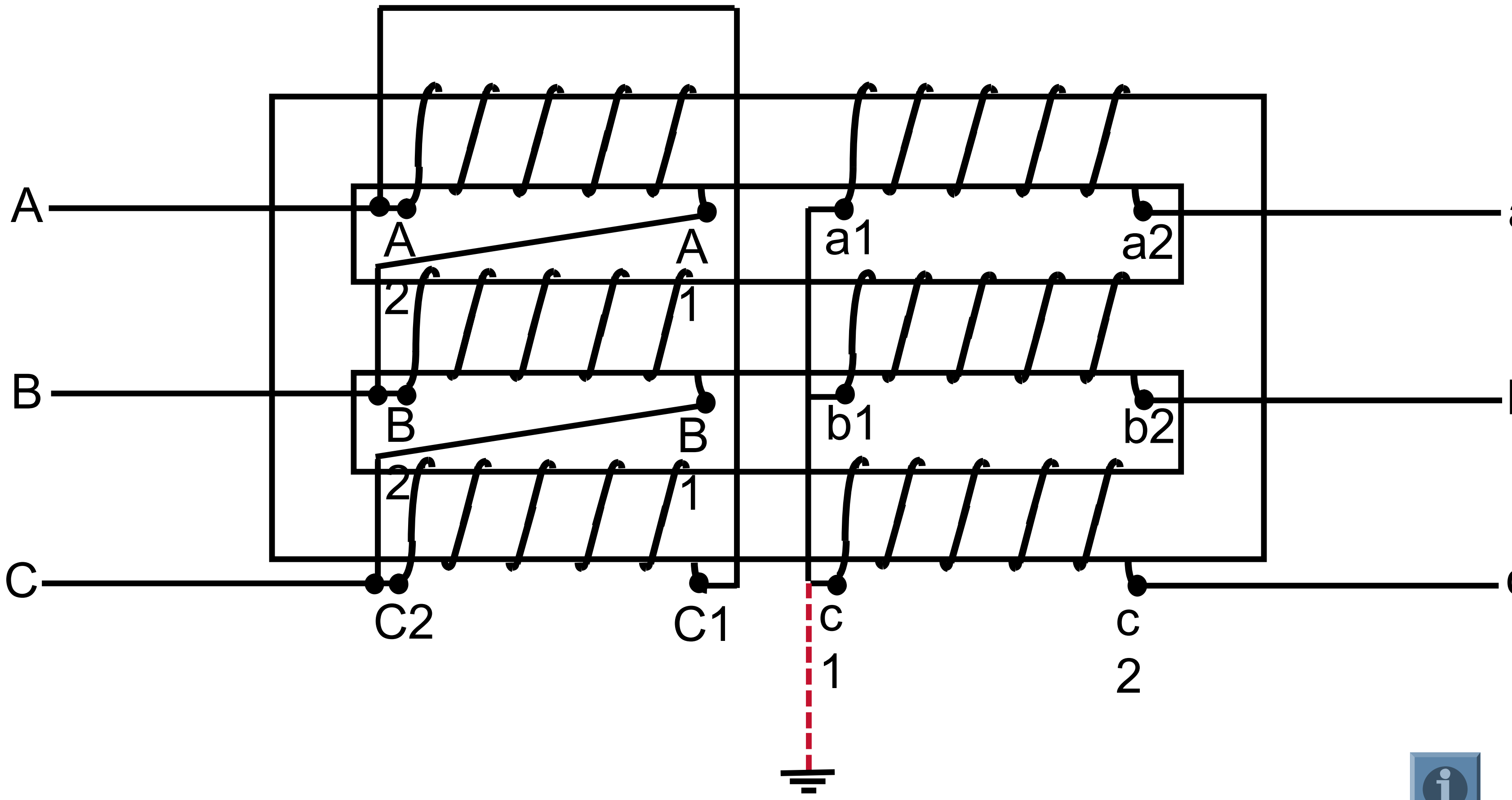
3. Draw A Phase Windings



4. Complete Connections (a)



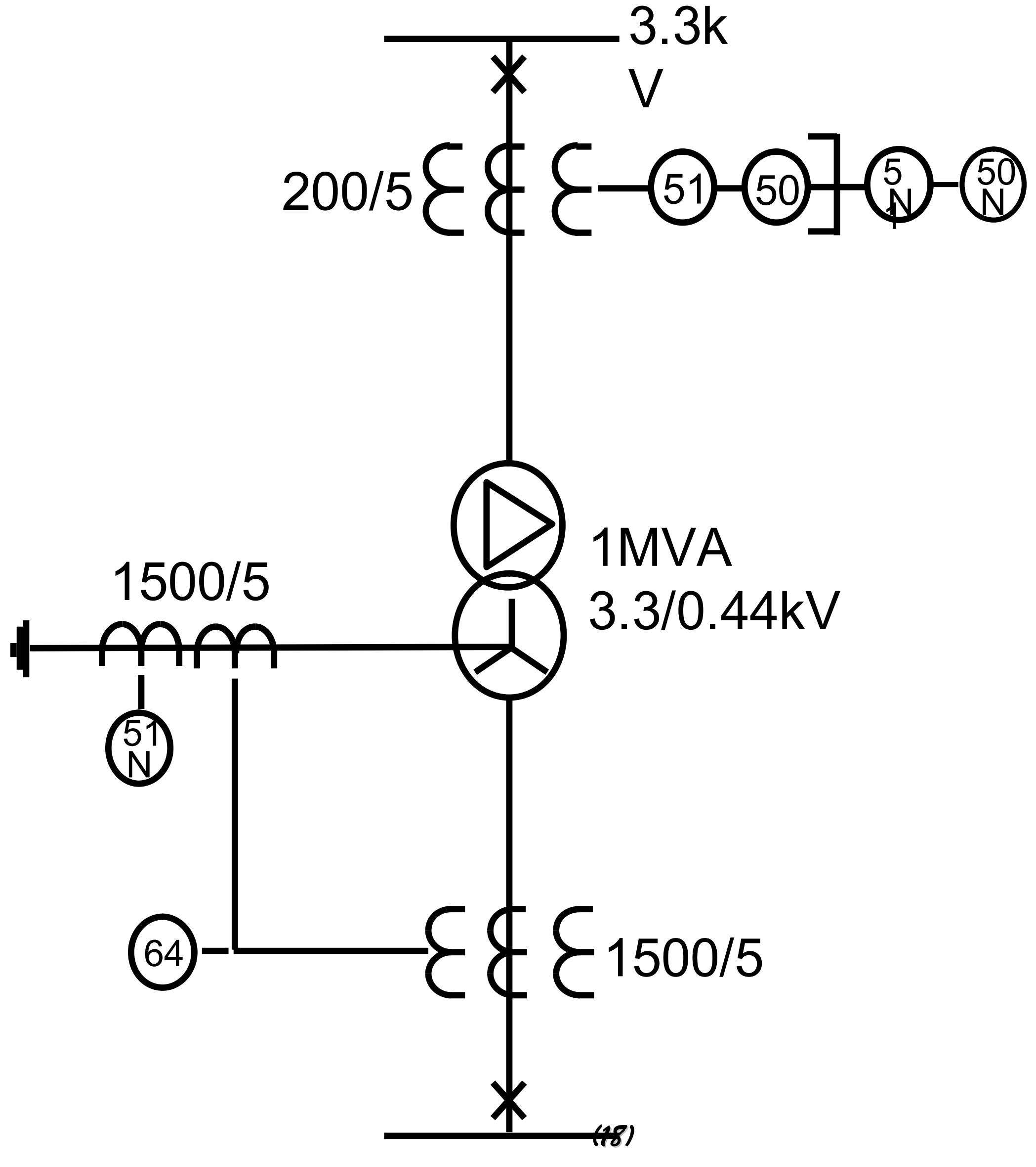
4. Complete Connections (b)



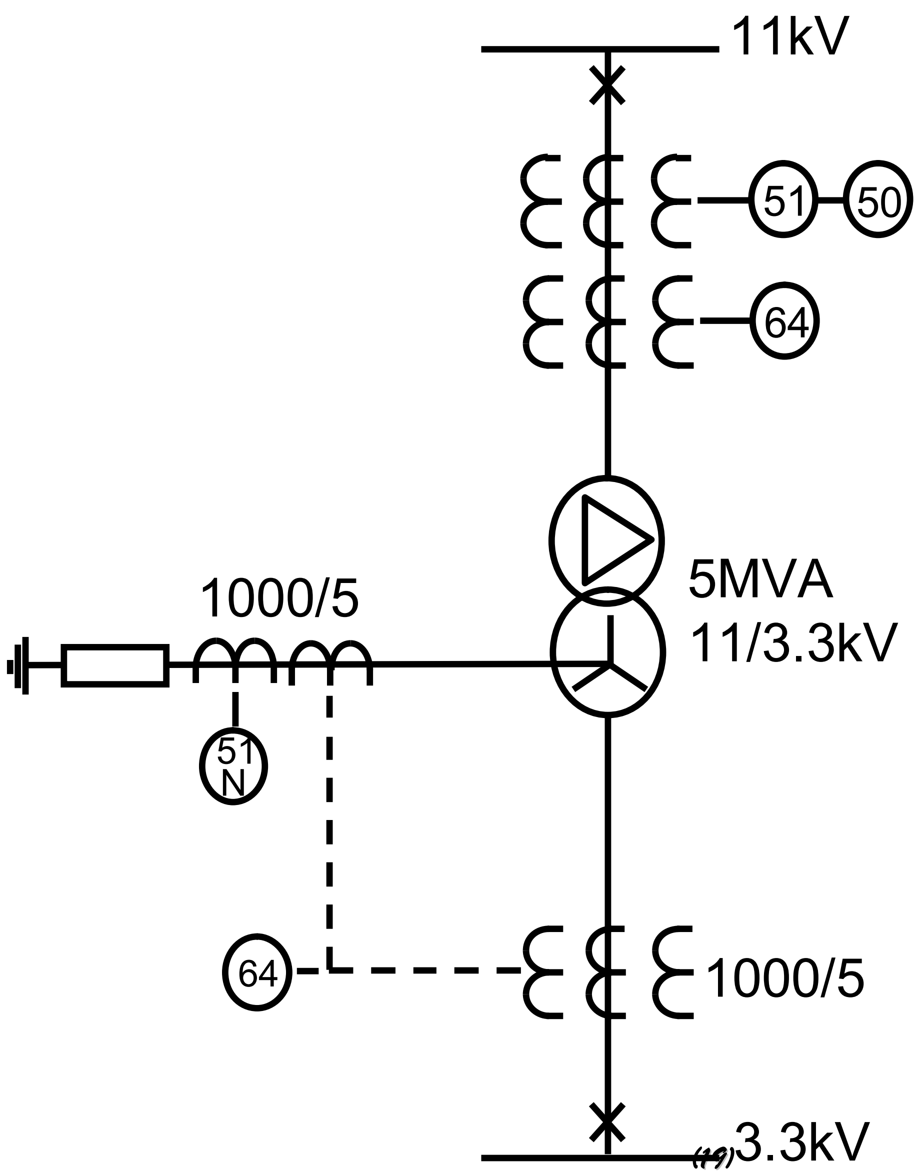
11kV Distribution Transformers Typical Fuse Ratings

Transformer rating		Fuse	
kVA	Full load current (A)	Rated current (A)	Operating time at 3 x rating(s)
100	5.25	16	3.0
200	10.5	25	3.0
300	15.8	36	10.0
500	26.2	50	20.0
1000	52.5	90	30.0

Traditional Small Transformer Protection Package



Traditional Medium Transformer Protection Package



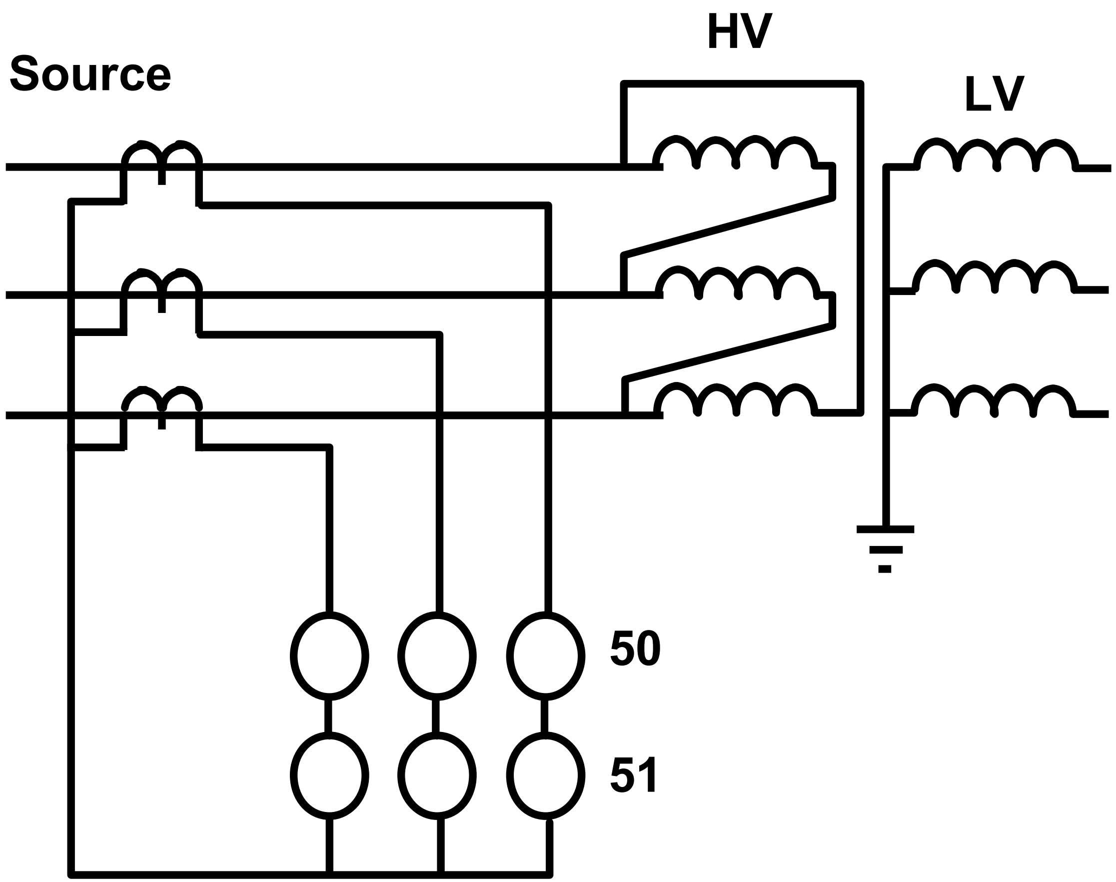
Overcurrent Protection

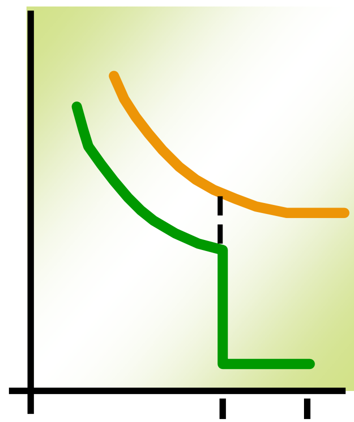
Transformer Overcurrent Protection

Requirements

- **Fast operation for primary short circuits**
- **Discrimination with downstream protections**
- **Operation within transformer withstand**
- **Non-operation for short or long term overloads**
- **Non-operation for magnetising inrush**

Use of Instantaneous Overcurrent Protection

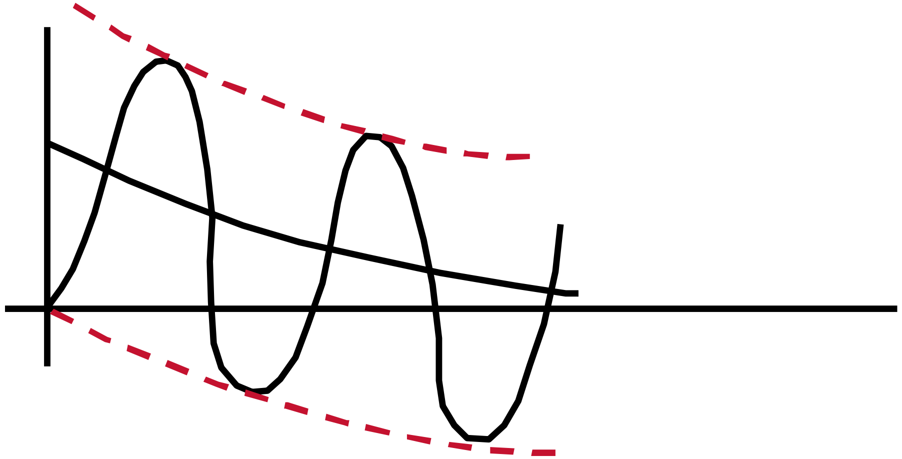




50 set to 1.2 - 1.3 x through fault level

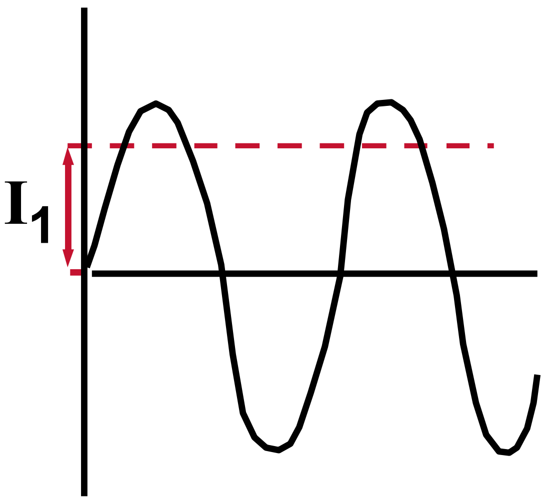
Transient Overreach

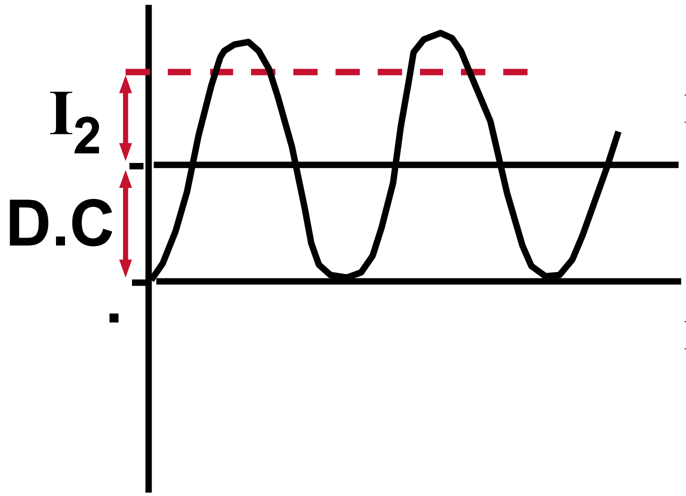
Concerns relay response to offset waveforms (DC transient)



Definition

$$\frac{I_1 - I_2}{I_2} \times 100$$

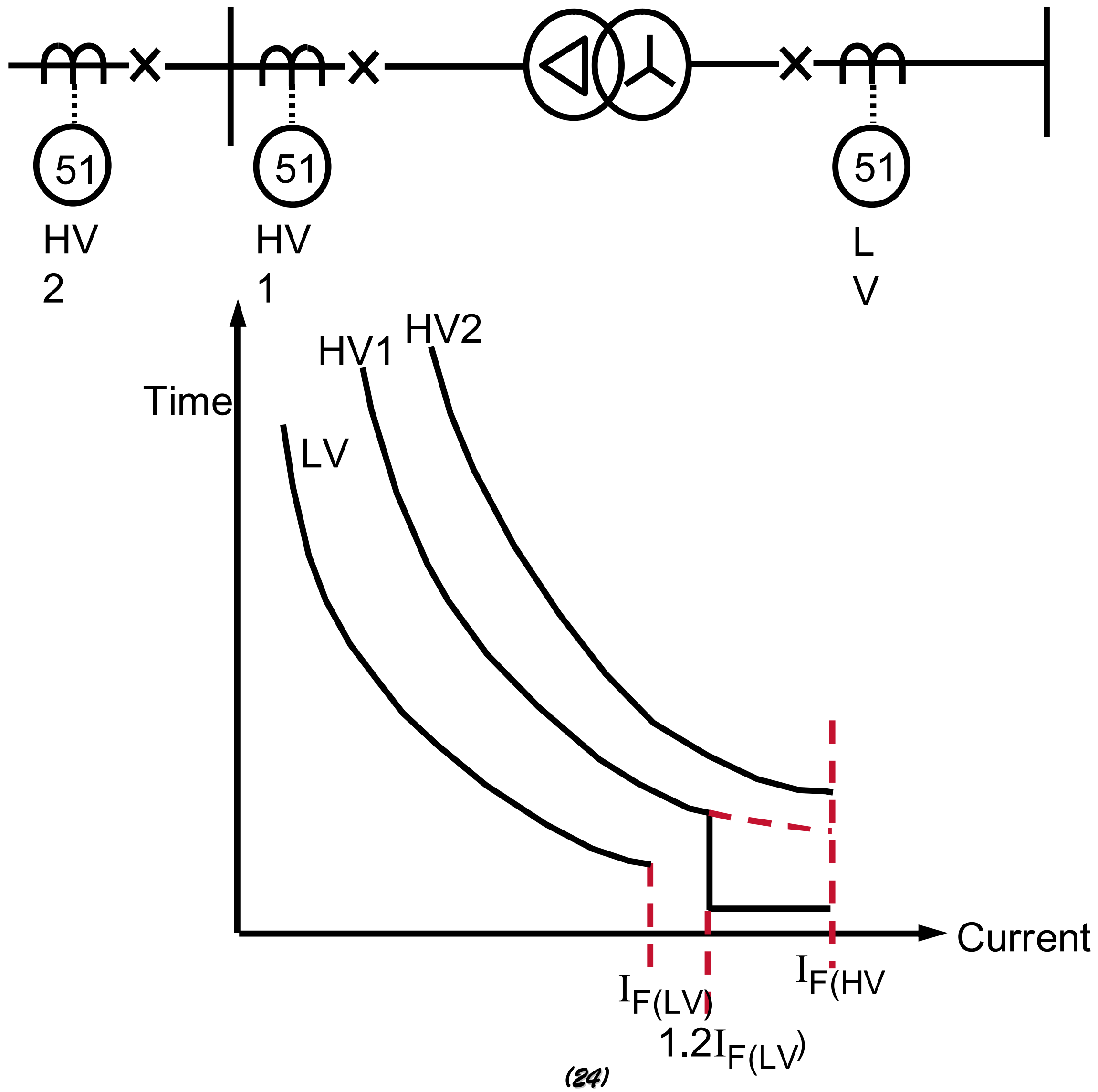




I_1 **= Steady state rms pick up current**

I_2 **= Fully offset rms pickup current**

Instantaneous High Set Overcurrent Relay Applied to a Transformer



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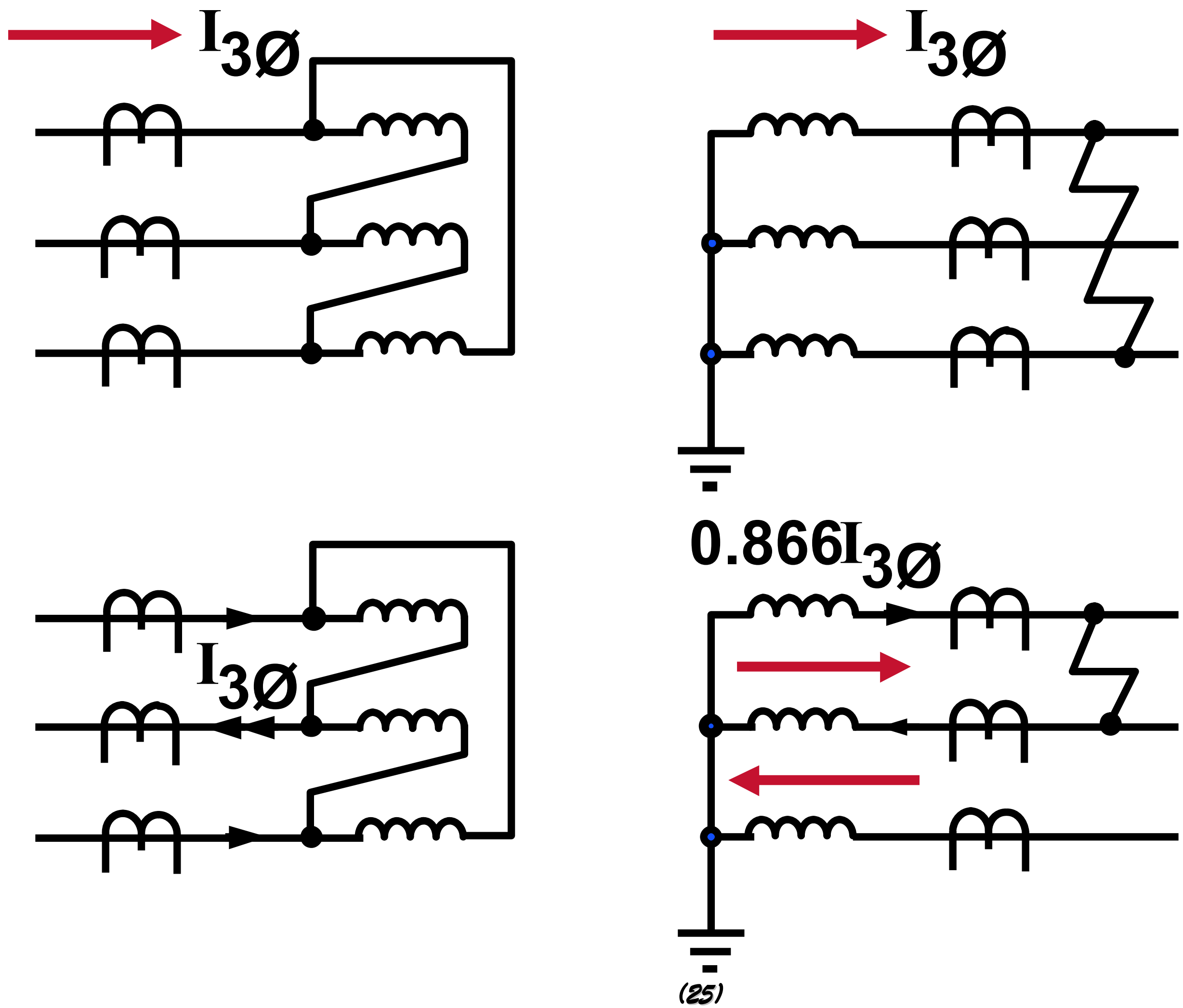
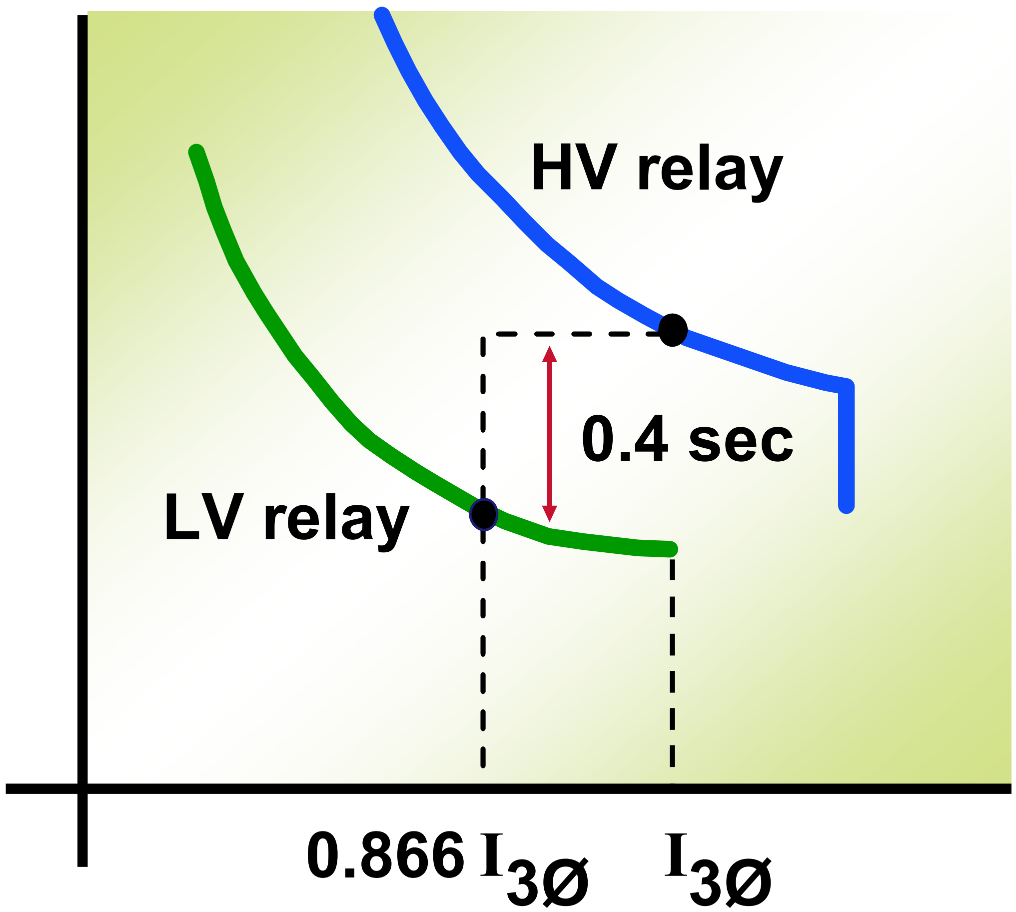
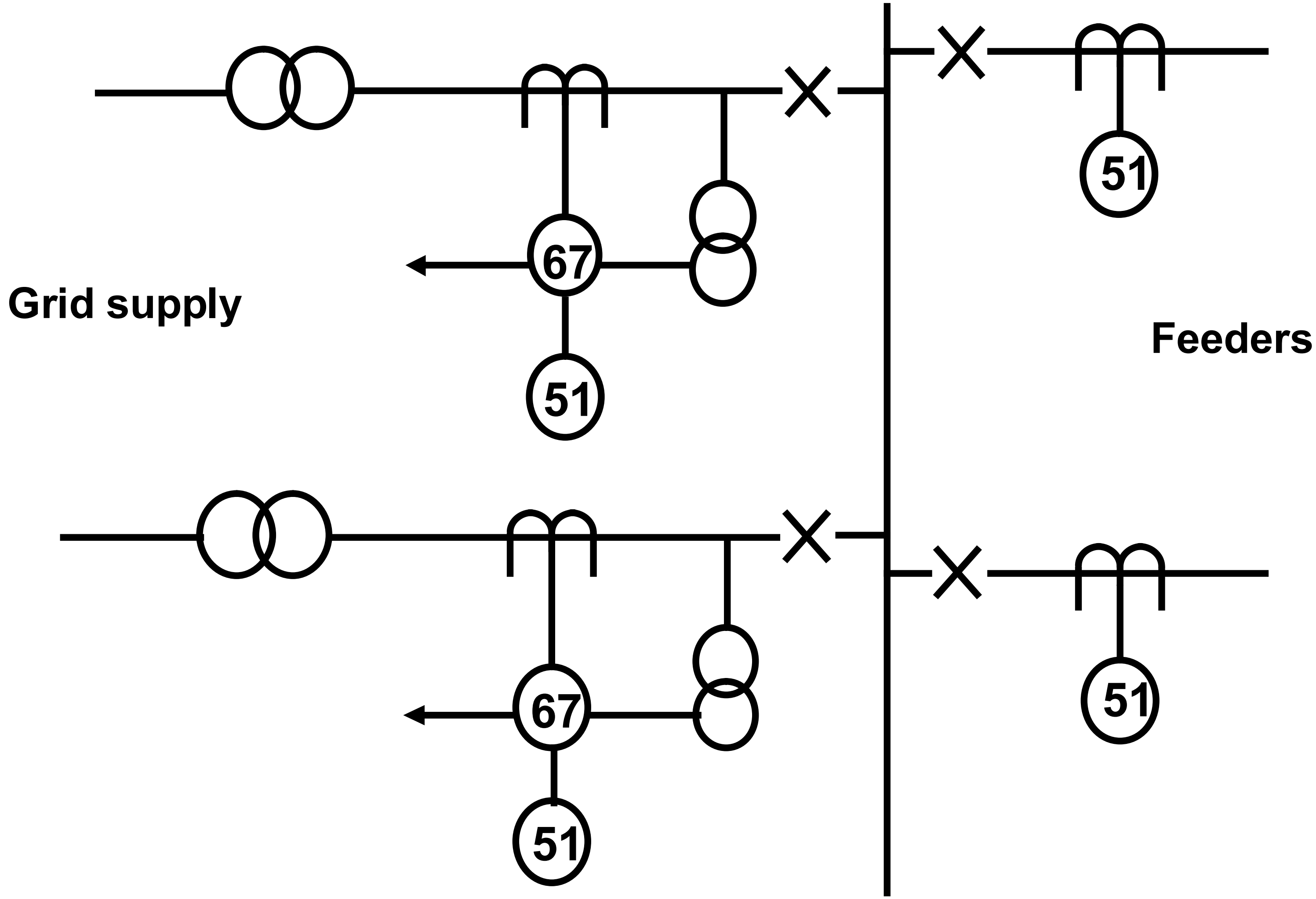
2-1-1 Distribution (1)



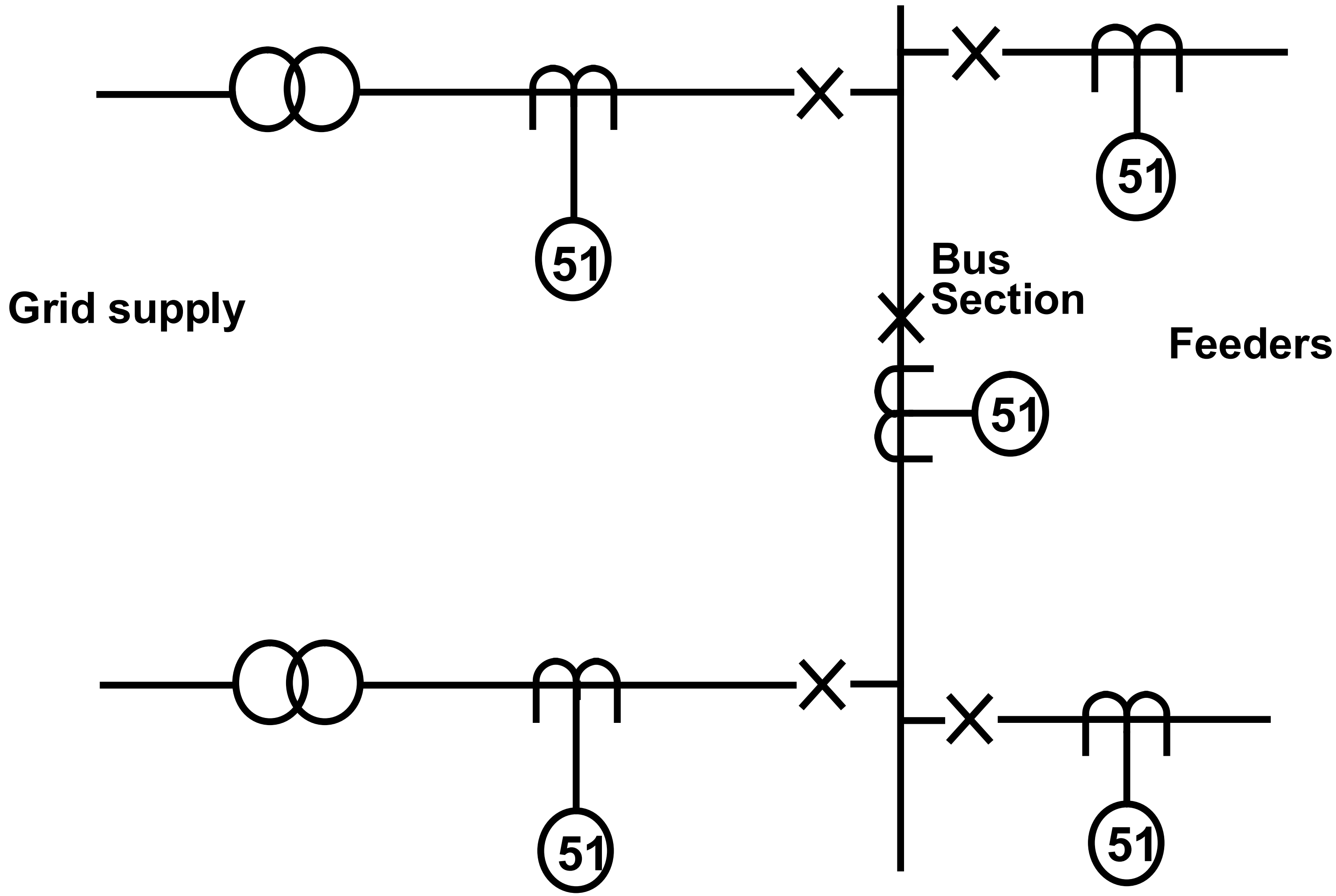
2-1-1 Distribution (2)



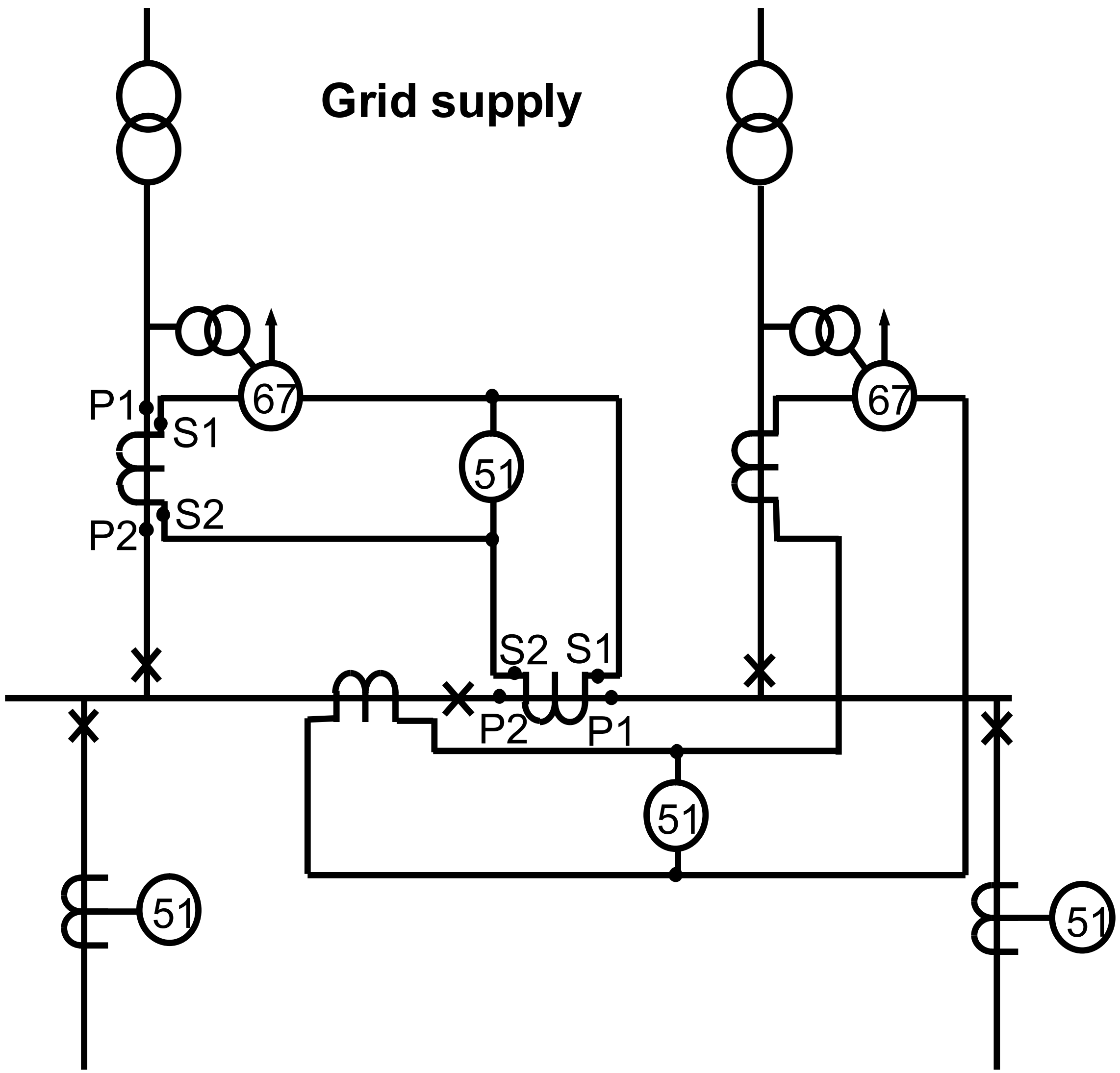
Parallel Transformers
Directional Relays (1)



Parallel Transformers Directional Relays (2)



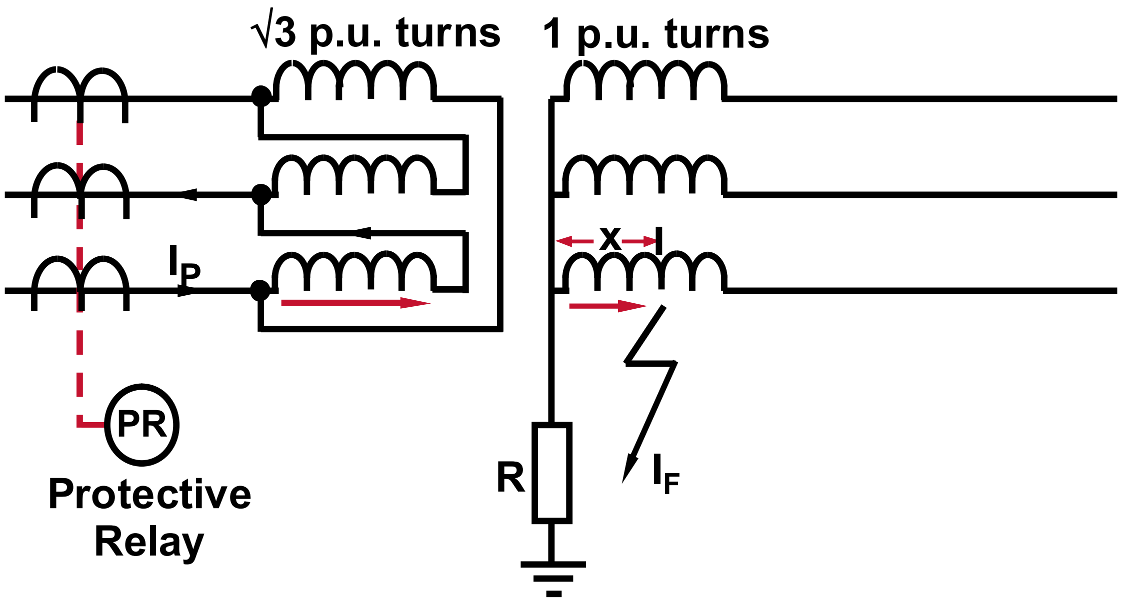
Parallel Transformers
Partial Differential Scheme



Advantage : Reduced number of grading stages

Earth Fault Protection

Transformer Earth Faults



Resistor limits E/F current to full load values

For a fault at χ : Fault current $= \chi \,.\, I_{F.L.}$

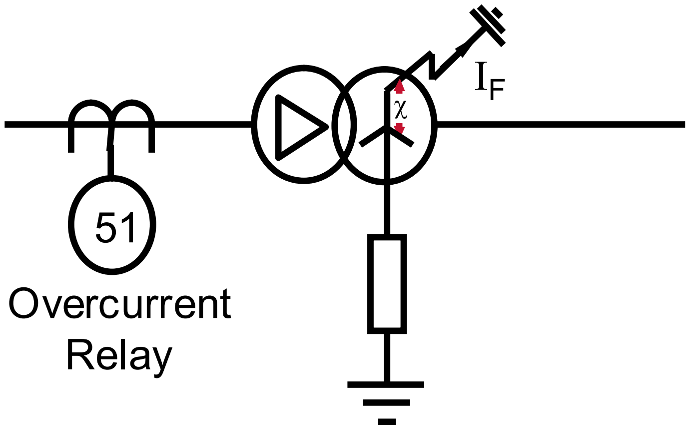
Effective turns ratio $= \sqrt{3} : \chi$

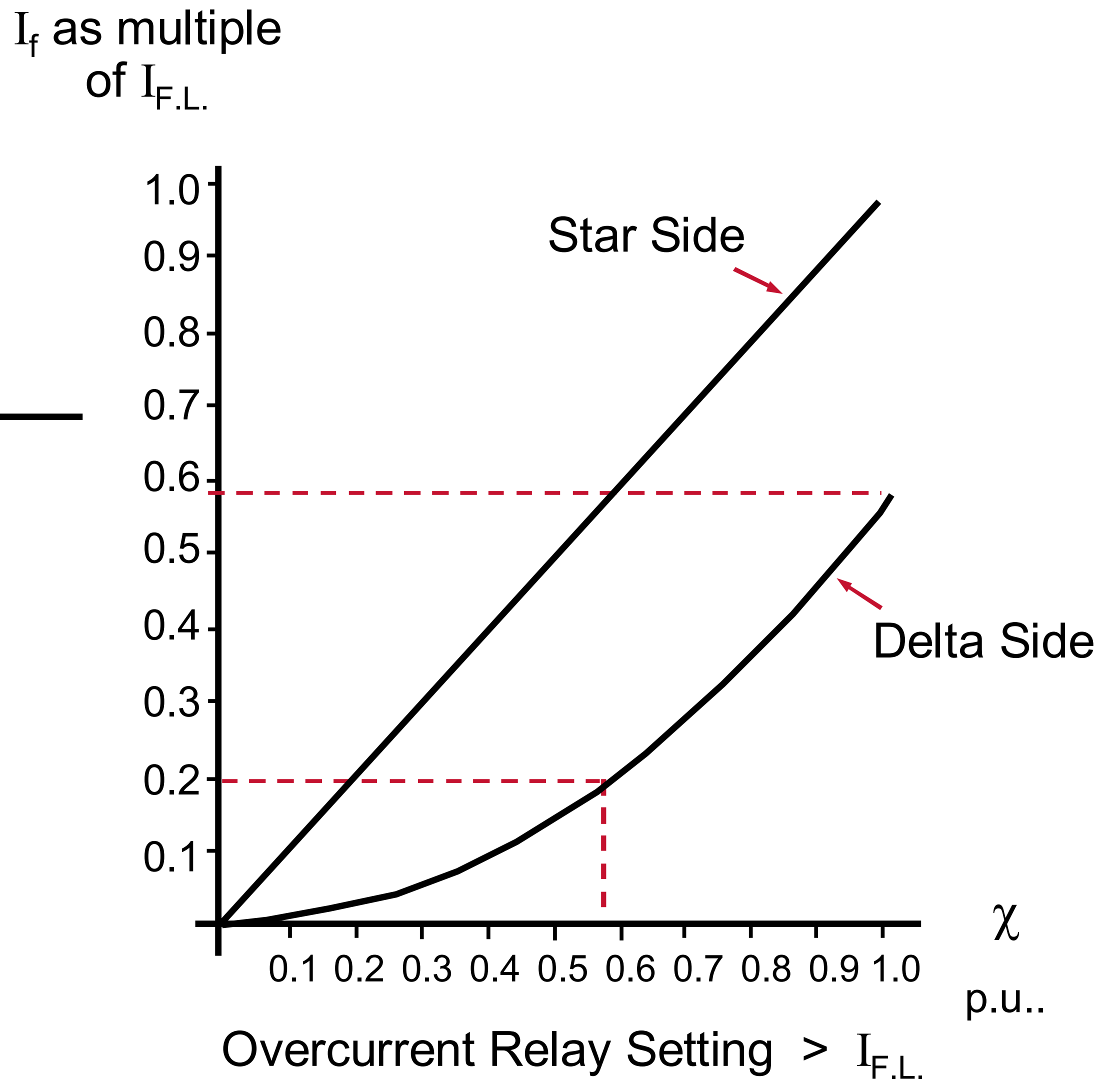
Thus primary current, $I_P = \frac{\chi}{\sqrt{3}} \times \chi . I_{F.L.}$

$= \frac{\chi^2}{\sqrt{3}} \,.\, I_{F.L.}$

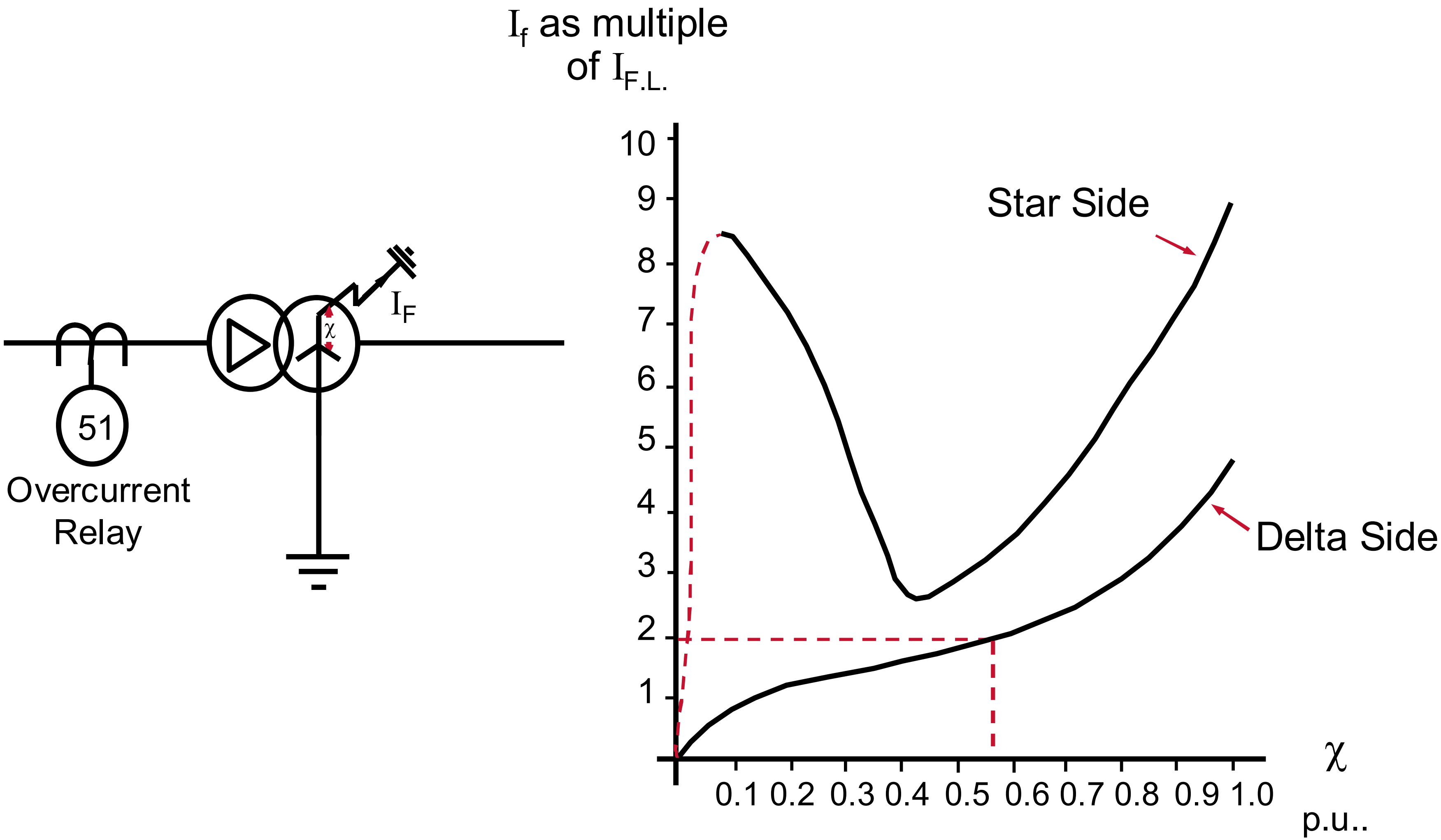
If C.T. ratio (on primary side) is based on full load current of transformer, then C.T. secondary circuit $= \frac{\chi^2}{\sqrt{3}}$

Overcurrent Relay Sensitivity to Earth Faults (1)

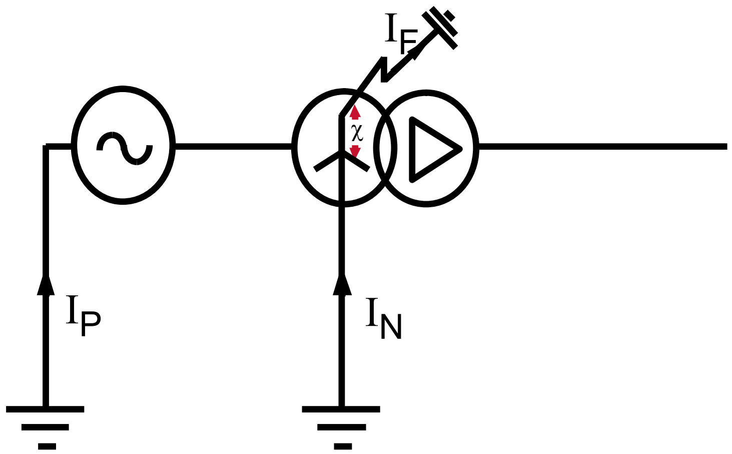


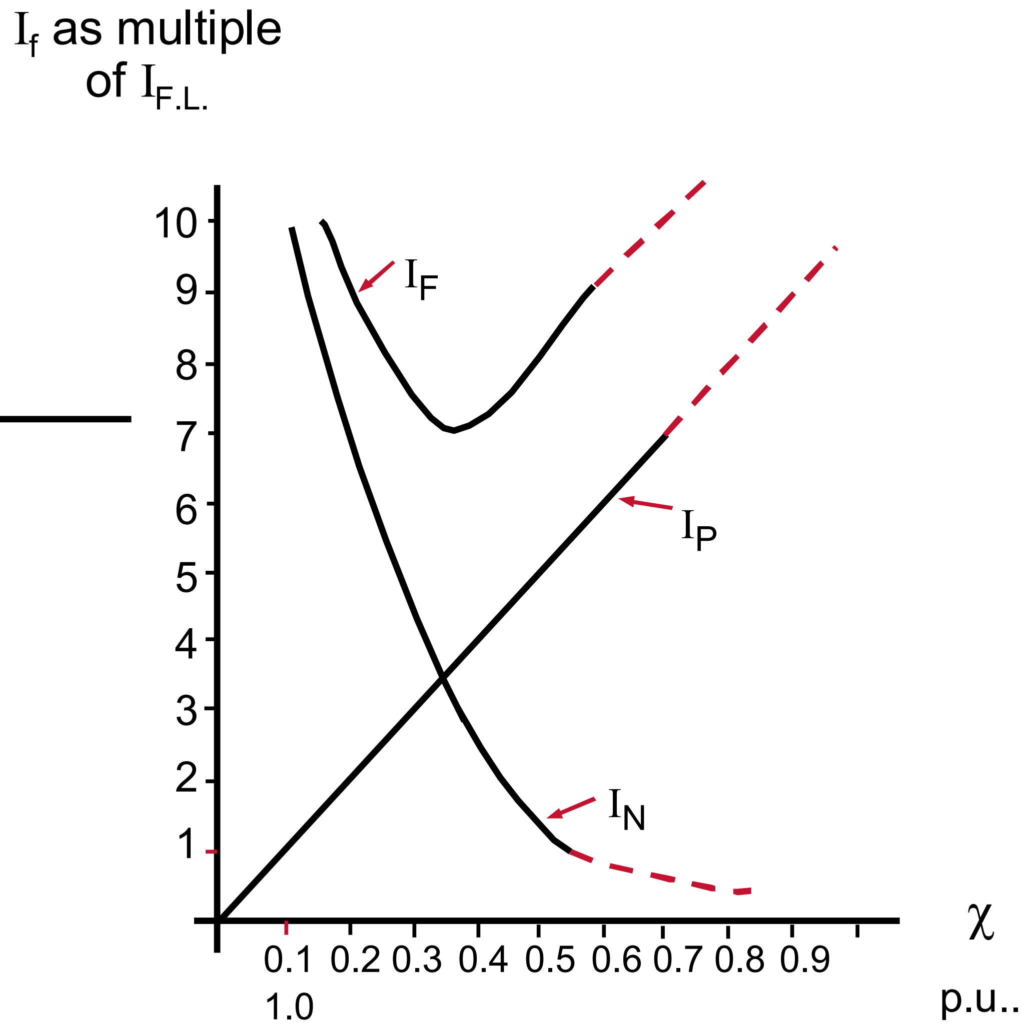


Overcurrent Relay Sensitivity to Earth Faults (2)

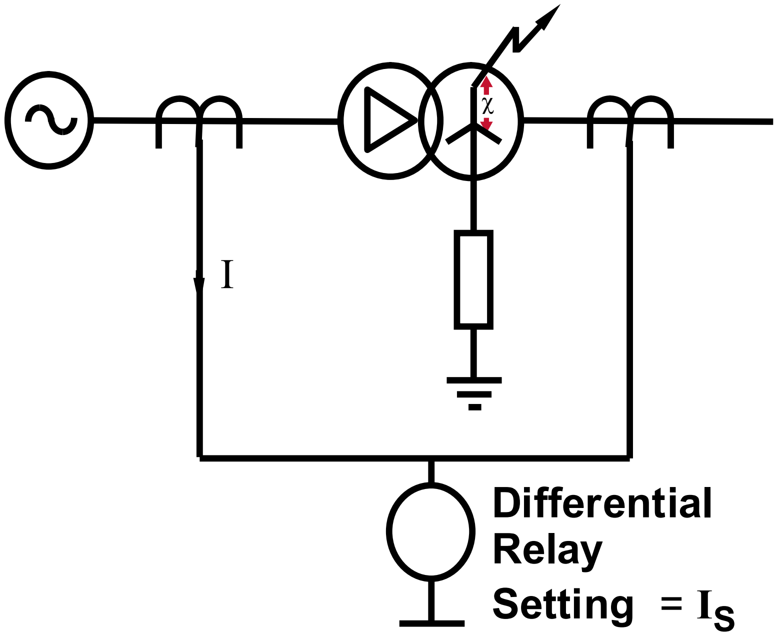


Overcurrent Relay Sensitivity to Earth Faults (3)





Earth Fault on Transformer Winding



$$I = \frac{\chi^2}{\sqrt{3}}$$

For relay operation, $I > I_S$

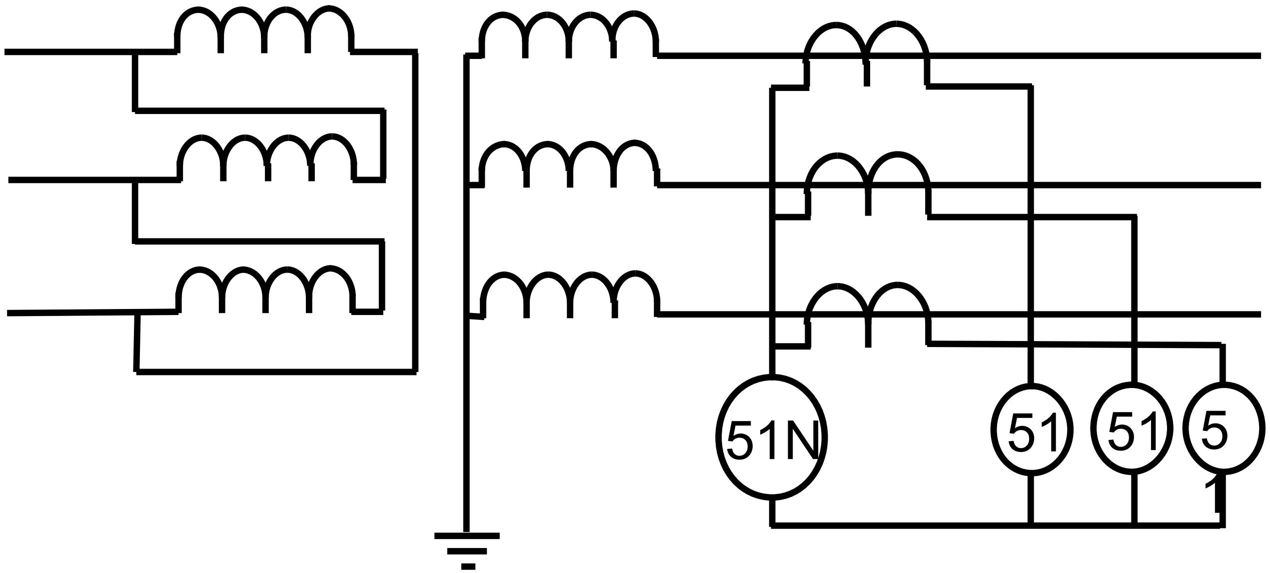
e.g. If I_S = 20%, then $\frac{\chi^2}{\sqrt{3}}$ > 20% for operation

i.e. χ > 59%

Thus 59% of ⅄ winding is not protected

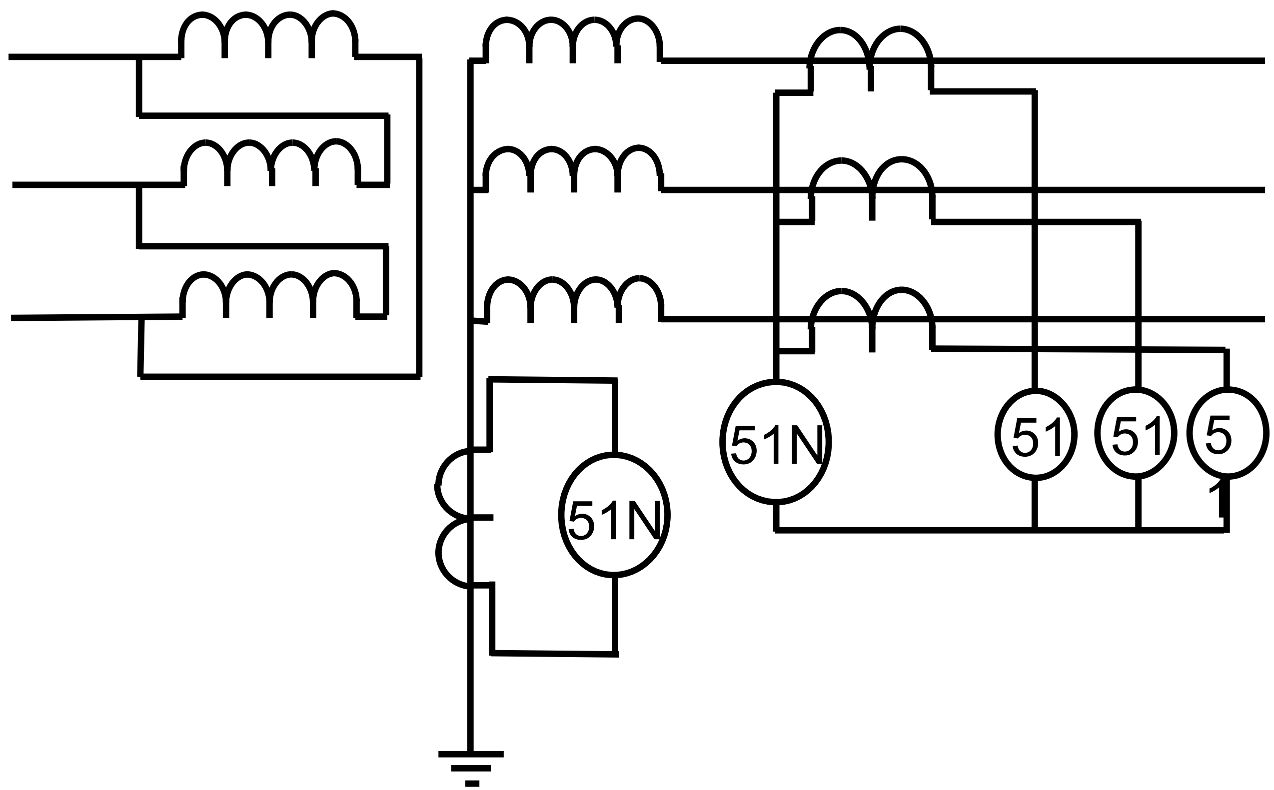
Differential Relay Setting	% of Star Winding Protected
10%	58%
20%	41%
30%	28%
40%	17%
50%	7%

Unrestricted Earthfault Protection (1)



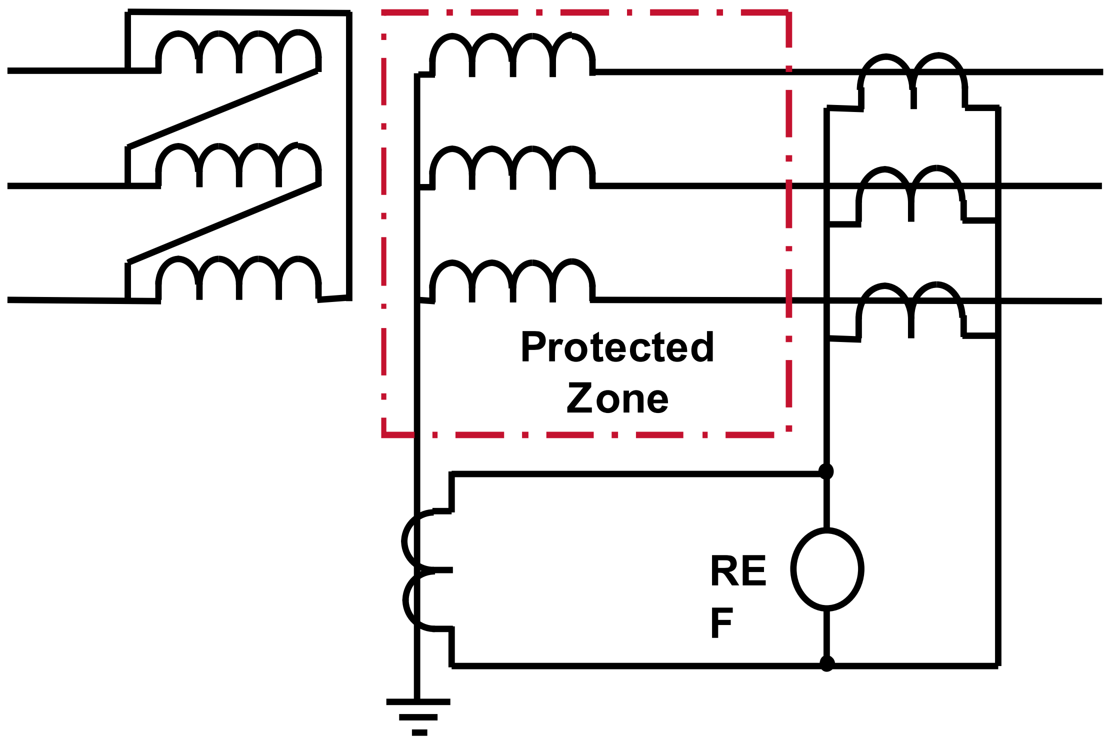
- **Provides back-up protection for system**
- **Time delay required for co-ordination**

Unrestricted Earthfault Protection (2)



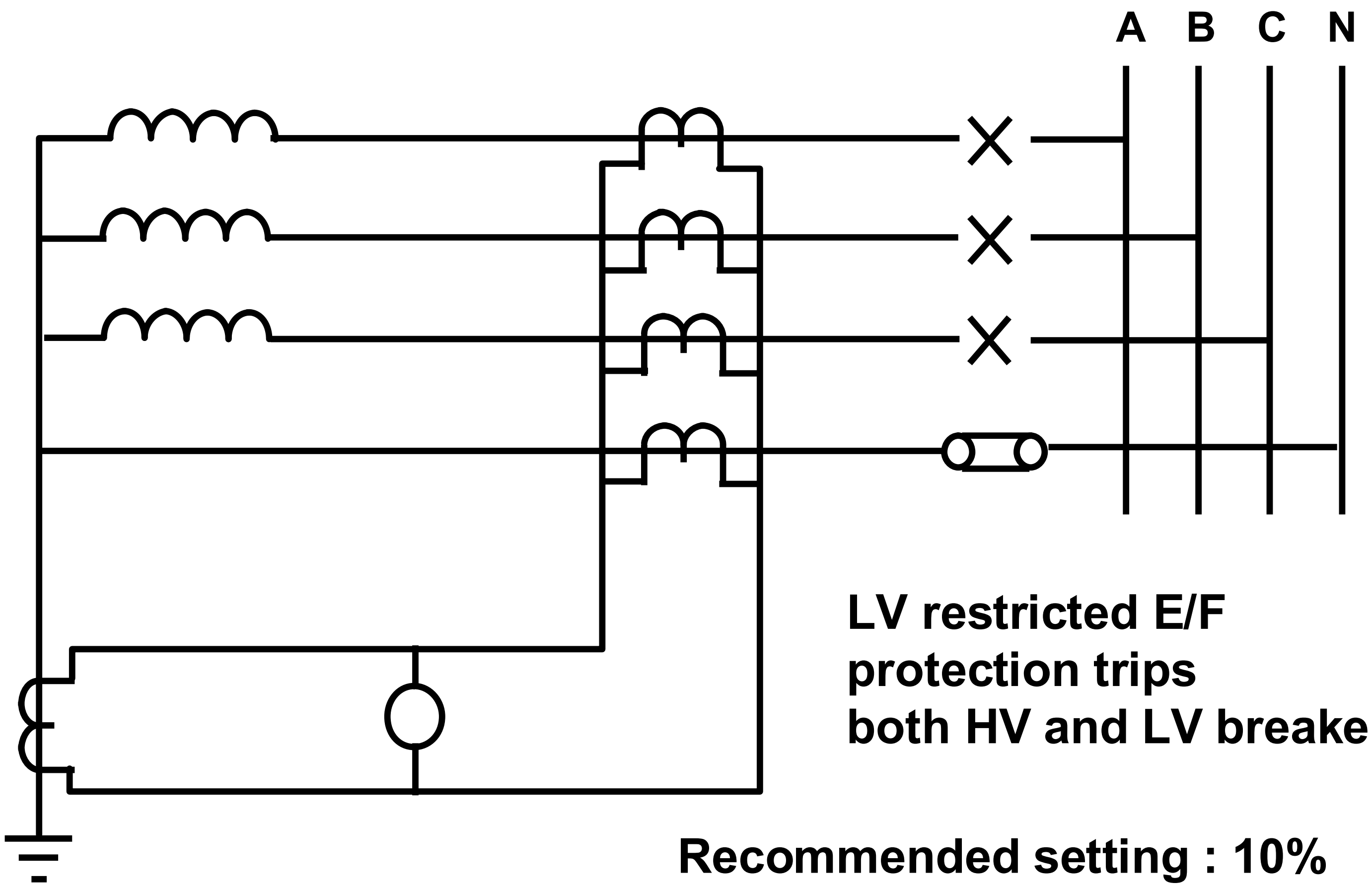
- **Can provide better sensitivity**
  (C.T. ratio not related to full load current)
  (Improved “effective” setting)
- **Provides back up protection for transformer and system**

Star Winding REF



- Relay only operates for earthfaults within protected zone.
- Uses high impedance principle.
- Stability level : usually maximum through fault level of transformer

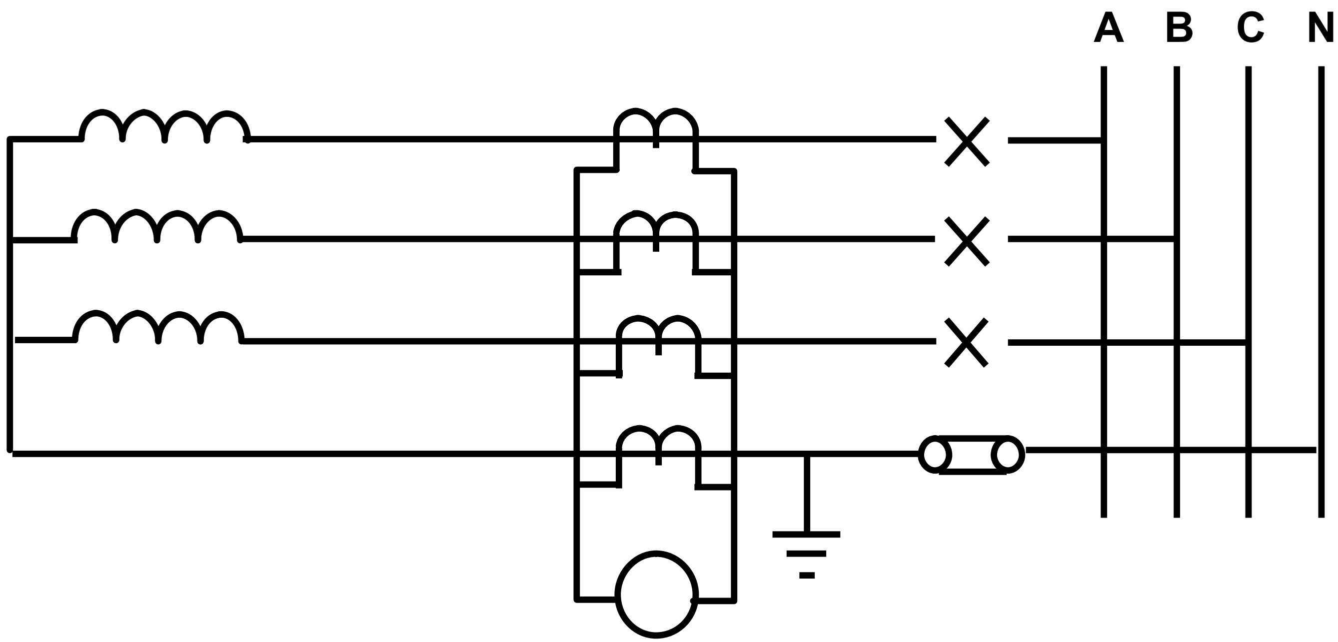
Restricted E/F Protection
Low Voltage Windings (1)



LV restricted E/F protection trips both HV and LV breaker

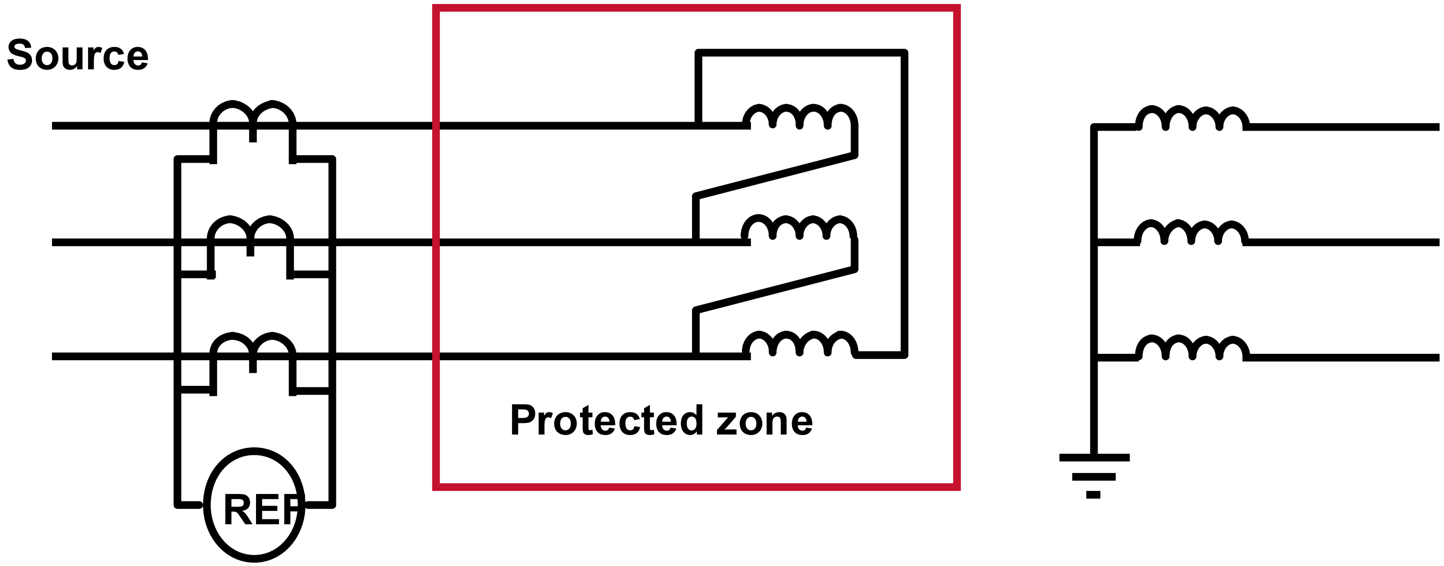
Recommended setting : 10% rated

Restricted E/F Protection
Low Voltage Windings (2)

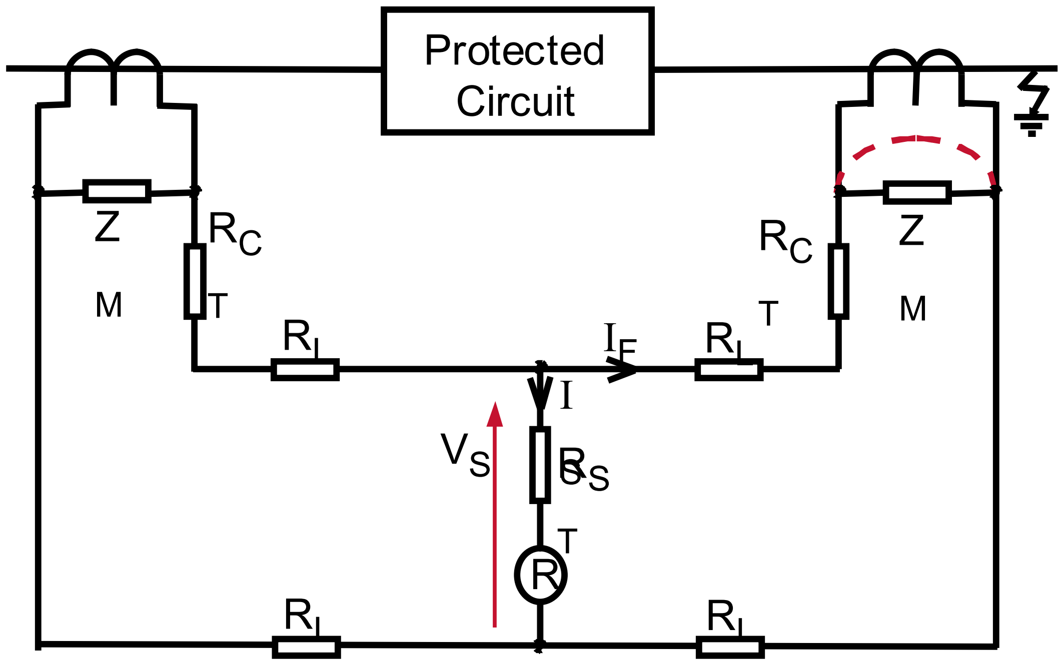


LV restricted E/F protection trips both HV and LV breaker
Recommended setting : 10% rated

Delta Winding Restricted Earth Fault



- Delta winding cannot supply zero sequence current to system
- Stability : Consider max LV fault level
- Recommended setting : less than 30% minimum earth fault level



Voltage Across Relay Circuit $V_S = I_F\,(R_{CT} + 2R_L)$

Stabilising resistor R_{ST} limits spill current to I_S (relay setting)

$$\therefore\ R_{ST} = \frac{V_S}{I_S} - R_R$$

where R_R = relay burden

CT knee point

$$V_{KP} = 2V_S = 2I_F\,(R_{CT} + 2R_L)$$

Non-Linear Resistors (Metrosils)

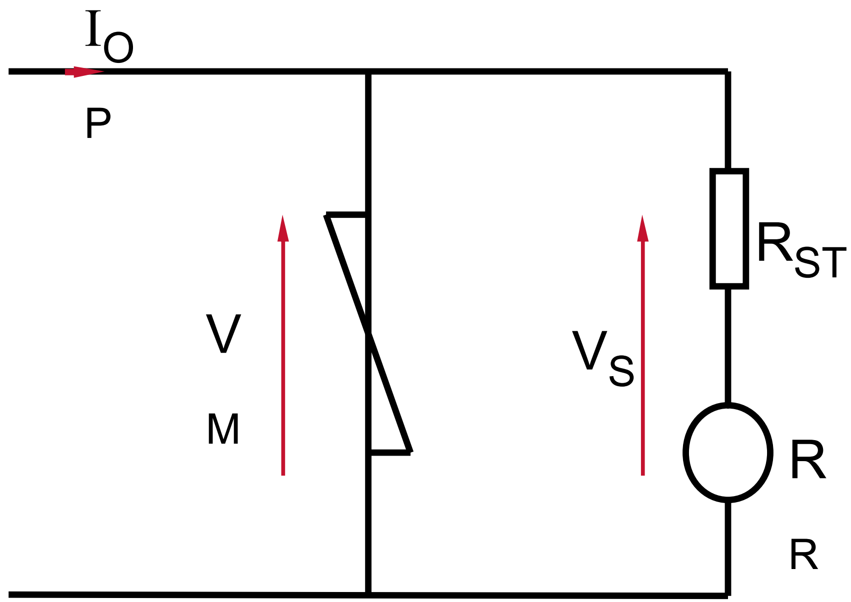
- During internal faults the high impedance relay circuit constitutes an excessive burden to the CT's.
- A very high voltage develops across the relay circuit and the CT's.
  - Causes damage to insulation of CT, secondary winding and relay.
- Magnitude of peak voltage V_P is given by an approximate formula (based on experimental results)

$$V_P = 2\sqrt{2V_K(V_F - V_K)}$$

Where $V_F = \dfrac{\text{Swgr. Fault Rating in amps}}{\text{CT ratio}} \times$ Z of relay circuit @ setting

- Metrosil required if $V_P > 3\text{kV}$

Non-Linear Resistors (Metrosils)

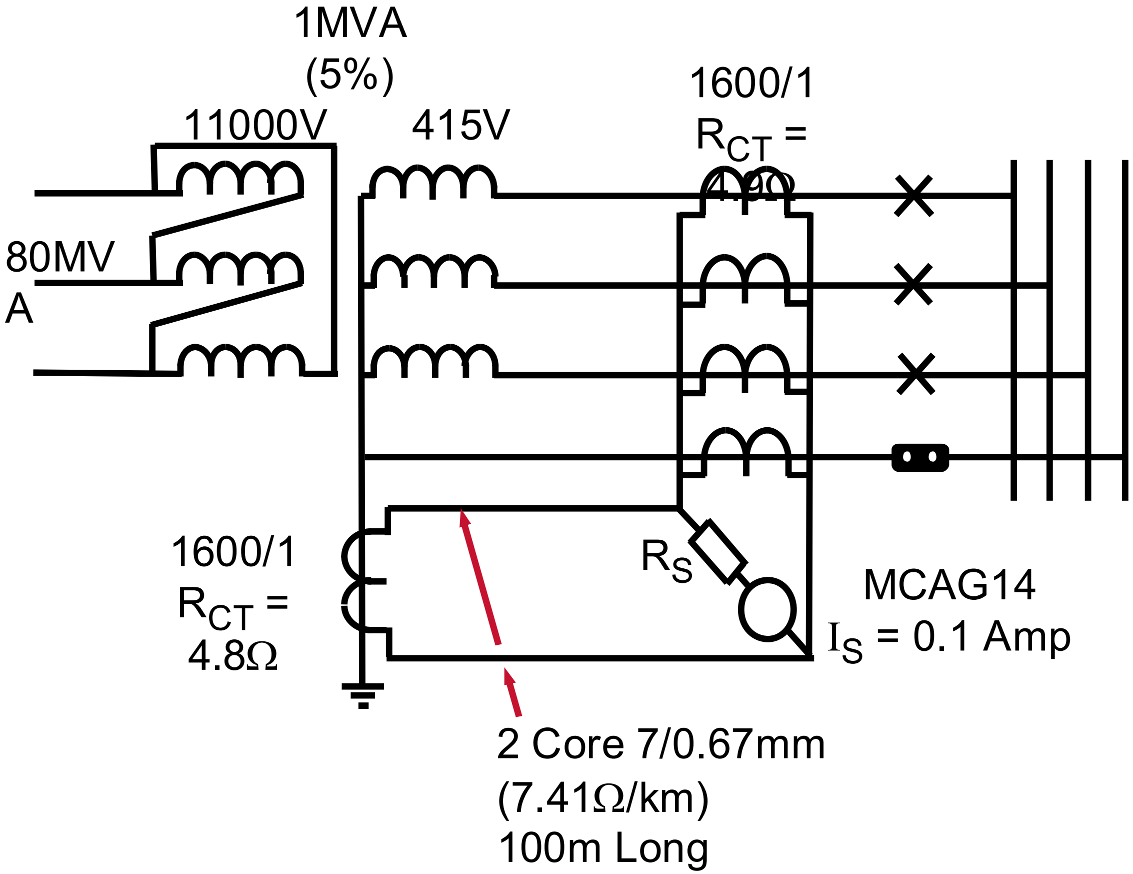


Metrosil Characteristic

$$V = C\,I^{\beta}$$

- **Suitable values of C & β chosen based on :**
  - **Max secondary current under fault conditions**
  - **Relay setting voltage**

REF Protection Example



Calculate :

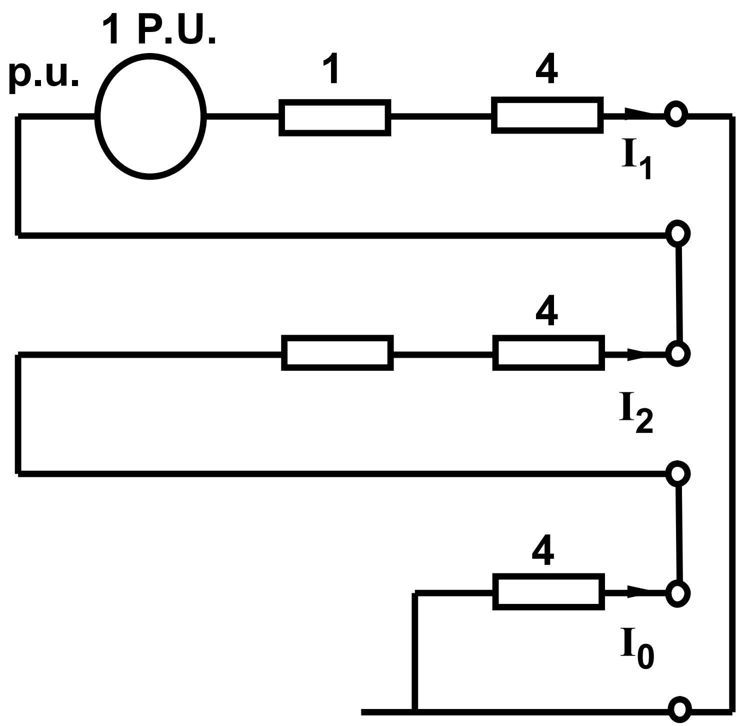
1) **Setting voltage (V_S)**
2) **Value of stabilising resistor required**
3) **Effective setting**
4) **Peak voltage developed by CT's for internal fault**

Earth fault calculation :-

Using 80MVA base

Source impedance = 1 p.u.

Transformer impedance $= 0.05 \times \frac{80}{1} = 4$ **p.u.**



Sequence Diagram

Total impedance = 14

$\therefore I_1 = \frac{1}{14} = 0.0714$ **p.u.**

Base current $= \frac{80 \times 10^6}{\sqrt{3} \times 415}$

$= 111296$ **Amps**

$\therefore I_F = 3 \times 0.0714 \times 111296$

$= 23840$ **Amps (primary)**

$= 14.9$ **Amps (secondary)**

(1) Setting voltage

$V_S = I_F (R_{CT} + 2_{RL})$

Assuming "earth" CT saturates,

$R_{CT} = 4.8$ ohms

$2_{RL} = 2 \times 100 \times 7.41 \times 10^{-3} = 1.482$ ohms

$\therefore$ Setting voltage $= 14.9 (4.8 + 1.482)$

$= \underline{\underline{93.6 \text{ Volts}}}$

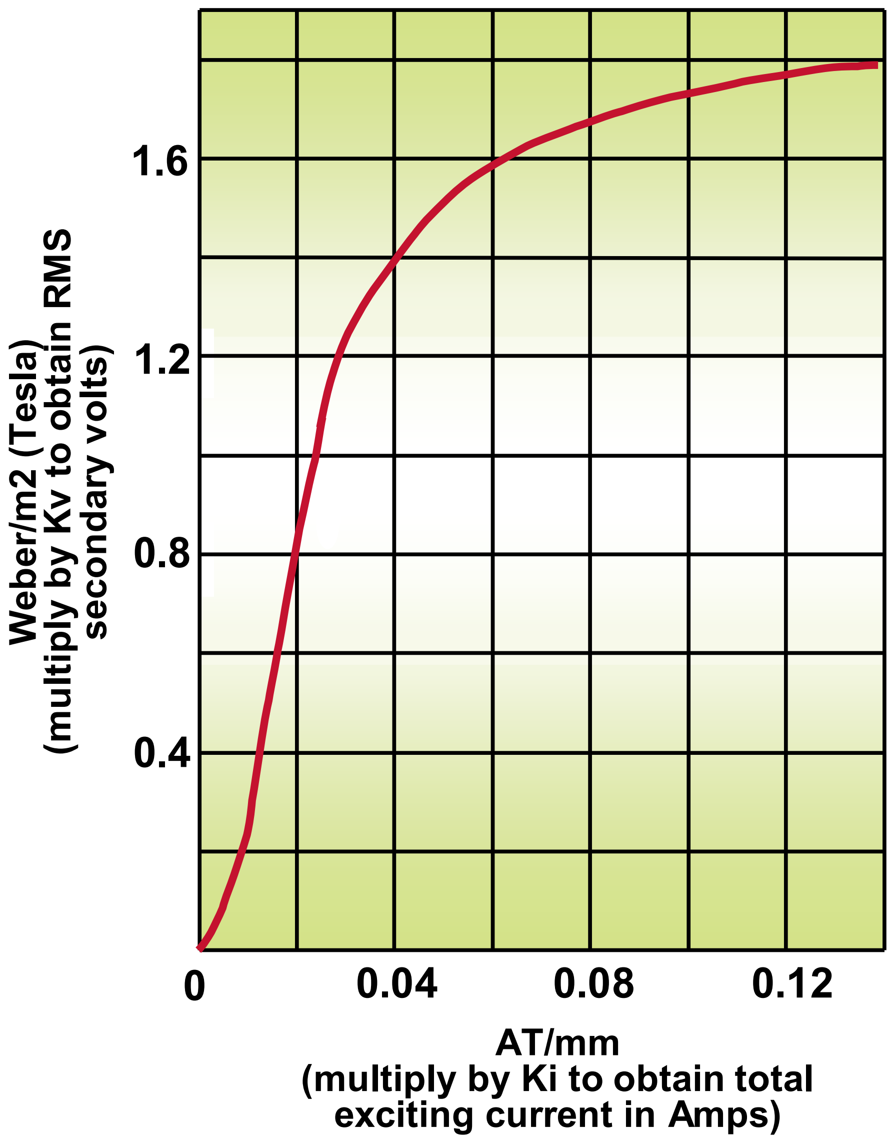
(2) Stabilising Resistor (R_S)

$$R_S = \frac{V_S}{I_S} - \frac{1}{I_S^2}$$

Where I_S = relay current setting

$$\therefore R_S = \frac{93.6}{0.1} - \frac{1}{0.1^2} = 836 \text{ ohms}$$

Solution (3)



	Kv	Ki
Line & Neutral CT	158	0.341
Earth CT	236	0.275

(3) **Effective setting I_P = CT ratio x ($I_S + \sum I_{MAG}$)**

Line & Neutral CTs

Flux density at 93.6V $= \frac{93.6}{158} = 0.592$ Tesla

From graph, mag. Force at 0.592 Tesla = 0.015 AT/mm

$\therefore$ Mag. Current = 0.015 x 0.341 = 0.0051 Amps

'Earth' CT

Flux density at 93.6V $= \frac{93.6}{236} = 0.396$ Tesla

From graph, mag. Force at 0.396 Tesla = 0.012 AT/mm

$\therefore$ Mag. Current = 0.012 x 0.275 = 0.0033 Amps

Thus, effective setting = 1600 x (0.1 + [(4 x 0.0051) + 0.0033])

Effective setting = 198 Amps

Transformer full load current = 1391 Amps

$\therefore$ Effective setting $= \frac{198}{1391} \times 100\% = 14.2\%$ x rated

Solution (5)

(4) Peak voltage $= 2\sqrt{2V_K(V_F - V_K)}$

$V_F = 14.9 \times \frac{V_S}{I_S} = 14.9 \times 936 = 13946$ Volts

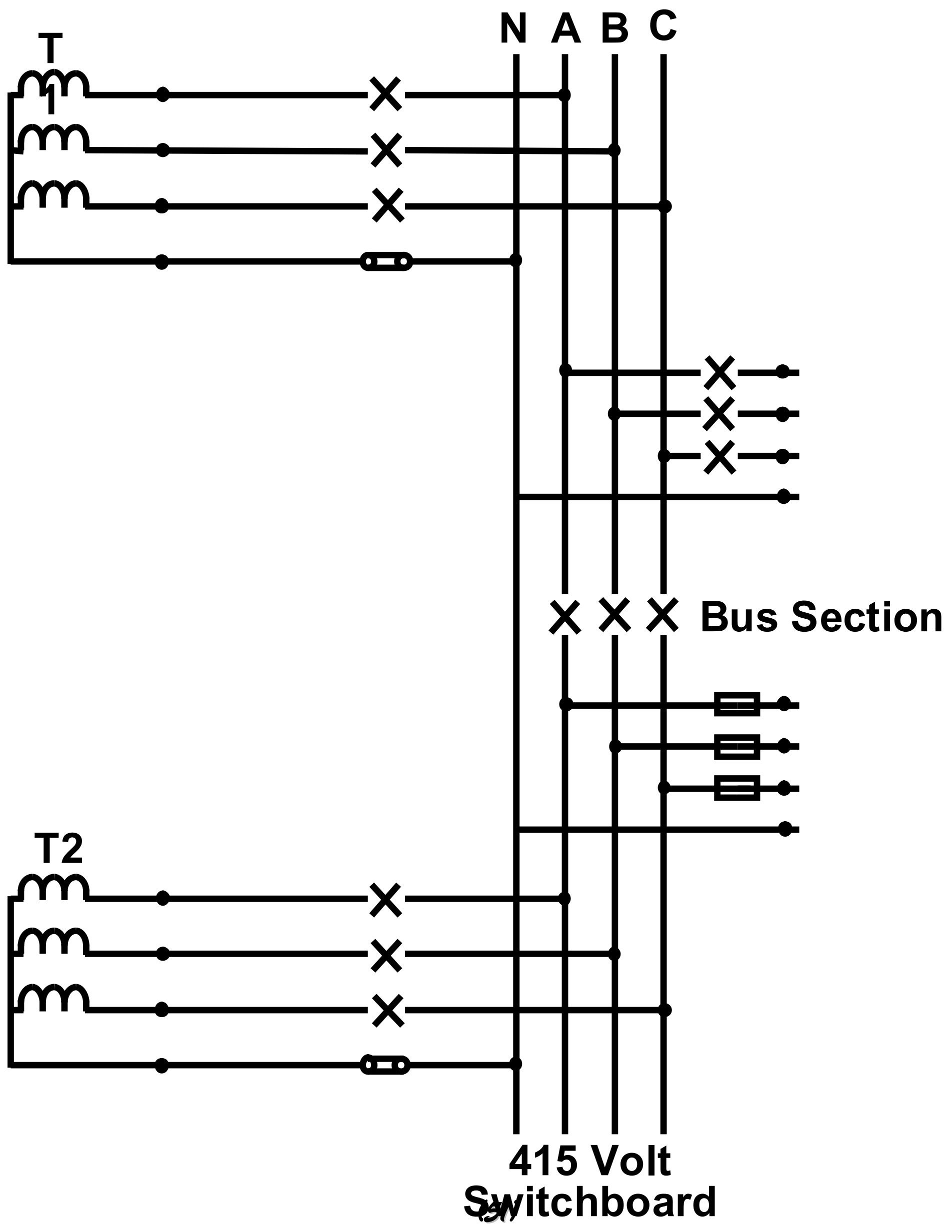
For 'Earth' CT, $V_K = 1.4 \times 236 = 330$ Volts (from graph)

$\therefore\ V_{PEAK} = 2\sqrt{2 \times 330 \times (13946 - 330)}$

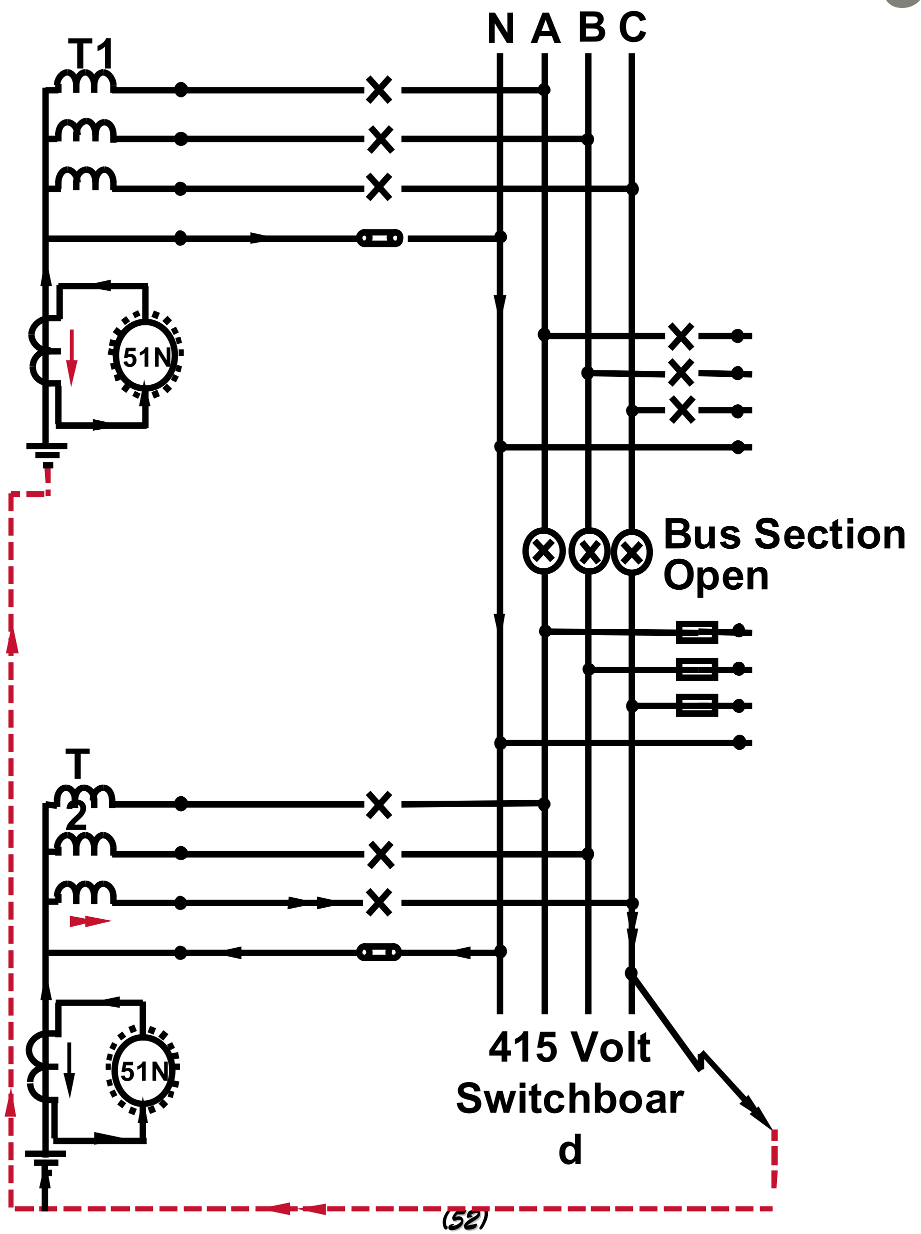
$= 6kV$

Thus, Metrosil voltage limiter will be required.

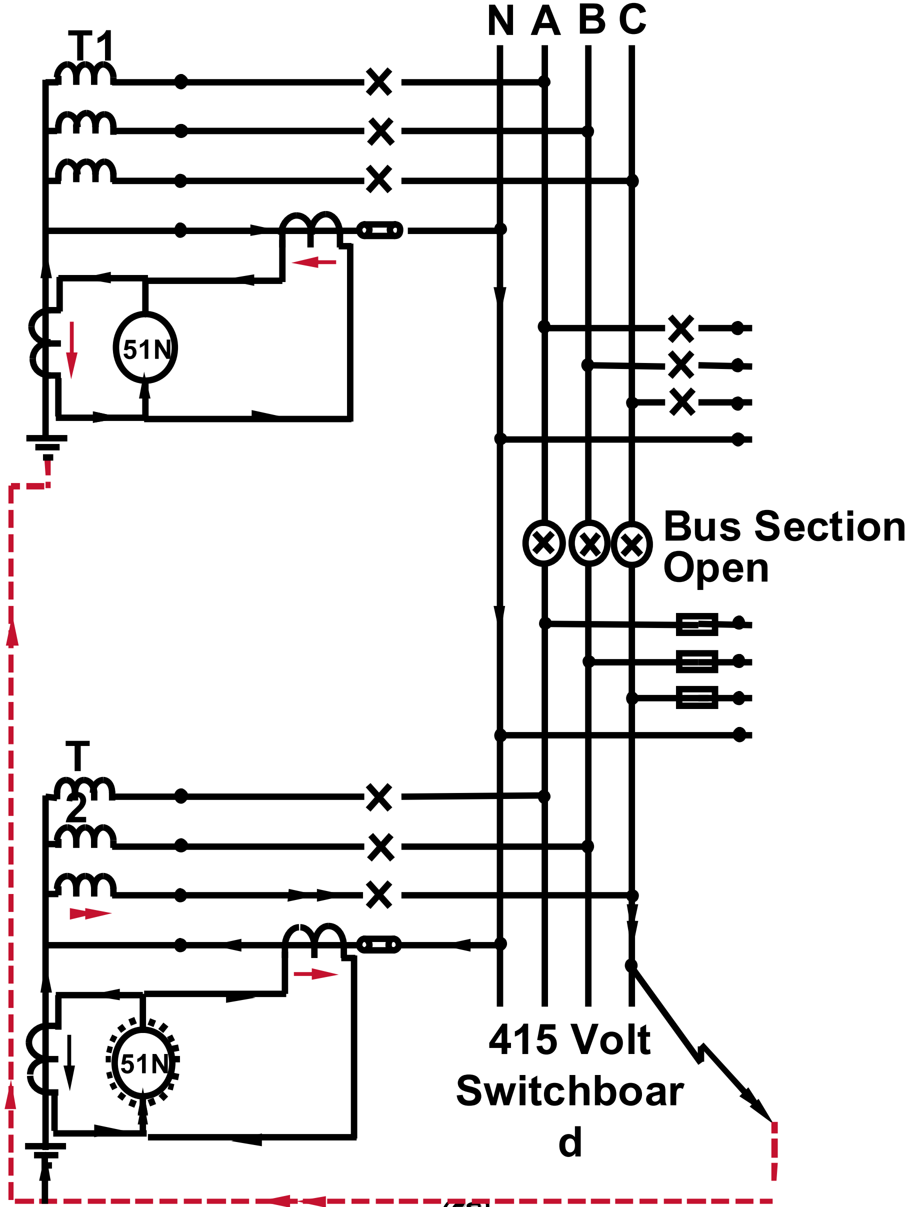
Parallel Transformers



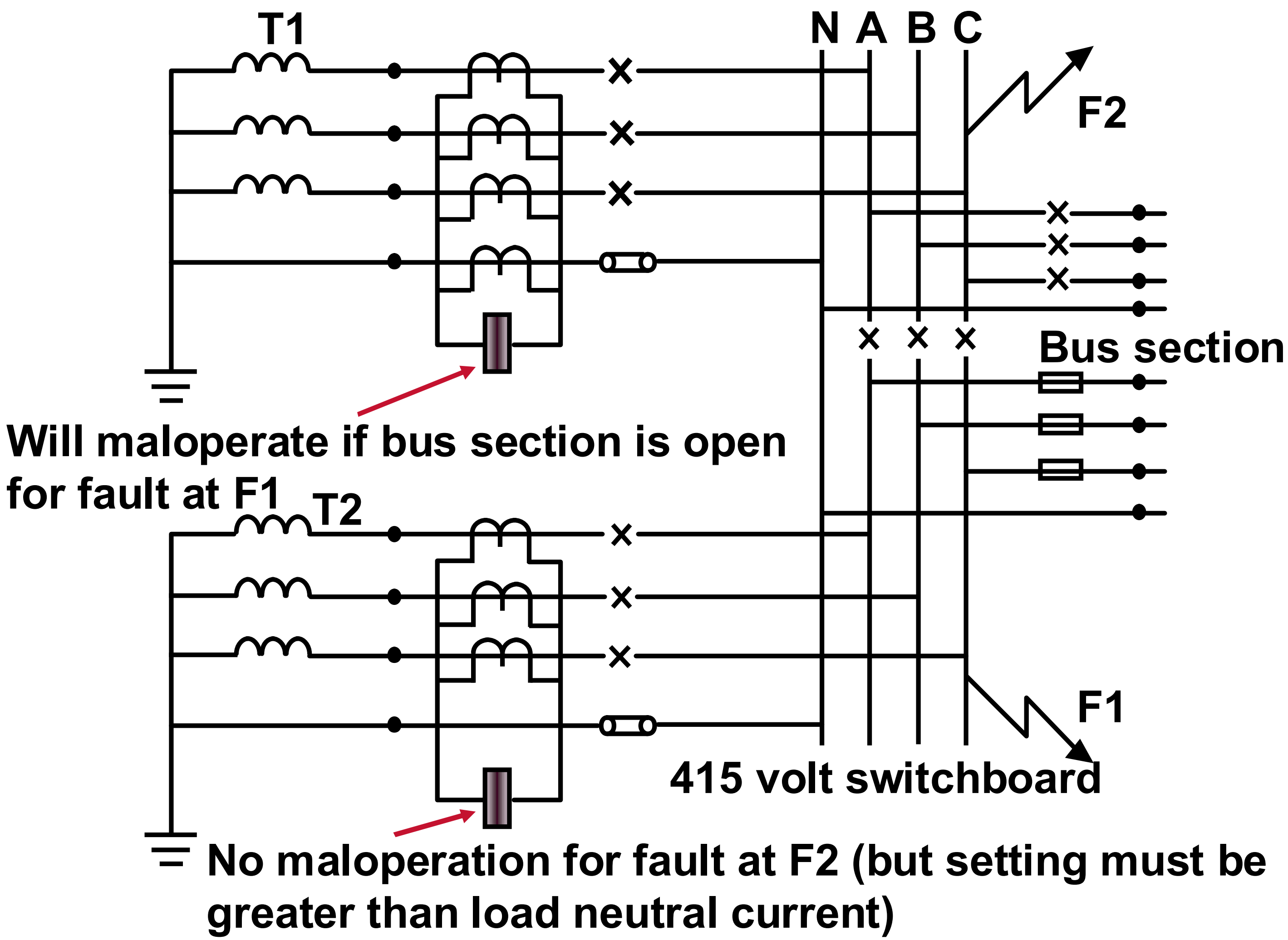
Parallel Transformers
CT in Earth



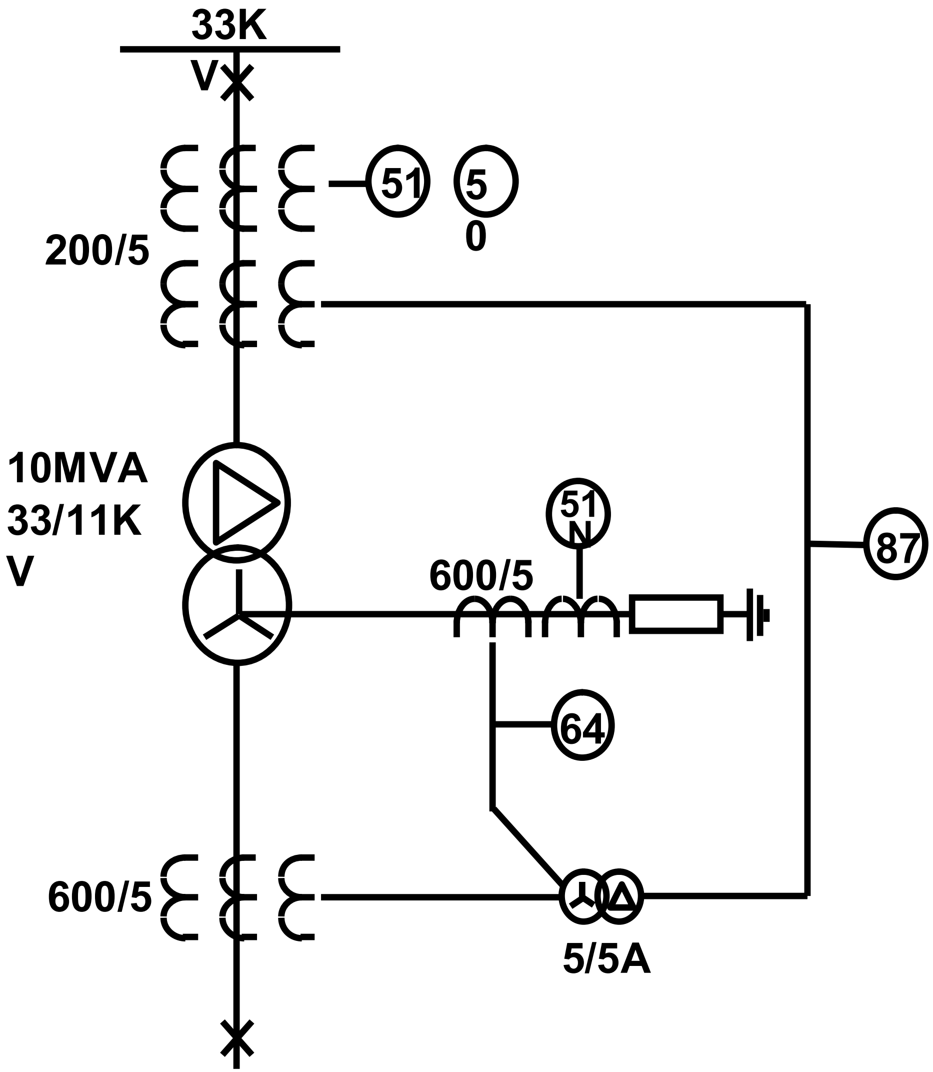
Parallel Transformers CT in Earth and Neutral



Parallel Transformers
Residual Connections



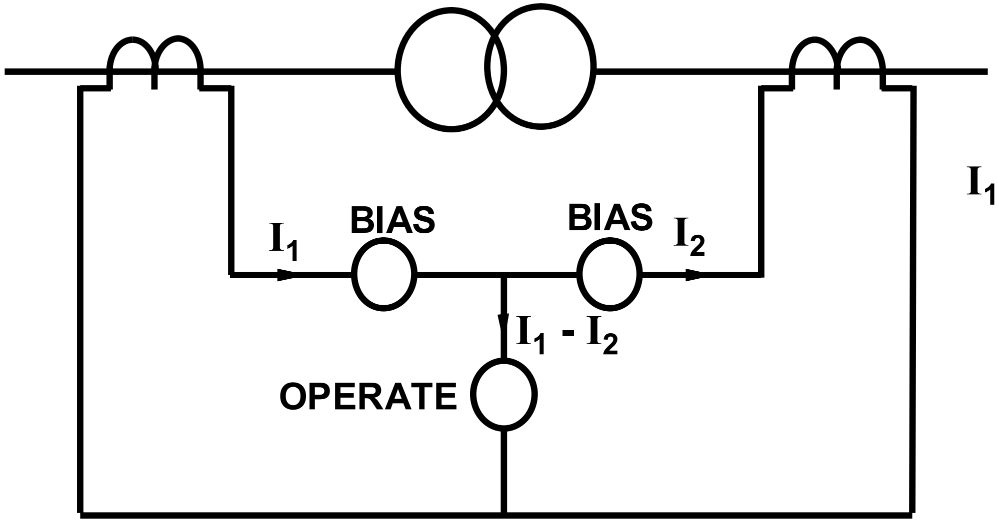
Traditional Large Transformer Protection Package

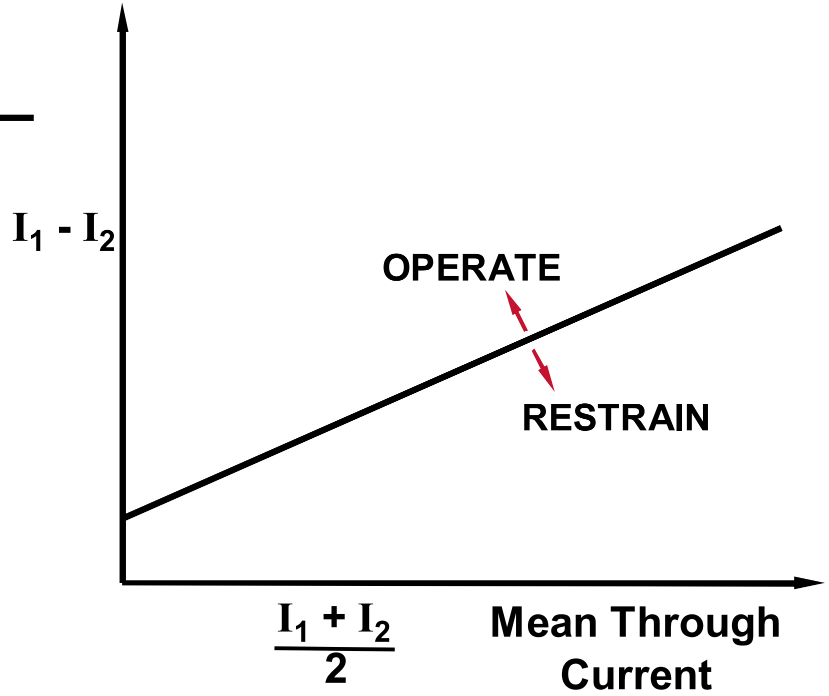


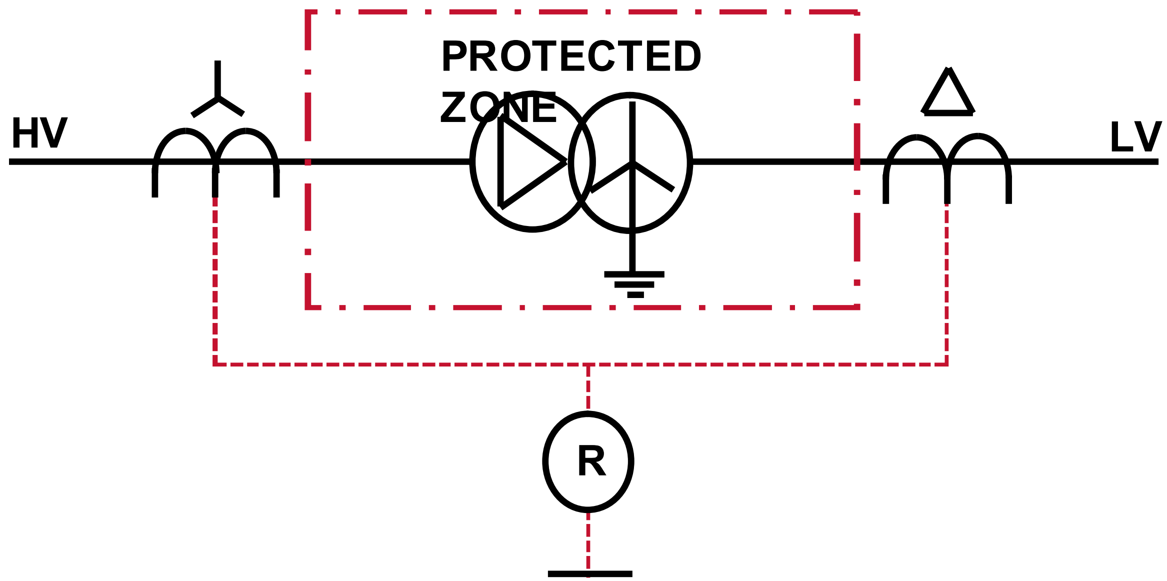
Differential Protection

- Overall differential protection may be justified for larger transformers (generally > 5MVA).
  - Provides fast operation on any winding
- Measuring principle :
  - Based on the same circulating current principle as the restricted earth fault protection
  - However, it employs the biasing technique, to maintain stability for heavy through fault current
- Biasing allows mismatch between CT outputs.
- It is essential for transformers with tap changing facility.
- Another important requirement of transformer differential protection is immunity to magnetising in rush current.

Biased Differential Scheme







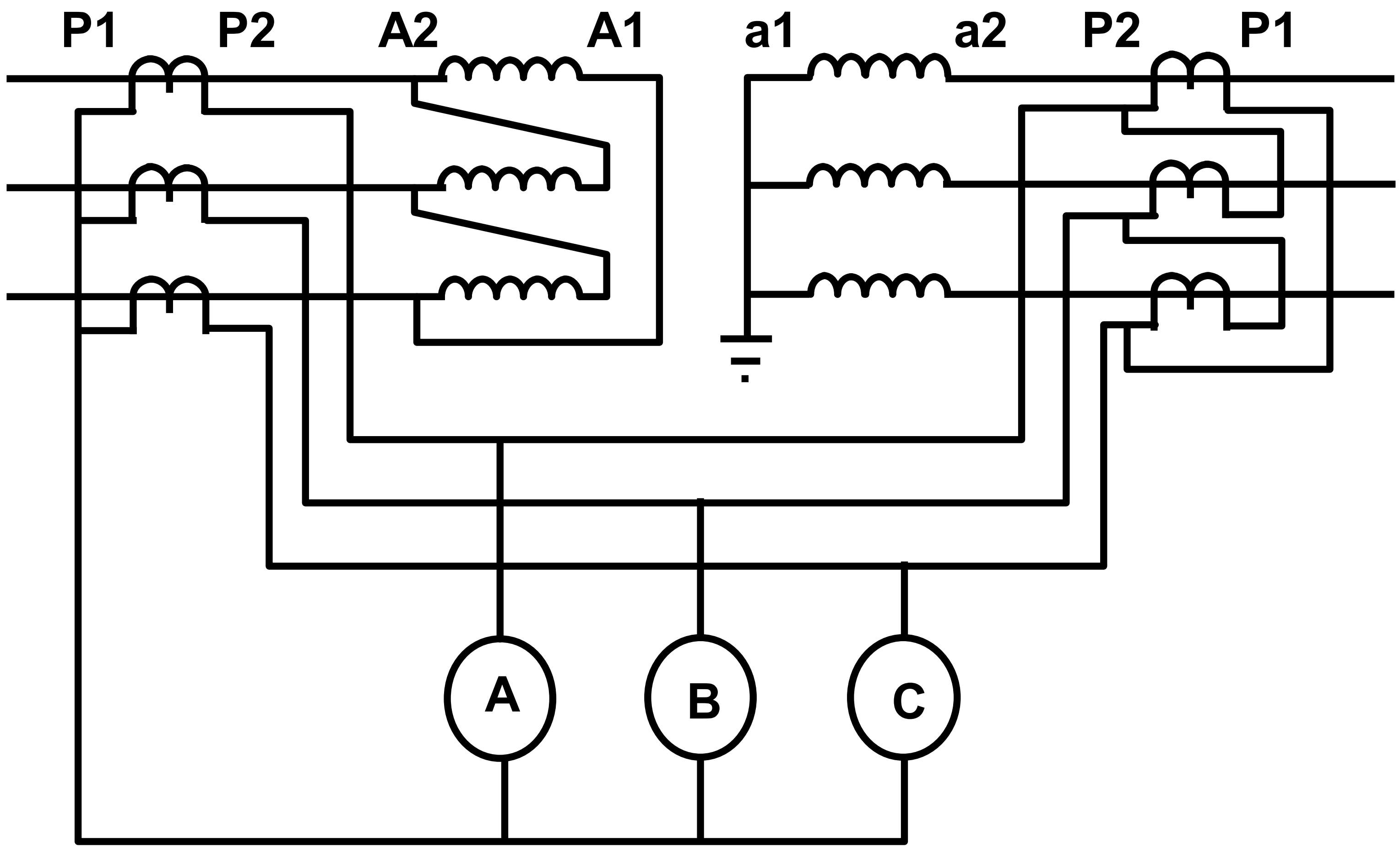
Correct application of differential protection requires CT ratio and winding connections to match those of transformer.

CT secondary circuit should be a "replica" of primary system.

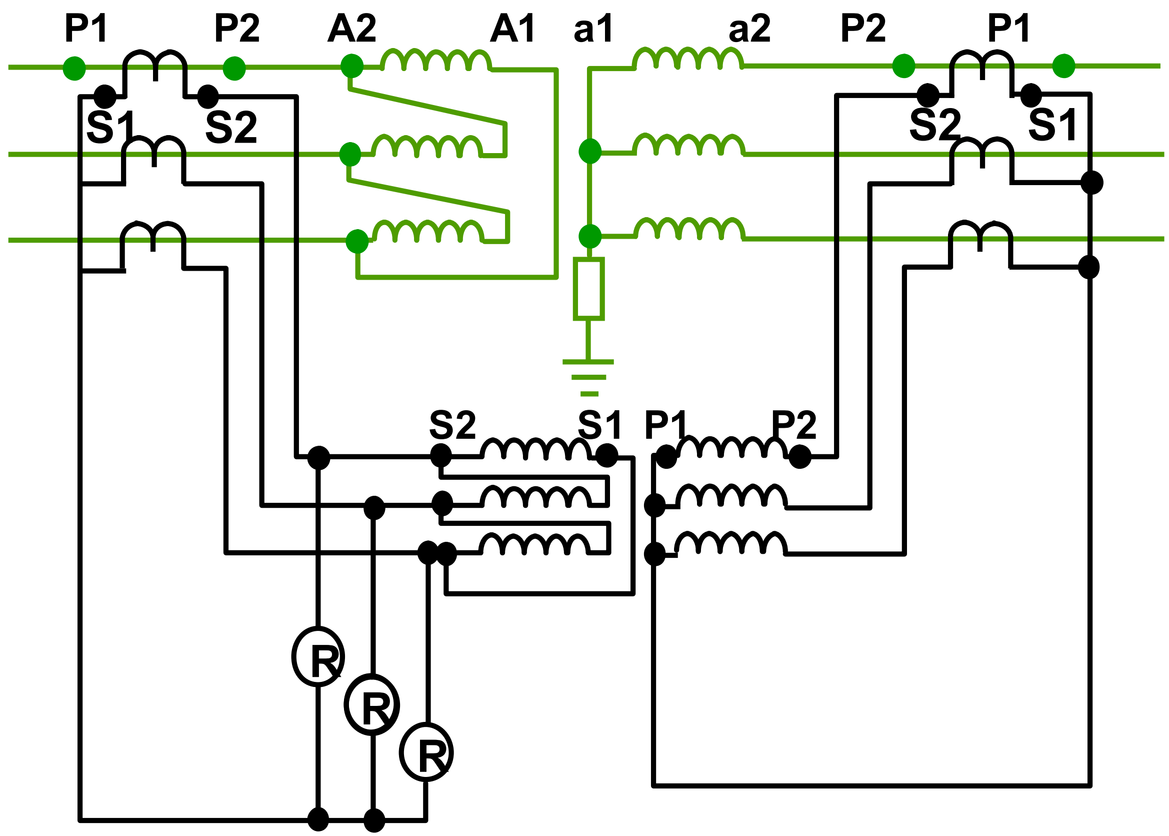
Consider :

- **(1) Difference in current magnitude**
- **(2) Phase shift**
- **(3) Zero sequence currents**

Differential Connections

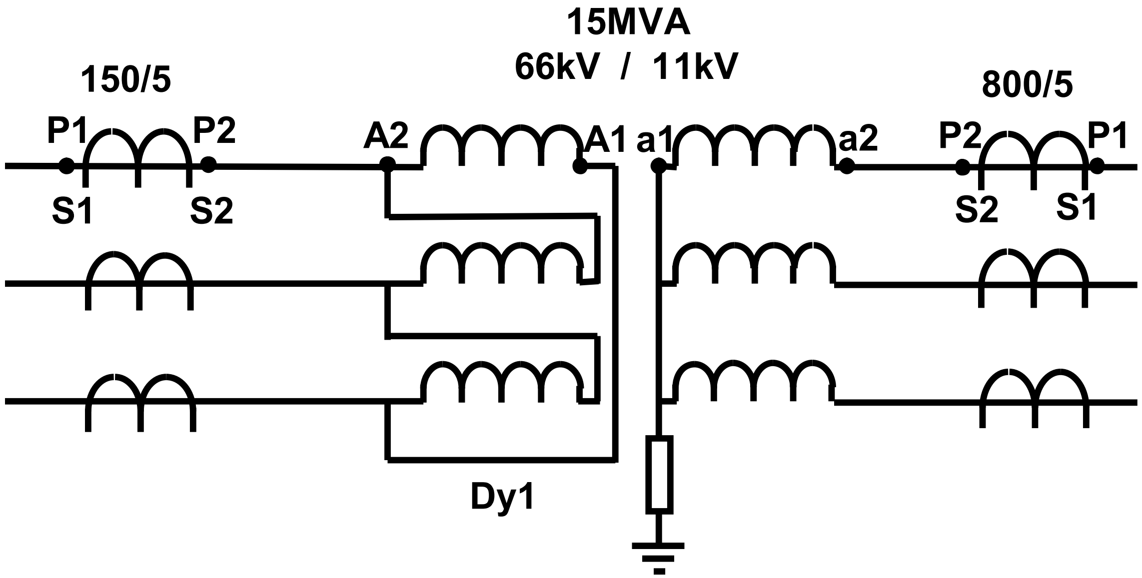


Use of Interposing CT



Interposing CT provides :

- Vector correction
- Ratio correction
- Zero sequence compensation



Given above: Need to consider -

(1) Winding full load current

(2) Effect of tap changer (if any)

(3) C.T. polarities

Assuming no tap changer

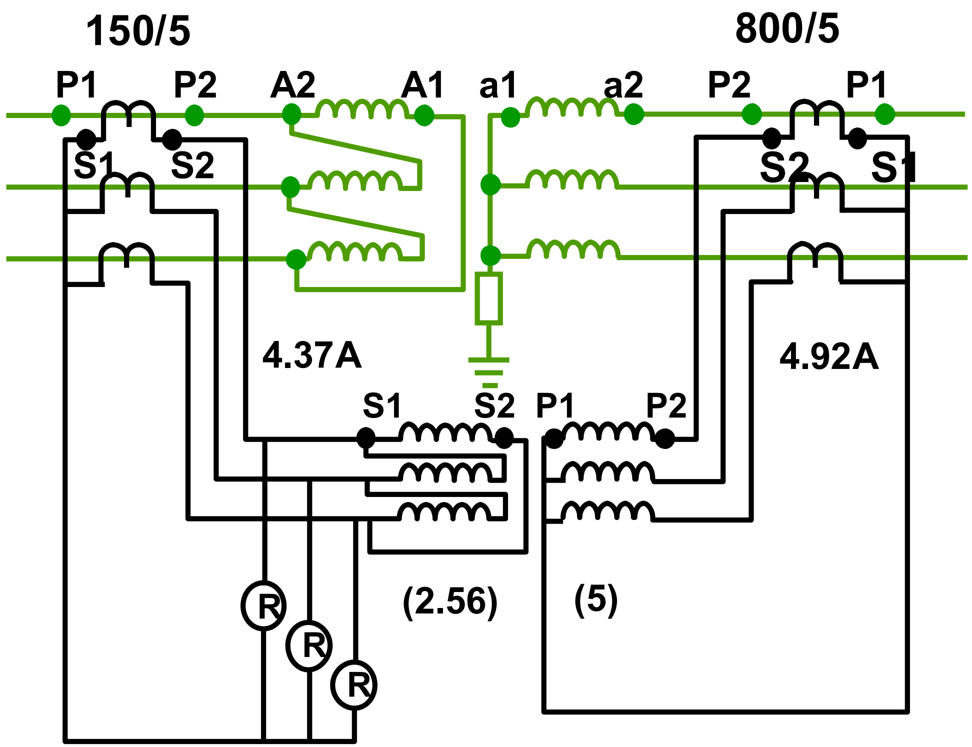
Full load currents:- 66kV: 131 Amp = 4.37 Amps secondary

11kV: 787 Amp = 4.92 Amps secondary

However, require 11kV C.T.'s to be connected in Δ

Thus, secondary current = √3 x 4.92 = 8.52A

∴ RATIO CORRECTION IS REQUIRED



It is usual to connect 11kV C.T.'s in ⅄ and utilise a ⅄ /Δ interposing C.T.
(this method reduces lead VA burden on the line C.T.'s)

Current from 66kV side = 4.37 Amp

Thus, current required from Δ winding of int. C.T. = 4.37 Amp

Current input to ⅄ winding of int. C.T. = 4.92 Amp

$\therefore$ Required int C.T. ratio = $4.92 / \dfrac{4.37}{\sqrt{3}} = \underline{\underline{4.92 / 2.52}}$

May also be expressed as : 5 / 2.56

Effect of Tap Changer

e.g. Assume 66kV +5%, -15%

Interposing C.T. ratio should be based on mid tap position

Mid Tap (-5%) = 62.7 kV

Primary current (15 MVA) = 138 Amp

Secondary current = 4.6 Amp

$\therefore$ Interposing C.T. ratio required = 4.92 / $\frac{4.6}{\sqrt{3}}$

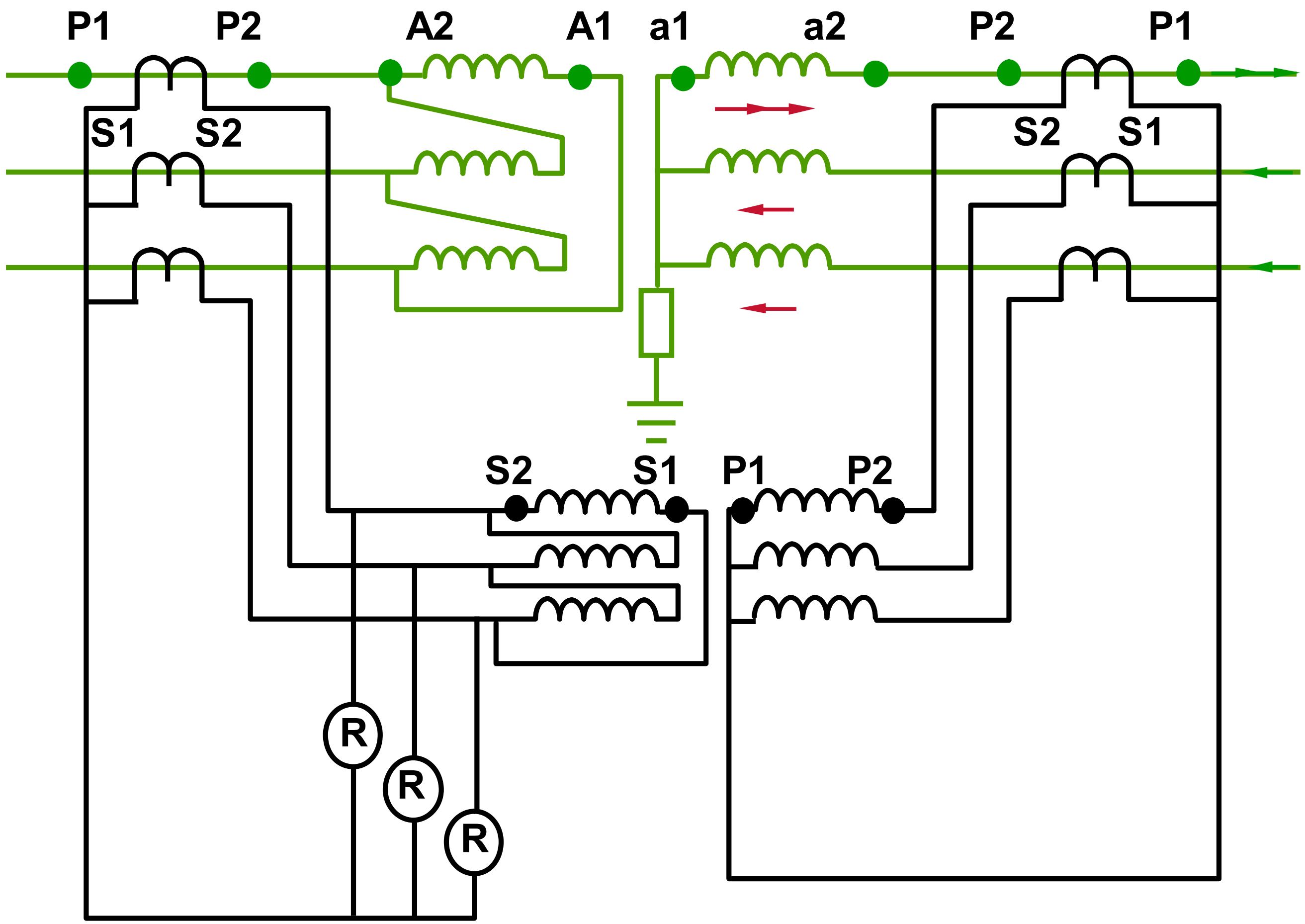
(Y / Δ)

= 4.92 / 2.66

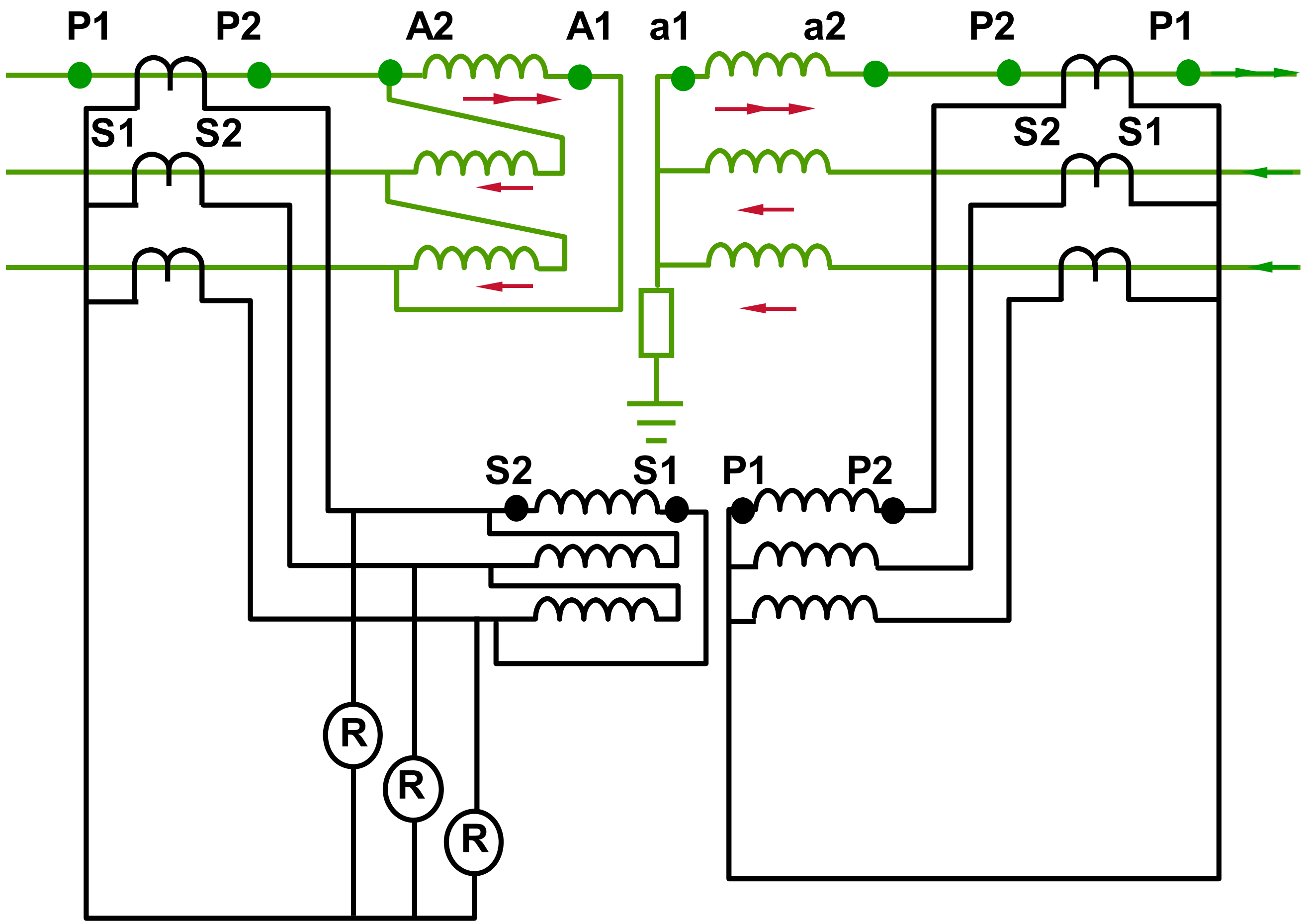
May also be expressed as : 5 / 2.7

Compared with 5 / 2.56 based on nominal voltage

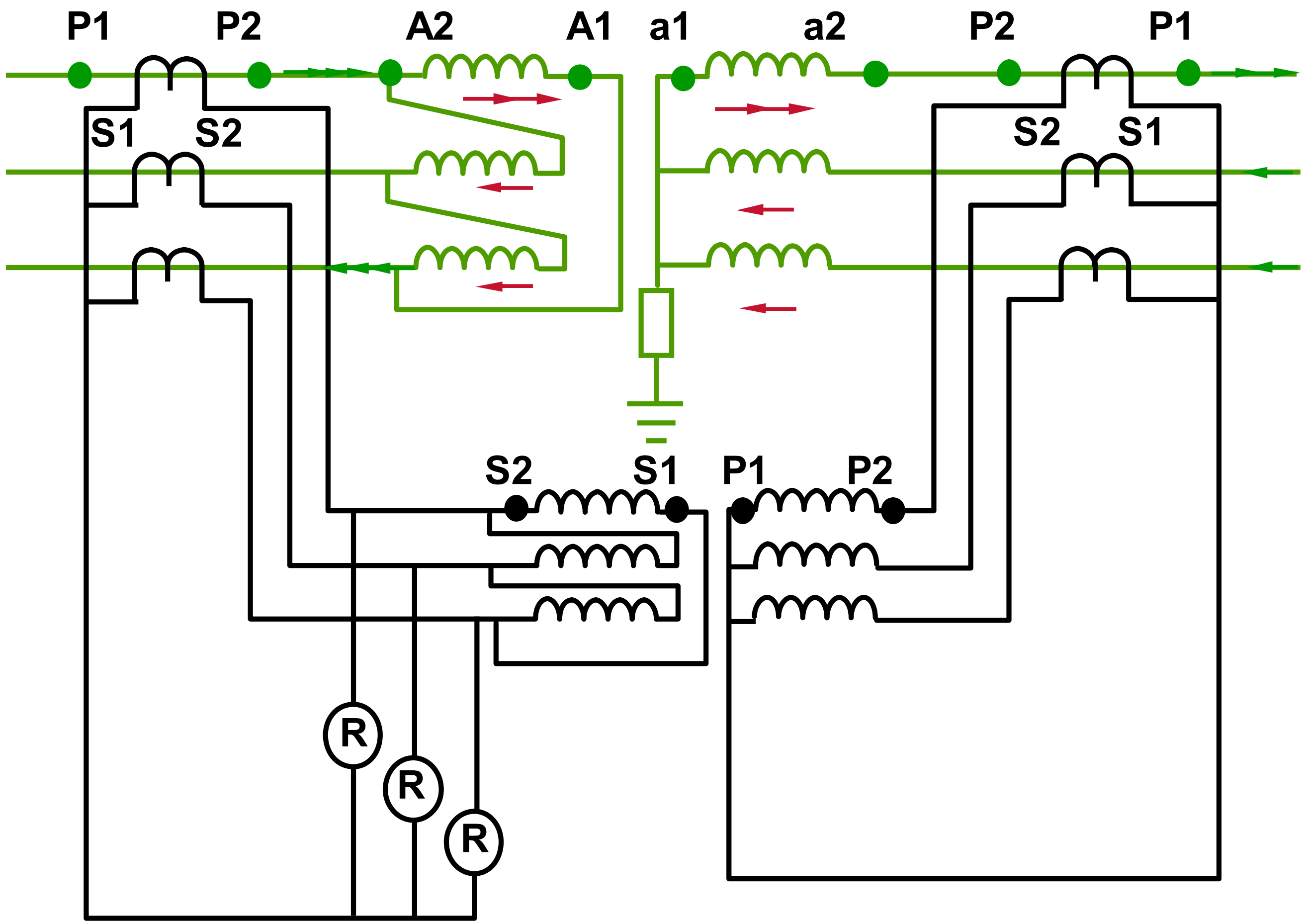
Connections Check
Arbitrary Current Distribution



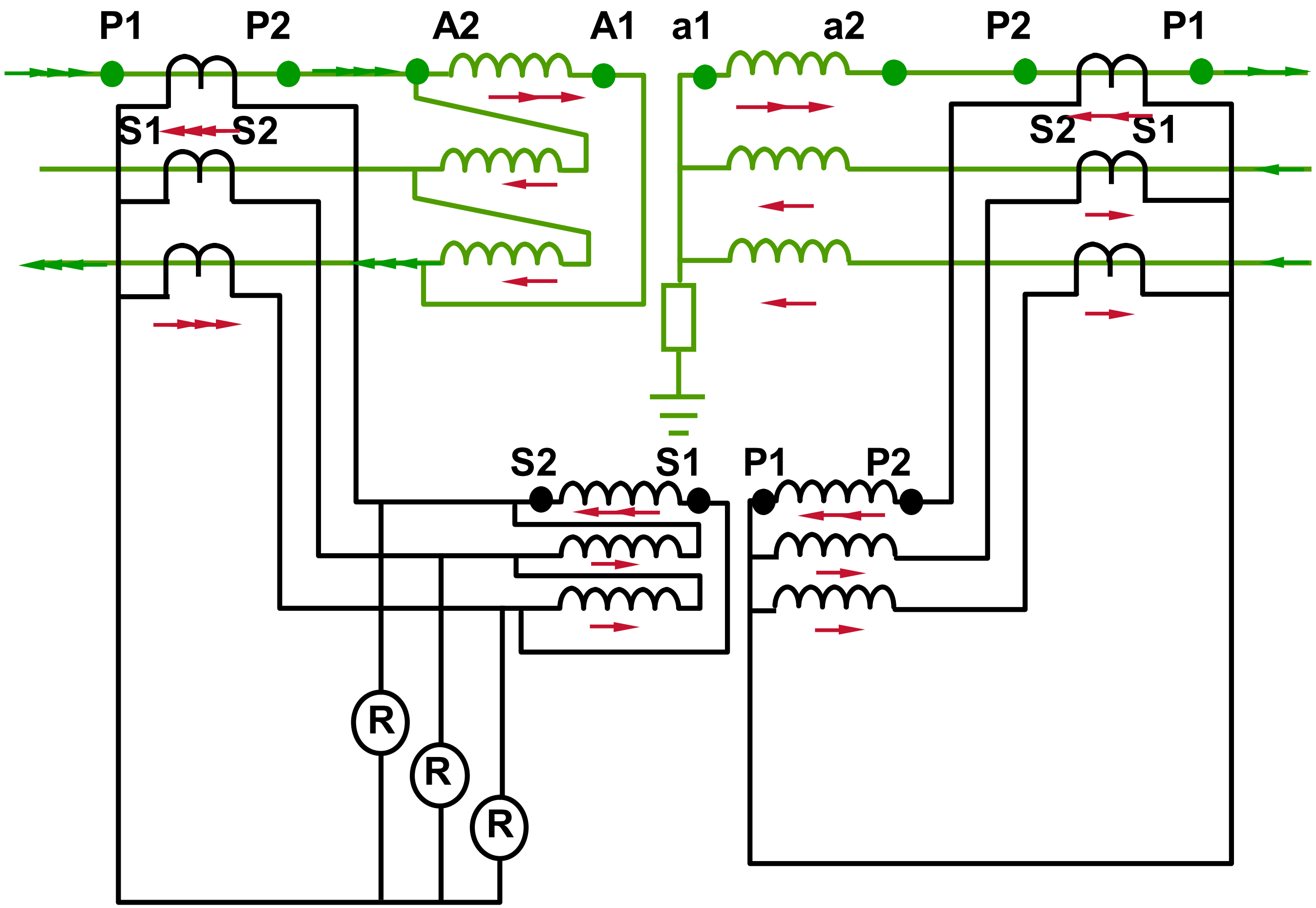
Connections Check
Add Delta Winding Current



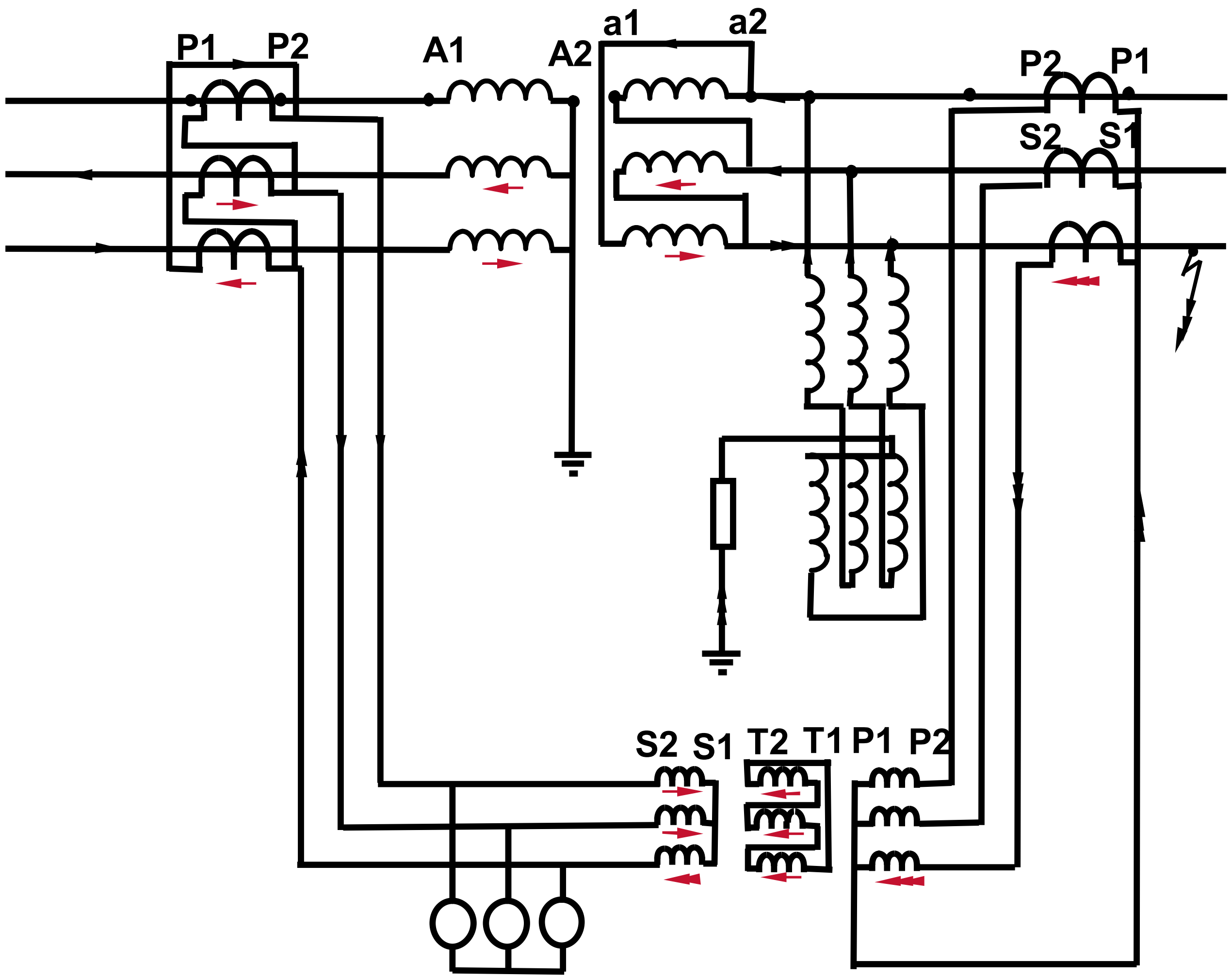
Connections Check
Complete Primary Distribution



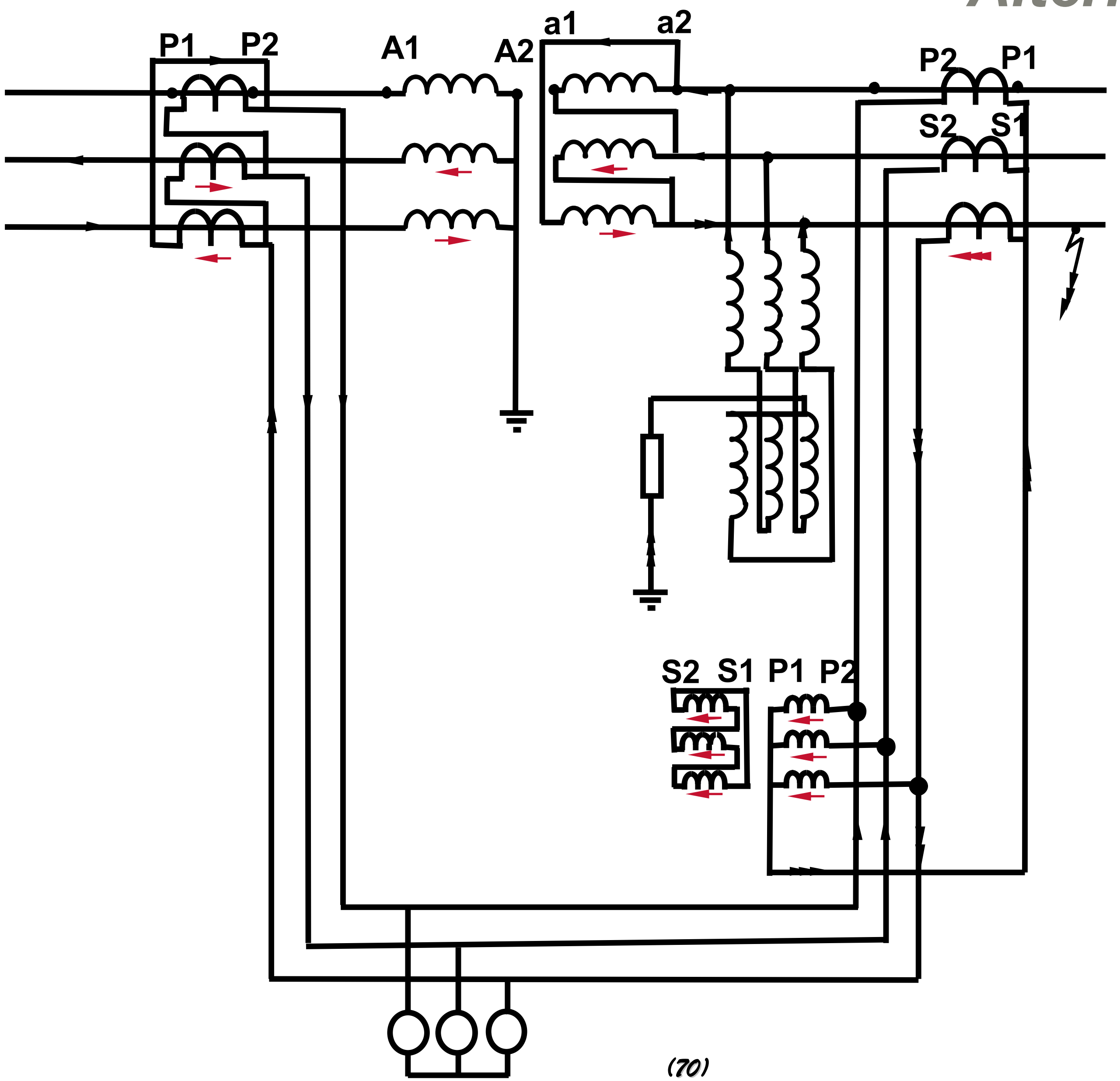
Connections Check
Complete Secondary Distribution



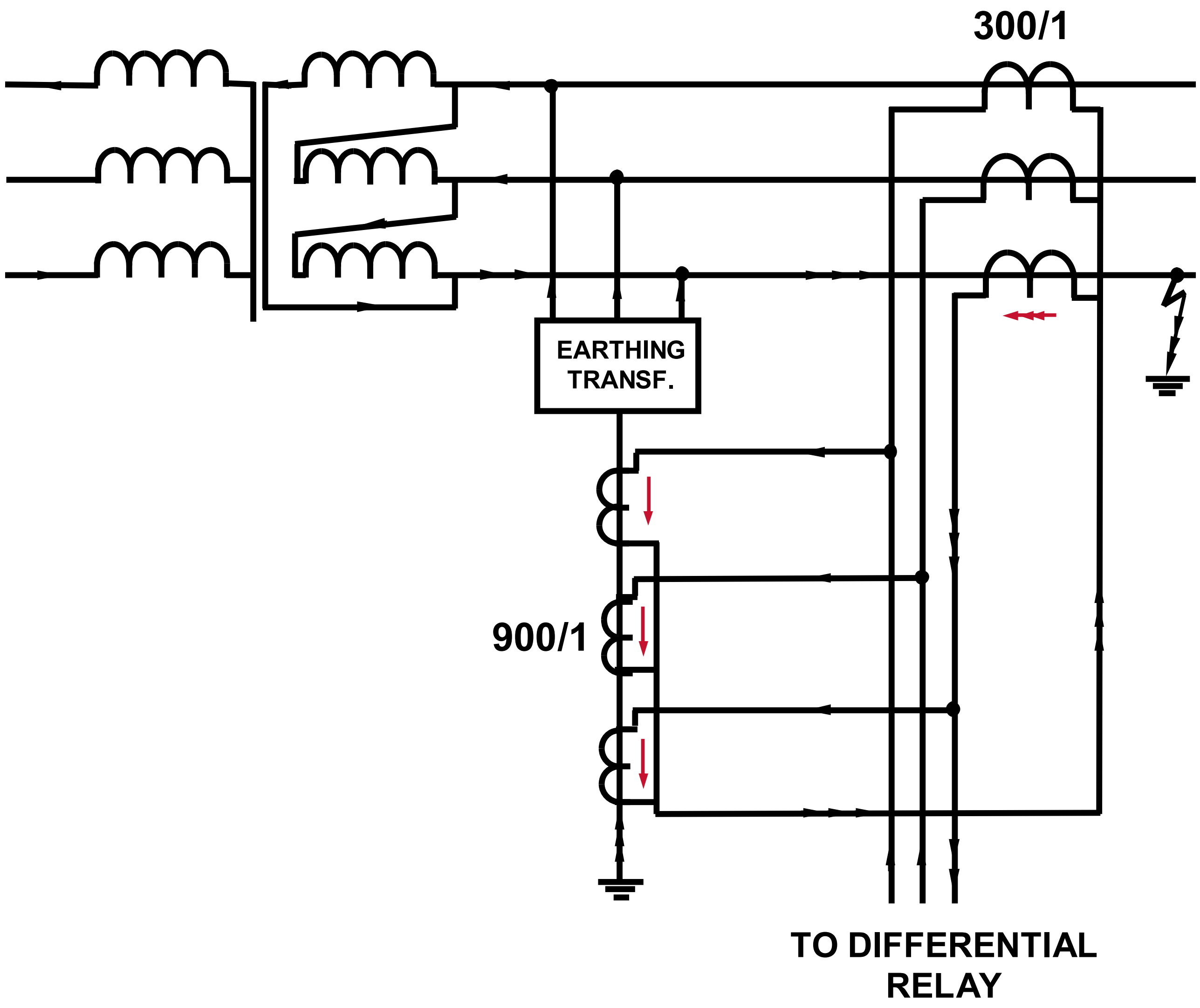
In-Zone Earthing Transformer



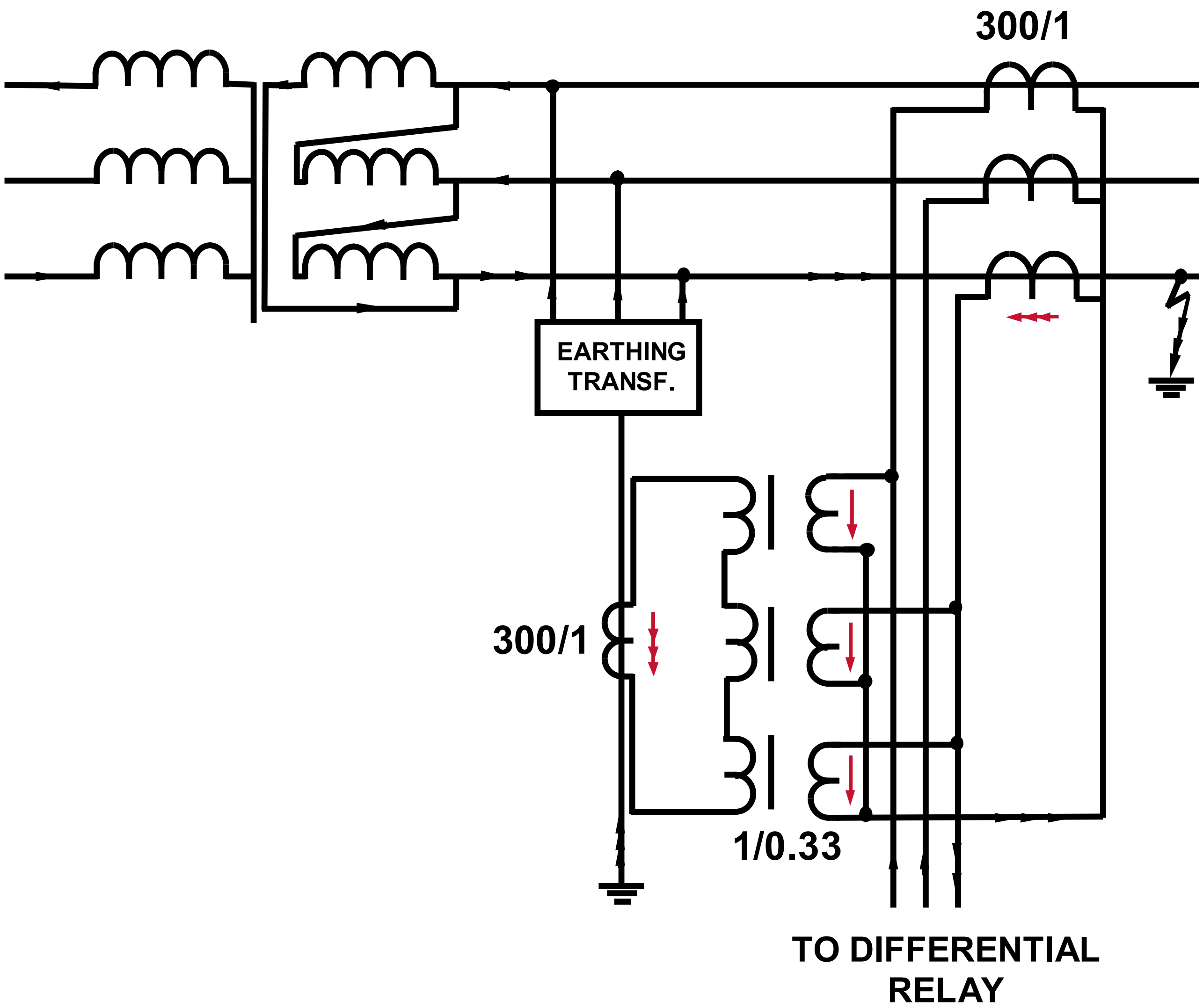
In-Zone Earthing Transformer Alternative (1)



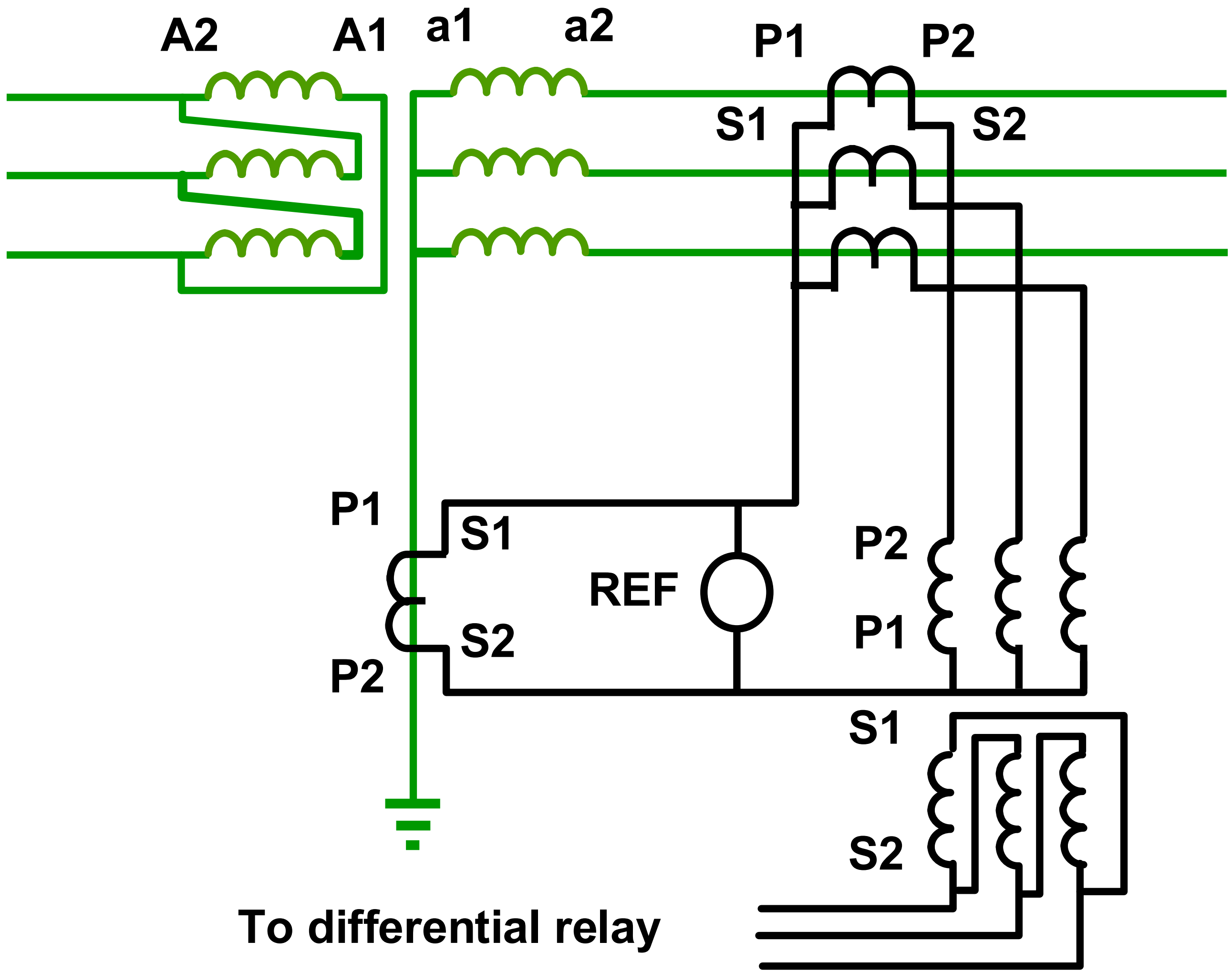
In-Zone Earthing Transformer Alternative (2)



In-Zone Earthing Transformer Alternative (3)

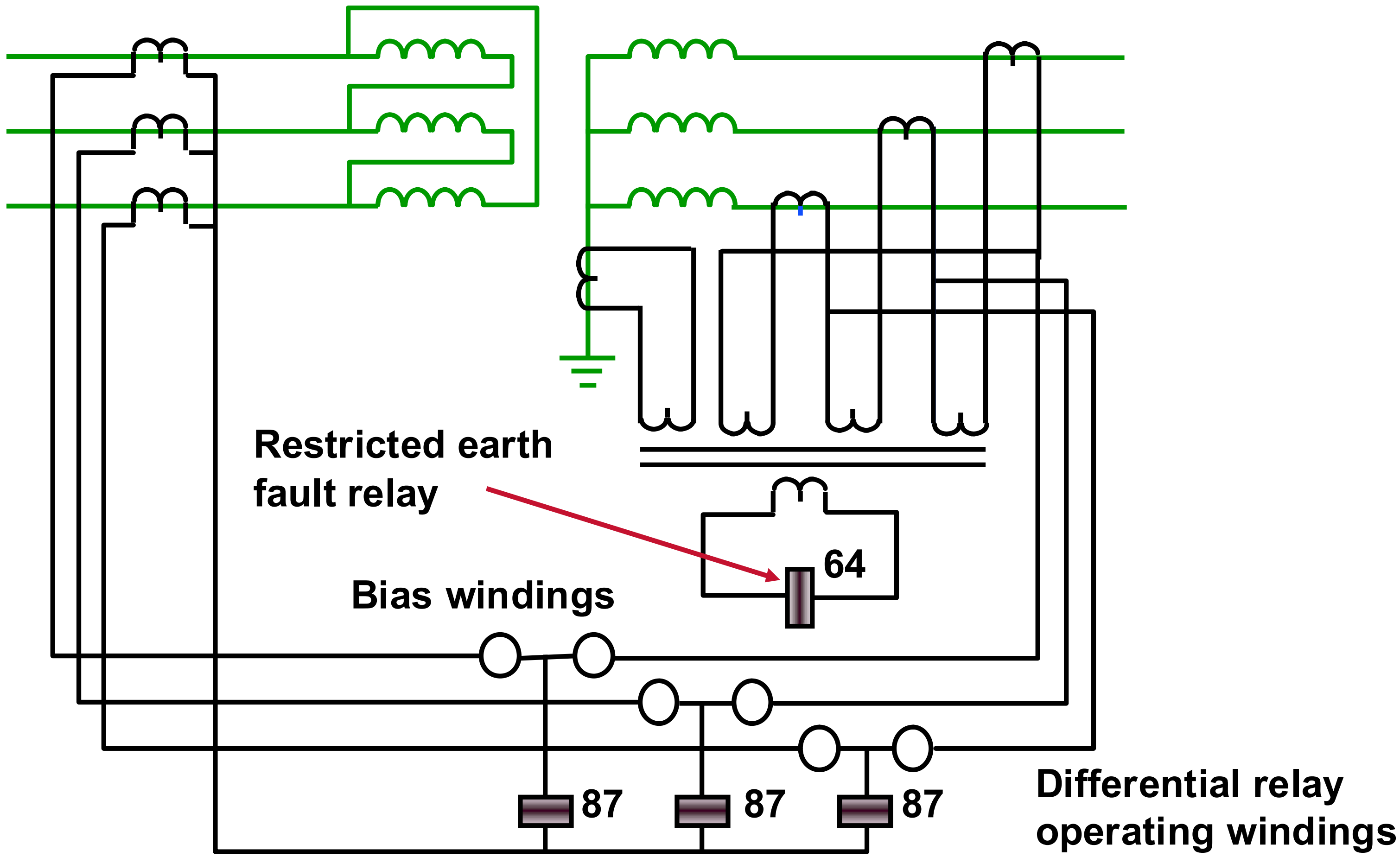


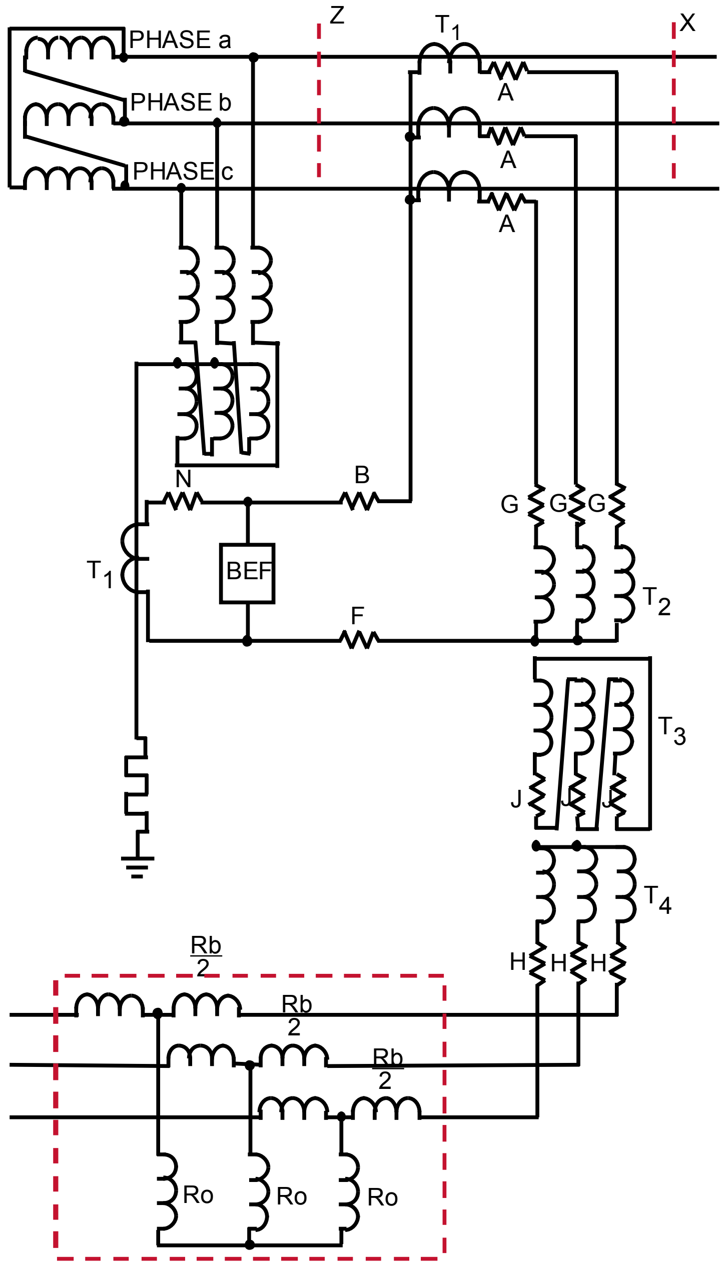
Combined Differential and Restricted Earth Fault Protection



Combined Differential and Earth Fault Protection

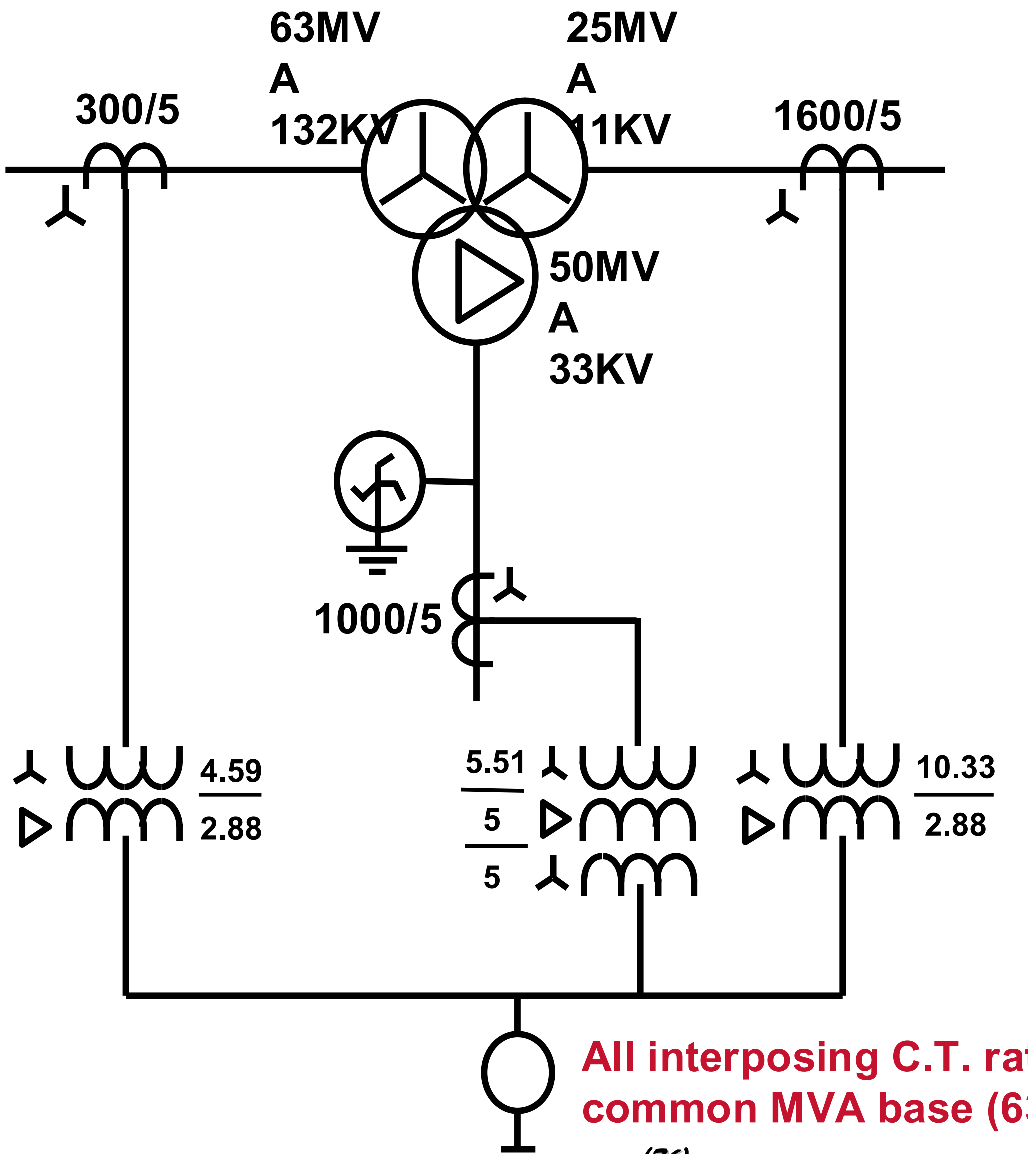
- Using Summation Auxiliary Current Transformer





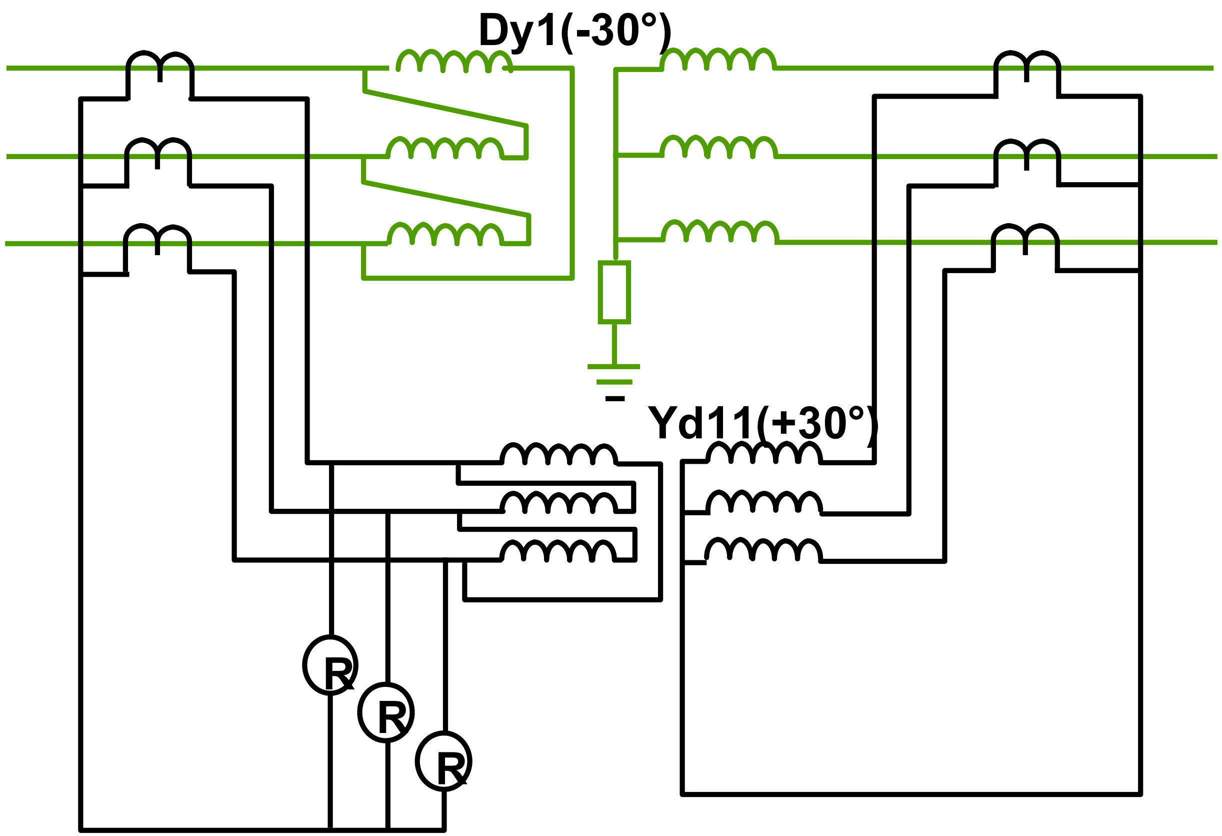
OVERALL DIFFERENTIAL RELAY

Three Winding Transformer



All interposing C.T. ratio's refer to common MVA base (63MVA)

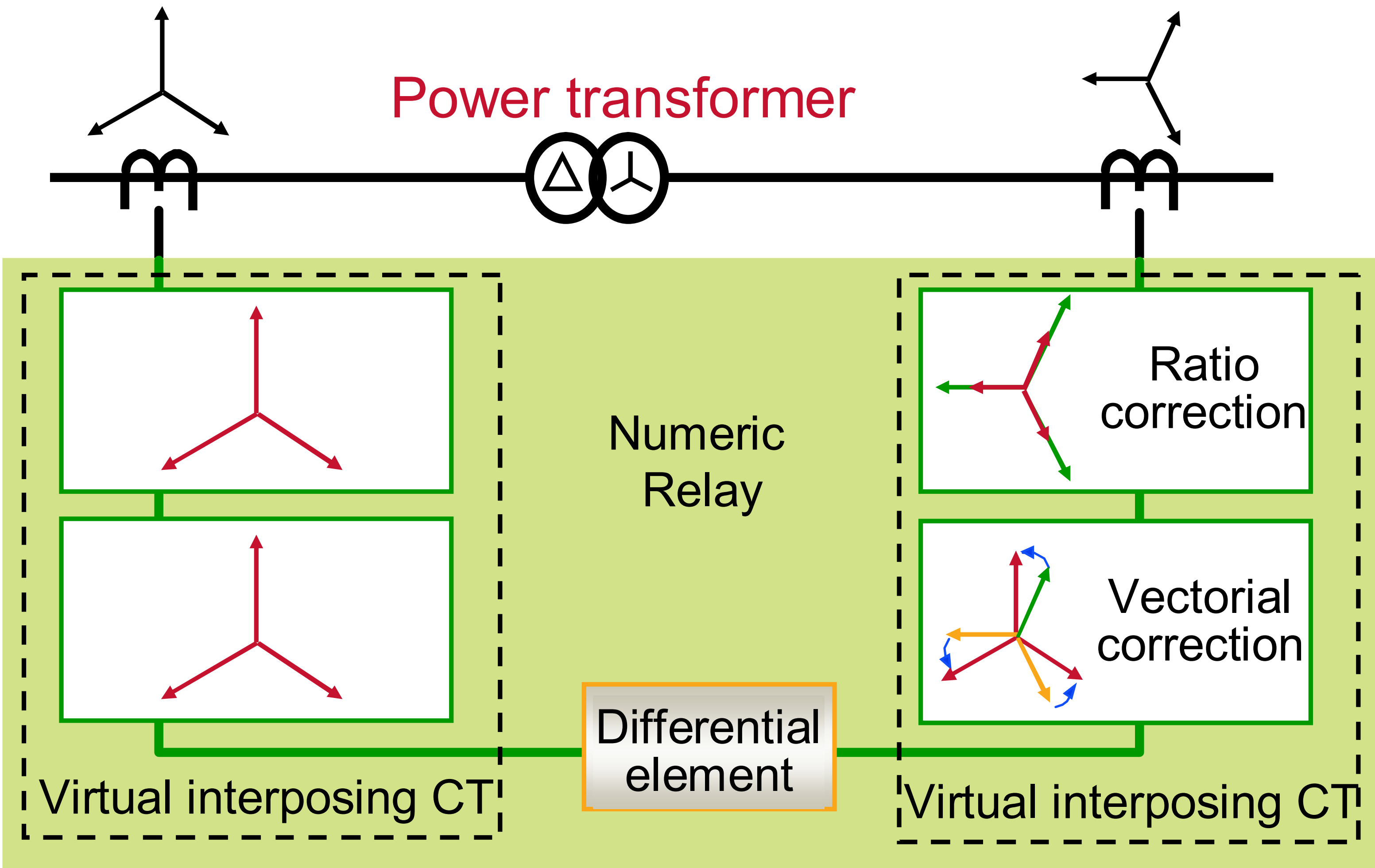
Traditional Use of Interposing CT



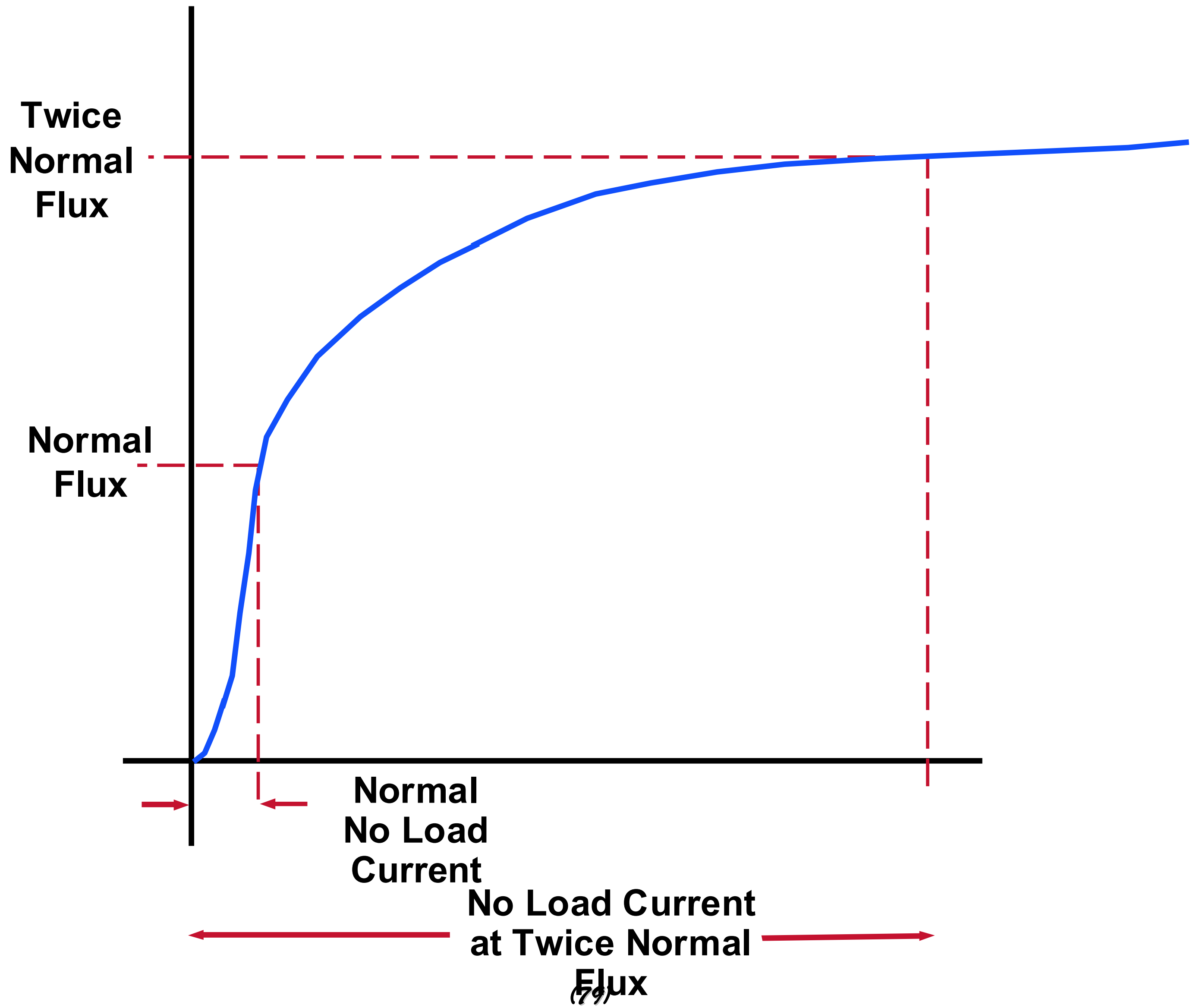
Interposing CT provides :

- Vector correction
- Ratio correction
- Zero sequence compensation

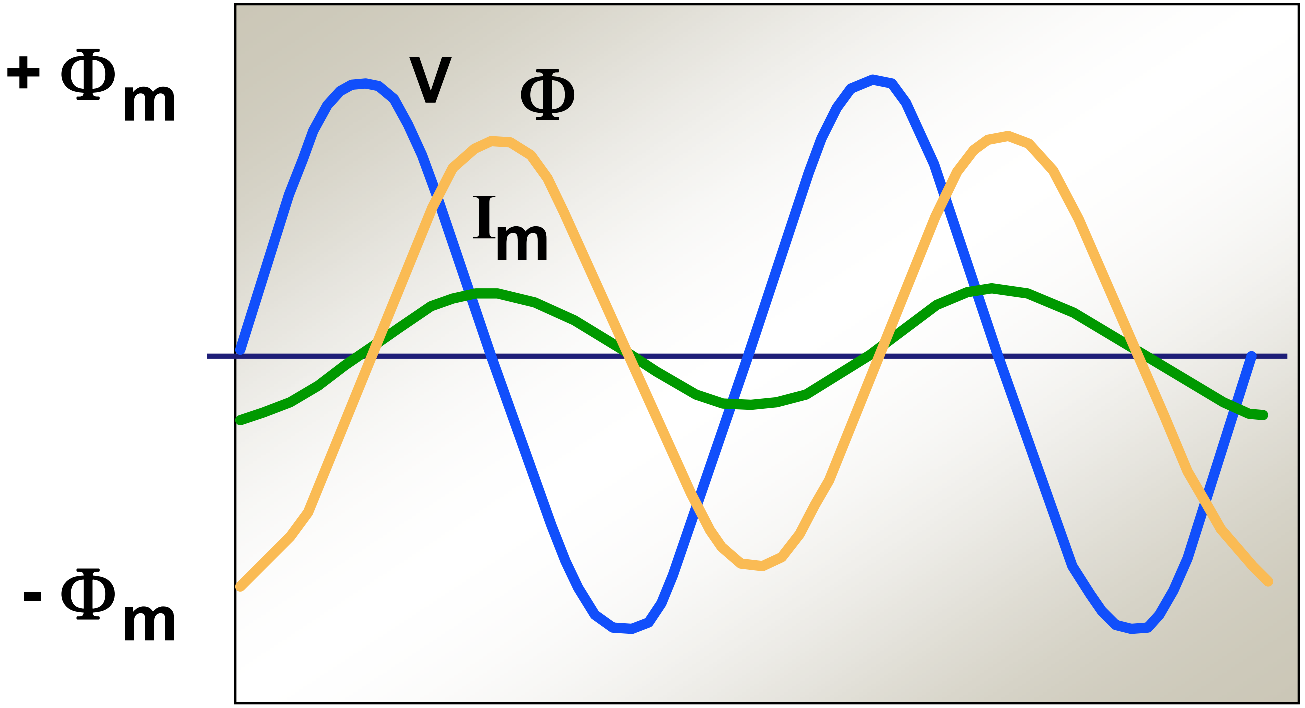
Integral Vectorial and Ratio Compensation



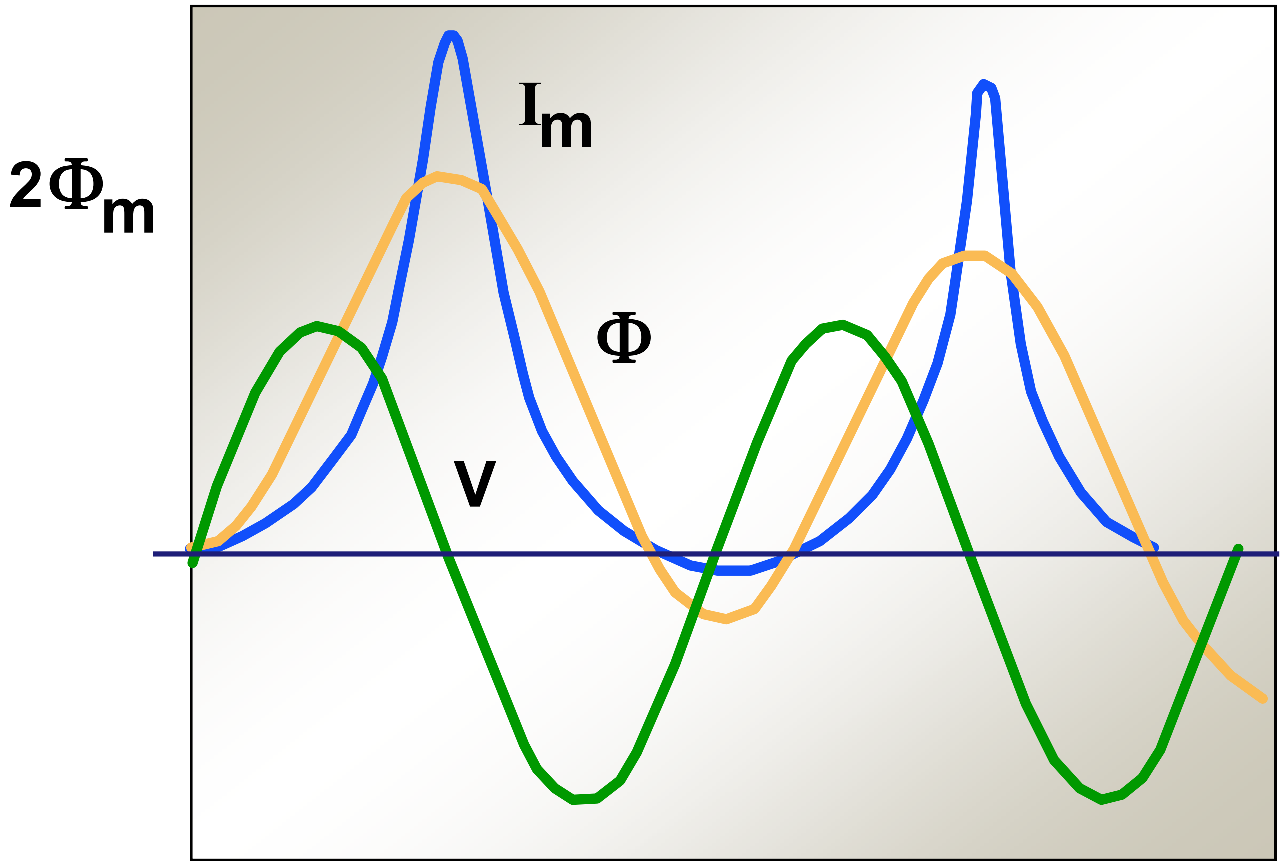
Transformer Magnetising Characteristic



Magnetising Inrush Current
Steady State



Magnetising Inrush Current
Switch on at Voltage Zero - No residual flux



Transformer Differential Protection
Effect of Magnetising Current

- **Appears on one side of transformer only**
- **Seen as fault by differential relay**
- **Normal steady state magnetising current is less than relay setting**
- **Transient magnetising inrush could cause relay to operate**

SOLUTION 1 : TIME DELAY

- **Allows magnetising current to die away before relay can operate**
- **Slow operation for genuine transformer faults**

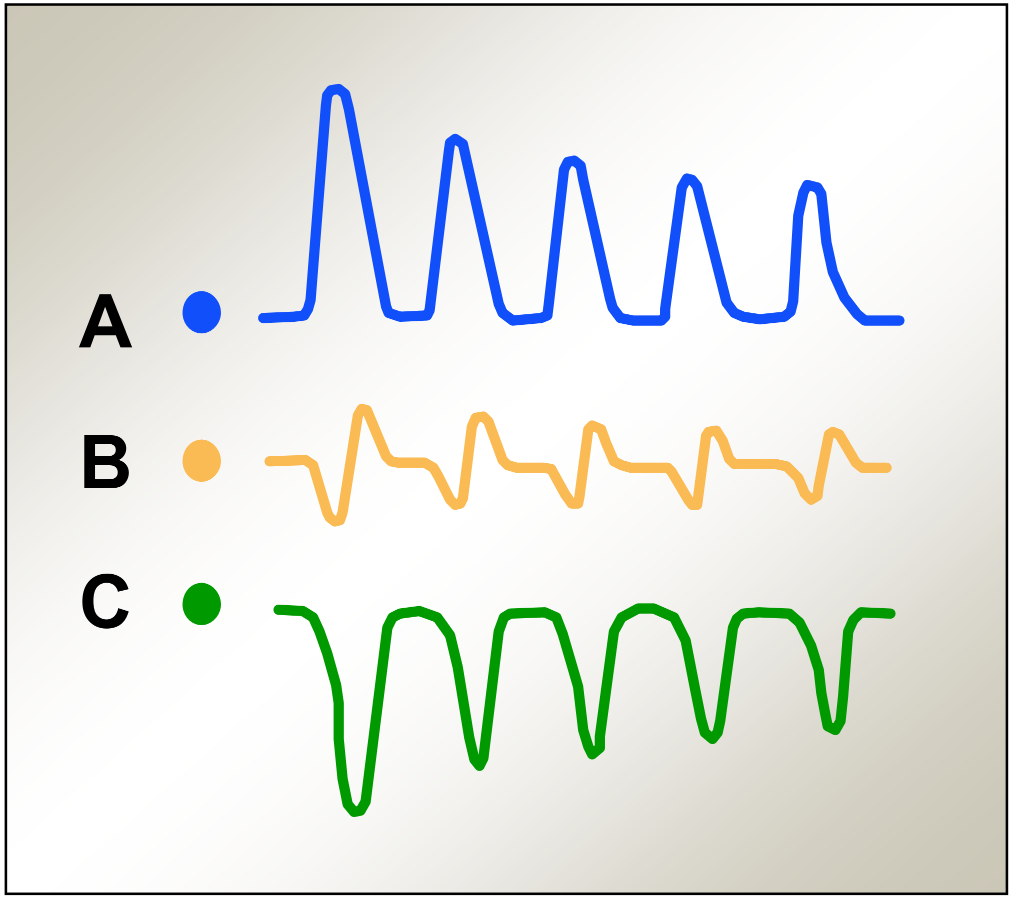
SOLUTION 2 : 2ND (and 5TH) HARMONIC RESTRAINT

- Makes relay immune to magnetising inrush
- Slower operation may result for genuine transformer faults if CT saturation occurs
- Used in MiCOM P63x

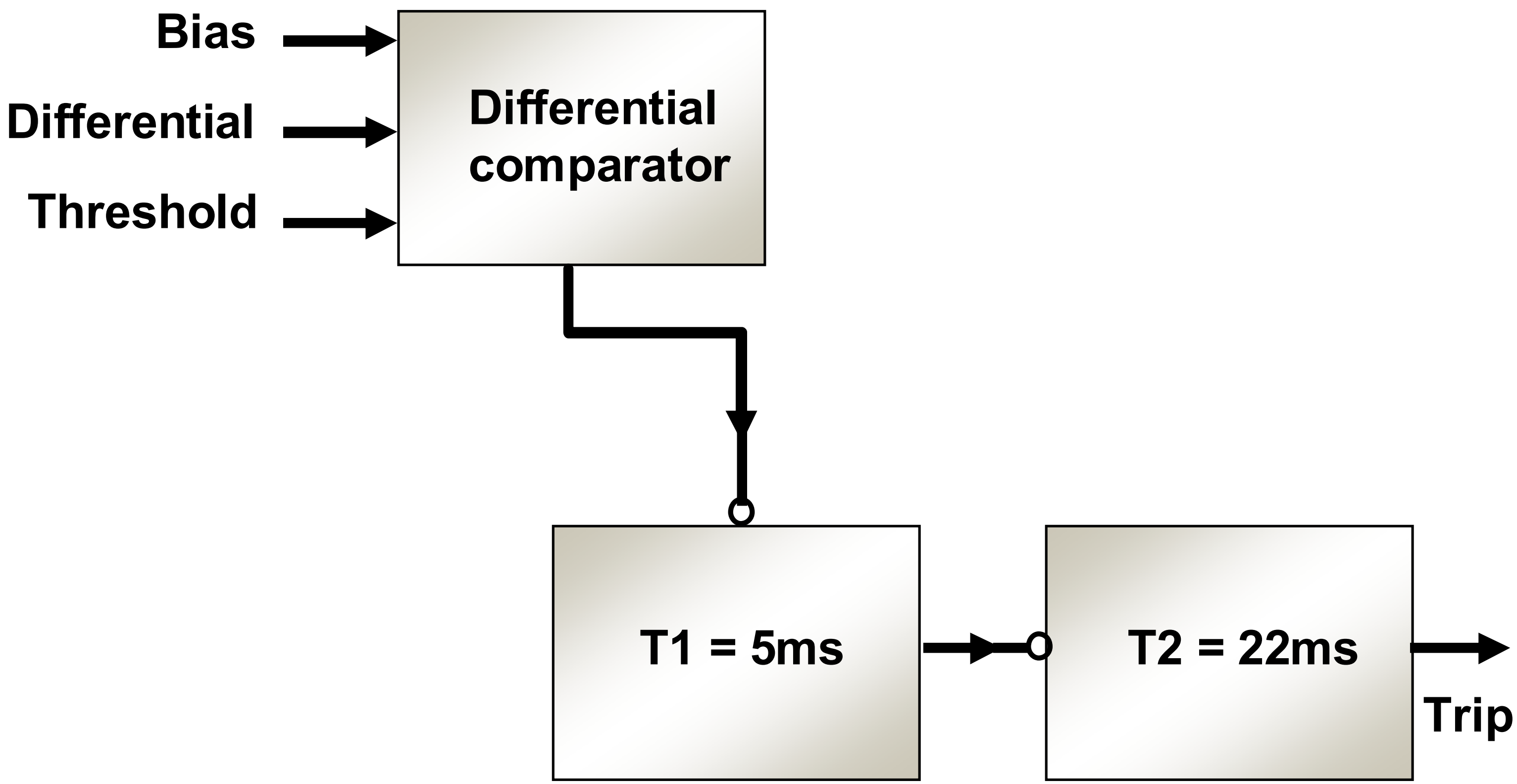
SOLUTION 3 : GAP MEASUREMENT TECHNIQUE

- **Inhibits relay operation during magnetising inrush**
- **Operate speed for genuine transformer faults unaffected by significant CT saturation**
- **Used in MBCH & KBCH relays**

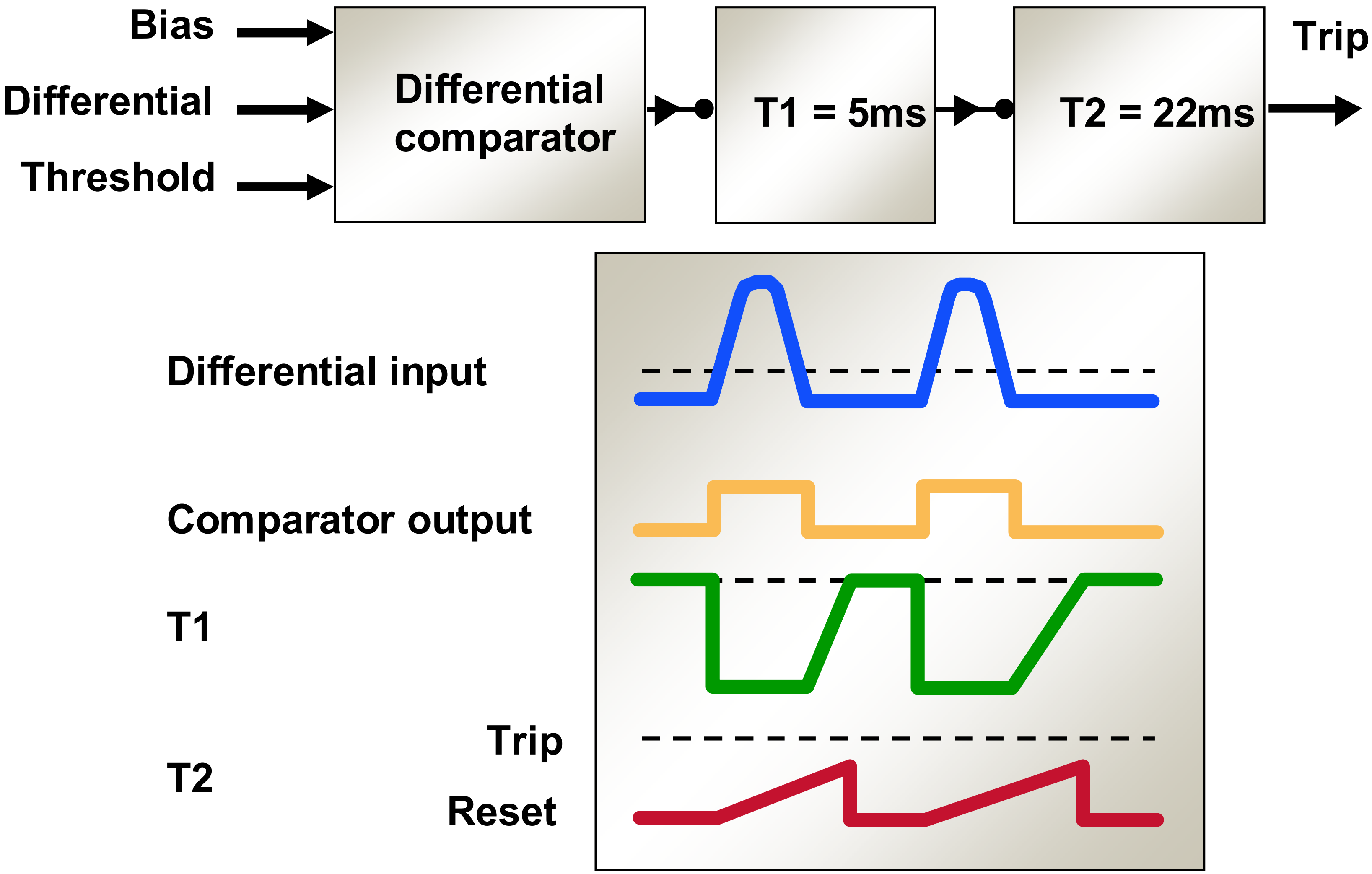
Typical Magnetising Inrush Waveforms



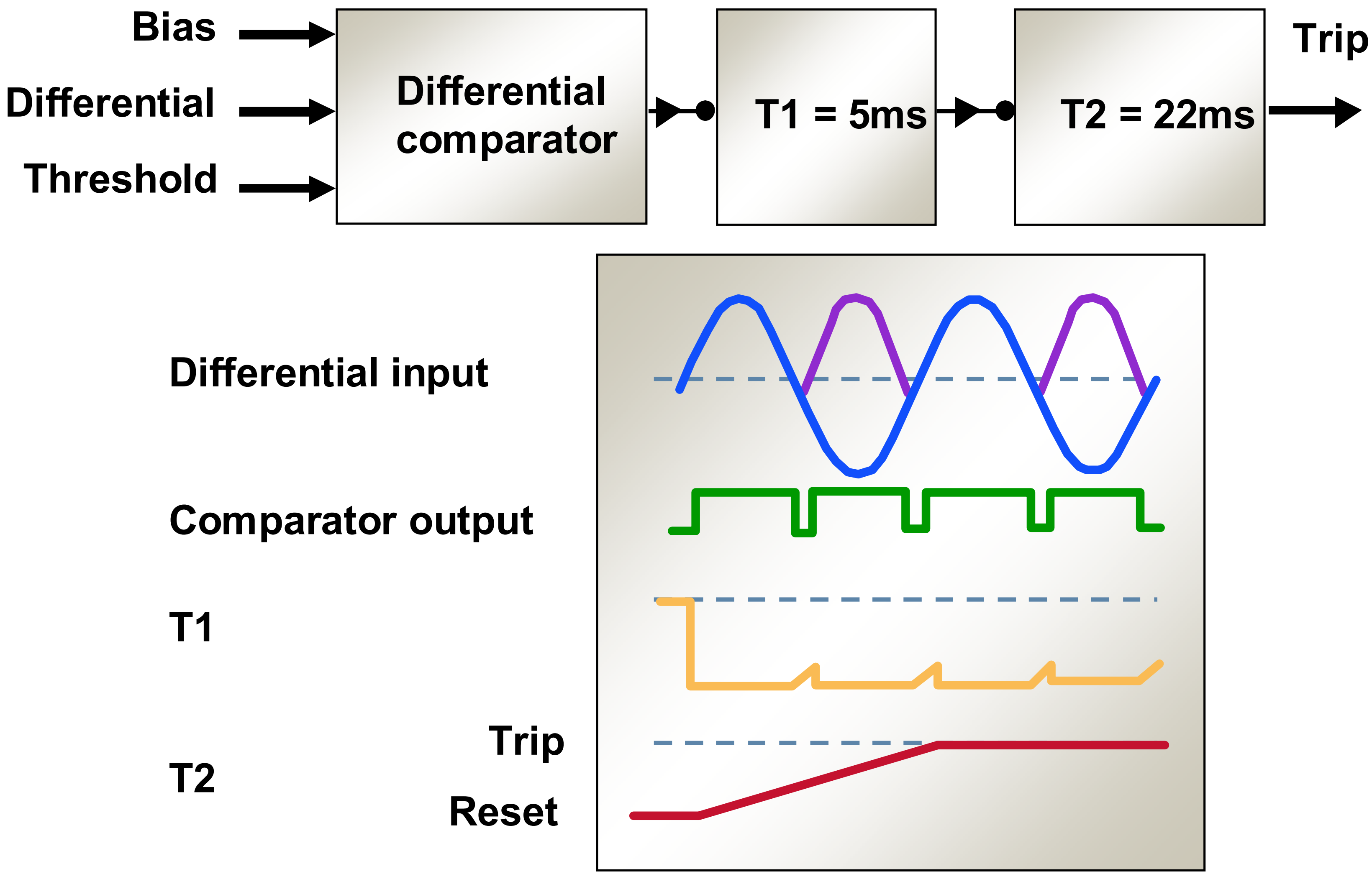
Detection of Typical Magnetising Inrush (50Hz)



Restraint for Transformer Magnetising Inrush

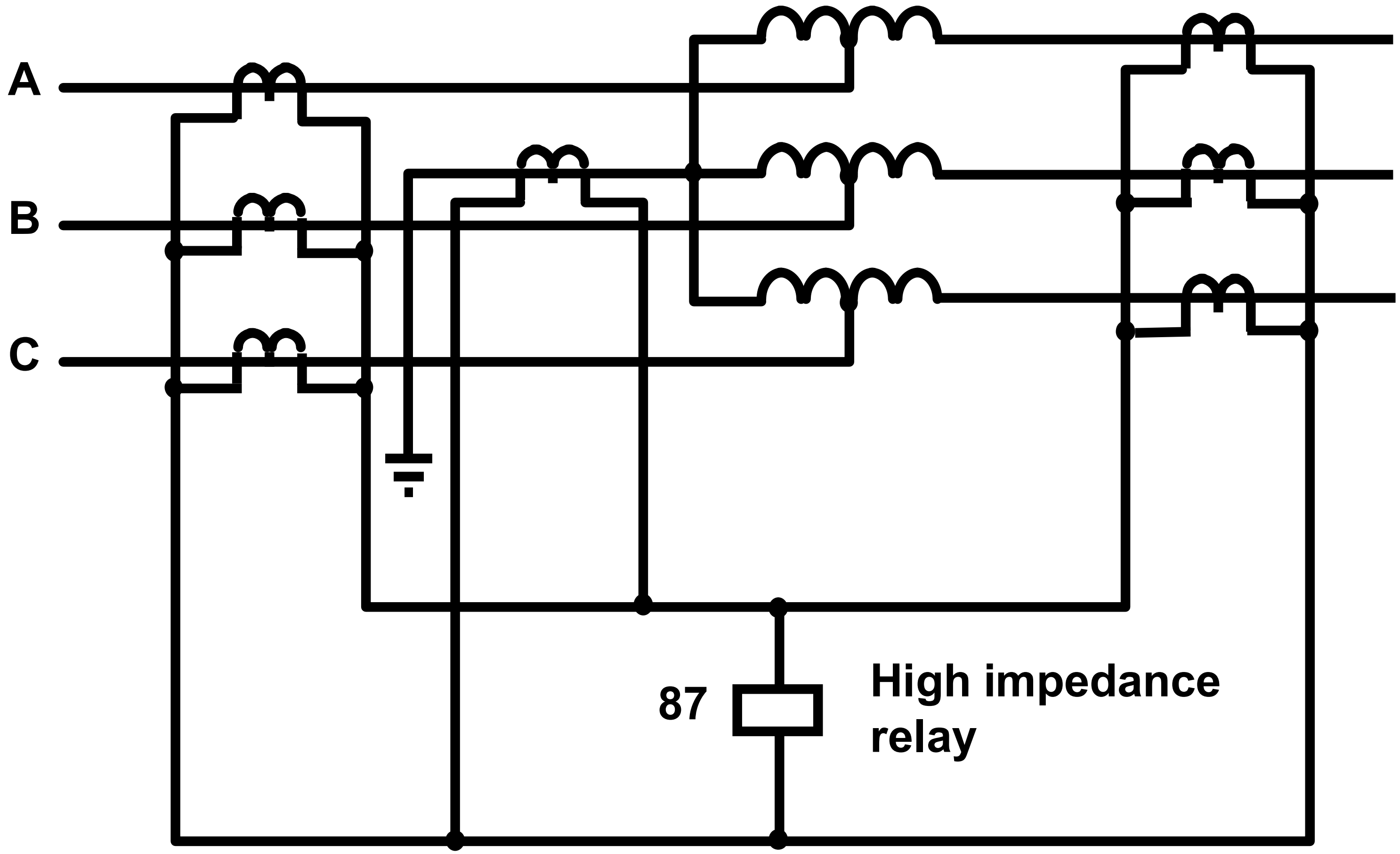


Operation for Transformer Faults



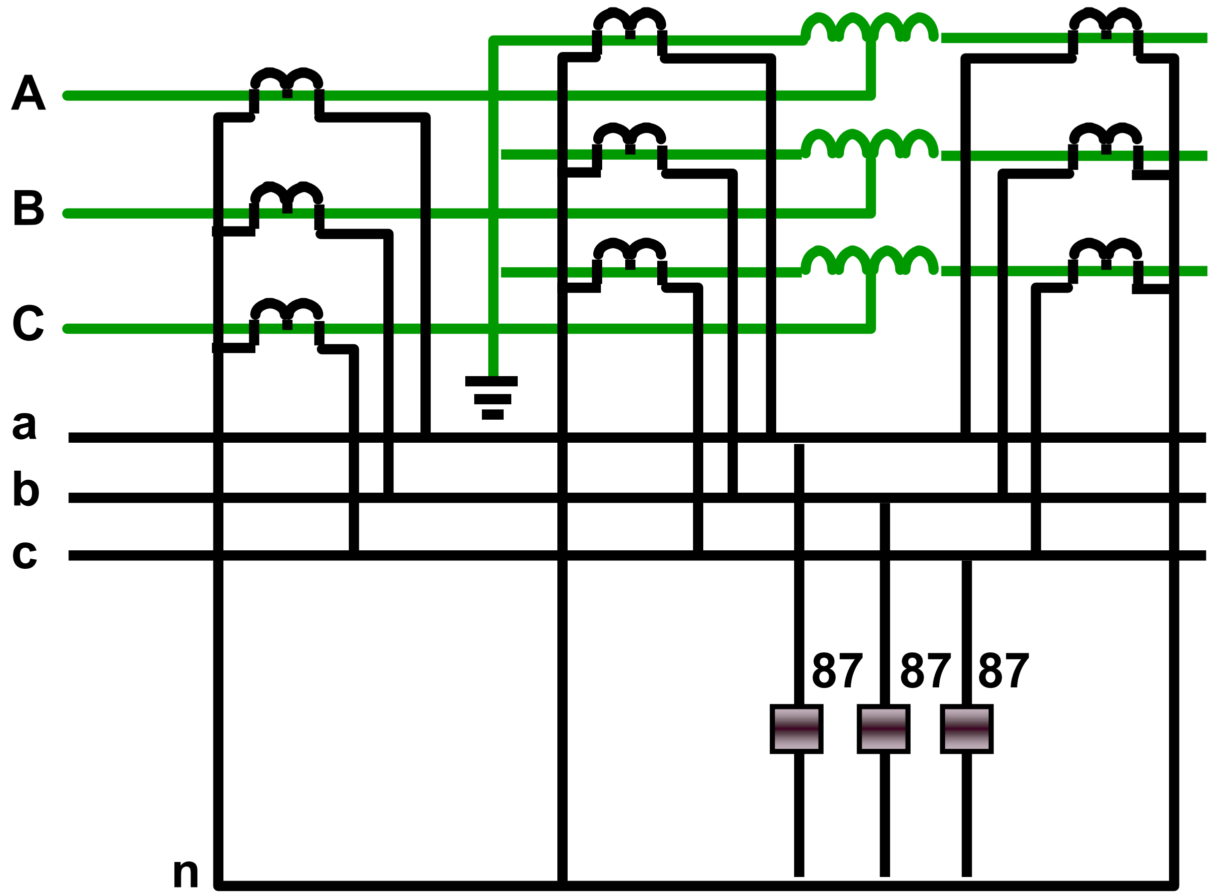
Protection of Auto-Transformer by High Impedance Differential Relays

(a) Earth Fault Scheme

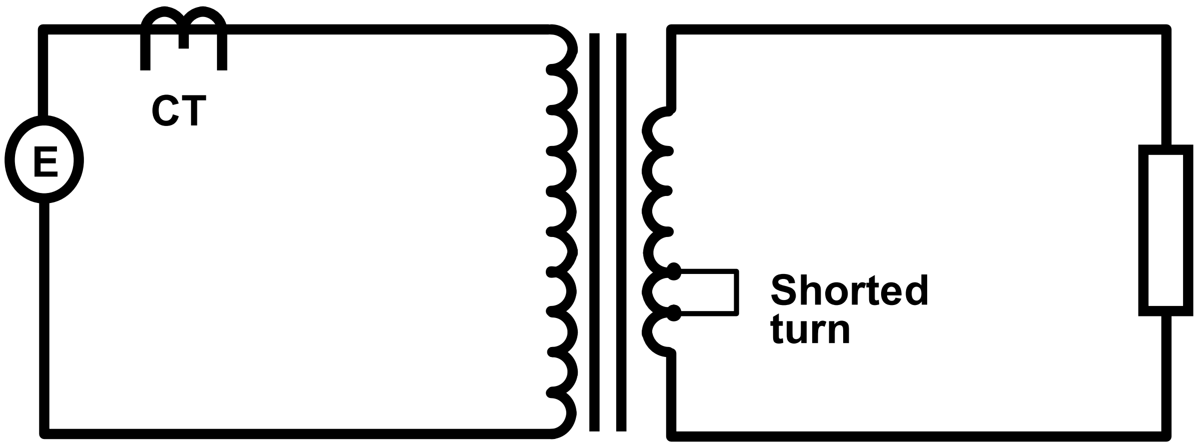


Protection of Auto-Transformer by High Impedance Differential Relays

(b) Phase and Earth Fault Scheme



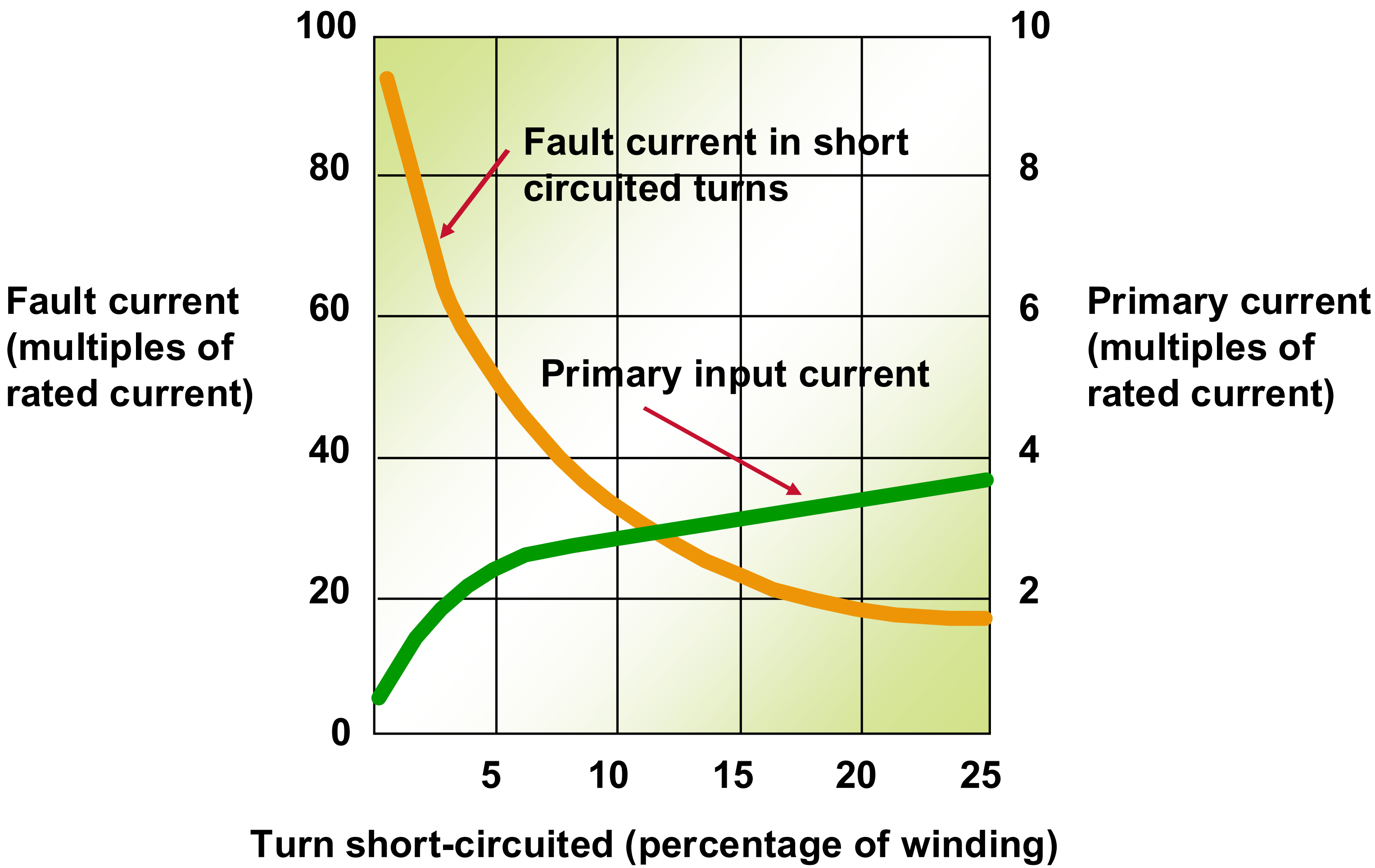
Inter-Turn Fault Protection



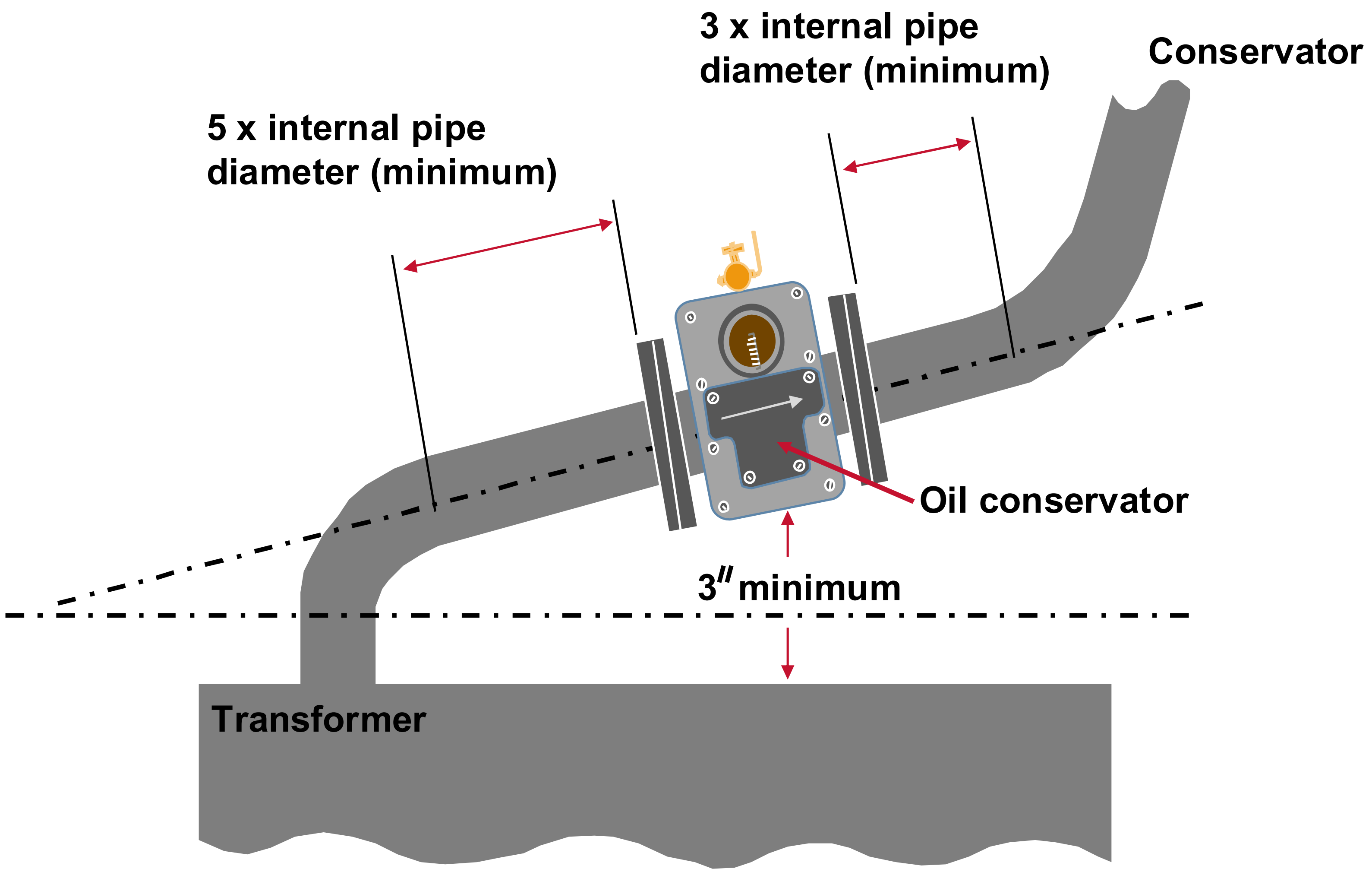
Nominal turns ratio	- 11,000 / 240
Fault turns ratio	- 11,000 / 1
Current ratio	- 1 / 11,000

Requires Buchholz relay

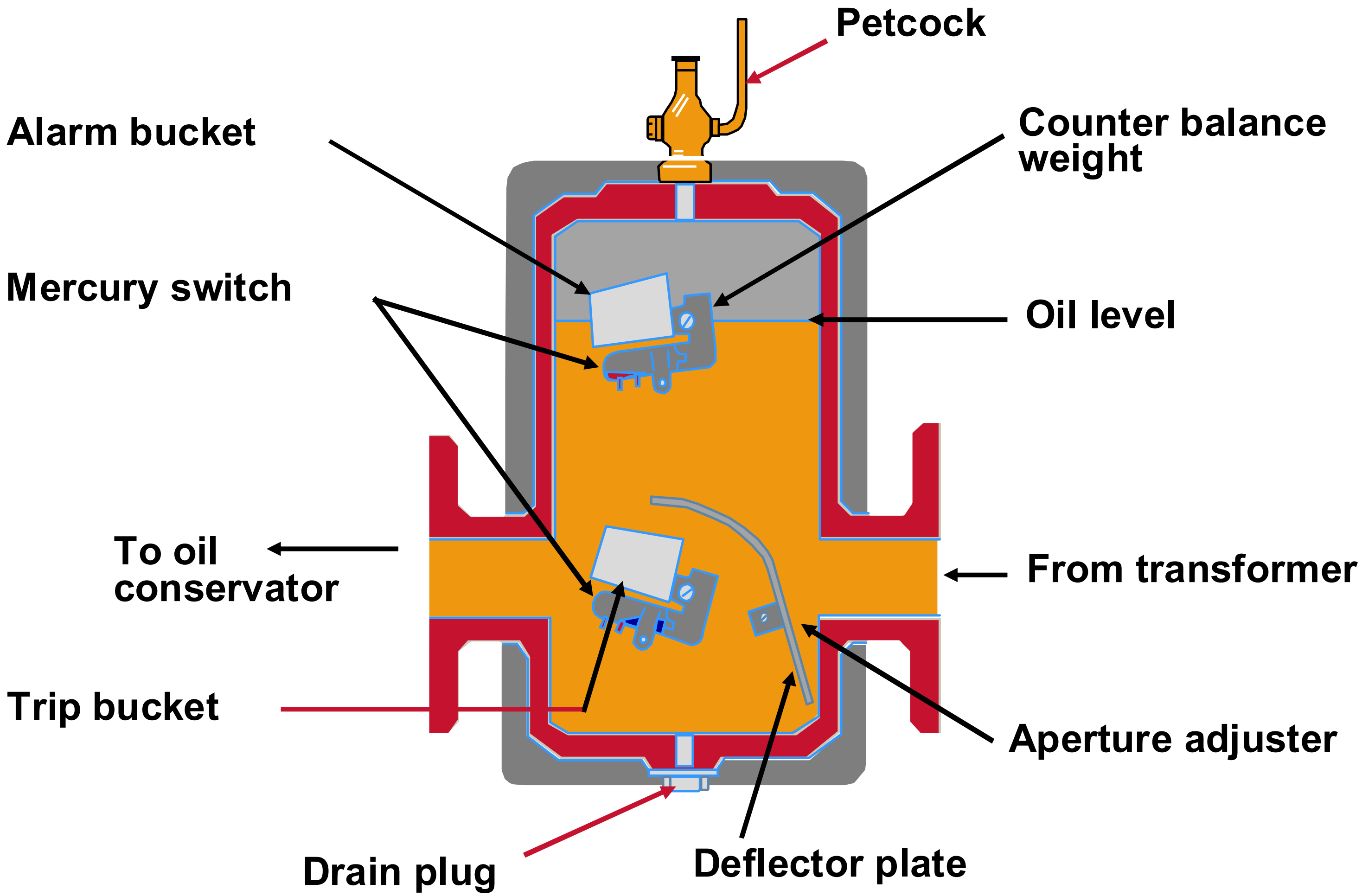
Interturn Fault Current / Number of Turns Short Circuited



Buchholz Relay Installation



Buchholz Relay



Overfluxing Protection

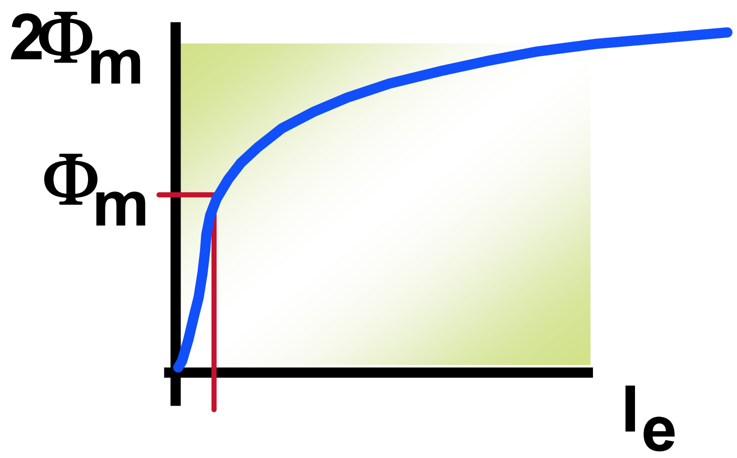
- **Generator transformers**
- **Grid transformers**

Usually only a problem during run-up or shut down, but can be caused by loss of load / load shedding etc.

$$\text{Flux } \Phi \propto \frac{V}{f}$$

- **Effects of overfluxing :**
  - Increase in magnetising current
  - Increase in winding temperature
  - Increase in noise and vibration
  - Overheating of laminations and metal parts (caused by stray flux)
- **Protective relay responds to V/f ratio**
  - Stage 1 - lower A.V.R.
  - Stage 2 - Trip field

$V = kf\Phi$



- **CAUSES**
  - Low frequency
  - High voltage
  - Geomagnetic disturbances
- **EFFECTS**
  - Tripping of differential element (Transient overfluxing)
  - Damage to transformers (Prolonged overfluxing)

V/Hz Overfluxing Protection

$$V/f \ \alpha \ K\Phi$$

Trip and alarm outputs for clearing prolonged overfluxing

Alarm : Definite time characteristic to initiate corrective action

Trip : IDMT or DT characteristic to clear overfluxing condition

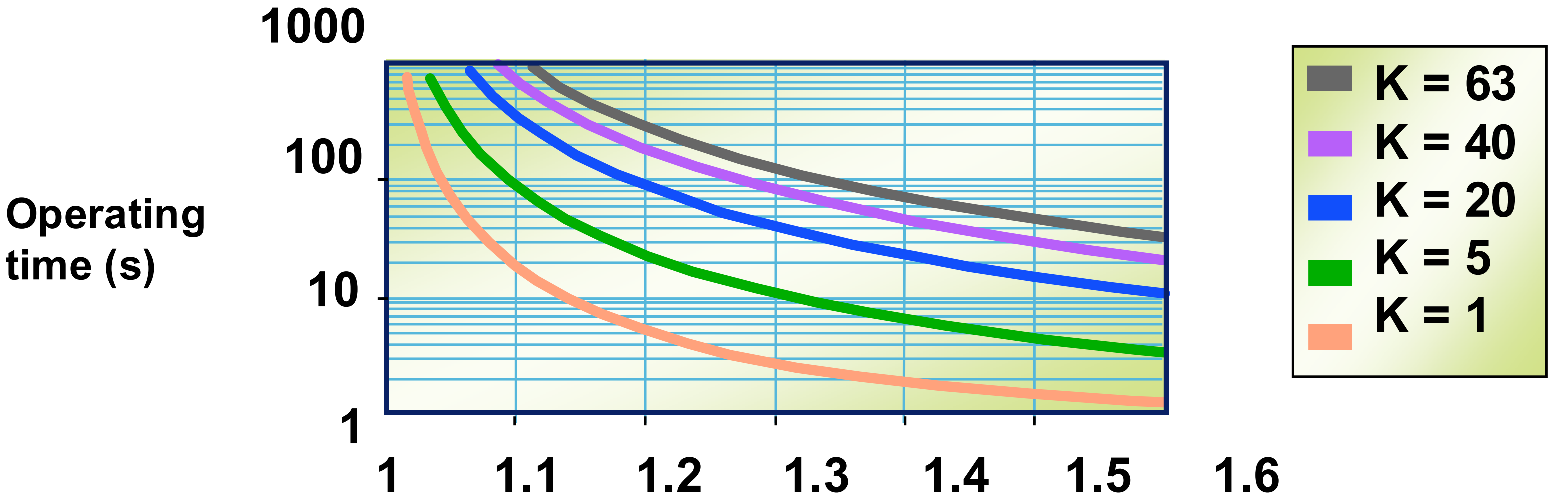
Settings

Pick-up 1.5 to 3.0 i.e. $\frac{110V}{50Hz} \times 1.05 = 2.31$

DT setting range 0.1 to 60 seconds

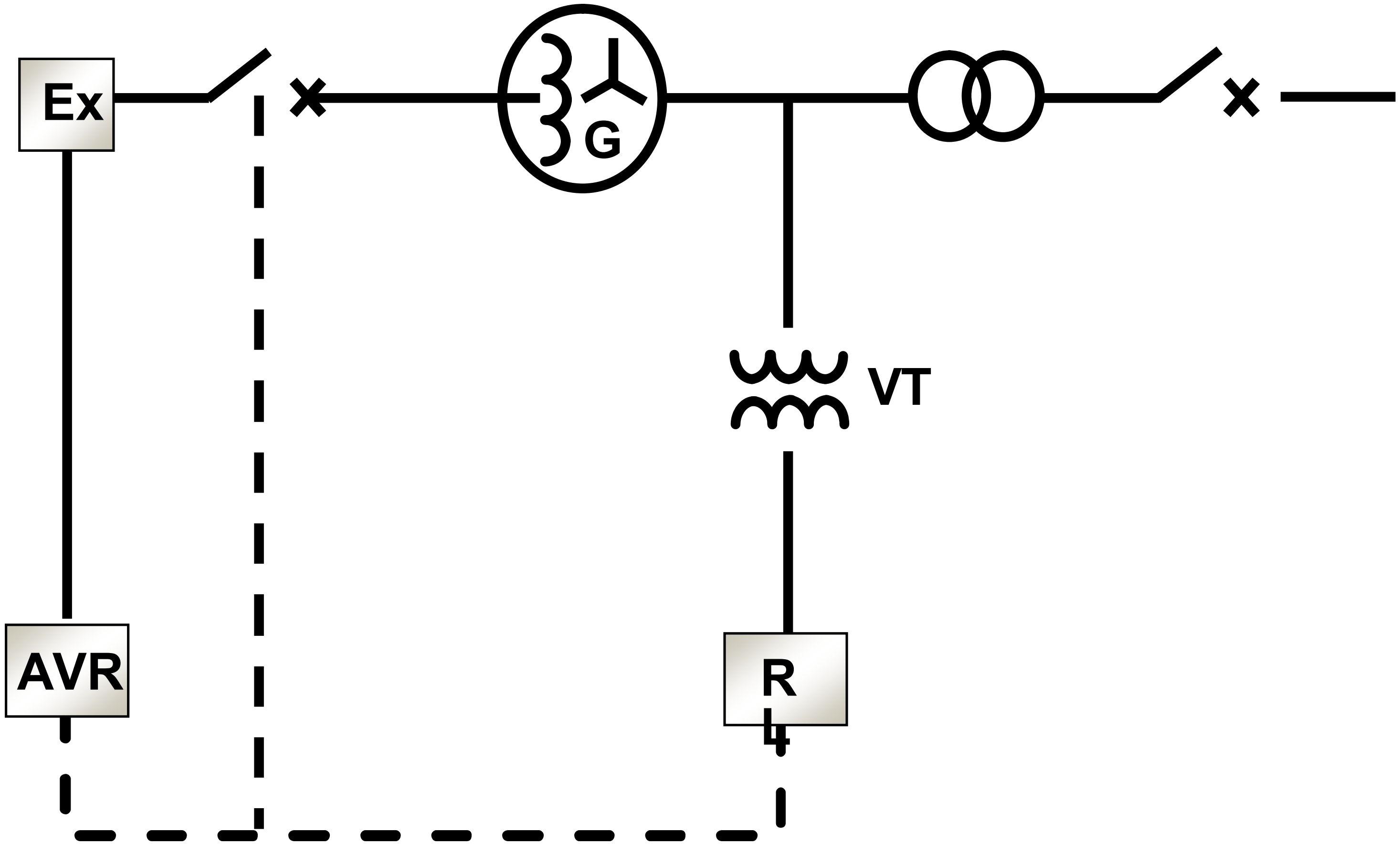
- Enables co-ordination with plant withstand characteristics

$$t = 0.8 + \frac{0.18 \times K}{(M - 1)^2}$$

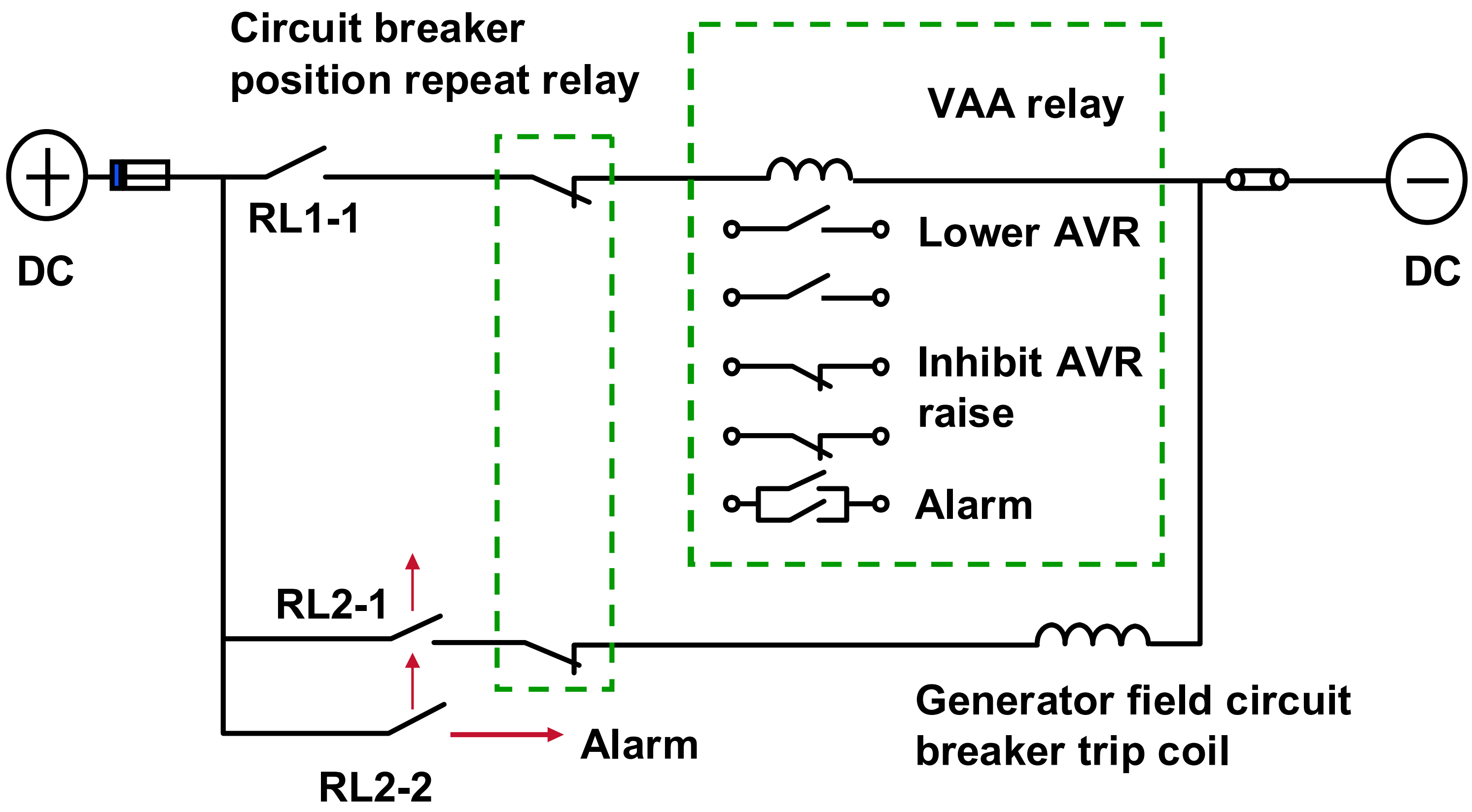


$$M = \frac{V/Hz}{Setting}$$

Overfluxing Relay

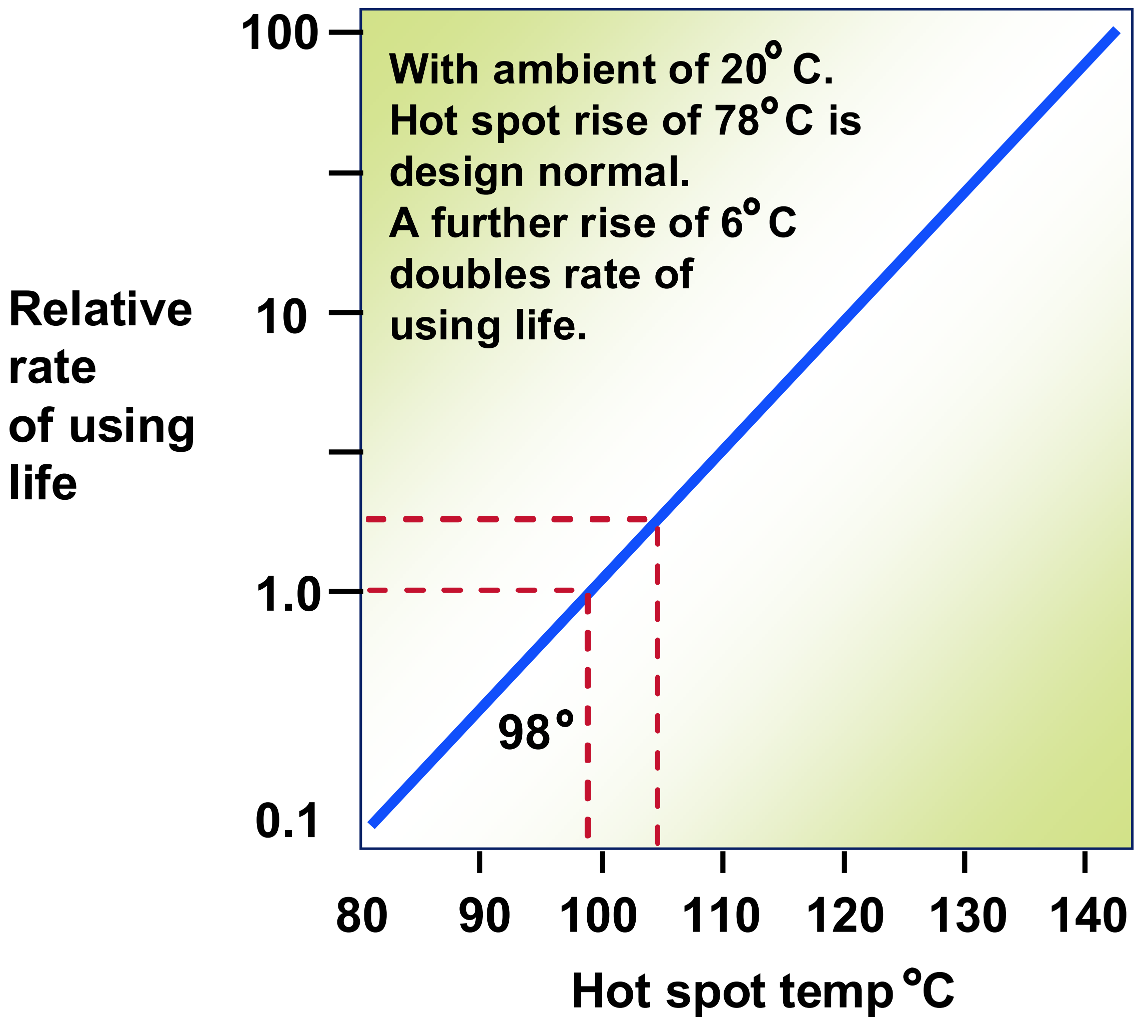


Application of Overfluxing Relay

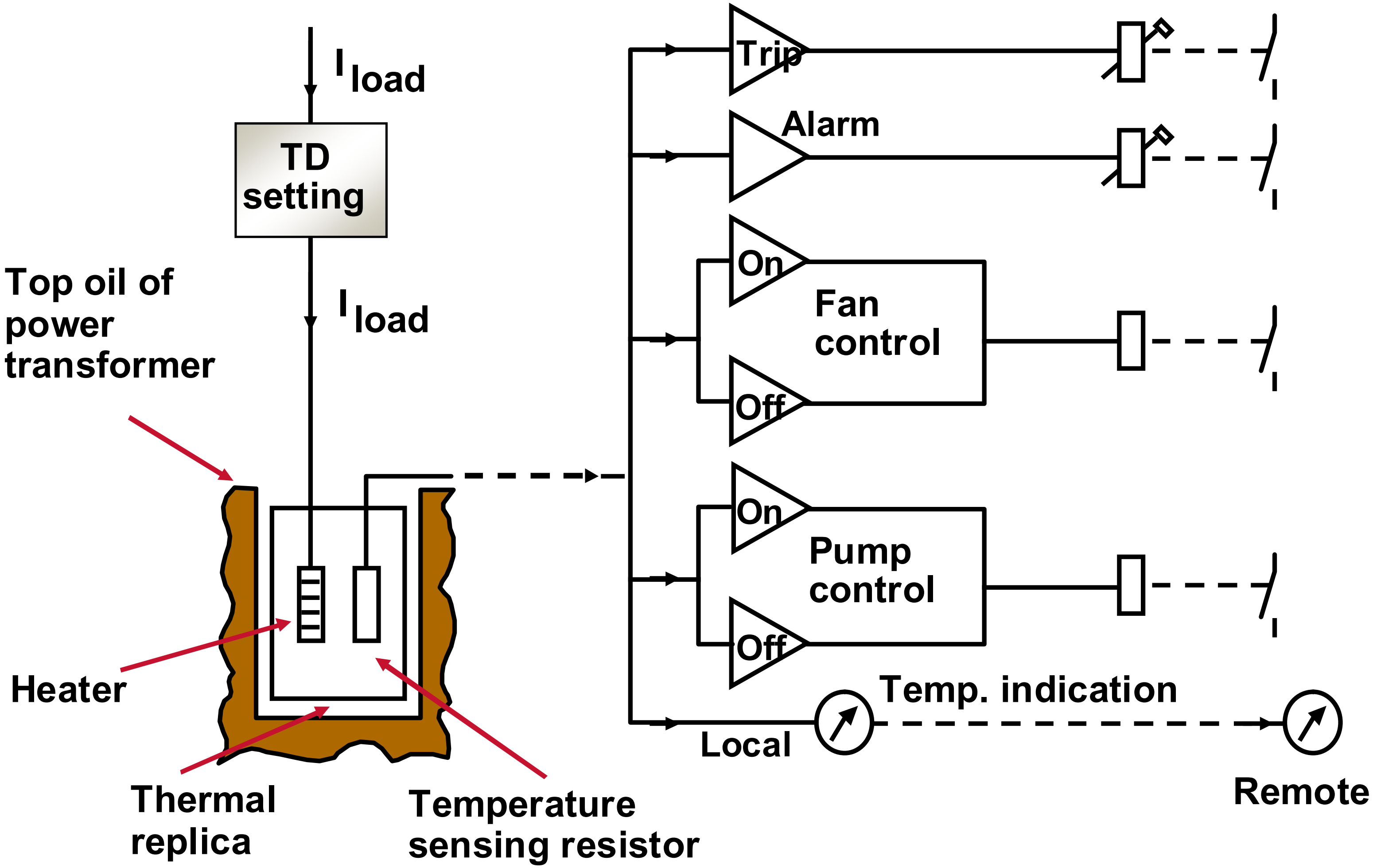


Thermal Overload Protection

Effect of Overload on Transformer Insulation Life

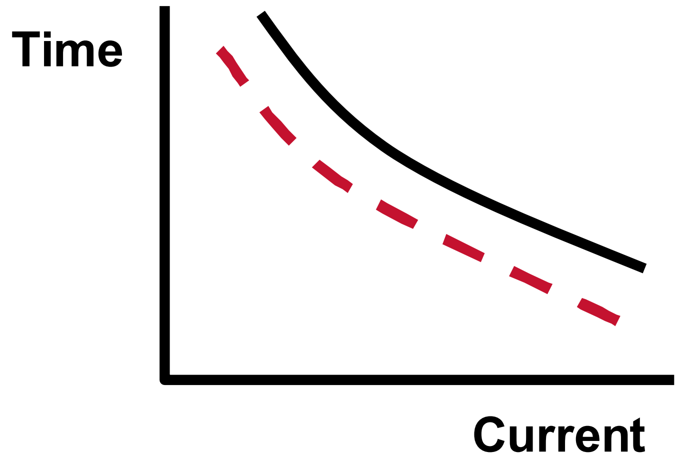


Overheating Protection

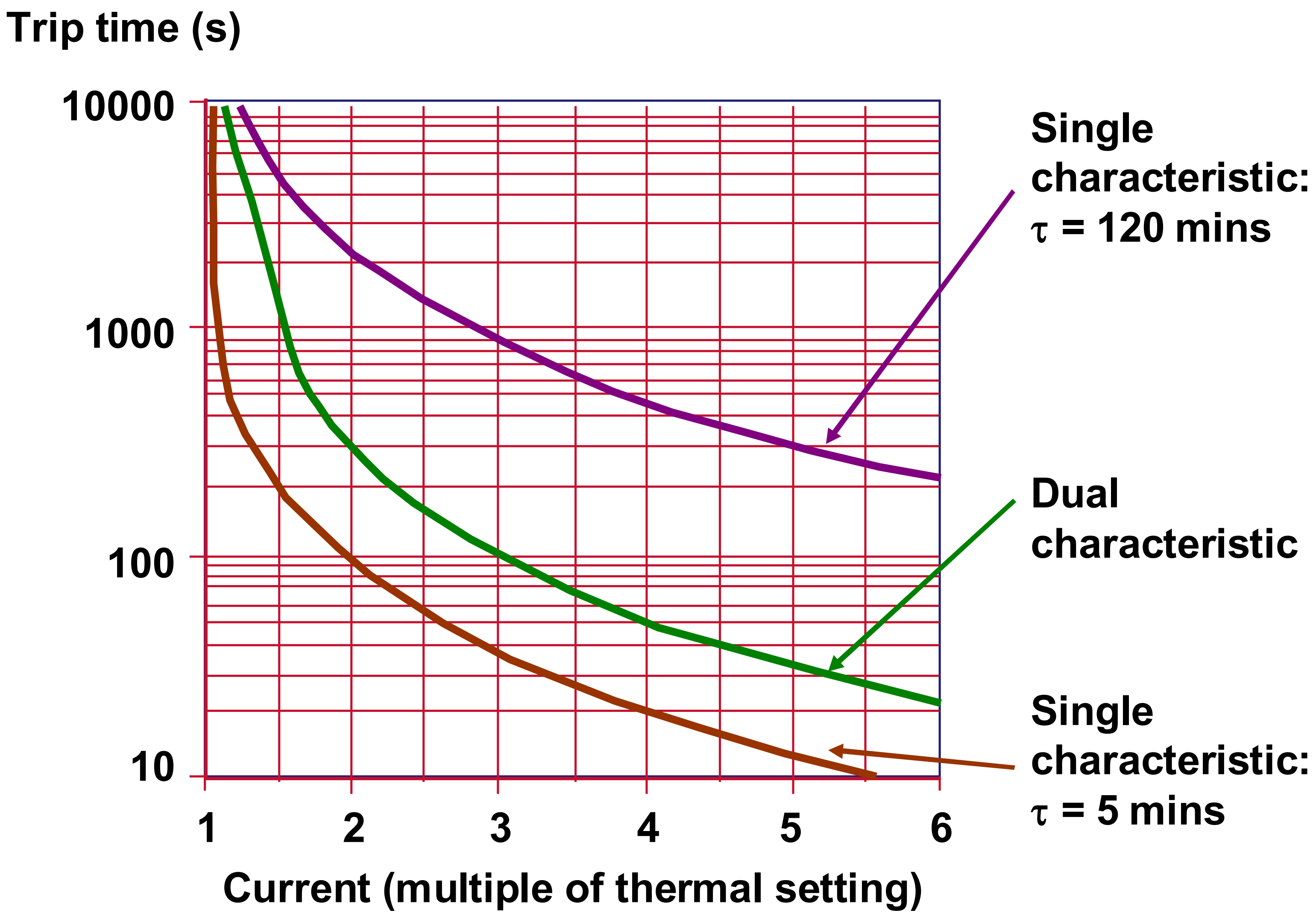


Overload Protection

- Overcurrent protection designed for fault condition
- Thermal replica provides better protection for overload
  - Current based
  - Flexible characteristics
  - Single or dual time constant
  - Reset facility
  - Non-volatile



Thermal Overload
Oil Filled Transformers



Thermal Trip Time

$$\text{TripTime} = \tau \ln \left[\frac{\left(\frac{I}{I_{REF}}\right)^2 - \theta_P}{\left(\frac{I}{I_{REF}}\right)^2 - K\,\theta_{TRIP}} \right]$$

where τ **= heating time constant**

I **= actual current measured by relay**

I_{REF} **= continuous current rating of protected plant**

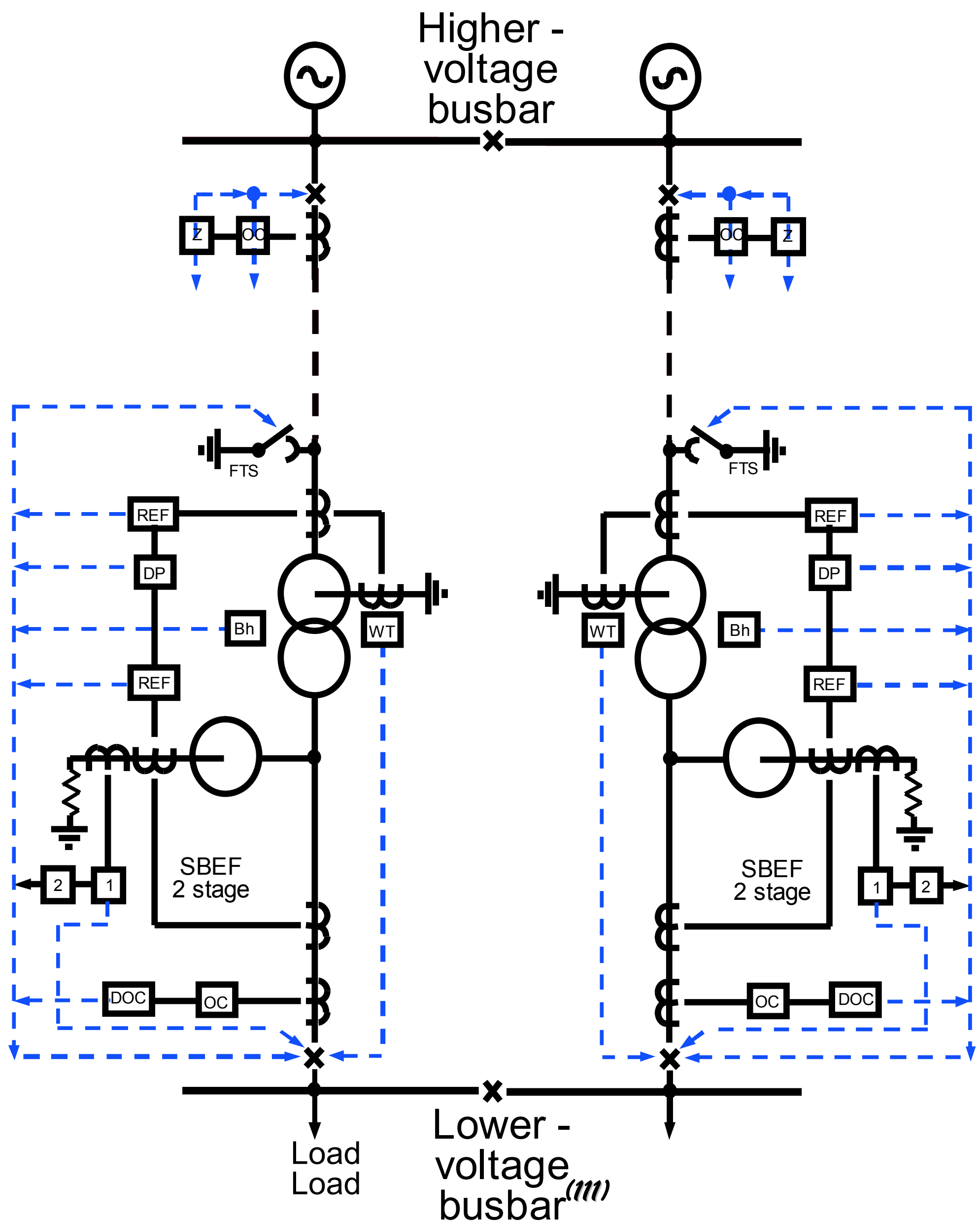
θ_P **= previous thermal state**

θ_{TRIP} **= trip threshold**

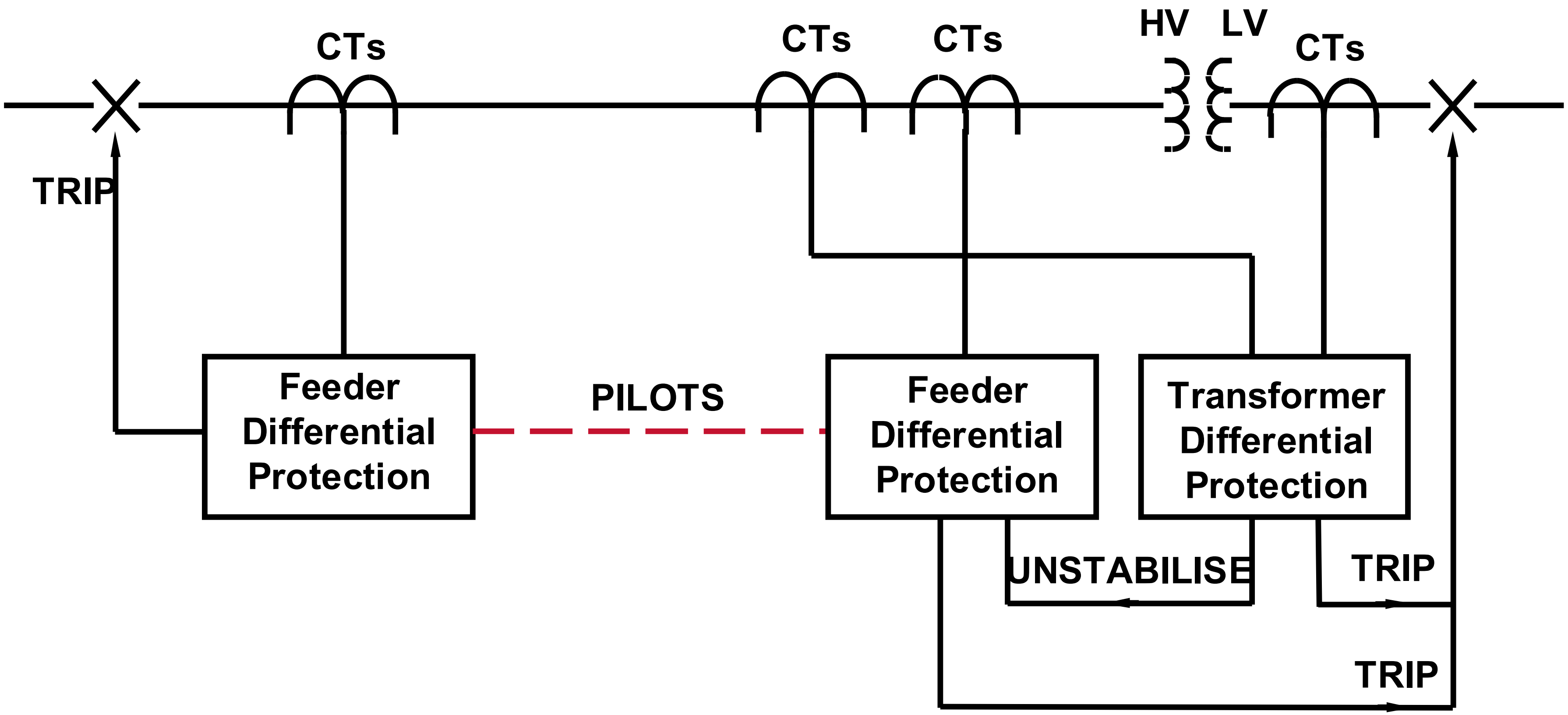
K **= multiplier (for actual temperature)**

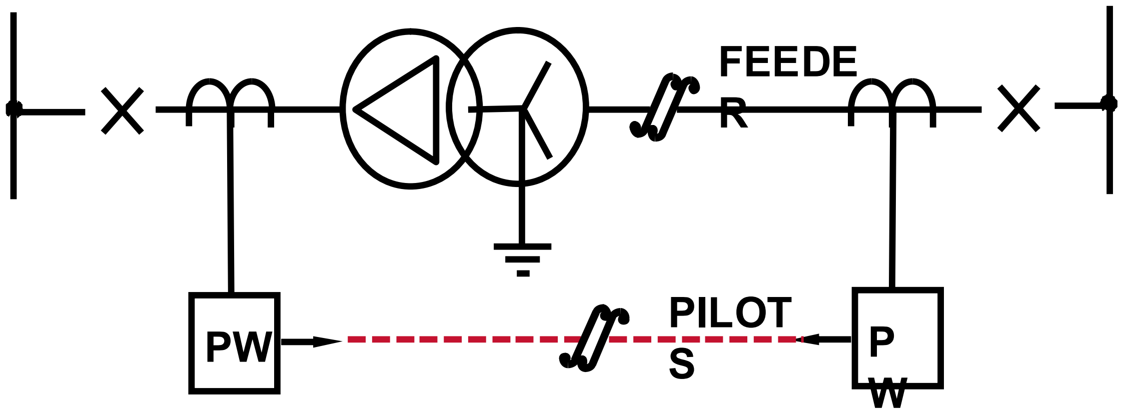
Transformer Feeders

Protection of Parallel Transformer Feeders



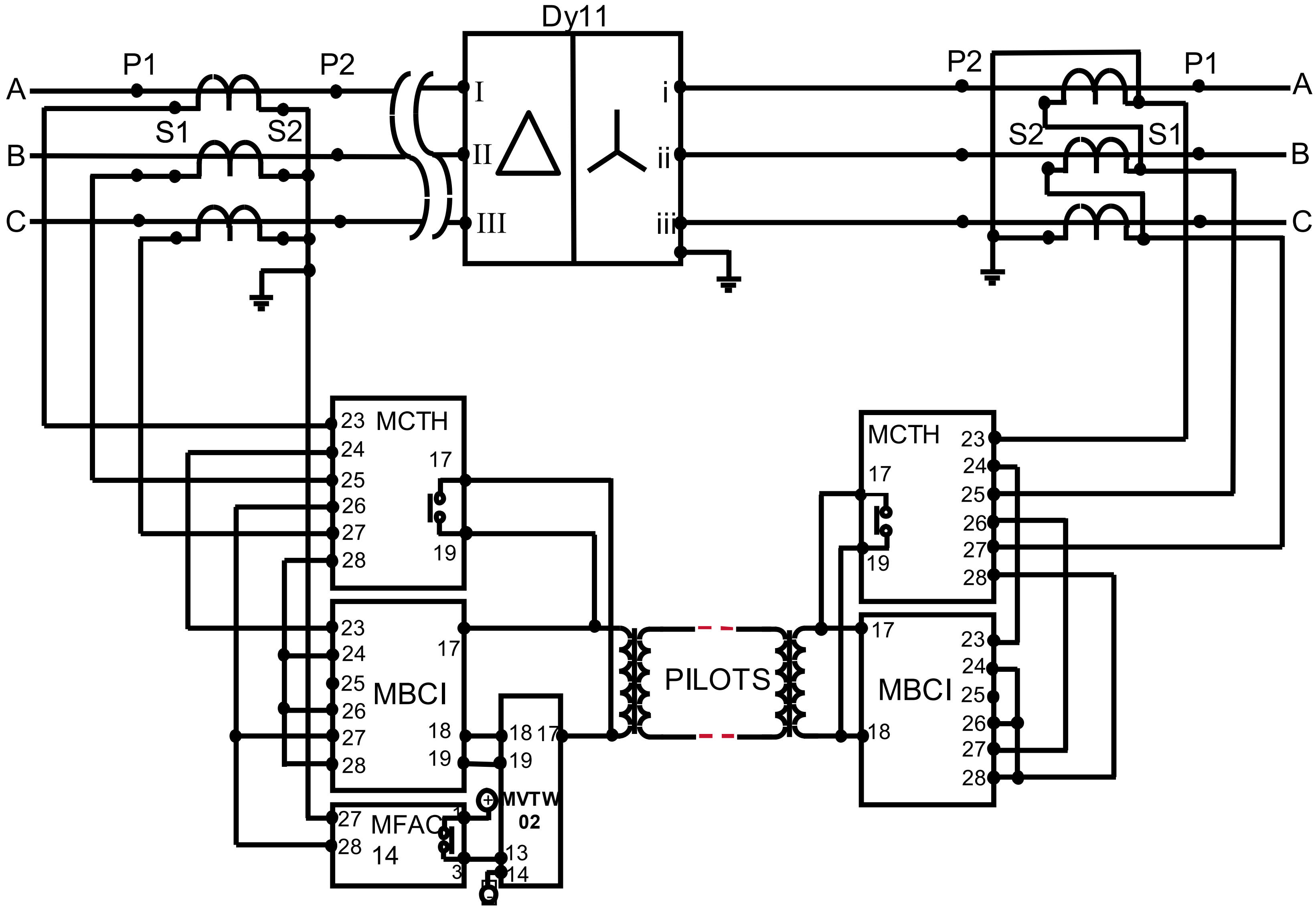
Protection of Transformer Feeders





- For use where no breaker separates the transformer from the feeder.
- Transformer inrush current must be considered.
- Inrush is a transient condition which may occur at the instant of transformer energisation.
- Mag. Inrush current is not a fault condition
  $\therefore$ Protection must remain stable.
- MCTH provides a blocking signal in the presence of inrush current and allows protection to be used on transformer feeders.

Transformer Feeder Protection



P541/ P542 - Protection of Transformer Feeders