

Power System Analysis:

Rules of Thumb (RoT) and Sanity Testing

Dave Loucks, PhD, PE, CEM

Power Systems Analysis Review

Today

- Per Unit Conversions
- Fault Current Estimation
- GF Isolation
- Transformer Connection Issues
 - GF and transient overvoltages

Tomorrow

- PFC, Filters and Harmonic Analysis
- Selective Coordination
 - Arc Flash
- Load Flow Calculations
 - Voltage Drop
 - Motor Starting

I_{sc} Calcs with Per Unit Impedance

- Consider a transformer with a 5% impedance. A voltage is applied to the primary with the secondary winding shorted (faulted).
 - At 5% input voltage → 100% FLA produced
 - At 10% input voltage → 200% FLA is produced
 - At 50% input voltage → 1000% FLA is produced
 - At 100% input voltage → 2000% FLA is produced

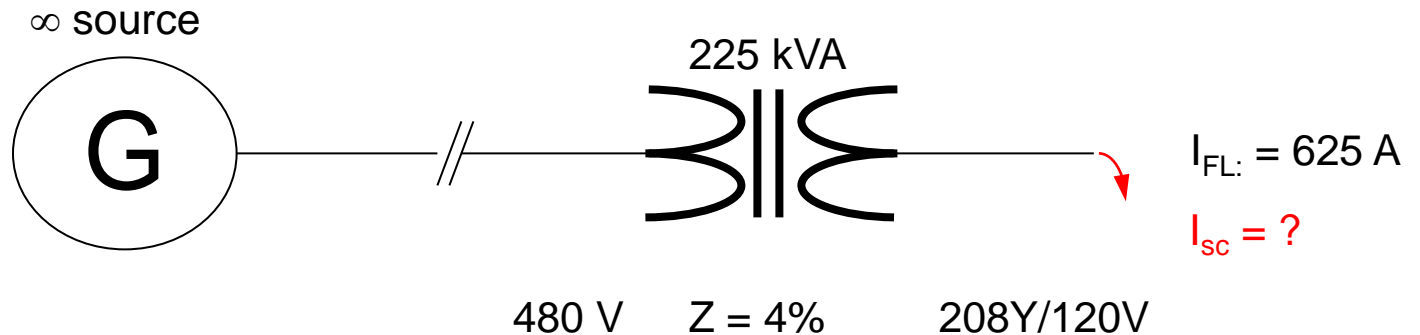
$$\frac{1}{5\%} = \frac{1}{0.05} = 20 \quad I_{SC} = I_{FL} \cdot \frac{1}{Z_{pu}} = I_{FL} \cdot \frac{100}{\%Z}$$

Per Unit

- **Collect** the Z (or X and R) data of the circuit elements.
- **Convert** to a common kVA and voltage base.
 - If the reactances and resistances are given either in ohms or per unit on a *different* voltage or power (MVA) base, all should be changed to the same power and voltage base.

$$pu_{new\ base} = pu_{old\ base} \left(\frac{new\ kVA}{old\ kVA} \right) \left(\frac{old\ kV^2}{new\ kV^2} \right)$$

Short Cut I_{sc} Calc

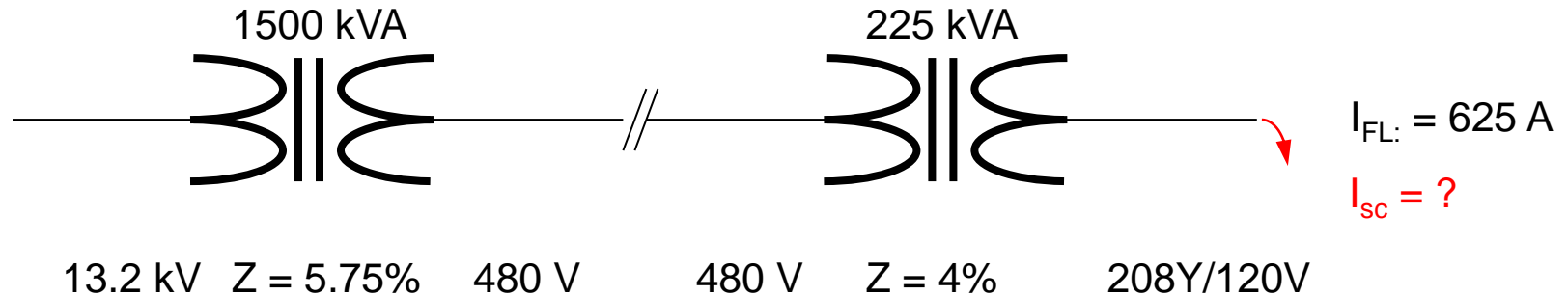


- Only impedance in circuit is 225 kVA Tx

$$I_{sc} = \left(\frac{I_{FL}}{Z_{pu}} \right) = \left(\frac{625A}{0.04} \right) = 15625A$$

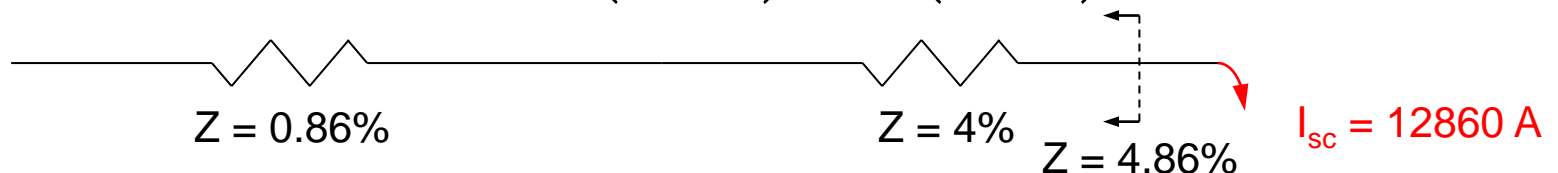
$$I_{sc} = 15625A$$

Convert to Common kVA Base



$$pu_{new \text{ base}} = pu_{old \text{ base}} \left(\frac{new \text{ kVA}}{old \text{ kVA}} \right) \left(\frac{old \text{ kV}^2}{new \text{ kV}^2} \right)$$

$$= 0.0575 \left(\frac{225}{1500} \right) \left(\frac{480^2}{480^2} \right) = 0.86\%$$



$$I_{sc} = \left(\frac{I_{FL}}{Z_{pu}} \right) = \left(\frac{625 \text{ A}}{0.0486} \right) = 12860 \text{ A}$$

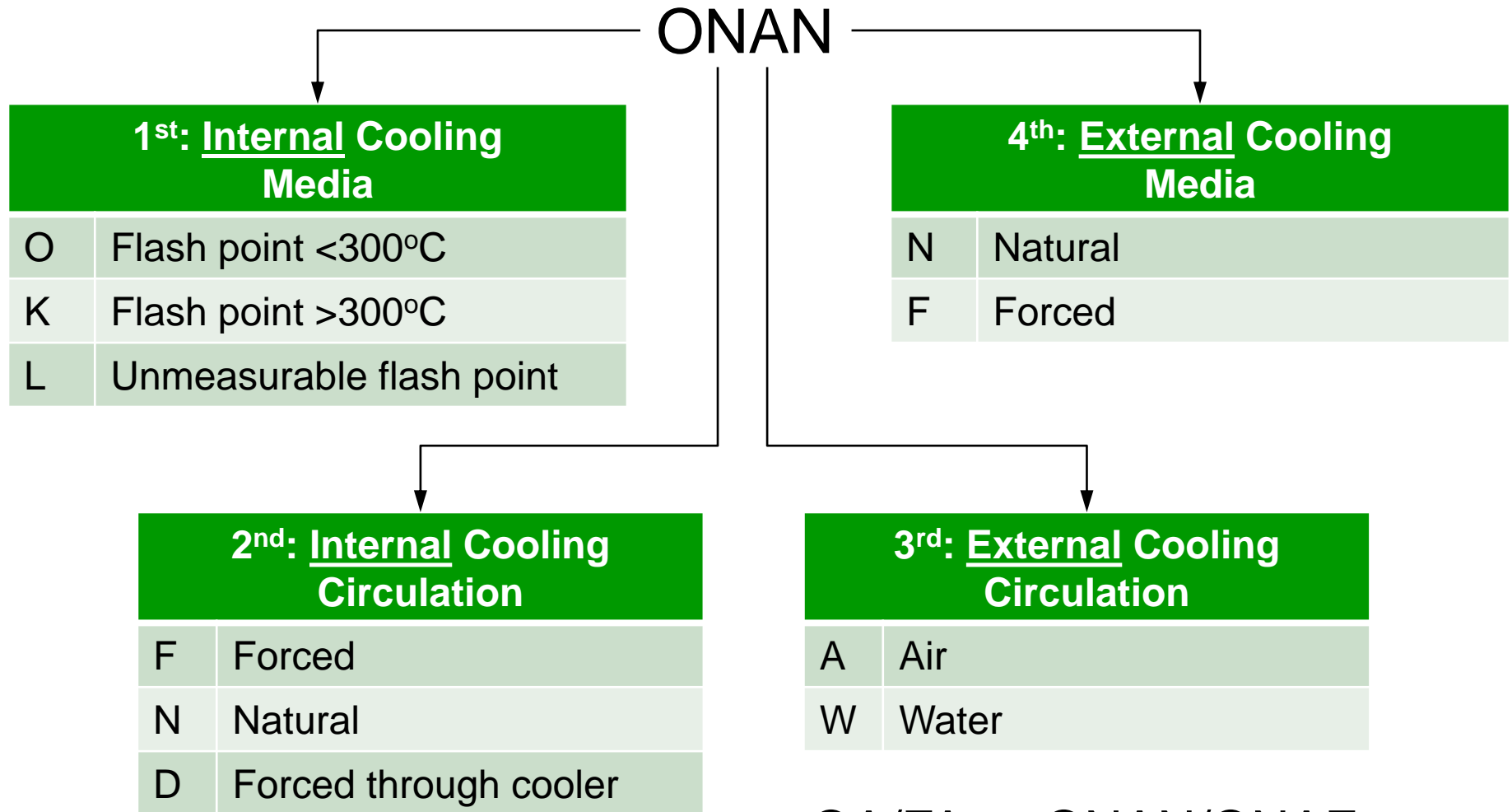
$$\Delta\% = \frac{15625 - 12860}{15625}$$

$$\Delta\% = -18\%$$

Per Unit Calculations

1. Transformer impedance generally relates to self-ventilated rating at rated temp (e.g., with ONAN/ONOF transformer **use ONAN base**).
2. kV refers to **line-to-line** voltage in kilovolts.
3. Z refers to **line-to-neutral** impedance of system to fault where $Z = R + jX$.
4. Generator nameplate: use X_d'' (subtransient reactance)
 1. But look at X_0 (zero sequence) impedance
 2. 2/3rd pitch generators can have low X_0

Liquid Filled Transformer Ratings



OA/FA → ONAN/ONAF

Non-Liquid Filled Transformer Ratings

	Description
AA	Ventilated, Self-Cooled (no fans)
AFA	Self cooled (A) but also optional forced air (FA) cooling
AA/FA	Dual Rated
ANV	Self cooled, non-ventilated (but not hermetically sealed)
GA	Sealed in gas (G), self-cooled (A)

Capacity Increase Depends on Size

Table 1. Three-Phase, Single Temperature kVA Ratings

**Three-Phase kVA
Self-Cooled and Forced-Air Cooled with 65 °C Temperature Rise**

65 °C Rise KNAN		65 °C Rise KNAN/KNAF
500		N/A
750		863
1000	+15%	1150
1500		1725
2000		2300
2500		3125
3750		4688
5000	+25%	6250
7500		9375
10000		12500
12000	+33%	16000

Table 3. Three-Phase, Dual Temperature kVA Ratings

Three-Phase kVA Self-Cooled and Forced-Air Cooled with Dual Rated 55 °C/65 °C Temperature Rise

55 °C Rise KNAN		65 °C Rise KNAN		55°C Rise KNAN/KNAF		65 °C Rise KNAN/KNAF
500		560		N/A		N/A
750		840		863		966
1000		1120		1150		1288
1500		1680		1725		1932
2000		2240		2300		2576
2500	+12%	2800	+12%	3125	+12%	3500 (+40%)
3750		4200		4688		5250
5000		5600		6250		7000
7500		8400		9375		10500
10000		11200		12500		14000
12000		13440		16000		17920

PEAK™ Transformers

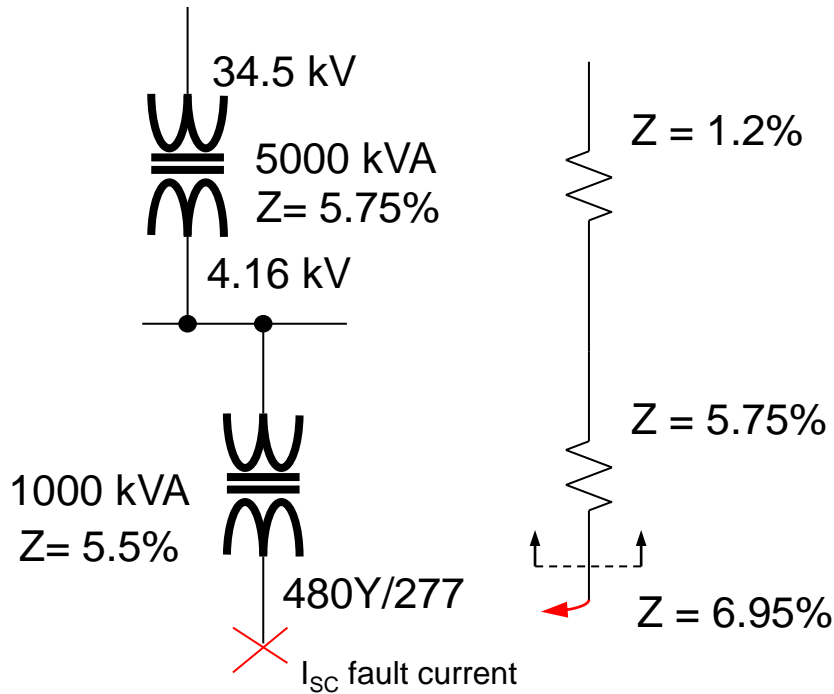
65/75°C

+12% (without fans)

55/75°C

+22% (without fans)

Problem



- Assume bus and conductor impedances = 0

- Find

- I_{SC} (3-phase) fault current?
- 1000 kVA TX $I_{FL} = 1202$ A
- $I_{SC} = I_{FL} / (0.0695)$
= 17306 A

$$pu_{new\ base} = pu_{old\ base} \left(\frac{new\ kVA}{old\ kVA} \right) \left(\frac{old\ kV^2}{new\ kV^2} \right)$$

$$pu_{new\ base} = 5.75\% \left(\frac{1000}{5000} \right) \left(\frac{4.16^2}{4.16^2} \right) = 1.2\%$$

I_{sc} Quick Reference Table

Transformer Rating Three-Phase kVA and Impedance Percent	Maximum Short-Circuit kVA Available from Primary System	208V, Three-Phase			
		Rated Load Contin- uous Current, Amps	Short-Circuit Current rms Symmetrical Amps		
			Trans- former Alone ①	50% Motor Load ②	Com- bined
300 5%	50,000	834	14,900	1700	16,600
	100,000	834	15,700	1700	17,400
	150,000	834	16,000	1700	17,700
	250,000	834	16,300	1700	18,000
	500,000	834	16,500	1700	18,200
	Unlimited	834	16,700	1700	18,400

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Power Distribution Systems Reference Data

1.5-9

Chart of Short Circuit Currents for Transformers

Table 1.5-4. Secondary Short-Circuit Current of Typical Power Transformers

Transformer Rating Three-Phase kVA and Impedance Percent	Maximum Short-Circuit kVA Available from Primary System	208V, Three-Phase			240V, Three-Phase			480V, Three-Phase			600V, Three-Phase		
		Rated Load Contin- uous Current, Amps	Short-Circuit Current rms Symmetrical Amps	Trans- former Alone ①	50% Motor Load ②	Com- bined	Rated Load Contin- uous Current, Amps	Short-Circuit Current rms Symmetrical Amps	Trans- former Alone ①	50% Motor Load ②	Com- bined	Rated Load Contin- uous Current, Amps	Short-Circuit Current rms Symmetrical Amps
300 5%	50,000	834	14,900	1700	16,600	722	12,900	2900	16,800	361	6400	1400	7800
	100,000	834	15,700	1700	17,400	722	13,600	2900	16,800	361	6800	1400	8200
	150,000	834	16,000	1700	17,700	722	13,900	2900	16,800	361	6900	1400	8300
	250,000	834	16,300	1700	18,000	722	14,100	2900	17,000	361	7000	1400	8400
	500,000	834	16,500	1700	18,200	722	14,300	2900	17,200	361	7100	1400	8500
	Unlimited	834	16,700	1700	18,400	722	14,400	2900	17,300	361	7200	1400	8600
750 5.75%	50,000	1388	21,300	2800	25,900	1203	20,000	4800	24,800	601	10,000	2400	12,400
	100,000	1388	25,300	2800	28,900	1203	21,000	4800	26,700	601	10,900	2400	13,300
	150,000	1388	26,000	2800	29,600	1203	22,500	4800	27,300	601	11,300	2400	13,700
	250,000	1388	26,700	2800	30,300	1203	23,100	4800	27,900	601	11,600	2400	14,000
	500,000	1388	27,200	2800	30,800	1203	23,600	4800	28,400	601	11,800	2400	14,200
	Unlimited	1388	27,800	2800	31,400	1203	24,100	4800	28,900	601	12,000	2400	14,400
1000 5.75%	50,000	2080	28,700	4200	32,900	1804	24,900	7200	32,100	902	12,400	3600	16,000
	100,000	2080	32,000	4200	36,200	1804	27,800	7200	35,000	902	13,900	3600	17,500
	150,000	2080	33,300	4200	37,500	1804	28,900	7200	36,100	902	14,400	3600	18,000
	250,000	2080	34,400	4200	38,600	1804	29,800	7200	37,000	902	14,900	3600	18,500
	500,000	2080	35,200	4200	39,400	1804	30,600	7200	37,800	902	15,300	3600	18,900
	Unlimited	2080	36,200	4200	40,400	1804	31,400	7200	38,600	902	15,700	3600	19,300
1500 5.75%	50,000	2776	35,900	5600	41,500	2406	31,000	9600	40,600	1203	15,500	4800	20,300
	100,000	2776	41,200	5600	46,800	2406	35,000	9600	44,200	1203	17,000	4800	22,000
	150,000	2776	43,300	5600	48,900	2406	37,500	9600	47,100	1203	18,700	4800	23,900
	250,000	2776	45,200	5600	50,800	2406	39,100	9600	48,700	1203	19,600	4800	24,800
	500,000	2776	46,700	5600	52,300	2406	40,400	9600	50,000	1203	20,200	4800	25,600
	Unlimited	2776	48,300	5600	53,900	2406	41,800	9600	51,400	1203	20,900	4800	26,300
2000 5.75%	50,000	4164	47,600	8300	55,900	3609	41,200	14,400	55,600	1804	20,600	7200	27,800
	100,000	4164	53,500	8300	61,800	3609	48,900	14,400	64,200	1804	24,900	7200	32,100
	150,000	4164	56,800	8300	65,100	3609	53,000	14,400	67,900	1804	26,700	7200	33,900
	250,000	4164	58,600	8300	66,900	3609	56,800	14,400	71,200	1804	28,400	7200	35,600
	500,000	4164	60,800	8300	69,100	3609	59,600	14,400	74,000	1804	29,800	7200	37,000
	Unlimited	4164	62,500	8300	70,800	3609	62,000	14,400	77,200	1804	31,400	7200	38,600
2500 5.75%	50,000	5448	50,000	10,800	60,800	4800	44,000	18,000	60,800	2406	22,400	9600	30,800
	100,000	5448	56,800	10,800	67,600	4800	50,800	18,000	67,600	2406	24,800	9600	33,200
	150,000	5448	59,600	10,800	70,400	4800	53,600	18,000	70,400	2406	26,600	9600	35,000
	250,000	5448	61,400	10,800	72,200	4800	55,400	18,000	72,200	2406	28,400	9600	36,800
	500,000	5448	63,200	10,800	74,000	4800	57,200	18,000	74,000	2406	30,200	9600	38,600
	Unlimited	5448	65,000	10,800	75,800	4800	59,000	18,000	75,800	2406	32,000	9600	40,400
3000 5.75%	50,000	6732	52,000	12,000	64,000	5600	46,000	20,000	64,000	2808	24,000	11,200	32,000
	100,000	6732	58,000	12,000	70,000	5600	52,000	20,000	70,000	2808	26,000	11,200	34,000
	150,000	6732	60,000	12,000	72,000	5600	54,000	20,000	72,000	2808	28,000	11,200	36,000
	250,000	6732	62,000	12,000	74,000	5600	56,000	20,000	74,000	2808	30,000	11,200	38,000
	500,000	6732	64,000	12,000	76,000	5600	58,000	20,000	76,000	2808	32,000	11,200	40,000
	Unlimited	6732	66,000	12,000	78,000	5600	60,000	20,000	78,000	2808	34,000	11,200	42,000
3750 5.75%	50,000	8416	54,000	13,200	66,000	7200	48,000	22,000	66,000	3600	26,000	12,400	34,000
	100,000	8416	60,000	13,200	72,000	7200	54,000	22,000	72,000	3600	28,000	12,400	36,000
	150,000	8416	62,000	13,200	74,000	7200	56,000	22,000	74,000	3600	30,000	12,400	38,000
	250,000	8416	64,000	13,200	76,000	7200	58,000	22,000	76,000	3600	32,000	12,400	40,000
	500,000	8416	66,000	13,200	78,000	7200	60,000	22,000	78,000	3600	34,000	12,400	42,000
	Unlimited	8416	68,000	13,200	80,000	7200	62,000	22,000	80,000	3600	36,000	12,400	44,000

① Short-circuit capacity values shown correspond to kVA and impedances shown in this table. For impedances other than these, short-circuit currents are inversely proportional to impedance.
② The motor's short-circuit current contributions are computed on the basis of motor characteristics that will give four times normal current. For 208V, 50% motor load is assumed while for other voltages 100% motor load is assumed. For other percentages, the motor short-circuit current will be in direct proportion.

CA08104001E

For more information, visit: www.eaton.com/consultants

Fault Current RoT – Curve Method

Approximations

- 208Y/120 systems
assume 50% motor load
- 240V & 480V systems
assume 100% motor load

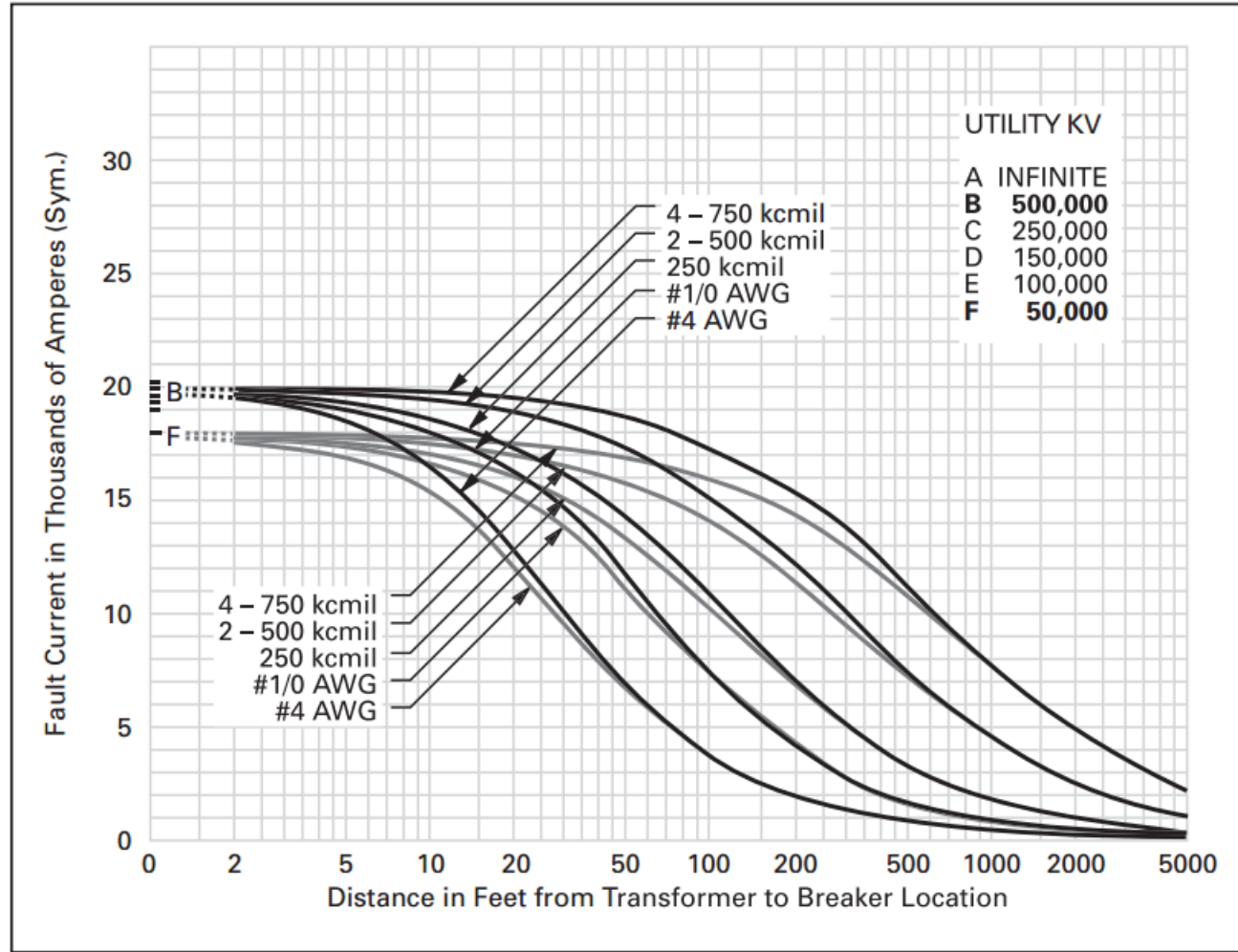


Figure 1.3-13. 300 kVA Transformer/4.5% Impedance/208V

Fault Current RoT – Curve Method

Approximations

- Peak current
 $208/480 =$
43% of 208V
 I_{sc} , (8.66 kA)
but this model
assumes
100% motor
load vs. 50%
motor load
- Raises I_{sc} to
9.6 kA

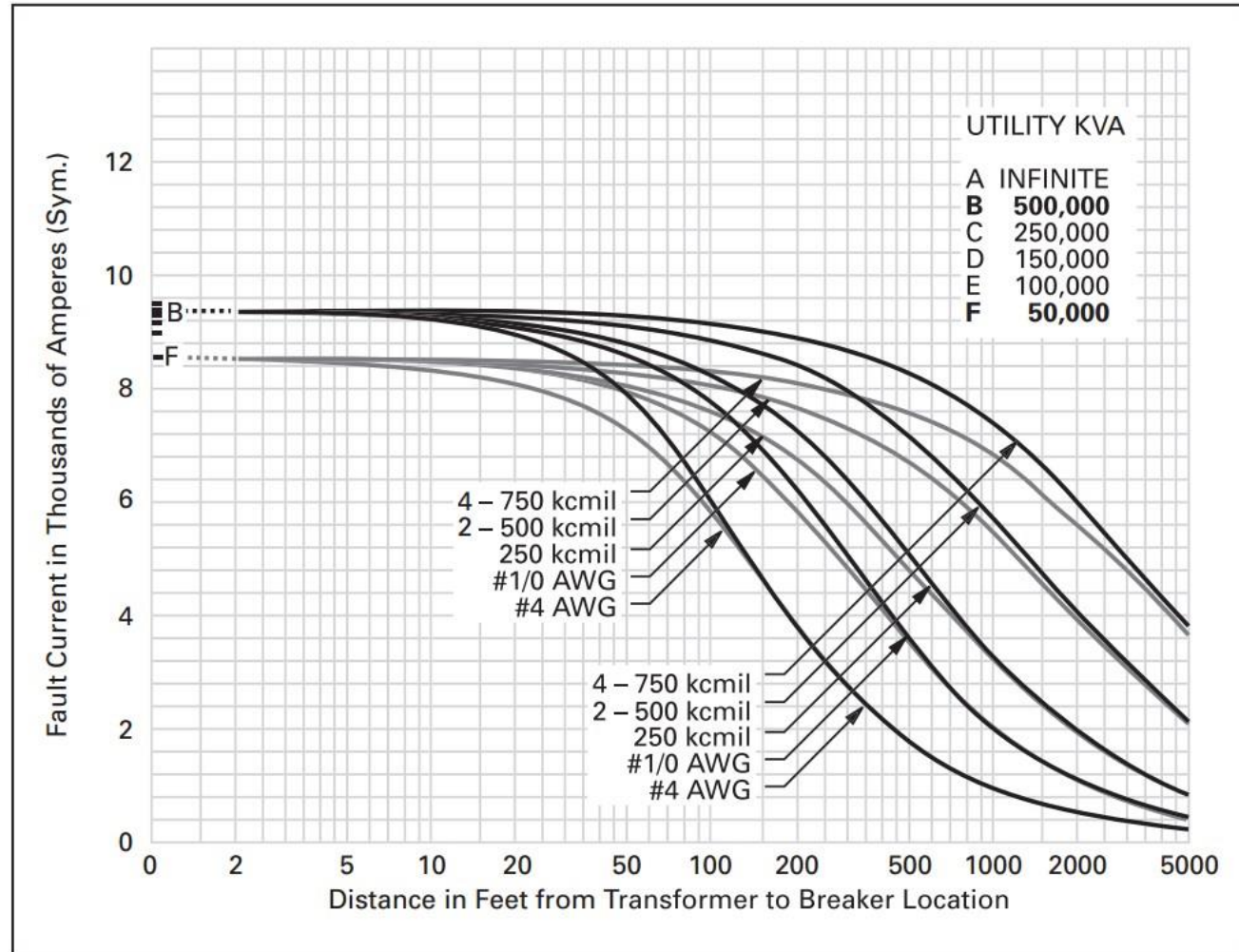
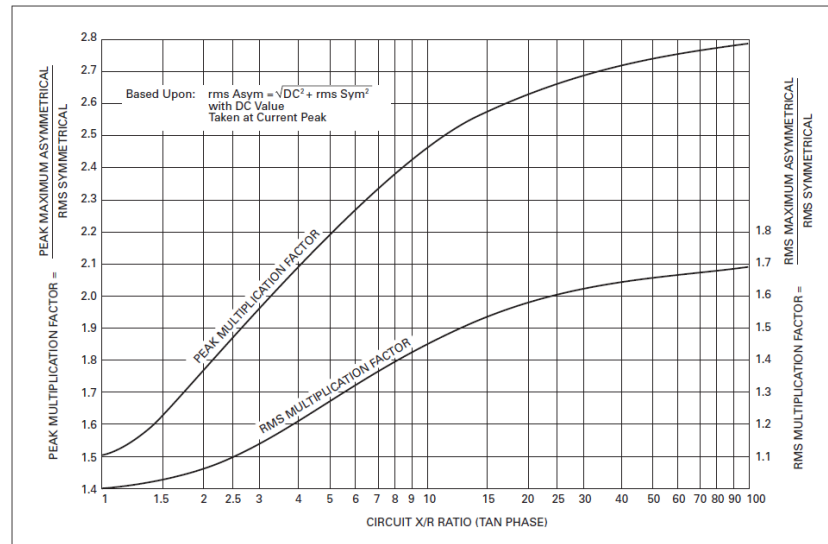
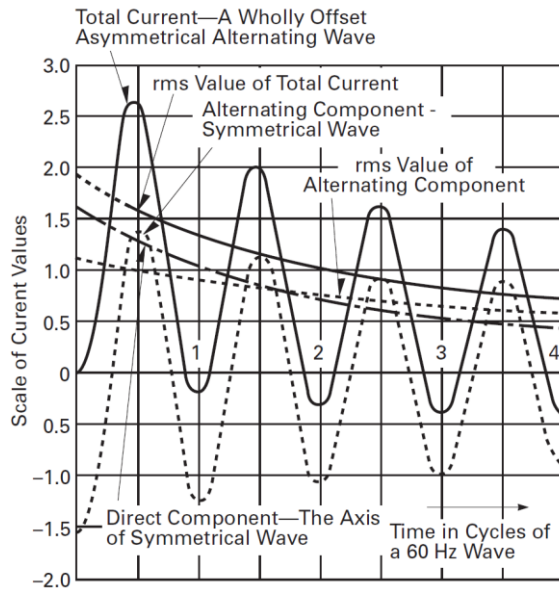
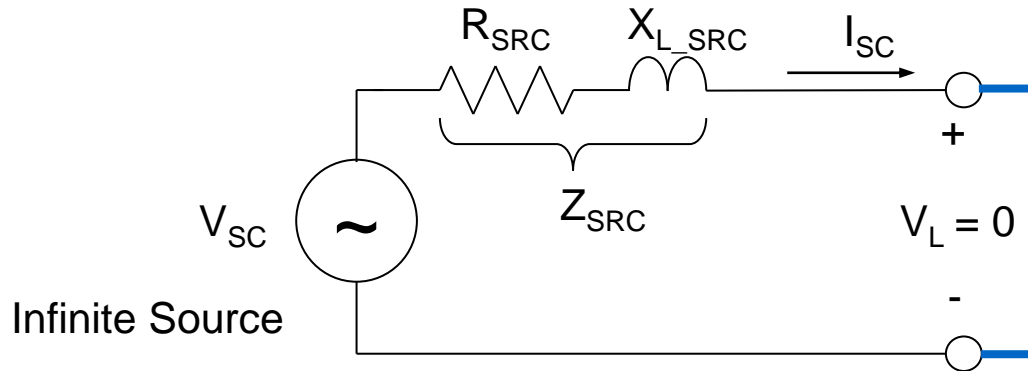


Figure 1.3-19. 300 kVA Transformer/4.5% Impedance/480V

Short Circuit Studies – DC Offset



$$PeakMultFactor = \sqrt{2} \left(1 + e^{\frac{-\pi}{X/R}} \right) @ 60 \text{ Hz}$$

X/R ratio: Rules of Thumb

Table 1.3-1. Reactance X

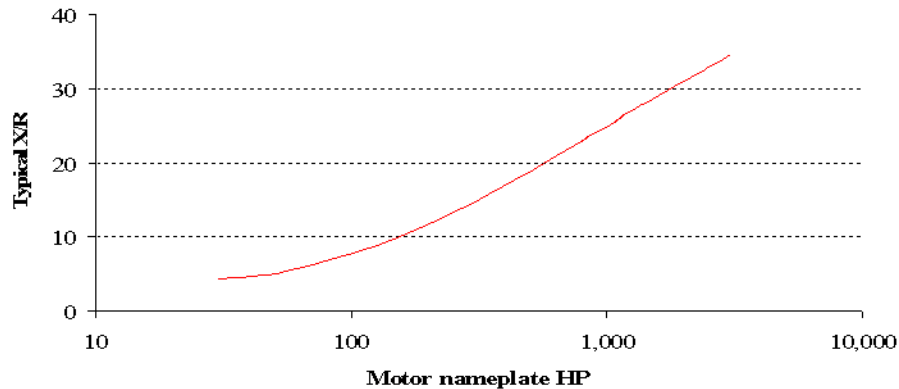
System Component	Reactance X Used for		Typical Values and Range on Component Base	
	Short-Circuit Duty	Close and Latch (Momentary)	% Reactance	X/R Ratio
Two-pole turbo generator	X	X	9 (7–14)	80 (40–120)
Four-pole turbo generator	X	X	15 (12–17)	80 (40–120)
Hydro generator with damper wedges and synchronous condensers	X	X	20 (13–32)	30 (10–60)
Hydro generator without damper windings	0.75X	0.75X	16 (16–50)	30 (10–60)
All synchronous motors	1.5X	1.0X	20 (13–35)	30 (10–60)
Induction motors above 1000 hp, 1800 rpm and above 250 hp, 3600 rpm	1.5X	1.0X	17 (15–25)	30 (15–40)
All other induction motors 50 hp and above	3.0X	1.2X	17 (15–25)	15 (2–40)
Induction motors below 50 hp and all single-phase motors	Neglect	Neglect	—	—
Distribution system from remote transformers	X	X	As specified or calculated	15 (5–15)
Current limiting reactors	X	X	As specified or calculated	80 (40–120)

Transformers

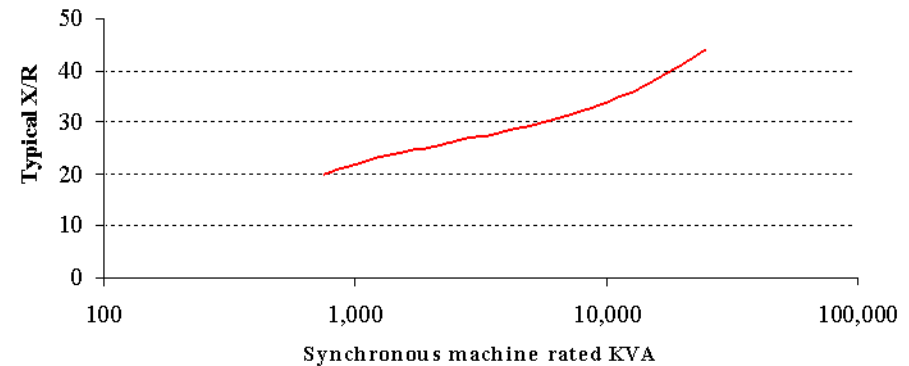
OA to 10 MVA, 69 kV	X	X	8.0	18 (7–24)
OA to 10 MVA, above 69 kV	X	X	8.0 to 10.5 Depends on primary windings BIL rating	18 (7–24)
FOA 12–30 MVA	X	X		20 (7–30)
FOA 40–100 MVA	X	X		38 (32–44)

X/R ratio: Rules of Thumb

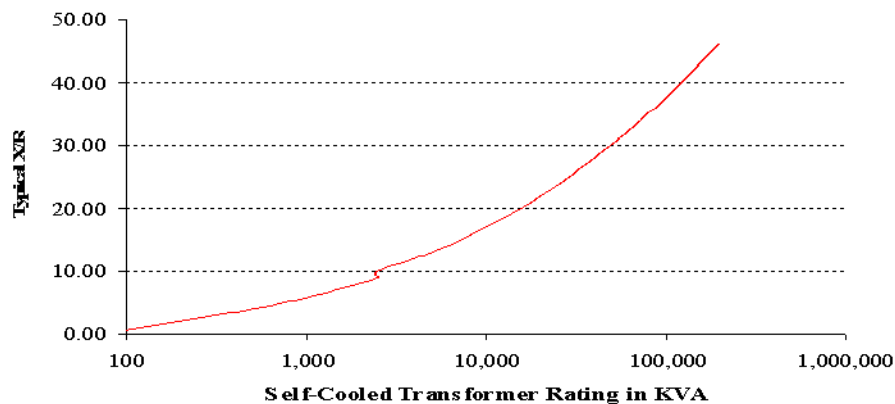
Medium X/R Ratio of Three-Phase Induction Motors
Based on ANSI/IEEE C37.010-1979



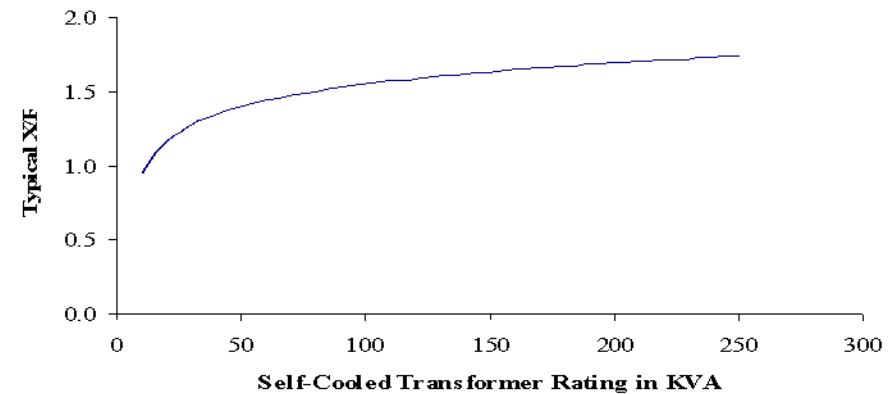
Medium X/R Ratio of Synchronous Machines
Based on ANSI/IEEE C37.010-1979



X/R Ratio of Oil-filled Transformers
Based on ANSI/IEEE C37.010-1979



X/R ratio for Dry Type Transformer

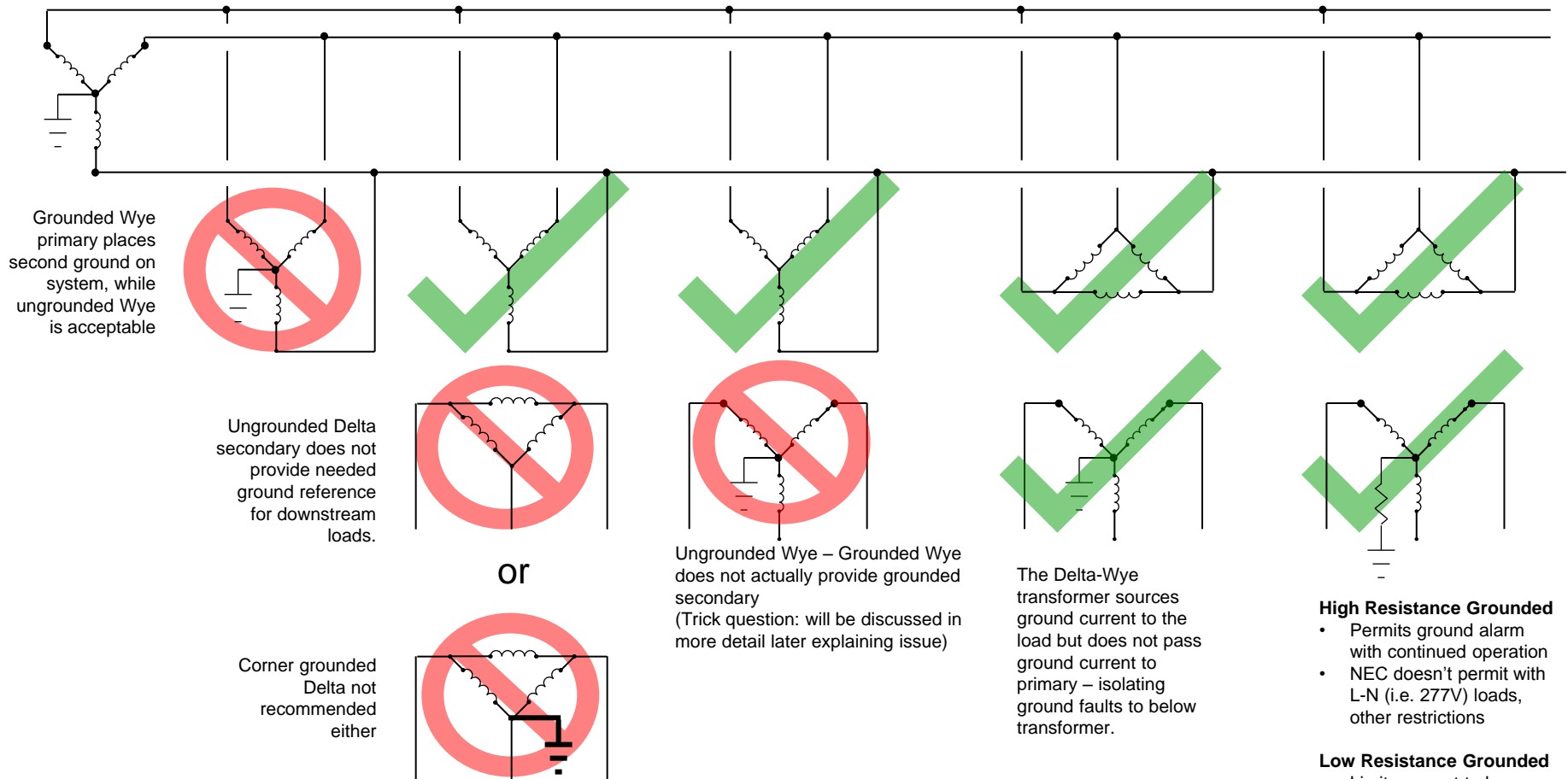


X/R ratio: Rules of Thumb

Table 1.3-2. Typical System X/R Ratio Range (for Estimating Purposes)

Type of Circuit	X/R Range
Remote generation through other types of circuits such as transformers rated 10 MVA or smaller for each three-phase bank, transmission lines, distribution feeders, etc.	15 or less
Remote generation connected through transformer rated 10 MVA to 100 MVA for each three-phase bank, where the transformers provide 90% or more of the total equivalent impedance to the fault point	15–40
Remote generation connected through transformers rated 100 MVA or larger for each three-phase bank where the transformers provide 90% or more of the total equivalent impedance to the fault point	30–50
Synchronous machines connected through transformers rated 25–100 MVA for each three-phase bank	30–50
Synchronous machines connected through transformers rated 100 MVA and larger	40–60
Synchronous machines connected directly to the bus or through reactors	40–120

Transformer Types



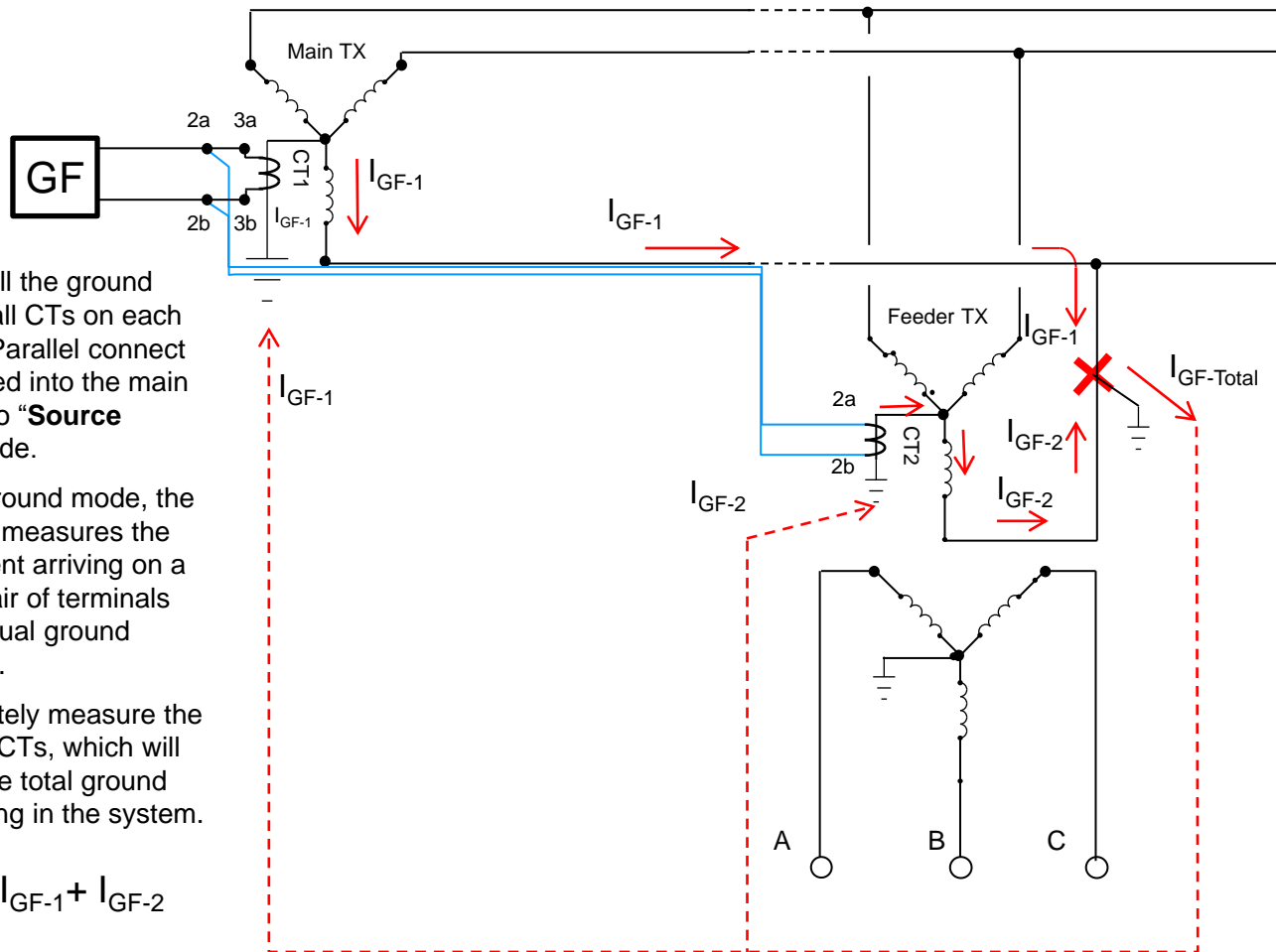
More info on grounding:

<http://www.eaton.com/ecm/groups/public/@pub/@electrical/documents/content/wp027004en.pdf>

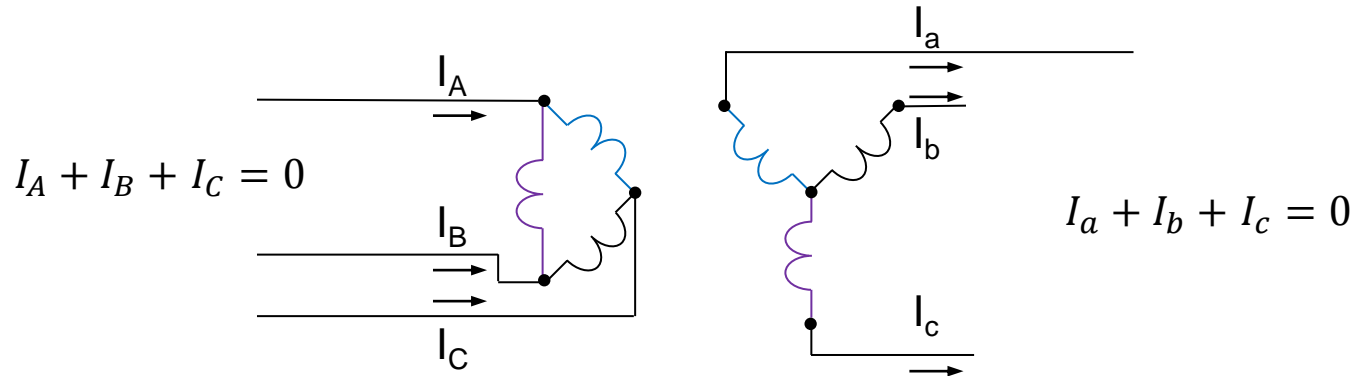
Multiple Grounds

- To capture all the ground current, install CTs on each N-G bond. Parallel connect them and feed into the main trip unit set to “**Source Ground**” mode.
- In Source Ground mode, the trip unit only measures the ground current arriving on a dedicated pair of terminals (ignore residual ground calculations).
- It will accurately measure the sum of both CTs, which will indeed be the total ground current flowing in the system.

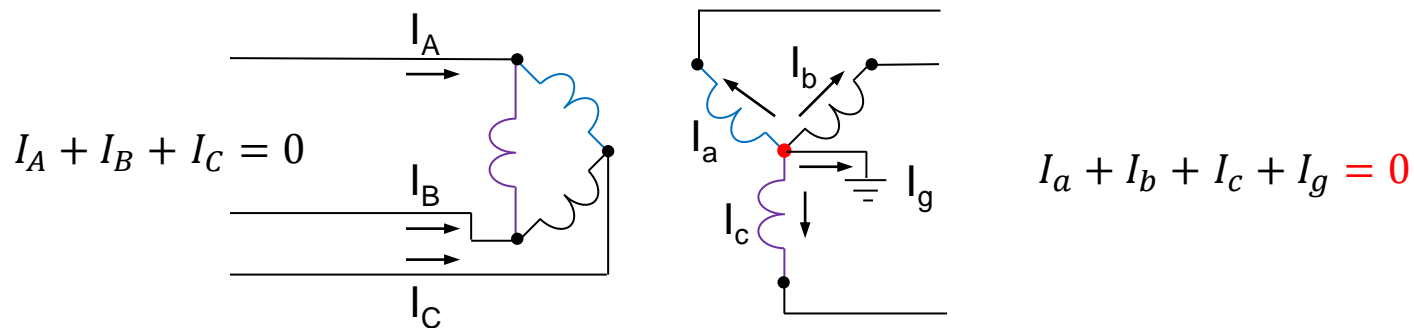
$$I_{GF-Total} = I_{GF-1} + I_{GF-2}$$



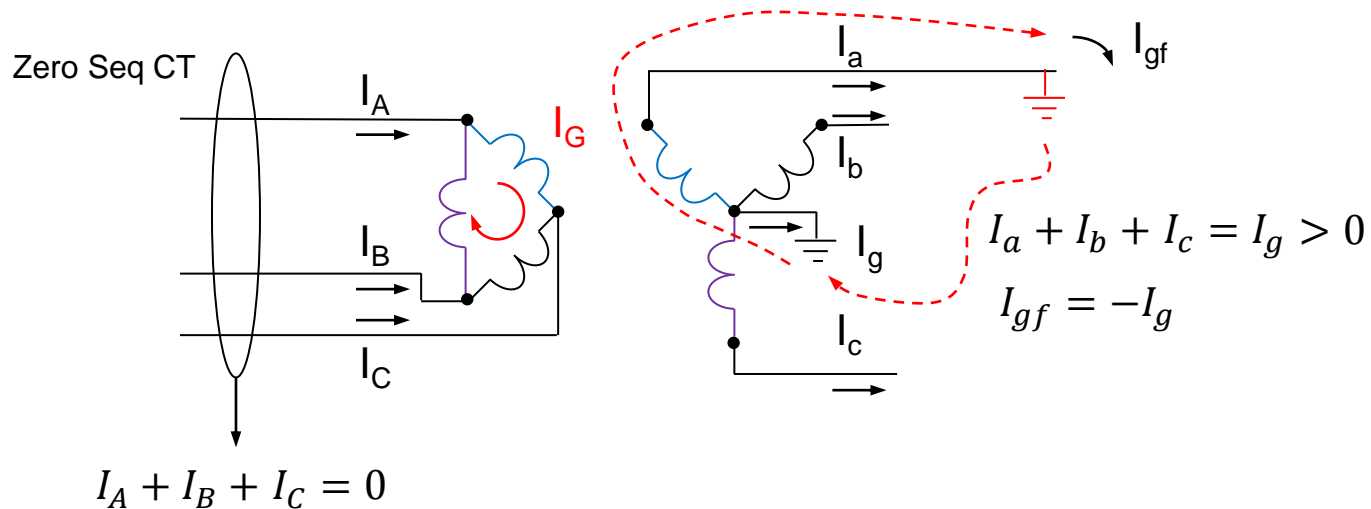
Faults Through Transformer



- Kirchhoff's Current Law (KCL) must be true for both primary and secondary windings

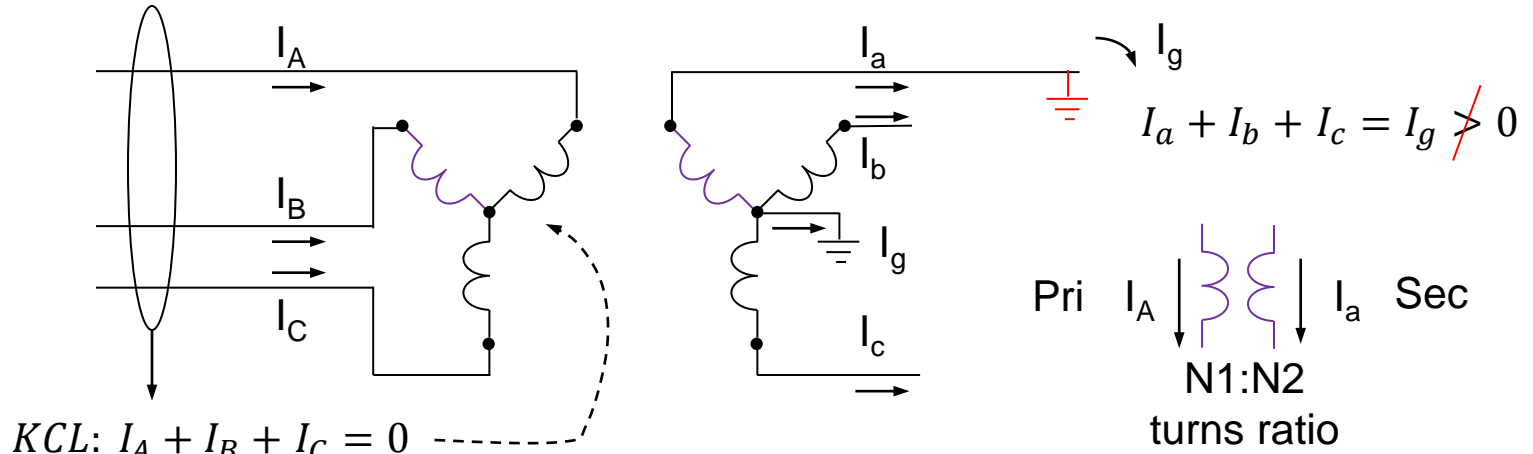


Ground Fault on Δ -Y Transformer



- KCL must sum on both sides
- Where is the ground current on the primary?
- Zero sequence currents circulate in delta
 - Triplen harmonics are zero sequence -- heating

Ground Fault on Y-GndY Transformer



$$V_a = V_A \frac{N2}{N1} \quad I_a = I_A \frac{N1}{N2}$$

$$I_a + I_b + I_c + I_g = 0 = I_A + I_B + I_C$$

$$I_A \frac{N1}{N2} + I_B \frac{N1}{N2} + I_C \frac{N1}{N2} + I_g = I_A + I_B + I_C$$

$$I_A \frac{N1}{N2} - I_A + I_B \frac{N1}{N2} - I_B + I_C \frac{N1}{N2} - I_C + I_g = 0$$

$$I_A \left(\frac{N1}{N2} - 1 \right) + I_B \left(\frac{N1}{N2} - 1 \right) + I_C \left(\frac{N1}{N2} - 1 \right) + I_g = 0$$

$$(I_A + I_B + I_C) \left(\frac{N1}{N2} - 1 \right) = -I_g$$

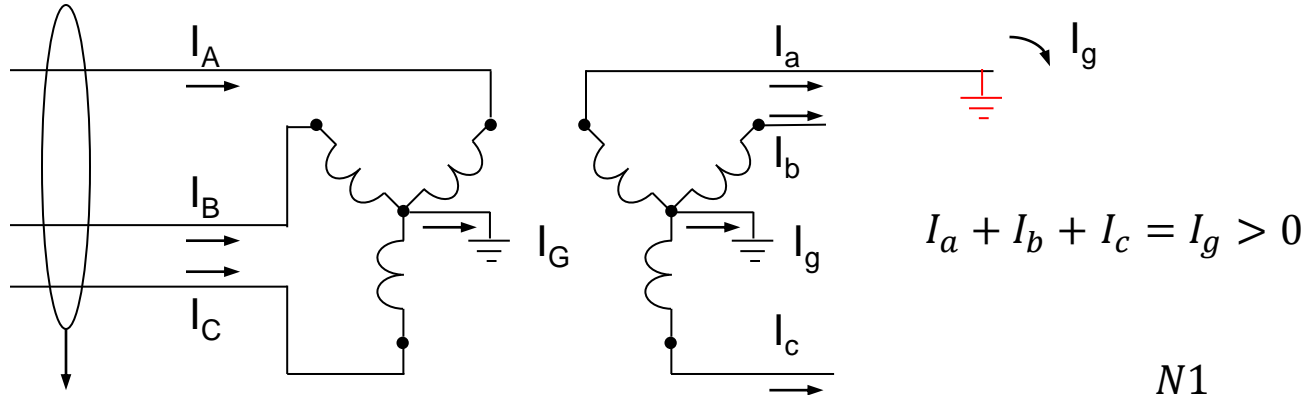
$$(0) \left(\frac{N1}{N2} - 1 \right) = -I_g$$

$$(0) = -I_g$$

$$I_g = 0$$

- Ungrounded secondary!

Ground Fault on GndY-GndY Transformer



$$I_a + I_b + I_c = I_g > 0$$

$$I_a = I_A \frac{N1}{N2} \quad I_A = I_a \frac{N2}{N1}$$

$$I_a + I_b + I_c + I_g = 0 = I_A + I_B + I_C + I_G$$

$$I_a + I_b + I_c + I_g = 0 = I_a \frac{N2}{N1} + I_b \frac{N2}{N1} + I_c \frac{N2}{N1} + I_g$$

$$I_a - I_a \frac{N2}{N1} + I_b - I_b \frac{N2}{N1} + I_c - I_c \frac{N2}{N1} + I_g = I_g$$

$$I_a \left(1 - \frac{N2}{N1}\right) + I_b \left(1 - \frac{N2}{N1}\right) + I_c \left(1 - \frac{N2}{N1}\right) + I_g = I_g$$

$$\left(1 - \frac{N2}{N1}\right) (I_a + I_b + I_c) + I_g = I_g$$

$$(I_a + I_b + I_c) = -I_g$$

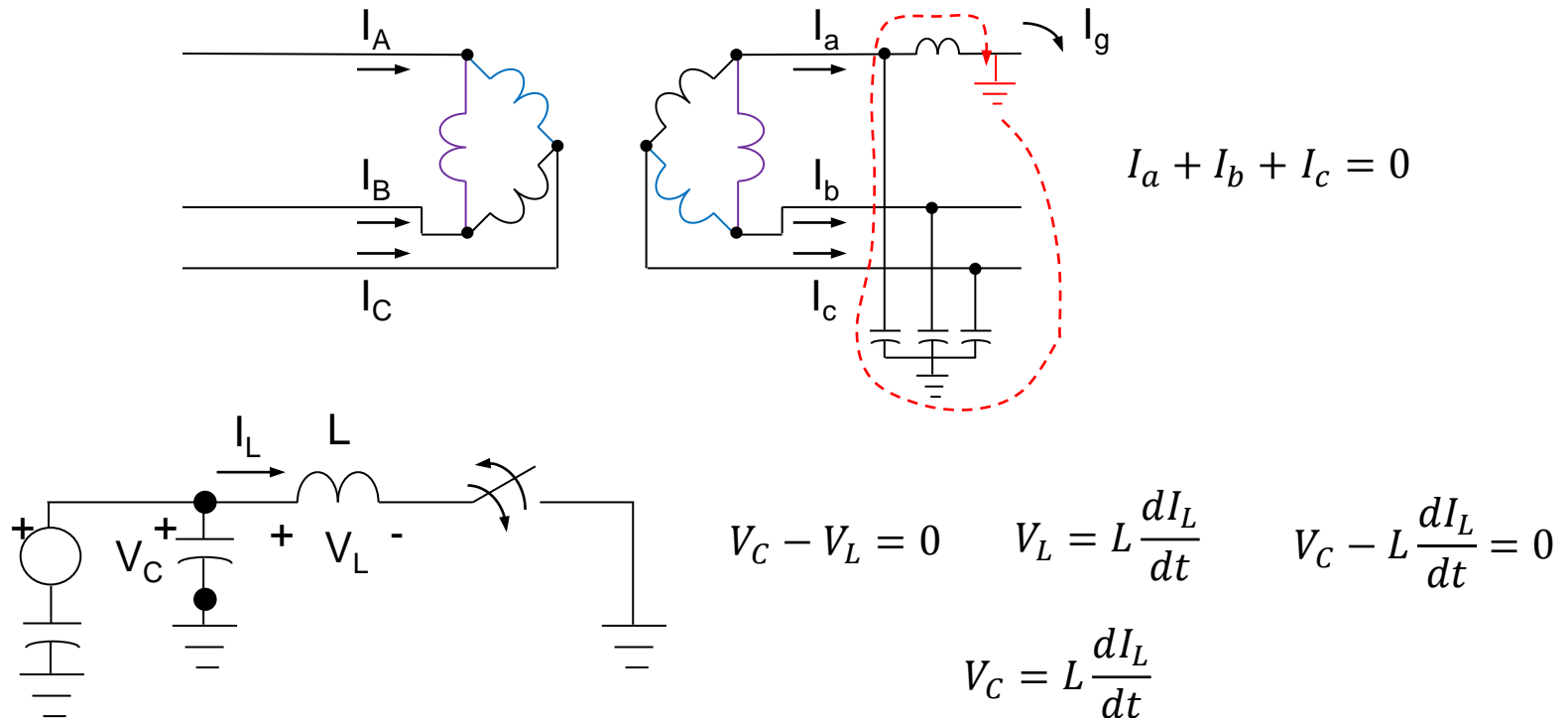
$$\left(1 - \frac{N2}{N1}\right) (-I_g) + I_g = I_g$$

$$\left(\frac{N2}{N1} - 1\right) (I_g) + I_g = I_g$$

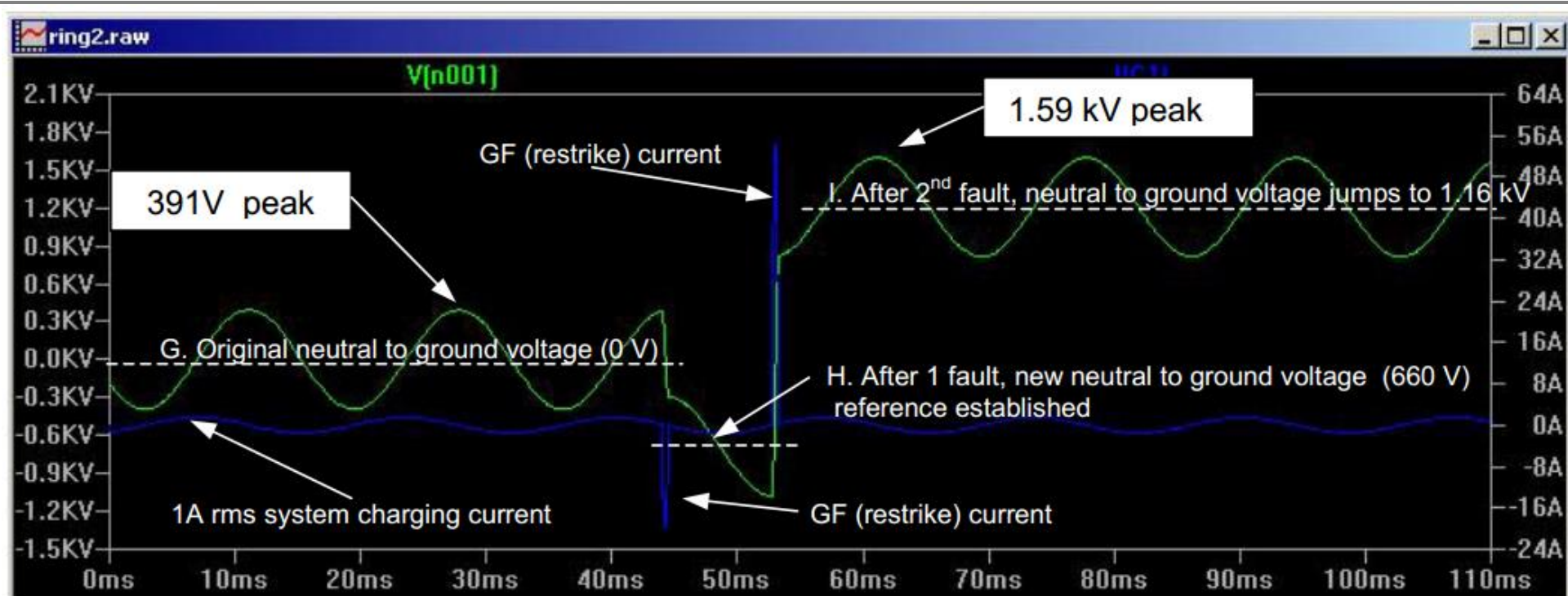
$$\left(\left(\frac{N2}{N1} - 1\right) + 1\right) I_g = I_g$$

A Word About Ungrounded Systems

- Tendency to consider for mission critical



Insulation Failure

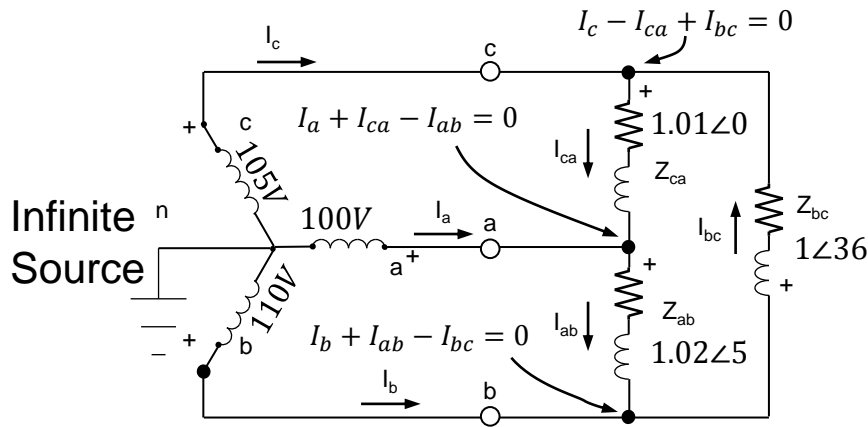
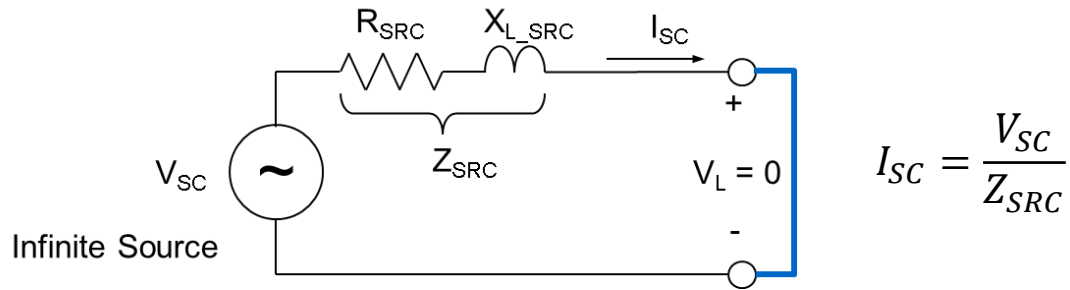


- Intermittent grounds can cause very high line-to-ground voltage across phase capacitance
- Avoid ungrounded systems



Powering Business Worldwide

Solving Unbalanced Systems



$$V_a = 100\angle 0 \quad V_b = 110\angle -120 \quad V_c = 105\angle -240$$

$$Z_{ab} = 1.02\angle 5 \quad Z_{bc} = 1\angle 36 \quad Z_{ca} = 1.01\angle 0$$

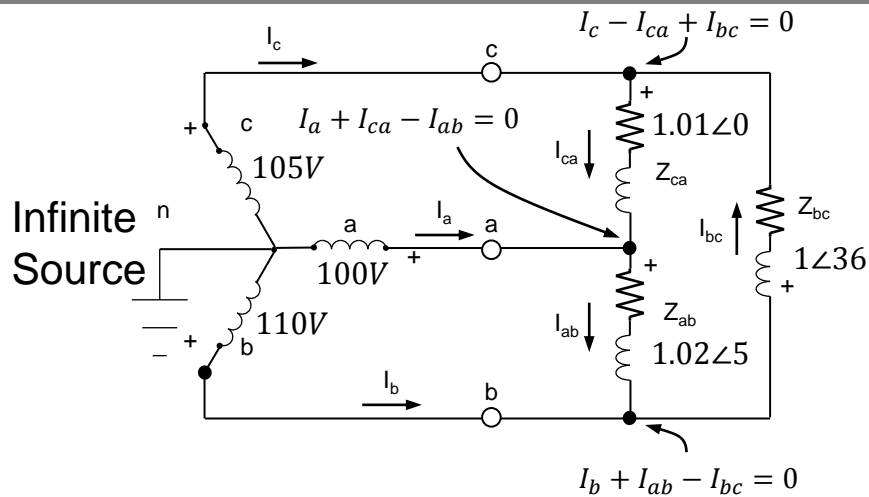
$$I_c = I_{ca} - I_{bc} \quad I_{ca} = \frac{V_c - V_a}{Z_{ca}} \quad I_{bc} = \frac{V_b - V_c}{Z_{bc}}$$

$$I_c = \frac{V_c - V_a}{Z_{ca}} - \frac{V_b - V_c}{Z_{bc}}$$

$$I_c = \frac{(105\angle -240^\circ) - (100\angle 0)}{1.01\angle 0} - \frac{110\angle (-120) - 105\angle (-240)}{1\angle 36}$$

$$I_c = 354\angle 223^\circ \quad I_b = 261\angle 98^\circ \quad I_a = 295\angle -3^\circ$$

Solution of I_a and I_b



$$V_a = 100\angle 0 \quad V_b = 110\angle 120 \quad V_c = 105\angle 240$$

$$Z_{ab} = 1.02\angle 5 \quad Z_{bc} = 1\angle 36 \quad Z_{ca} = 1.01\angle 0$$

$$I_c = I_{ca} - I_{bc} \quad I_{ca} = \frac{V_c - V_a}{Z_{ca}}$$

$$I_a = I_{ab} - I_{ca} \quad I_{ab} = \frac{V_a - V_b}{Z_{ab}} \quad I_{ca} = \frac{V_c - V_a}{Z_{ca}}$$

$$I_a = \frac{V_a - V_b}{Z_{ab}} - \frac{V_c - V_a}{Z_{ca}}$$

$$I_a = \frac{100\angle 0 - 110\angle 120}{1.02\angle 5} - \frac{105\angle 240 - 100\angle 0}{1.01\angle 0}$$

$$I_a = 295\angle -3^\circ$$

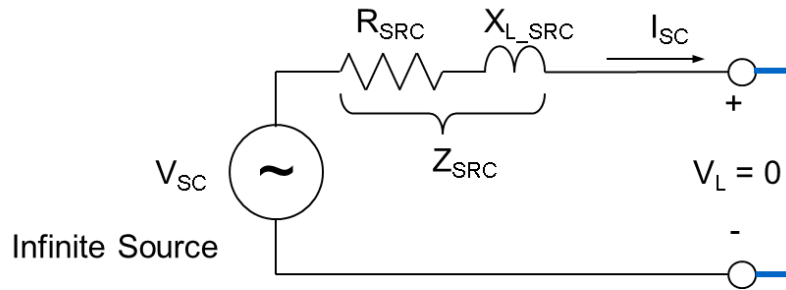
$$I_b = I_{bc} - I_{ab} \quad I_{bc} = \frac{V_b - V_c}{Z_{bc}} \quad I_{ab} = \frac{V_a - V_b}{Z_{ab}}$$

$$I_b = \frac{V_b - V_c}{Z_{bc}} - \frac{V_a - V_b}{Z_{ab}}$$

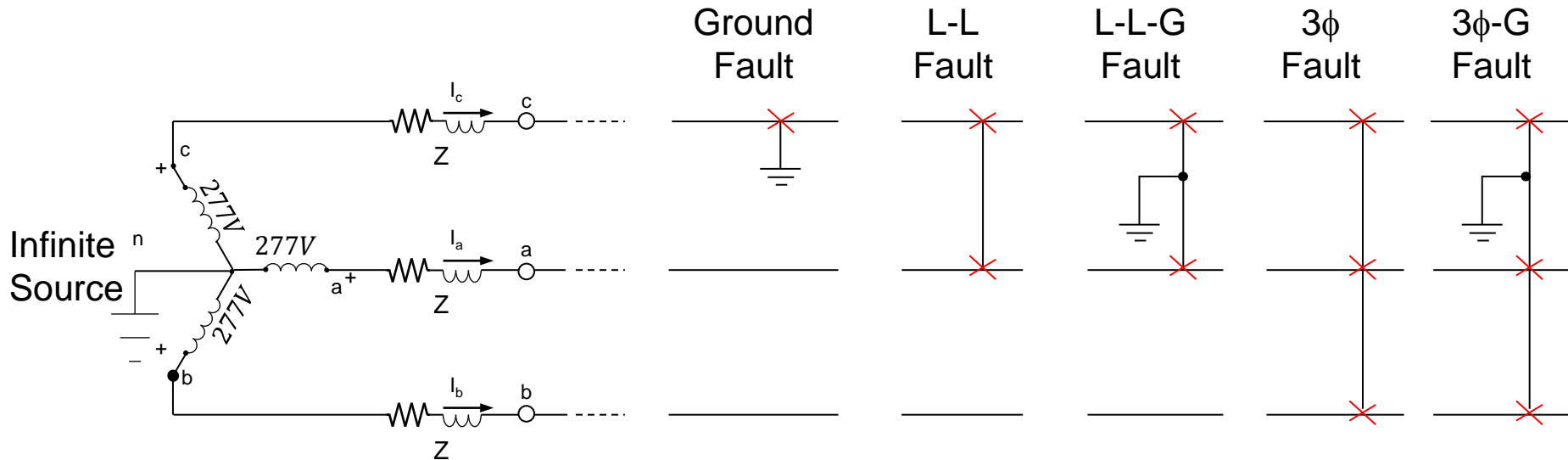
$$I_b = \frac{110\angle 120 - 105\angle 240}{1\angle 36} - \frac{100\angle 0 - 110\angle 120}{1.02\angle 5}$$

$$I_b = 261\angle 98^\circ$$

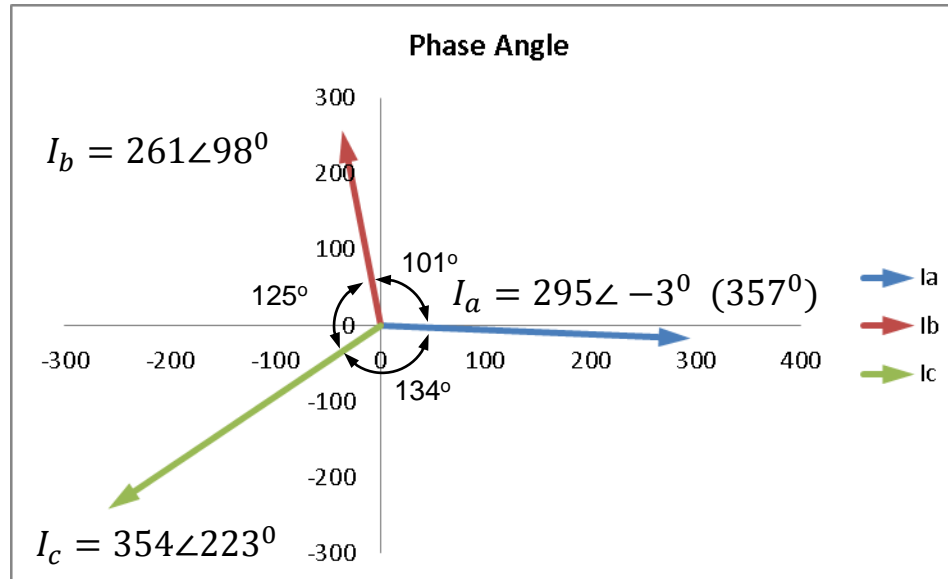
Solving Unbalanced Systems



$$I_{SC} = \frac{V_{SC}}{Z_{SRC}}$$



Unbalanced Systems

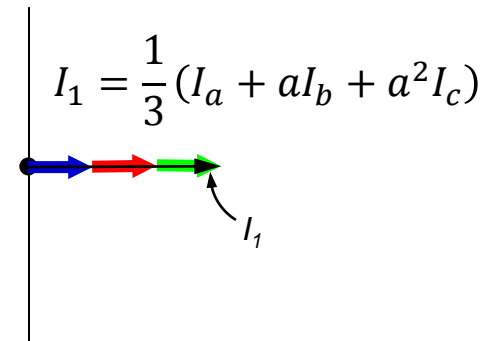
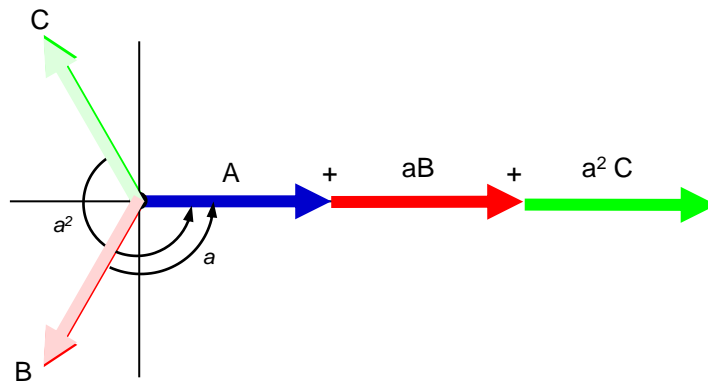
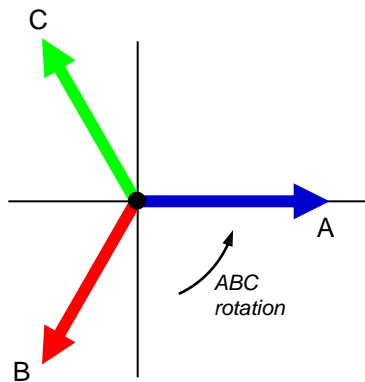


- Is there a simpler method?

Symmetrical Components

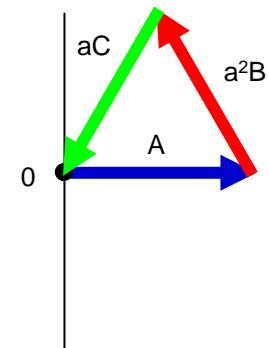
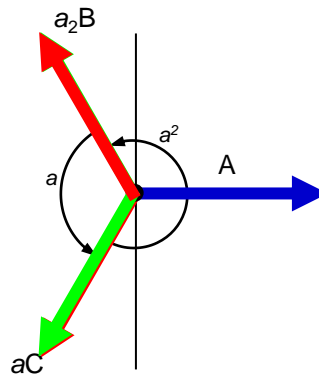
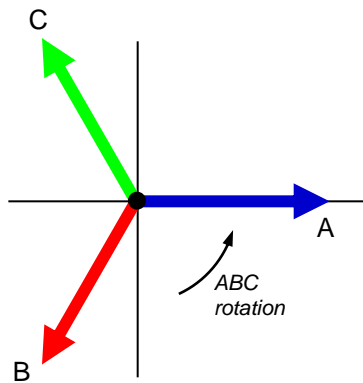
- Unbalanced systems converted to balanced
- Positive (1), negative (2) and zero (0)
“sequence” components

$$I_1 = \frac{1}{3} (I_a + aI_b + a^2I_c) \quad \text{Positive Sequence}$$



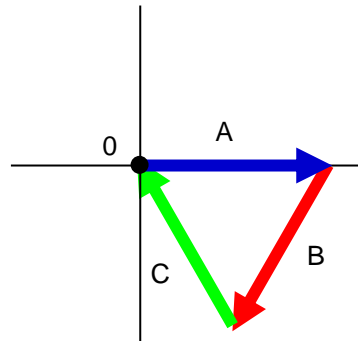
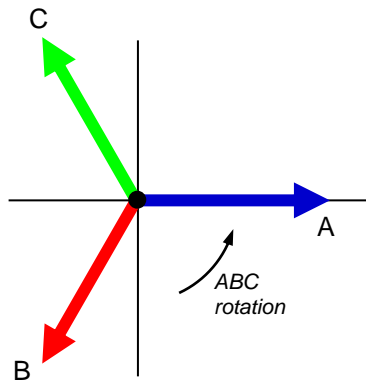
Negative Sequence

$$I_2 = \frac{1}{3} (I_a + a^2 I_b + a I_c)$$



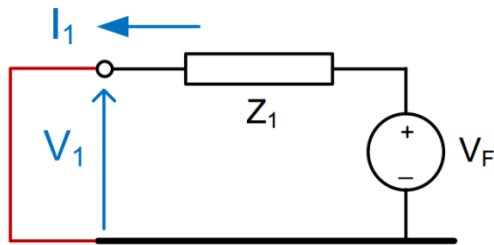
Zero Sequence

$$I_0 = \frac{1}{3}(I_a + I_b + I_c)$$

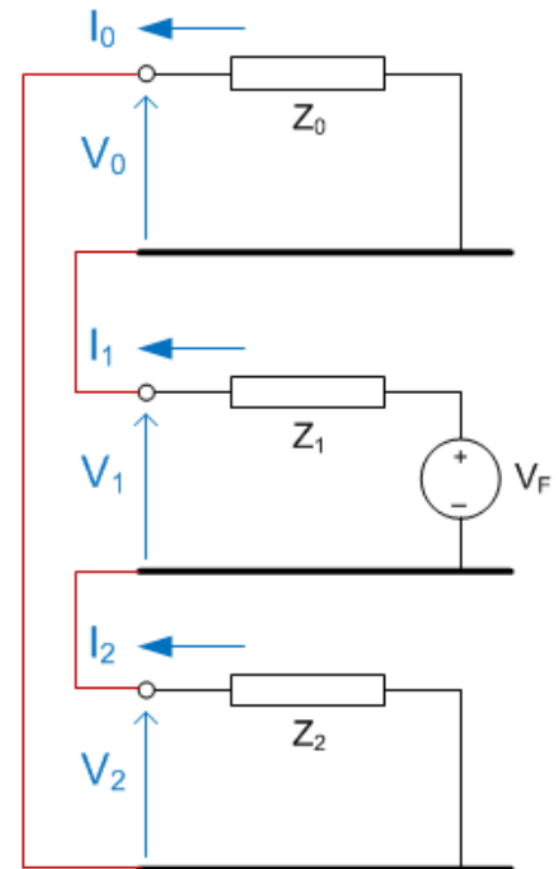


Unsymmetrical Faults

- 3-phase fault
 - Fault current = V_F / Z_1



- Single line to ground fault (SLGF)
 - Fault current = $3 * V_F / (Z_0 + Z_1 + Z_2)$
 - $I_0 = I_1 = I_2$



Symmetrical Components Conversions

$$I_0 = \frac{1}{3}(I_a + I_b + I_c)$$

$$I_1 = \frac{1}{3}(I_a + aI_b + a^2I_c)$$

$$I_2 = \frac{1}{3}(I_a + a^2I_b + aI_c)$$

$$I_a = I_0 + I_1 + I_2$$

$$I_b = I_0 + a^2I_1 + aI_2$$

$$I_c = I_0 + aI_1 + a^2I_2$$

Where:

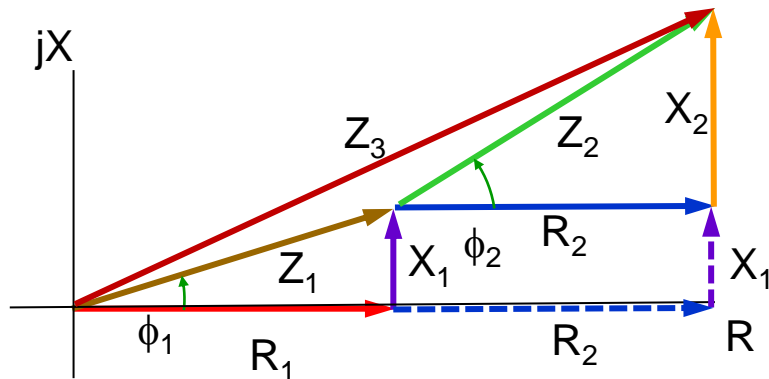
$$a \quad 1\angle 120^\circ = \frac{-1}{2} + j\frac{\sqrt{3}}{2} = -0.5 + j0.866 = \cos\left(\frac{2\pi}{3}\right) + j \cdot \sin\left(\frac{2\pi}{3}\right)$$

$$a^2 \quad 1\angle -120^\circ \text{ or } 1\angle 240^\circ = -0.5 - j0.866 = \cos\left(-\frac{2\pi}{3}\right) + j \cdot \sin\left(-\frac{2\pi}{3}\right) = \cos\left(\frac{4\pi}{3}\right) + j \cdot \sin\left(\frac{4\pi}{3}\right)$$

Z versus R+jX

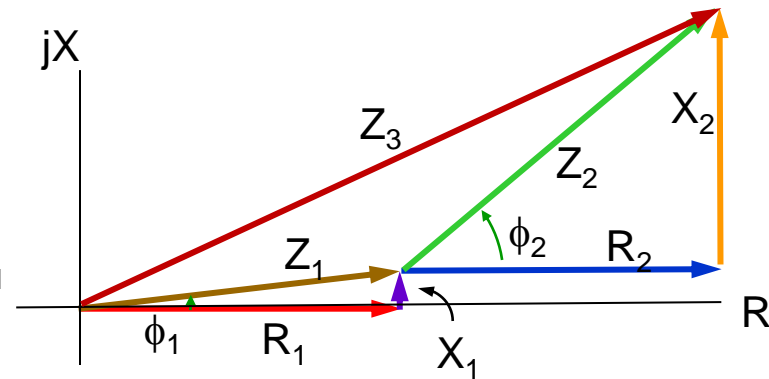
- CAG 1.3-8 to 1.3-10
- Uses R and X (jX) values instead of Z

Very small (<1%) difference ~3% difference



$$|Z_1| = \sqrt{(R_1)^2 + (X_1)^2}$$

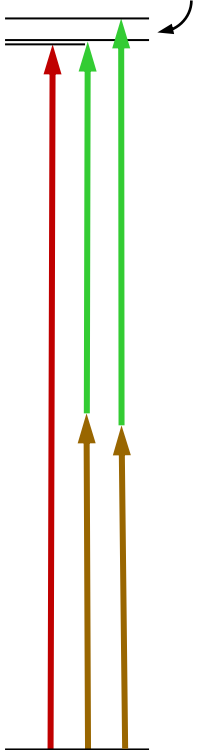
$$|Z_2| = \sqrt{(R_2)^2 + (X_2)^2}$$



$$|Z_3| = \sqrt{(R_1 + R_2)^2 + (X_1 + X_2)^2}$$

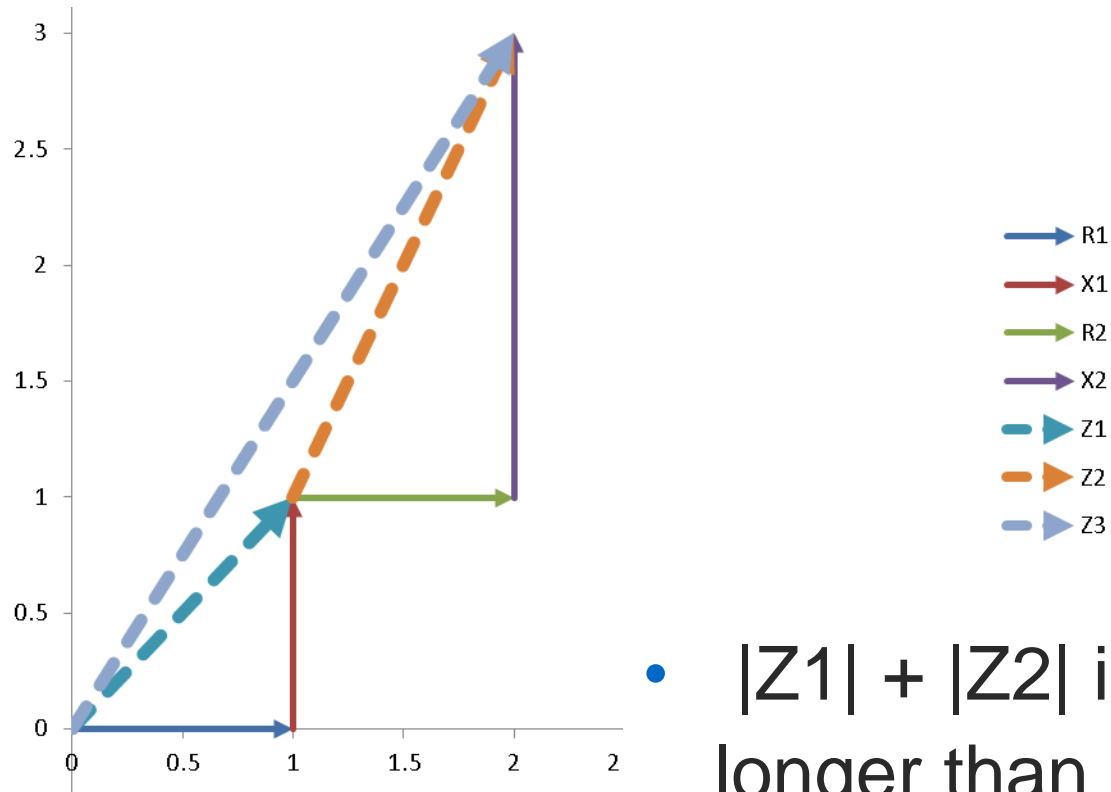
$$|Z_1| + |Z_2| = \sqrt{(R_1)^2 + (X_1)^2} + \sqrt{(R_2)^2 + (X_2)^2}$$

$$|Z_3| \neq |Z_1| + |Z_2|$$



Nominal Case

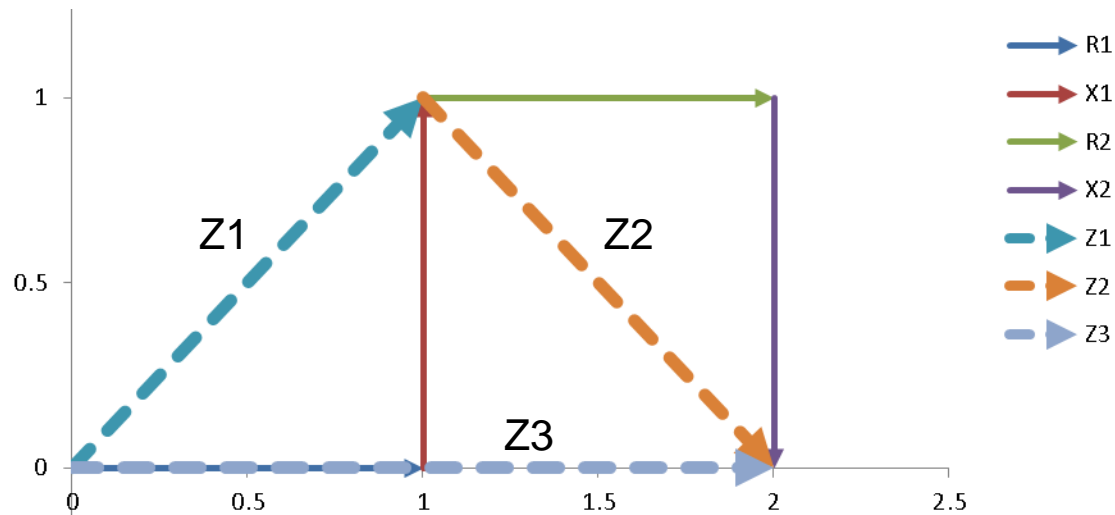
R1	R2	X1	X2	Z1	Z2	Z1+Z2	Z3	% err
1	1	1	2	1.414214	2.236068	3.650282	3.605551	1.2%



- $|Z1| + |Z2|$ is 1.2% longer than $|Z3|$

Extreme Case

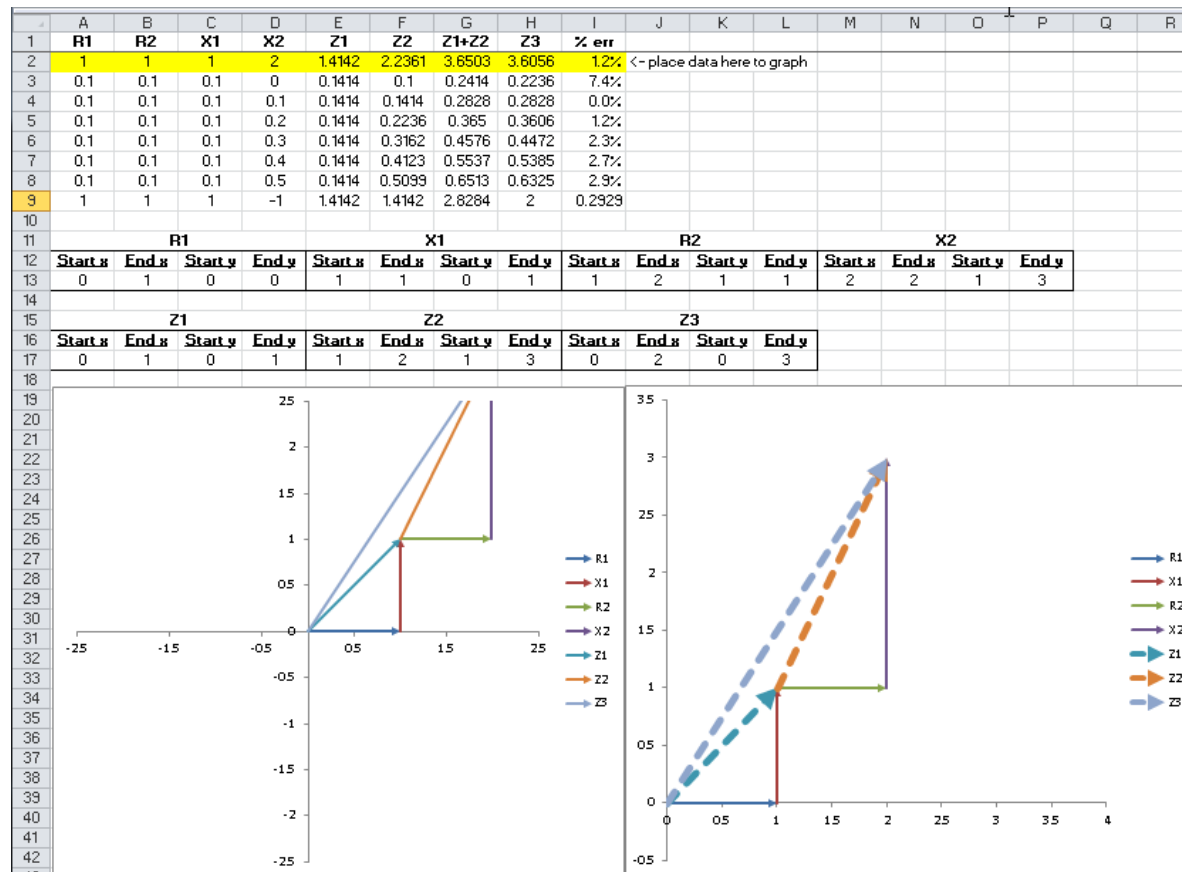
R1	R2	X1	X2	Z1	Z2	Z1+Z2	Z3	% err
1	1	1	-1	1.414214	1.414214	2.828427	2	29.3%



- $|Z1| + |Z2|$ is 29.3% longer than $|Z3|$

Download Copy of Excel Tool

- <http://pps2.com/smf/index.php/topic,46.0.html>



Determining X and R Values from Transformer Loss Data (Method 1)

- Given a 500 kVA, 5.5% Z transformer with 9000W total loss; 1700W no-load loss; 7300W load loss and primary voltage of 480V.

$$\text{Watts Loss} = \left(\frac{kVA}{\sqrt{3} * kV} \right)^2 * R * 3$$

$$\text{Watts Loss} = \left(\frac{500 \text{ kVA}}{\sqrt{3} * 0.48} \right)^2 * R * 3 = 7300$$

solve	$3r \left(\frac{500}{\sqrt{3} \times 0.48} \right)^2 - 7300 = 0$	for	R
-------	---	-----	---

Result

$$r = \frac{2628}{390625} \approx 0.0067277$$

$$\% \text{ impedance} = \% Z = \frac{(\text{ohms impedance})(kVA \text{ base})}{(kV)^2 (10)}$$

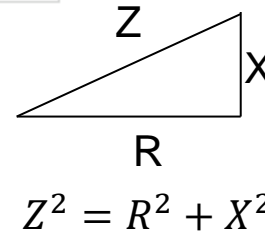
$$\%R = \frac{R * kVA}{kV^2 * 10}$$

$$\%R = \frac{0.0067277 * 500}{0.48^2 * 10}$$

$$\%R = 1.46\%$$

$$X = \sqrt{Z^2 - R^2}$$

$$\%X = \sqrt{5.5^2 - 1.46^2} = 5.3\%$$



Determining X and R Values from Transformer Loss Data (Method 2)

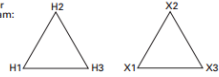
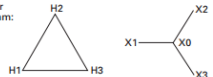
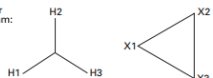
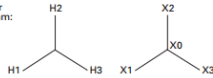
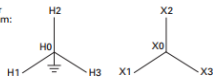
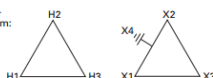
- Given a 500 kVA, 5.5% Z transformer with 9000W total loss; 1700W no-load loss; 7300W load loss and primary voltage of 480V.

$$\%R = \frac{I^2 R \text{ losses}}{10 * kVA}$$

$$\%R = \frac{7300}{10 * 500} = 1.46\%$$

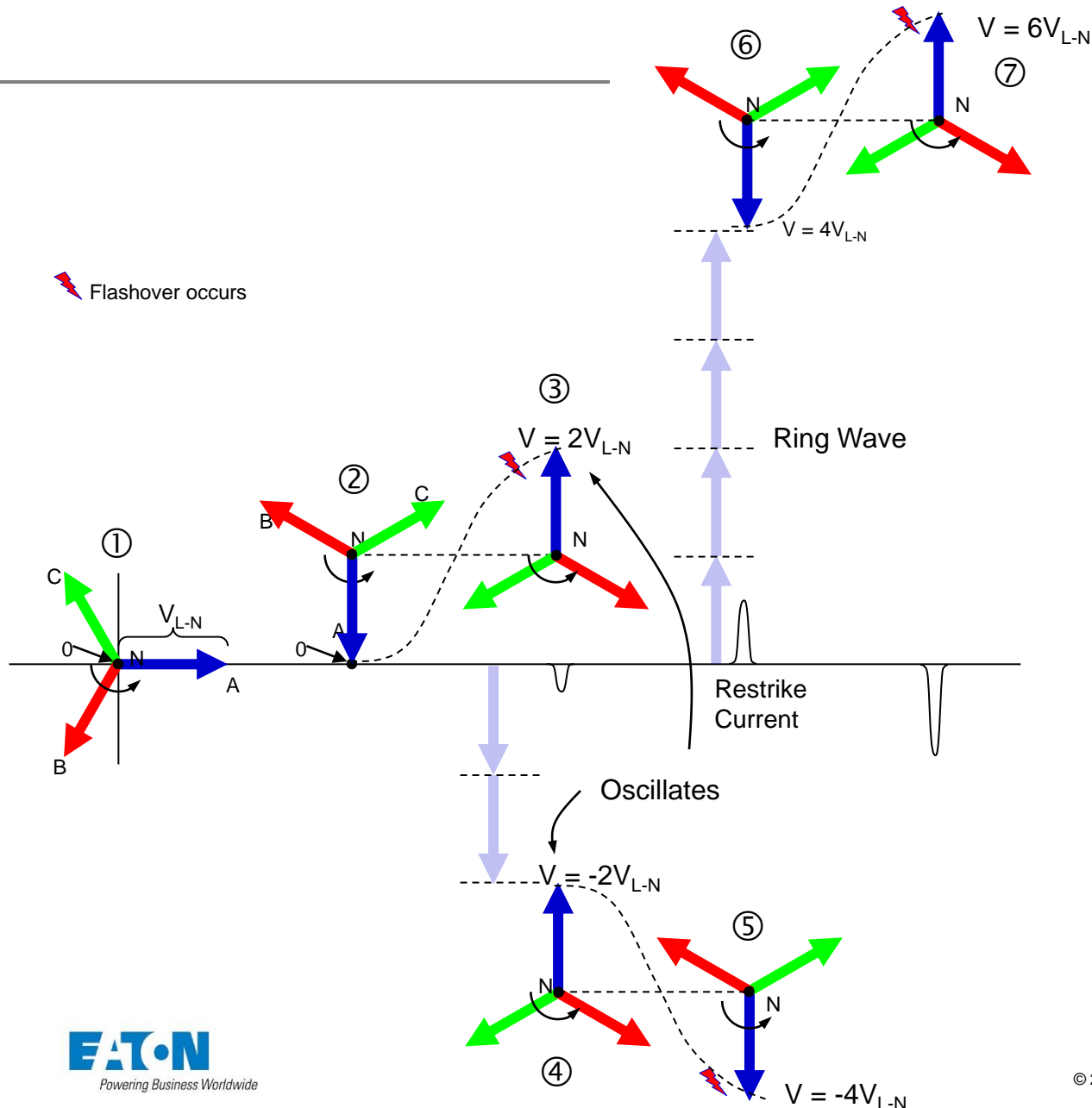
$$\%X = \sqrt{5.5^2 - 1.46^2} = 5.3\%$$

3 ϕ Transformer Winding Connections

Phasor Diagram	Notes
DELTA-DELTA Connection Phasor Diagram:  Angular Displacement (Degrees): 0	1. Suitable for both ungrounded and effectively grounded sources. 2. Suitable for a three-wire service or a four-wire service with a mid-tap ground.
DELTA-WYE Connection Phasor Diagram:  Angular Displacement (Degrees): 30	1. Suitable for both ungrounded and effectively grounded sources. 2. Suitable for a three-wire service or a four-wire grounded service with XO grounded. 3. With XO grounded, the transformer acts as a ground source for the secondary system. 4. Fundamental and harmonic frequency zero-sequence currents in the secondary lines supplied by the transformer do not flow in the primary lines. Instead the zero sequence currents circulate in the closed delta primary windings. 5. When supplied from an effectively grounded primary system does not see load unbalances and ground faults in the secondary system.
WYE-DELTA Connection Phasor Diagram:  Angular Displacement (Degrees): 30	1. Suitable for both ungrounded and effectively grounded sources. 2. Suitable for a three-wire service or a four-wire delta service with a mid-tap ground. 3. Grounding the primary neutral of this connection would create a ground source for the primary system. This could subject the transformer to severe overloading during a primary system disturbance or load unbalance. 4. Frequently installed with mid-tap ground on one leg when supplying combination three-phase and single-phase load where the three-phase load is much larger than single-phase load. 5. When used in 25 kV and 35 kV three-phase four-wire primary systems, ferroresonance can occur when energizing or de-energizing the transformer using single-pole switches located at the primary terminals. With smaller kVA transformers the probability of ferroresonance is higher.
WYE-WYE Connection Phasor Diagram:  Angular Displacement (Degrees): 0	1. Suitable for both ungrounded and effectively grounded sources. 2. Suitable for a three-wire service only, even if XO is grounded. 3. This connection is incapable of furnishing a stabilized neutral and its use may result in phase-to-neutral overvoltage (neutral shift) as a result of unbalanced phase-to-neutral load. 4. If a three-phase unit is built on a three-legged core, the neutral point of the primary windings is practically locked at ground potential.
GROUND WYE-WYE Connection Phasor Diagram:  Angular Displacement (Degrees): 0	1. Suitable for four-wire effectively grounded source only. 2. Suitable for a three-wire service or for four-wire grounded service with XO grounded. 3. Three-phase transformers with this connection may experience stray flux tank heating during certain external system unbalances unless the core configuration (four or five legged) used provides a return path for the flux. 4. Fundamental and harmonic frequency zero-sequence currents in the secondary lines supplied by the transformer also flow in the primary lines (and primary neutral conductor). 5. Ground relay for the primary system may see load unbalances and ground faults in the secondary system. This must be considered when coordinating overcurrent protective devices. 6. Three-phase transformers with the neutral points of the high voltage and low voltage windings connected together internally and brought out through an HOXO bushing should not be operated with the HOXO bushing ungrounded (floating). To do so can result in very high voltages in the secondary systems.
DELTA-DELTA Connection with Tap Phasor Diagram:  Angular Displacement (Degrees): 0	1. Suitable for both ungrounded and effectively grounded sources. 2. Suitable for a three-wire service or a four-wire service with a mid-tap ground. 3. When using the tap for single-phase circuits, the single-phase load kVA should not exceed 5% of the three-phase kVA rating of the transformer. The three-phase rating of the transformer is also substantially reduced.

- Protection
 - Ground fault
- Transient overvoltages

Intermittent GF on Ungrounded System



- ① Normal operation
- ② Phase grounded
- ③ Gnd removed (phasor rotates $2V_{L-N}$)
- ④ Flashover inversion
- ⑤ Phasor rotates $3V_{L-N}$
- ⑥ Flashover inversion
- ⑦ Phasor rotates $4V_{L-N}$