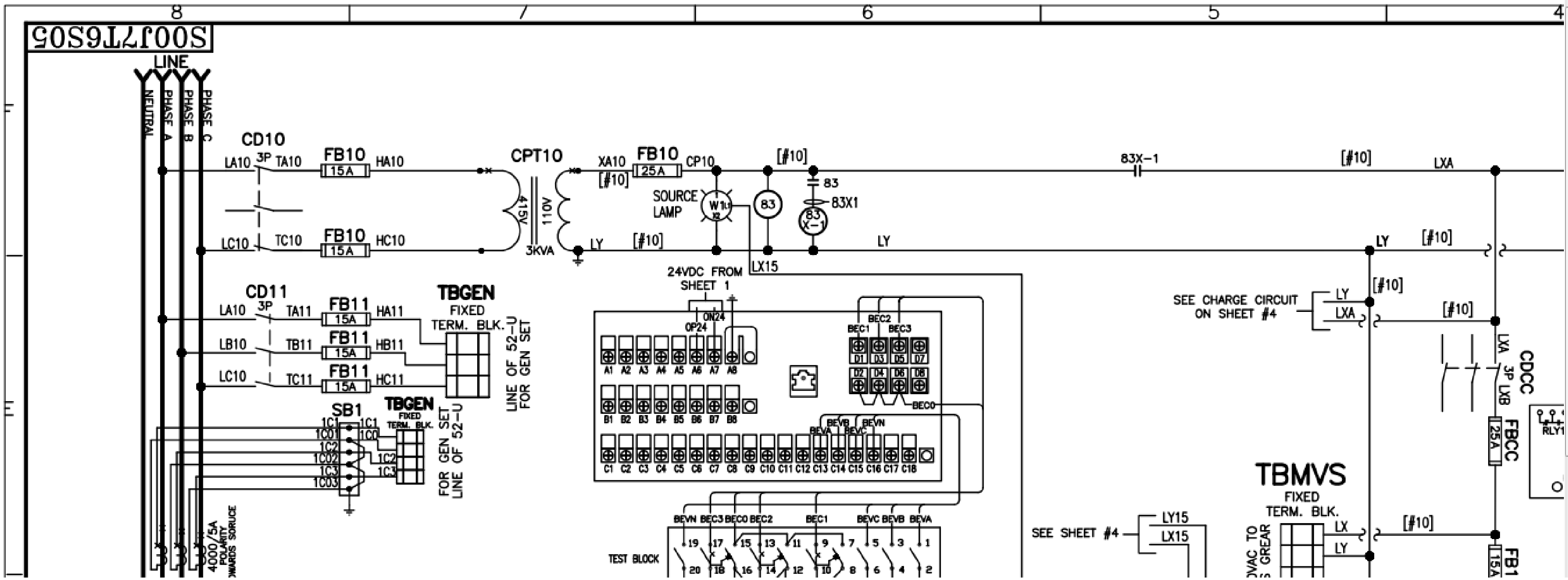

Power System Analysis:

Rules of Thumb (RoT) and Sanity Testing

Dave Loucks, PhD, PE, CEM

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Power Systems Analysis Review

Today

- Per Unit Conversions
- Symmetrical Components
- Fault Current Estimation
- 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

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

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CAG 1.3-13

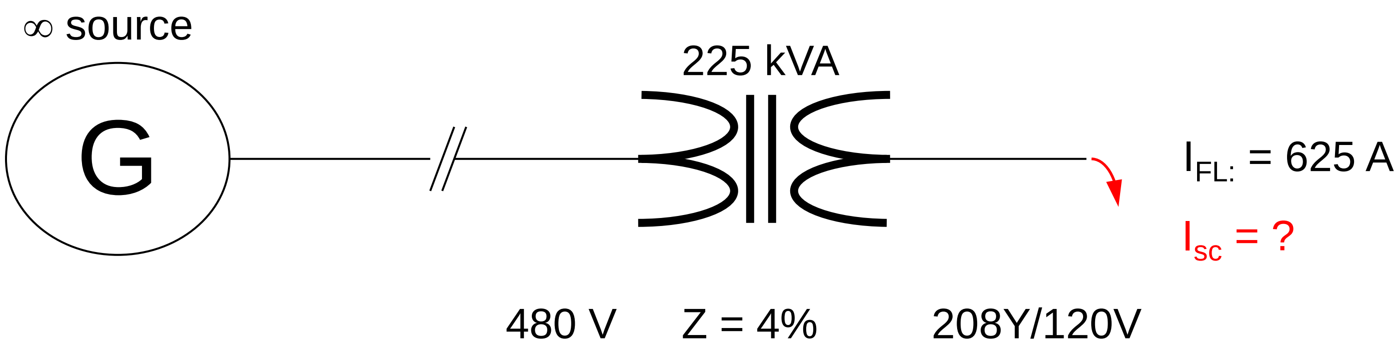
Per Unit

- **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.

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

CAG 1.3-6

Short Cut I_{SC} Calc

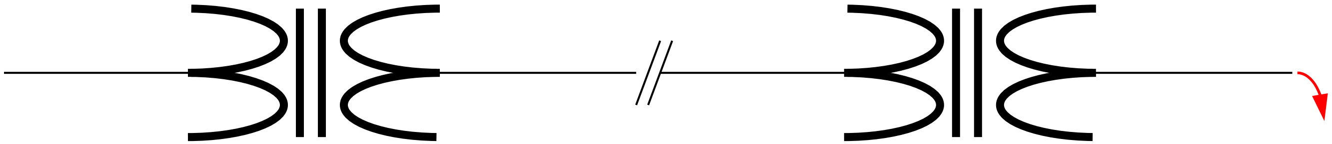


- Only impedance in circuit is 225 kVA Tx

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

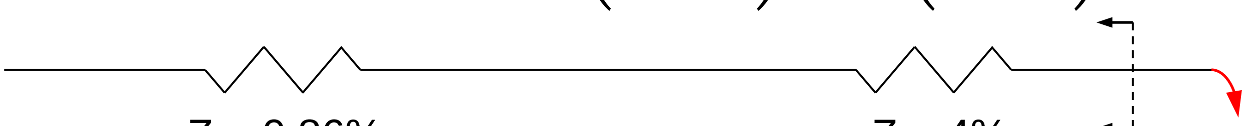
I_{sc} = 15625A

Convert to Common kVA Base



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

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



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

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

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

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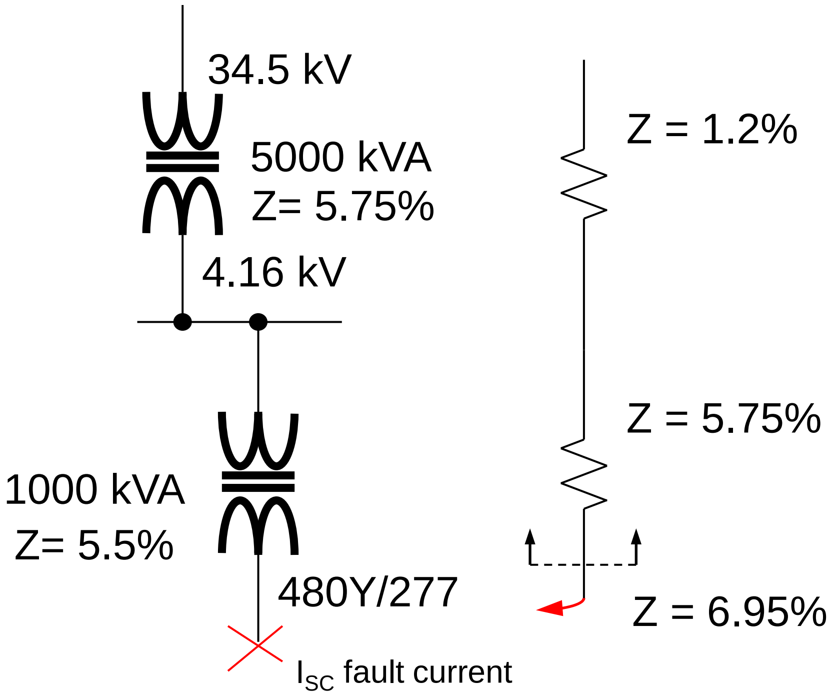
Per Unit Calculations

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 l**ine-to-neutral** impedance of system to fault where Z = R + jX .
4. Generator nameplate: use Xd'' (subtransient reactance)
    1. But look at X_0 (zero sequence) impedance
    2. 2/3rd pitch generators can have low X_0

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

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

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

Fault Current RoT – Curve Method

Approximations

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

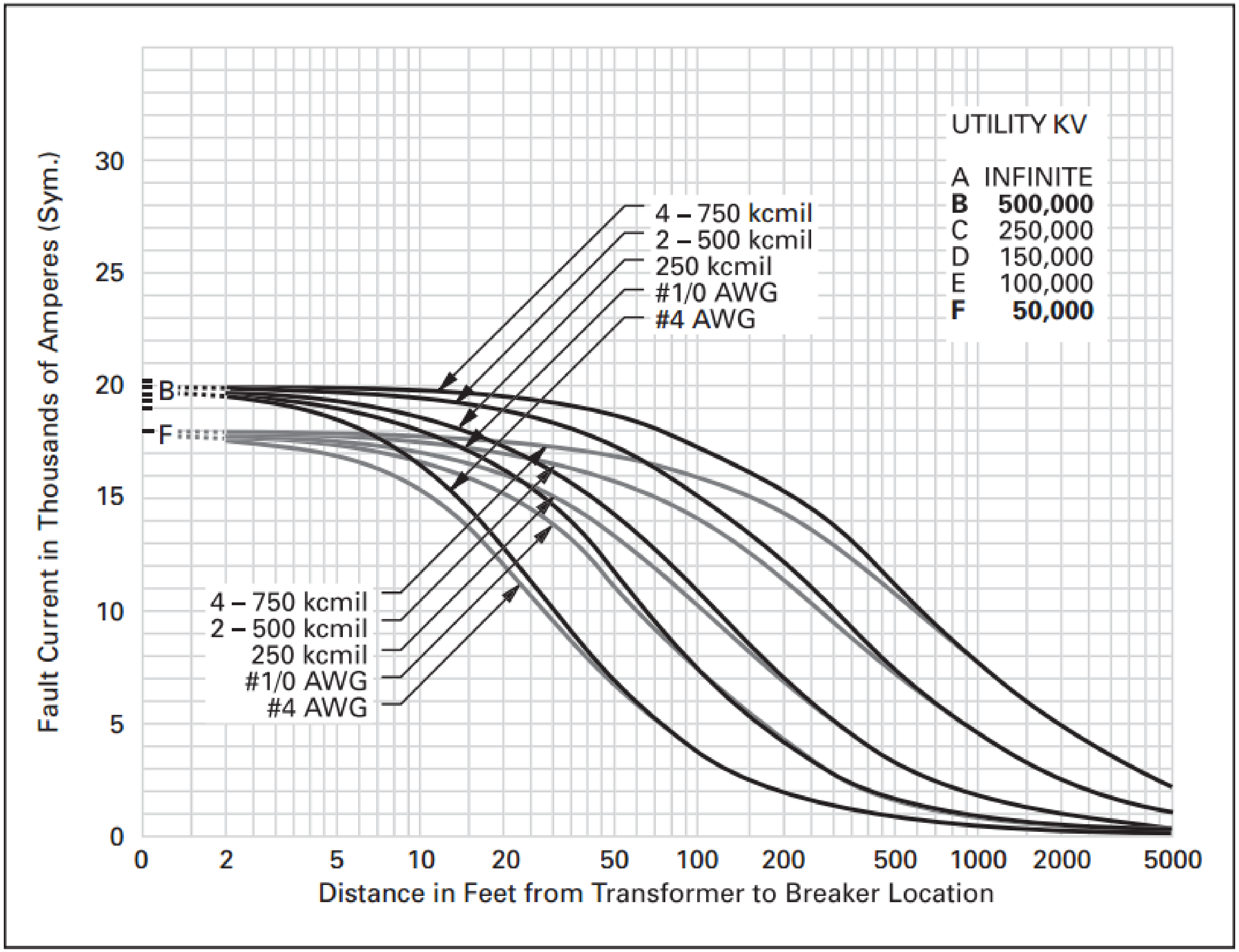


Figure 1.3-13. 300 kVA Transformer/4.5% Impedance/208V

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

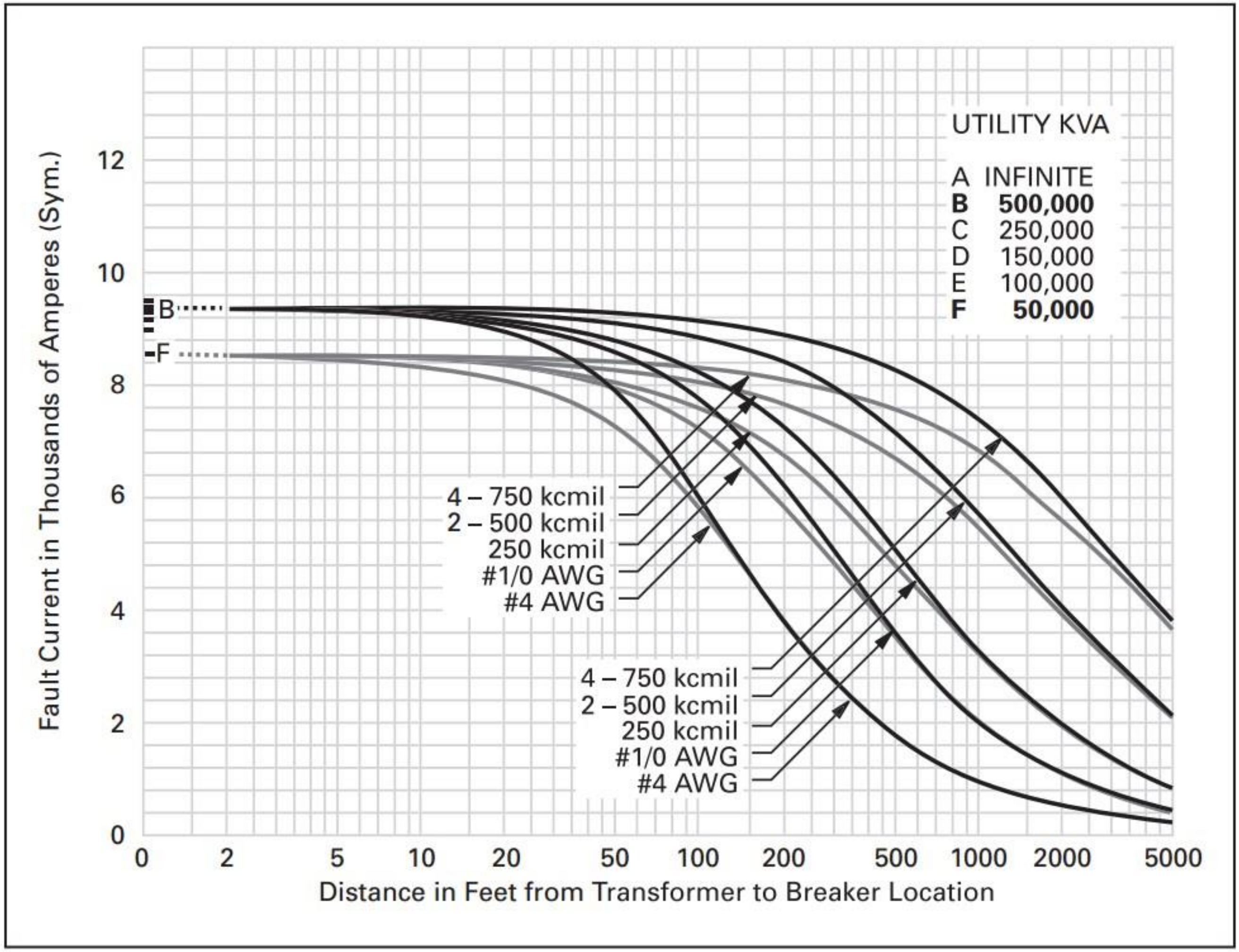
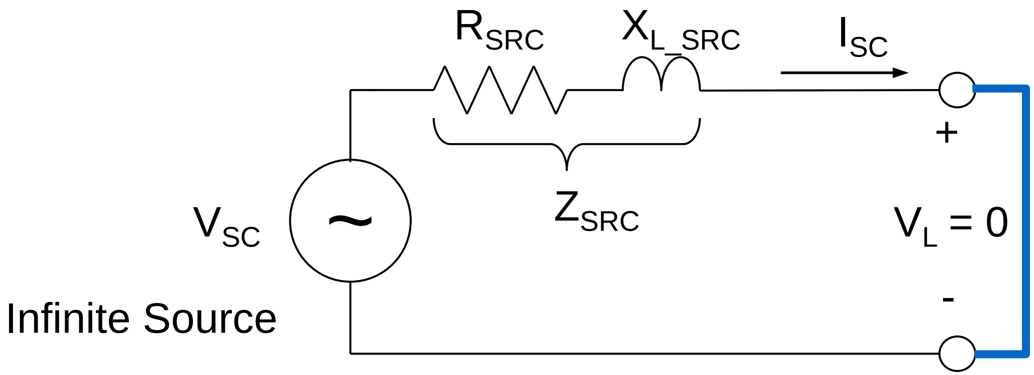
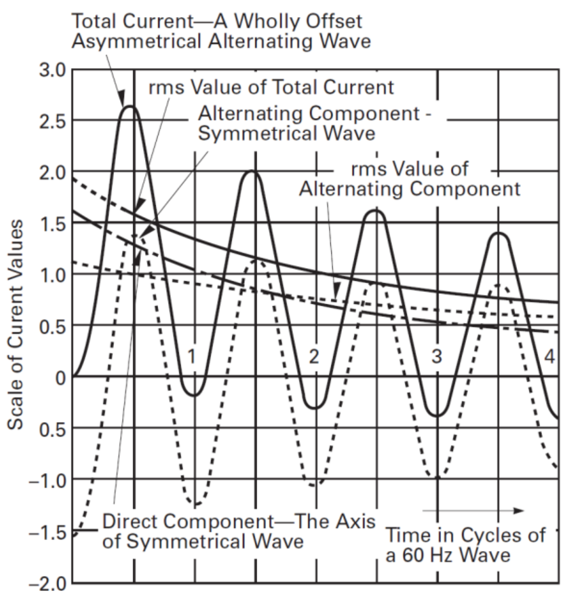


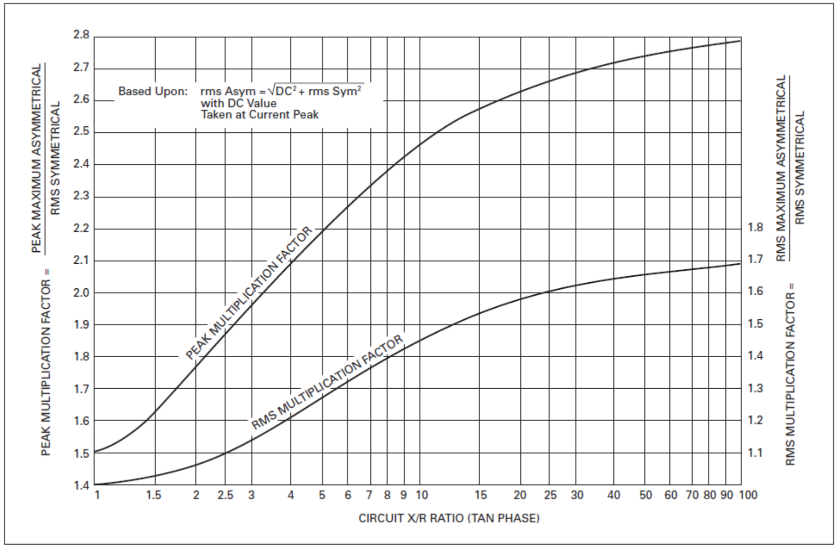
Figure 1.3-19. 300 kVA Transformer/4.5% Impedance/480V

CAG 1.3-16 to 1.3-18

Short Circuit Studies – DC Offset







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

CAG 1.3-2 to 1.3-3

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 Four-pole turbo generator	X X	X X	9 (7–14) 15 (12–17)	80 (40–120) 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)

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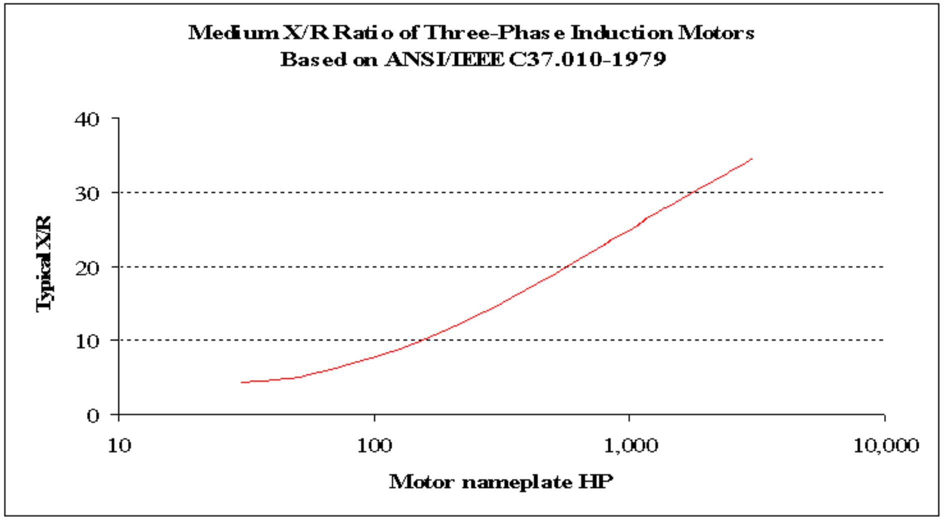
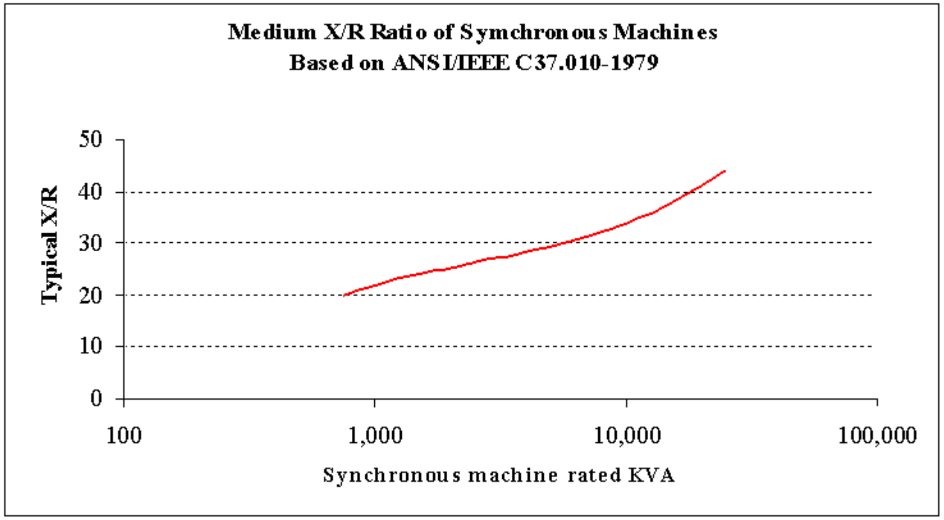
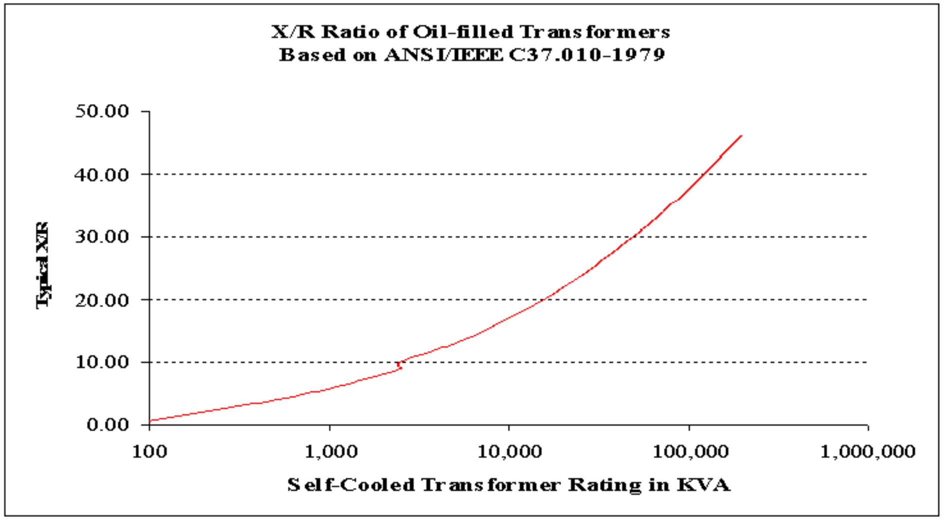
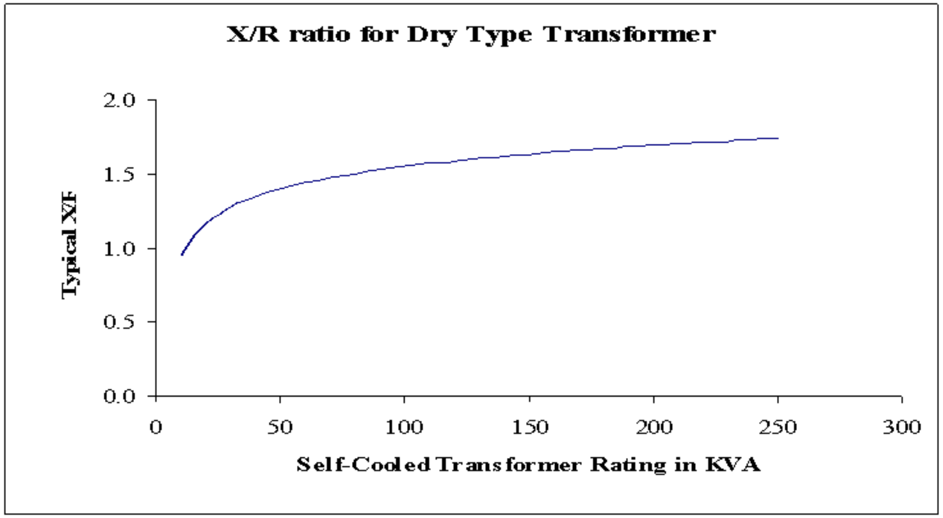
CAG 1.3-5

X/R ratio: Rules of Thumb









CAG 1.3-5

X/R ratio: Rules of Thumb

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

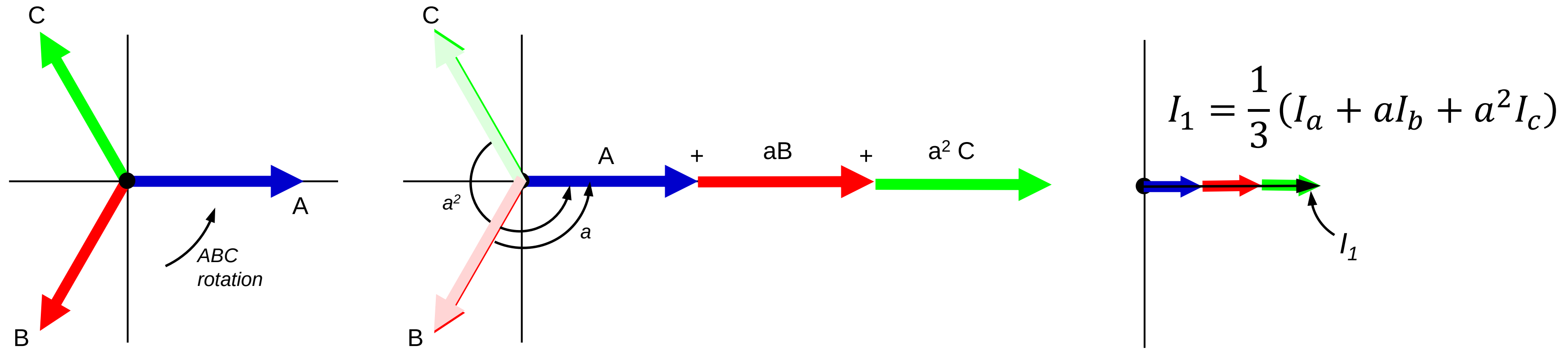
Type of Circuit	X/R Range
Remote generation through other types of circuits such as transformers rated 10 MVA or smaller for each three-phase bank, transmission lines, distribution feeders, etc.	15 or less
Remote generation connected through transformer rated 10 MVA to 100 MVA for each three-phase bank, 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

CAG 1.3-5

Symmetrical Components

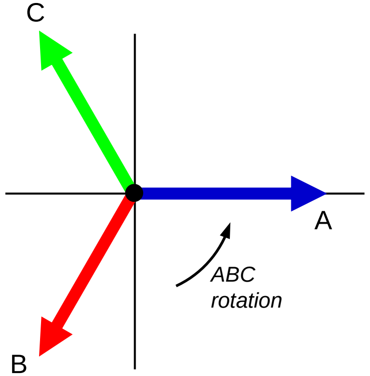
- Unbalanced faults can be solved easily
- Defines positive (1), negative (2) and zero (0) sequence components

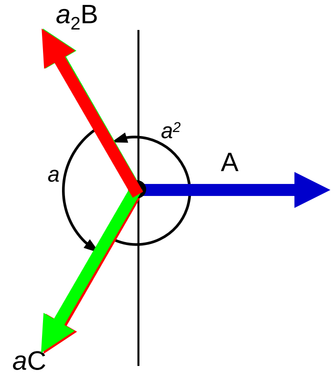
$$I_1 = \frac{1}{3}(I_a + aI_b + a^2 I_c)$$ Positive Sequence

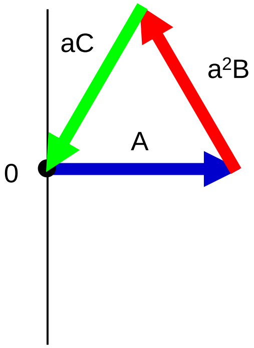


Negative Sequence

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

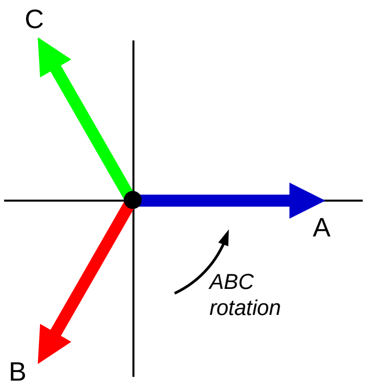


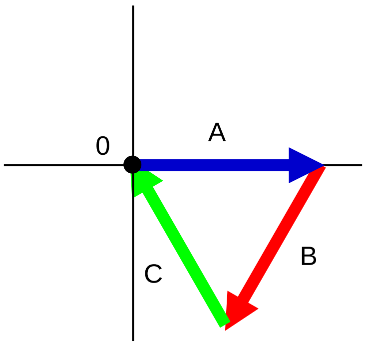




Zero Sequence

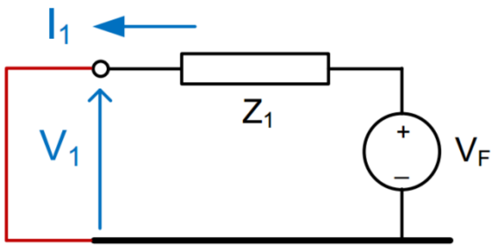
$$I_0 = \frac{1}{3}(I_a + I_b + I_c)$$



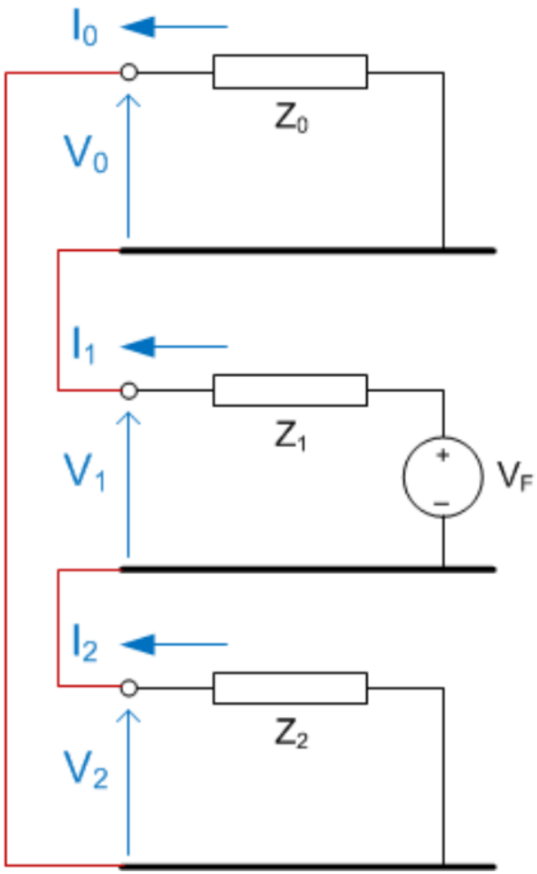


Unsymmetrical Faults

- 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

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

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

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

$$I_a = I_0 + I_1 + I_2$$

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

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

Where:

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

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

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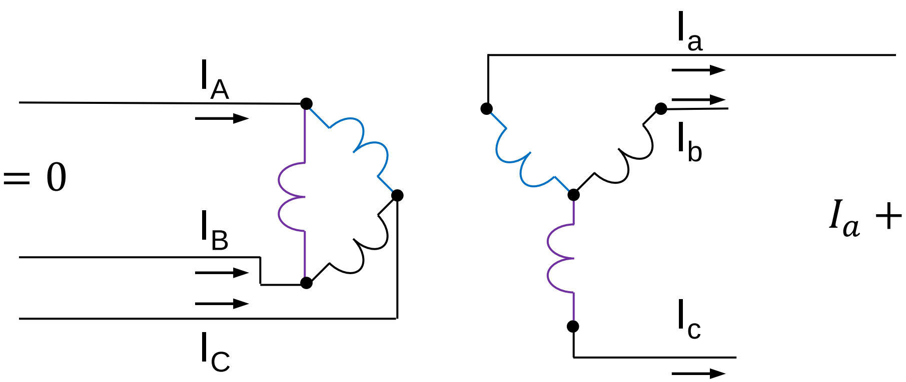
Faults Through Transformer

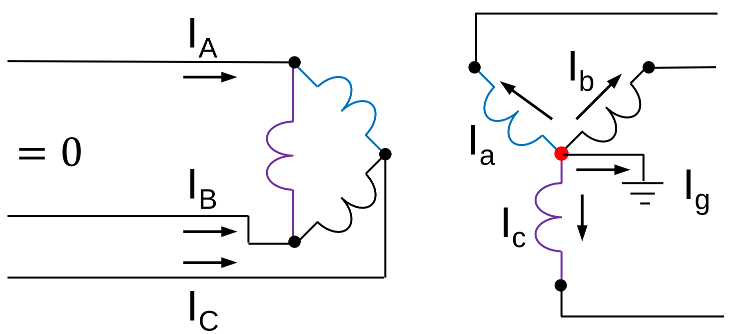
$$I_A + I_B + I_C = 0$$



$$I_a + I_b + I_c = 0$$

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

$$I_A + I_B + I_C = 0$$



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

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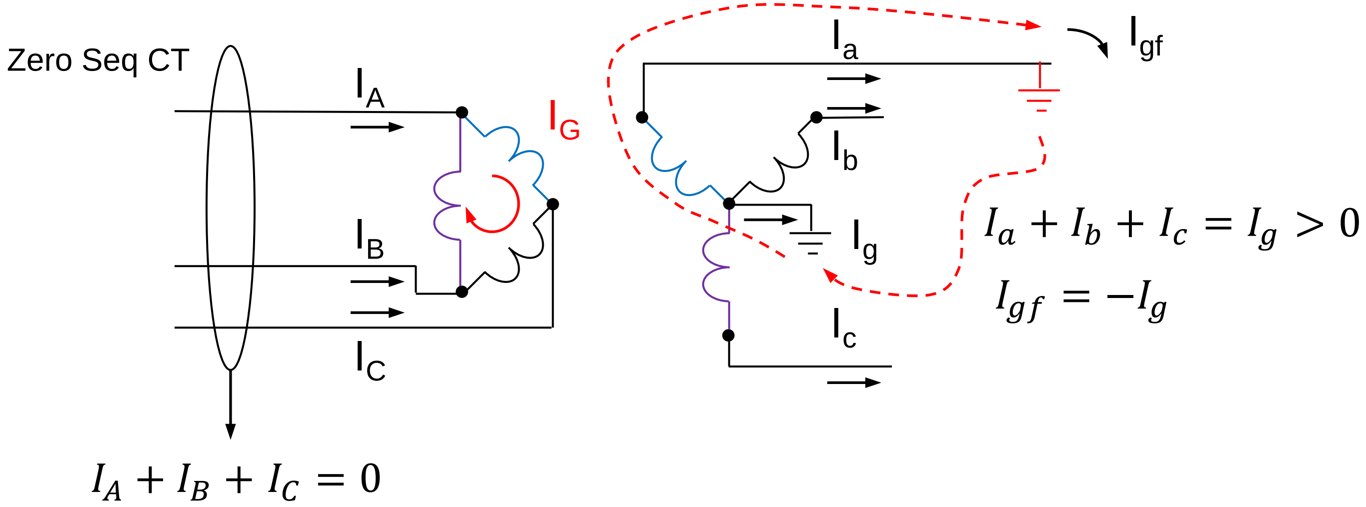
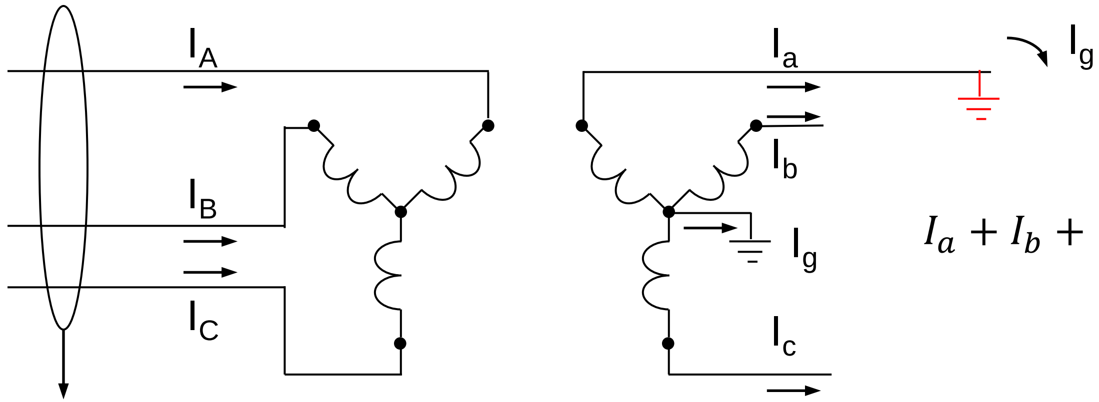
Ground Fault on Δ-Y Transformer



- 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

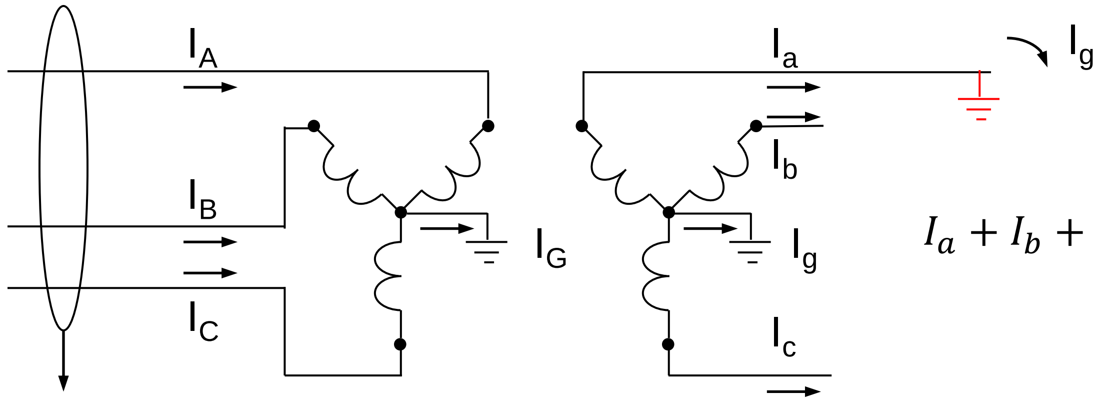


$$I_a + I_b + I_c = I_g \not> 0$$

$$I_A + I_B + I_C = 0$$

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

Ground Fault on GndY-GndY Transformer



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

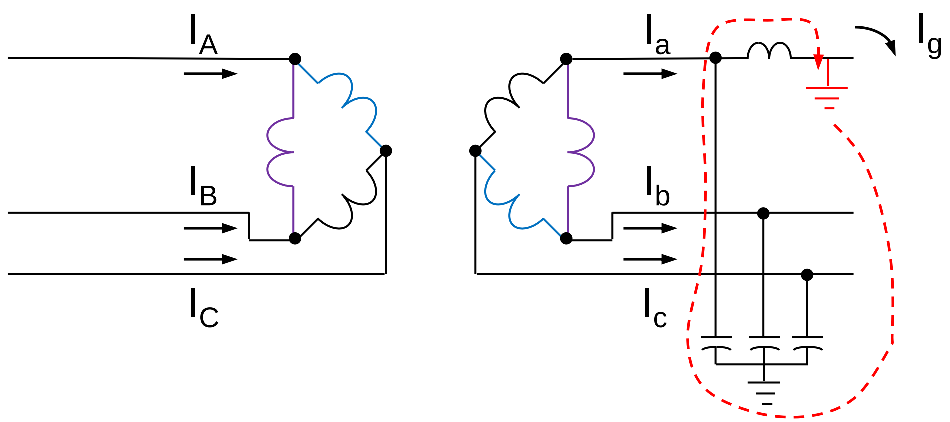
$$I_A + I_B + I_C - I_G = 0$$

$$\therefore I_A + I_B + I_C \neq 0$$

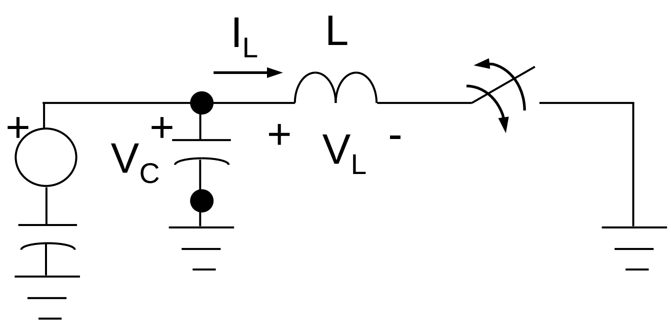
- KCL must sum on both sides
- Ground current flows so zero sequence CT detects GF on secondary

A Word About Ungrounded Systems

- Tendency to consider for mission critical



$$I_a + I_b + I_c = 0$$



$$V_C - V_L = 0 \qquad V_L = L\frac{dI_L}{dt} \qquad V_C - L\frac{dI_L}{dt} = 0$$

$$V_C = L\frac{dI_L}{dt}$$

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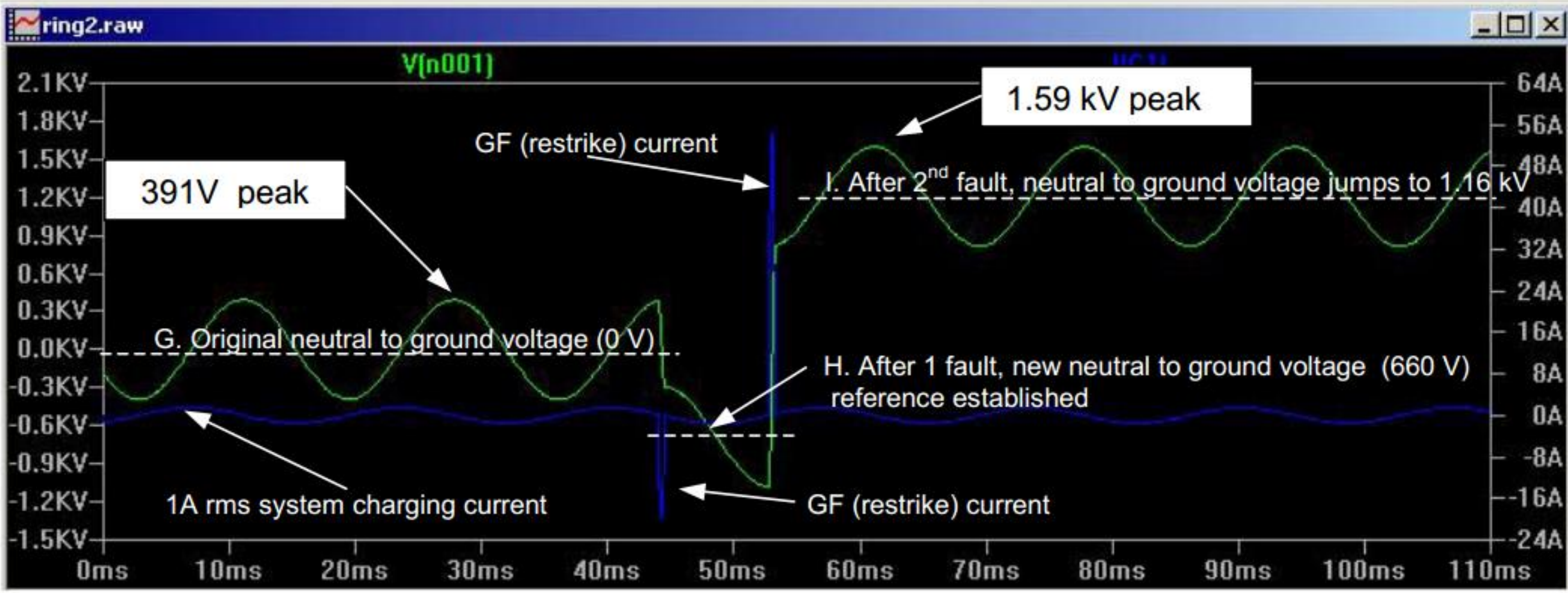
Insulation Failure



- 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

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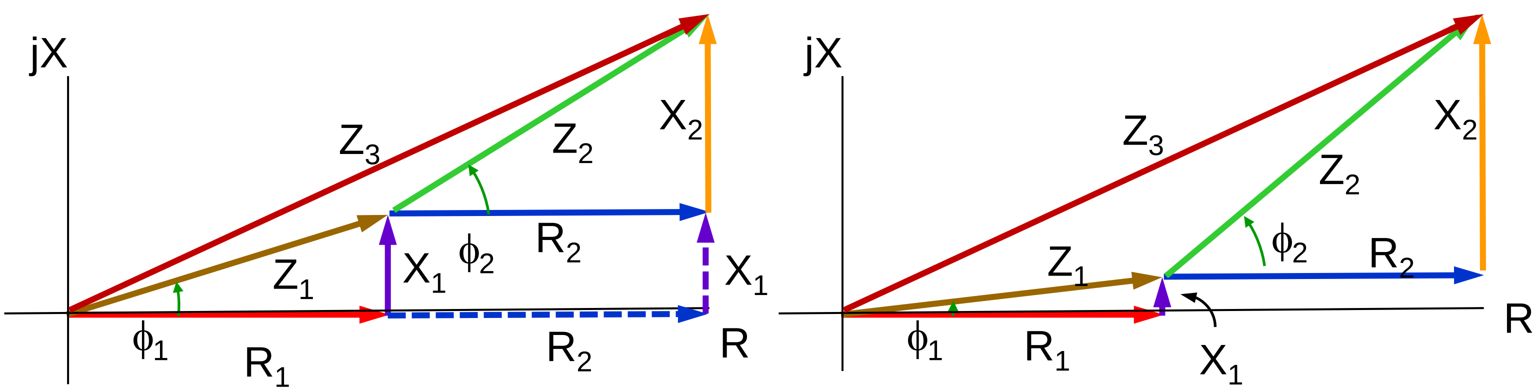
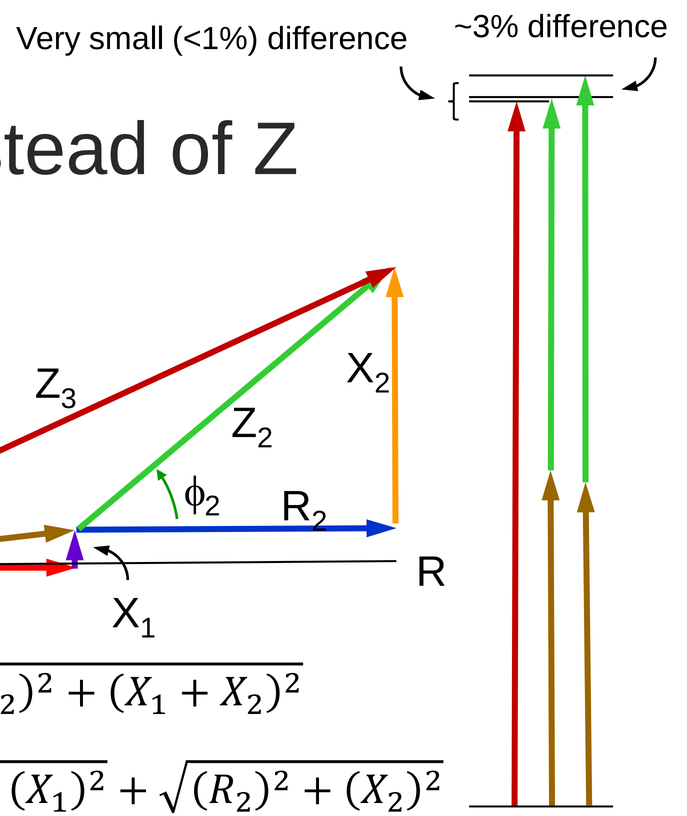
Z versus R+jX

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





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

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

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

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

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

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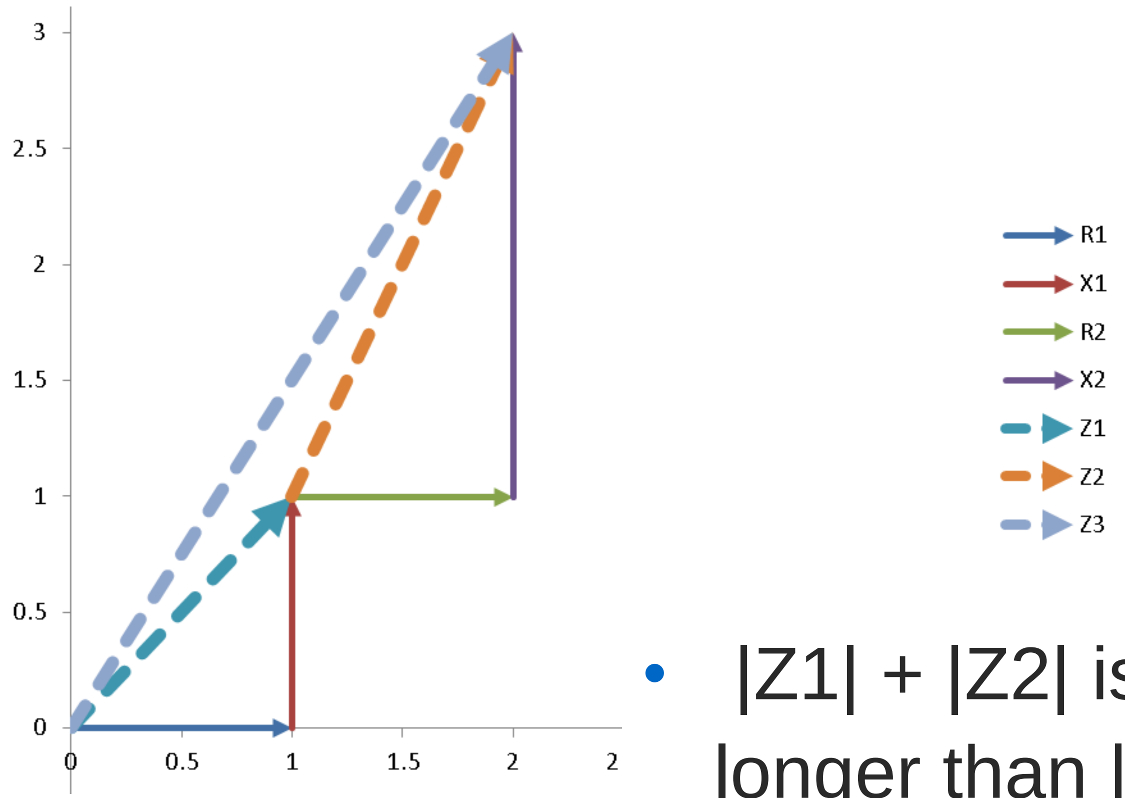
Nominal Case

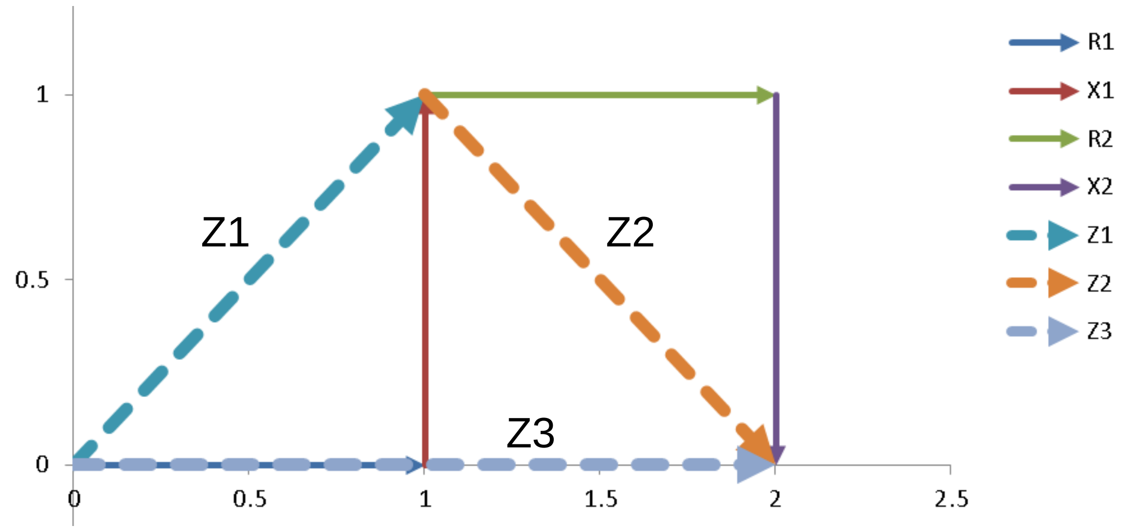
R1	R2	X1	X2	Z1	Z2	Z1+Z2	Z3	% err
1	1	1	2	1.414214	2.236068	3.650282	3.605551	1.2%



- |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|

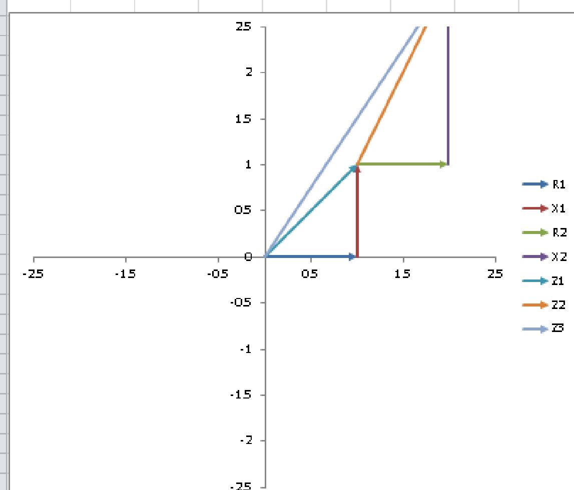
Download Copy of Excel Tool

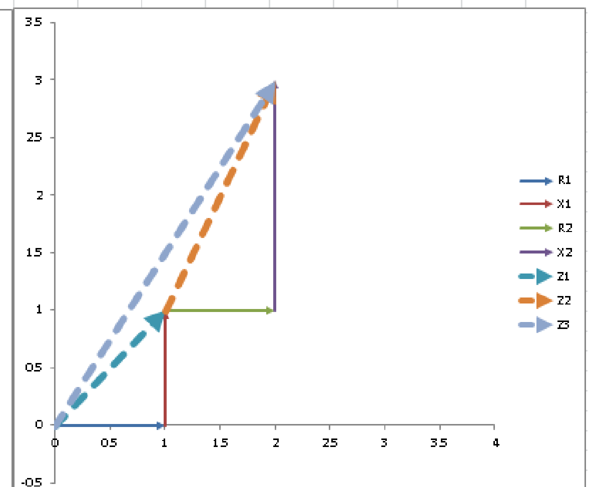
- http://pps2.com/smf/index.php/topic,46.0.html

R1	R2	X1	X2	Z1	Z2	Z1+Z2	Z3	% err	
1	1	1	2	1.4142	2.2361	3.6503	3.6056	1.2%	<- place data here to graph
0.1	0.1	0.1	0	0.1414	0.1	0.2414	0.2236	7.4%	
0.1	0.1	0.1	0.1	0.1414	0.1414	0.2828	0.2828	0.0%	
0.1	0.1	0.1	0.2	0.1414	0.2236	0.365	0.3606	1.2%	
0.1	0.1	0.1	0.3	0.1414	0.3162	0.4576	0.4472	2.3%	
0.1	0.1	0.1	0.4	0.1414	0.4123	0.5537	0.5385	2.7%	
0.1	0.1	0.1	0.5	0.1414	0.5099	0.6513	0.6325	2.9%	
1	1	1	-1	1.4142	1.4142	2.8284	2	0.2929	

R1				X1				R2				X2			
Start x	End x	Start y	End y	Start x	End x	Start y	End y	Start x	End x	Start y	End y	Start x	End x	Start y	End y
0	1	0	0	1	1	0	1	1	2	1	1	2	2	1	3

Z1				Z2				Z3			
Start x	End x	Start y	End y	Start x	End x	Start y	End y	Start x	End x	Start y	End y
0	1	0	1	1	2	1	3	0	2	0	3





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.

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

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

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

Result:

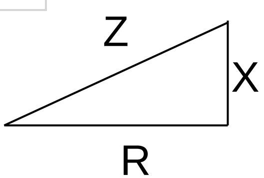
$$r = \frac{2628}{390\,625} \approx 0.0067277$$

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

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

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

$$\%R = 1.46\%$$



$$Z^2 = R^2 + X^2$$

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

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

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.

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

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

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

CAG 1.3-19

Liquid Filled Transformer Ratings

ONAN

1st: Internal Cooling Media	
O	Flash point <300ºC
K	Flash point >300ºC
L	Unmeasurable flash point

2nd: Internal Cooling Circulation	
F	Forced
N	Natural
D	Forced through cooler

3rd: External Cooling Circulation	
A	Air
W	Water

4th: External Cooling Media	
N	Natural
F	Forced

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	+15%	N/A
750		863
1000		1150
1500		1725
2000		2300
2500	+25%	3125
3750		4688
5000		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	+12%	560	N/A	N/A
750		840	863	966
1000		1120	1150	1288
1500		1680	1725	1932
2000		2240	2300	2576
2500		2800	3125	3500
3750		4200	4688	5250
5000		5600	6250	7000
7500		8400	9375	10500
10000		11200	12500	14000
12000		13440	16000	17920

PEAK™ Transformers	
65°C	+9% (without fans)
55°C	+22% (without fans)

EATON
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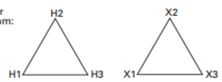
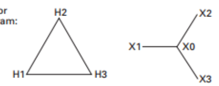
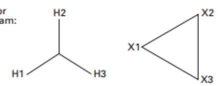
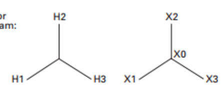
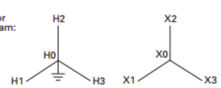
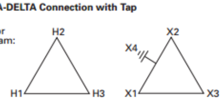
3ϕ Transformer Winding Connections

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.
GROUNDED 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