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ABB Protection Relay School Webinar Series

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ABB Protective Relay School Webinar Series, Michael Fleck, July 9, 2013

Symmetrical Components Examples & Application

Power System Fundamentals

Profile
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- Regional Technical Manager, Midwest USA
- BSEE, Rose-Hulman Inst. of Technology, Indiana
- MSEE, Arizona State University, Arizona
- Professional Engineer (P.E.), Indiana
- IEEE – Power & Energy Society Member
- Experiences:
  - ✓ ABB DA Regional Technical Manager, configuration of products to meet customer applications, customer training
  - ✓ Protection and Control Engineer, system modeling, control design, mentoring junior engineers for national consulting company,
  - ✓ Transmission and Distribution P&C engineer, system modelling, system study, design, relay setting, trouble shooting for utility company

Learning Objectives

- What we will discuss
  - Overview of converting phase quantities to symmetrical quantities and symmetrical to phase
  - Sequence Impedance networks – How do we build one?
  - Evaluating a Impedance network – Example Problem
  - Insights into the Example Problem
- Why do we use this method?
  - Not using it would require writing loop equations for the system and solving. – For simple systems it's not an easy task
  - To date it is still the only real practical solution to problems of unbalanced electrical circuits.

Symmetrical Components

- The method of symmetrical components was discovered by **Dr Charles Fortescue** while investigating problems of a single phase railway system.
- Introduced in 1918 in a classic AIEE transaction “Method of Symmetrical Co-ordinates Applied to Solution of Polyphase Networks”.
- The application to the analysis and operation of three phase power systems was broadened by **C. F. Wagner, R. D. Evans** through a series of articles they published in the Westinghouse magazine “*The Electric Journal*” that ran from March 1928 through November 1931

Symmetrical Components

- Symmetrical Components is often referred to as the language of the Relay Engineer but it is important for all engineers that are involved in power.
- The terminology is used extensively in the power engineering field and it is important to understand the basic concepts and terminology.
- Used to be more important as a calculating technique before the advanced computer age.
- Is still useful and important to make sanity checks and back-of-an-envelope calculation.

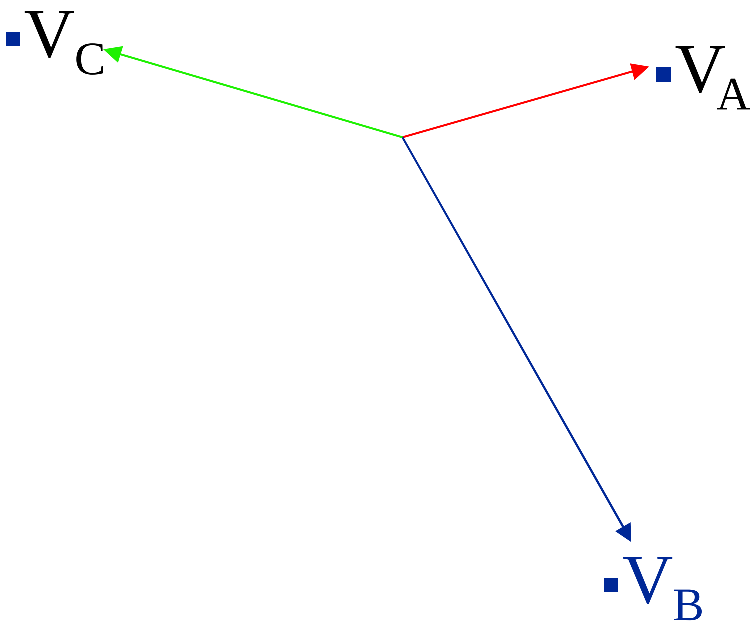
Symmetrical components and fault analysis
Voltage & Current Conversion Review

Symmetrical Components

- Balanced load supplied by balanced voltage results in balanced current.
  1. This situation results in only positive sequence components
  2. Seldom achievable in real world applications
- Positive Sequence currents produce only positive sequence voltages, Negative sequence currents produce only negative sequence voltages, and zero sequence currents produce only zero sequence voltages
- For unbalanced systems: Positive Sequence currents produce positive, negative and sometimes zero sequence voltages, Negative sequence currents produce positive, negative and sometimes zero sequence voltages, and zero sequence currents produce positive, negative, and zero sequence voltages

Symmetrical Components

- For the General Case of 3 unbalanced voltages

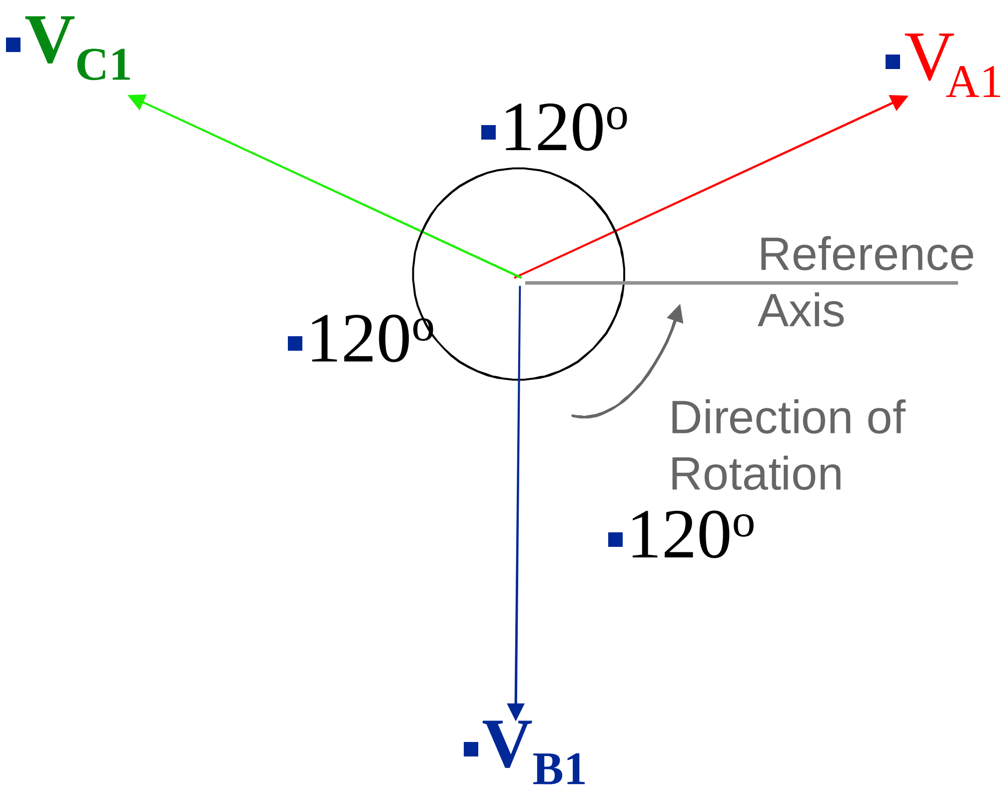


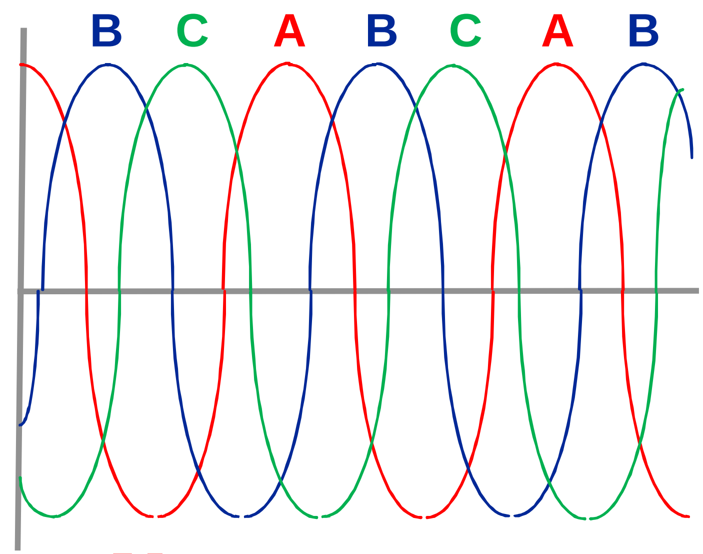
- **6 degrees of freedom**

- **Can define 3 sets of voltages designated as positive sequence, negative sequence and zero sequence**

Symmetrical Components
Positive Sequence

- **2 degrees of freedom**



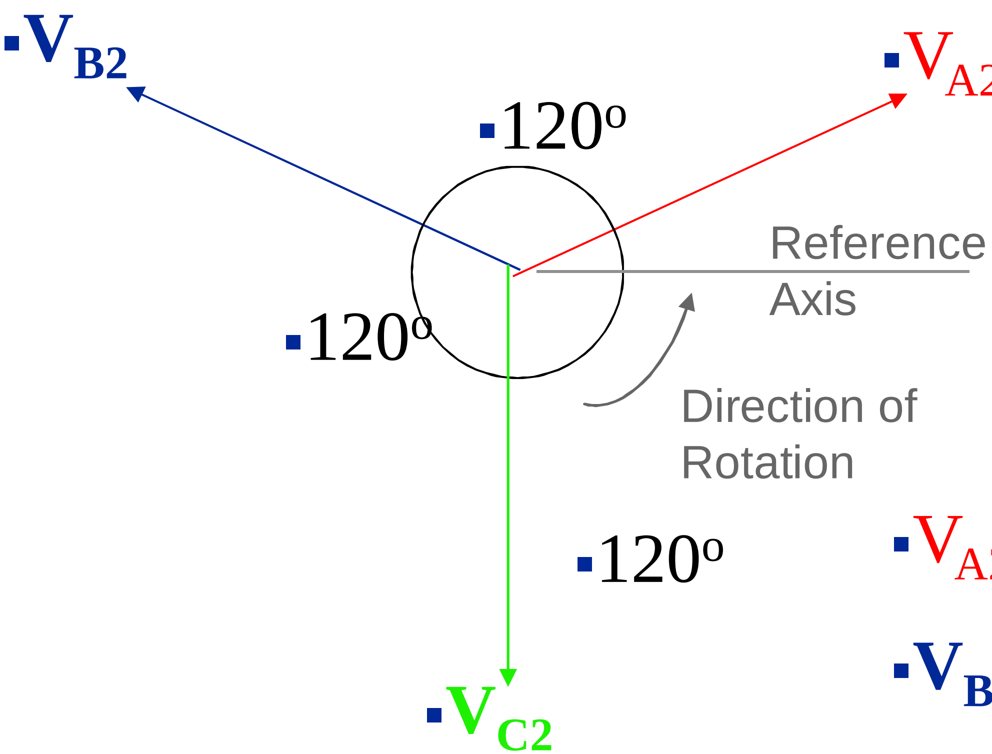


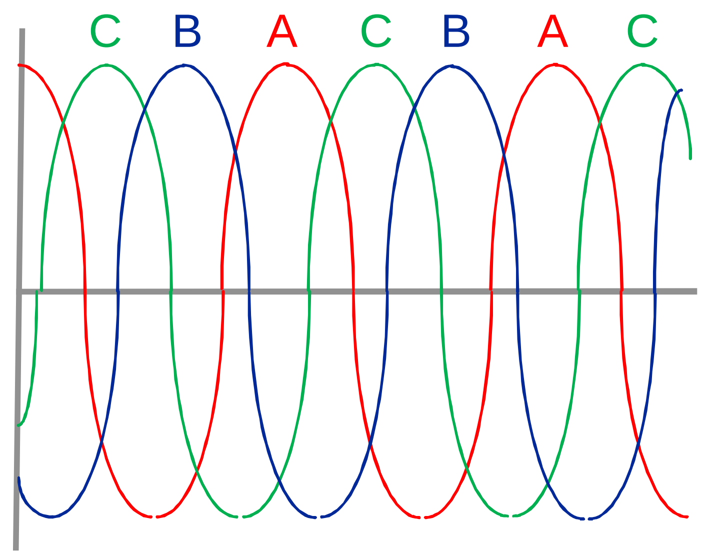
- $V_{A1} = V_{A1}$
- $V_{B1} = a^2 V_{A1}$
- $V_{C1} = a\, V_{A1}$

- **a is operator 1/120°**

Symmetrical Components
Negative Sequence

- **2 degrees of freedom**



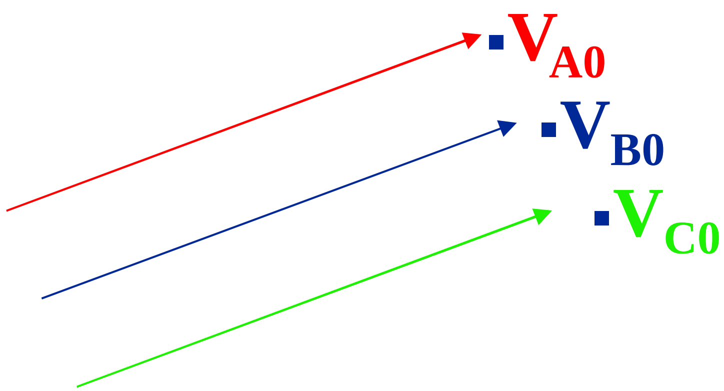


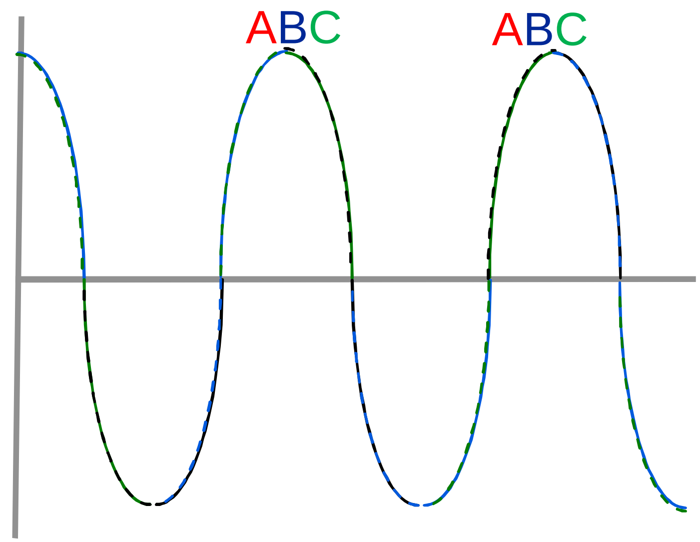
- $V_{A2} = V_{A2}$
- $V_{B2} = aV_{A2}$
- $V_{C2} = a^2 V_{A2}$

- **a is operator 1/<u>120°</u>**

Symmetrical Components
Zero Sequence

- **2 degrees of freedom**





- $\mathbf{V_{A0} = V_{B0} = V_{C0}}$

Symmetrical Components

- **Reforming the phase voltages in terms of the symmetrical component voltages:**

$$V_A = V_{A0} + V_{A1} + V_{A2}$$

$$V_B = V_{B0} + V_{B1} + V_{B2}$$

$$V_C = V_{C0} + V_{C1} + V_{C2}$$

- **What have we gained? We started with 3 phase voltages and now have 9 sequence voltages. The answer is that the 9 sequence voltages are not independent and can be defined in terms of other voltages.**

Symmetrical Components

Rewriting the sequence voltages in term of the Phase A sequence voltages:

$$V_A = V_{A0} + V_{A1} + V_{A2}$$

$$V_B = V_{A0} + a^2 V_{A1} + aV_{A2}$$

$$V_C = V_{A0} + aV_{A1} + a^2 V_{A2}$$

$\xrightarrow{\text{Drop A}}$

$$V_A = V_0 + V_1 + V_2$$

$$V_B = V_0 + a^2 V_1 + aV_2$$

$$V_C = V_0 + aV_1 + a^2 V_2$$

Suggests matrix notation:

$$\begin{pmatrix} V_A \\ V_B \\ V_C \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix} \begin{pmatrix} V_0 \\ V_1 \\ V_2 \end{pmatrix}$$

$$[V_P] = [A] \quad [V_S]$$

Symmetrical Components

$[V_P]$ = Phase Voltages

$[V_S]$ = Sequence Voltages

$$[\mathbf{A}] = \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix}$$

$$[V_P] = [A][V_S]$$

Pre-multiplying by $[A]^{-1}$

$$[A]^{-1}[V_P] = [A]^{-1}[A][V_S] = [I][V_S]$$

$$[V_S] = [A]^{-1}\,[V_P]$$

$$[\mathbf{A}]^{-1} = 1/3 \begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix}$$

$$[V_S] = [A]^{-1}[V_P]$$

Symmetrical components & Fault Analysis

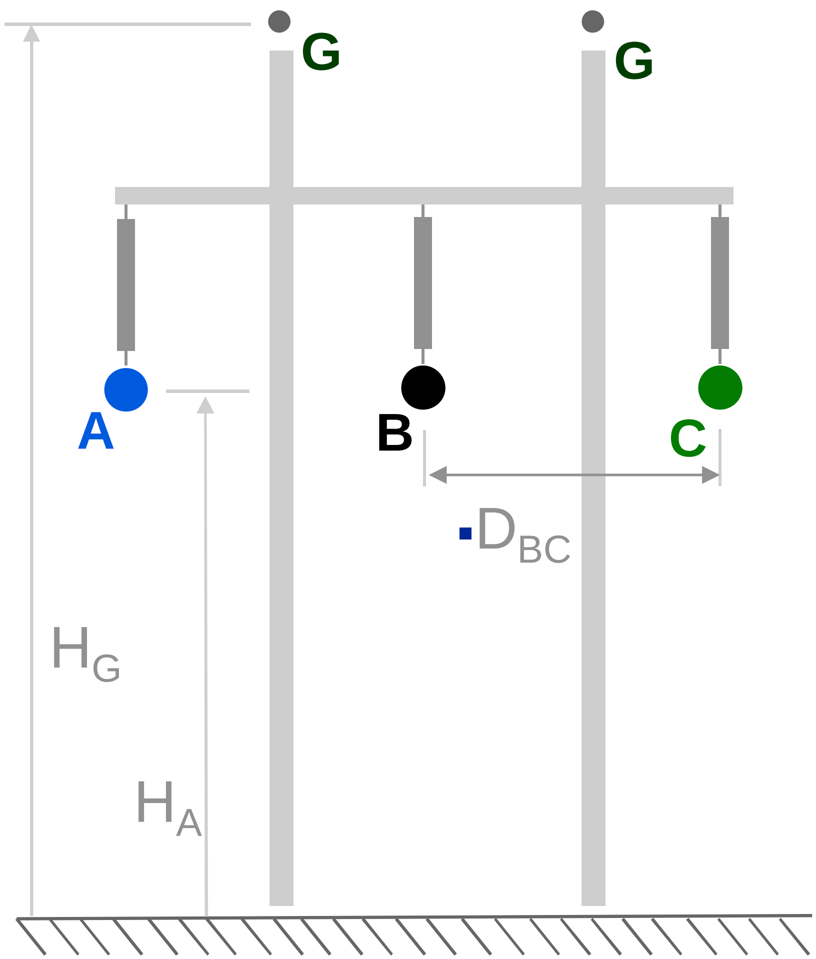
Impedance Networks

Symmetrical Components

Typical System Parameter used in Symmetrical Component Analysis

- Transmission Lines
- Transformers
- Generators

Symmetrical Components – Line Constants



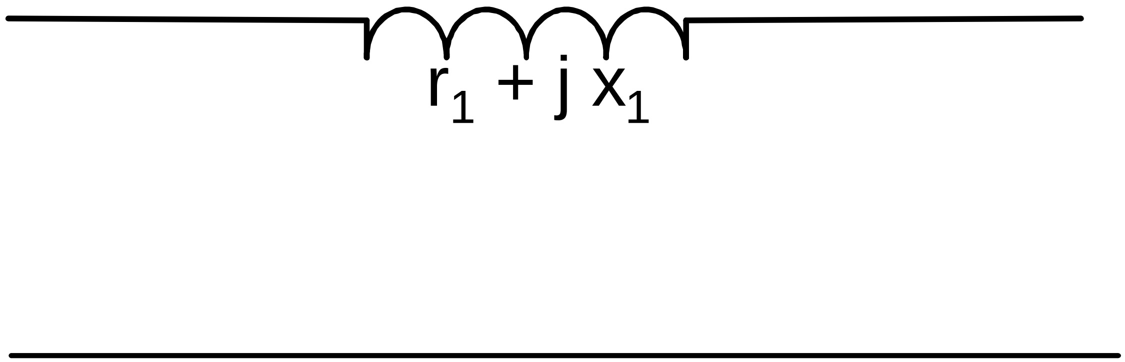
Transmission Line Impedance

- Size and type of phase and ground conductors
- Geometric configuration of the transmission line
- Transpositions over the length of the line
- Shunt capacitance is generally neglected for fault studies

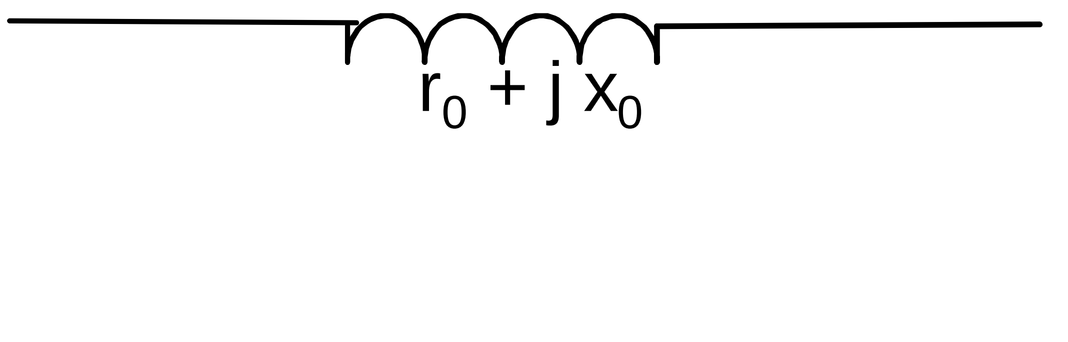
Transmission Line Models

The general models for transmission lines

Positive and Negative Sequence



- **Zero Sequence**



Transmission Line Models

Positive & Negative Sequence ($Z_1 = Z_2$)

- **$Z_1 = R_1 + jX_1$**
- **$R_1 = r/n$ for n conductors per phase:**
- **r can be found in lookup tables showing cable resistance**

Note skin effect: $r_{dc} < r_{60Hz}$

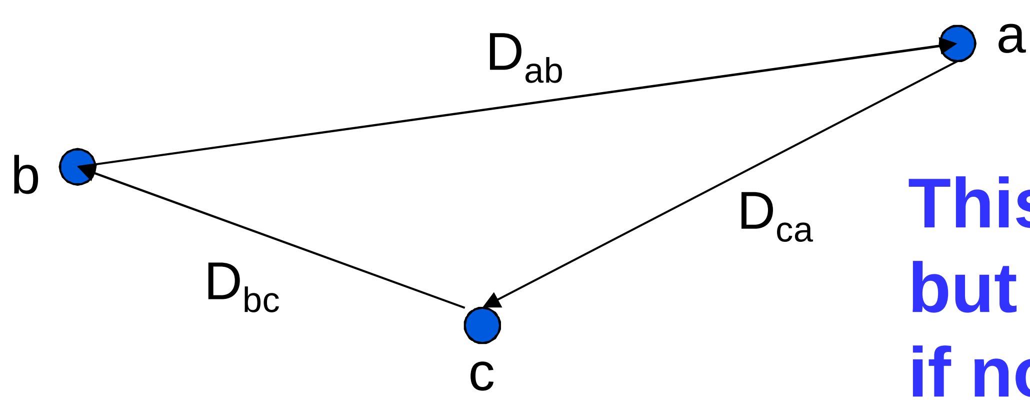
- **X_1 can be found from the general equation for inductance**

$$L_1 = 2x10^{-7} \ln \frac{D_{EQ}}{D_{SL}}$$ Henries/meter

Transmission Line Models

$$X_1 = 2\pi f L_1 = .1213 \ln \frac{D_{EQ}}{D_{SL}}$$ Ω per mile for 60 Hz

$$D_{EQ} = (D_{ab} \times D_{bc} \times D_{ca})^{\frac{1}{3}}$$



This assumes transposition but is reasonably accurate if not transposed.

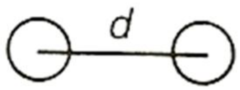
Transmission Line Models

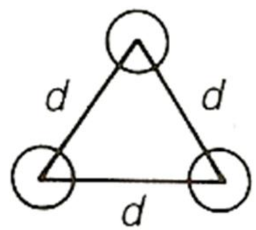
How to calculate D_{SL}

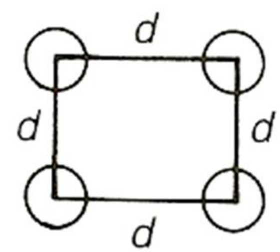
If there are n conductors per phase, D_{SL} is the distance from every conductor in the bundle to every other conductor to the $1/n^2$

- **For 3 conductor bundle** $D_{SL} = \left[(d)(d)(gmr)(d)(gmr)(d)(gmr)(d)(d)\right]^{1/9}$

$$D_{SL} = \left[(gmr)d^2\right]^{1/3}$$







For a 1-conductor bundle: $D_{SL} = gmr$

For a 2-conductor bundle: $D_{SL} = \sqrt{gmr \times d}$

For a 3-conductor bundle: $D_{SL} = \sqrt[3]{gmr \times d^2}$

For a 4-conductor bundle: $D_{SL} = 1.091 \times \sqrt[4]{gmr \times d^3}$

Transmission Line Models

Example:

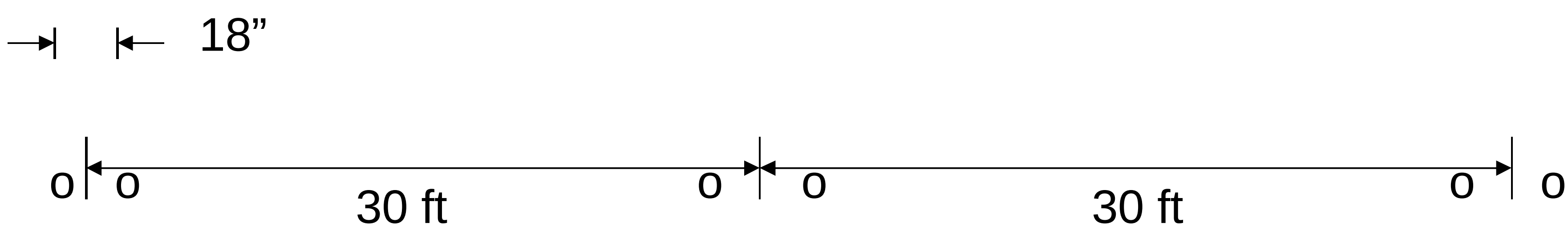
Find the positive sequence model for 20 mile of transmission line with 2-conductor bundle 2156 KCM ACSR Conductors (Bluebird) and the following conductor configuration:

Found from cable lookup table:

Diameter = 1.762 in. Radius = 0.881 in. = 0.0734 ft.

gmr = 0.0586 ft.   Resistance = 0.0515 Ω/mile

Find: Positive and Negative Sequence Impedance for a 20 mile line



Transmission Line Models

Code word	Aluminum area, cmil	Stranding Al/St	Layers of aluminum	Outside diameter, in	Resistance: Dc, 20°C, Ω/1,000 ft	Resistance: Ac, 60 Hz: 20°C, Ω/mi	Resistance: Ac, 60 Hz: 50°C, Ω/mi	GMR $\approx r'$ D_s, ft	Reactance 1-ft spacin: Inductive X_a, Ω/mi
Waxwing	266,800	18/1	2	0.609	0.0646	0.3488	0.3831	0.0198	0.476
Partridge	266,800	26/7	2	0.642	0.0640	0.3452	0.3792	0.0217	0.465
Ostrich	300,000	26/7	2	0.680	0.0569	0.3070	0.3372	0.0229	0.458
Merlin	336,400	18/1	2	0.684	0.0512	0.2767	0.3037	0.0222	0.462
Linnet	336,400	26/7	2	0.721	0.0507	0.2737	0.3006	0.0243	0.451
Oriole	336,400	30/7	2	0.741	0.0504	0.2719	0.2987	0.0255	0.445
Chickadee	397,500	18/1	2	0.743	0.0433	0.2342	0.2572	0.0241	0.452
bis	397,500	26/7	2	0.783	0.0430	0.2323	0.2551	0.0264	0.441
Pelican	477,000	18/1	2	0.814	0.0361	0.1957	0.2148	0.0264	0.441
Flicker	477,000	24/7	2	0.846	0.0359	0.1943	0.2134	0.0284	0.432
Hawk	477,000	26/7	2	0.858	0.0357	0.1931	0.2120	0.0289	0.430
Hen	477,000	30/7	2	0.883	0.0355	0.1919	0.2107	0.0304	0.424
Osprey	556,500	18/1	2	0.879	0.0309	0.1679	0.1843	0.0284	0.432
Parakeet	556,500	24/7	2	0.914	0.0308	0.1669	0.1832	0.0306	0.423
Dove	556,500	26/7	2	0.927	0.0307	0.1663	0.1826	0.0314	0.420
Rook	636,000	24/7	2	0.977	0.0269	0.1461	0.1603	0.0327	0.415
Grosbeak	636,000	26/7	2	0.990	0.0268	0.1454	0.1596	0.0335	0.412
Drake	795,000	26/7	2	1.108	0.0215	0.1172	0.1284	0.0373	0.399
Tern	795,000	45/7	3	1.063	0.0217	0.1188	0.1302	0.0352	0.406
Rail	954,000	45/7	3	1.165	0.0181	0.0997	0.1092	0.0386	0.395
Cardinal	954,000	54/7	3	1.196	0.0180	0.0988	0.1082	0.0402	0.390
rtolan	1,033,500	45/7	3	1.213	0.0167	0.0924	0.1011	0.0402	0.390
luejay	1,113,000	45/7	3	1.259	0.0155	0.0861	0.0941	0.0415	0.386
inch	1,113,000	54/19	3	1.293	0.0155	0.0856	0.0937	0.0436	0.380
ittern	1,272,000	45/7	3	1.345	0.0136	0.0762	0.0832	0.0444	0.378
heasant	1,272,000	54/19	3	1.382	0.0135	0.0751	0.0821	0.0466	0.372
obolink	1,431,000	45/7	3	1.427	0.0121	0.0684	0.0746	0.0470	0.371
lover	1,431,000	54/19	3	1.465	0.0120	0.0673	0.0735	0.0494	0.365
apwing	1,590,000	45/7	3	1.502	0.0109	0.0623	0.0678	0.0498	0.364
alcon	1,590,000	54/19	3	1.545	0.0108	0.0612	0.0667	0.0523	0.358
luebird	2,156,000	84/19	4	1.762	0.0080	0.0476	0.0515	0.0586	0.344

Transmission Line Example

Diameter = 1.762 in. Radius = 0.881 in. = 0.0734 ft.

gmr = 0.0586 ft.   Resistance = 0.0515 Ω/mile

$$\boxed{r_1 = \frac{.0515}{2} = .0258\Omega / mi}$$

$$Deq = \left[(30)(30)(60)\right]^{1/3} = (54{,}000)^{1/3} = 37.8\, ft.$$

$$D_{sL} = \left[(1.5)(.0586)\right]^{1/2} = 0.296\, ft.$$

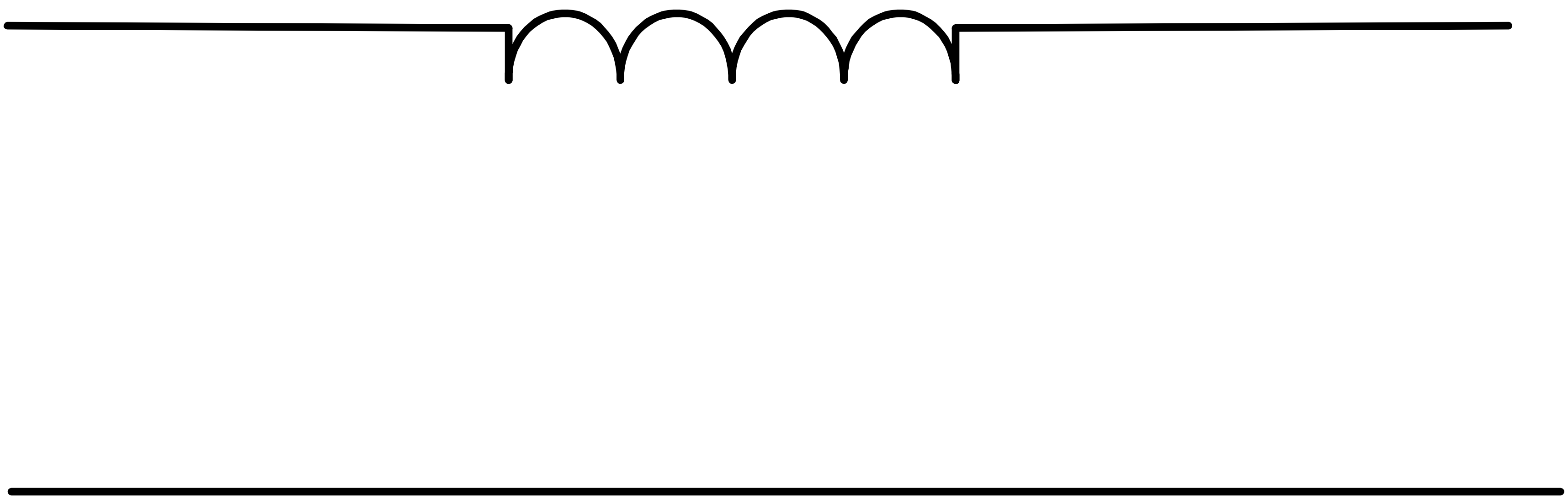
$$\boxed{x_1 = .1213 \ln \frac{37.8}{.296} \Omega / mi}$$

Transmission Line Example

$$\boxed{Z_1 = Z_2 = (r_1 + x_1)Line_{length}}$$

$$\boxed{Z_1 = Z_2 = 0.52 + j11.8\Omega = 11.81\angle 87.57^{\circ}}$$

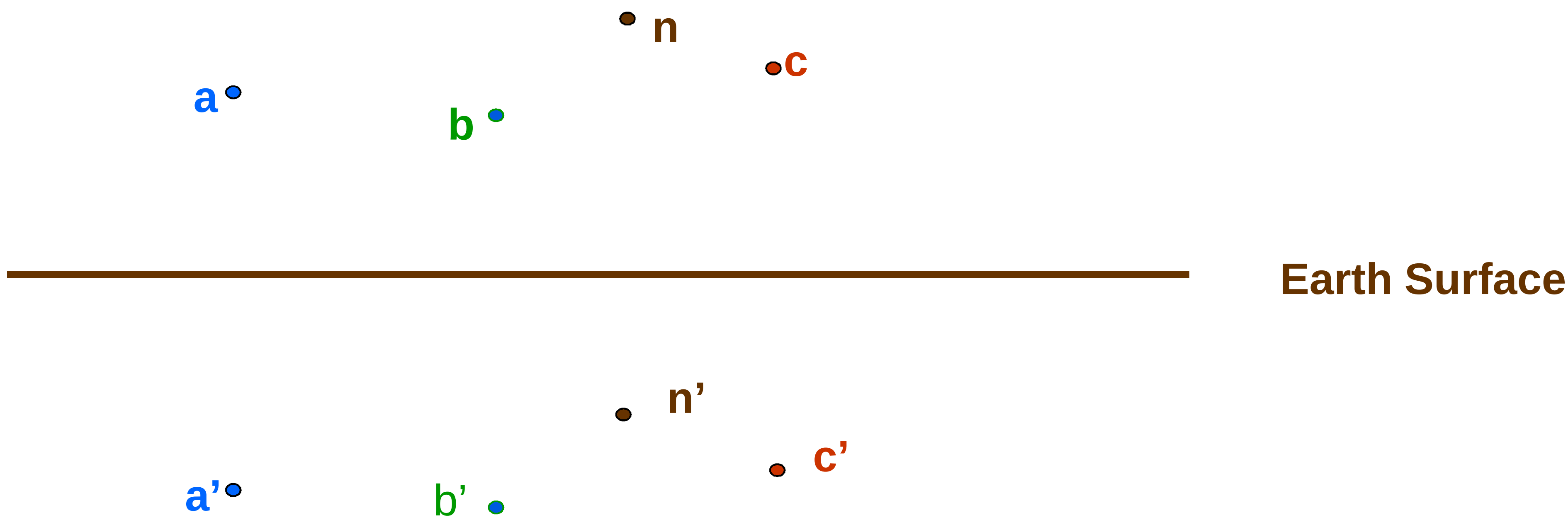
$$11.81\angle 87.57^{\circ}$$



Transmission Line Models Z0

- If Ia + Ib + Ic ≠ 0 there will be neutral current flow
- If the neutral is grounded all of part of the neutral current will flow in the ground
- Need to determine the impedance to the flow of this current: Z0
- Made possible by Carson’s work which shows that earth can be modeled by one or more equivalent conductors
- We will use one equivalent conductor below the earth’s surface for each real conductor.

Transmission Line Models Z0



Just one OHGW to simplify work but showing principal

Transmission Line Models Z0 – Carson's Formula

$D_{k'k'} = D_{kk}$ **= gmr of the overhead conductor**

$D_{kk'} = 658.5\sqrt{\rho / f}$ **Meters**

ρ = earth resistively in ohm-meters

$R_{k'} = 9.869 * 10^{-7} f$ **Ohms / meter**

where: f = frequency in Hz

Transmission Line Models – Z0

Z_0 is much more difficult to find and depend on:

- Ground resistance
- Conductor height above ground
- Distance from phase conductors to overhead ground wires (OHGW)
- Characteristics of OHGW
- Z0 > Z1 due to mutual coupling between phases. Mutual coupling to adjacent circuits must be considered
- Rule of Thumb: 2Z1< Z0 < 4Z1

Transformer Constants

- Factors to Consider
  - Polarity
  - Three Phase Connections
  - Number of Windings
  - Core Design

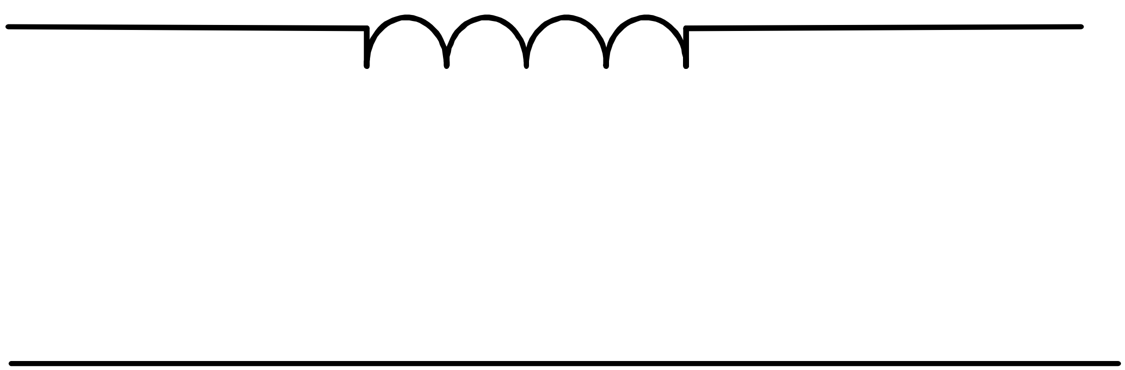
Transformer Models

The general models for transformer lines

$$jX_1 = jX_2 = jX_0$$

The one exception to this is when we have a three phase core-type transformer

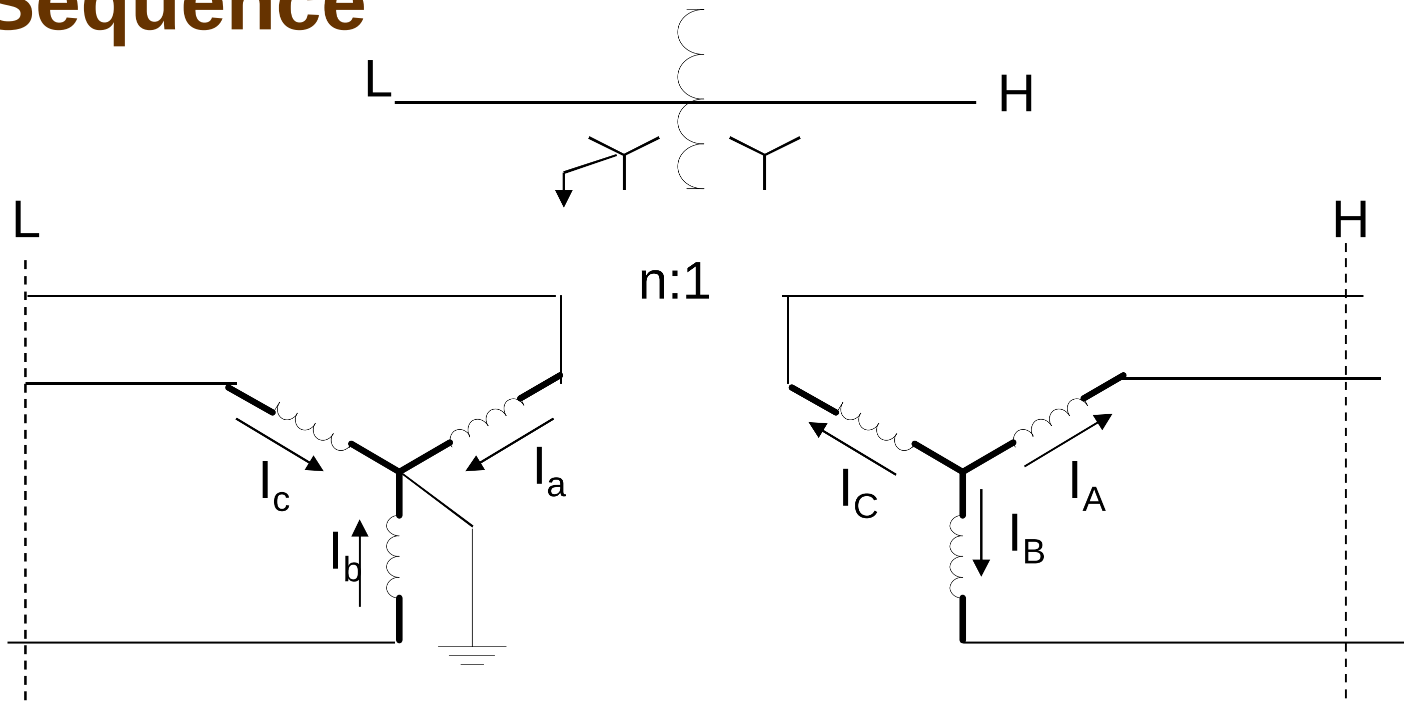
Positive and Negative Sequence Connections



Zero Sequence

Dependant on Transformer winding connections

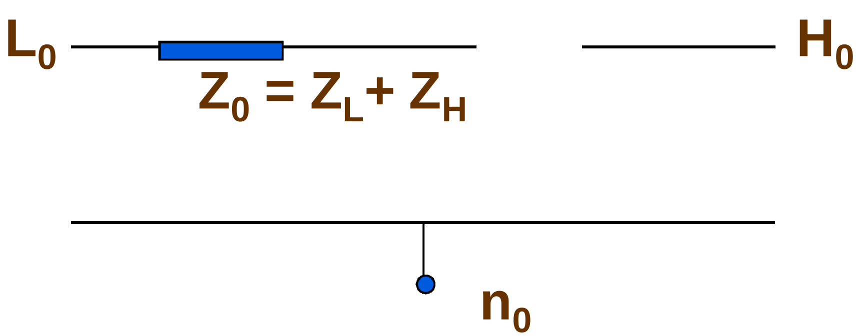
Transformer Connections for Zero **Sequence**



$I_a + I_b + I_c$ is not necessarily 0 if we only look at Low Voltage circuit

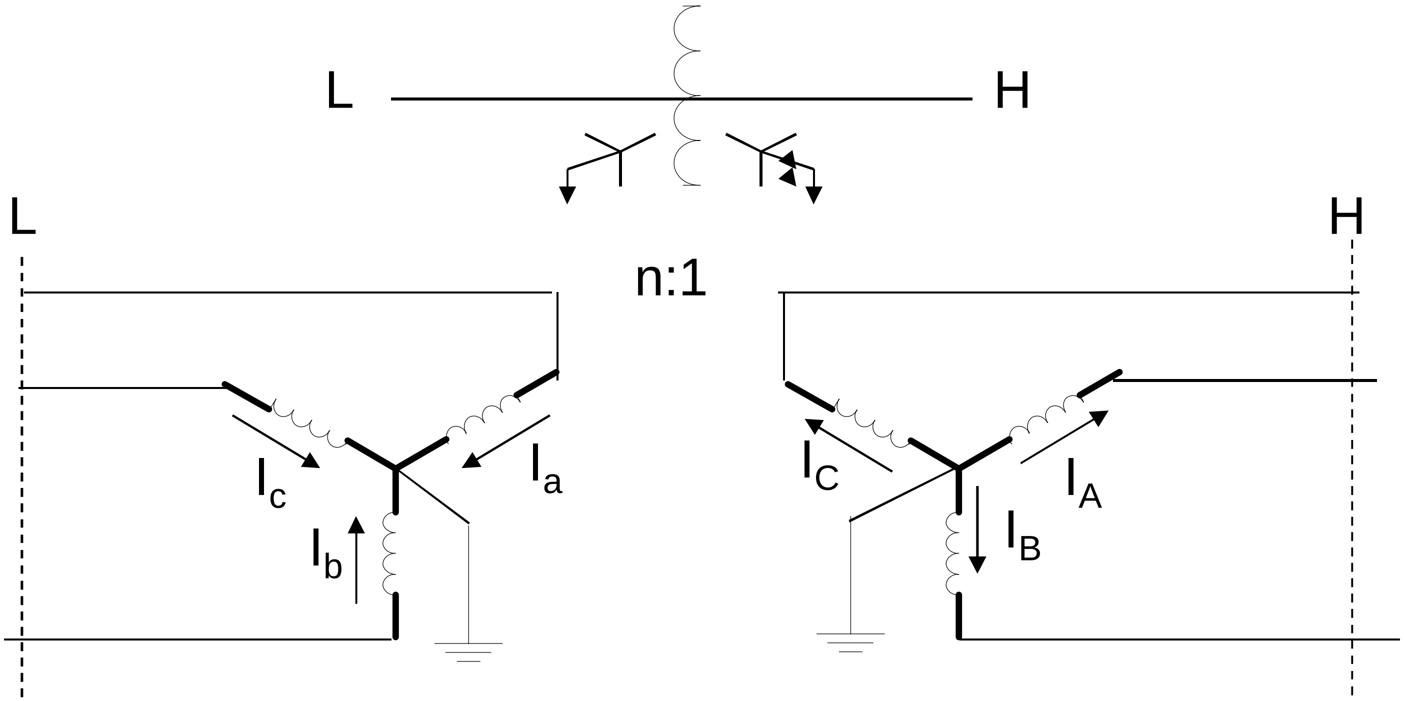
But we know $I_L = nI_H$: $I_a = nI_A$ $I_b = nI_B$ and $I_c = nI_C$

Since $I_A + I_B + I_C = 0$, $I_a + I_b + I_c = 0$ and $I_0 = 0$



No zero sequence current flow through transformer

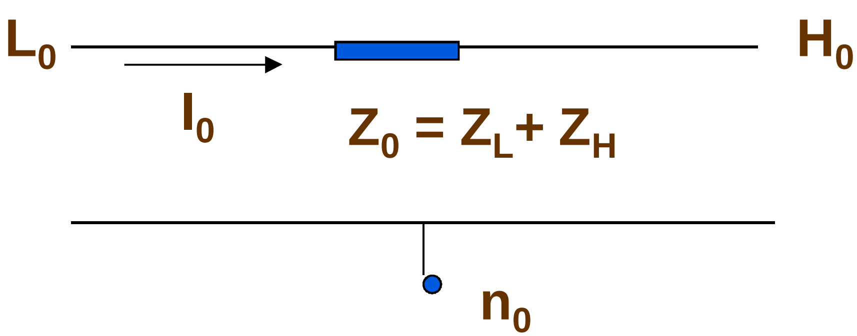
Transformer Connections for Zero **Sequence**



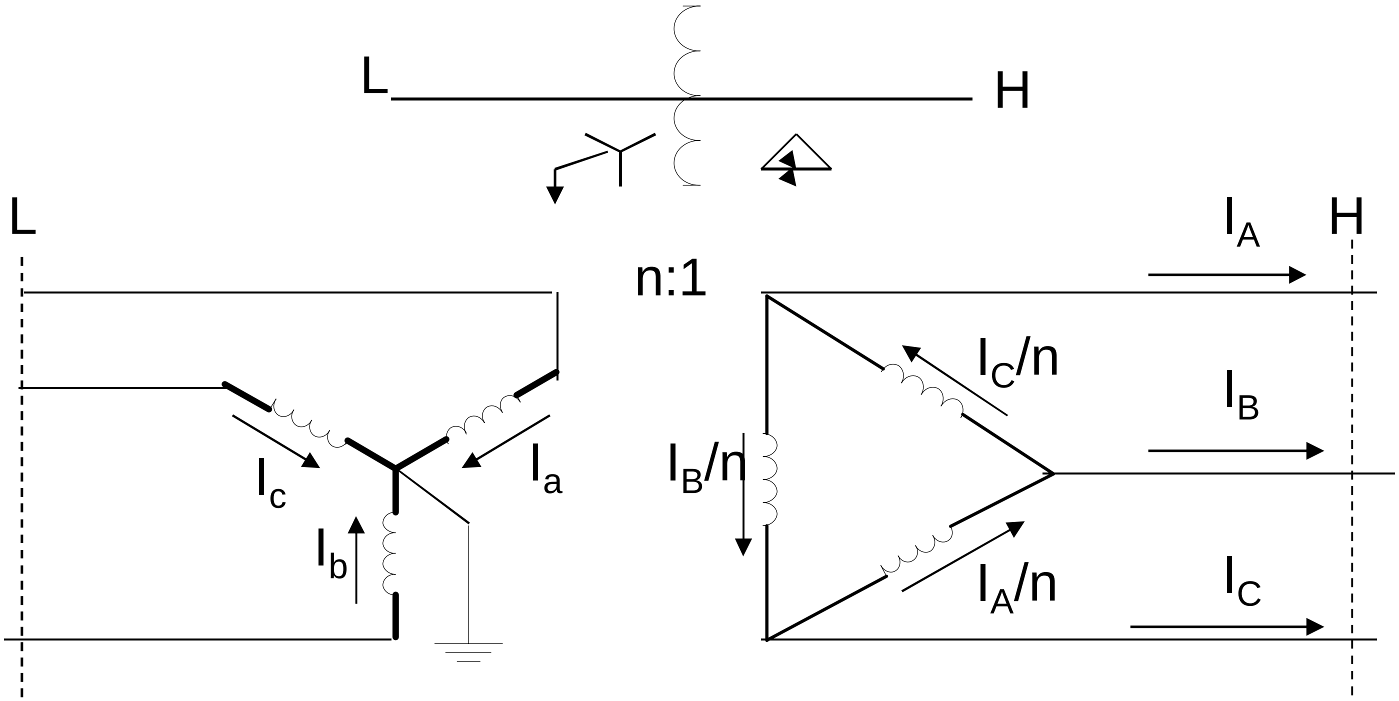
$I_a + I_b + I_c$ is not necessarily 0 and $I_A + I_B + I_C$ is not necessarily.

Therefore I_0 is not necessarily 0,

I_0 can flow through the transformer.



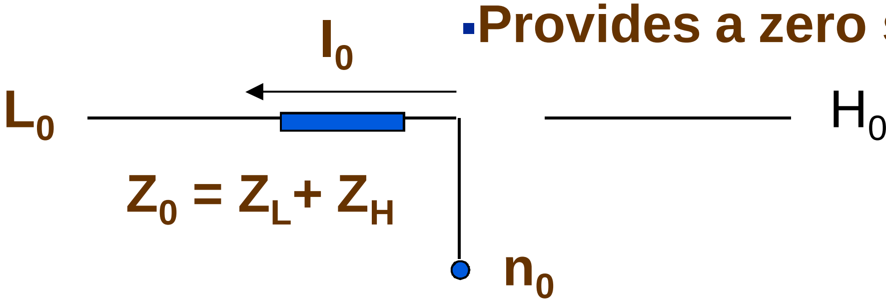
Transformer Connections for Zero Sequence



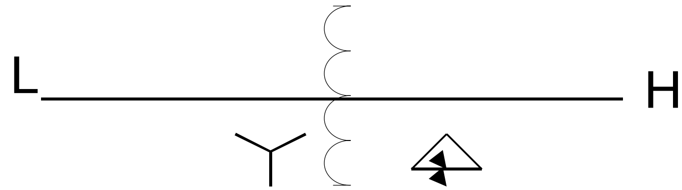
$I_a + I_b + I_c$ **is not necessarily 0 and** $I_A/n + I_B/n + I_C/n$ **is not necessarily 0**

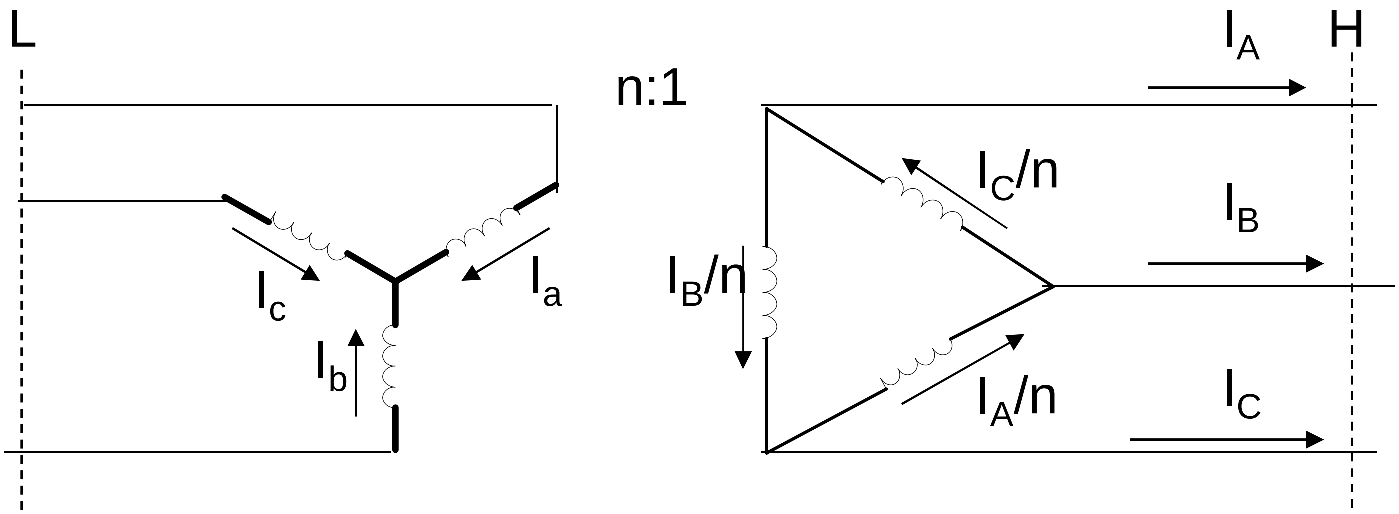
But $I_A + I_B + I_C = 0$

- **Provides a zero sequence current source**



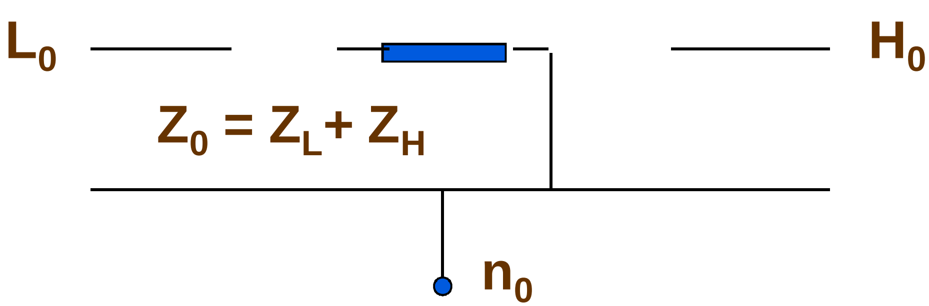
Transformer Connections for Zero Sequence



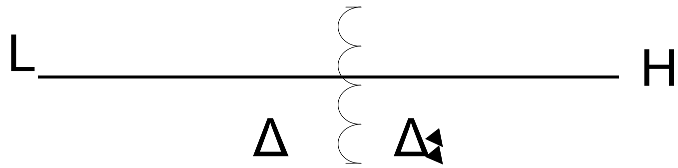


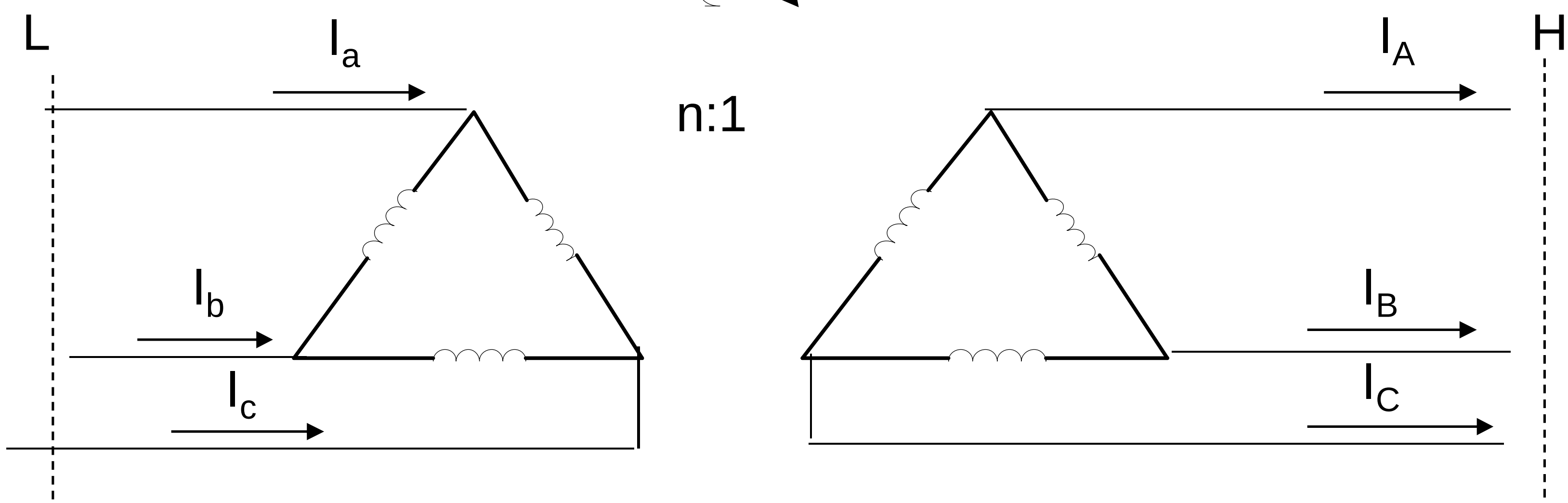
$I_a + I_b + I_c = 0$ $I_A/n + I_B/n + I_C/n$ is not necessarily 0, but $I_A + I_B + I_C = 0$

- **No zero sequence current flow**



Transformer Connections for Zero Sequence

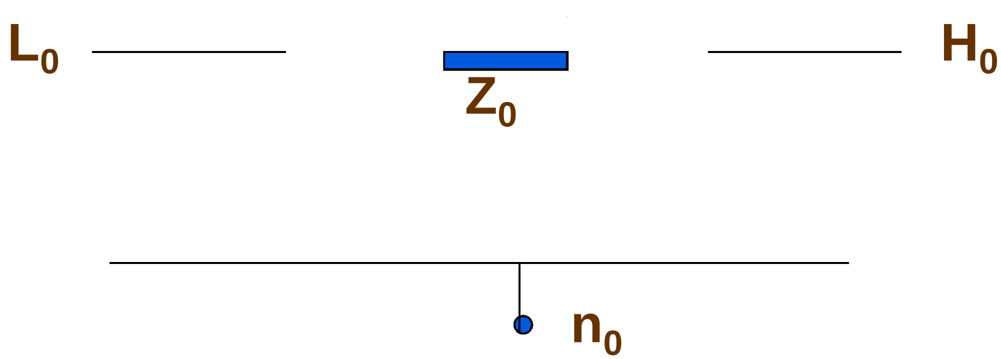




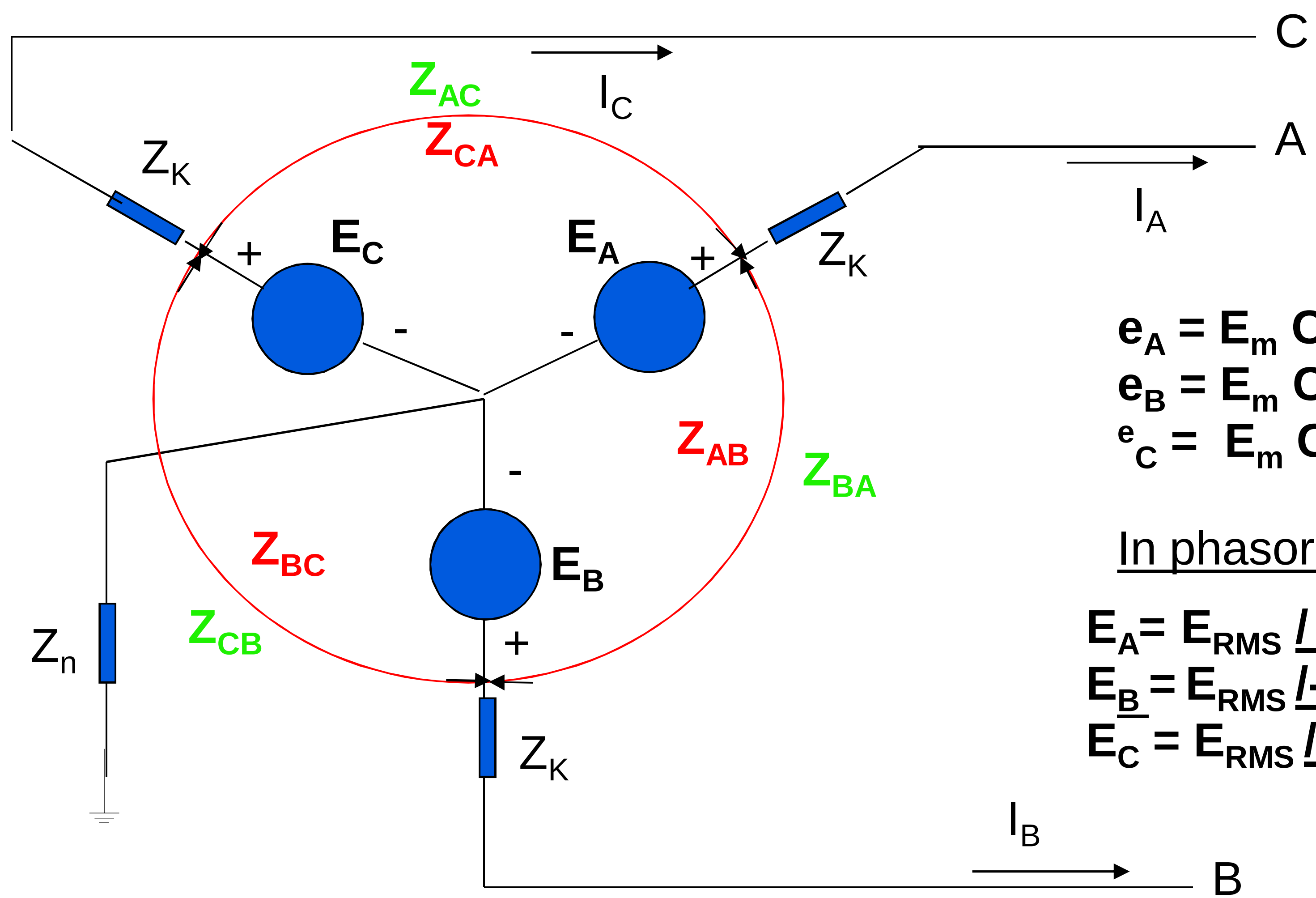
$I_a + I_b + I_c = 0$

$I_A + I_B + I_C = 0$

No zero sequence current flow



Rotating Machine Sequence Networks



$e_A = E_m \text{ Cos } \omega t$
$e_B = E_m \text{ Cos}(\omega t - 120^o)$
$e_C = E_m \text{ Cos}(\omega t + 120^o)$

In phasor form:

$E_A = E_{RMS} \underline{/\ 0} = E$
$E_B = E_{RMS} \underline{/-120^o} = a^2 E$
$E_C = E_{RMS} \underline{/120^o} = a E$

Rotating Machine Sequence Networks

$E_A = E_{RMS}\ \underline{/\ 0} = E$
$E_B = E_{RMS}\ \underline{/-120^o} = a^2 E$
$E_C = E_{RMS}\ \underline{/120^o} = a E$

or

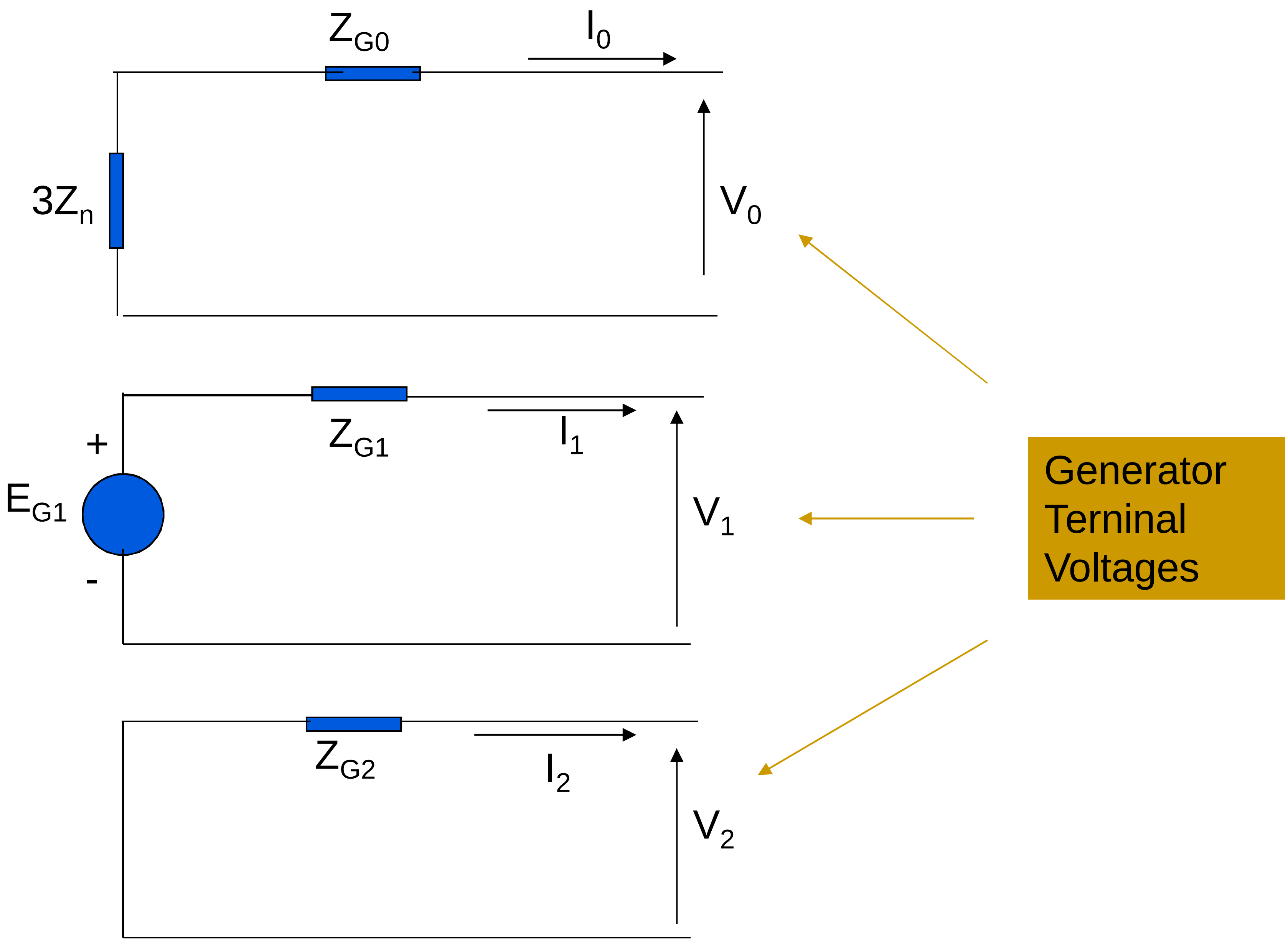
$$\left[E_{Pg}\right] = \begin{array}{c|c} \begin{bmatrix} E \\ a^2 E \\ aE \end{bmatrix} & \begin{matrix} a \\ b \\ c \end{matrix} \end{array}$$

$$\left[E_{Sg}\right] = [A]^{-1}\left[E_{Pg}\right] = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} E \\ a^2 E \\ aE \end{bmatrix} = \begin{array}{c|c} \begin{bmatrix} 0 \\ E \\ 0 \end{bmatrix} & \begin{matrix} 0 \\ 1 \\ 2 \end{matrix} \end{array}$$

- **Therefore, only the positive sequence system has a generator voltage source.**

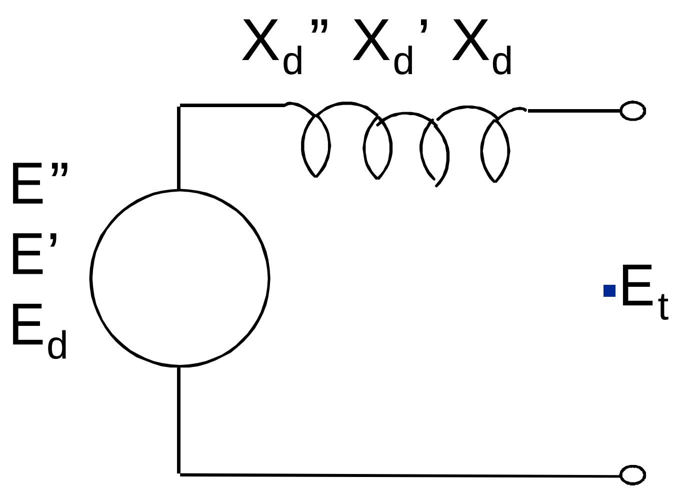
Rotating Machine Sequence Networks

- Generator sequence circuits are uncoupled



Symmetrical Components– Gen Constants

Internal Machine Voltages and Reactances



X_d" - Subtransient Reactance

X_d' - Transient Reactance

X_d - Synchronous Reactance

Example Problem

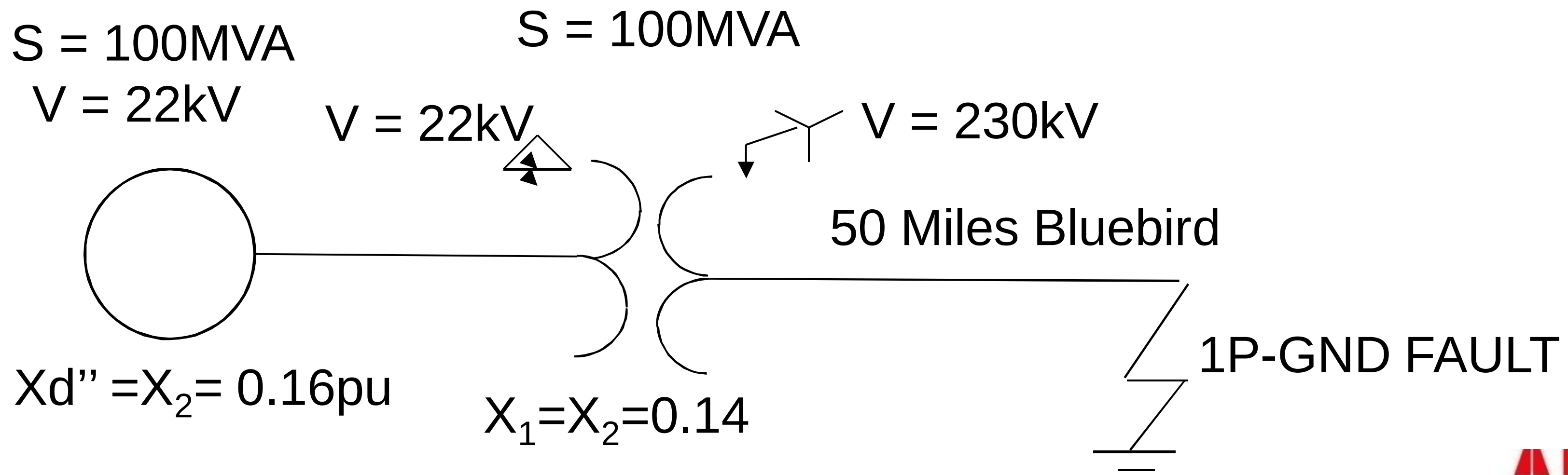
A Generator is connected to a power system through a 22kV delta to 230kV grounded wye transformer rated at 100MVA and with a series reactance of 0.14pu. The generator is rated at 100MVA and 22kV and has $X''d = X_2 =$ 0.16pu. The generator neutral is not grounded. A bolted single line to ground fault occurs at 50 miles down the line on the 230kV terminals of the transformer on Phase A. Assume transmission line is the same 2156KCM Bluebird conductor and arrangement, which was evaluated earlier

Find:

The fault current in Phase a, b, and c in pu and primary current

The phase voltages at the point of the fault in pu and primary voltage

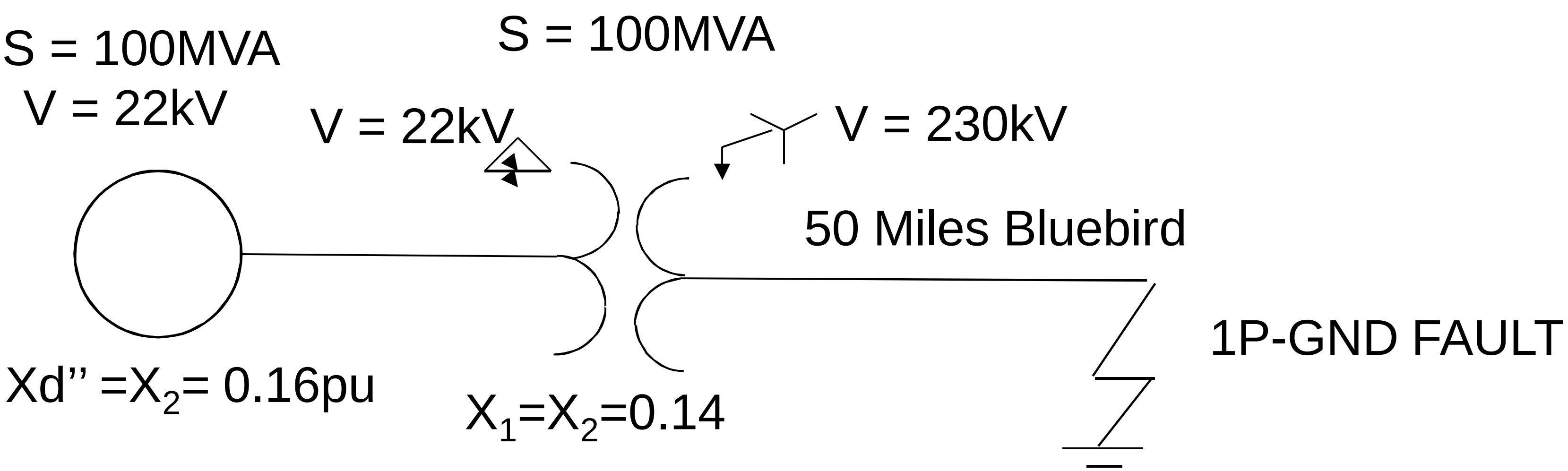
The fault current in Phase a, b, and c in pu and primary current on 22kV side



Example Problem

Find:

The fault current in Phase a, b, and c in pu and primary values



Found earlier that Bluebird conductor characteristics at 60Hz was

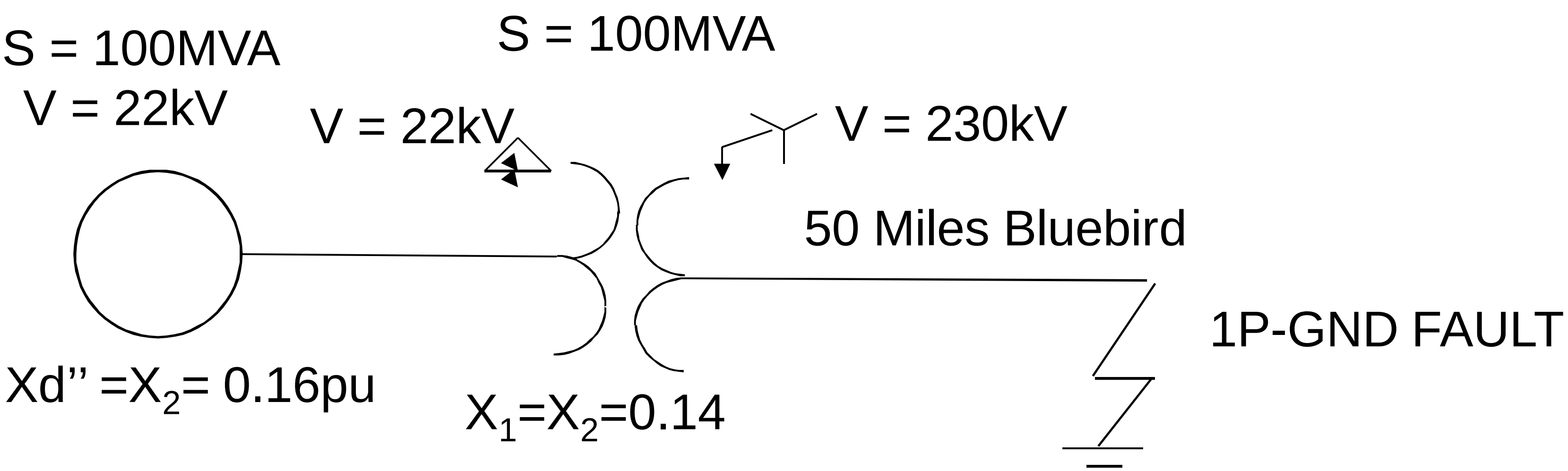
$$\boxed{r_1 = \frac{.0515}{2} = .0258\Omega / mi}$$

$$\boxed{x_1 = .1213 \ln \frac{37.8}{.296} \Omega / mi}$$

Example Problem

Find:

The fault current in Phase a, b, and c in pu and primary values



$$Z_{50MILES} = 50 \times (0.0258 + j0.59)\Omega$$

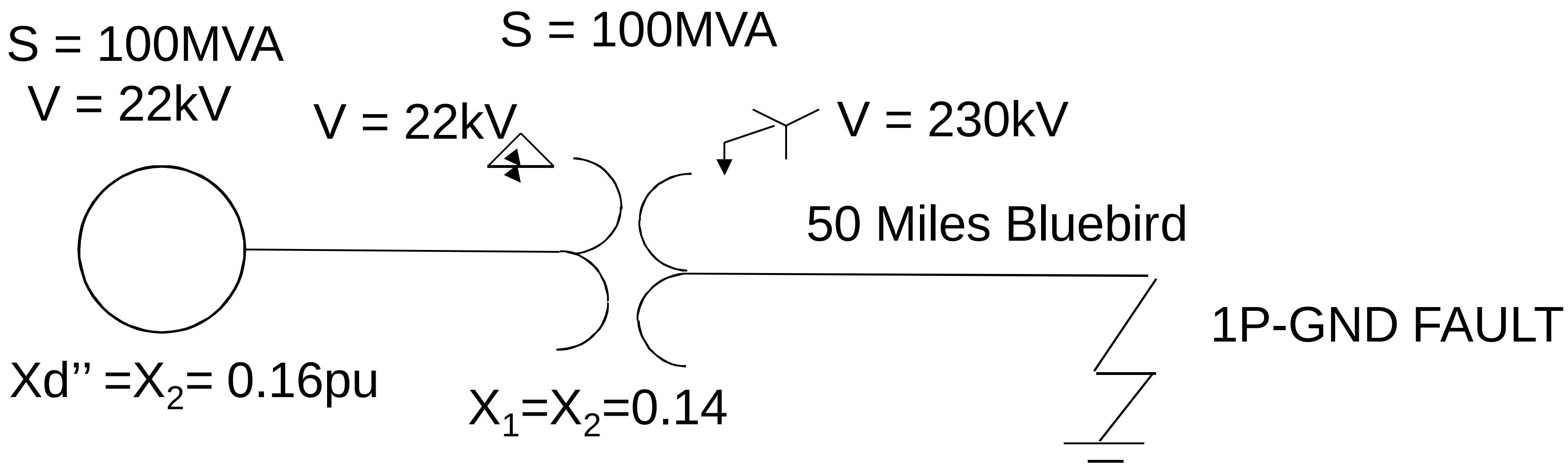
$$Z_{BASE} = \frac{kV_{BASE}^2}{MVA_{BASE}} = \frac{230^2}{100} = 529\Omega$$

$$Z_{PU\,50MILES} = \frac{1.29 + j29.41\Omega}{529} = 0.056\angle 87.5^\circ\ pu$$

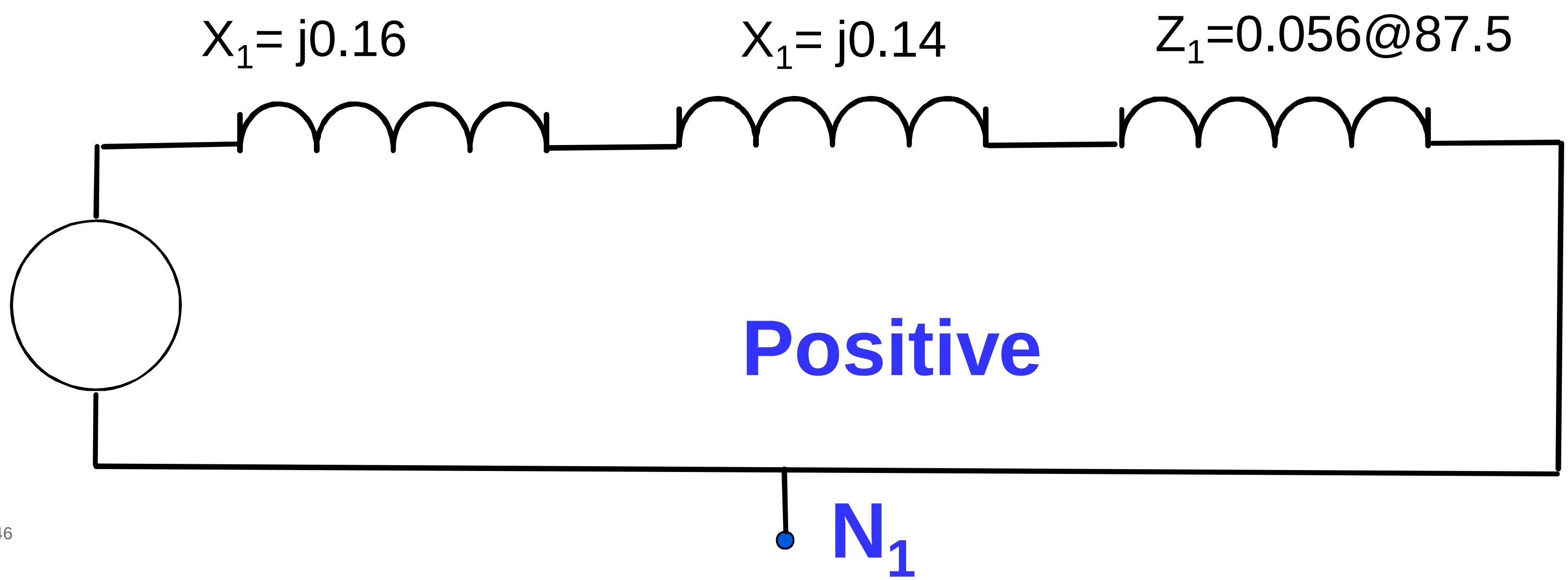
Example Problem

Find:

The fault current in Phase a, b, and c in pu and primary values



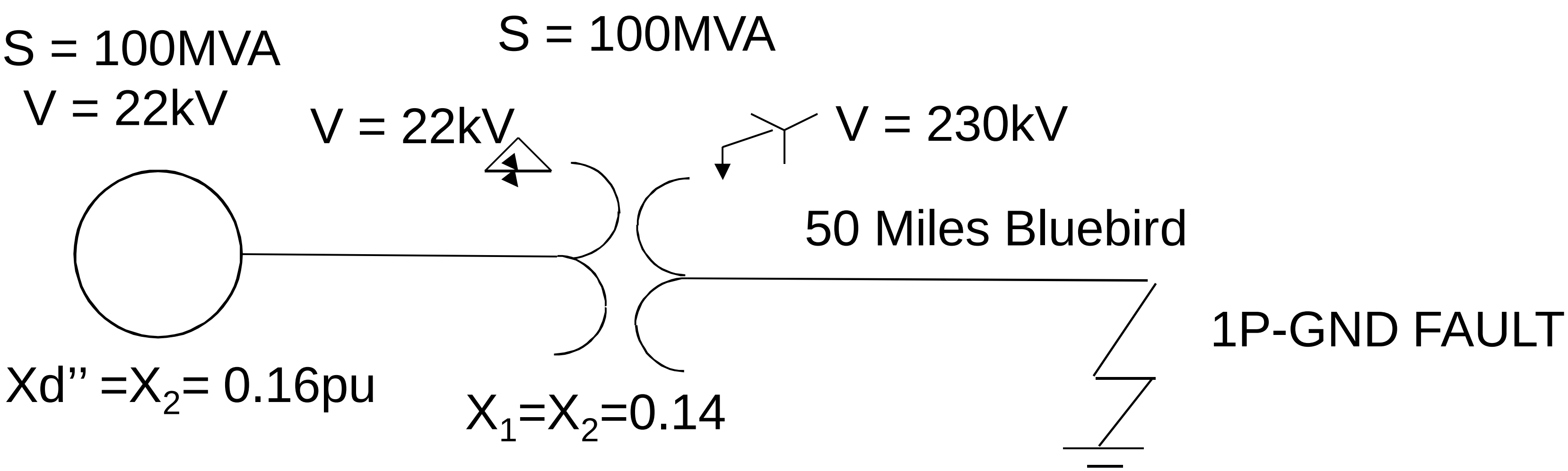
Create our Positive and Negative Sequence networks



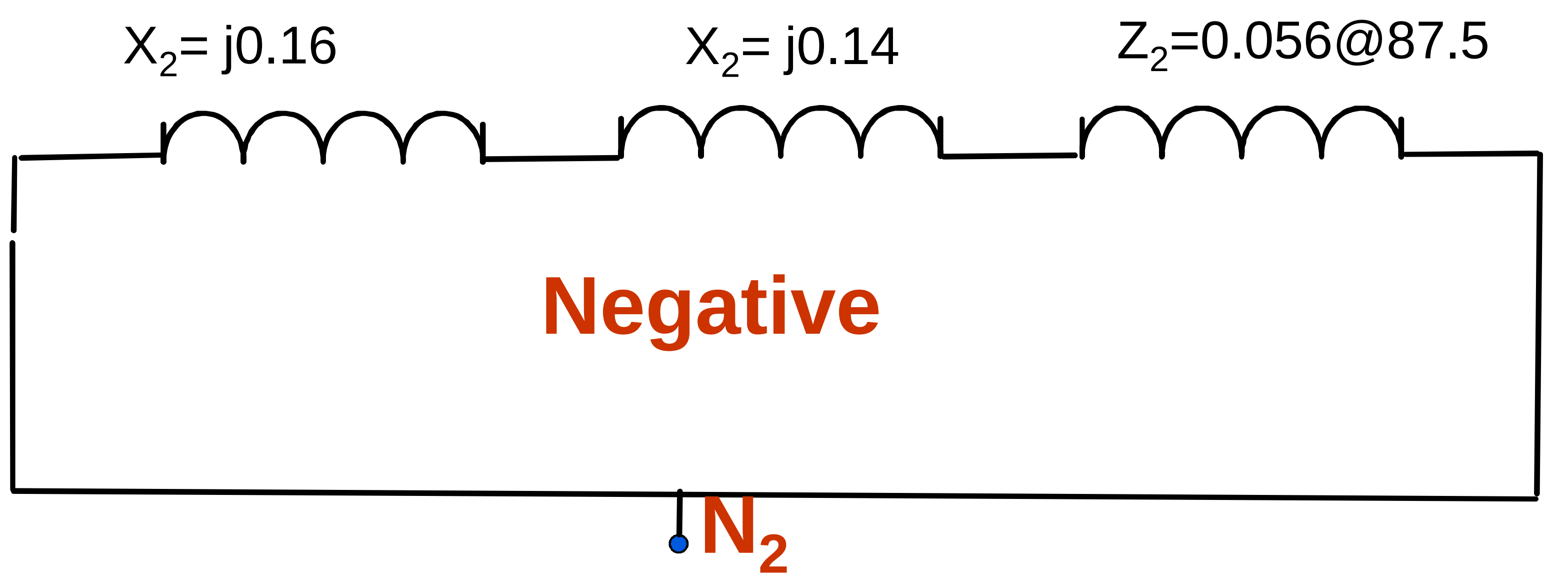
Example Problem

Find:

The fault current in Phase a, b, and c in pu and primary values



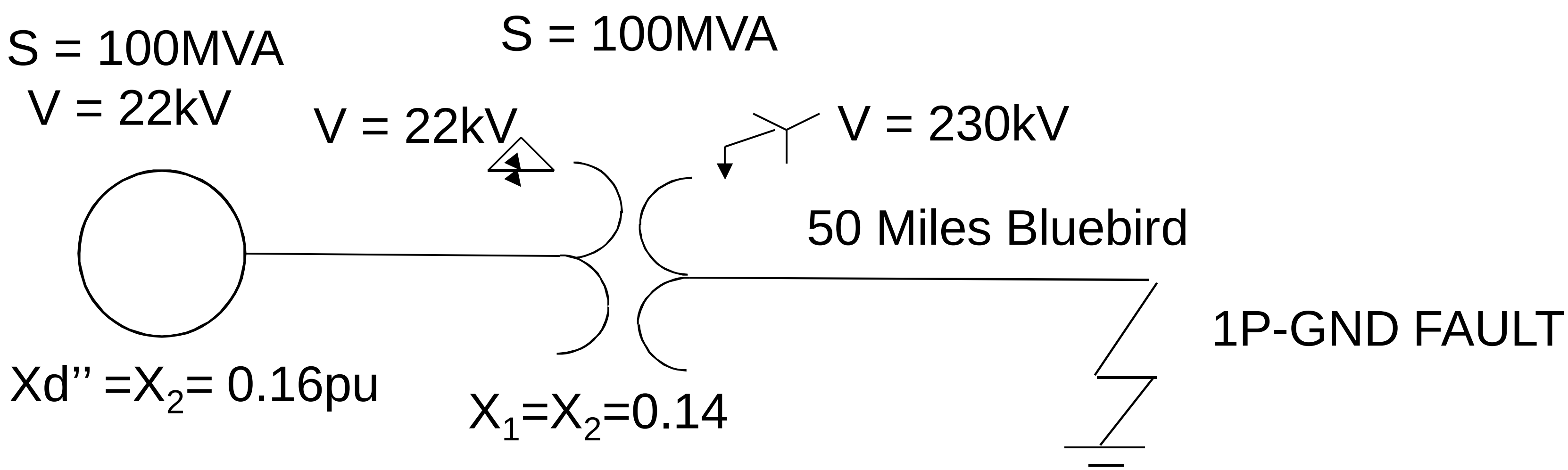
Create our Positive and Negative Sequence networks



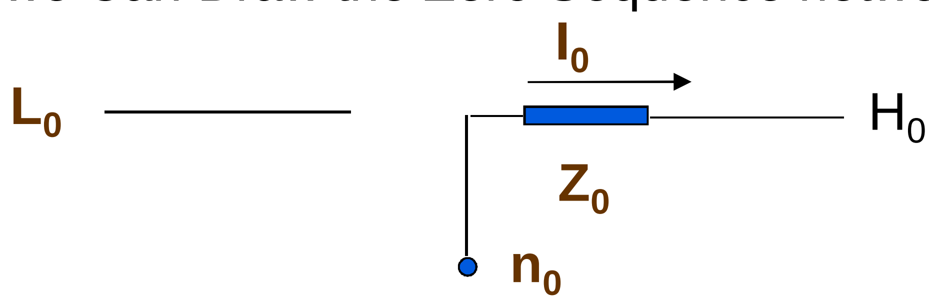
Example Problem

Find:

The fault current in Phase a, b, and c in pu and primary values



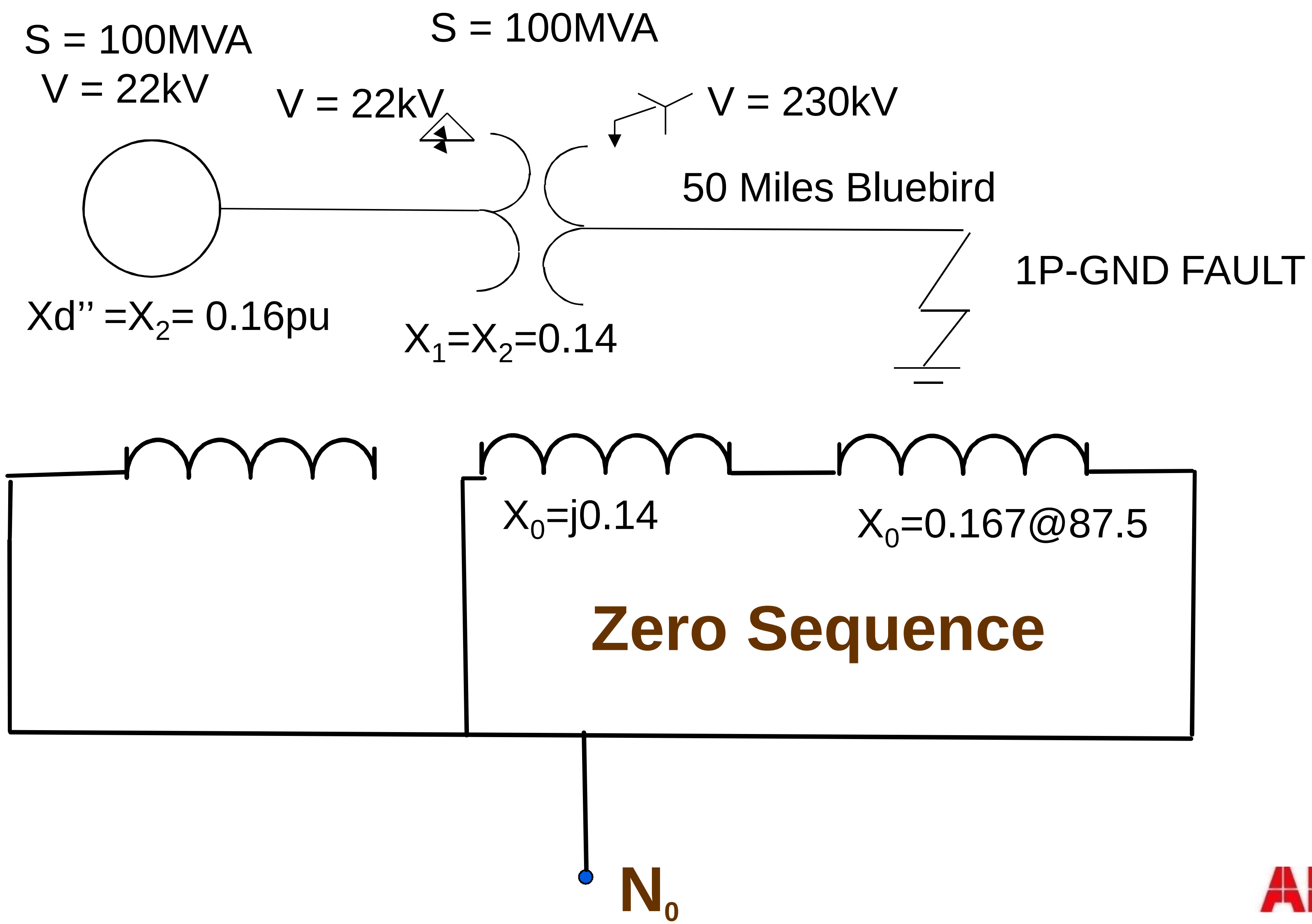
- Create Zero Sequence, For Simplicity Assume Z0 = 3 x Z1 for Transmission Line
- Zero Sequence configuration for a transformer that is delta grounded wye is shown once again below.
- Remembering this we Can Draw the Zero Sequence network for this problem



Example Problem

Find:

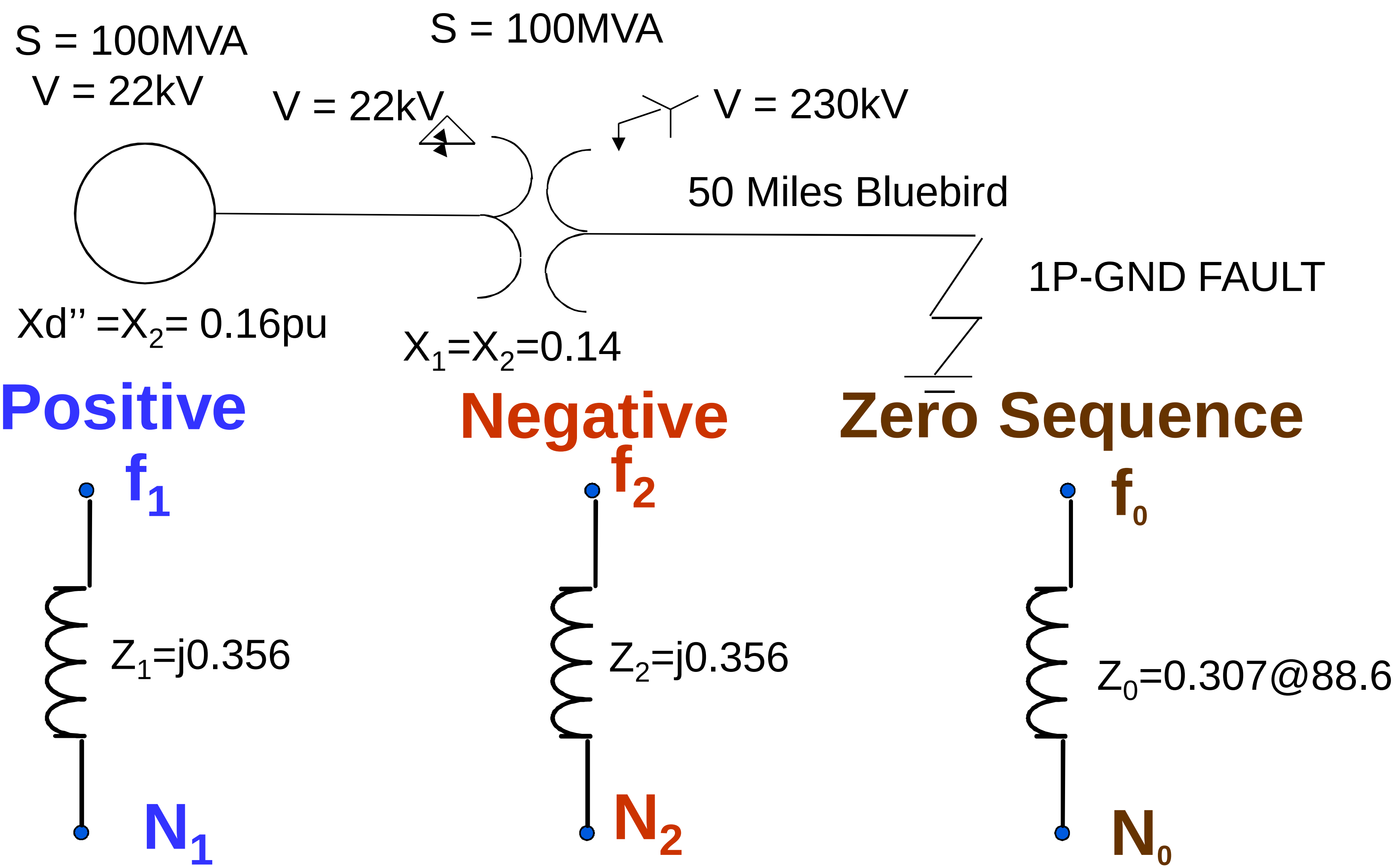
The fault current in Phase a, b, and c in pu and primary values



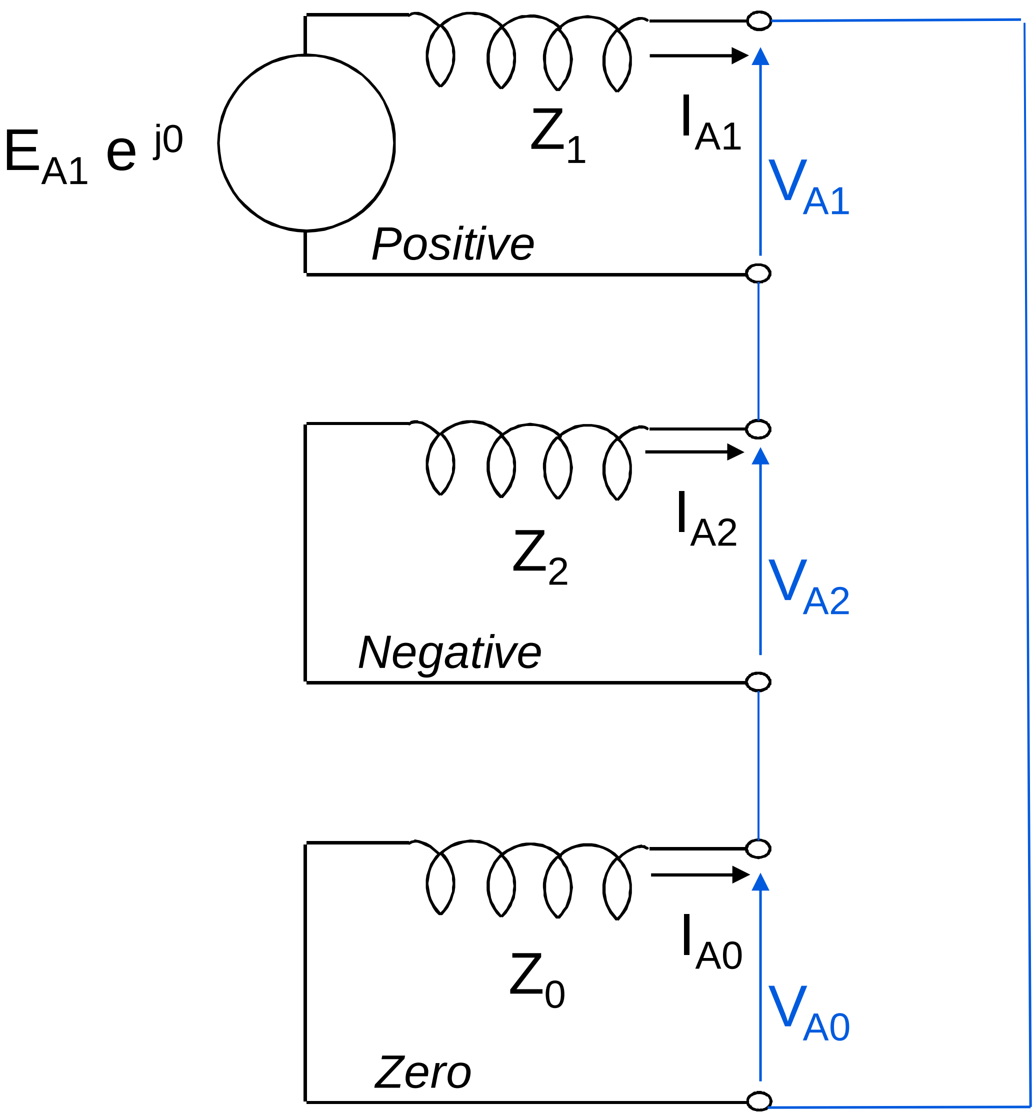
Example Problem

Find:

The fault current in Phase a, b, and c in pu and primary values



Example Problem



$$I_{PU} = \frac{V_{PU}}{Z_{PU}} = \frac{1\angle 0^\circ}{j0.356 + j0.356 + 0.307\angle 88.7^\circ}$$

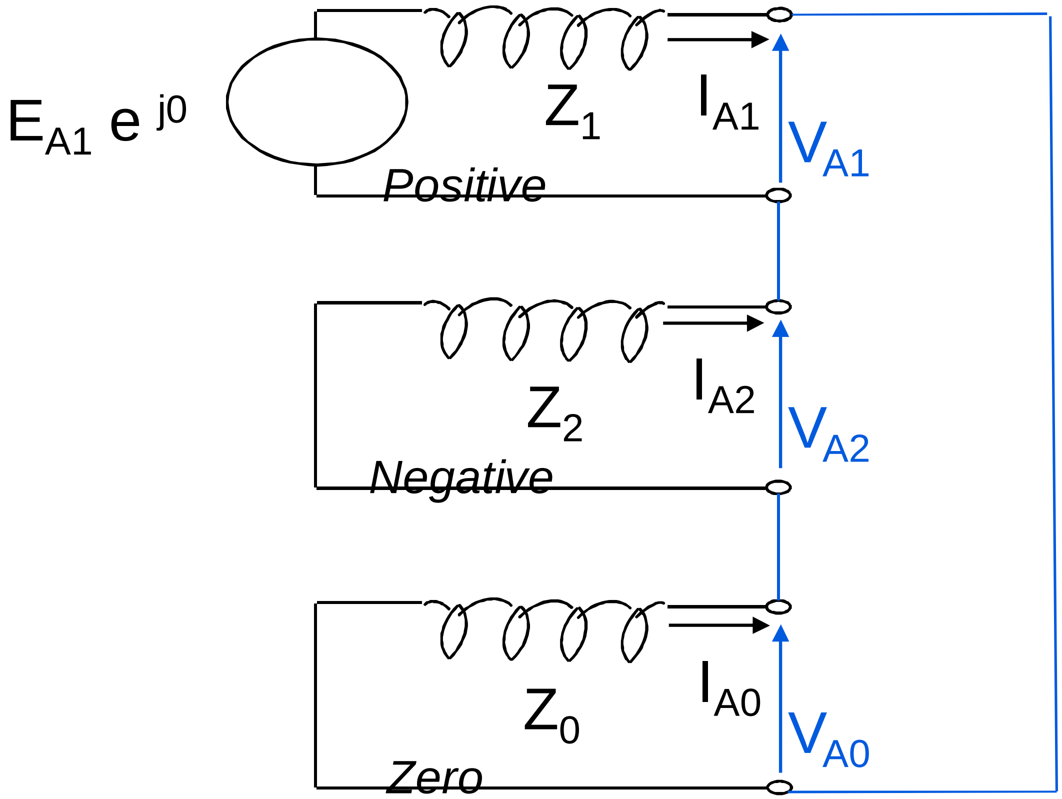
$$I_{PU} = 1\angle -89.6^\circ \; pu$$

$$\mathbf{[I_P] = [A][I_S]}$$

$$\mathbf{[I_P]} = \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix} \begin{pmatrix} -j1 \\ -j1 \\ -j1 \end{pmatrix}$$

$$\mathbf{[I_P]} = \begin{array}{c} \begin{pmatrix} -j3 \\ 0 \\ 0 \end{pmatrix} \end{array} \begin{array}{c} A \\ B \\ C \end{array} \quad pu$$

Example Problem



$$I_{BASE} = \frac{S_{BASE}}{\sqrt{3}V_{BASE}} = \frac{100x10^6}{\sqrt{3}x230x10^3} = 251A$$

$$\begin{array}{cc} & \\ [\mathbf{I_P}] = \begin{pmatrix} -j753A \\ 0 \\ 0 \end{pmatrix} & \begin{array}{c} A \\ B \\ C \end{array} \end{array} \quad \text{Actual}$$

The phase voltages at the point of the fault

$$\begin{pmatrix} V_0 \\ V_1 \\ V_2 \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} - \begin{pmatrix} j0.307 & 0 & 0 \\ 0 & j0.356 & 0 \\ 0 & 0 & j0.356 \end{pmatrix} \begin{pmatrix} -j1 \\ -j1 \\ -j1 \end{pmatrix} = \begin{pmatrix} -0.307 \\ 0.644 \\ -0.356 \end{pmatrix}$$

Example Problem

The phase voltages at the point of the fault

$$\begin{pmatrix} V_0 \\ V_1 \\ V_2 \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} - \begin{pmatrix} j0.307 & 0 & 0 \\ 0 & j0.356 & 0 \\ 0 & 0 & j0.356 \end{pmatrix} \begin{pmatrix} -j1 \\ -j1 \\ -j1 \end{pmatrix} = \begin{pmatrix} -0.307 \\ 0.644 \\ -0.356 \end{pmatrix}$$

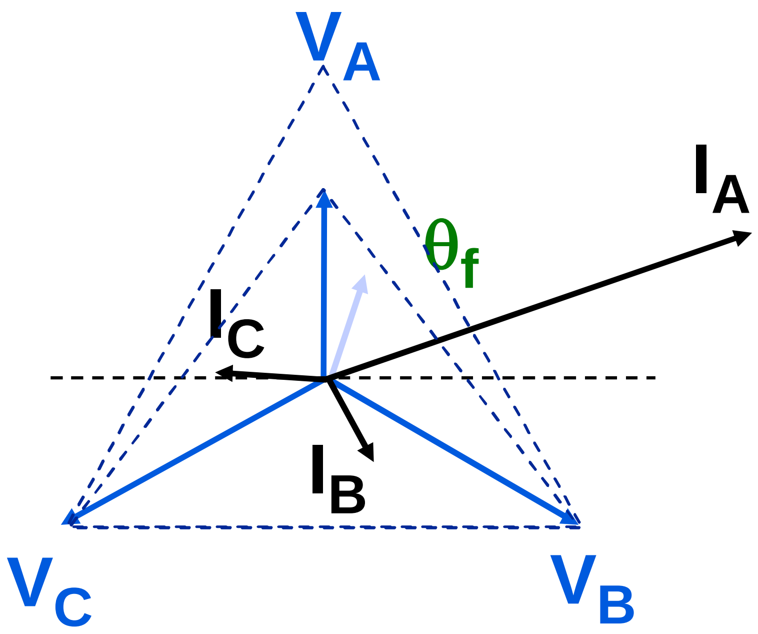
$$\mathbf{[V_P] = [A][V_S]}$$

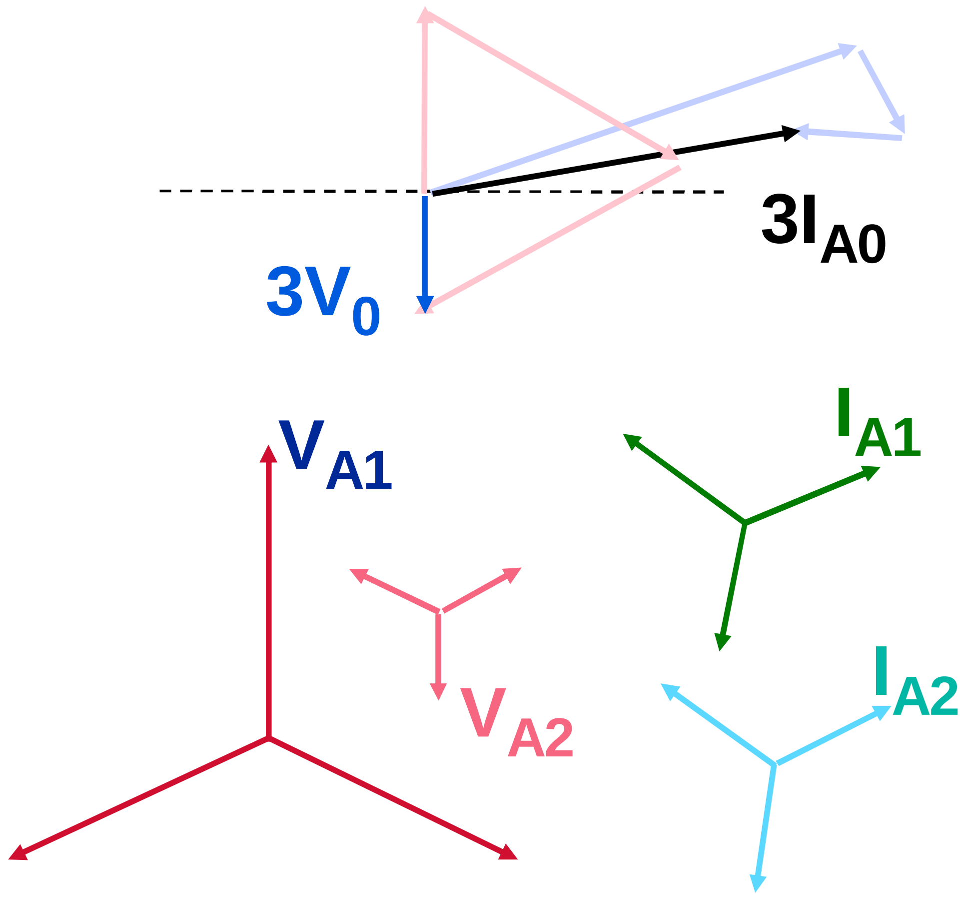
$$\mathbf{[V_P]} = \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix} \begin{pmatrix} -0.307 \\ 0.644 \\ -0.356 \end{pmatrix} = \begin{pmatrix} 0 \\ 0.976@-117.5 \\ 0.976@117.5 \end{pmatrix} \quad \text{pu}$$

$$V_{PHASE} = V_{BASE} \times V_{PU}$$

$$\mathbf{[V_P]} = \begin{pmatrix} 0 \\ 224.5@-87.5 \text{ kV} \\ 224.5@147.5 \text{ kV} \end{pmatrix} \begin{matrix} \text{A} \\ \text{B} \\ \text{C} \end{matrix} \quad \text{Actual}$$

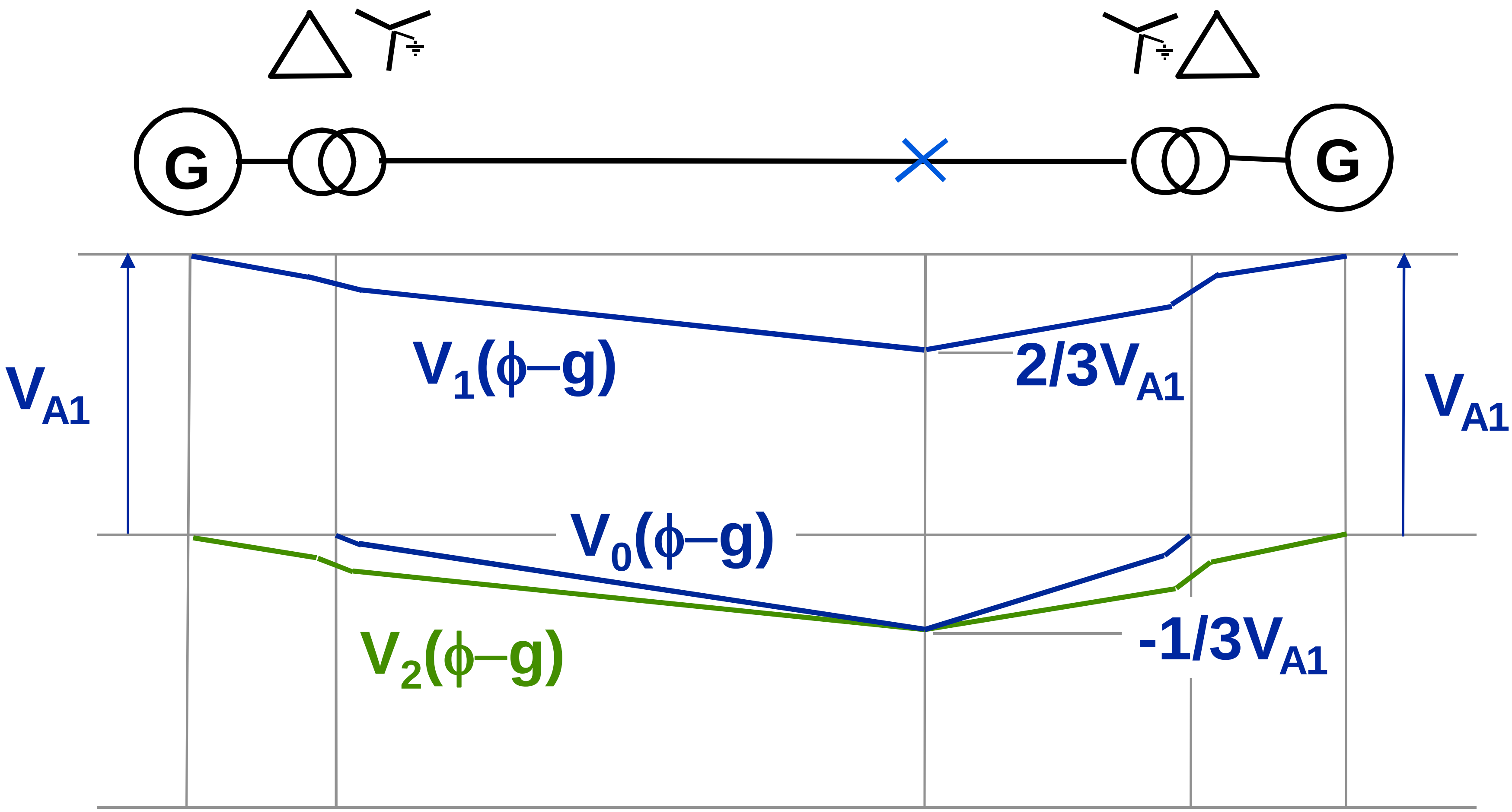
Phase-to-ground Fault





Phase Quantities **Symmetrical Components**

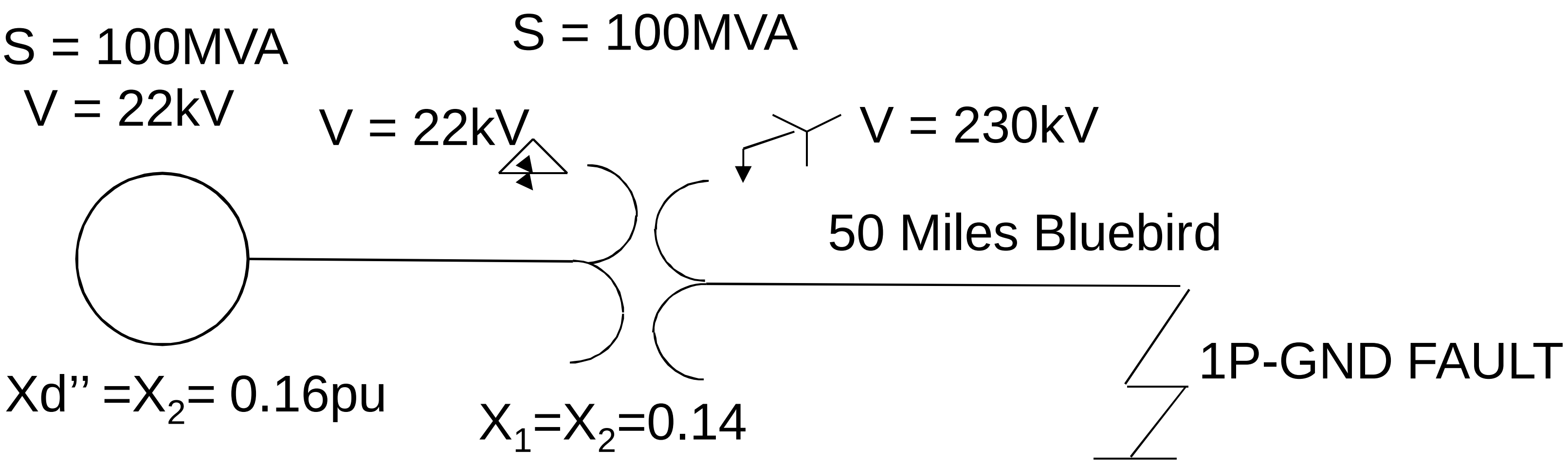
Phase-to-ground Fault Voltage Profile



These magnitudes assume $Z_1 = Z_2 = Z_0$

Example Problem

The fault current in Phase a, b, and c in pu and primary current on 22kV side



Found Earlier our phase and sequence quantities in pu on the 230kV side of Transformer

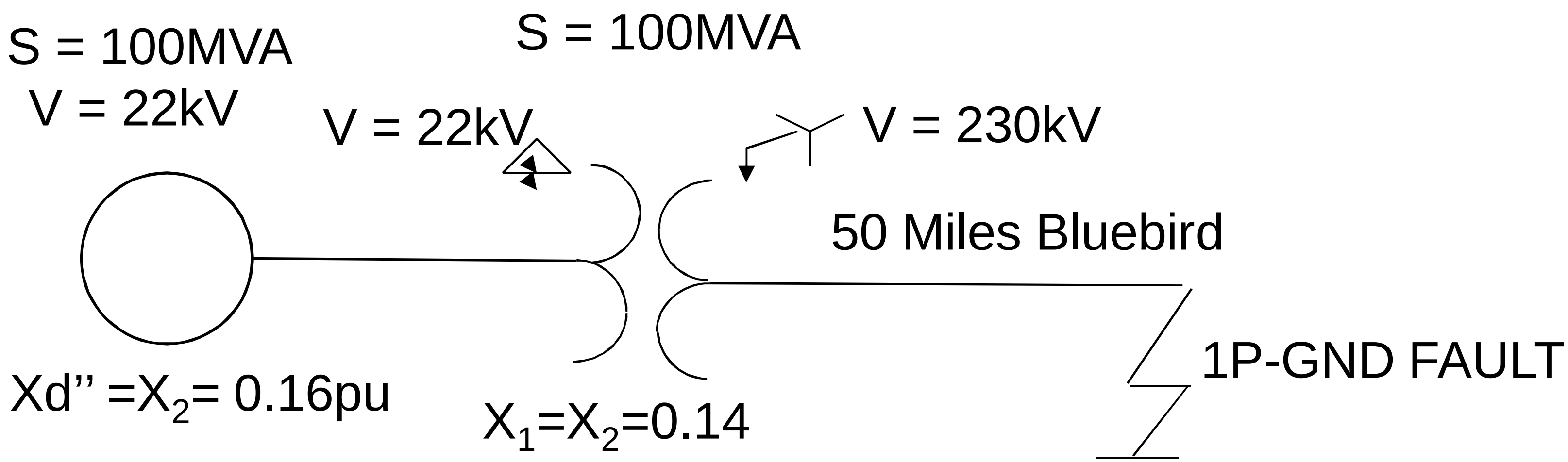
$$[\mathbf{I_P}] = [\mathbf{A}][\mathbf{I_S}]$$

$$[\mathbf{I_{Sprimary}}] = \begin{array}{cl} \left(\begin{matrix} -j1 \\ -j1 \\ -j1 \end{matrix}\right) & \begin{matrix} \text{Zero} \\ \text{Positive} \\ \text{Negative} \end{matrix} \end{array}$$

Knowing this information we can find Phase currents on the 22kV side of Transformer

Example Problem

The fault current in Phase a, b, and c in pu and primary current on 22kV side



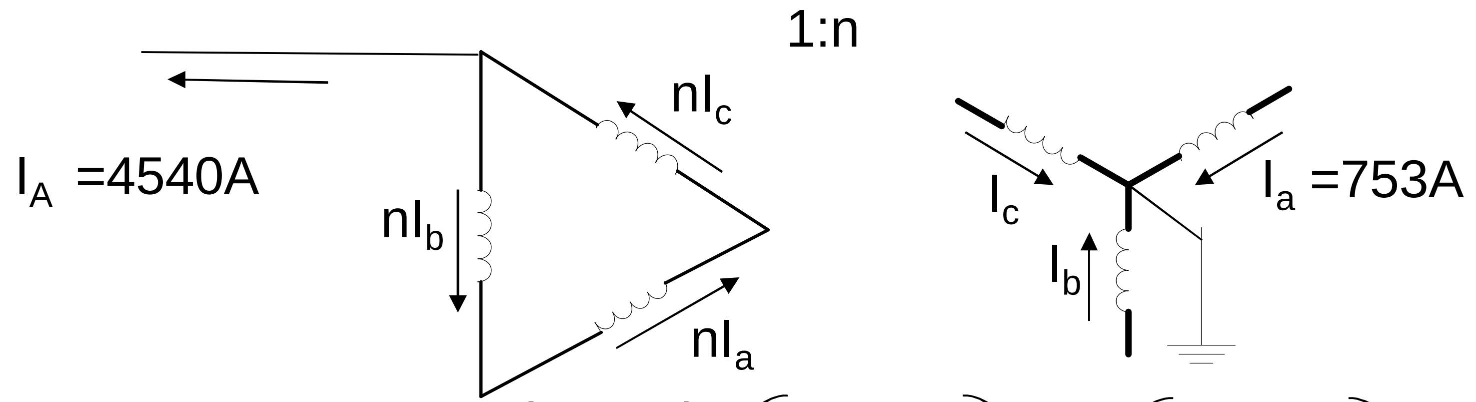
Looking back Zero Sequence current has no path to flow on the 22kV side

$$[\mathbf{I}_{\mathbf{Ssecondary}}] = \begin{array}{l} \begin{pmatrix} 0 \\ 1@\text{-}120 \\ 1@\text{-}60 \end{pmatrix} \end{array} \begin{array}{l} \text{Zero} \\ \text{Positive} \\ \text{Negative} \end{array}$$

How do these differ from currents on the 230kV side?

Example Problem

The fault current in Phase a, b, and c in pu and primary current on 22kV side



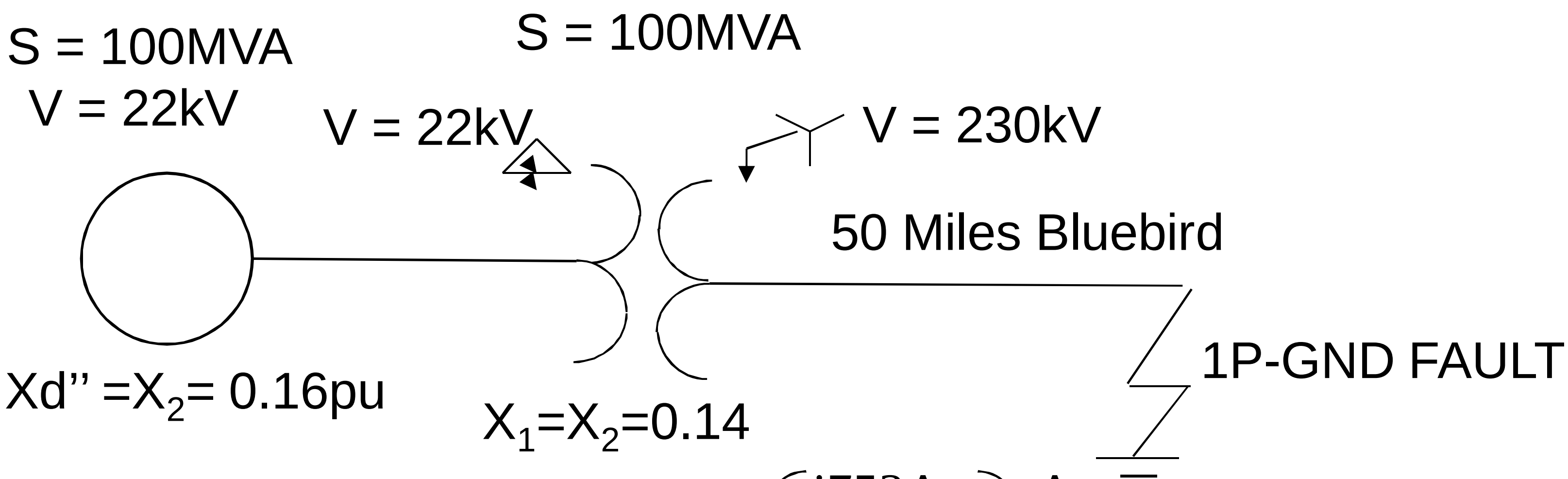
$$[\mathbf{I_{Psecondary}}] = \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix} \begin{pmatrix} 0 \\ 1@\text{-}120 \\ 1@\text{-}60 \end{pmatrix} = \begin{pmatrix} 1.73@\text{-}90 \\ 1.73@90 \\ 0 \end{pmatrix} \quad \text{pu}$$

$$I_{\text{sec\_}act} = \frac{753x\dfrac{220kV}{22kV}}{\sqrt{3}} = 4540 \qquad I_{base} = \frac{S_{BASE}}{\sqrt{3}xV_{BASE}} = \frac{100x10^6}{\sqrt{3}x22x10^3} = 2624A$$

$$[\mathbf{I_{Psecondary}}] = \begin{pmatrix} -j4540A \\ j4540A \\ 0 \end{pmatrix} \begin{matrix} A \\ B \\ C \end{matrix} \quad \text{Actual}$$

Example Problem

The fault current in Phase a, b, and c in pu and primary current on 22kV side

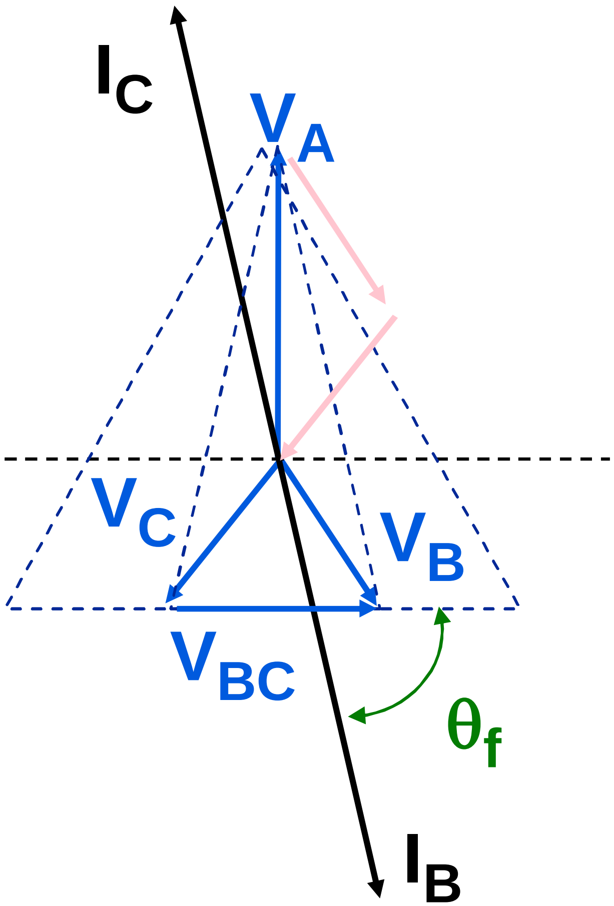


$$[\mathbf{I}_{\mathbf{Pprimary}}] = \begin{array}{c|c} \begin{pmatrix} -j753A \\ 0 \\ 0 \end{pmatrix} & \begin{array}{c} A \\ B \\ C \end{array} \end{array} \quad \text{Actual}$$

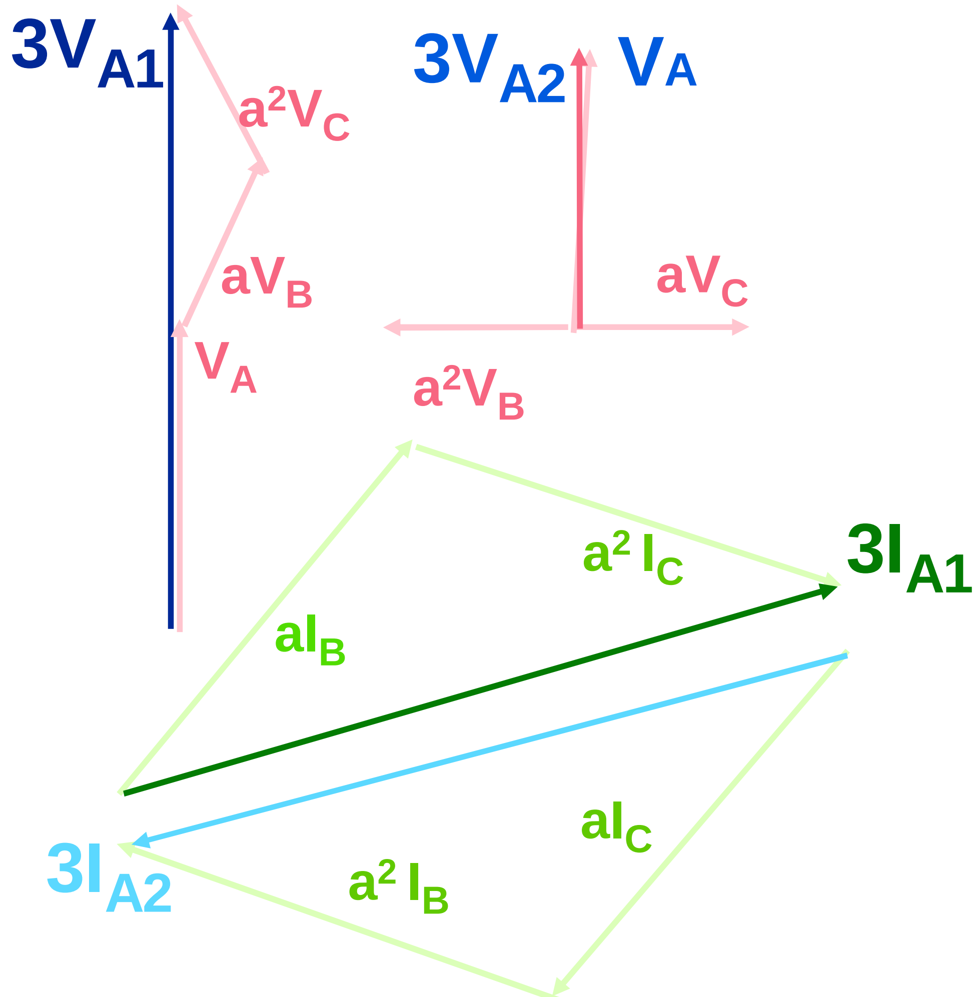
$$[\mathbf{I}_{\mathbf{Psecondary}}] = \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix} \begin{pmatrix} 0 \\ 1@\text{-}120 \\ 1@\text{-}60 \end{pmatrix} = \begin{pmatrix} 4540@\text{-}90 \\ 4540@90 \\ 0 \end{pmatrix} \quad \text{Actual}$$

What has this taught us?

Phase-to-phase Fault

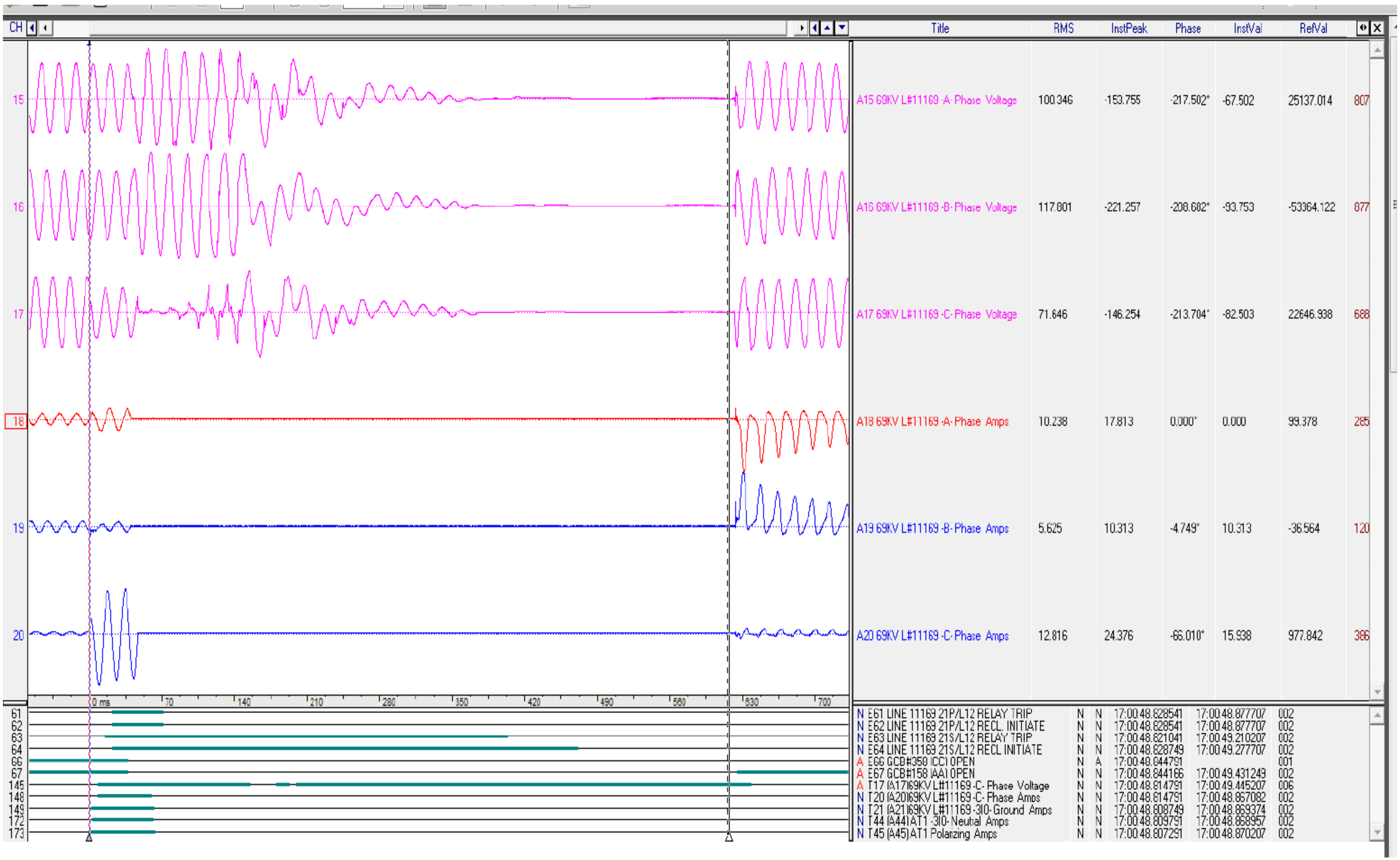


Phase Quantities



Symmetrical Components

Waveforms from SLG fault



Symmetrical Components Learned Objectives

- What we will discuss
  - Overview of converting phase quantities to symmetrical quantities and symmetrical to phase
  - Sequence Impedance networks – How do we build one?
  - Evaluating a Impedance network – Example Problem
  - Insights into the Example Problem
- Why do we use this method?
  - Not using it would require writing loop equations for the system and solving. – For simple systems it's not an easy task
  - To date it is still the only real practical solution to problems of unbalanced electrical circuits.

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