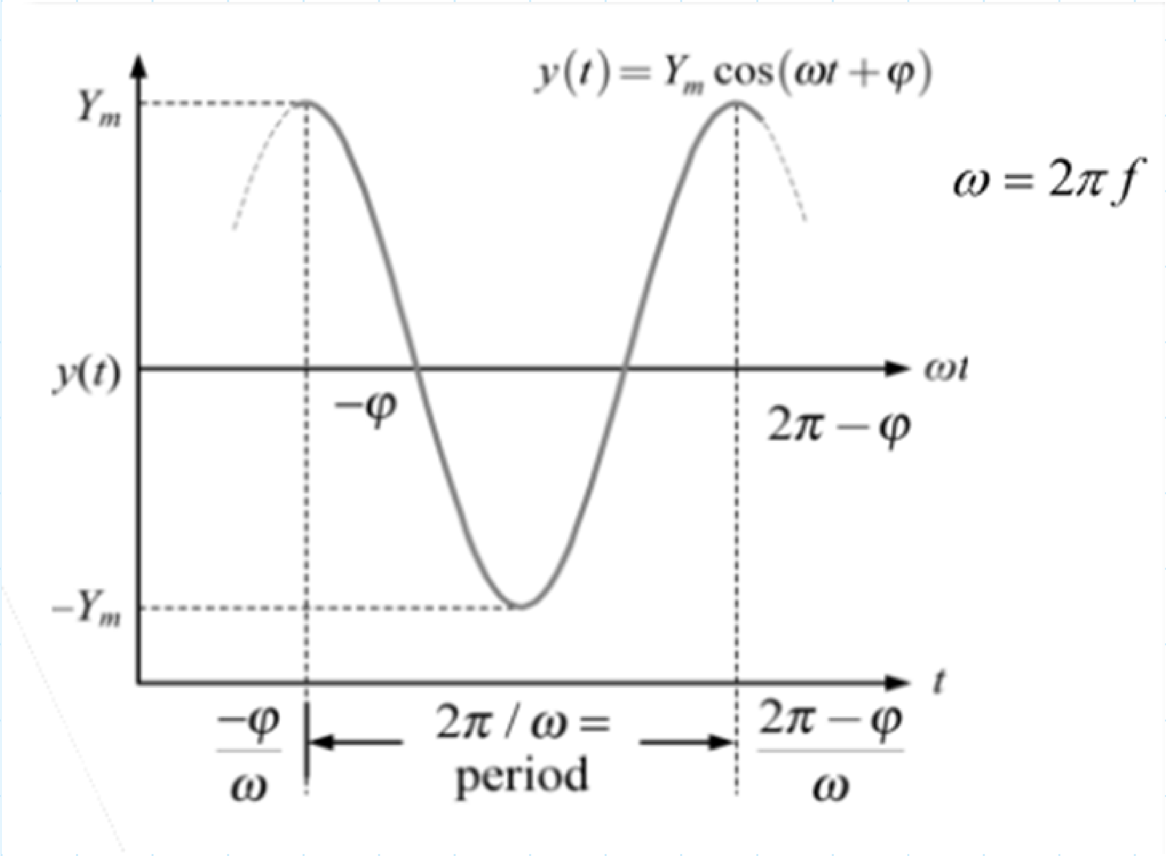
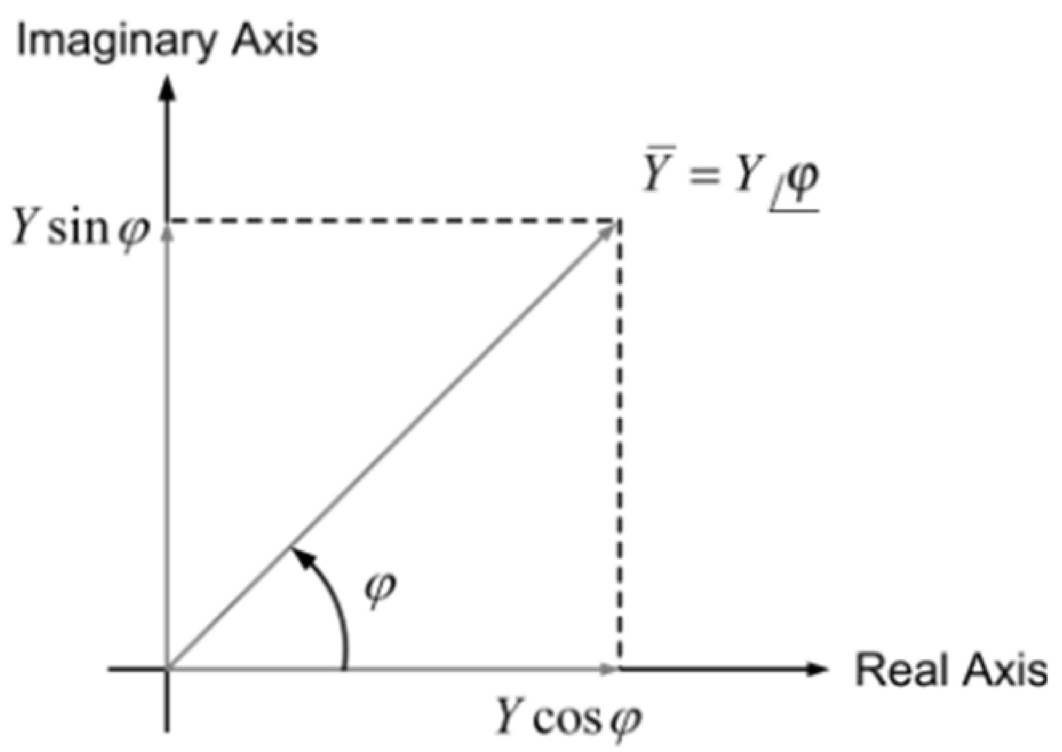


F = Frequency (50Hz or 60Hz)

For cosine function peaks @ zero angle

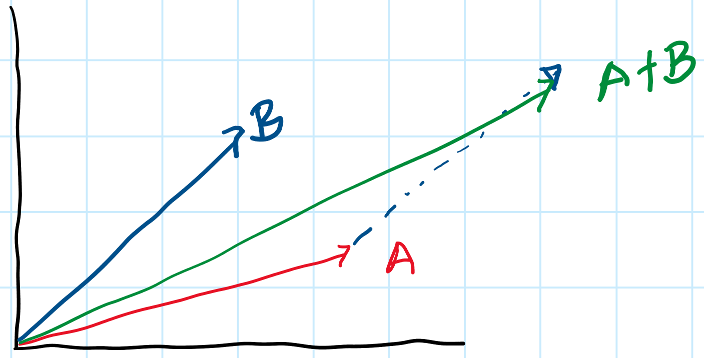
For sine function minimum @ zero angle



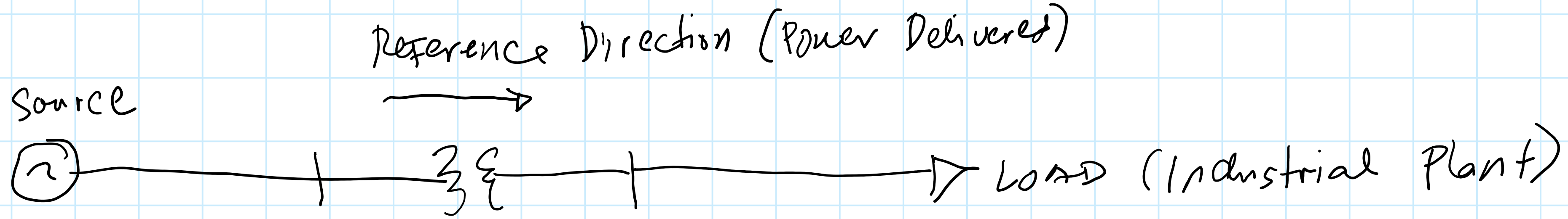
$\bar{Y} = Y\angle\phi$

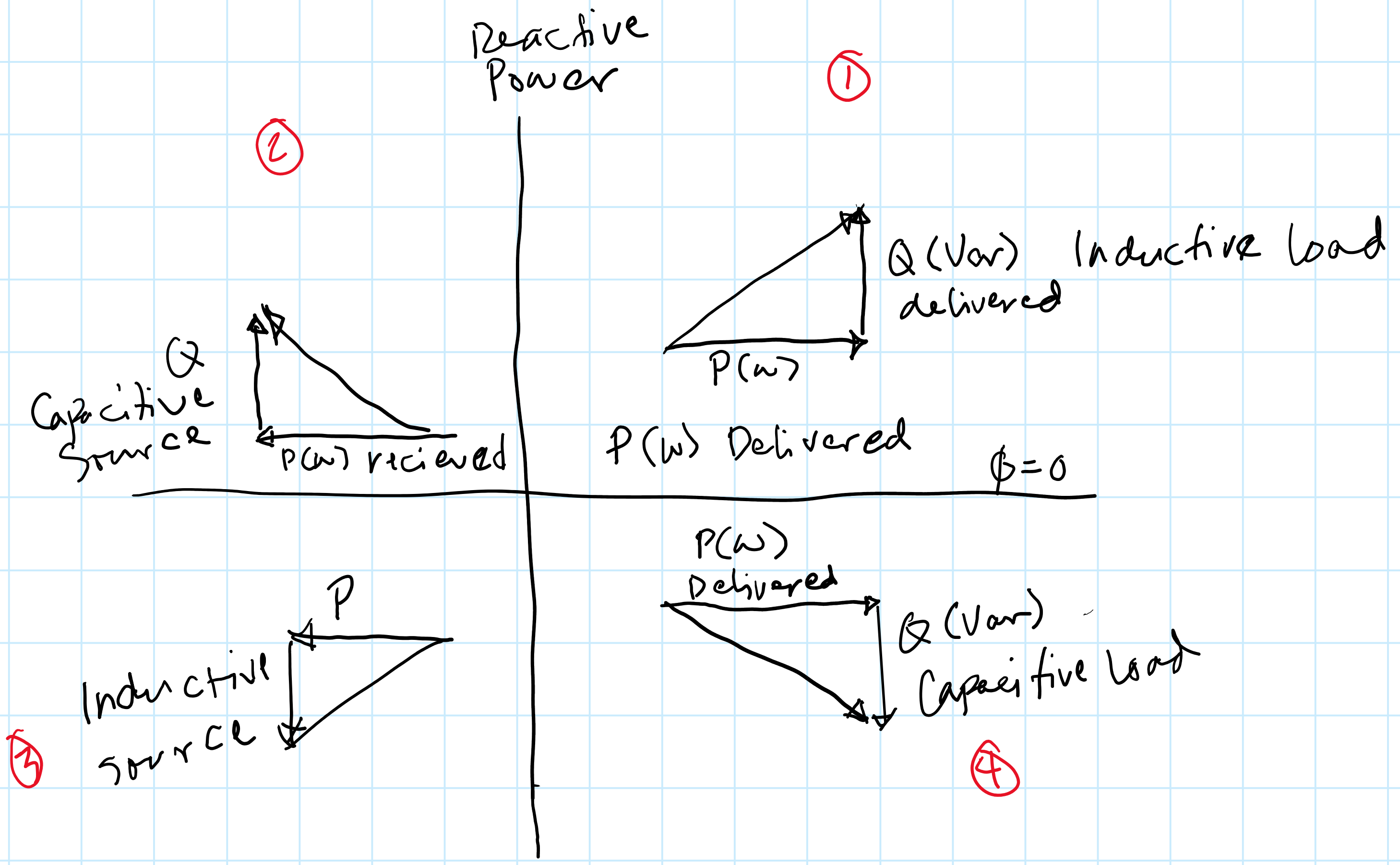
Phasors Operation

1) Addition
2) Multiplication
3) Division



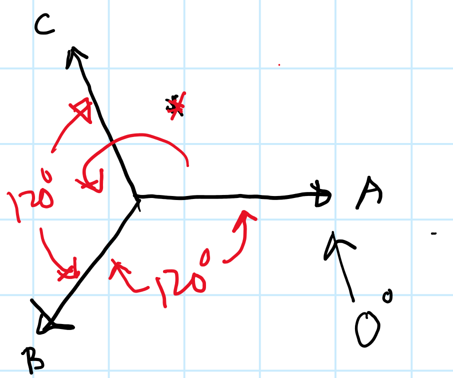
Power Singn Convention (IEEE 1459)



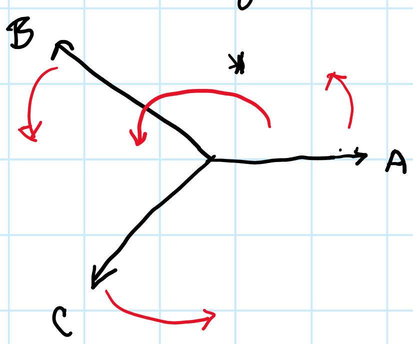


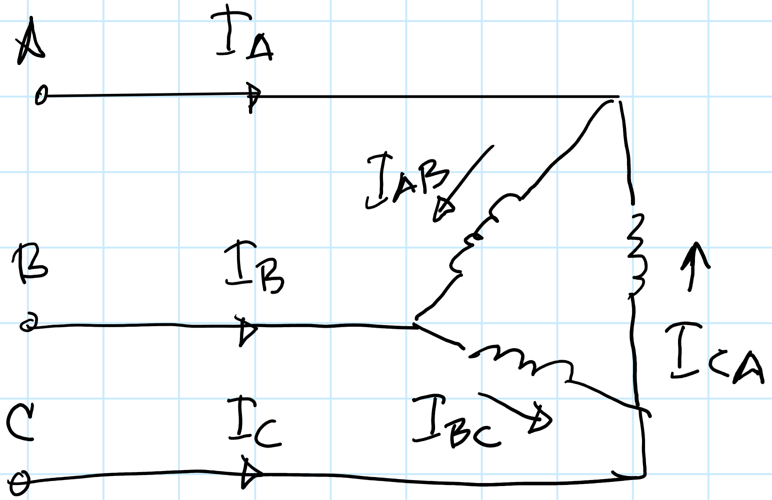
Balanced 3 Phase System

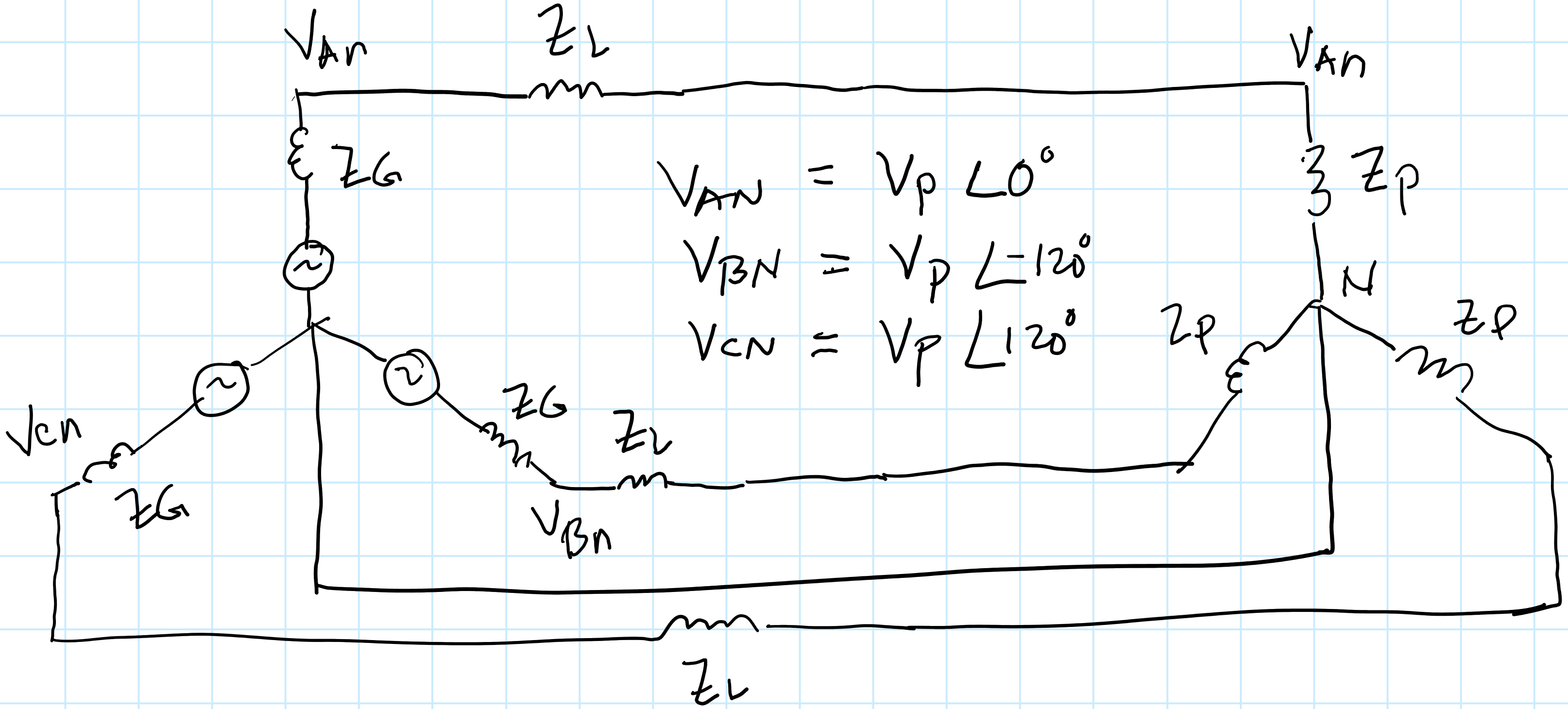
A-B-C sequence



A-C-B sequence







$V_{AN} = V_p \angle 0°$

$V_{BN} = V_p \angle -120°$

$V_{CN} = V_p \angle 120°$

Wye Connected Load

$V_p = V_L / \sqrt{3}$, $I_p = I_L$

Delta Connected Load

$V_p = V_L$, $I_p = I_L / \sqrt{3}$

Power System Faults

① Shunt Faults
- A) Short Circuits
- B) Contacts w/ Ground (Ground Faults)

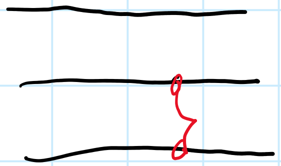
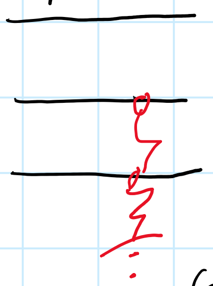
② Series Faults
- A) One phase Open
- B) Two phases Open

SHORT CIRCUITS

① High Currents
- A) Human safety
- B) Mechanical Stress – (SWG, XACC, Panel, Motor, Gen)
- C) Thermal stress

② Low Voltage
- A) Stability B) Power Quality

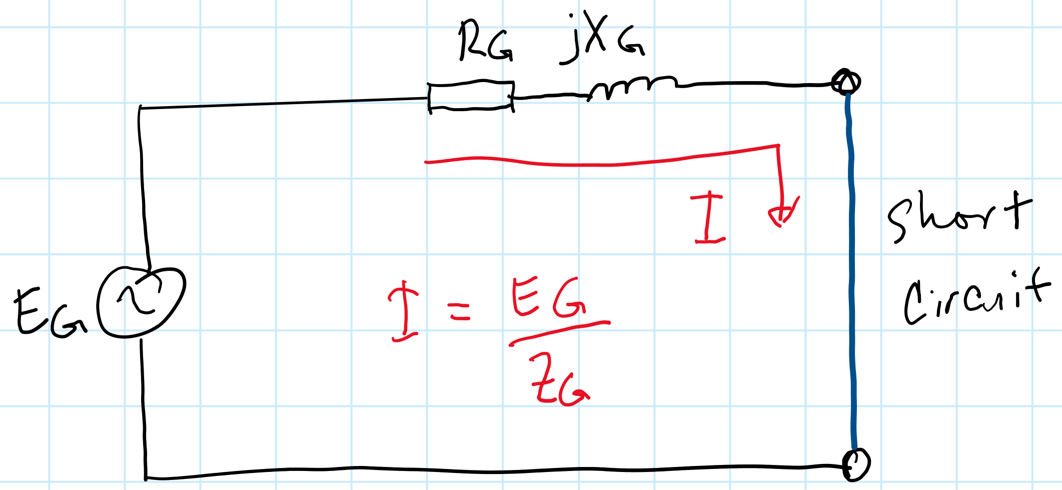
Types of Short Circuits

3 phase	Phase To Phase	Single Line To Ground	Double Line To Ground
			
	(3)	(3)	(3)
3 - Phase	A to B	A to Gnd	A to B to Gnd
	B to C	B to Gnd	B to C to Gnd
3 - phase To Gnd	C to A	C to Gnd	C to A to Gnd

Typical Short Circuit Statistics

- 3 phase — 2-3%
- phase - phase — 8-10%
- phase - phase - Gnd — 10-17%
- Single Phase To Gnd — 70-80%

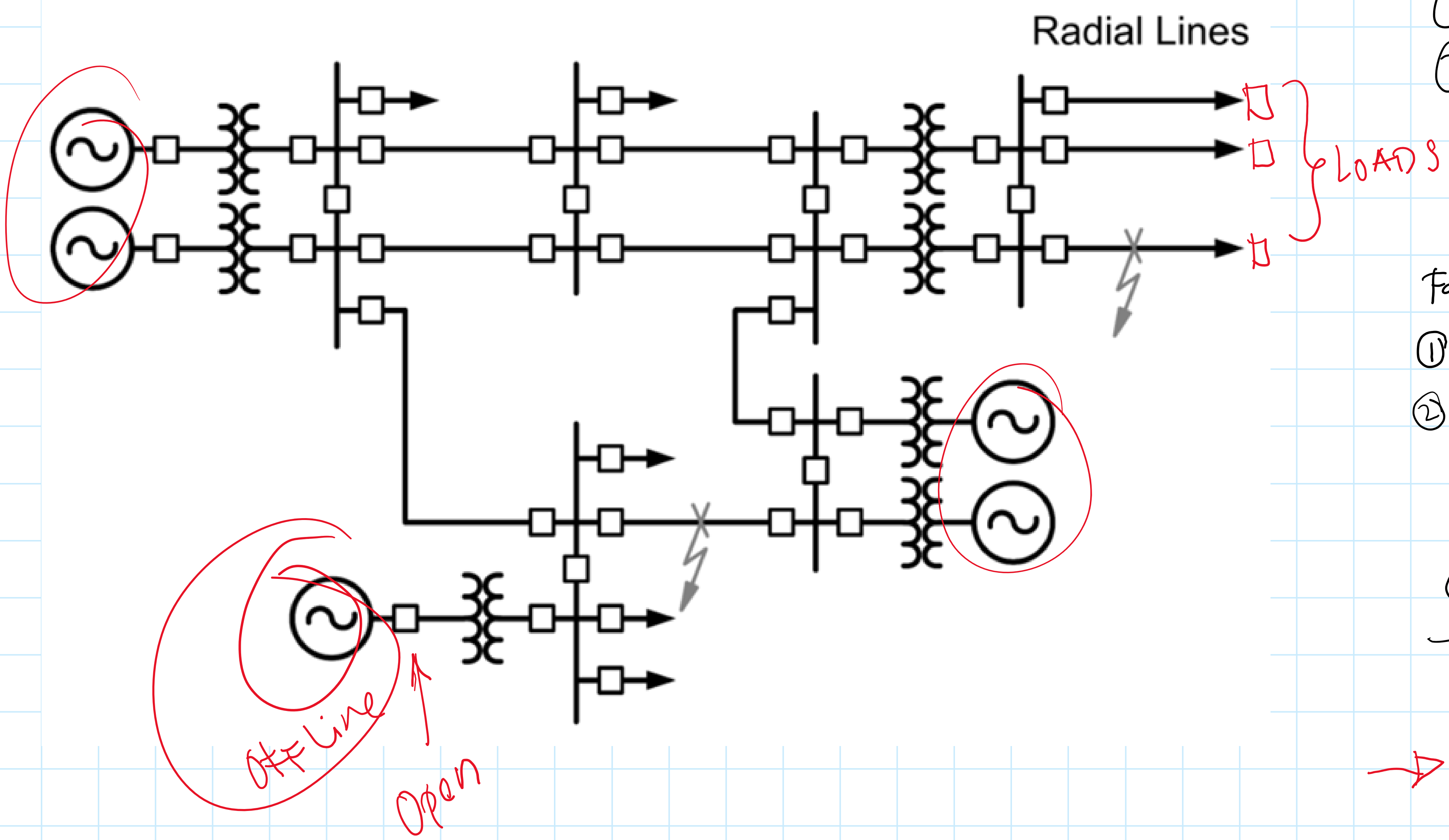
Simplified Model (3 phase Fault)



$I_A = I \angle \phi$

$I_B = I \angle \phi - 120°$

$I_C = I \angle \phi + 120°$



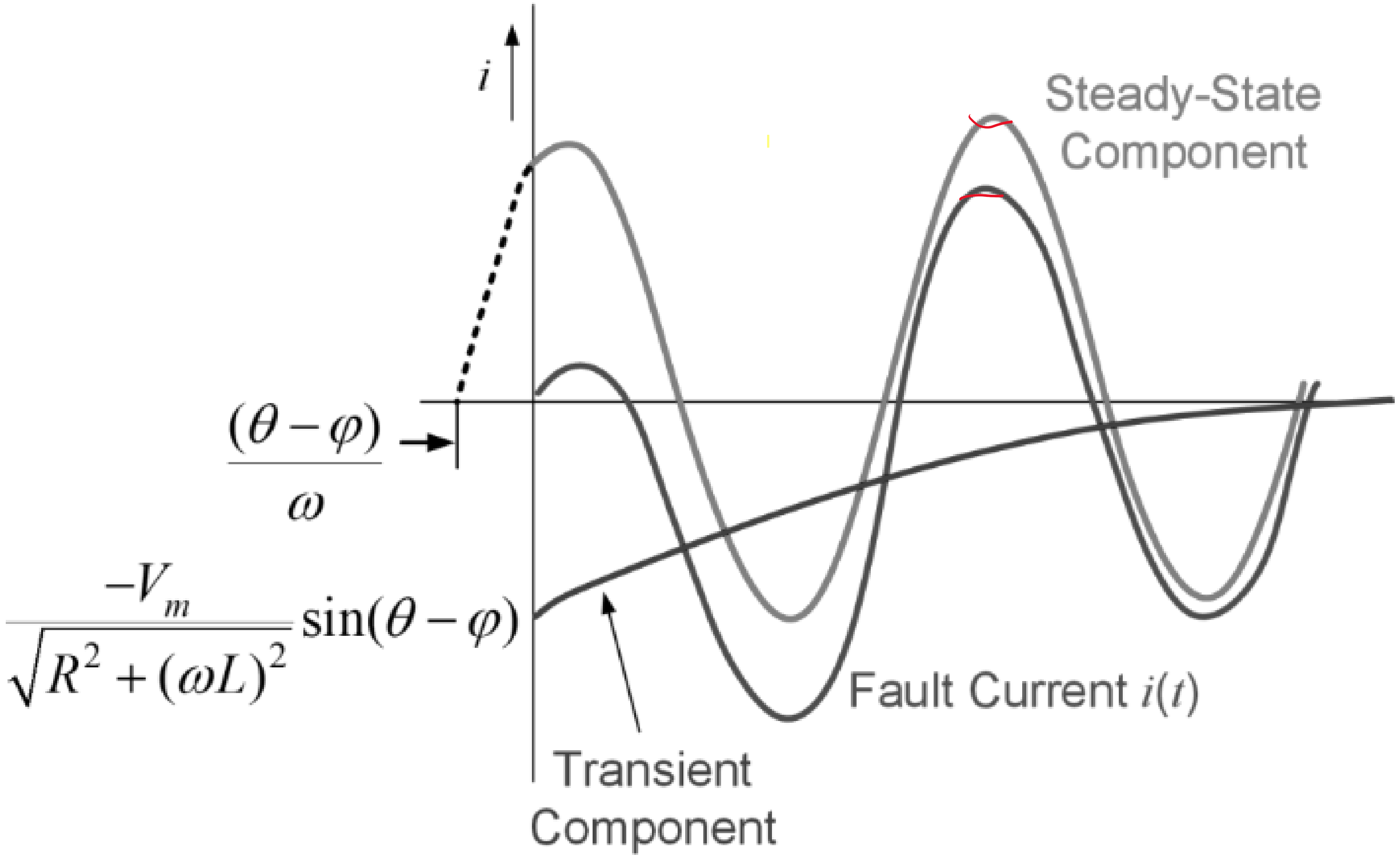
① Radial System
② Looped System

Fault Analysis

① Minimum Fault Current – Sensitivity Issues?
② Maximum Fault Current

Group Settings → Relays (Numerical Relays)

Group 1 – 5 A pickup
→ Group 2 – 3 A pickup



RMS Value of Fault Current

① For Symmetrical Fault

$$I = \frac{E}{Z}$$

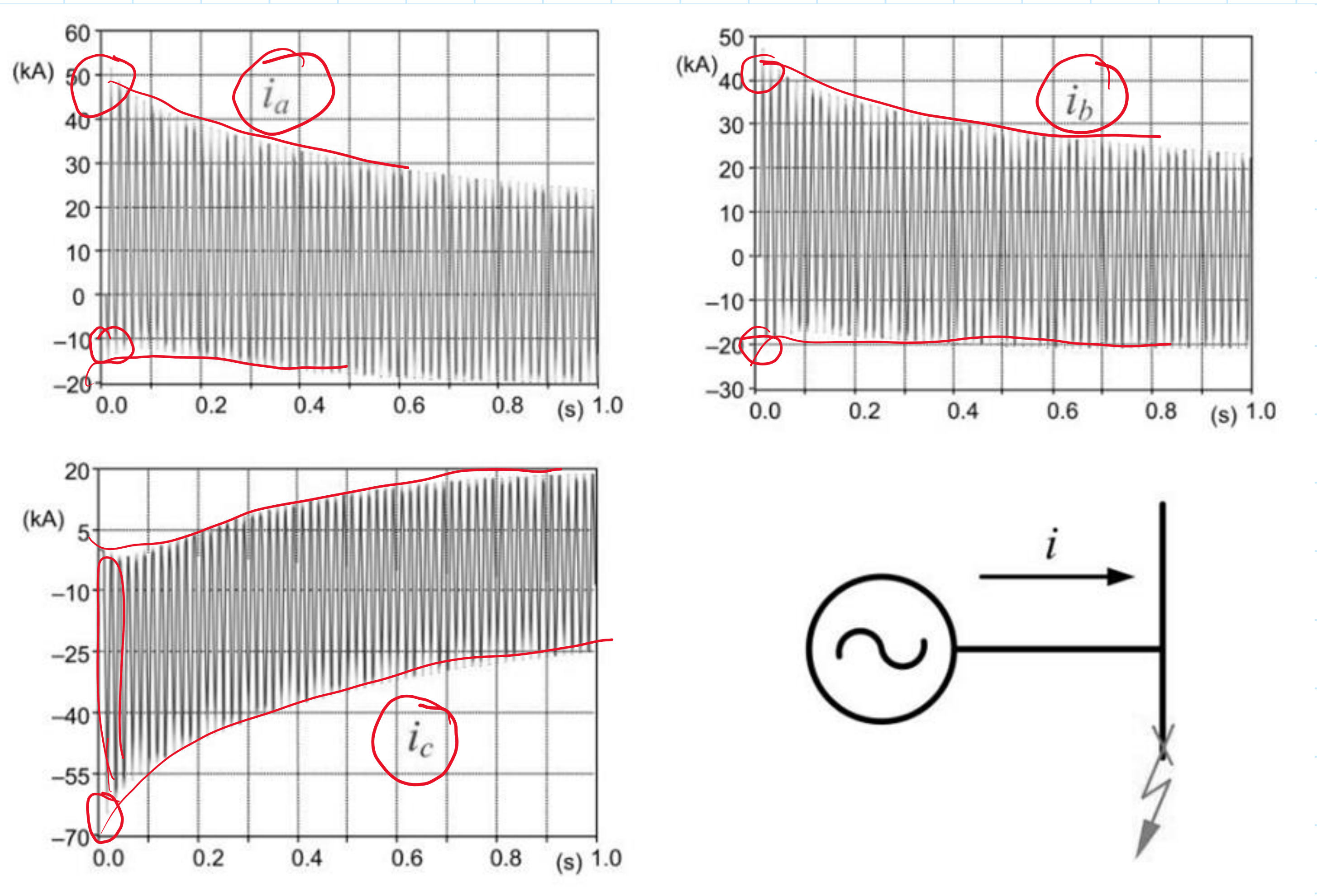
② For Asymmetrical Fault

$$I_{rms} = I \cdot \sqrt{1 + 2e^{-2t/\tau}}$$

$$i(t) = \frac{V_m}{Z}\sin(\omega t + \theta - \phi) - \frac{V_m}{Z}\sin(\theta - \phi)\, e^{-\frac{R}{L}t}$$

$$Z = \sqrt{R^2 + X^2} = \sqrt{R^2 + (\omega L)^2} \qquad \omega = 2\pi F$$

$$\phi = \arctan\left(\frac{\omega L}{R}\right)$$



Three Phase Fault At the Terminals of A Generator

$I''_d = E''/X''_d$ X''_d → Subtransient Reactance

$I'_d = E'/X'_d$ X'_d → Transient Reactance

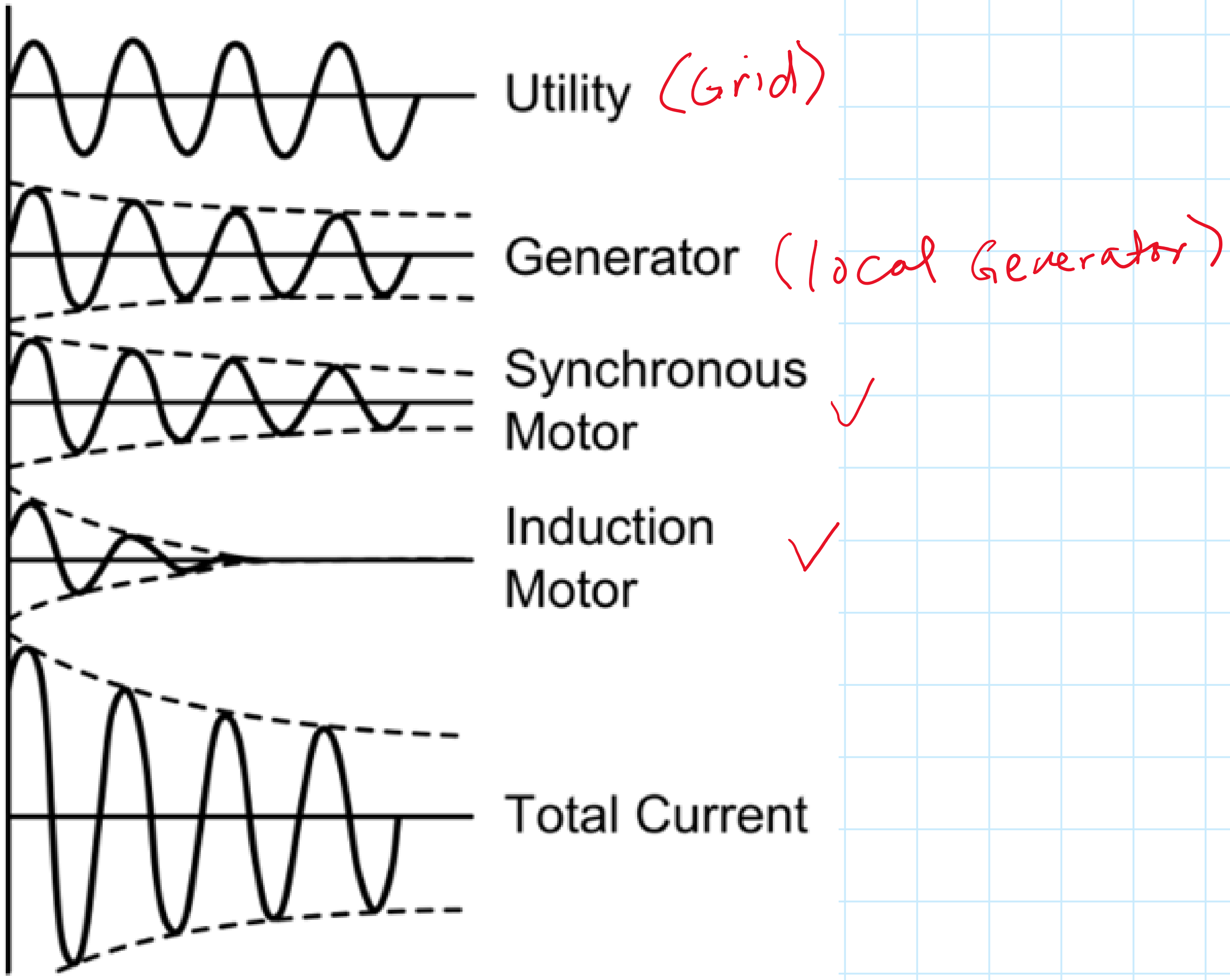
$I_d = E/X_d$ X_d → Synchronous Reactance

$X''_d \approx 0.10$ pu (2 cycles) → 10 pu Current

$X'_d \approx 0.20$ pu (10 - 20 cycles) → 5 pu current

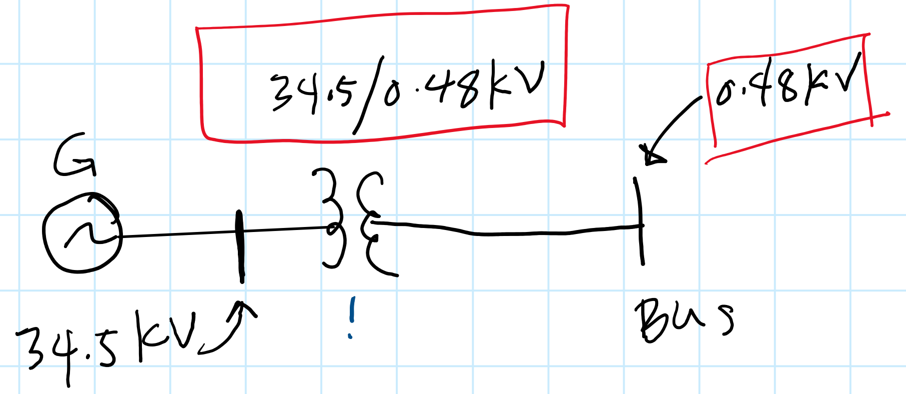
$X_d \approx 1.7$ pu (1 to 2 seconds) → 0.6 pu current

Typical Contributions To Fault



During Faults – Motor terminal voltage collapses to zero

Per Unit Representation



Per Unit Quantity = $\dfrac{\text{Actual Quantity}}{\text{Base Quantity}}$

Step 1 → select 10 MVA power base

Actual Quantity can be scalar or complex

Step 2 → select 34.5 kV base
0.48 kV base

Percent Quantity = per unit quantity × 100%

$\dfrac{.46}{.48}$

Per unit Steps

1. Select 3Φ power Base
2. Select phase-phase voltage base
   - A) One per voltage level
   - B) Select one value and use the transformer ratio to calculate (or the other

3. Calculate per current and Impedance Bases (one per voltage level)

$I_{base} = \dfrac{S_{base}}{\sqrt{3}\, V_{base}} = \dfrac{kVA_{base}}{\sqrt{3}\, kV_{base}}$

$= \dfrac{V_{base}/\sqrt{3}}{} \quad \dfrac{(V_{base})^2}{} \quad \dfrac{(kV_{base})^2}{}$

transformer ratio to calculate
for the other

$\sqrt{3}\ V_{base} \qquad \sqrt{3}\ kV_{base}$

$$Z_{base} = \frac{V_{base}/\sqrt{3}}{I_{base}} = \frac{(V_{base})^2}{S_{base}} = \frac{(kV_{base})^2}{MVA_{base}}$$

Change of Base

$$Z_{pu}^{OLD} = \frac{Z}{Z_{base}^{OLD}} = Z\left[\frac{S_{base}^{OLD}}{{V_{base}^{OLD}}^2}\right]$$

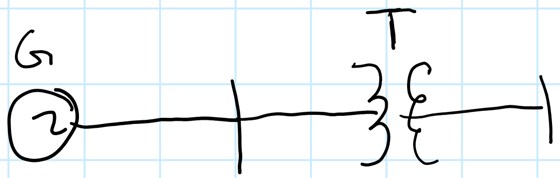
$$Z_{pu}^{new} = \frac{Z}{Z_{base}^{new}} = Z\left[\frac{S_{base}^{new}}{{V_{base}^{new}}^2}\right]$$

$$Z_{pu}^{new} = Z_{pu}^{OLD}\left[\frac{S_{base}^{new}}{S_{base}^{OLD}}\right]\left[\frac{V_{base}^{OLD}}{V_{base}^{new}}\right]^2$$

EXAMPLE:

Find the equivalent reactance on a 100MVA, 115kV base:

- Generator: 50MVA, 13.2 kV, $X_G = 15\%$
- Transformer: 50MVA, 13.8kV, $X_T = 8\%$



$$X_G^{new} = \frac{15\%}{100\%} \times \left[\frac{100}{50}\right]\left[\frac{13.2}{115}\right]^2 = 0.00395\,pu$$

$$X_T^{new} = \frac{8\%}{100\%} \times \left[\frac{100}{50}\right]\left[\frac{13.8}{115}\right]^2 = 0.002304\,pu$$

$$I_{FAULT} = \frac{E}{X_G + X_T} = \frac{1.0\angle 0^\circ}{j0.00395 + j0.002304} = 159.9\,pu$$

$$I_{base\text{-}34.5} = \frac{100{,}000}{\sqrt{3} \times 34.5} = 1673.5\ \text{Amps}$$

$$I_{FAULT\text{-}34.5} = 159.9 \times 1673.5 = 267{,}592\,A$$

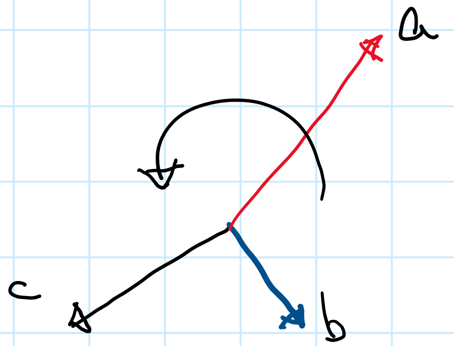
Introductory Facts about Symmetrical Components

① A single phase calculation can determine the A-phase current in a balanced 3-phase fault

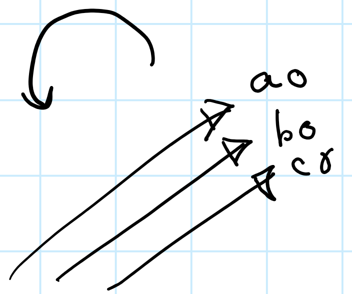
② other phases have same magnitude but are 120° apart

③ If the fault is not balanced, then none of the above is true.

$a = 1 \angle 120°$



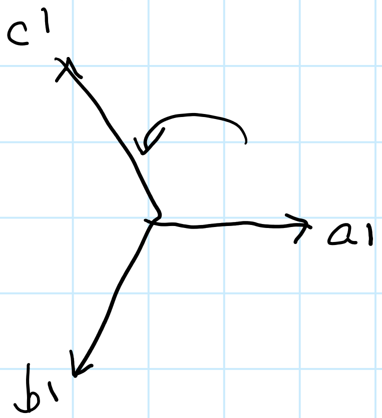
Original Physical Domain



Zero Sequence

$I_{A0} = I_{B0} = I_{C0}$

+

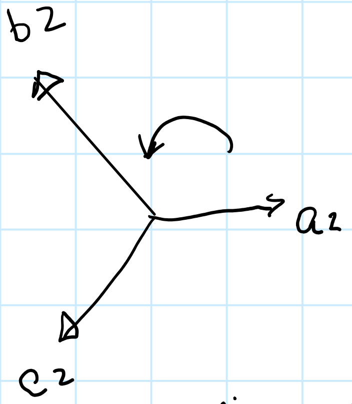


Positive Sequence

$I_{B1} = a^2 I_{A1}$

$I_{C1} = a I_{A1}$

+

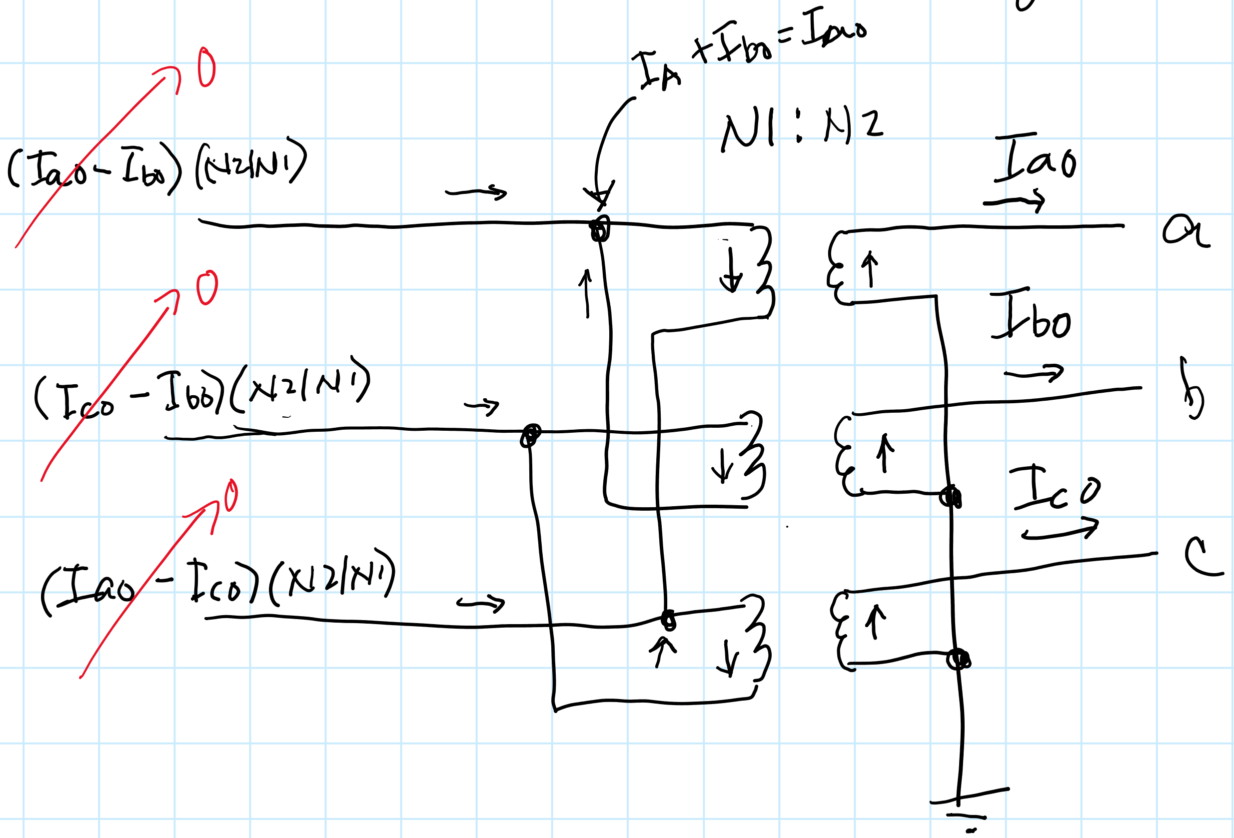


Negative sequence

$I_{B2} = a I_{A2}$

$I_{C} = a^2 I_{A2}$

Delta Connections Trap Zero-Sequence Currents



Since $I_{ao} = I_{bo} = I_{co}$

Information From Sequence Quantities During Faults

Positive Sequence – Load and fault information (all types of faults)

Negative Sequence – Load unbalance and fault info (unbalanced faults – LL, LLG, SLG)

Zero Sequence – load unbalance and fault info (Ground faults – SLG, LLG)

Power System Grounding

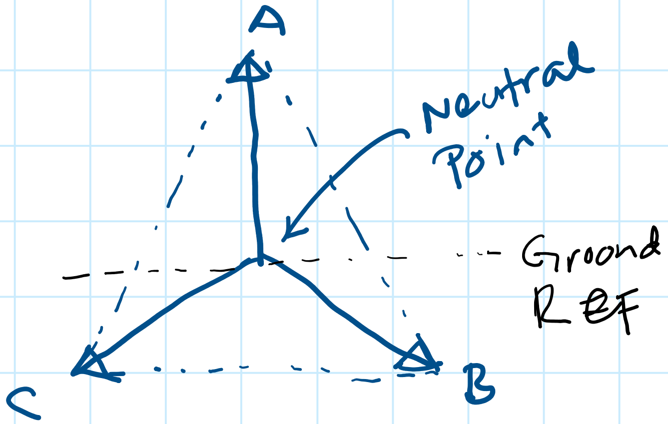
① Isolated Ground (Ungrounded) - Risk of overvoltages

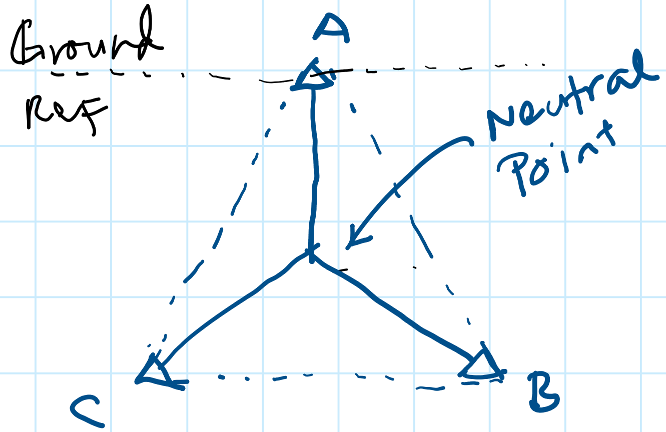
② Effectively grounded (Solidly Grounded)

③ Low - Impedance Grounding

④ High - Impedance Grounding (limits fault current to 15A)

⑤ Resonant Grounding

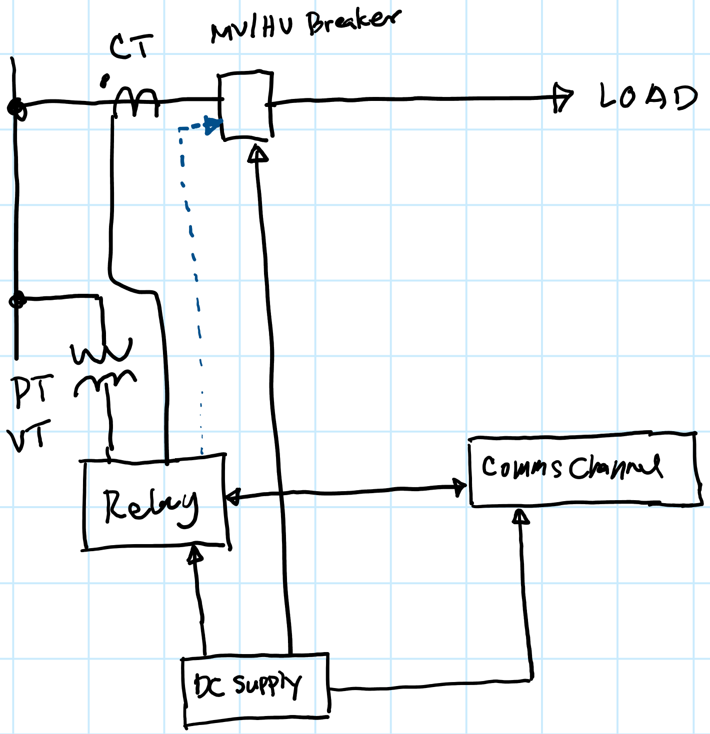




ANSI IEEE C37.2 Device Number

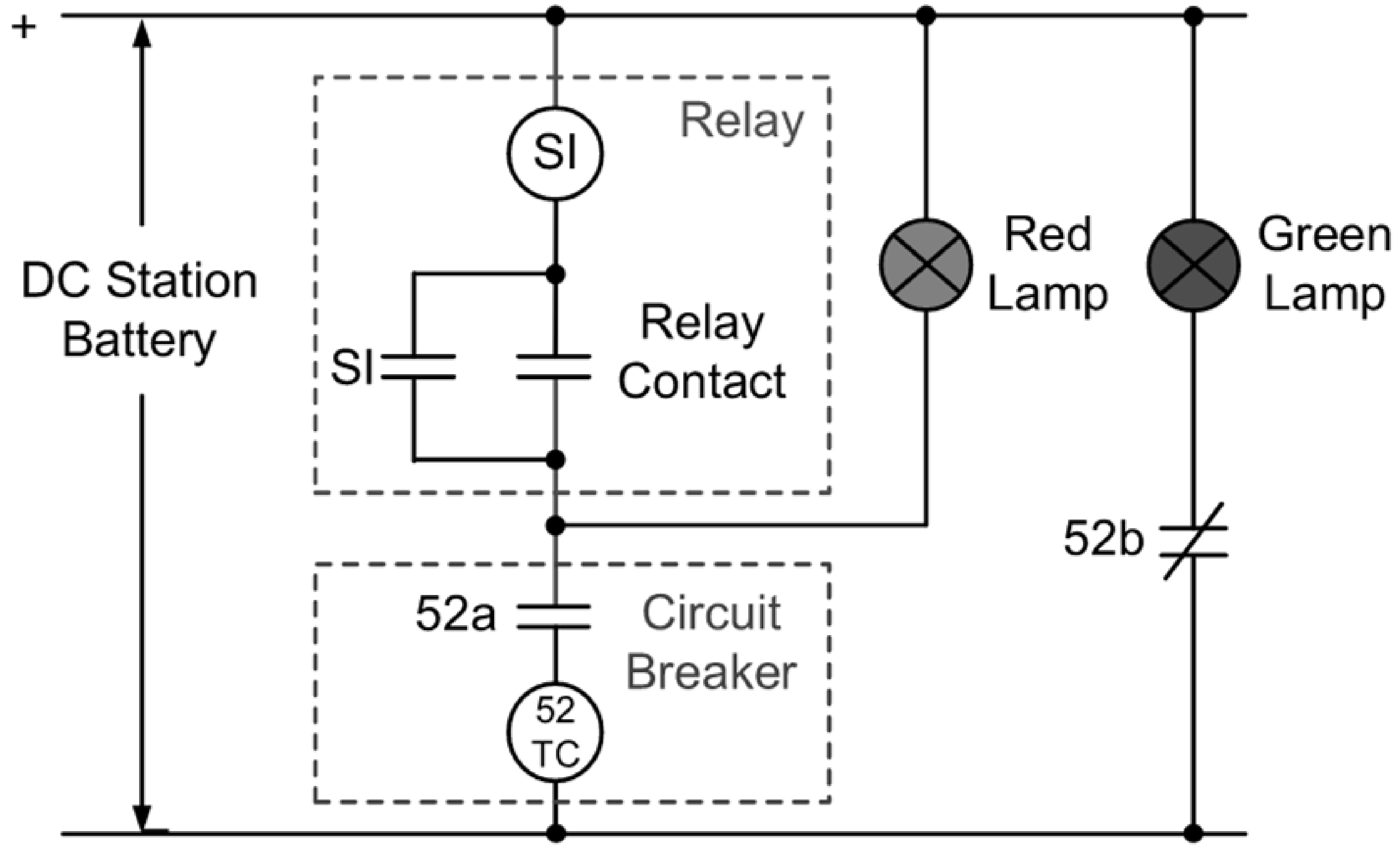
50 - Instantaneous Overcurrent Relay
51 - Time-overcurrent Relay
67 - Directional overcurrent Relay
87 - Differential Relay
52 - Circuit Breaker

Relay Protection System



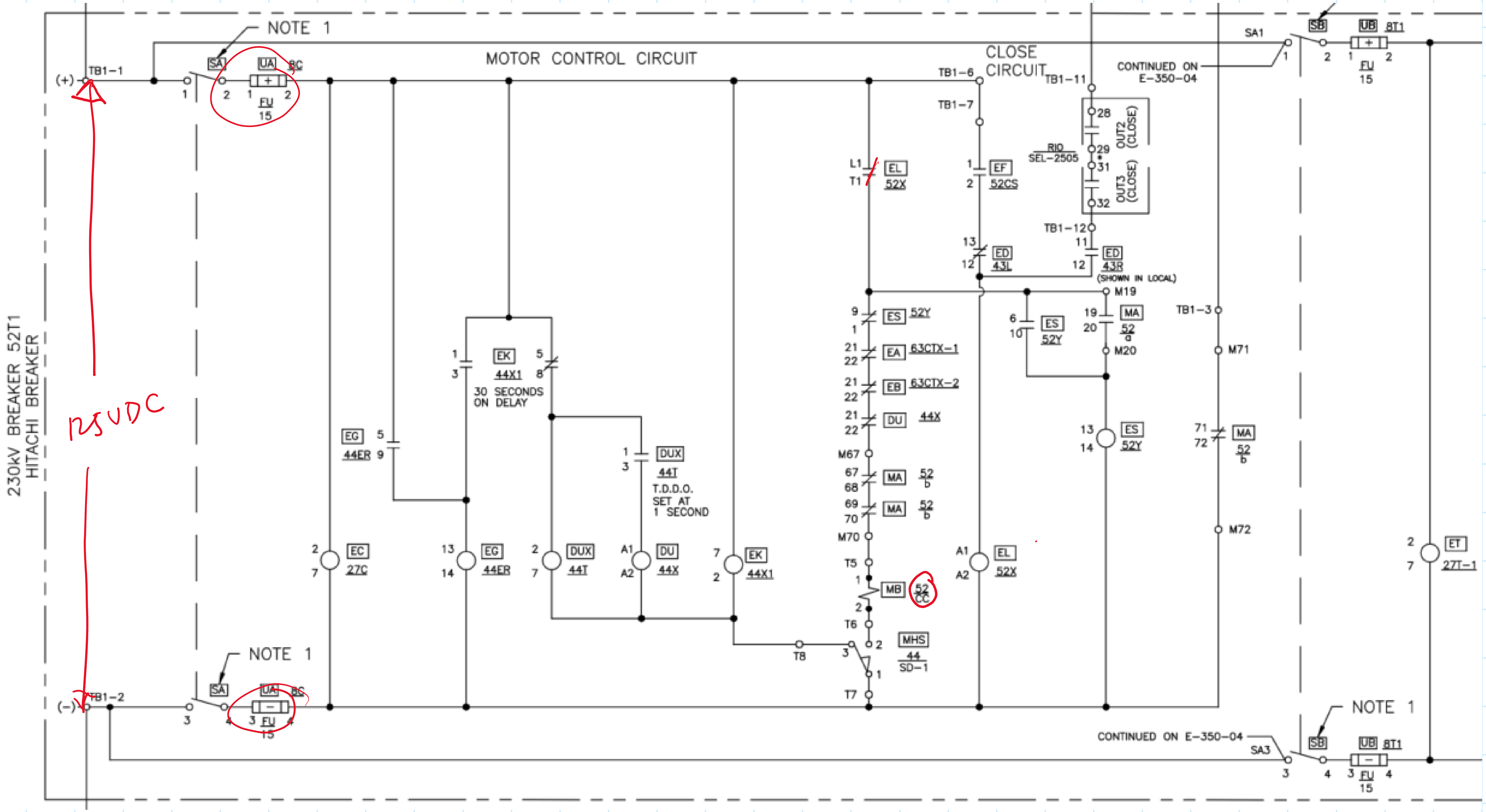
Power System protection Function

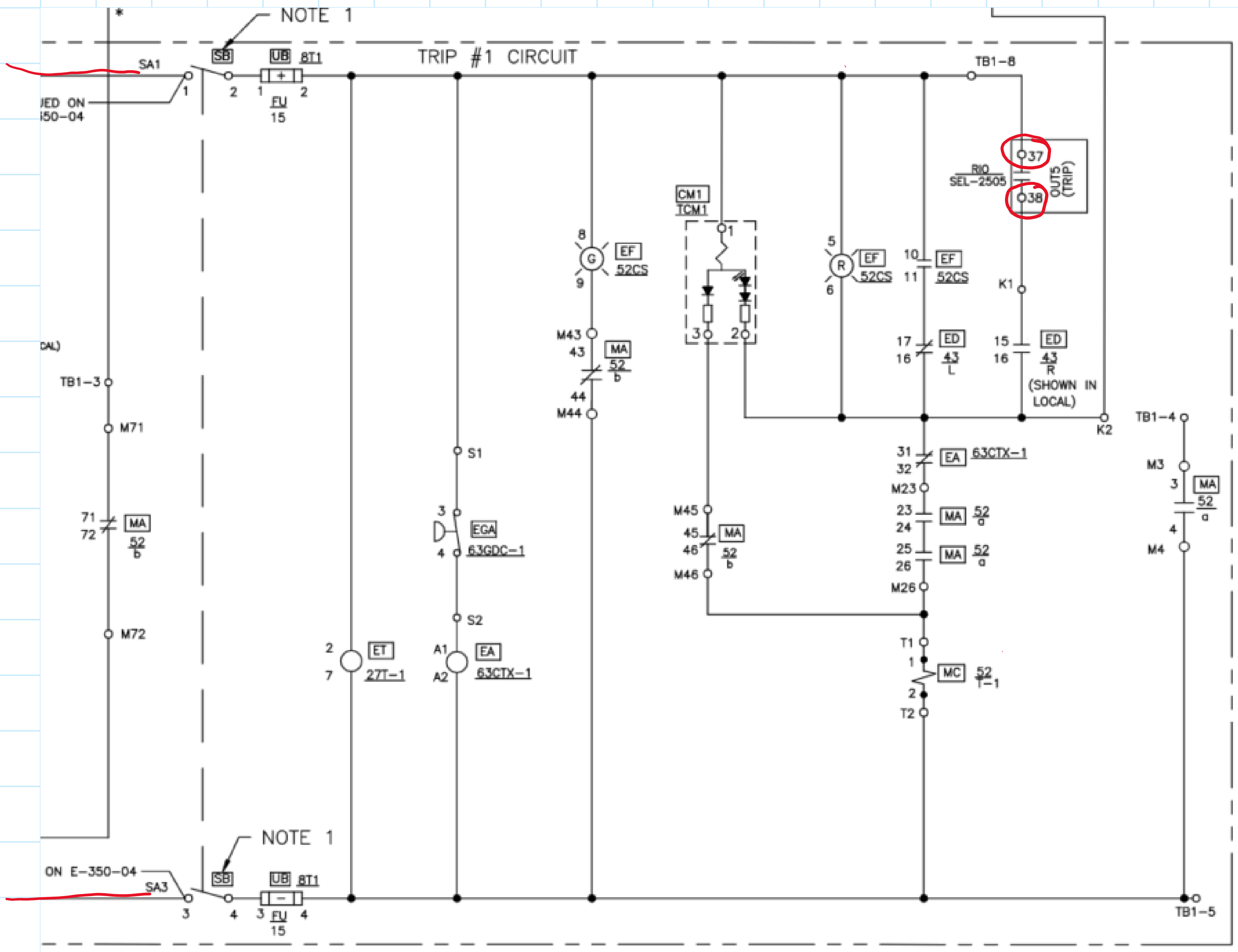
1) Fault detection
2) Current Interruption
3) Fault Indication (signaling, alarm)



52a Contact → Contact is Open when breaker is Open

52b Contact → Contact is closed when breaker is Open


230kV BREAKER 52T1
HITACHI BREAKER
125VDC
NOTE 1
MOTOR CONTROL CIRCUIT
CLOSE
CIRCUIT
CONTINUED ON
E-350-04
(+)
TB1-1
(-)
TB1-2
SA
UA
BC
FU
15
SB
UB
8T1
SA1
SA3
TB1-6
TB1-7
TB1-11
TB1-12
TB1-3
RIO
SEL-2505
OUT2
(CLOSE)
OUT3
(CLOSE)
EL
52X
EF
52CS
ED
43L
43R
(SHOWN IN LOCAL)
M19
M20
M67
M70
M71
M72
ES
52Y
MA
EA
63CTX-1
EB
63CTX-2
DU
44X
EK
44X1
30 SECONDS
ON DELAY
EG
44ER
DUX
44T
T.D.D.O.
SET AT
1 SECOND
EC
27C
MB
52
CC
MHS
44
SD-1
T5
T6
T7
T8
ET
27T-1
CONTINUED ON E-350-04


NOTE 1
TRIP #1 CIRCUIT
SB
UB 8T1
FU 15
SA1
TB1-8
RIO SEL-2505
37
38
OUT5 (TRIP)
CM1 TCM1
EF 52CS
ED 43 L
ED 43 R
(SHOWN IN LOCAL)
K1
K2
TB1-3
M71
M72
MA 52 b
M43
M44
M45
M46
S1
S2
EGA 63GDC-1
ET 27T-1
EA 63CTX-1
EA 63CTX-1
M23
M26
MA 52 a
T1
T2
MC 52 T-1
TB1-4
M3
M4
TB1-5
ON E-350-04
SA3
NOTE 1

ANSI standard burden for relaying CTs with 5 A secondary

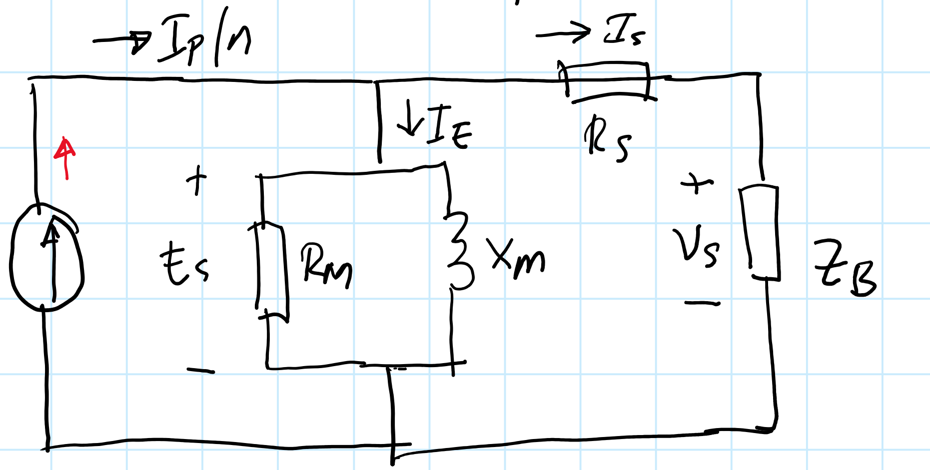
ANSI class	Burden designation	Impedance (ohms)	Volt-amperes (at 5 A)	Power factor
C10	B-0.1	0.1	2.5	0.9
C20	B-0.2	0.2	5.0	0.9
C50	B-0.5	0.5	12.5	0.9
C100	B-1.0	1.0	25	0.5
C200	B-2.0	2.0	50	0.5
C400	B-4.0	4.0	100	0.5
C800	B-8.0	8.0	200	0.5

$20 \times 5A \times 8\Omega = 800V$ — C800

Types of Current Transformer

1) Metering CT
   - Revenue metering
   - Accuracy is define for normal load current

2) Relaying CT
   - used for protection
   - Accuracy is defined for fault currents



$$\text{Ratio Error} = \frac{[I_s - I_p/n]}{I_p/n} = I_E/I_s$$

ANSI versus IEC

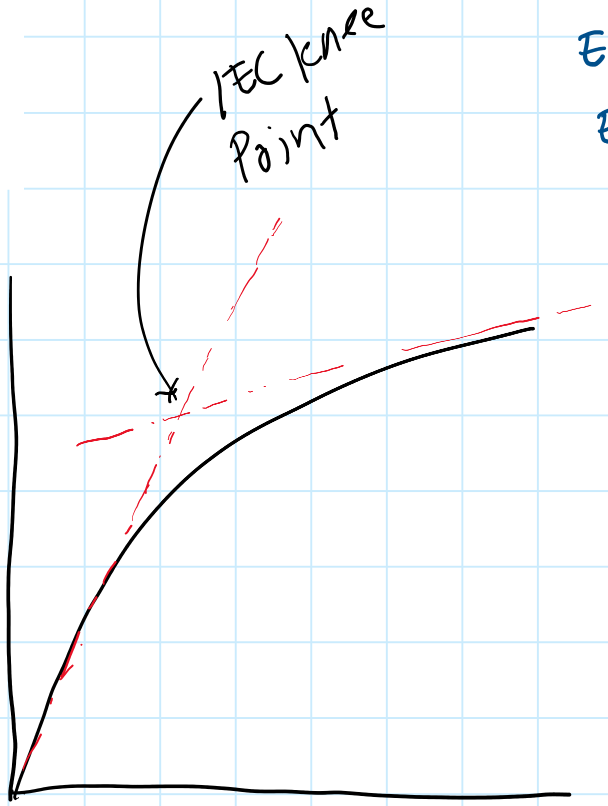
Knee point

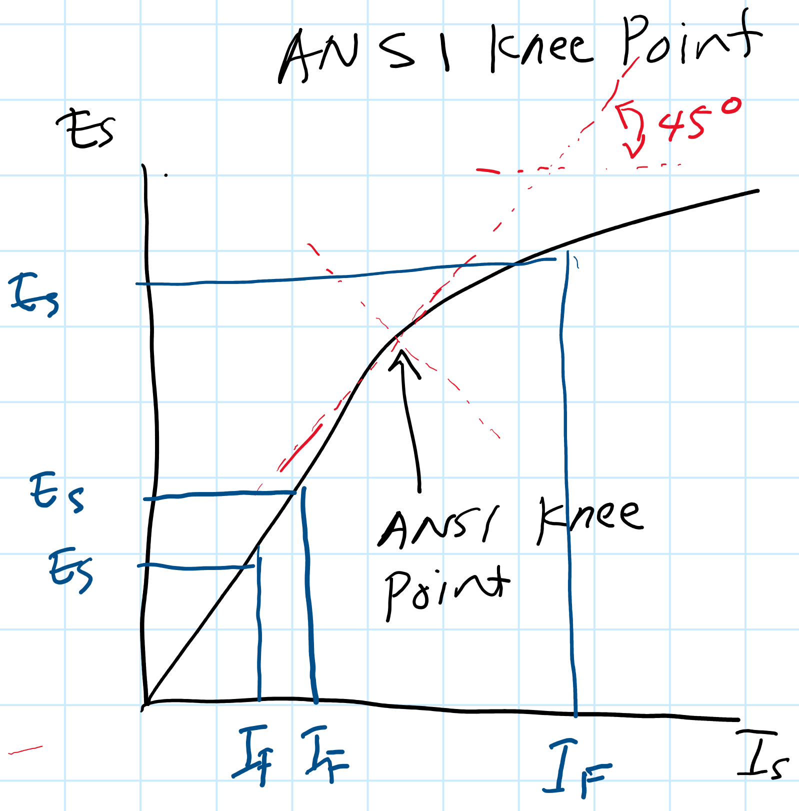
ANSI

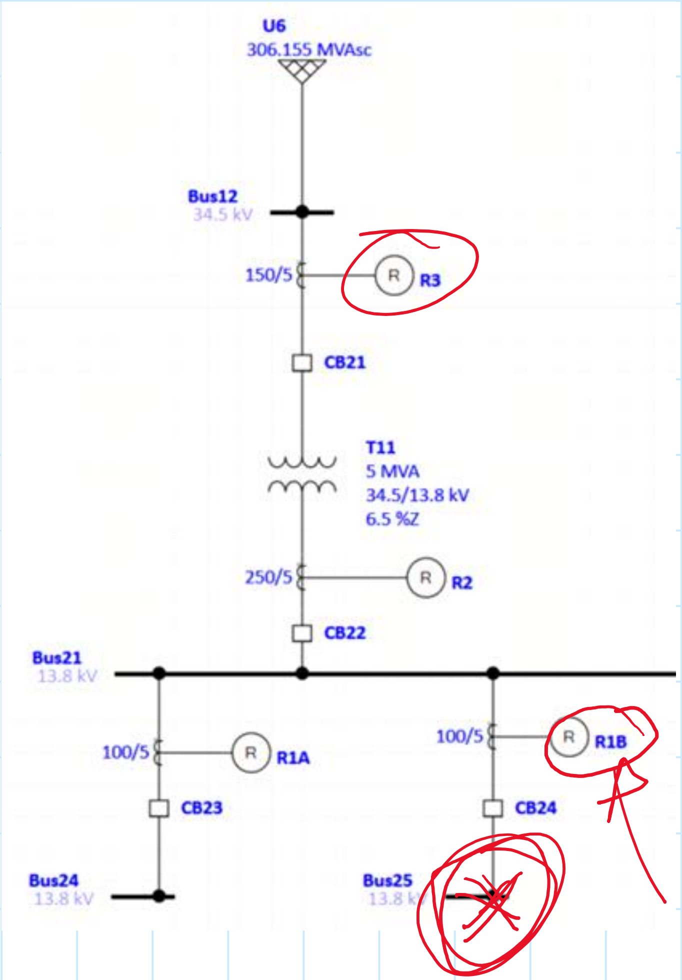
- Point on excitation curve where 45-degree line is tangent
- Near one-half ANSI C rating

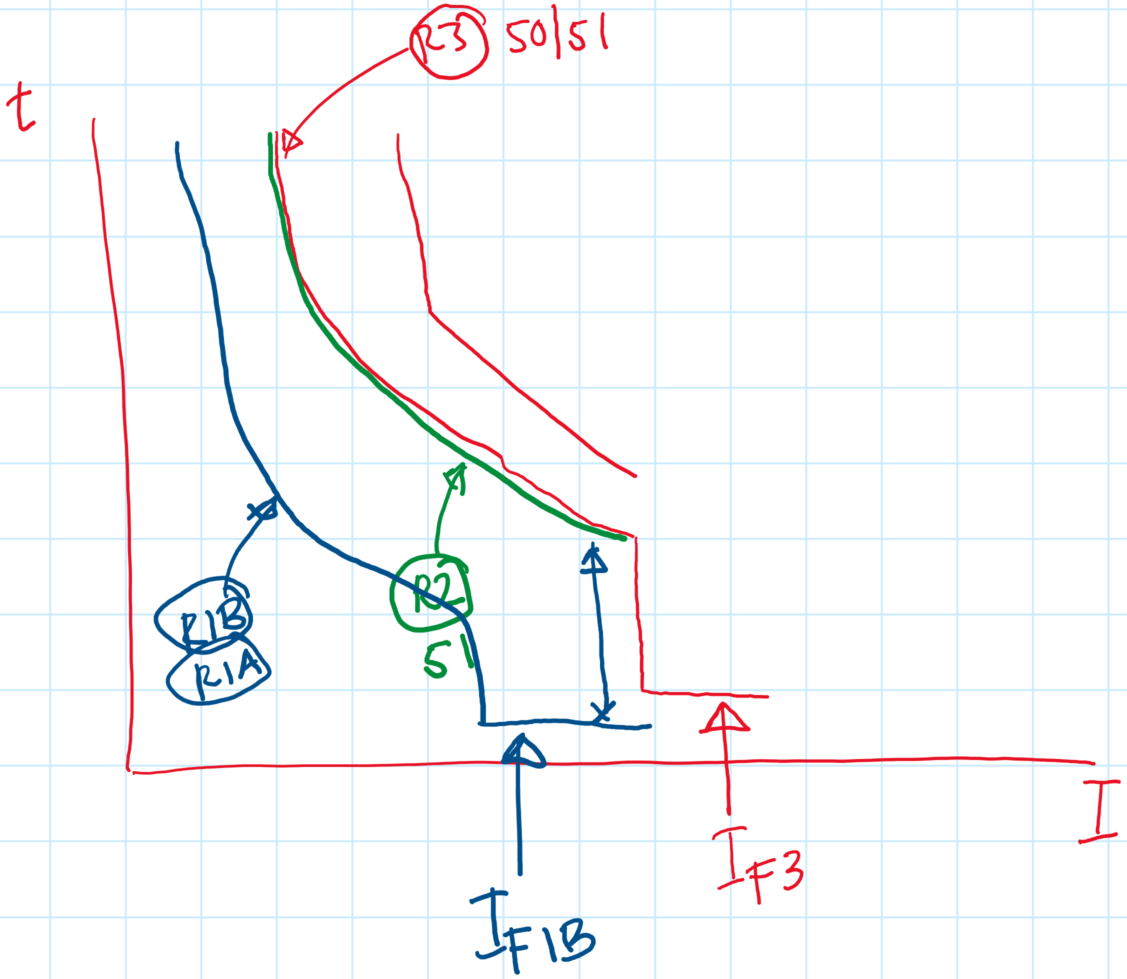
IEC

- 10 percent change in excitation voltage causes 50 percent change in excitation current
- Near ANSI C rating

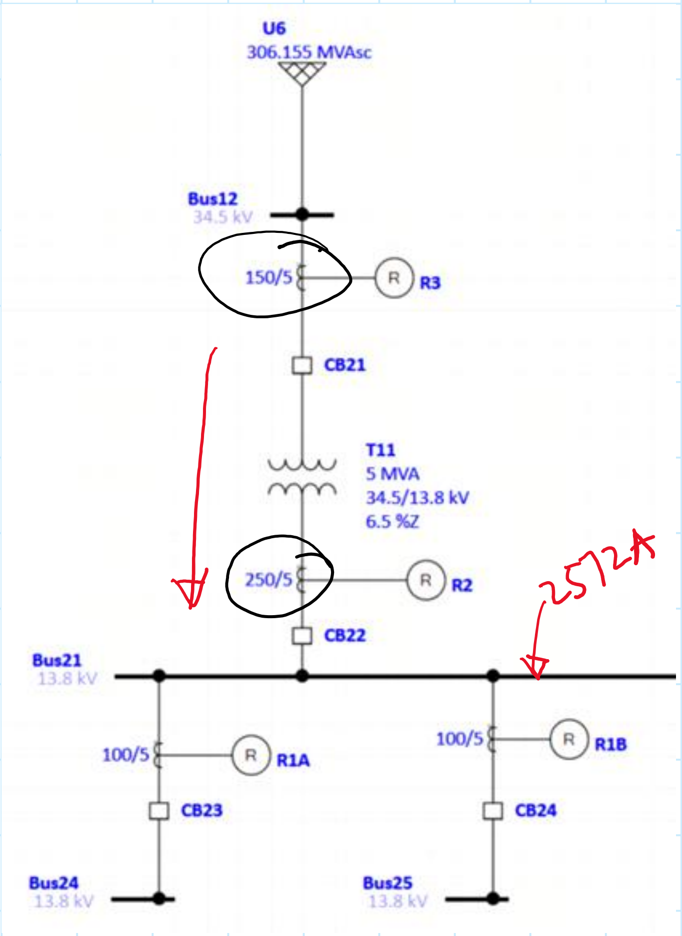





U6
306.155 MVAsc
Bus12
34.5 kV
150/5
R
R3
CB21
T11
5 MVA
34.5/13.8 kV
6.5 %Z
250/5
R
R2
CB22
Bus21
13.8 kV
100/5
R
R1A
100/5
R
R1B
CB23
CB24
Bus24
13.8 kV
Bus25


R3 50/51
t
R1B
R1A
R2
51
I
I_{F1B}
I_{F3}

Determine Setting for Relay #3 50 Element (Inst. OC)



① Should not detect the heaviest fault on the secondary side of bus.

$$I_{pu50} = \frac{125\% \times I_F \times (13.8/34.5)}{CTR} = \frac{1.25 \times 2572 \times (13.8/34.5)}{150/5} = 42.87\,A$$

② Should not detect transformer inrush current.

$$I_{pu50} = \frac{15 \times I_N}{CTR} = \frac{15 \times (5{,}000{,}000/\sqrt{3}/34500)}{150/5} = 41.84\,A$$

Choose 45A pickup

Determine the Relay #3 51 element setting (Inverse-Time OC)

Relay 3 Pickup:

I_{pu51} = 125% × I_N / CTR = 125% × 83.67 / (150/5) = 3.49 A, choose I_{pu51} = 3.5 A

Relay 3 Time Dial:

Choose US Inverse curve

$$T = TD\left[\frac{5.95}{M^2-1} + 0.18\right]$$

where: M = Multiple of pickup

TD = Time Dial

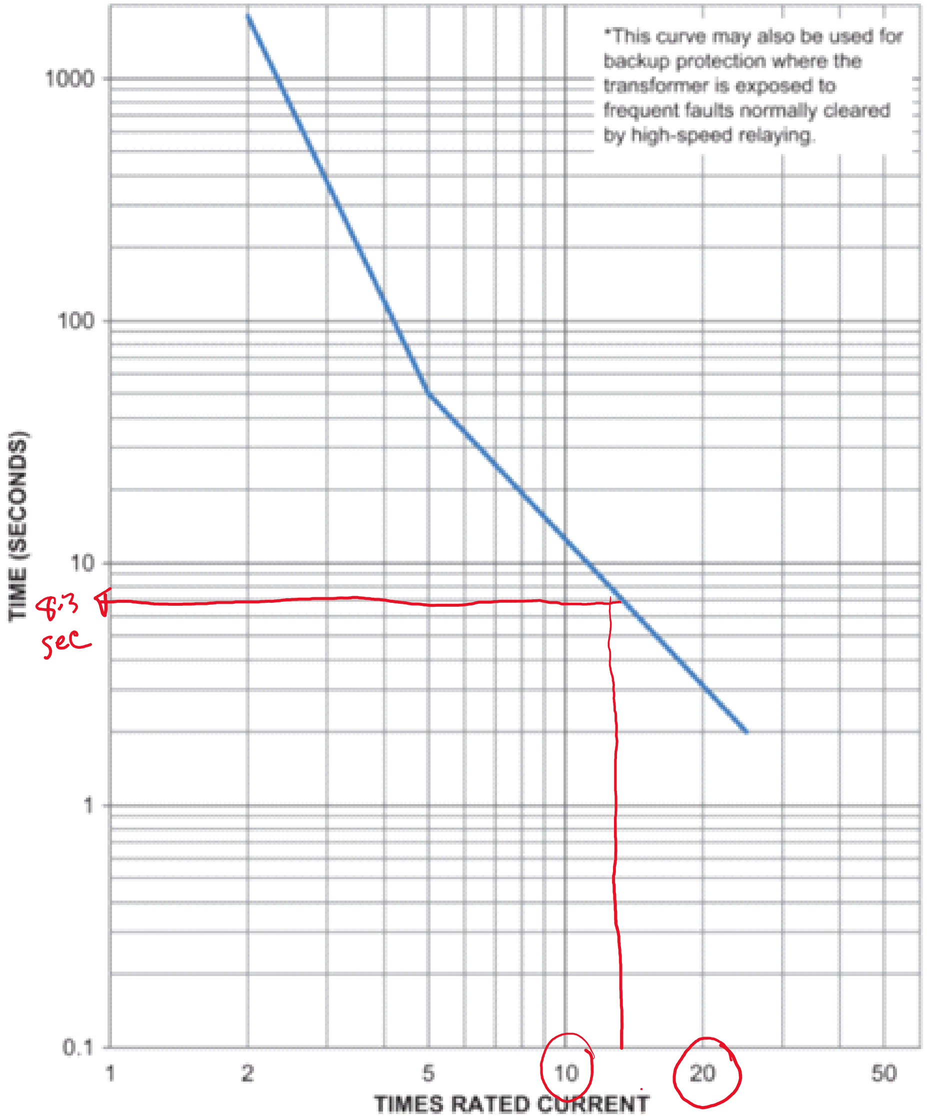
T = Relay Time

For T_3, assume 0.1 sec plus safety factor of 0.2 sec (Total T_3 = 0.3 sec)

For $M_3 = 12 \times I_N / [CTR \times I_{pu51}]$ = (12 × 83.67) / (150/5 × 3.5) = 9.56 pu

For $TD_3 = \dfrac{0.3}{\left[\dfrac{5.95}{9.56^2-1} + 0.18\right]} = 1.22$; Choose $TD_3 = 1.3$

THROUGH-FAULT PROTECTION CURVE FOR FAULTS THAT WILL OCCUR INFREQUENTLY (TYPICALLY NOT MORE THAN TEN IN A TRANSFORMER'S LIFETIME)*



NOTE—Low current values of less than or equal to five times rated current may result from overloads rather than faults. An appropriate loading guide should be referred to for specific allowable time durations.

Figure 3—Category II transformers: 501 kVA to 1667 kVA single-phase and 501 kVA to 5000 kVA three phase

Verify Relay #3 protection

$I^2t = k$, $k = 1250$

$25^2 \times 2 = 1250$

$I_{N\_LV} = \frac{5000}{\sqrt{3} \times 13.8} = 209.18\ A$

$M_T = \frac{I_F}{I_{N\_LV}} = \frac{2572}{209.18} = 12.29\ pu$

$T_{DAMAGE} = 1250 / (12.29^2) = 8.3\ sec$

$M_3 = I_{F\_LV} \times (13.8/34.5) / (CTR \times I_{pus1}) = 2572 \times (13.8/34.5) / (150/5 \times 3.5) = 9.80$ pu

$$T_3 = TD_3 \left[\frac{5.95}{M^2-1} + 0.18\right] = 1.3 \left[\frac{5.95}{9.8^2-1} + 0.18\right] = 0.315 \text{ sec}$$

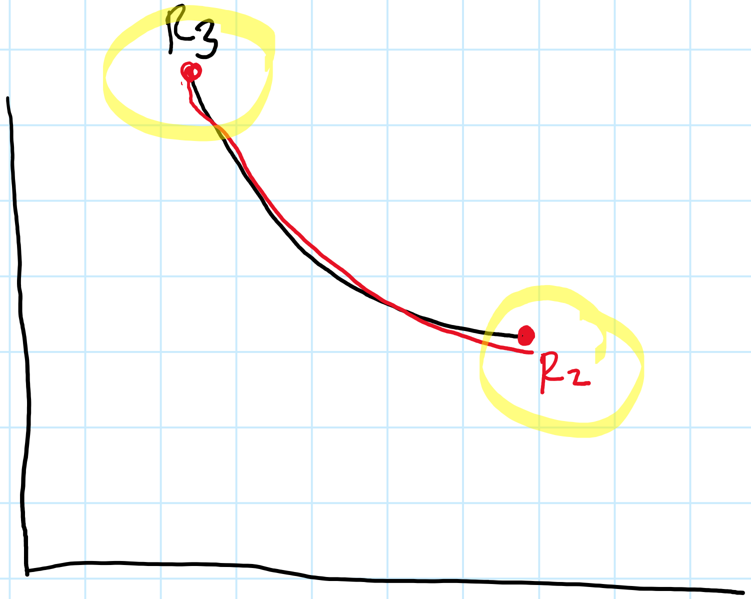
Comparing T_3 versus T_{DAMAGE} :

$T_3 < T_{DAMAGE}$

0.315 sec < 8.3 sec ; requirement is achieved

① For Relay #2 50 element — recommended to be disabled

② For Relay #2 51 element – determine pickup and Time Dial. Recommended to match Relay #3 characteristics.

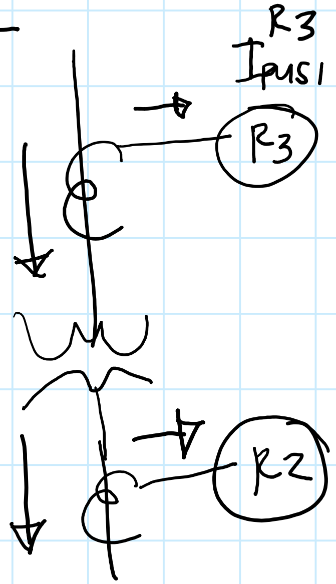


Relay #2 Pickup:

Use R_3 51 element pickup as an end point.

$$I^{R2}_{pu51} = I^{R3}_{pu51} \times CTR_{R3} \times TR\text{-}Ratio \,/\, CTR_{R2}$$

$$= \frac{3.5 \times 150/5 \times (34.5/13.8)}{250/5} = \underline{5.25\ A}$$



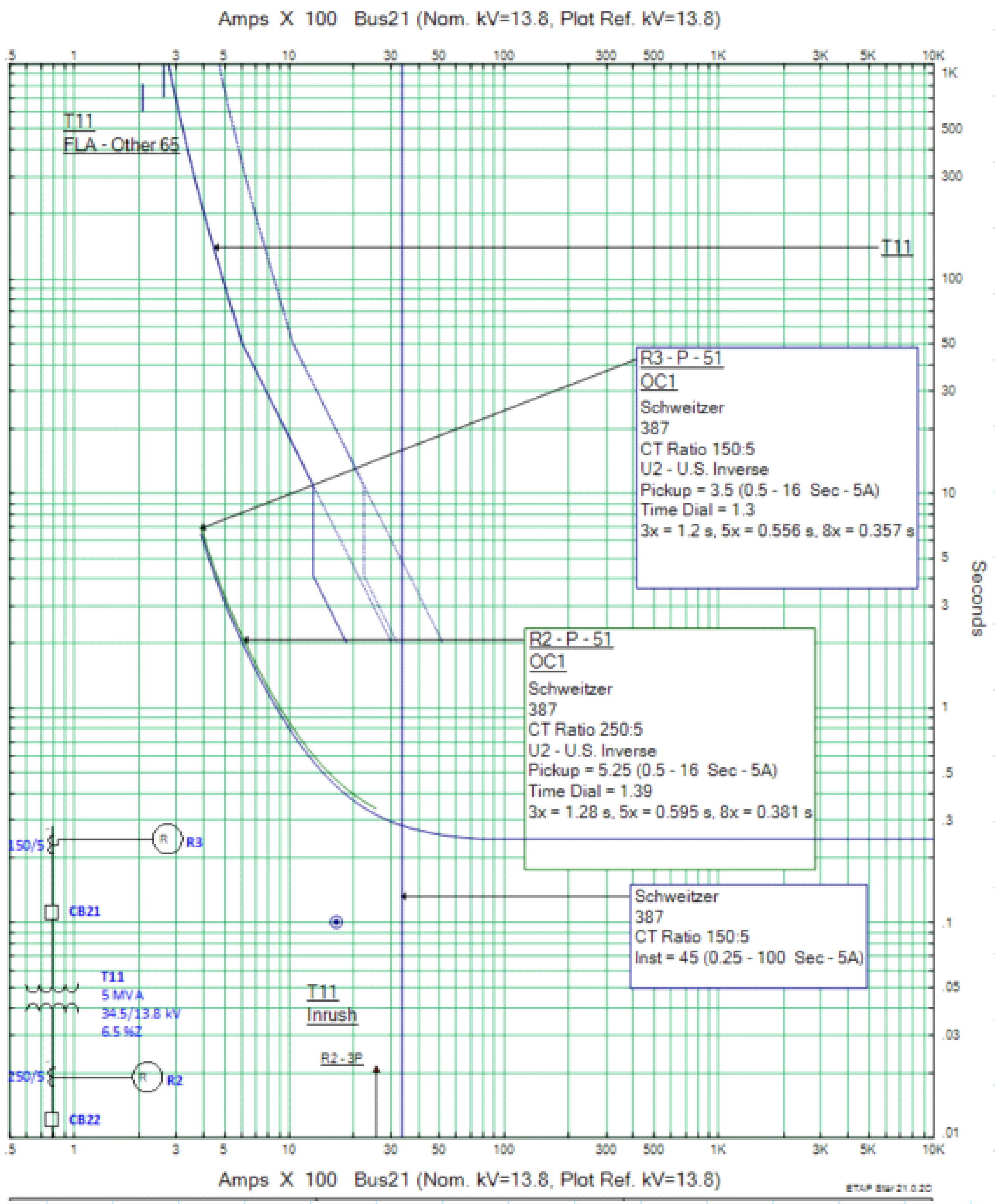
Relay #2 Time Dial:

$$M_2 = I^{R3}_{pu50} \times CTR_{R3} \times TR\text{-}Ratio \,/\, [CTR_{R2} \times I^{R2}_{pu51}]$$

$$M_2 = 45 \times (150/5) \times (34.5/13.8) \,/\, (250/5 \times 5.25)$$

$$M_2 = 12.86\ pu$$

$$TD_2 = 0.3\left[\frac{5.95}{12.86^2 - 1} + 0.18\right] = \underline{1.39}$$


Amps X 100 Bus21 (Nom. kV=13.8, Plot Ref. kV=13.8)
T11
FLA - Other 65
T11
R3 - P - 51
OC1
Schweitzer
387
CT Ratio 150:5
U2 - U.S. Inverse
Pickup = 3.5 (0.5 - 16 Sec - 5A)
Time Dial = 1.3
3x = 1.2 s, 5x = 0.556 s, 8x = 0.357 s
R2 - P - 51
OC1
Schweitzer
387
CT Ratio 250:5
U2 - U.S. Inverse
Pickup = 5.25 (0.5 - 16 Sec - 5A)
Time Dial = 1.39
3x = 1.28 s, 5x = 0.595 s, 8x = 0.381 s
Schweitzer
387
CT Ratio 150:5
Inst = 45 (0.25 - 100 Sec - 5A)
150/5
R3
CB21
T11
5 MVA
34.5/13.8 kV
6.5 %Z
T11
Inrush
R2 - 3P
250/5
R2
CB22
Seconds
Amps X 100 Bus21 (Nom. kV=13.8, Plot Ref. kV=13.8)

recommend to protect transformer @ $125\% \; I_N$

$I_{DAMAGE} \approx 230\% \; I_N$

$I_{SHIFTED} = 58\% \; I_{DAMAGE}$

$I_{PU} = (58\%)(230\% \; I_N) = 133\% \; I_N$

$$\left(\frac{I}{CM}\right)^2 (tF_{ac}) = 0.0297 \log_{10} \frac{T_f + 234}{T_O + 234} \text{ for copper}$$

$$\left(\frac{I}{CM}\right)^2 (tF_{ac}) = 0.0125 \log_{10} \frac{T_f + 228}{T_O + 228} \text{ for aluminum}$$

$$\left[\frac{2572}{66,630}\right]^2 t = 0.0297 \log_{10} \left[\frac{200 + 234}{90 + 234}\right]$$

$t = 2.53$ sec

Protection Clearing Time = Relay Time + Breaker Time
= 1 cycle + 2 cycle
= 3 cycles
= 3/60 sec
= 0.05 sec