



Power System Analysis:

Rules of Thumb (RoT) and Sanity Testing

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System Analysis

- Short Circuit Studies
 - Arc Flash Studies
 - Protective Device Coordination
 - Load Flow
 - Motor Starting
 - Power Factor and Harmonic Analysis
 - Transient Stability
 - Insulation Coordination
 - Grounding Study
 - Switching Transient Study
- 
- 
- Tomorrow

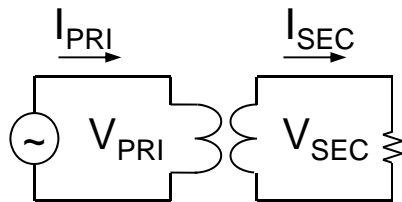
Transformer Review

1-Phase

$$VA = V * I$$

$$kVA = kV * I$$

$$MVA = MV * I \quad MVA = kV * kA$$

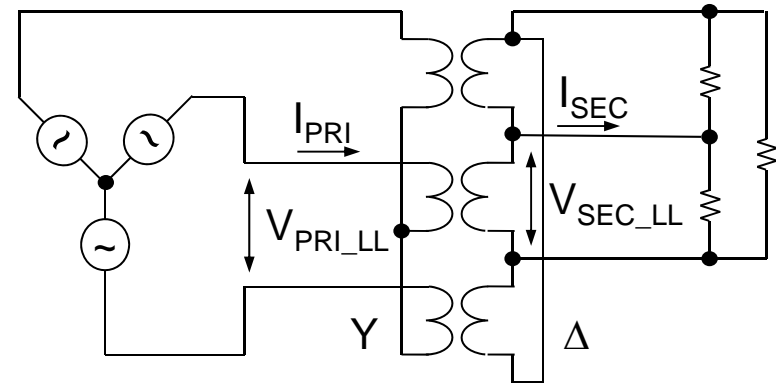


3-Phase

$$VA = \sqrt{3} * V_{LL} * I$$

$$kVA = \sqrt{3} * kV_{LL} * I$$

$$MVA = \sqrt{3} * kV_{LL} * kA$$



- VA is “conserved. $V * I$ (or $V * A$) calculated from either PRI or SEC gives same answer
 - $V_{PRI} * I_{PRI} = V_{SEC} * I_{SEC}$ (ideal transformer)

Example

- 75 kVA, 480V-208Y/120V, 3-phase, $Z = 5\%$
 - What is the nominal primary current?
 - What is the nominal secondary current (@208 V)?

$$kVA = kV_{PRI} * I_{PRI} * \sqrt{3} = 75 = 0.48 * I_{PRI} * 1.732$$

$$I_{PRI} = \frac{75}{0.48 * 1.732} = 90.2A$$

$$I_{SEC} = \frac{75}{0.208 * 1.732} = 208.2A$$

I_{SC} Calcs with Per Unit Impedance

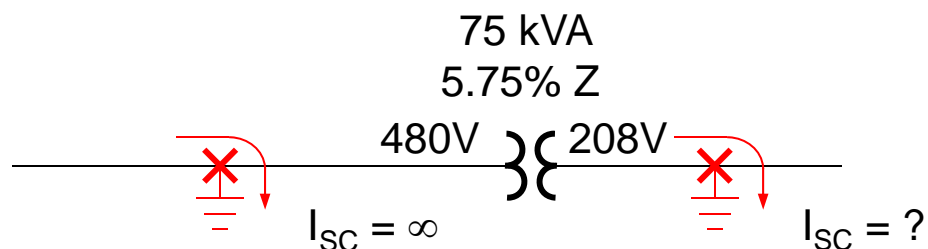
- Consider a transformer with a 5% impedance. A voltage is applied to the primary with the secondary winding shorted (faulted).
 - At 5% input voltage → 100% FLA produced
 - At 10% input voltage → 200% FLA is produced
 - At 50% input voltage → 1000% FLA is produced
 - At 100% input voltage → 2000% FLA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

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

Example

- 75 kVA, 480V-208Y/120V, 3-phase, $Z = 5.75\%$

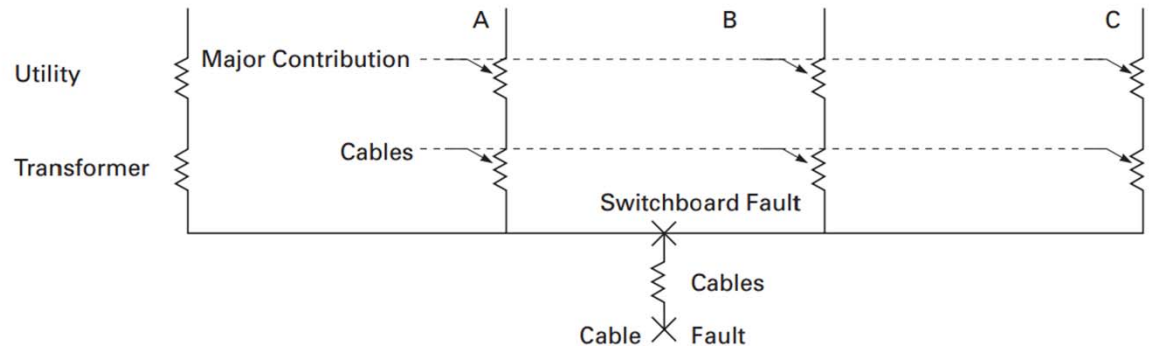
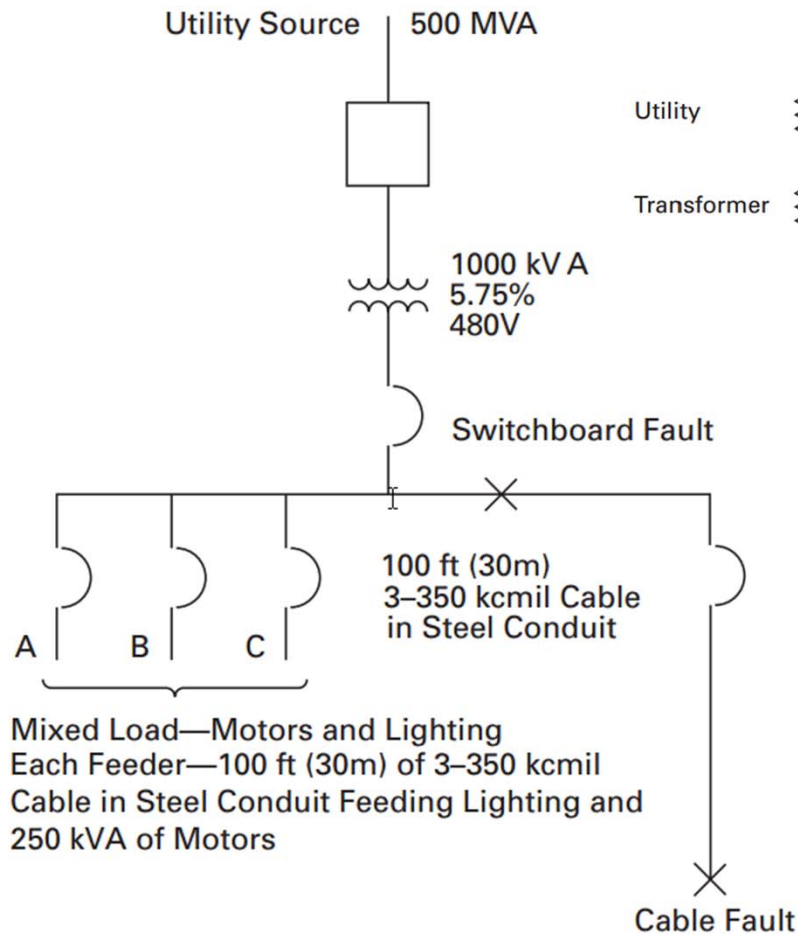
$$I_{FL_SEC} = \frac{75}{0.208 * 1.732} = 208.2A \text{ Full Load}$$



- What is the secondary I_{SC} @ 208V? (assume infinite source)

$$I_{SC} = \frac{I_{FL_SEC}}{Z_{pu}} = \frac{208.2 A}{0.0575} = 3621A$$

Short Cut Z Method



Combining Series Impedances: $Z_{TOTAL} = Z_1 + Z_2 + \dots + Z_n$

Combining Parallel Impedances: $\frac{1}{Z_{TOTAL}} = \frac{1}{Z_1} + \frac{1}{Z_2} + \dots + \frac{1}{Z_n}$

Per Unit Calculations

1. Transformer impedance generally relates to self-ventilated rating at rated temp (e.g., with OA/FA/FOA transformer **use OA base**).
2. kV refers to **line-to-line** voltage in kilovolts.
3. Z refers to line-to-neutral impedance of system to fault where $R + jX = Z$.

When totaling the components of system Z, arithmetic combining of impedances as “ohms Z”. “per unit Z”. etc., is considered a shortcut or approximate method; proper combining of impedances (e.g., source, cables transformers, conductors, etc.). should use individual R and X components. This Total $Z = \text{Total } R + j \text{ Total } X$ (see IEEE “Red Book” Standard No. 141).

Per Unit Cheat Sheet

Convert To/From Bases

$$\text{Per unit} = \text{pu impedance kVA base 2} = \frac{\text{kVA base 2}}{\text{kVA base 1}} \times (\text{pu impedance on kVA base 1})$$

$$\text{Percent} = \% \text{ impedance kVA base 2} = \frac{\text{kVA base 2}}{\text{kVA base 1}} \times (\% \text{ impedance on kVA base 1})$$

$$\text{Per unit impedance} = \text{pu } Z = \frac{\text{percent impedance}}{100} = \frac{(\text{ohms impedance}) (\text{kVA base})}{(\text{kV})^2 (1000)}$$

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

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

Convert Z to Isc to MVA

—if utility fault capacity given in kVA

$$\text{Per-unit impedance} = \text{pu } Z = \frac{\text{kVA base in study}}{\text{power-source kVA fault capacity}}$$

—if utility fault capacity given in rms symmetrical short circuit amperes

$$\text{Per-unit impedance} = \text{pu } Z = \frac{\text{kVA base in study}}{(\text{short-circuit current}) (\sqrt{3}) (\text{kV of source})}$$

—motor kVA — $(\sqrt{3}) (\text{kV}) (I)$ where I = motor nameplate full-load amperes

—if 1.0 power factor synchronous motor kVA = (0.8) (hp)

—if 0.8 power factor synchronous motor kVA = (1.0) (hp)

—if induction motor kVA = (1.0) (hp)

Find Base and pu Isc Current

$$\text{Base current} = I_{\text{Base}} = \frac{\text{Three-phase kVA}}{(\sqrt{3})(\text{kV})} \text{ or } \frac{\text{Single-phase kVA}}{\text{kV line-to-neutral}}$$

$$\text{Per unit } I_{\text{sc}} = \frac{1.0}{\text{pu } Z}$$

Find Isc

$$\text{rms Symmetrical current} = I_{\text{SC}} = (\text{pu } I_{\text{SC}}) (I_{\text{Base}} \text{ Amperes})$$

$$\begin{aligned} \text{rms Symmetrical current} = \text{Amperes} &= \frac{\text{Three-phase KVA base}}{(\text{pu } Z) (\sqrt{3}) (\text{kV})} \text{ or } \frac{\text{Single-phase kVA base}}{(\text{pu } Z) (\text{kV})} \\ &= \frac{(\text{Three-phase kVA base}) (100)}{(\% Z) (\sqrt{3}) (\text{kV})} \text{ or } \frac{\text{Single-phase kVA base} (100)}{(\% Z) (\text{kV})} \\ &= \frac{(\text{kV}) (1000)}{\sqrt{3} (\text{ohms } Z)} \end{aligned}$$

$$\begin{aligned} \text{Symmetrical short-circuit kVA} &= \frac{\text{kVA base}}{(\text{pu } Z)} = \frac{(\text{kVA base}) (100)}{\% Z} = \frac{(\text{kV})^2 (1000)}{\text{ohms } Z} \\ &= \frac{3(\text{line-to-neutral kV})^2 (1000)}{(\text{ohms } Z)} \end{aligned}$$

—from three-phase transformer—approx. 86% of three-phase current

—three single-phase transformers (e.g., 75 kVA, $Z = 2\%$) calculate same as one three-phase unit (i.e., $3 \times 75 \text{ kVA} = 225 \text{ kVA}$, $Z = 2\%$).

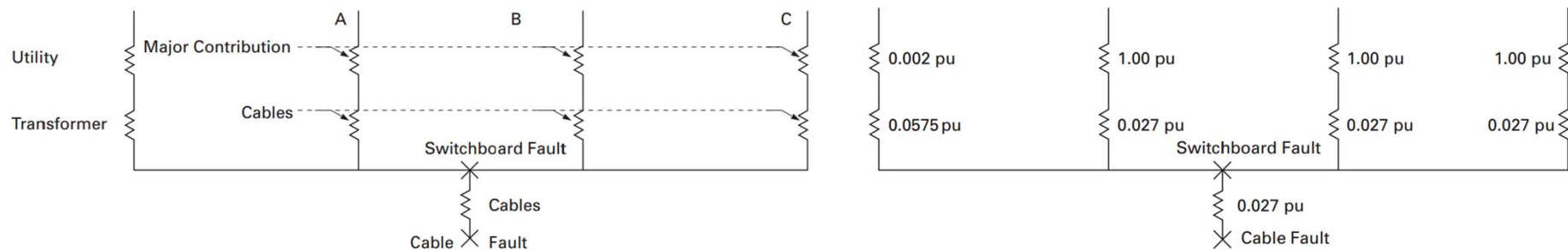
—from single-phase transformer—see **Page 1.3-15**.

Calculate Motor Contribution

- synchronous motor—5 times motor full load current (impedance 20%)
 - induction motor—4 times motor full-load current (impedance 25%)
- } See IEEE Standard No. 141
- motor loads not individually identified, use contribution from group of motors as follows:
 - on 208Y/120V systems—2.0 times transformer full-load current
 - on 240-480-600V three-phase, three-wire systems—4.0 times transformer full-load current
 - on 480Y/277V three-phase, four-wire systems
 - In commercial buildings, 2.0 times transformers full-load current (50% motor load)
 - In industrial plants, 4.0 times transformer full-load current (100% motor load)

Short Cut Z Method

$$\frac{1}{\frac{1}{1 + 0.027} + \frac{1}{1 + 0.027} + \frac{1}{1 + 0.027}} = 0.342$$



$$\text{Utility per unit impedance} = Z_{pu} = \frac{\text{kVA base}}{\text{utility fault kVA}} = \frac{1000}{500,000} = 0.002 \text{ pu}$$

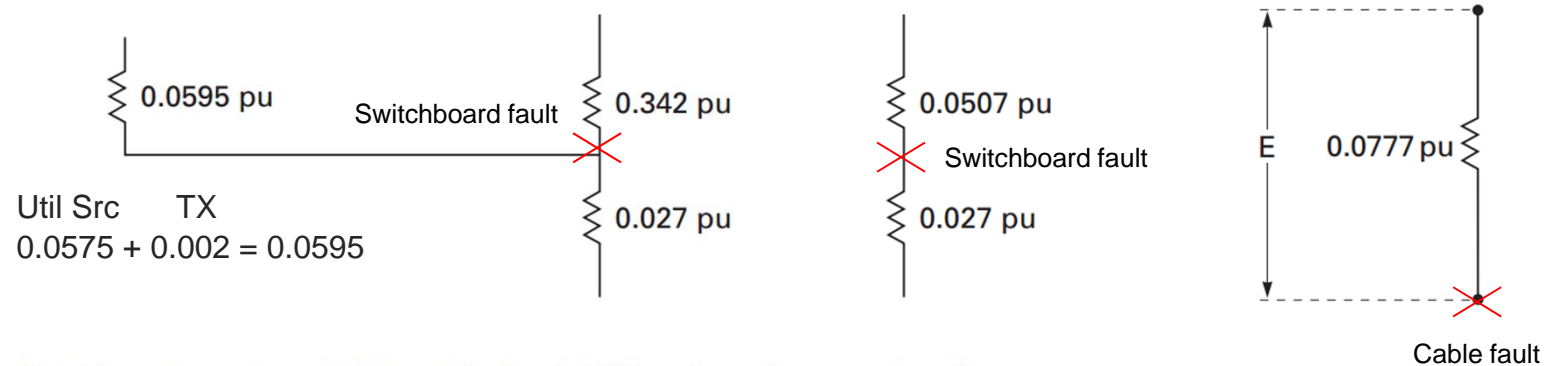
$$\text{Transformer per unit impedance} = Z_{pu} = \frac{\%Z}{100} = \frac{5.75}{100} = 0.0575 \text{ pu}$$

$$\text{Motor contribution per unit impedance} = Z_{pu} = \frac{\text{kVA base}}{4 \times \text{motor kVA}} = \frac{1000}{4 \times 250} = 1.00 \text{ pu}$$

Conductor impedance (CAG Table 1.5-16, Page 1.5-14). **Conductors:** 3–350 kcmil copper, single conductors. **Circuit length:** 100 ft (30m), in steel (magnetic) **Impedance in Conduit** = 0.00619 ohms/100 ft (30m) or **Z_{TOT} = 0.00619 ohms** (100 circuit feet)

$$\text{Cable impedance per unit} = Z_{pu} = \frac{(\text{ohms})(\text{kVA base})}{(\text{kV})^2(1000)} = \frac{(0.00619)(1000)}{(0.480)^2(1000)} = 0.027 \text{ pu}$$

Short Cut Z Method



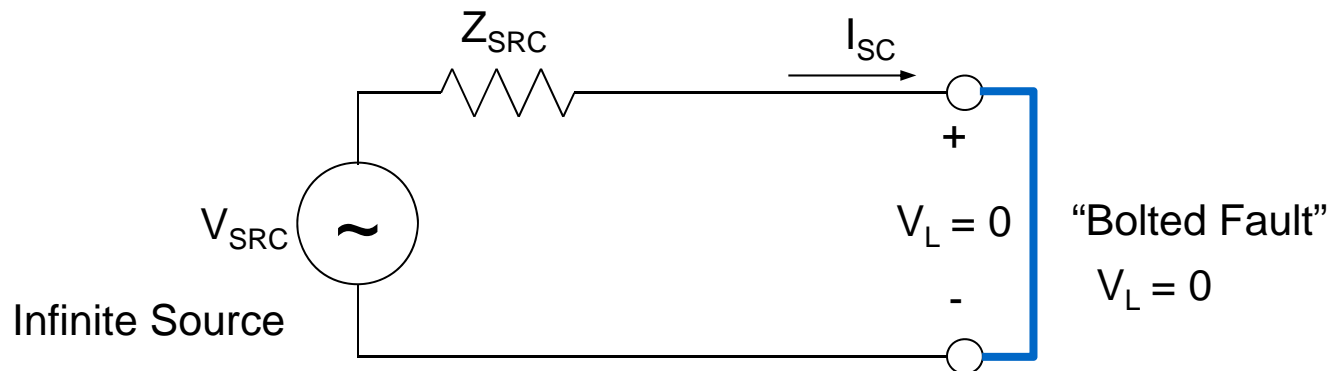
Total impedance to switchboard fault = 0.0507 pu (see diagram above)

$$\text{Symmetrical short circuit current at switchboard fault} = \frac{3\text{-phase kVA base}}{(Z_{pu})(\sqrt{3})(kV)} = \frac{1000}{(0.0507)(\sqrt{3})(0.480)} = 23,720 \text{ amperes rms}$$

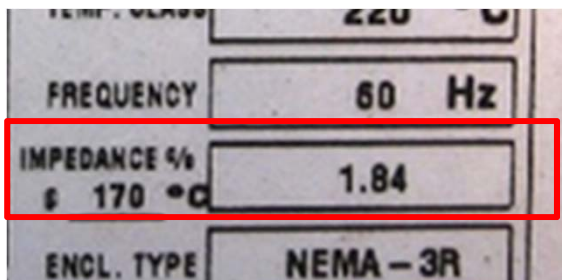
Total impedance to cable fault = 0.0777 pu (see diagram above)

$$\text{Symmetrical short circuit current at cable fault} = \frac{3\text{-phase kVA base}}{(Z_{pu})(\sqrt{3})(kV)} = \frac{1000}{(0.0777)(\sqrt{3})(0.480)} = 15,480 \text{ amperes rms}$$

Short Circuit Studies – Ohmic Method

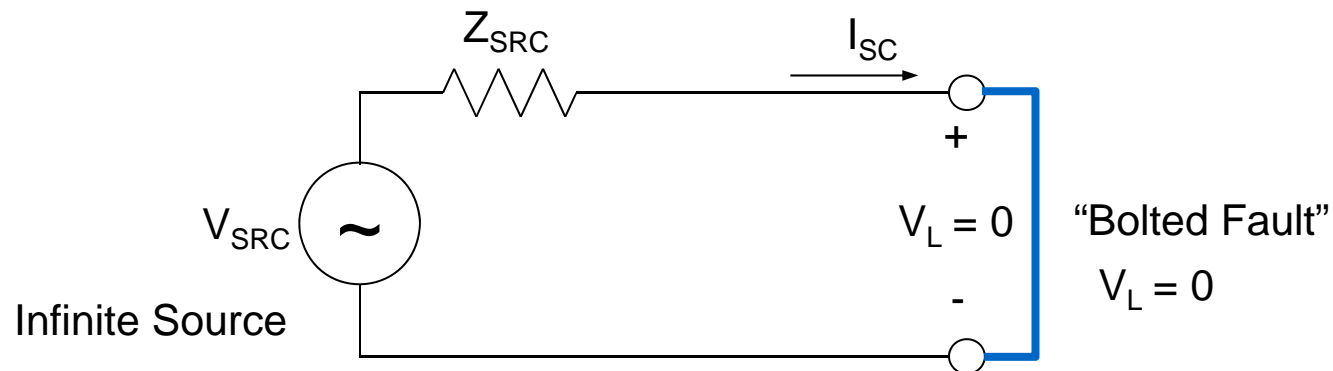


- Ohm's Law
$$I_{SC} = \frac{V_{SRC} - V_L}{Z_{SRC}} = \frac{V_{SRC}}{Z_{SRC}}$$



- Z % per unit, not ohms
- Must convert to use



Short Circuit Studies



$$Z_{SRC}(\Omega) = Z_{pu} \frac{V_{LL}^2}{S_{base}}$$

$$Z_{SRC} = 0.0184 \frac{120^2}{25000}$$

$$Z_{SRC} = 0.0106\Omega$$

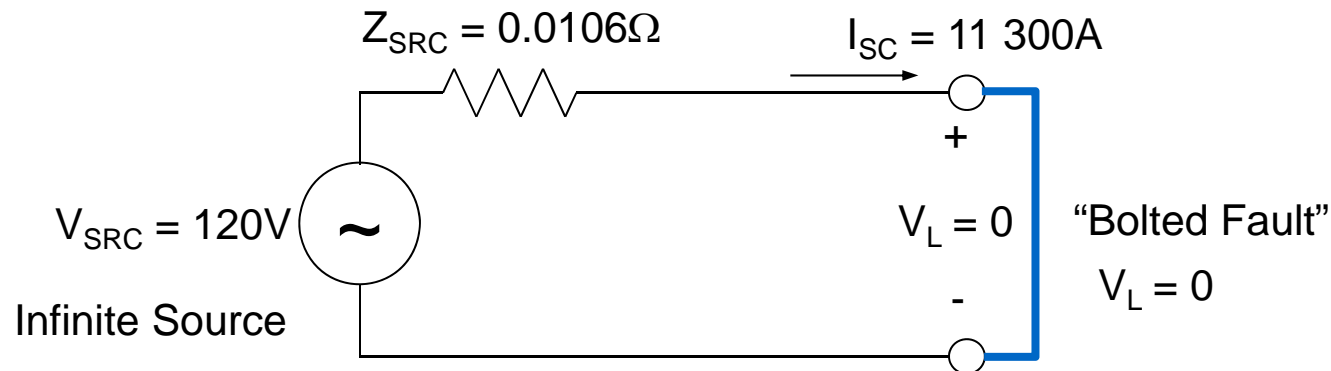
SINGLE PHASE DRY TYPE TRANSFORMER				
HV	480			
BIL	-			
TERM.	H1 H2			
	VOLTS	CURRENT	% RATED VOLTAGE	CONNECT EACH PHASE
	504	49.5	105	1-2
	492	50.8	102.5	2-3
	480	52.1	100	3-4
	468	53.4	97.5	4-5
	456	54.8	95	5-6
LV	120			
BIL	-			
TERM.	X2 X1			
<div style="display: flex; justify-content: space-around; align-items: center;"> <div style="text-align: center;">  HV </div> <div style="text-align: center;">  HT </div> </div>				

CUST. REF.	
SERIAL NO.	EPX000775-002
PART NO.	90258995L
kVA	25
TYPE	F
COOLING	ANN
TEMP. RISE	150 °C
TEMP. CLASS	220 °C
FREQUENCY	60 Hz
IMPEDANCE % @ 170 °C	1.84
ENCL. TYPE	NEMA-3R
WT. LBS	340
WINDING MATERIAL	AL

SPACING BETWEEN ENCLOSURE AND ANY ADJACENT WALL SHALL BE A MINIMUM OF 8 INCHES.

Ref: CAG 1.3-2

Short Circuit Studies – Per Unit Method



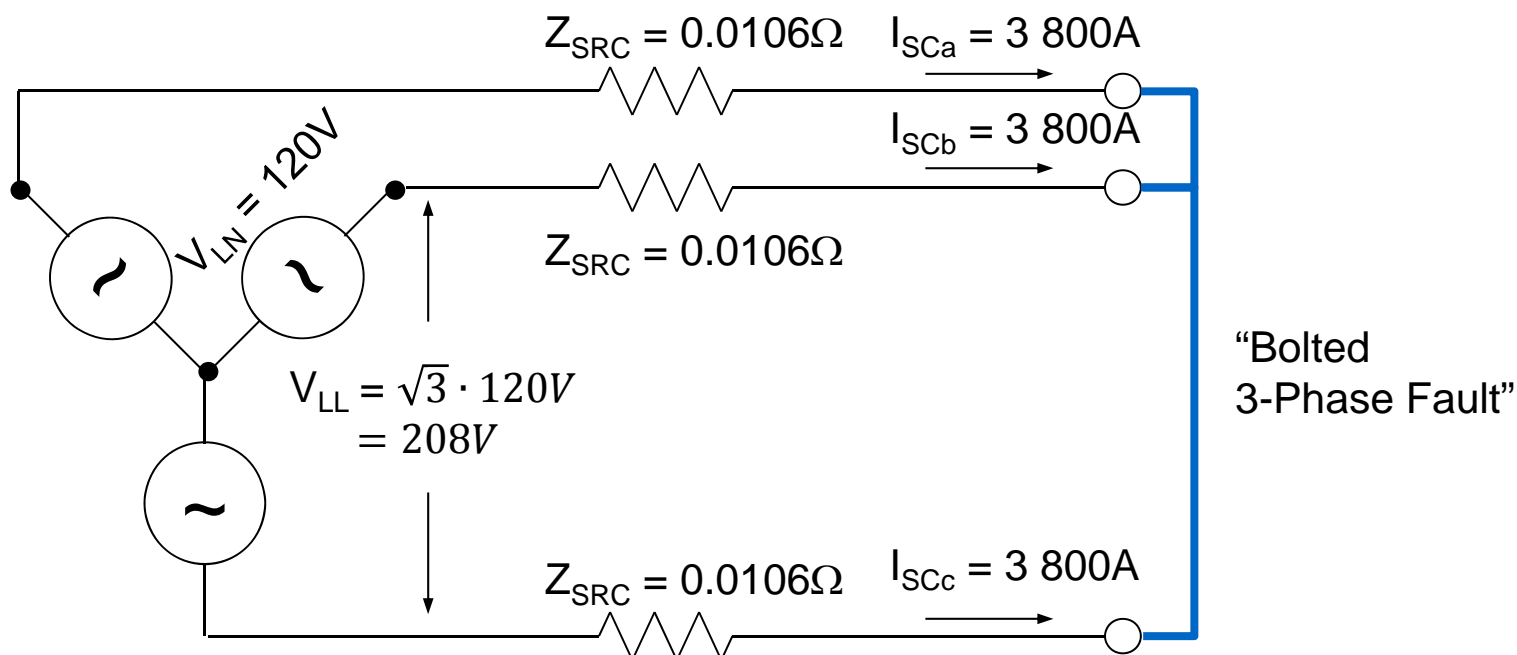
$$I_{SC_1\phi} = \frac{V_{SRC} - V_L}{Z_{SRC}} = \frac{V_{SRC}}{Z_{SRC}} = \frac{120}{0.0106} = 11.3 \text{ kA}$$

- Using Z_{pu} directly (without calculating actual Z)

$$I_{SC_1\phi} = \frac{I_{FL}}{\%Z} = \frac{kVA/V}{\%Z} = \frac{25000/120}{0.0184} = 11.3 \text{ kA}$$

Ref: CAG 1.3-8

Short Circuit Studies – 3 Phase



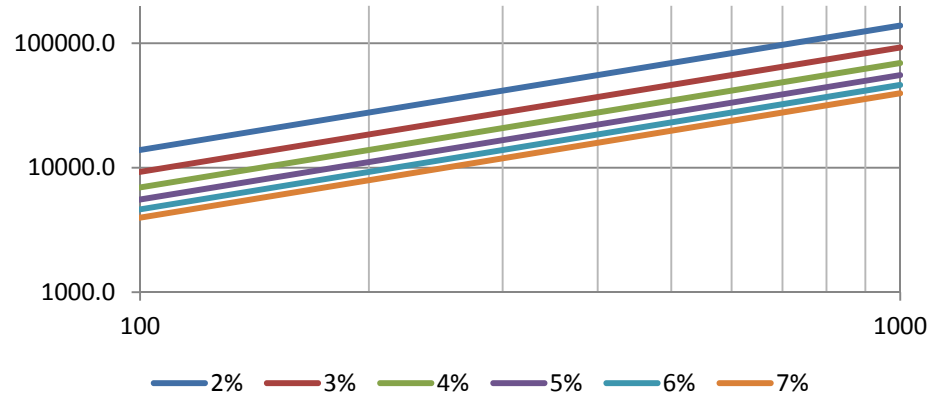
$$I_{SC_3\phi} = \frac{I_{FL}}{\%Z} = \frac{kVA / (\sqrt{3}V_{LL})}{\%Z} = \frac{25000 / \sqrt{3} \cdot 208}{0.0184} = 3.8 \text{ kA}$$

$$I_{SC_3\phi} = \frac{I_{FL}}{\%Z} = \frac{kVA / (\sqrt{3}V_{LL})}{\%Z} = \frac{75000 / \sqrt{3} \cdot 208}{0.0184} = 11.3 \text{ kA}$$

Ref: CAG 1.3-8

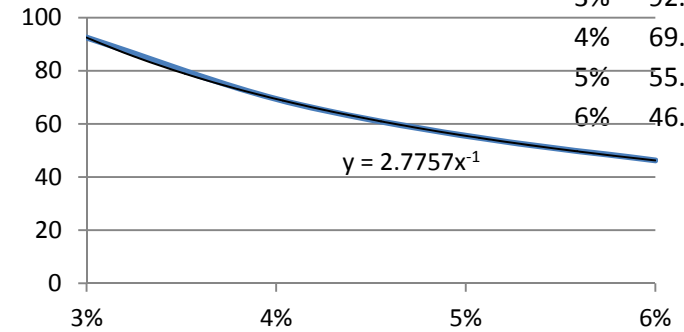
Short Circuit RoT

208V

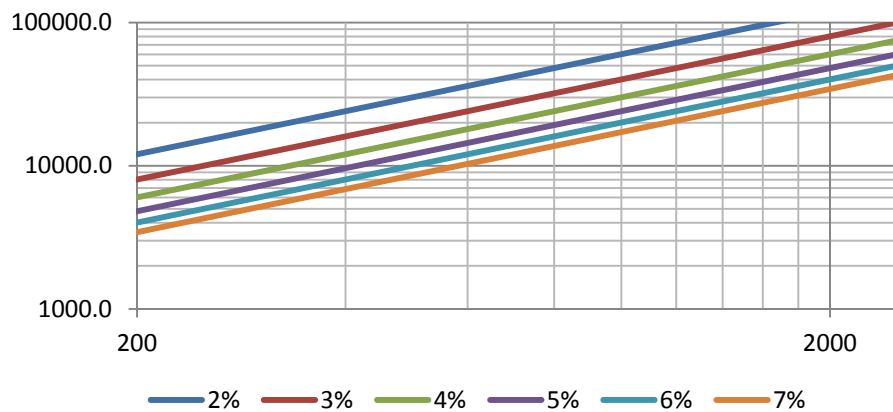


$$I_{sc} = SCF * kVA$$

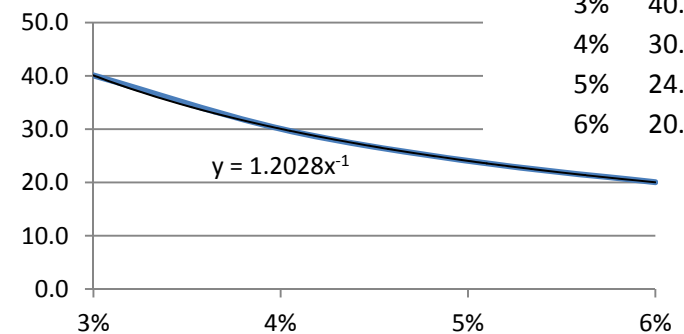
<u>%Z</u>	<u>SCF</u>
3%	92.5
4%	69.4
5%	55.5
6%	46.3



480V



<u>%Z</u>	<u>SCF</u>
3%	40.1
4%	30.1
5%	24.1
6%	20.0



Fault Current RoT – Curve Method

Approximations

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

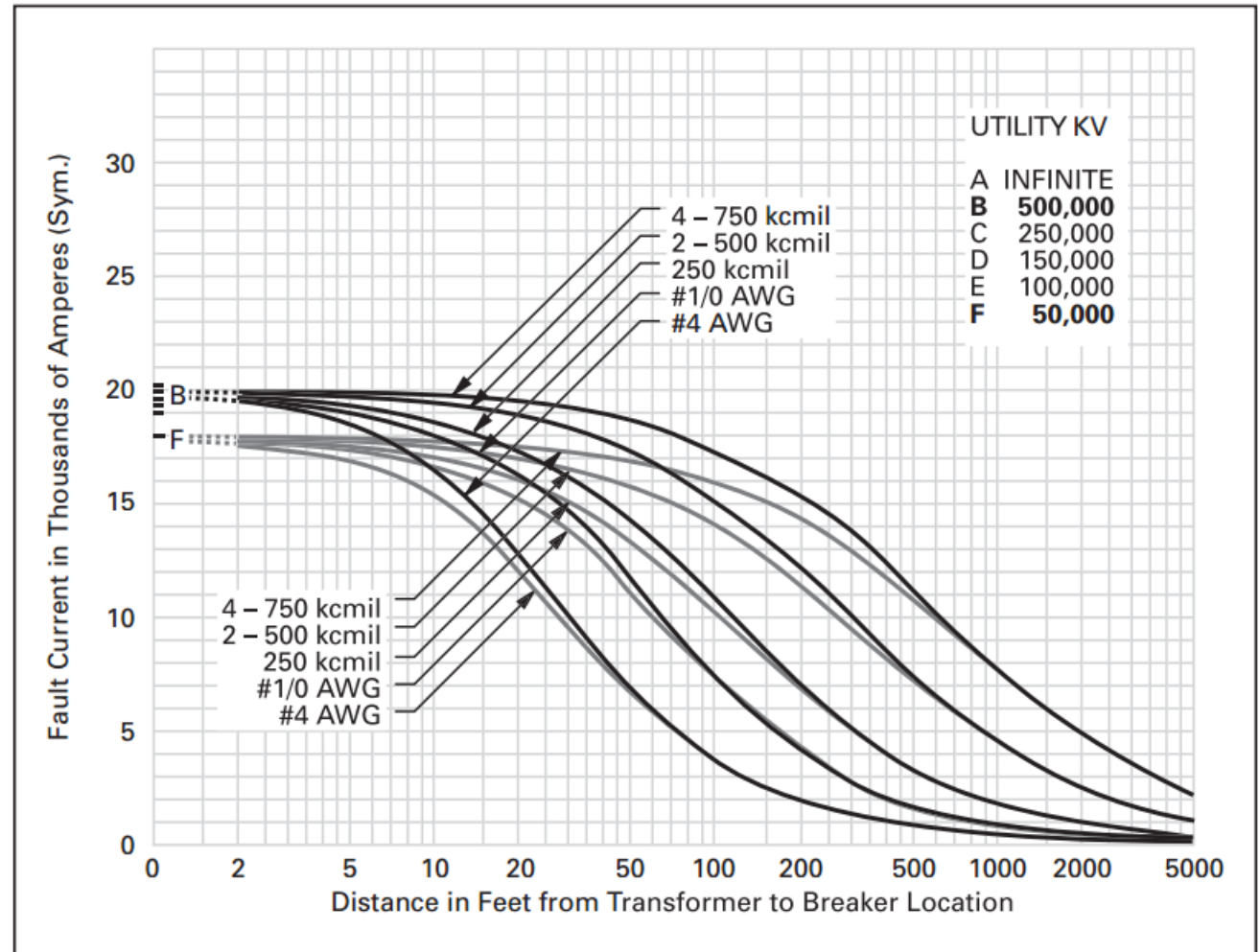


Figure 1.3-13. 300 kVA Transformer/4.5% Impedance/208V

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

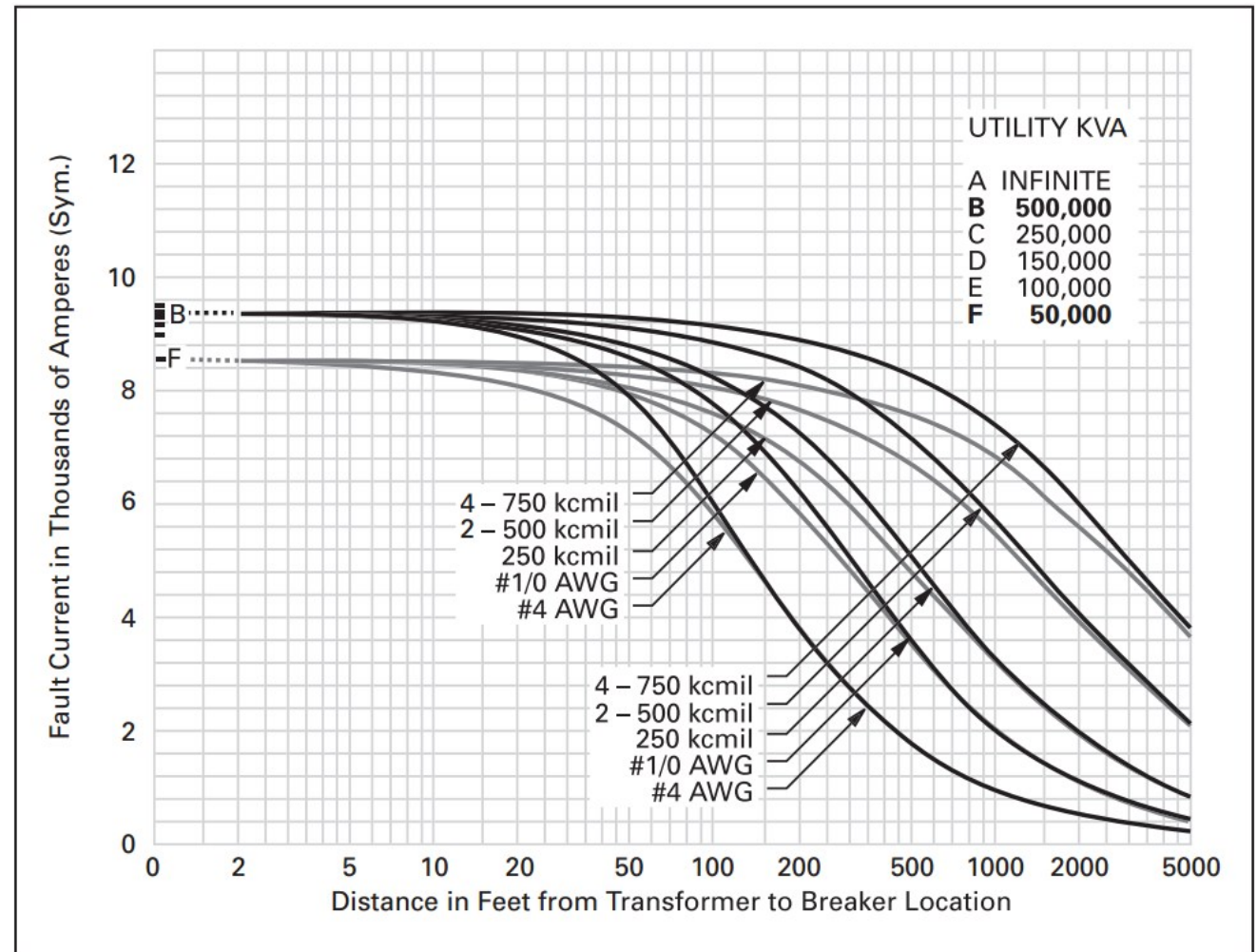
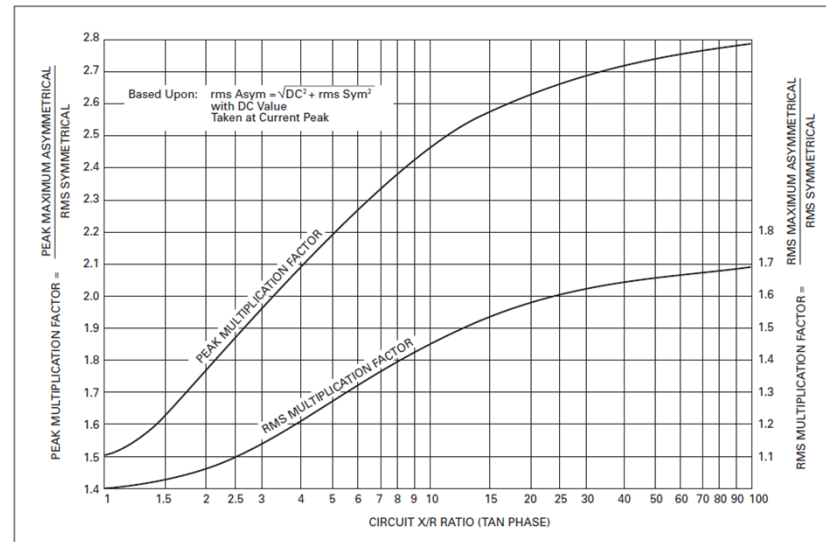
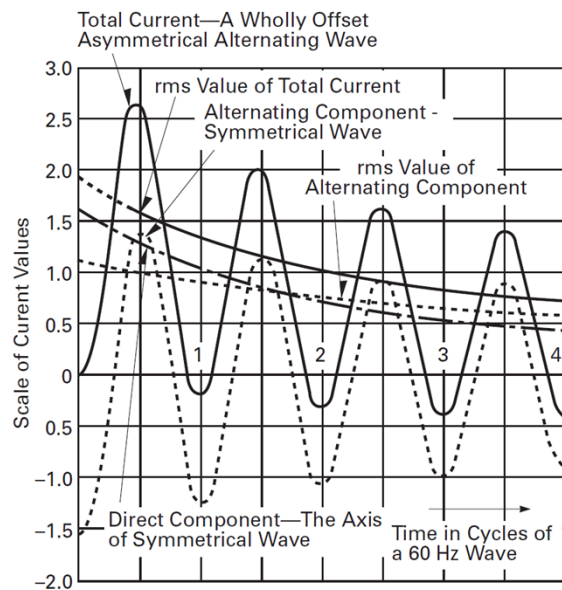
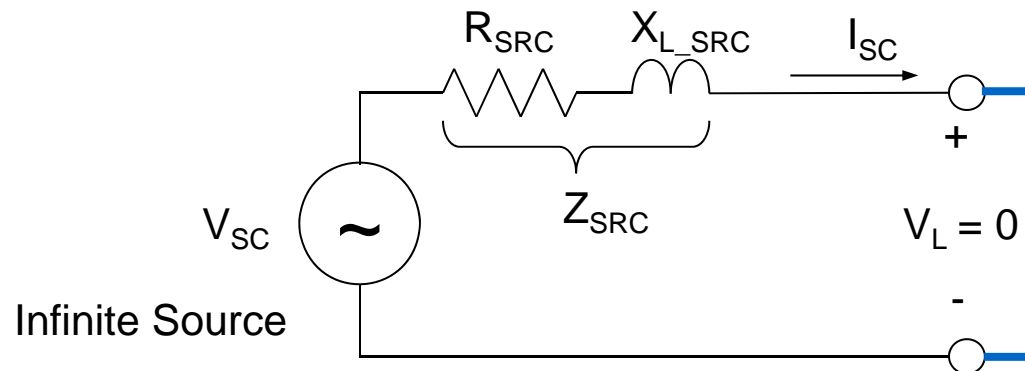


Figure 1.3-19. 300 kVA Transformer/4.5% Impedance/480V

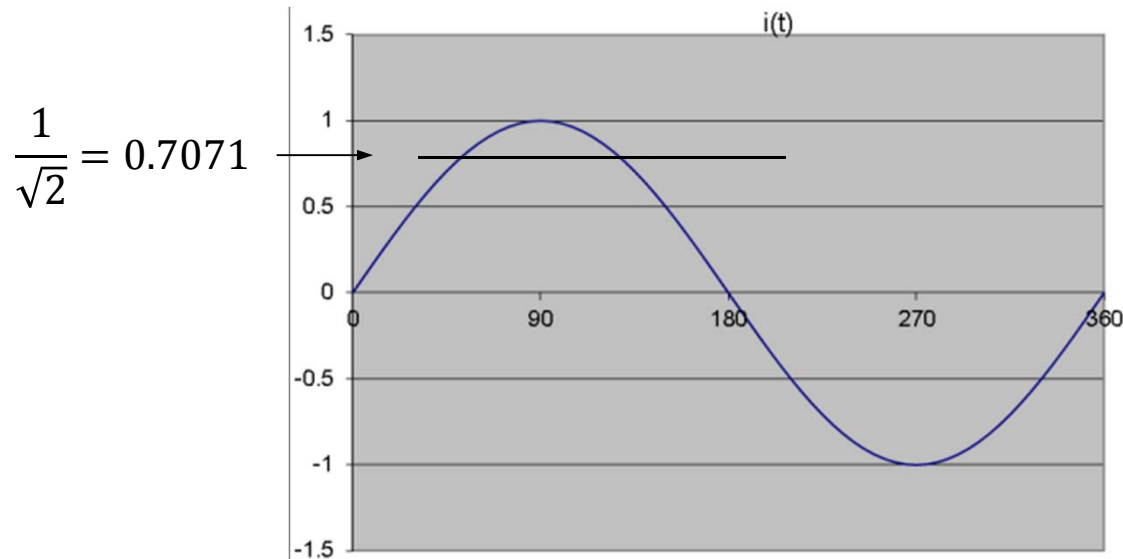
Short Circuit Studies – DC Offset



Fault Asymmetry Factor

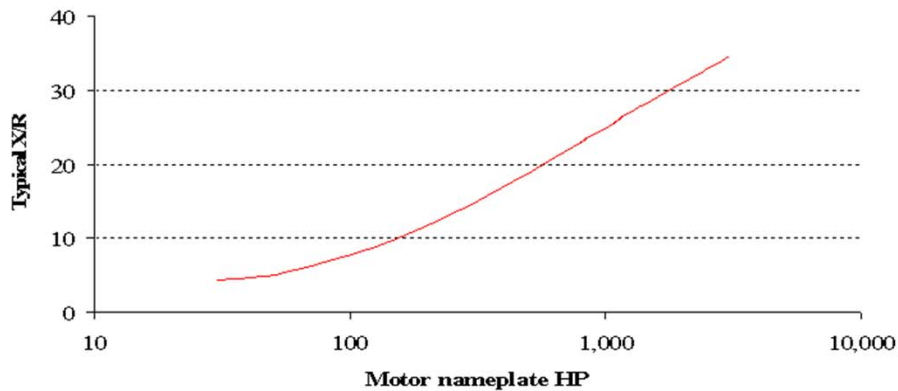
- Peak normally $\sqrt{2} \times \text{rms}$ ($\therefore \text{rms} = \frac{1}{\sqrt{2}} * \text{peak}$)
 - Assumes no harmonics
 - Assumes no energy storage in circuit (i.e. no inductance)

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

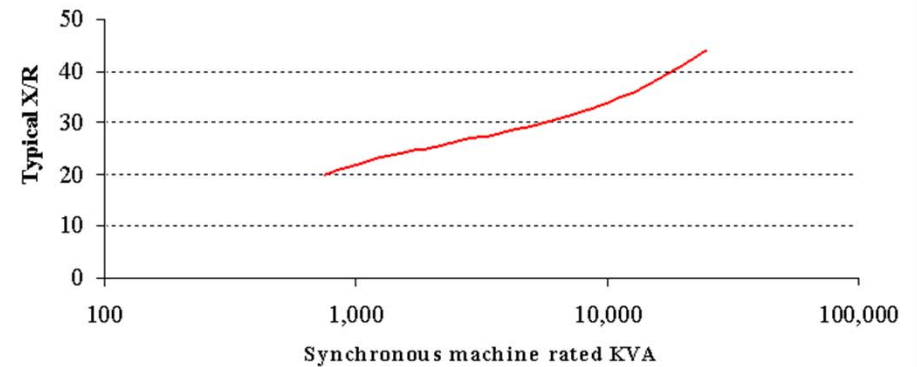


X/R ratio: Rules of Thumb

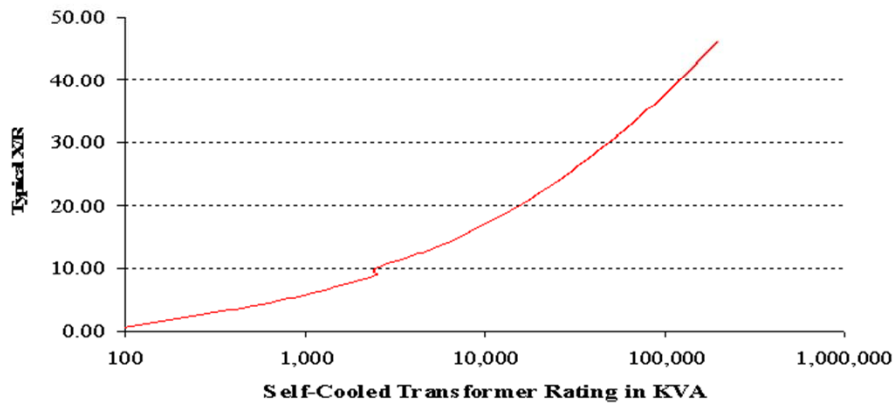
Medium X/R Ratio of Three-Phase Induction Motors
Based on ANSI/IEEE C37.010-1979



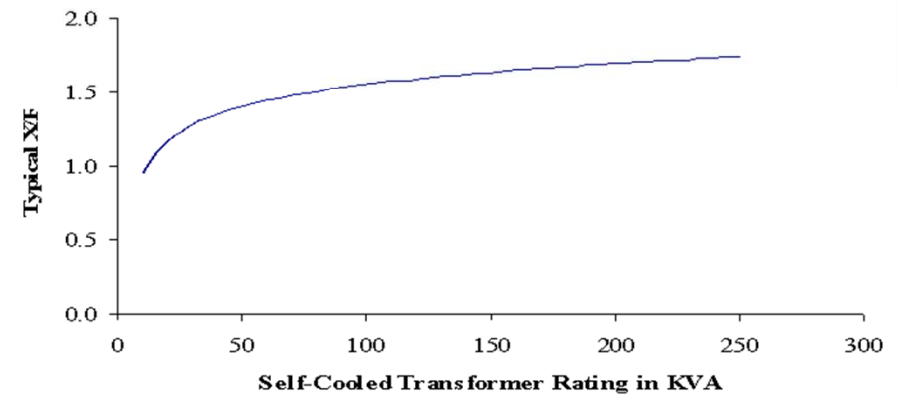
Medium X/R Ratio of Synchronous Machines
Based on ANSI/IEEE C37.010-1979



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



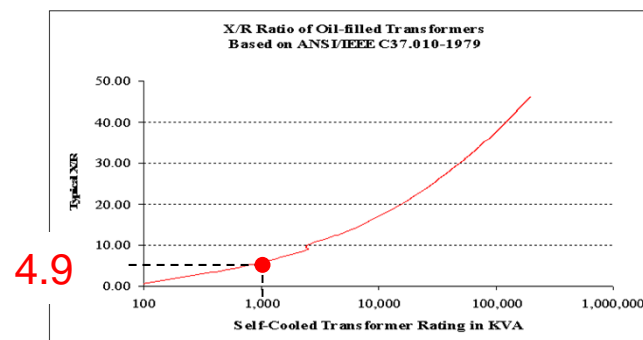
X/R ratio for Dry Type Transformer



Fault Asymmetry Factor

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

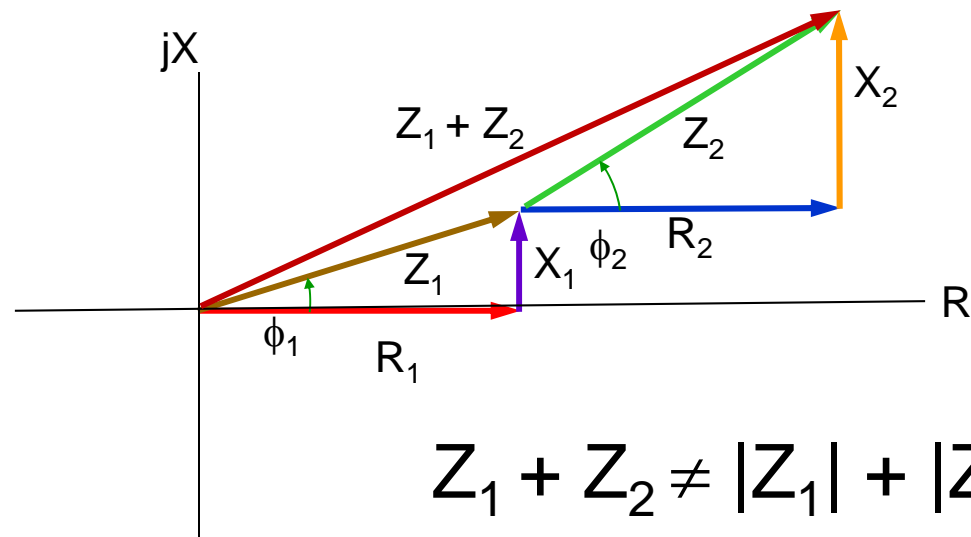
- Example: 1000 kVA, 480V
 $X/R = 4.9 I_{SEC_FL}$



$$PeakMultFactor = 1.414 \left(1 + e^{\frac{-\pi}{4.9}} \right) = 2.16$$

Exact Method

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



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
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Result

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

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

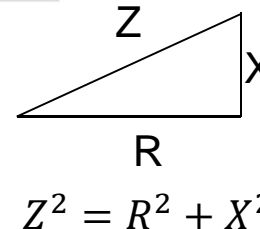
$$\%R = \frac{R * kVA}{kV^2 * 10}$$

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

$$\%R = 1.46\%$$

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

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



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

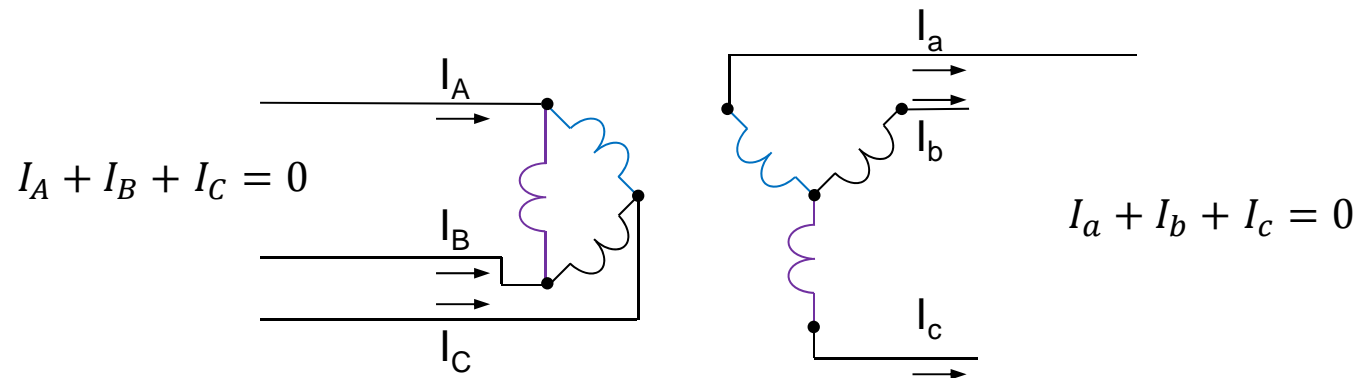
- Given a 500 kVA, 5.5% Z transformer with 9000W total loss; 1700W no-load loss; 7300W load loss and primary voltage of 480V.

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

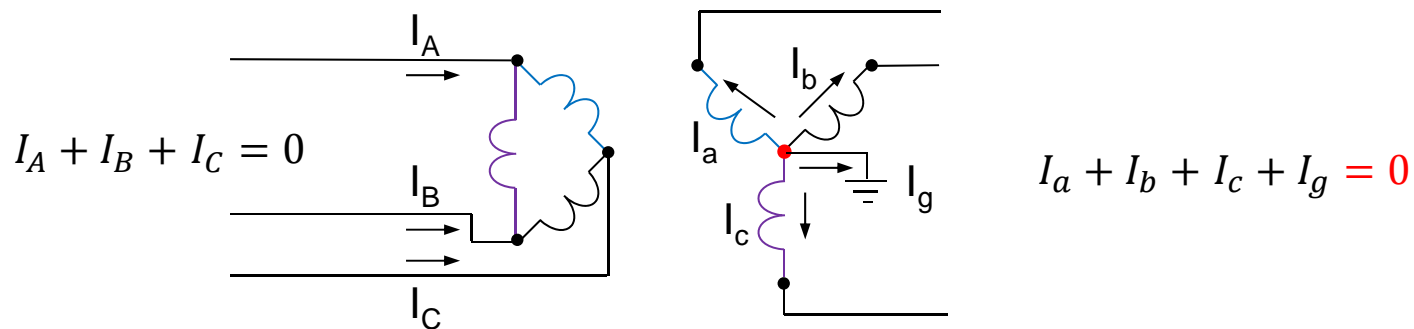
$$\%R = \frac{7300}{10 * 500} = 1.46$$

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

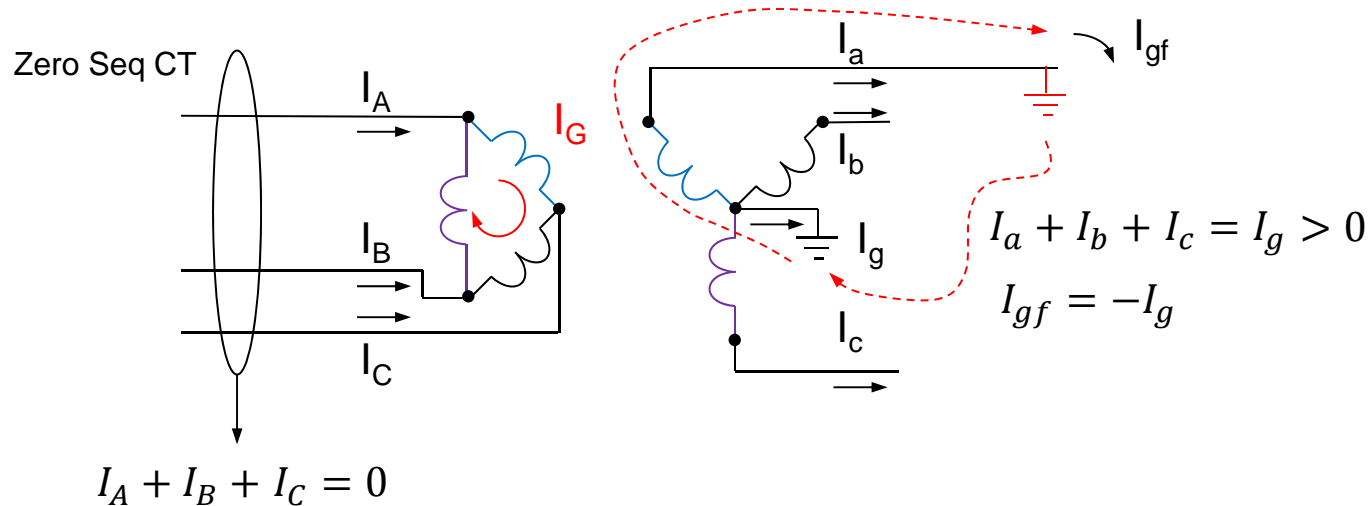
Faults Through Transformer



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

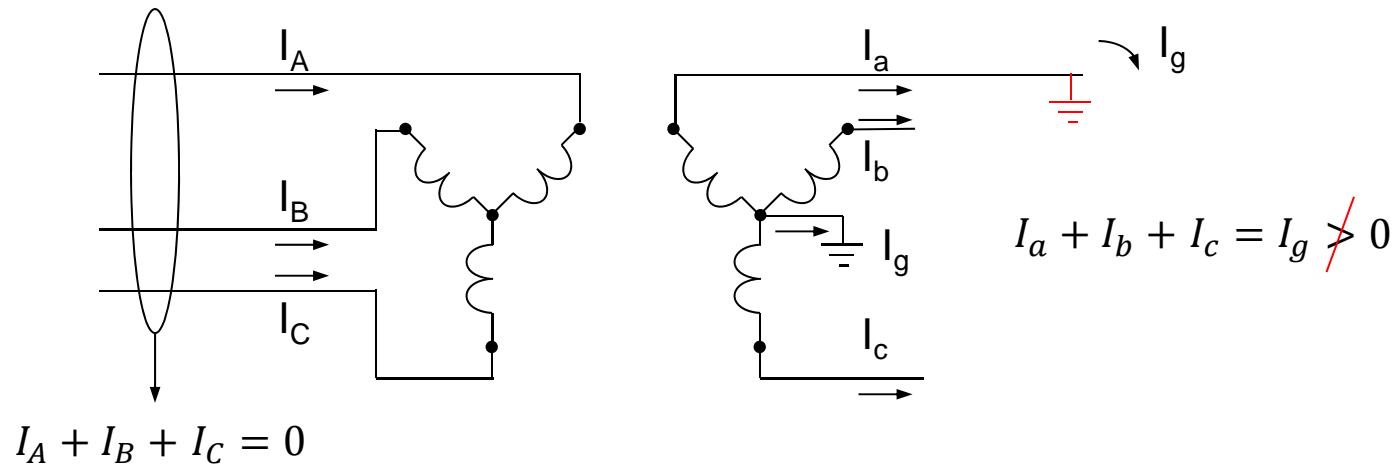


Ground Fault on Δ -Y Transformer



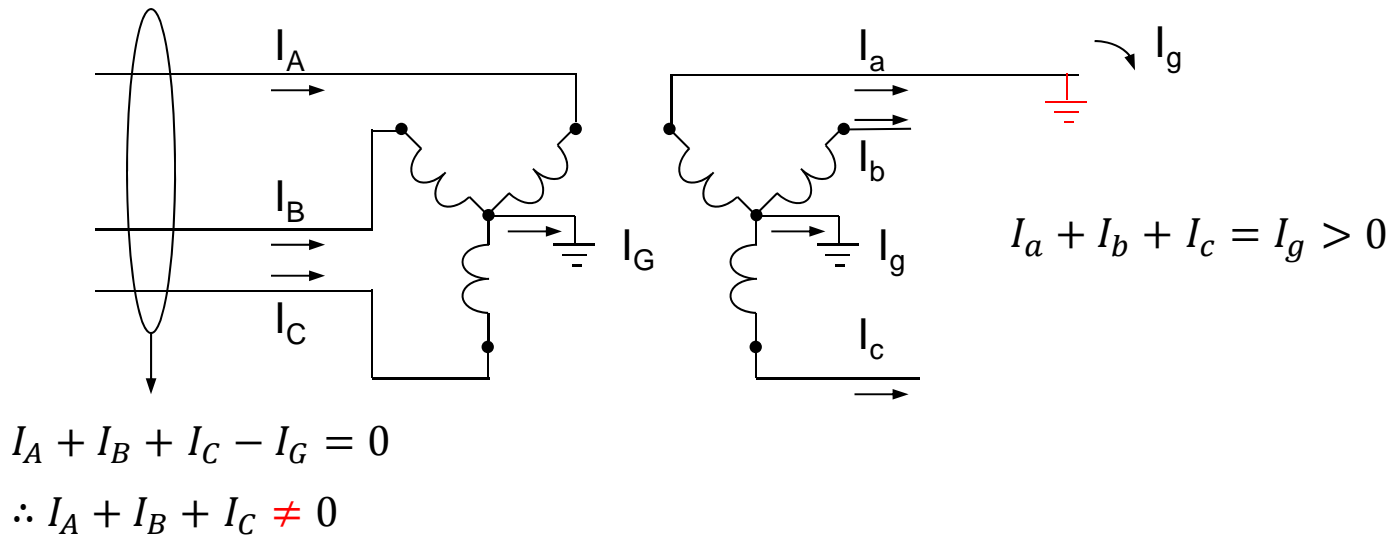
- KCL must sum on both sides
- Where is the ground current on the primary?
- Zero sequence currents circulate in delta
 - Triplen harmonics are zero sequence -- heating

Ground Fault on Y-GndY Transformer



- KCL must sum on both sides
- Where is the ground current on the primary?

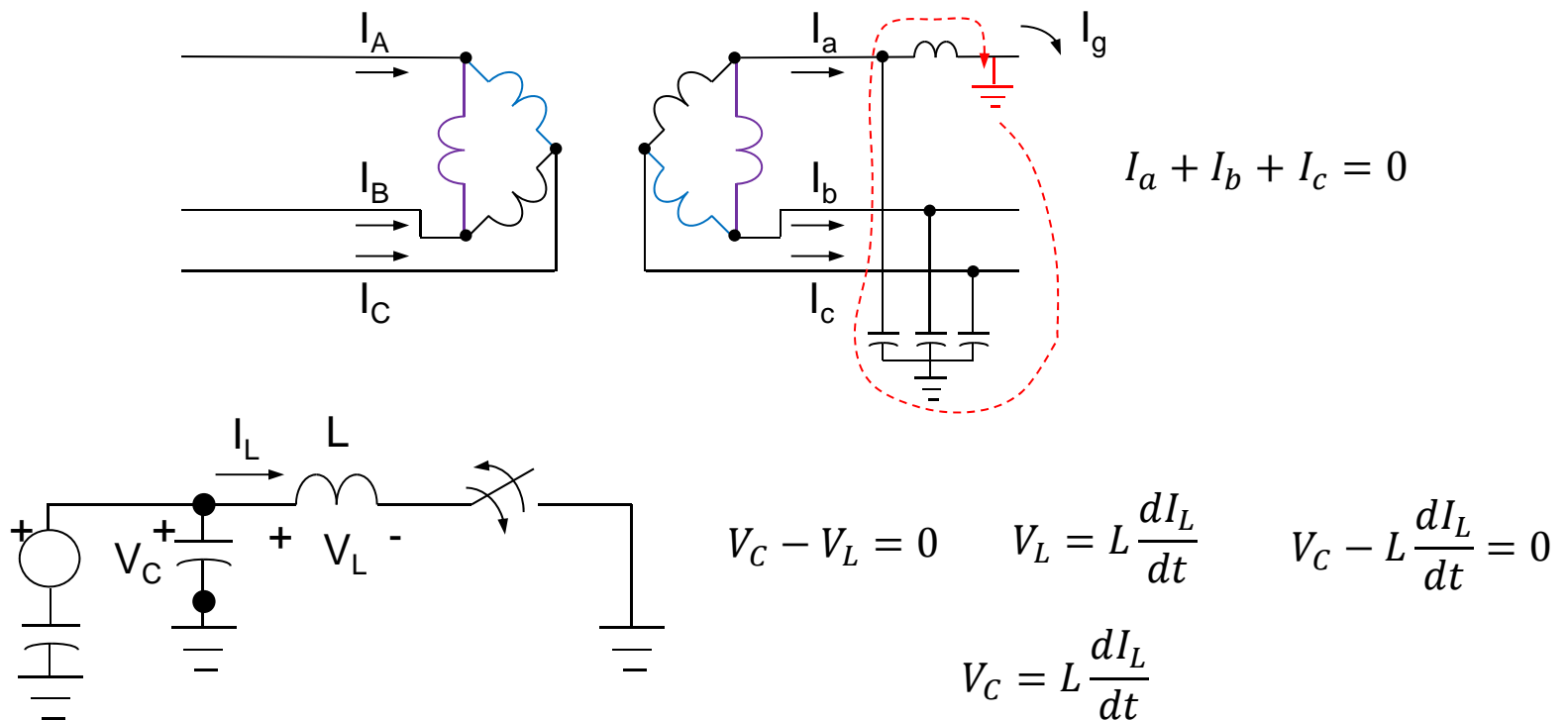
Ground Fault on GndY-GndY Transformer



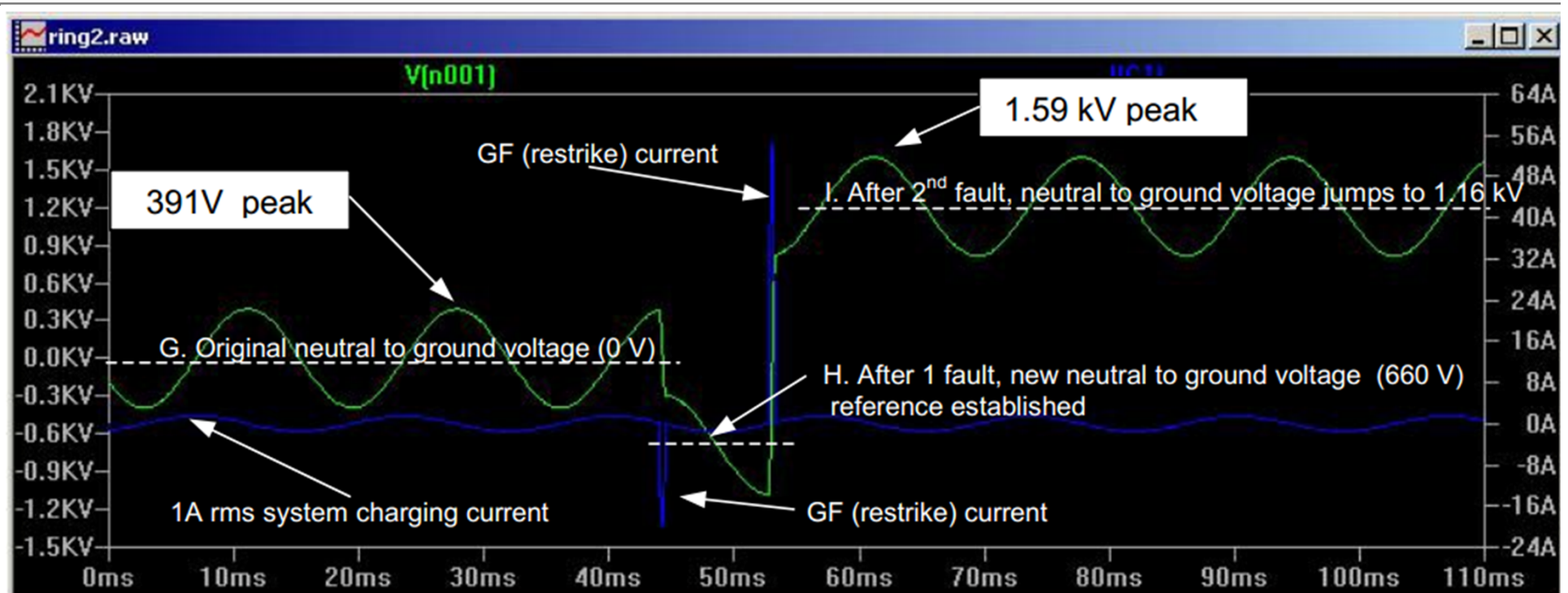
- KCL must sum on both sides
- Ground current flows so zero sequence CT detects GF on secondary

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

<http://www.eaton.com/ecm/groups/public/@pub/@electrical/documents/content/ia08700001e.pdf>

Transformer Calculations

Find the following transformers and gather the information to estimate the short circuit (3-phase fault) current and full load (primary and secondary) current for each:

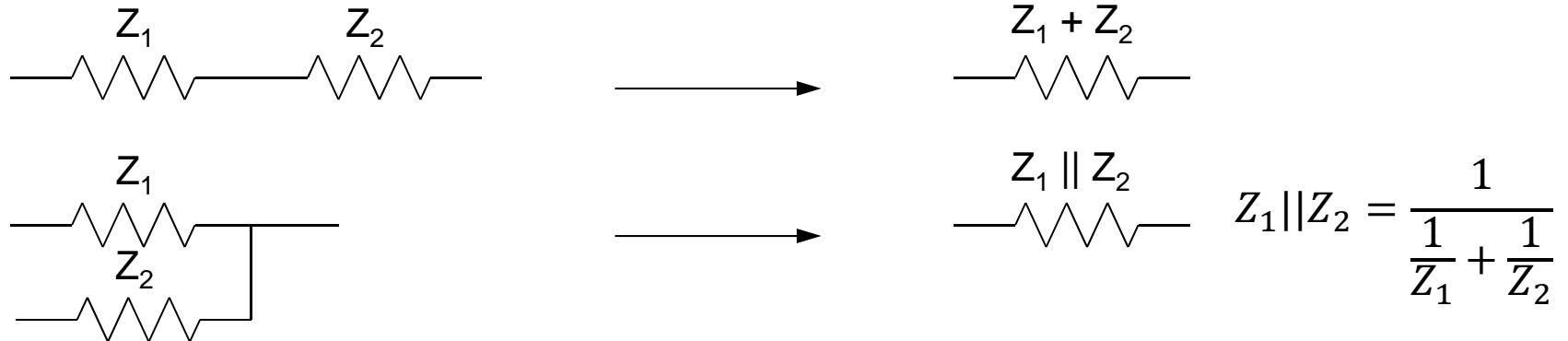
- Transformer 1: PQ Lab Isolation Transformer (550 kVA) - Carnovale
- Transformer 2: PQ Lab – 75 kVA K13 - Loucks
- Transformer 3: ITL – 750 kVA Oil Filled Transformer - Groden
- Transformer 4 (Bonus!): PQ Lab – Pole mounted transformer



Powering Business Worldwide

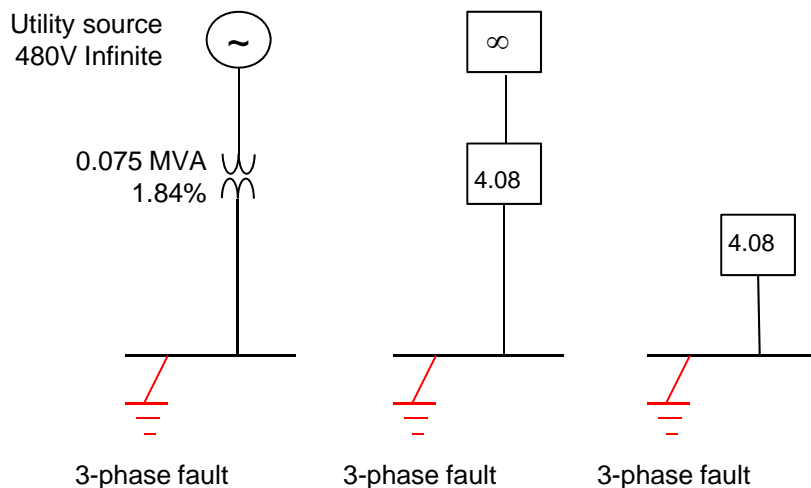
Admittance and Impedance

- Converting impedance to admittance simplifies paralleling



- But since $1/Y = Z$ then: $Z_1 || Z_2 = \frac{1}{\frac{1}{Y_1} + \frac{1}{Y_2}} = Y_1 + Y_2$

MVA Method – Admittances in series



Utility source ∞ MVA

Transformer $\frac{0.075}{0.0184} = 4.08 \text{ MVA}$

- Admittances in series same as paralleling resistances

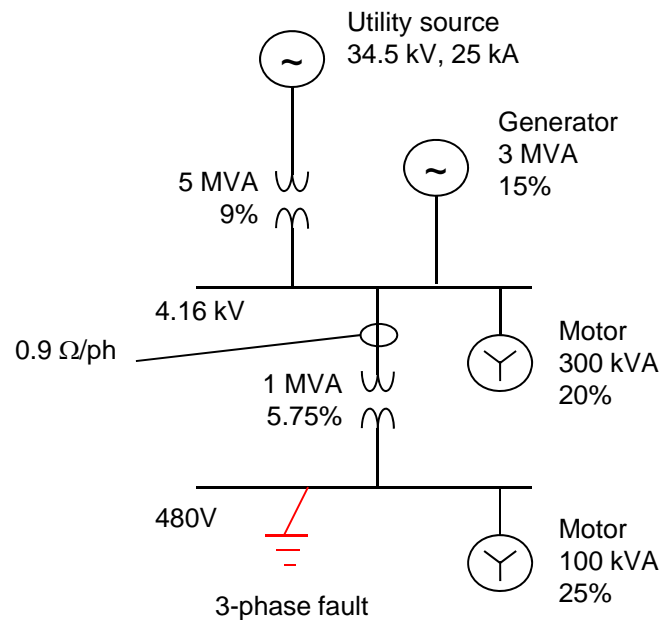
$$Y_1 || Y_2 = \frac{1}{\frac{1}{Y_1} + \frac{1}{Y_2}} = \frac{1}{\frac{1}{\infty} + \frac{1}{4.08}} = 4.08$$

- 4.08 MVA available. Find kA

$$\frac{4080 \text{ kVA}}{0.208 \text{ kV} \cdot \sqrt{3}} = 11.3 \text{ kA}$$

- Same as ohmic and pu methods

MVA Method – More Complex Model



Utility source $\sqrt{3} \cdot 34.5 \cdot 15 = 896.3 \text{ MVA}$

5 MVA transformer $5/0.09 = 55.6 \text{ MVA}$

3 MVA generator $3/0.15 = 20 \text{ MVA}$

4.16 kV conductor $\frac{V^2}{Z} = \frac{4.16^2}{0.9} = 19.2 \text{ MVA}$

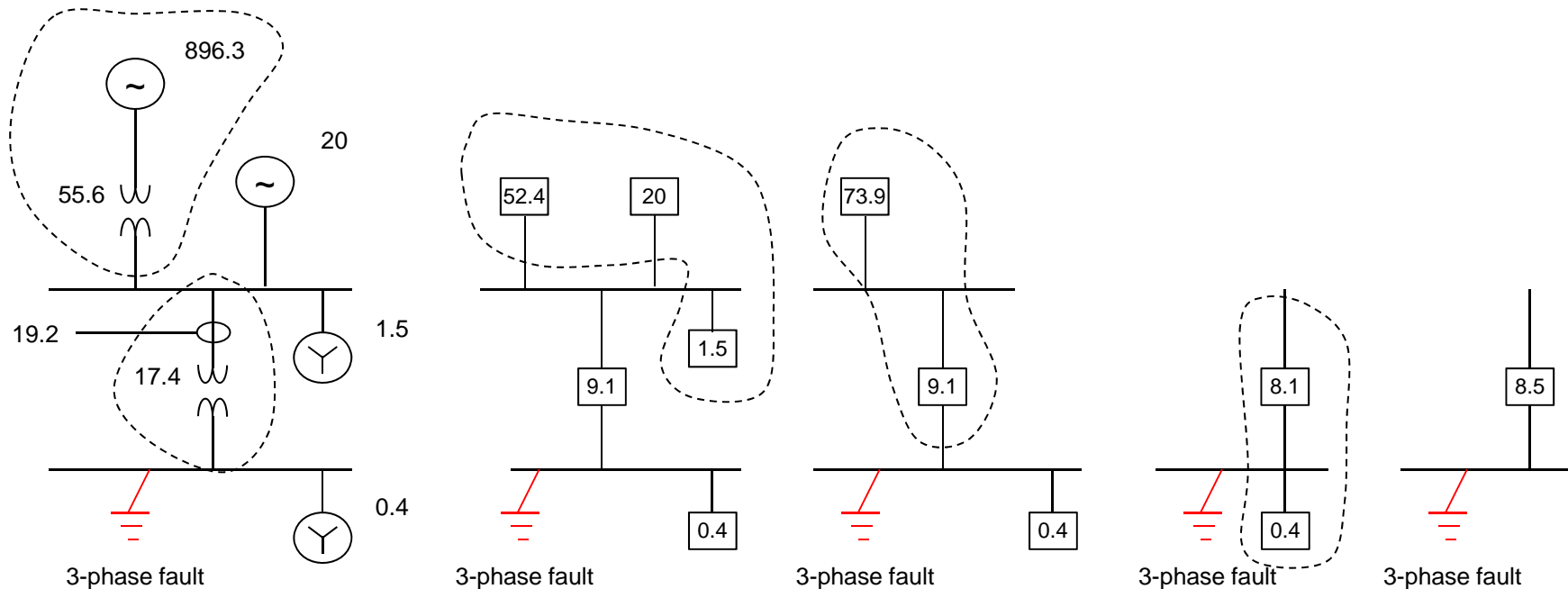
1 MVA transformer $1/0.0575 = 17.4 \text{ MVA}$

300 kVA motor $0.3/.2 = 1.5 \text{ MVA}$

480V motor $0.1/0.25 = 0.4 \text{ MVA}$

- Convert each source to equivalent short circuit MVA capacity/rating

MVA Method – Convert to Admittances



- 8.5 MVA available $\frac{8500 \text{ kVA}}{0.48 \text{ kV} \cdot \sqrt{3}} = 10224 \text{ A}$ available
- Method works if X/R is high