# Symmetrical Components

IEEE PES Boston Chapter

Protection Engineering Course Series
Fall 2013

Instructor: Dean V. Sorensen (National Grid)

# Symmetrical Components
# Discussion Topics

- History and Description
- The General Method of Symmetrical Components
  - N-Phase Systems
  - 3-Phase Systems
- Circuit Element Sequence Representations
- Fault Analysis Using Symmetrical Components

---

[1] J. Lewis Blackburn and Thomas J. Domin, *Protective Relaying Principles and Applications*, 3rd Ed., CRC Press, 2007

.

[2] John, A Horak, Derivation of Symmetrical Component Theory and Symmetrical Component Networks, Georgia Tech protective Relaying Conference, Atlanta, GA, April 2005, http://www.basler.com/downloads/Symmcomp.pdf

# Symmetrical Components – History and Description

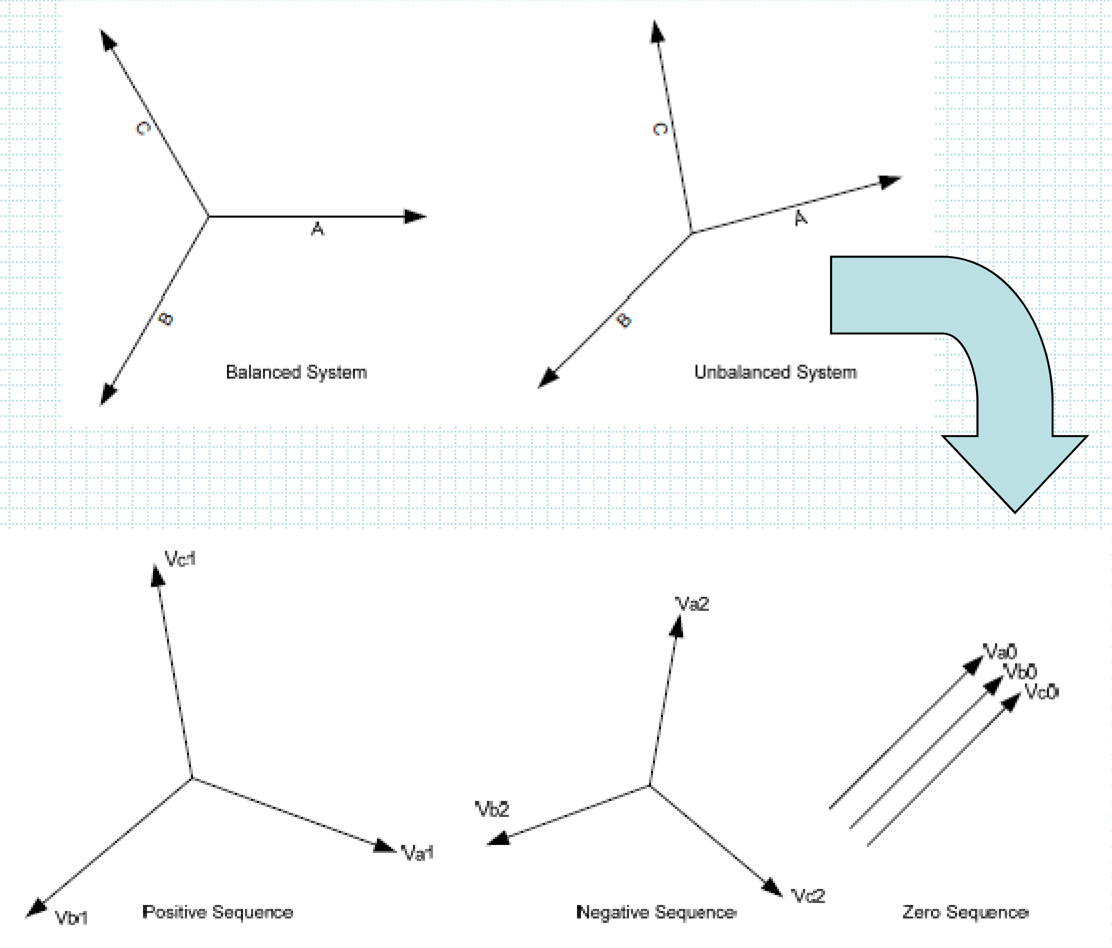
- The method of symmetrical components provides a tool to study systems with unbalanced phasors.
- Developed by Charles Fortescue in 1913, who presented a paper entitled' "Method of Symmetrical Co-ordinates Applied to the Solution of Polyphase Networks."[3]
- In mathematics terms, it is a linear transformation[4] mapping quantities (ABC) from a physical domain into quantities (012) in a sequence domain.
- Simplifies circuit analysis of a three-phase mutually coupled circuit by transforming it into 3 single phase circuits with no mutual coupling.

---

[3] Fortescue's paper is available at http://thunderbox.uwaterloo.ca/~ccanizar/papers/classical/Fortescue.pdf from the University of Waterloo.

[4] Rowland, Todd and Weisstein, Eric W. "Linear Transformation." From *MathWorld*—A Wolfram Web Resource http://mathworld.wolfram.com/LinearTransformation.html

# A Tool for Simplifying Fault Analysis



- A balanced system is easily analyzed because only one phase needs to be considered.
- Unbalanced systems require a full circuit analysis of all three phases, neutral and ground elements.
- Therefore transforming an unbalanced system into balanced systems promises to simplify our analysis

# The General Method of Symmetrical Components

- The use of symmetrical components for three-phase power system analysis is a subset of a more general transformation method. The general method resolves ***N*** unbalanced phasors which share the same reference plane into ***N*** sets of balanced phasors, each of which has ***N*** members.

- Within each set, each of the phasors has the same magnitude and successive phases have the same phase angle separation between them.

- Let ***α*** be the angle between phases in an ***N***-phase system. Then let's define a useful operator dubbed the "***a***" operator. The "***a***" operator is a unit phasor (magnitude = 1) with an angle equal to ***α***. Multiplying a phasor by ***a*** simply rotates that phasor by ***α*** degrees in the **counterclockwise** direction.

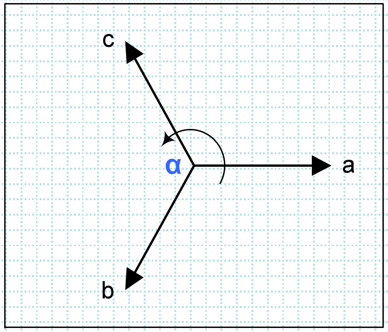
$$\alpha = \frac{360^\circ}{N} \qquad\qquad a = 1\angle\alpha$$

***Rotation operator***

- Within each sequence network, the angular displacement of successive phasors is ***-α·n*** where ***n*** is the phase sequence network number and where ***n = 0, 1, 2, …N-1***.

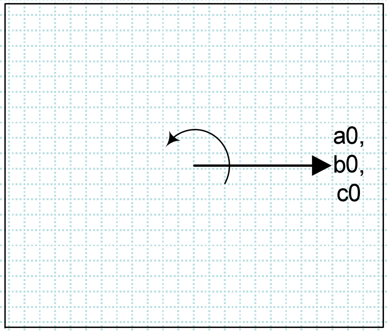
# 3-Phase System Example

Physical System

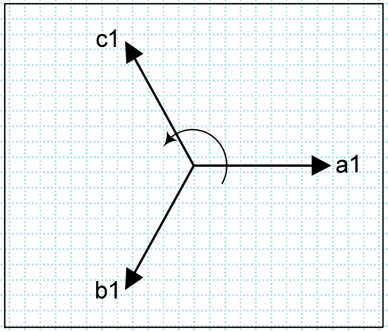


N = 3
n = 0, 1, 2, …N-1
α = 120 deg

Seq #0 System (Zero Seq)

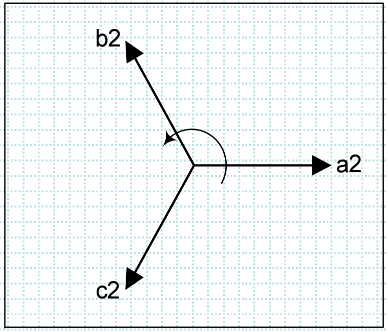


Seq #1 System (Pos Seq)



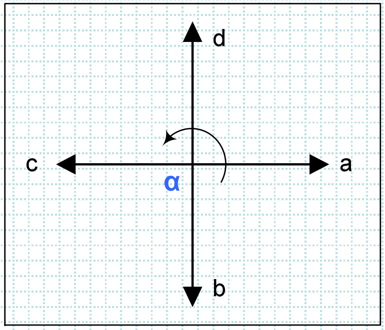
**Note:** All system rotation, even “negative-sequence” phasors, is counterclockwise!

Seq #2 System (Neg Seq)

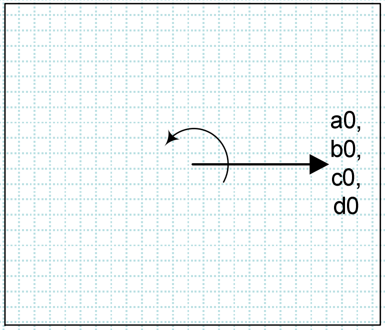


# 4-Phase System Example

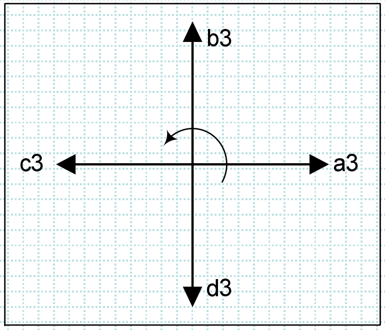
**Physical System**



**Seq #0 System**

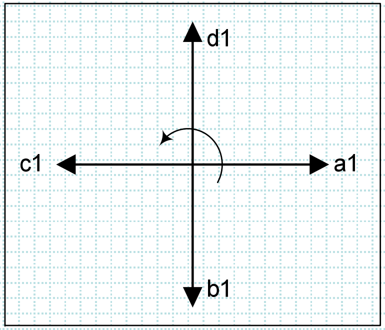


**Seq #3 System**

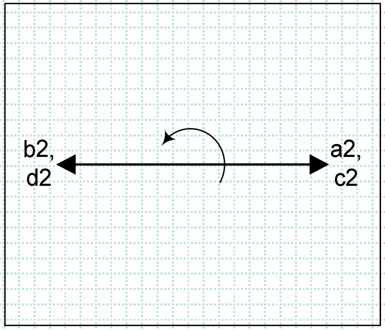


**N = 4**
**n = 0, 1, 2, …N-1**
**α = 90 deg**

**Seq #1 System**

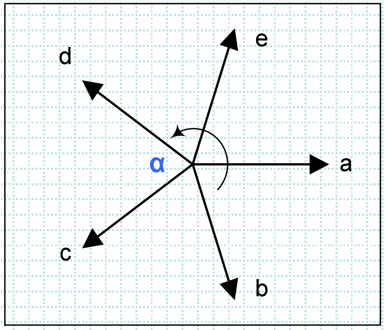


**Seq #2 System**



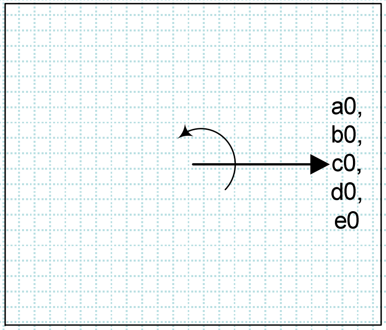
# 5-Phase System Example

Physical System

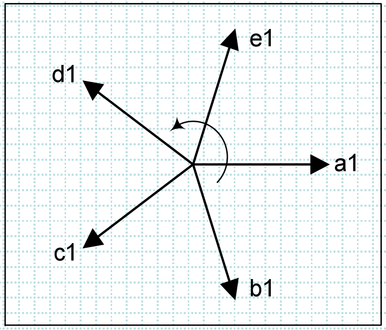


N = 5
n = 0, 1, 2, …N-1
α = 72 deg

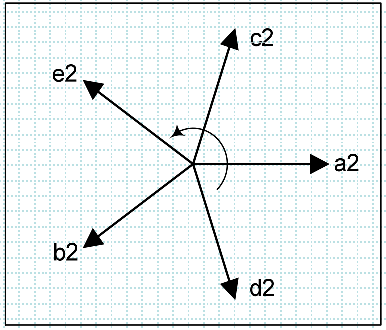
Seq #0 System



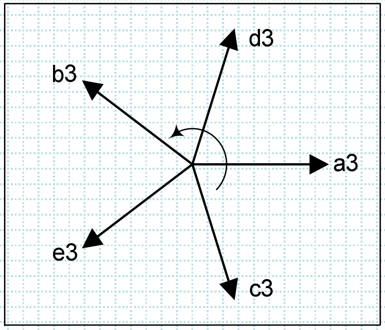
Seq #1 System



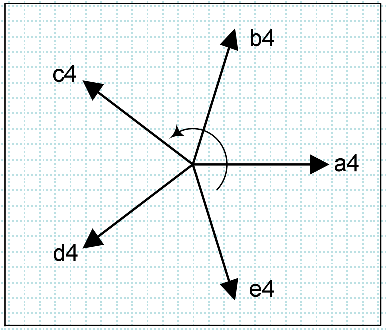
Seq #2 System



Seq #3 System

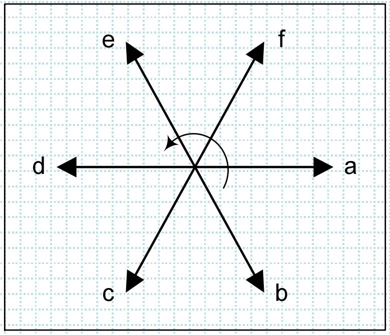


Seq #4 System



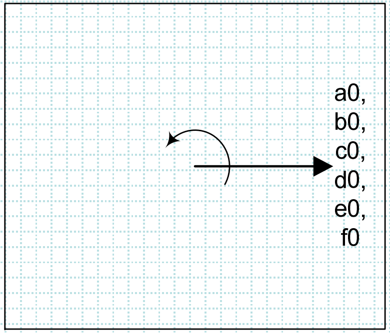
# 6-Phase System Example

**Physical System**

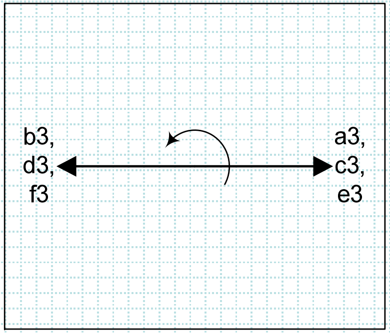


**N = 6**
**n = 0, 1, 2, …N-1**
**$\alpha$ = 60 deg**

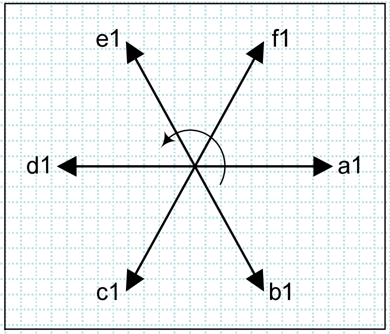
**Seq #0 System**



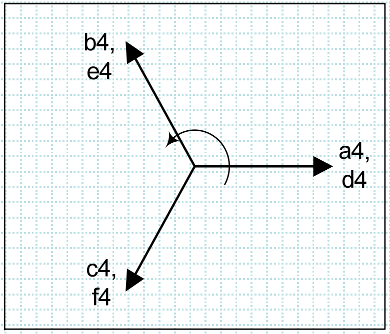
**Seq #3 System**



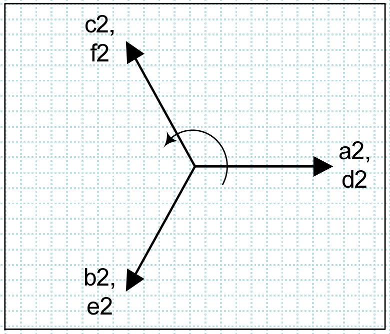
**Seq #1 System**



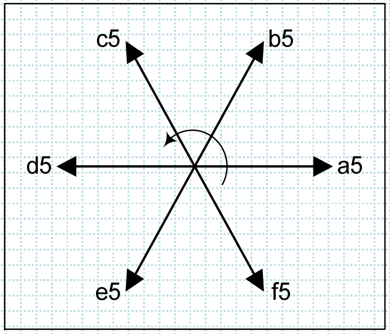
**Seq #4 System**



**Seq #2 System**



**Seq #5 System**



## Trivia Factoid:

When N is prime, each set where n>0 will form a regular N-sided polygon. Consider n=0 as being a 1-sided polygon. For N=6, prime factors are 1, 2, 3 and 6. Can you find a 1-sided, 2-sided, 3-sided and 6-sided polygon among these sets? Try this for any value of N.

A more detailed fault analysis and development of 6-phase sequence network applications can be found in the following paper:

[5] *Bhatt, Navin B., Six-Phase (Multi-Phase) Power Transmission Systems: Fault Analysis, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-96, No. 3, May/June 1977, http://www.libsou.com/pdf/01601991.pdf*

# Back to the 3-Phase System Example

We can relate physical domain quantities to sequence domain quantities by superposition.

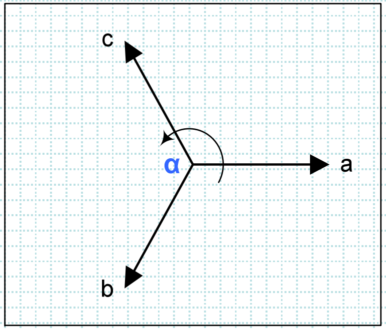
$$V_a = V_{a0} + V_{a1} + V_{a2}$$
$$V_b = V_{b0} + V_{b1} + V_{b2}$$
$$V_c = V_{c0} + V_{c1} + V_{c2}$$

This transforms 3 quantities into a total of 9 quantities. Simplified?

We can then define quantities *V0*, *V1* and *V2* in the sequence domain using a-phase (or specifically Va) as a reference and along with the “a” operator substitute the new “sequence” quantities into b and c-phases.

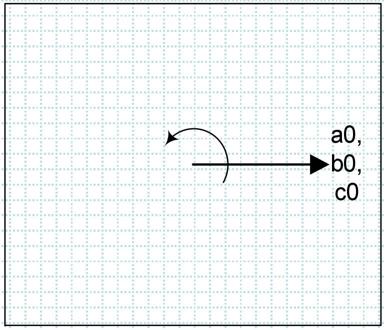
$$V_0 = V_{a0} \qquad V_a = V_0 + V_1 + V_2$$
$$V_1 = V_{a1} \quad \Rightarrow \quad V_b = V_0 + a^2 V_1 + a V_2$$
$$V_2 = V_{a2} \qquad V_c = V_0 + a V_1 + a^2 V_2$$

**Physical System**

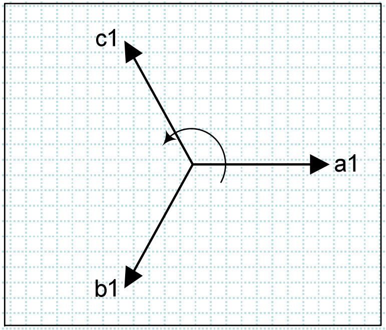


**N = 3**
**n = 0, 1, 2, …N-1**
**α = 120 deg**

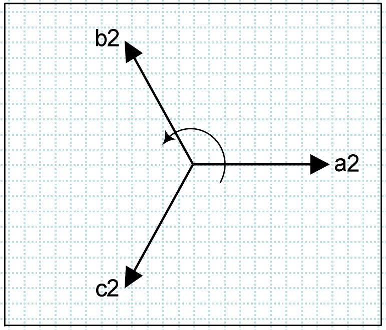
**Seq #0 System (Zero Seq)**



**Seq #1 System (Pos Seq)**



**Seq #2 System (Neg Seq)**



# 3-Phase System Example Using Matrix Notation

Expressing the transformation in matrix notation makes the transformation format easier to remember.

$$\begin{aligned} V_a &= V_0 + V_1 + V_2 \\ V_b &= V_0 + a^2 V_1 + a V_2 \\ V_c &= V_0 + a V_1 + a^2 V_2 \end{aligned}$$

⇒

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \times \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix}$$

⇒

$$[V_{abc}] = [A] \times [V_{012}]$$

Matrix notation also lets us easily derive an inverse transform.

$$[V_{012}] = [A]^{-1} \times [V_{abc}]$$

⇒

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \times \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

# 3-Phase System Example Using Matrix Notation

Naturally, current phasors will have the same transformation form as voltage phasors.

$$\begin{aligned} I_a &= I_0 + I_1 + I_2 \\ I_b &= I_0 + a^2 I_1 + a I_2 \\ I_c &= I_0 + a I_1 + a^2 I_2 \end{aligned} \quad \Rightarrow \quad \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \times \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} \quad \Rightarrow \quad [I_{abc}] = [A] \times [I_{012}]$$

$$[I_{012}] = [A]^{-1} \times [I_{abc}] \quad \Rightarrow \quad \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \times \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

# Symmetrical Component Transformation
# Worked Example

**Example 7.1**

Given $V_a = 5\angle 53^o$, $V_b = 7\angle -164^o$, $V_c = 7\angle 105^o$, find the symmetrical components. The phase components are shown in the phasor form in Fig. 7.3

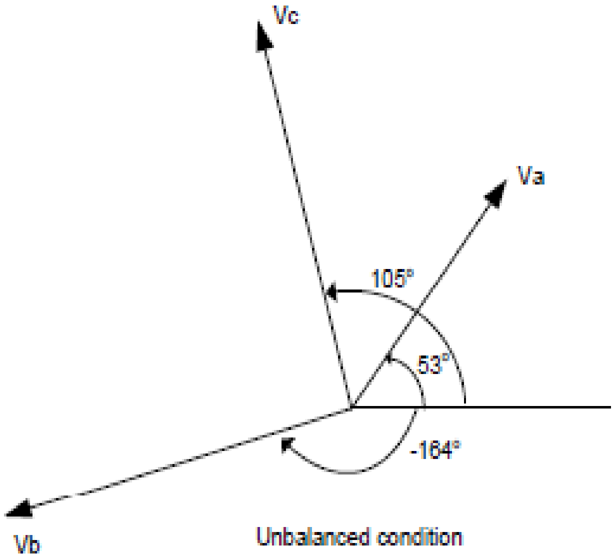
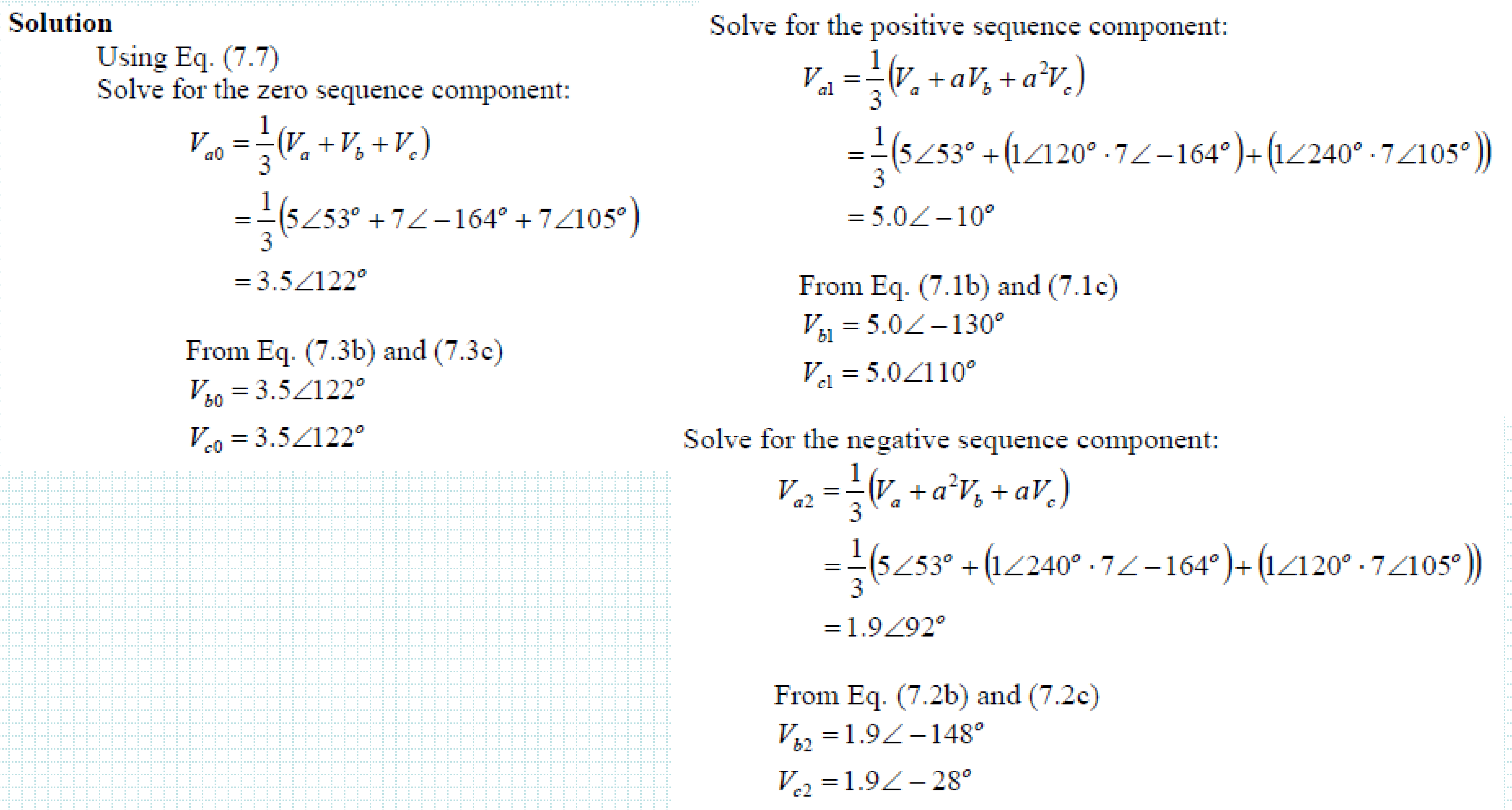


Fig. 7.3

[6] *This example is from Washington State University's March 2011 Hands-On Relay School*

# Symmetrical Component Transformation Worked Example (Continued)



**Solution**

Using Eq. (7.7)

Solve for the zero sequence component:

$$V_{a0} = \frac{1}{3}(V_a + V_b + V_c)$$

$$= \frac{1}{3}(5\angle 53^o + 7\angle -164^o + 7\angle 105^o)$$

$$= 3.5\angle 122^o$$

From Eq. (7.3b) and (7.3c)

$$V_{b0} = 3.5\angle 122^o$$

$$V_{c0} = 3.5\angle 122^o$$

Solve for the positive sequence component:

$$V_{a1} = \frac{1}{3}(V_a + aV_b + a^2V_c)$$

$$= \frac{1}{3}\left(5\angle 53^o + (1\angle 120^o \cdot 7\angle -164^o) + (1\angle 240^o \cdot 7\angle 105^o)\right)$$

$$= 5.0\angle -10^o$$

From Eq. (7.1b) and (7.1c)

$$V_{b1} = 5.0\angle -130^o$$

$$V_{c1} = 5.0\angle 110^o$$

Solve for the negative sequence component:

$$V_{a2} = \frac{1}{3}(V_a + a^2V_b + aV_c)$$

$$= \frac{1}{3}\left(5\angle 53^o + (1\angle 240^o \cdot 7\angle -164^o) + (1\angle 120^o \cdot 7\angle 105^o)\right)$$

$$= 1.9\angle 92^o$$

From Eq. (7.2b) and (7.2c)

$$V_{b2} = 1.9\angle -148^o$$

$$V_{c2} = 1.9\angle -28^o$$

*This example is from Washington State University's March 2011 Hands-On Relay School*

# Symmetrical Component Transformation Worked Example (Continued)

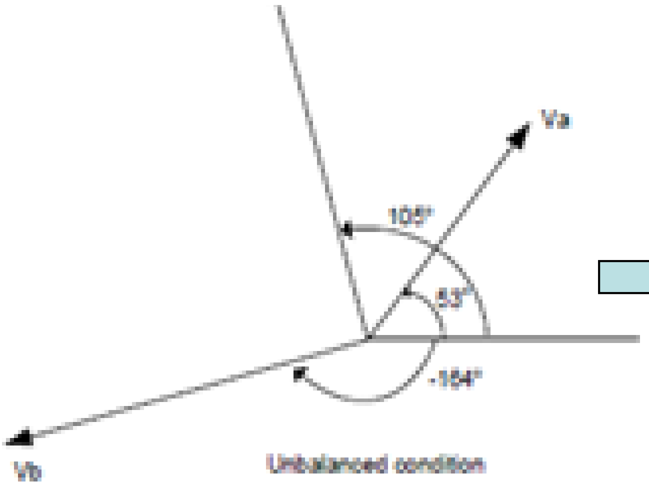


Fig. 7.3

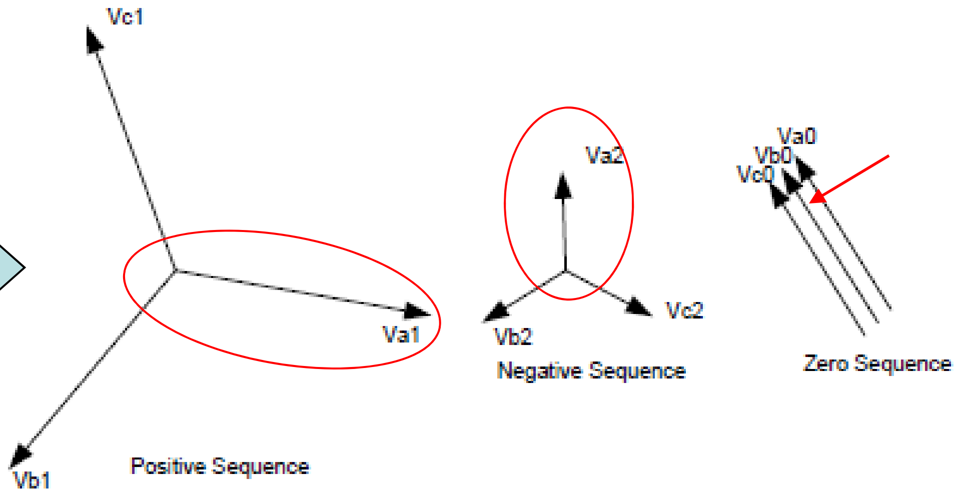
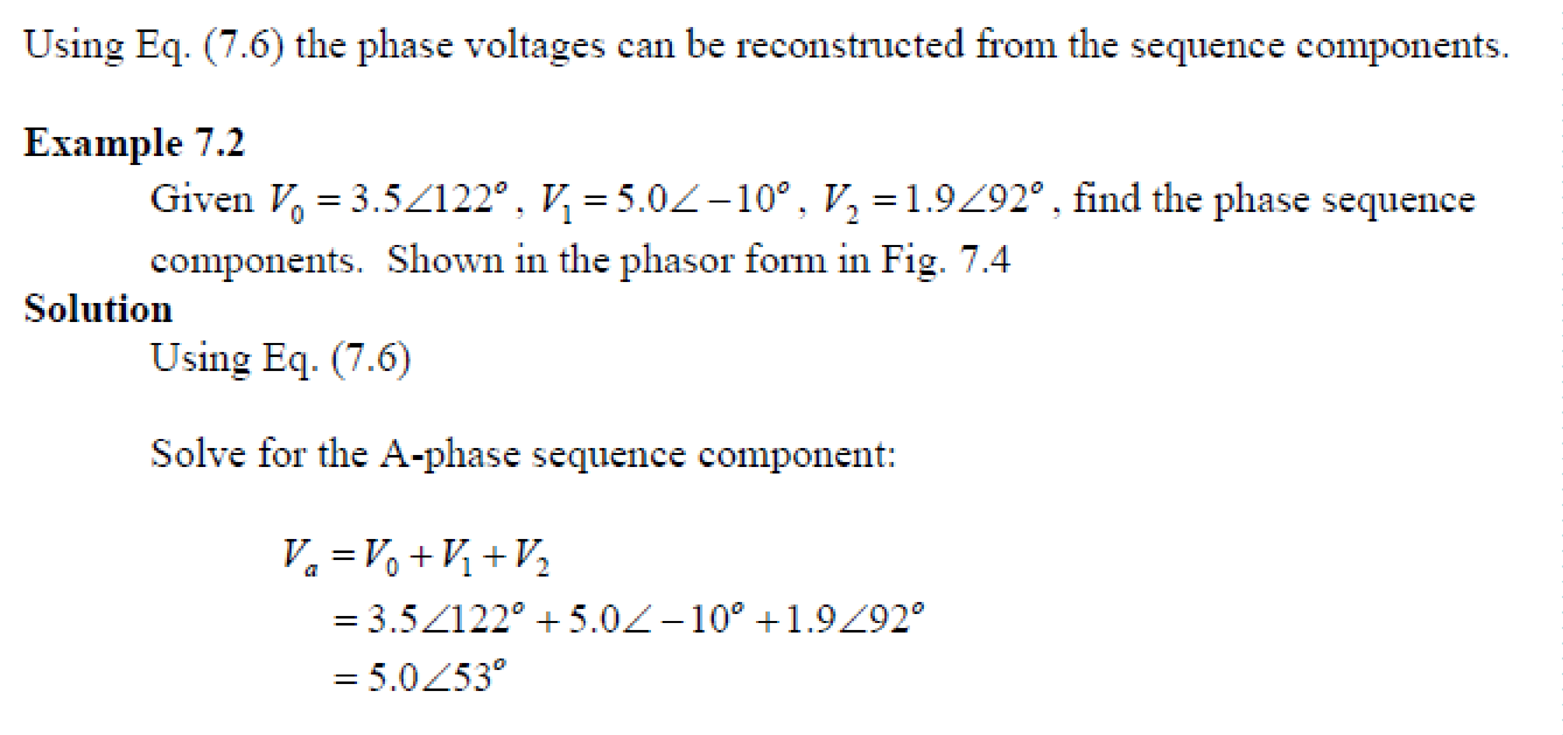


Fig. 7.4

*This example is from Washington State University's March 2011 Hands-On Relay School*

# Symmetrical Component Transformation Worked Example (Continued)



Using Eq. (7.6) the phase voltages can be reconstructed from the sequence components.

**Example 7.2**

Given $V_0 = 3.5\angle 122^o$, $V_1 = 5.0\angle -10^o$, $V_2 = 1.9\angle 92^o$, find the phase sequence components. Shown in the phasor form in Fig. 7.4

**Solution**

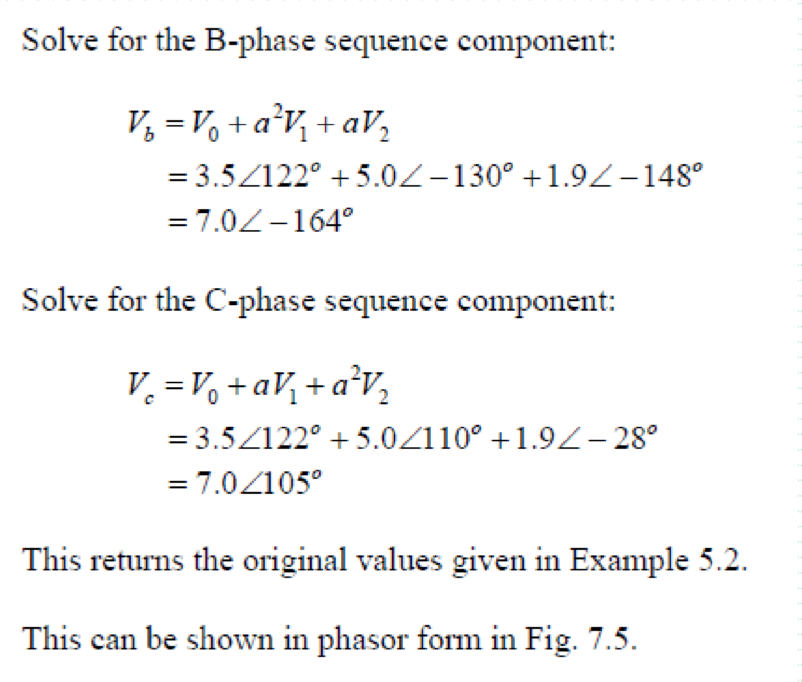
Using Eq. (7.6)

Solve for the A-phase sequence component:

$$\begin{aligned} V_a &= V_0 + V_1 + V_2 \\ &= 3.5\angle 122^o + 5.0\angle -10^o + 1.9\angle 92^o \\ &= 5.0\angle 53^o \end{aligned}$$

*This example is from Washington State University's March 2011 Hands-On Relay School*

# Symmetrical Component Transformation Worked Example (Continued)



Solve for the B-phase sequence component:

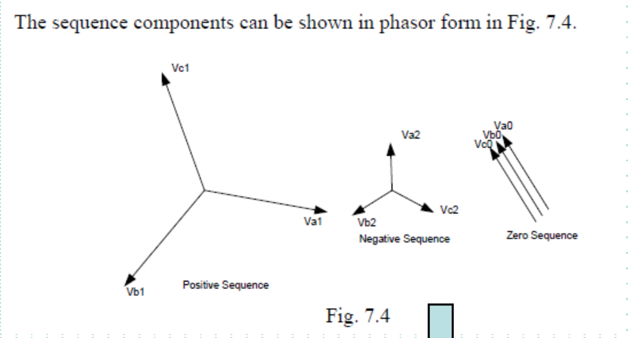
$$
\begin{aligned}
V_b &= V_0 + a^2V_1 + aV_2 \\
&= 3.5\angle 122^o + 5.0\angle -130^o + 1.9\angle -148^o \\
&= 7.0\angle -164^o
\end{aligned}
$$

Solve for the C-phase sequence component:

$$
\begin{aligned}
V_c &= V_0 + aV_1 + a^2V_2 \\
&= 3.5\angle 122^o + 5.0\angle 110^o + 1.9\angle -28^o \\
&= 7.0\angle 105^o
\end{aligned}
$$

This returns the original values given in Example 5.2.

This can be shown in phasor form in Fig. 7.5.



The sequence components can be shown in phasor form in Fig. 7.4.

Fig. 7.4

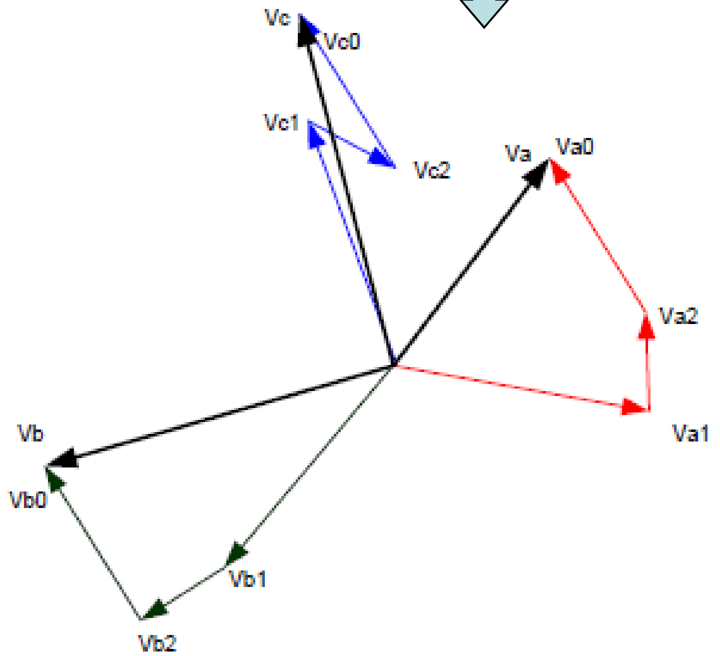
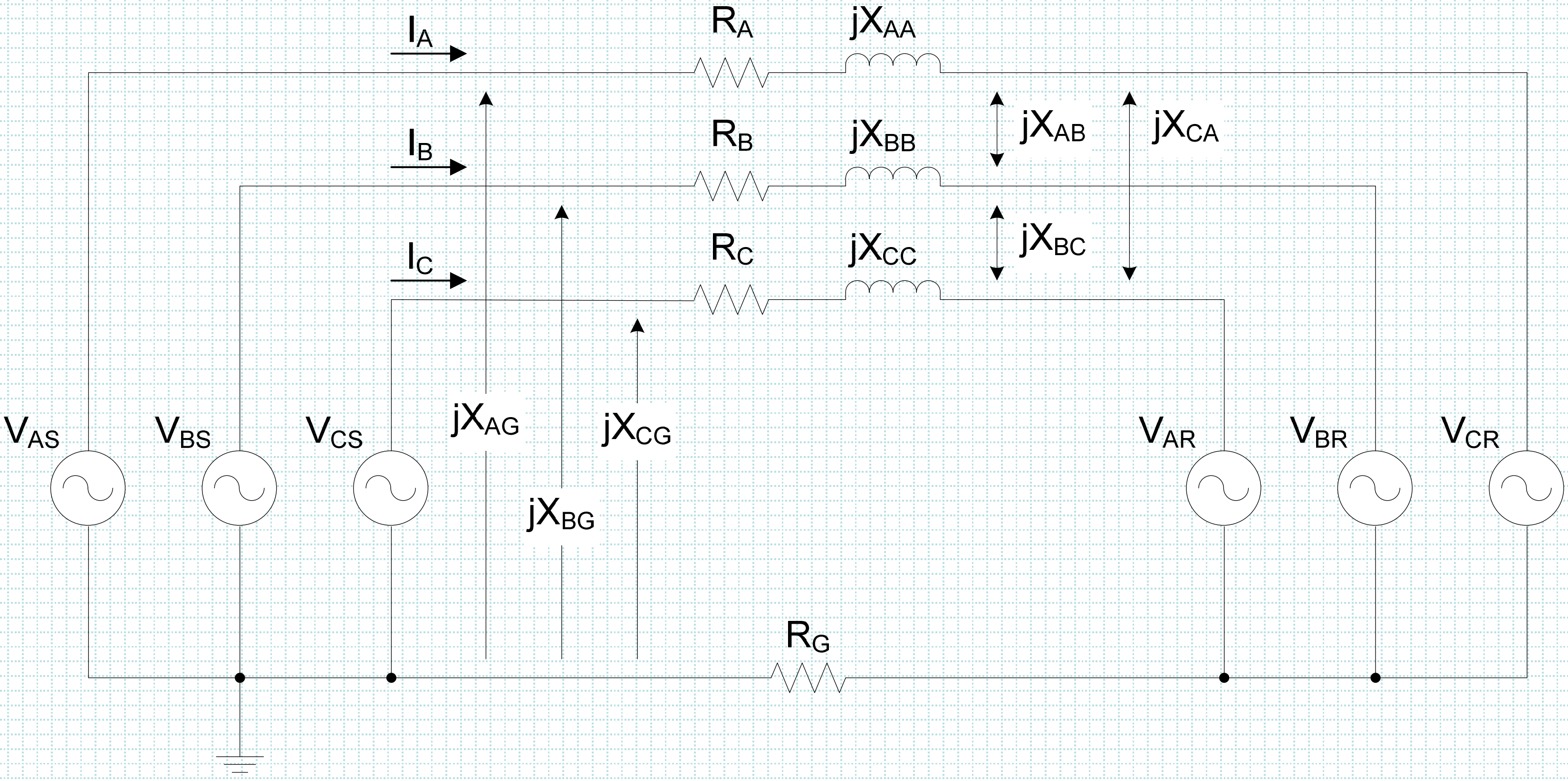


Fig. 7.5

*This example is from Washington State University's March 2011 Hands-On Relay School*

# Circuit Element Sequence Representations

# Circuit Element Sequence Representations
# 3-Phase System with Sending and Receiving End Voltages



# Circuit Element Sequence Representations
# Self Impedances

- The voltage drop equations in matrix form for our system are

$$\begin{bmatrix} V_{AS} \\ V_{BS} \\ V_{CS} \end{bmatrix} - \begin{bmatrix} V_{AR} \\ V_{BR} \\ V_{CR} \end{bmatrix} = \begin{bmatrix} Z_{AA} & Z_{AB} & Z_{AC} \\ Z_{BA} & Z_{BB} & Z_{BC} \\ Z_{CA} & Z_{CB} & Z_{CC} \end{bmatrix} \cdot \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix}$$

- Starting with KVL around the loop, the self impedance of loop A (i.e. the voltage drop in loop A resulting from the current in loop A) is

$$V_{AS} - V_{AR} = (R_A + R_G) I_A + j(X_{AA} + X_{AG}) I_A$$

$$Z_{AA} = \frac{V_{AS} - V_{AR}}{I_A} = (R_A + R_G) + j(X_{AA} + X_{AG})$$

- $Z_{BB}$ and $Z_{CC}$ in the impedance matrix are similarly defined.

# Circuit Element Sequence Representations
# Mutual Impedances

- Again, our voltage drop equations in matrix form are

$$\begin{bmatrix} V_{AS} \\ V_{BS} \\ V_{CS} \end{bmatrix} - \begin{bmatrix} V_{AR} \\ V_{BR} \\ V_{CR} \end{bmatrix} = \begin{bmatrix} Z_{AA} & Z_{AB} & Z_{AC} \\ Z_{BA} & Z_{BB} & Z_{BC} \\ Z_{CA} & Z_{CB} & Z_{CC} \end{bmatrix} \cdot \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix}$$

- The mutual impedance from Loop A to Loop B (i.e. the voltage drop in loop A resulting from the current in Loop B) is

$$Z_{AB} = \frac{V_{AS} - V_{AR}}{I_B} = R_G + j\left(X_{AB} + \boxed{X_{AG}}\right)$$

- The $X_{AG}$ term might look like a typo but recall the following for flux linkage in Phase A:

$$\phi_A = L_{AA} i_A(t) + L_{AB} i_B(t) + L_{AC} i_C(t) + L_{AG} i_G(t)$$

$$where \quad i_G(t) = i_A(t) + i_B(t) + i_C(t)$$

$$\phi_A = \left(L_{AA} + L_{AG}\right) i_A(t) + \left(L_{AB} + L_{AG}\right) i_B(t) + \left(L_{AC} + L_{AG}\right) i_C(t)$$

# Circuit Element Sequence Representations
# ABC-to-012 Conversion the Voltage Drop Expressions

- Start with our voltage drop equations in matrix form

$$\begin{bmatrix} V_{AS} \\ V_{BS} \\ V_{CS} \end{bmatrix} - \begin{bmatrix} V_{AR} \\ V_{BR} \\ V_{CR} \end{bmatrix} = \begin{bmatrix} Z_{AA} & Z_{AB} & Z_{AC} \\ Z_{BA} & Z_{BB} & Z_{BC} \\ Z_{CA} & Z_{CB} & Z_{CC} \end{bmatrix} \cdot \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix}$$

- Multiply both sides of the expression by *[A$^{-1}$]* which preserves the equality and multiply *[Z$_{ABC}$]* by *[A$^{-1}$]·[A]* which is the same as multiplying it by the identity matrix *[I]*.

$$[A]^{-1} \begin{bmatrix} V_{AS} \\ V_{BS} \\ V_{CS} \end{bmatrix} - [A]^{-1} \begin{bmatrix} V_{AR} \\ V_{BR} \\ V_{CR} \end{bmatrix} = [A]^{-1} \begin{bmatrix} Z_{AA} & Z_{AB} & Z_{AC} \\ Z_{BA} & Z_{BB} & Z_{BC} \\ Z_{CA} & Z_{CB} & Z_{CC} \end{bmatrix} [A] \cdot [A]^{-1} \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix}$$

- This leaves us with the voltage drop expressions in the sequence domain.

$$\begin{bmatrix} V_{0S} \\ V_{1S} \\ V_{2S} \end{bmatrix} - \begin{bmatrix} V_{0R} \\ V_{1R} \\ V_{2R} \end{bmatrix} = \begin{bmatrix} Z_{00} & Z_{01} & Z_{02} \\ Z_{10} & Z_{11} & Z_{12} \\ Z_{20} & Z_{21} & Z_{22} \end{bmatrix} \cdot \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

# Circuit Element Sequence Representations
# Sequence Independence and Sequence Coupling

- Let's examine each of the impedance terms of $Z_{012}$.

$$\begin{bmatrix} V_{0S} \\ V_{1S} \\ V_{2S} \end{bmatrix} - \begin{bmatrix} V_{0R} \\ V_{1R} \\ V_{2R} \end{bmatrix} = \begin{bmatrix} Z_{00} & Z_{01} & Z_{02} \\ Z_{10} & Z_{11} & Z_{12} \\ Z_{20} & Z_{21} & Z_{22} \end{bmatrix} \cdot \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

- See how the diagonal terms indicate impedances with no coupling between the sequence networks whereas the off-diagonal terms indicate impedances with coupling between the sequence networks.

$$Z_{00} = \frac{V_{0S} - V_{0R}}{I_0} \qquad Z_{01} = \frac{V_{0S} - V_{0R}}{I_1} \qquad Z_{02} = \frac{V_{0S} - V_{0R}}{I_2}$$

$$Z_{10} = \frac{V_{1S} - V_{1R}}{I_0} \qquad Z_{11} = \frac{V_{1S} - V_{1R}}{I_1} \qquad Z_{12} = \frac{V_{1S} - V_{1R}}{I_2}$$

$$Z_{20} = \frac{V_{2S} - V_{2R}}{I_0} \qquad Z_{21} = \frac{V_{2S} - V_{2R}}{I_1} \qquad Z_{22} = \frac{V_{2S} - V_{2R}}{I_2}$$

# Cases of Impedance Matrices with High Symmetry
# Case 1 – Symmetrical Passive Elements

- In the case of transmission lines, common assumptions include symmetrically spaced phase conductors with regular conductor transposition. This yields the following equalities:

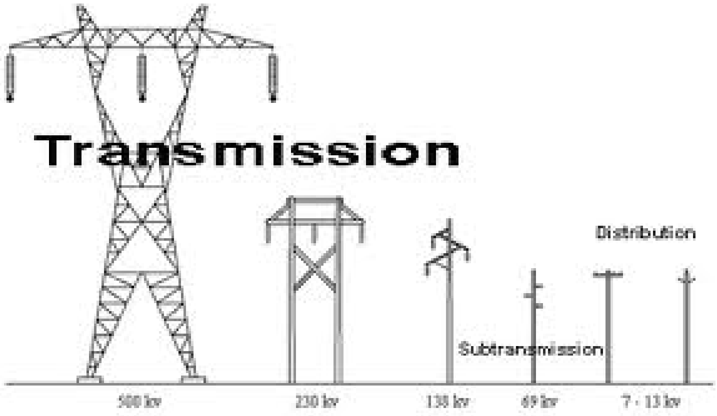
$$R_P = R_A = R_B = R_C$$

$$X_S = X_{AA} = X_{BB} = X_{CC}$$

$$X_M = X_{AB} = X_{BC} = X_{CA} = X_{BA} = X_{CB} = X_{AC}$$

$$X_G = X_{AG} = X_{BG} = X_{CG}$$

- This in turn enables the introduction of new variables representing self and mutual impedances.



$$\begin{aligned} Z_S &= Z_{AA} = Z_{BB} = Z_{CC} \\ &= R_P + R_G + j(X_S + X_G) \end{aligned}$$

$$\begin{aligned} Z_M &= Z_{AB} = Z_{BC} = Z_{CA} = Z_{BA} = Z_{CB} = Z_{AC} \\ &= R_G + j(X_M + X_G) \end{aligned}$$

# Cases of Impedance Matrices with High Symmetry
# Case 1 – Symmetrical Passive Elements

- Now we substitute $Z_S$ for the self impedance and $Z_M$ for the mutual impedances in the $Z_{ABC}$ impedance matrix

$$Z_{ABC} = \begin{bmatrix} Z_{AA} & Z_{AB} & Z_{AC} \\ Z_{BA} & Z_{BB} & Z_{BC} \\ Z_{CA} & Z_{CB} & Z_{CC} \end{bmatrix} = \begin{bmatrix} Z_S & Z_M & Z_M \\ Z_M & Z_S & Z_M \\ Z_M & Z_M & Z_S \end{bmatrix}$$

- And convert to $Z_{012}$.

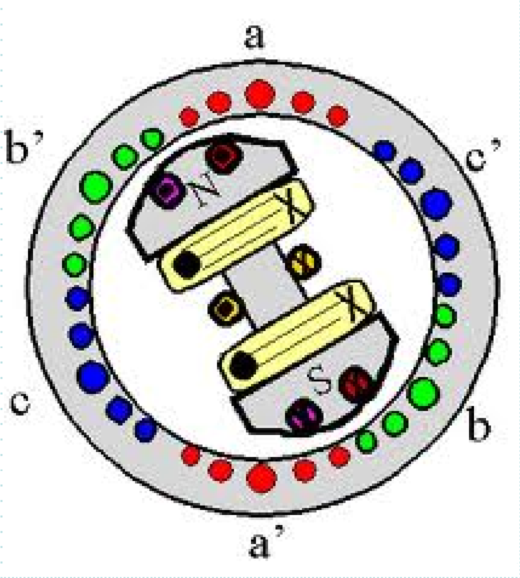
$$Z_{012} = \left[A^{-1}\right] \cdot \begin{bmatrix} Z_S & Z_M & Z_M \\ Z_M & Z_S & Z_M \\ Z_M & Z_M & Z_S \end{bmatrix} \cdot [A] = \begin{bmatrix} Z_S + 2Z_M & 0 & 0 \\ 0 & Z_S - Z_M & 0 \\ 0 & 0 & Z_S - Z_M \end{bmatrix}$$

- Notice that $Z_{012}$ contains only diagonal elements (i.e. no coupling between sequence networks) and that $Z_{11} = Z_{22}$. The more common form of expression is that $Z_1 = Z_2$.

# Cases of Impedance Matrices with High Symmetry
# Case 2 – Rotating Machines

- In the case of rotating machines (motors and generators), mutual coupling between phases includes rotation as well as physical geometry. This differs from non-rotating circuit elements because now $Z_{AB} \neq Z_{BA}$, $Z_{BC} \neq Z_{CB}$ and $Z_{CA} \neq Z_{AC}$.

$$R_P = R_A = R_B = R_C$$
$$X_S = X_{AA} = X_{BB} = X_{CC}$$
$$X_{M+} = X_{AB} = X_{BC} = X_{CA}$$
$$X_{M-} = X_{BA} = X_{CB} = X_{AC}$$
$$X_G = X_{AG} = X_{BG} = X_{CG}$$



- This in turn enables the introduction of new variables representing self and mutual impedances.

$$\begin{aligned} Z_S &= Z_{AA} = Z_{BB} = Z_{CC} \\ &= R_P + R_G + j(X_S + X_G) \end{aligned}$$

$$\begin{aligned} Z_{M+} &= Z_{AB} = Z_{BC} = Z_{CA} \\ &= R_G + j(X_{M+} + X_G) \end{aligned} \qquad \begin{aligned} Z_{M-} &= Z_{BA} = Z_{CB} = Z_{AC} \\ &= R_G + j(X_{M-} + X_G) \end{aligned}$$

# Cases of Impedance Matrices with High Symmetry
# Case 2 – Rotating Machines

- Now we substitute $Z_S$ for the self impedance and $Z_M$ for the mutual impedances in the $Z_{ABC}$ impedance matrix

$$Z_{ABC} = \begin{bmatrix} Z_{AA} & Z_{AB} & Z_{AC} \\ Z_{BA} & Z_{BB} & Z_{BC} \\ Z_{CA} & Z_{CB} & Z_{CC} \end{bmatrix} = \begin{bmatrix} Z_S & Z_{M+} & Z_{M-} \\ Z_{M-} & Z_S & Z_{M+} \\ Z_{M+} & Z_{M-} & Z_S \end{bmatrix}$$

- And convert to $Z_{012}$.

$$Z_{012} = \left[A^{-1}\right] \cdot \begin{bmatrix} Z_S & Z_{M+} & Z_{M-} \\ Z_{M-} & Z_S & Z_{M+} \\ Z_{M+} & Z_{M-} & Z_S \end{bmatrix} \cdot [A] = \begin{bmatrix} Z_S + Z_{M+} + Z_{M-} & 0 & 0 \\ 0 & Z_S + a^2 Z_{M+} + aZ_{M-} & 0 \\ 0 & 0 & Z_S + aZ_{M+} + a^2 Z_{M-} \end{bmatrix}$$

- Notice that $Z_{012}$ contains only diagonal elements (i.e. no coupling between sequence networks) and that this time $Z_{11} \neq Z_{22}$ or the more common form of expression is that $Z_1 \neq Z_2$.

# Circuit Element Sequence Representations
## Sequence Networks

- Elements of a power system are represented by their impedances and characteristics in each of sequence networks. For a 3-phase power system:
  - **Zero sequence** - represents impedances of the system to equal (in-phase) currents in all three phases.
  - **Positive sequence** - represents impedances of the system to normal (balanced) currents in all three phases.
  - **Negative sequence** - represents impedances of the system to currents with reversed phase sequence.

# Circuit Element Sequence Representations
# Sequence Network Independence

- Each of the sequence networks is independent of the others.

- For a balanced network:
  - Sequence currents flowing in a balanced network produce only like sequence network voltage drops.
    - Thus the sequence networks are not connected to each other.
    - Unbalanced sources resolve to zero, positive and negative sequence sources.

- For unbalanced network:
  - In general, sequence currents can produce all three sequence network voltage drops.
    - Thus, we model unbalances by setting up independent sequence networks and interconnecting them at the point of the unbalance (i.e. the fault location).
    - For these studies we assume the rest of the system and all the sources are balanced (i.e. no sources in the zero and negative sequence networks).

# Circuit Element Sequence Representations
# System Equivalent Sources (i.e. Non-rotating)

- Short circuit kVA or MVA values are used to express the fault duty of an equivalent source at a point in the power system and can be converted to equivalent impedances.
  - Sometimes you may get driving point a.k.a. Thevenin impedances from a short circuit program such as CAPE or Aspen. Generally they provide $Z_0$ and $Z_1$ values and you assume $Z_2 = Z_1$.
  - Alternatively you may be given fault duties expressed in MVA or kVA based on the driving point (i.e. base system) voltage and available fault current. You need both 3 phase ($S_{3ph}$ or $MVA_{SC}$) and SLG ($S_{1ph}$ or $MVA_{GSC}$) fault duties to calculate sequence impedances (see next slide). With this method assume impedances to be all reactive.
- For hand calculations you can often assume an ideal voltage source, a.k.a. an infinite bus, *(i.e.* $Z_0 = Z_1 = Z_2 = 0$*)*.

# Circuit Element Sequence Representations System Equivalent Sources (i.e. Non-rotating)

Following is a calculation method for $Z_0$, $Z_1$ and $Z_2$ from given 3ph ($S_{3ph}$) and SLG ($S_{1ph}$) fault duties in MVA. Resulting impedances are in per unit.

$$Z_1 = Z_2 = \frac{S_{Base}}{S_{3ph}}$$

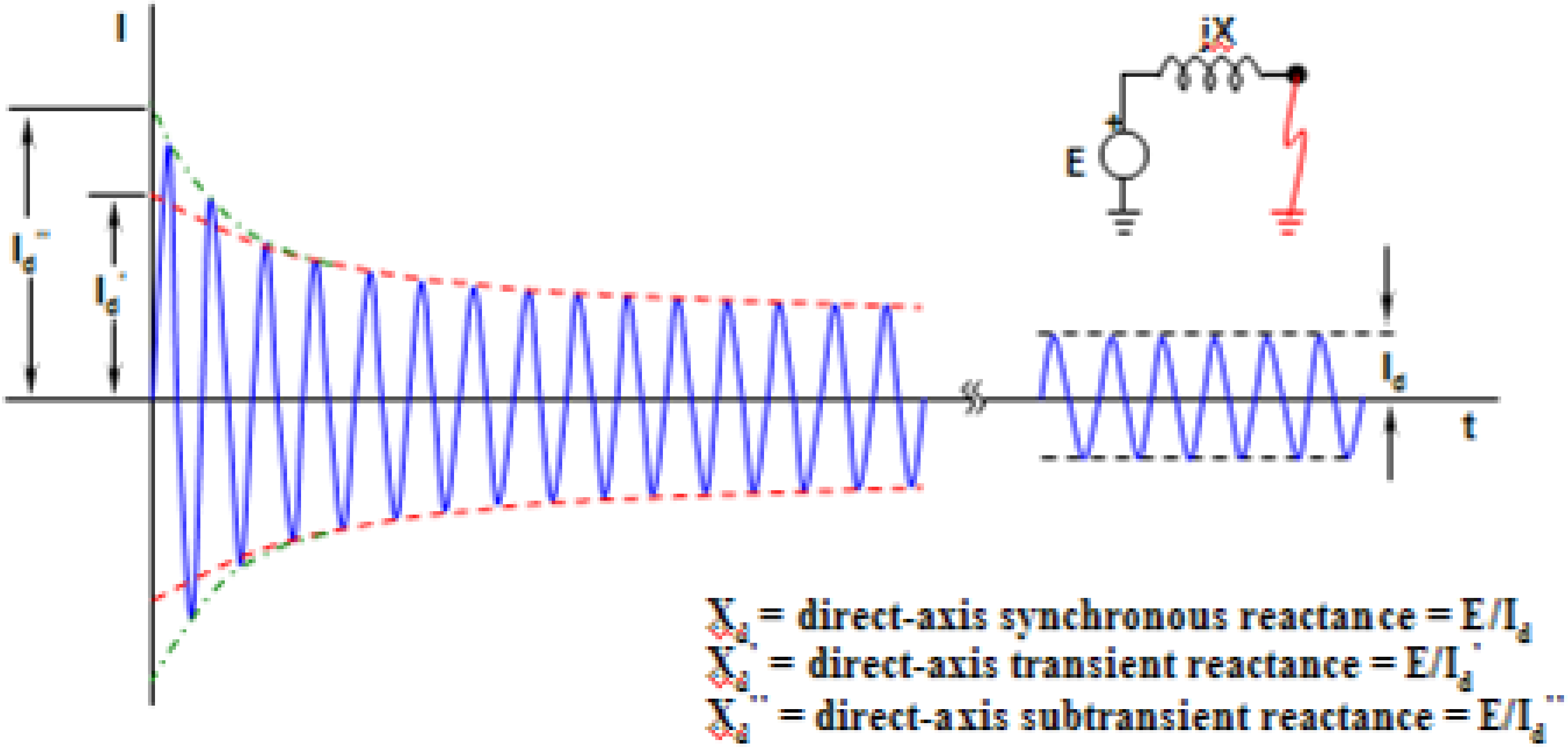
$$Z_g = \frac{3S_{Base}}{S_{1ph}} = Z_0 + Z_1 + Z_2$$

$$\begin{aligned} Z_0 &= Z_g - Z_1 - Z_2 \\ &= \left(\frac{3S_{Base}}{S_{1ph}}\right) - 2\left(\frac{S_{Base}}{S_{3ph}}\right) \end{aligned}$$

*See Blackburn Appendix 4.1 for a detailed derivation.*

# Circuit Element Sequence Representations
# Synchronous Generators

For a sustained fault on the terminals of an unloaded generator, the armature current has a decrement as shown below. This defines generator impedances.



$X_d$ = direct-axis synchronous reactance = $E/I_d$
$X_d'$ = direct-axis transient reactance = $E/I_d'$
$X_d''$ = direct-axis subtransient reactance = $E/I_d''$

# Circuit Element Sequence Representations
# Synchronous Generators

- Reactance increases with time after a short circuit because of the demagnetizing effect of the fault current on the air-gap flux. For round rotor machines, typical positive sequence impedances are as follows:

$$\left.\begin{array}{l} 0.95 < X_d < 1.45 \\ 0.12 < X_d' < 0.28 \\ 0.07 < X_d'' < 0.17 \end{array}\right\} \text{pu on generator base}$$

- Negative-sequence impedance is often approximated by equating it to the subtransient reactance.

$$X_2 = Xd''$$

# Circuit Element Sequence Representations
# Generators – Induction Machines

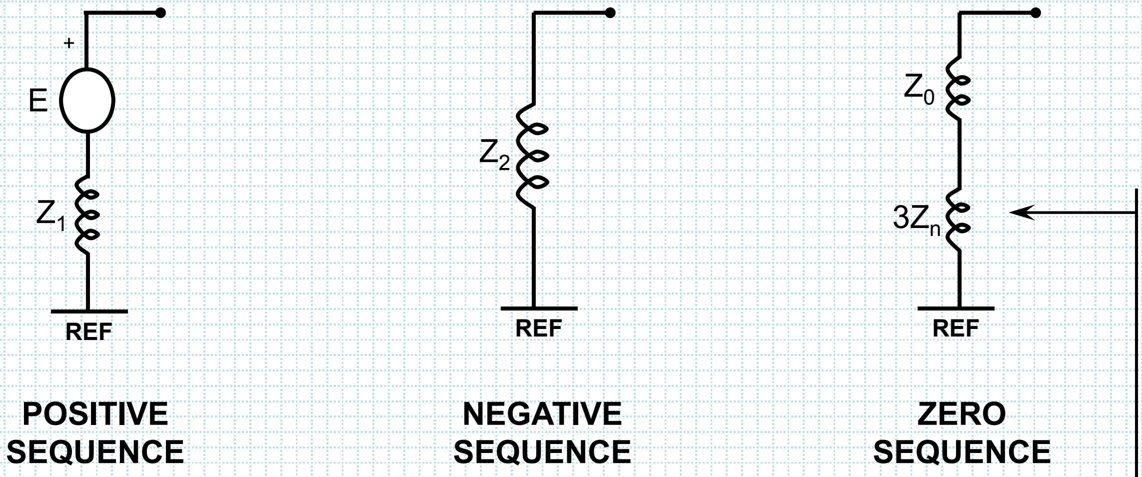
- Induction machines (motors or generators) are not generally considered sources of fault current for relaying purposes.

- The fault current contribution from an induction machine decays in a few cycles.

- Induction machine contribution to fault current (subtransient reactance) may be considered when performing maximum instantaneous fault current studies for bus and switchgear rating purposes.

# Circuit Element Sequence Representations Balanced 3-Phase Sources

Zero-sequence impedance depends on the manner in which the generator is grounded. Any impedance in the neutral circuit ($Z_n$) is represented as three times this value ($3Z_n$) in the zero-sequence model since $3I_0$ flows through the neutral.



External neutral impedance.

For solidly grounded neutral $3Z_n = 0$.

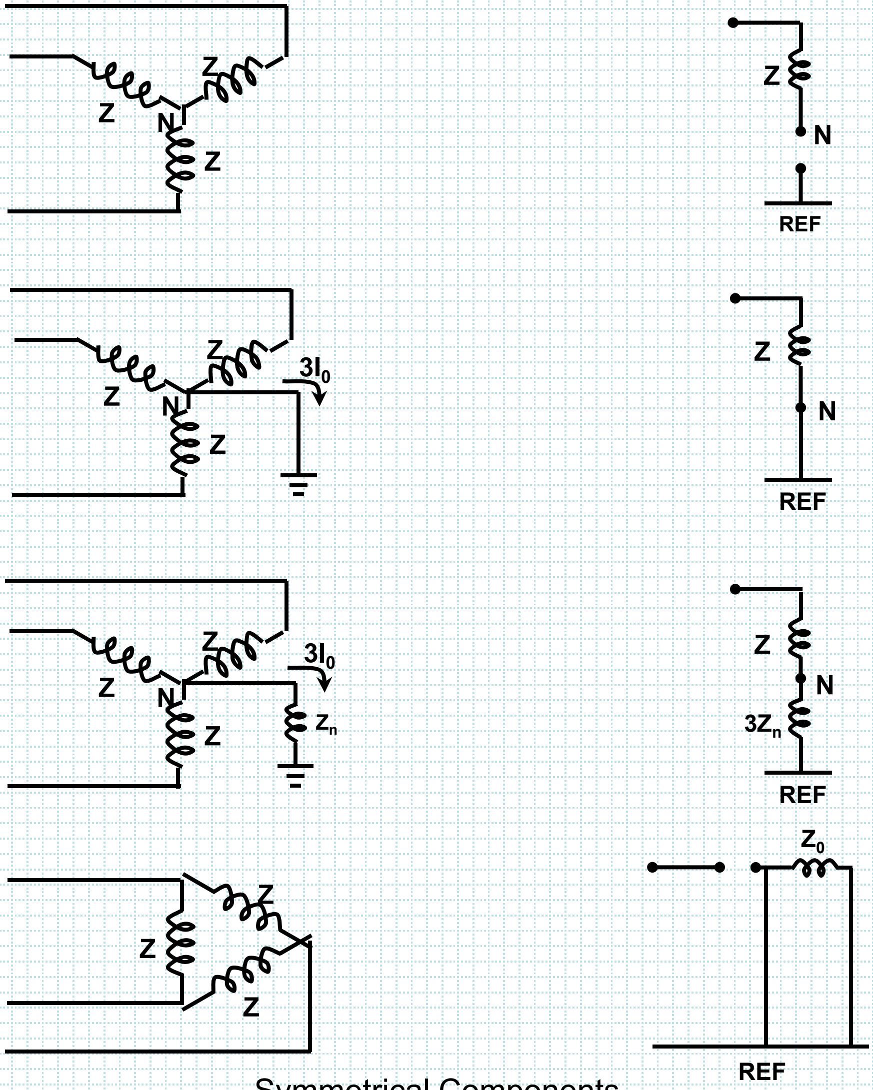
For ungrounded neutral $3Z_n = \infty$

# Circuit Element Sequence Representations Load Impedances

- Positive and negative sequence impedances of loads are generally equal. These are shown on a reference phase basis in sequence networks.
- For synchronous motors, particularly those that are designed with salient poles, the negative sequence impedance generally lies between $X_d'$ and $X_d''$.
- Zero sequence impedance of loads depends on the manner in which they are connected and grounded as shown on the following page.

# Circuit Element Sequence Representations
# Zero Sequence Models for Different Load Connections

**Connection Arrangement**



**Zero Sequence Equivalent Circuit**

# Circuit Element Sequence Representations Transmission Lines and Cables

- In sequence network calculations, the per-phase values of line resistance, reactance and shunt capacitive susceptance are used.
  - These values can be found from conductor tables or calculated by hand using Carson's equations.
  - Several software apps are available such as ATP-EMTP which can derive the per-phase line constants from physical dimensions of the line or cable.

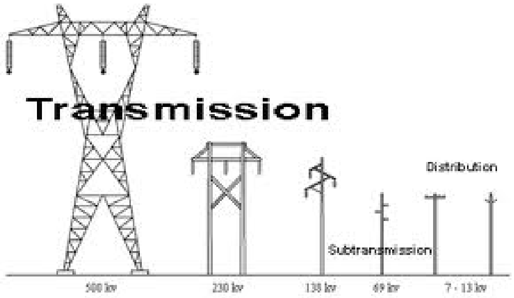
- Recall from earlier expressions that for lines and cables, $Z_{L1} = Z_{L2}$ while $Z_{L0} > Z_{L1}$ .

$$Z_{012} = \left[A^{-1}\right] \cdot \begin{bmatrix} Z_S & Z_M & Z_M \\ Z_M & Z_S & Z_M \\ Z_M & Z_M & Z_S \end{bmatrix} \cdot \left[A\right] = \begin{bmatrix} Z_S + 2Z_M & 0 & 0 \\ 0 & Z_S - Z_M & 0 \\ 0 & 0 & Z_S - Z_M \end{bmatrix}$$

# Circuit Element Sequence Representations
# Sample ATP-EMTP Output for OH Transmission Lines

Calculated impedances are for a typical 345kV transmission line (left-most tower configuration shown below) with two bundled conductors per phase.

```
Impedance matrix,  in units of [ohms/mile ] for the system of equivalent phase conductors.
Rows and columns proceed in the same order as the sorted input.
         ZAA
   1   2.780137E-01
       1.099286E+00
         ZBA            ZBB
   2   2.305740E-01  2.910487E-01
       5.180598E-01  1.085324E+00
         ZCA            ZCB            ZCC
   3   2.230820E-01  2.305750E-01  2.780138E-01
       4.412611E-01  5.181495E-01  1.099286E+00
```



```
Impedance matrix,  in units of [ohms/mile ] for symmetrical components of the equivalent phase conductor
Rows proceed in the sequence  (0, 1, 2),  (0, 1, 2),  etc.;
Columns proceed in the sequence  (0, 2, 1),  (0, 2, 1),  etc.
         Z00
   0   7.385127E-01
       2.079613E+00
         Z10            Z12
   1  -2.156088E-02 -4.804473E-02
      -4.577000E-03  2.854904E-02
         Z20            Z22            Z21
   2   1.471788E-02  5.428174E-02  4.869572E-02
      -1.642828E-02  6.021421E-01  2.742369E-02
```

$$Z_{AA} = (R_A + R_G) + j(X_{AA} + X_{AG})$$

$$Z_{AB} = R_G + j(X_{AB} + X_{AG})$$

$$Z_{012} = \begin{bmatrix} Z_S + 2Z_M & 0 & 0 \\ 0 & Z_S - Z_M & 0 \\ 0 & 0 & Z_S - Z_M \end{bmatrix}$$

# Circuit Element Sequence Representations
# $Z_{L0}$ for Overhead Transmission Lines

- The zero sequence impedance, $Z_{L0}$, of an overhead line depends on several factors which can result in wide variation.
  - The use of overhead shield wires and the type of tower grounding and counterpoise.
  - Ground resistivity.
  - Zero-sequence impedance is usually 2 to 3.5 times the positive-sequence impedance.

# Circuit Element Sequence Representations
# $Z_{L0}$ for Transmission Line Cables

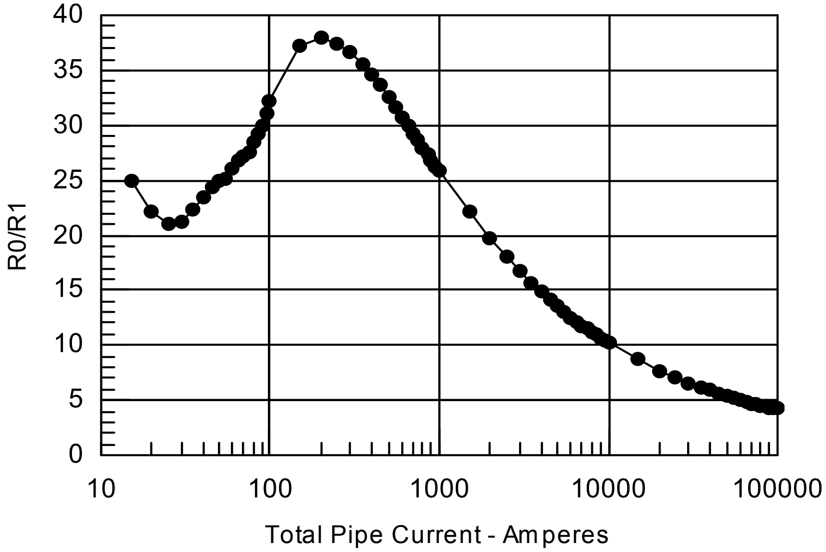
- For cables, the type of sheath or pipe used in the construction is a major factor in the zero-sequence impedance.

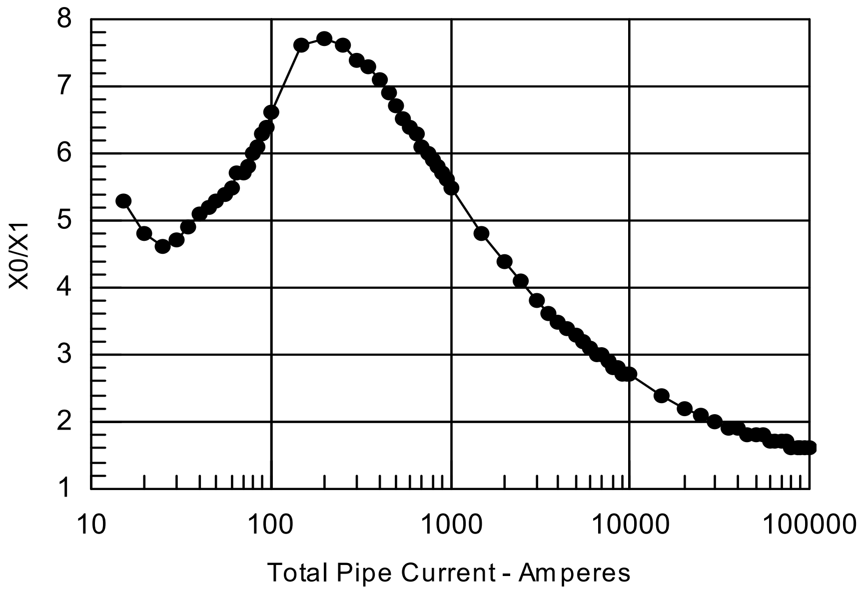
- In addition, the placement of the phase conductors relative to each other affects the amount of current flow in the cable sheaths or pipe and thus has a significant impact on the zero-sequence impedance.

# Circuit Element Sequence Representations Pipe-type Cables – $R_0$ and $X_0$

- Things expand when they heat up so $R_0$ and $X_0$ in pipe type cables vary with current loading.

- Most fault studies will choose a current level at which to study the cable, usually a level corresponding with the available fault current.



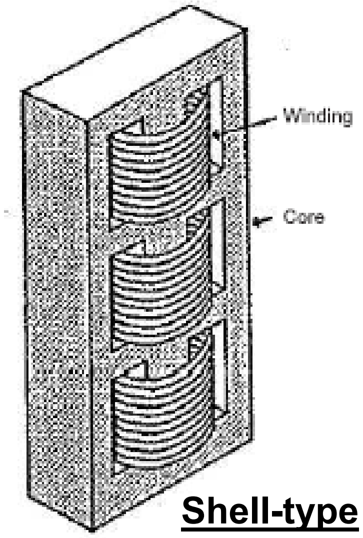


# Circuit Element Sequence Representations
# Transformers – Positive and Negative Sequence

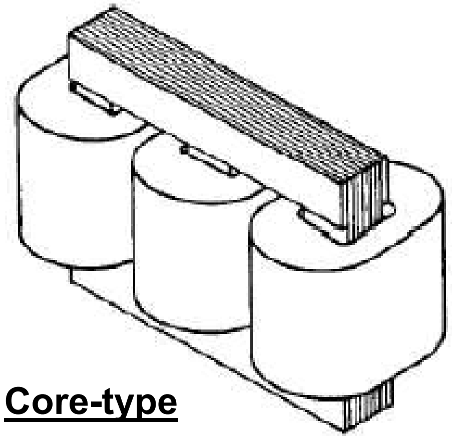
- The positive and negative-sequence impedances of a transformer are equal and are the leakage impedance of the transformer.
- Positive-sequence voltages and currents are shifted ± 30° when passing through a Delta - Wye transformer bank. The sign of the phase shift is determined by the transformer connections.
- Negative sequence voltages and currents are correspondingly shifted by the opposite phase shift.
- No phase shift occurs in the zero sequence network.

# Circuit Element Sequence Representations
# Transformers – Zero Sequence

- Where a three-phase transformer bank is arranged without interlinking magnetic flux (that is a three-phase shell type, or three single-phase units) and provided there is a path for zero sequence currents, the zero sequence impedance is equal to the positive sequence impedance.
- In the case of three-phase core type units, the zero sequence fluxes produced by zero sequence currents can find a high reluctance path, the effect being to reduce the zero sequence impedance to about 90% of the positive sequence impedance.
- However, in hand calculations, it is usual to ignore this variation and consider the positive and zero sequence impedances to be equal. It is common when using software to perform fault calculations to enter a value of zero-sequence impedance in accordance with the above guidelines, if the manufacturer is unable to provide a value.



**Shell-type**

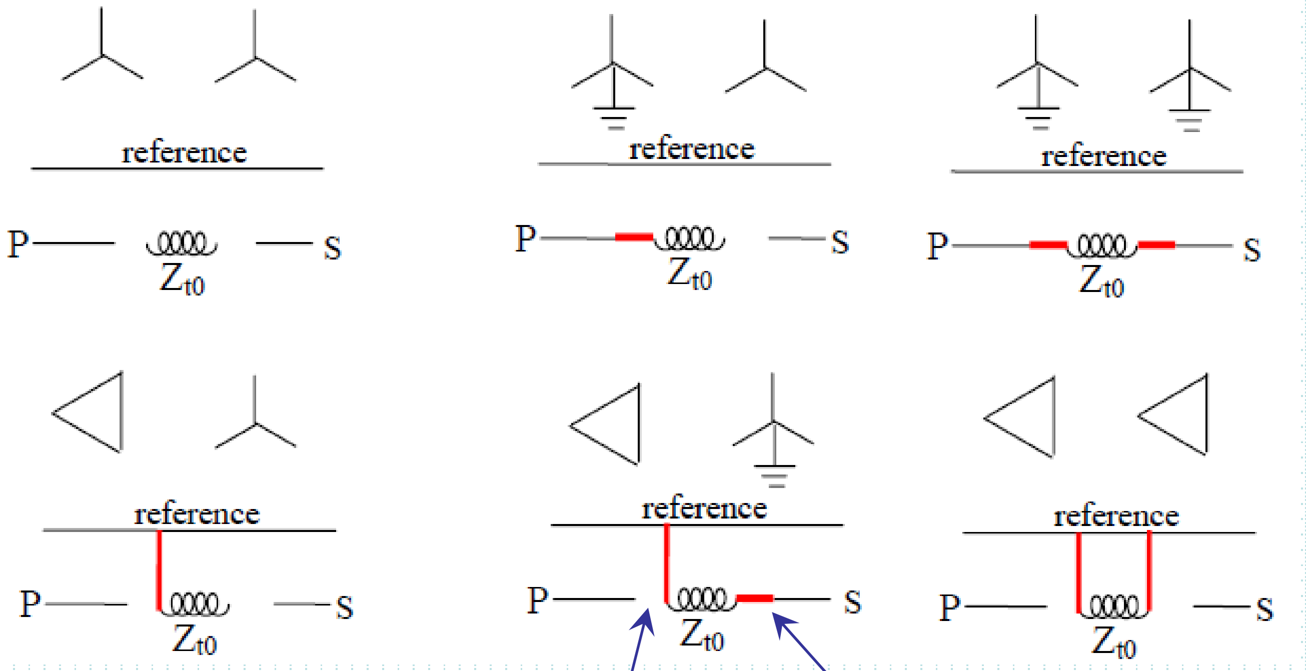


**Core-type**

*Source: Areva Network Protection and Automation Guide, Chapter 5, page 57.*

# Circuit Element Sequence Representations

## 2-Winding Transformers – Zero Sequence



**The connection from internal impedance to the reference and the open connection to the external terminal represents a delta connection.**

**This represents a solidly grounded neutral (i.e. $3Z_n = 0$).**

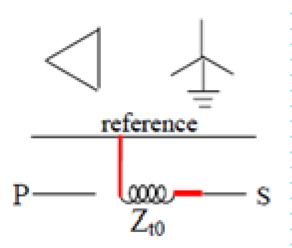
**Replace with $3Z_n$ for an impedance grounded neutral.**

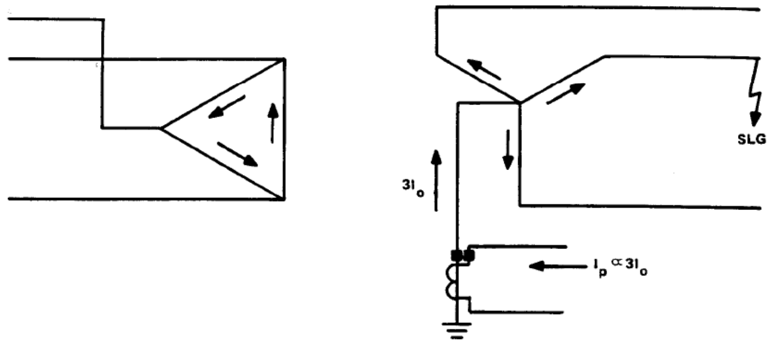
**Replace with an open (i.e. $3Z_n = \infty$) for an ungrounded neutral.**

*You can also refer to a similar table on p.122 in Blackburn.*

# Zero Sequence Network Series and Shunt Elements How They Relate to Neutral Current

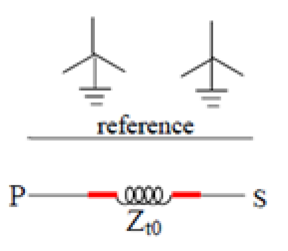
Current across shunt elements in the zero sequence representation corresponds with neutral current.

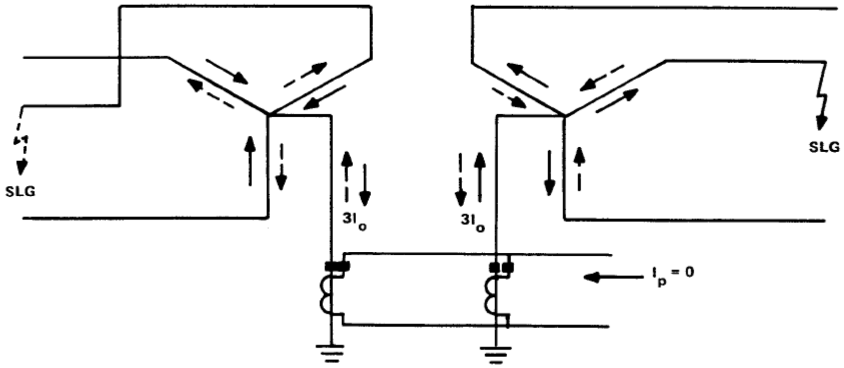




A. Delta-wye grounded power transformer, suitable for current polarization.

If the zero sequence is open as for a delta-delta transformer or ungrounded wye winding clearly there is no neutral current. When there is only a series path there is zero sequence current flow but not through the neutral.

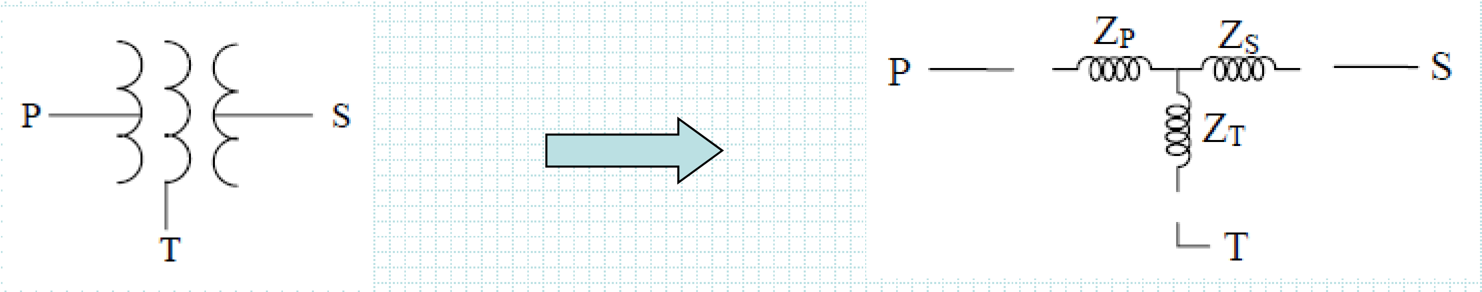




C. Wye grounded-wye grounded power transformer, unsuitable for current polarization.

# Circuit Element Sequence Representations
## 3-Winding and Autotransformers

3-winding transformers can be represented with a T-model.



Recall that the impedances derived from measurements (i.e test reports) are those between pairs of windings with the third winding being an open circuit. Thus we can relate the values $Z_{PS}$, $Z_{PT}$ and $Z_{ST}$ to effective individual winding impedances $Z_P$, $Z_S$ and $Z_T$ as follows:

$$Z_{PS} = Z_P + Z_S, \qquad Z_{PT} = Z_P + Z_T, \qquad Z_{ST} = Z_S + Z_T,$$

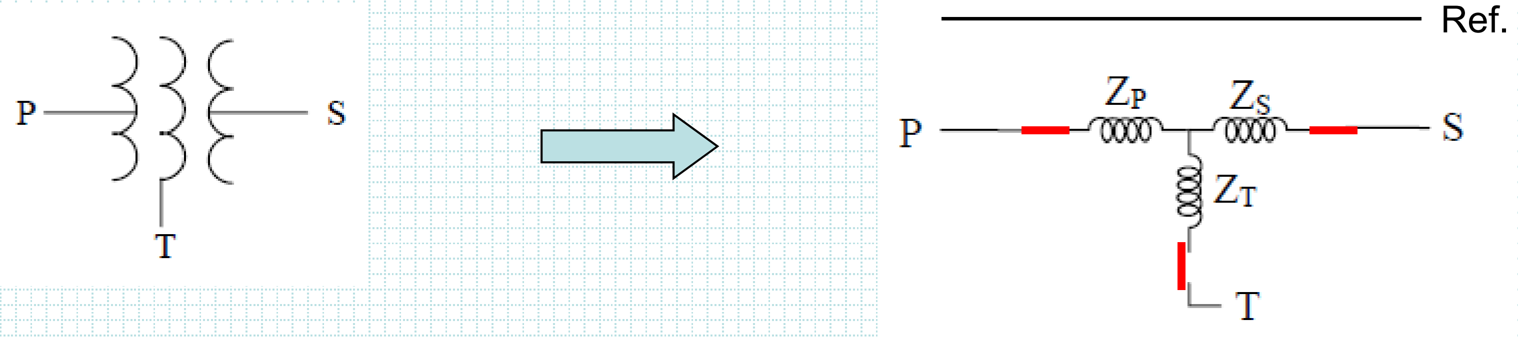
Then with some algebraic manipulation we can arrive at the following:

$$Z_P = \tfrac{1}{2}\left(Z_{PS} + Z_{PT} - Z_{ST}\right), \quad Z_S = \tfrac{1}{2}\left(Z_{PS} + Z_{ST} - Z_{PT}\right), \quad Z_T = \tfrac{1}{2}\left(Z_{PT} + Z_{ST} - Z_{PS}\right)$$

# Circuit Element Sequence Representations

## 3-Winding and Autotransformers – Positive and Negative Sequence

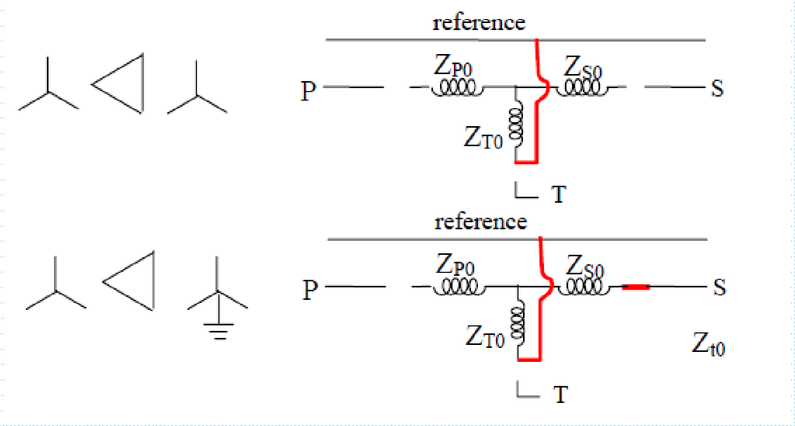
The positive and negative sequence representations are the same and simply include solid connections from the internal impedances $Z_P$, $Z_S$ and $Z_T$ to the external terminals P, S and T as shown below right.

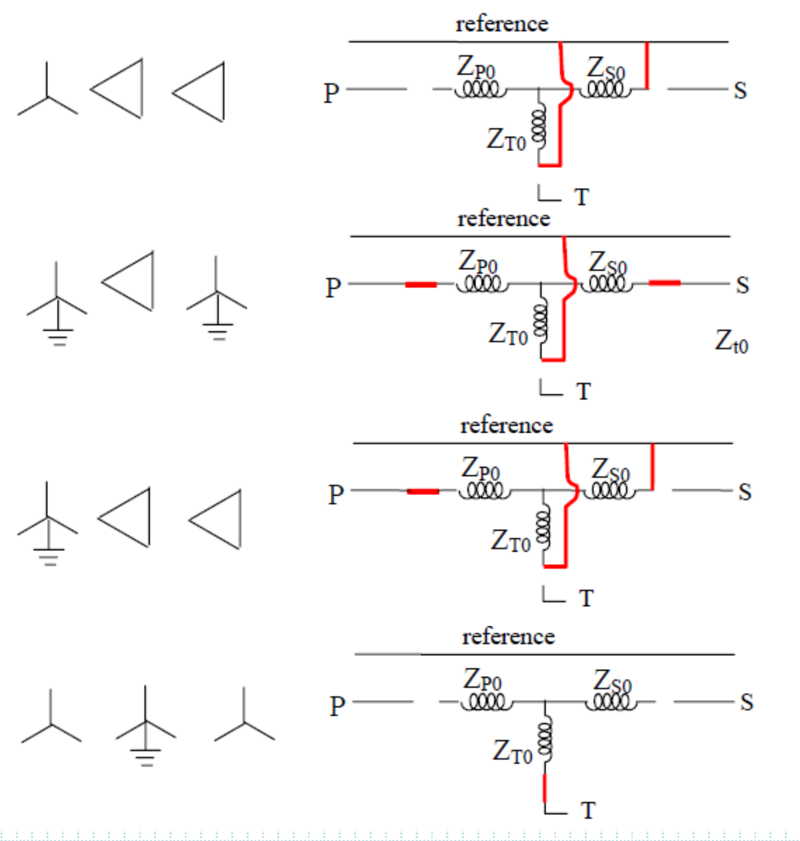


# Circuit Element Sequence Representations

## 3-Winding and Autotransformers – Zero Sequence

Zero sequence representations use the same internal connection rules for each winding configuration as seen in the 2-winding example.



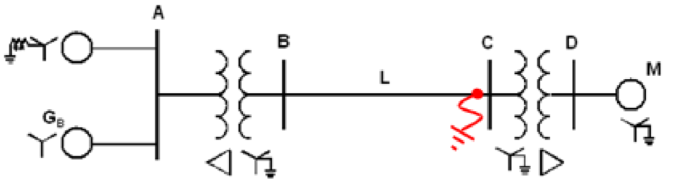


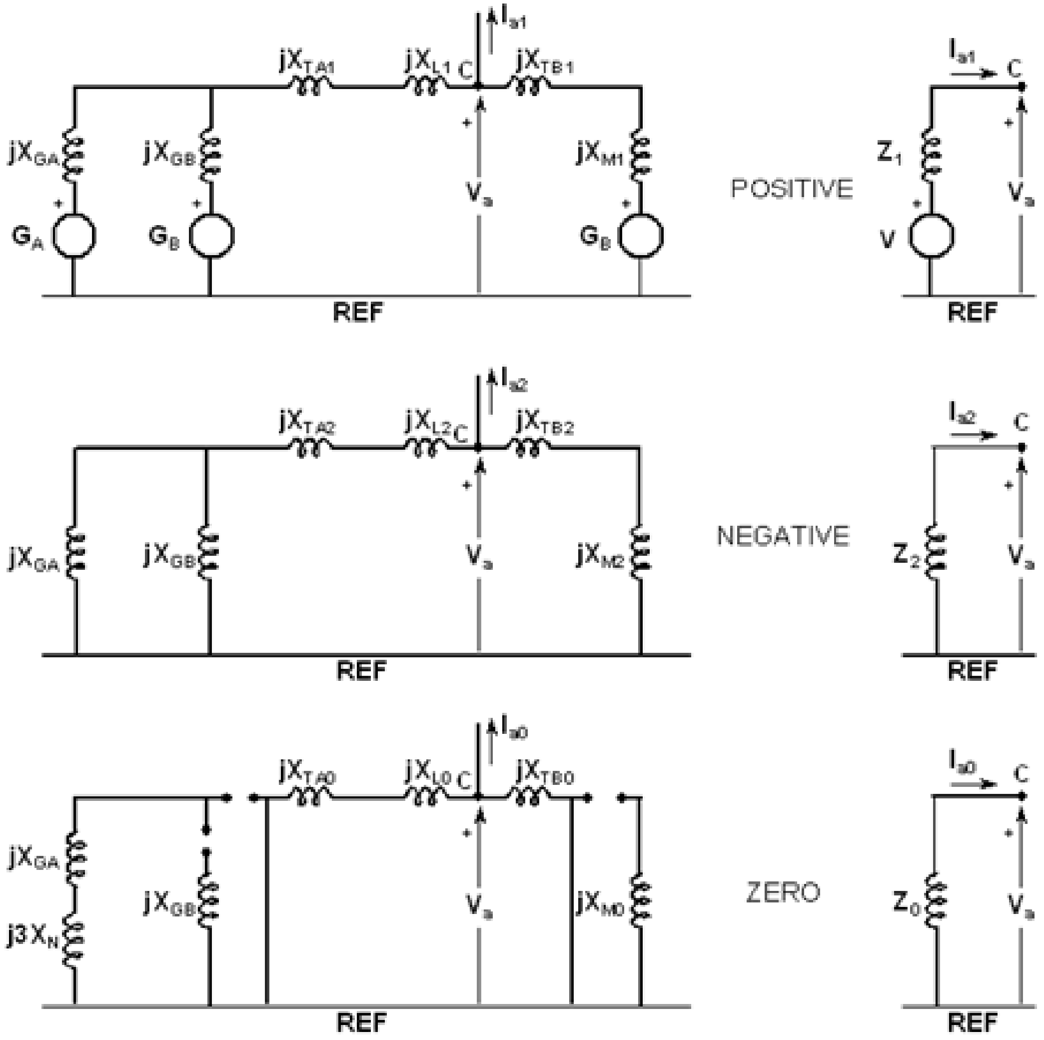
*You can also refer to a similar table on p.124 in Blackburn.*

### **Note for N-Winding Transformers:**

Representation of transformers with more than 3 windings (i.e. N-winding transformers) follow the same process and connection rules as 3-winding transformers.

# Fault Analysis Using Symmetrical Components
# Example System (Fault at Bus C)



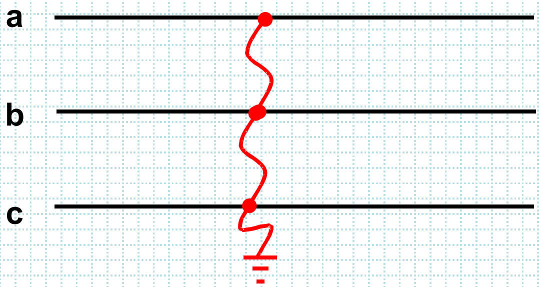


# Fault Analysis Using Symmetrical Components
## 3-Phase (3PH) Fault

At the fault point $V_a = V_b = V_c = 0$ and $I_a = I_b = I_c$

Since $V_a = V_b = V_c = 0$
From the definitions: $V_0 = V_1 = V_2 = 0$

Since $I_a = I_b = I_c$
From the definitions: $I_0 = 0$ and $I_2 = 0$



As expected, these relationships suggest only the positive sequence network to be connected at the fault point.

**REFERENCE EQUATIONS**

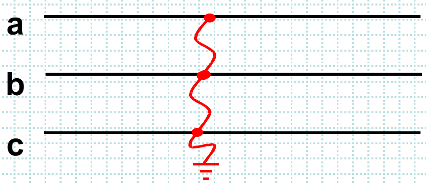
$$V_0 = \frac{1}{3}(V_a + V_b + V_c)$$
$$V_1 = \frac{1}{3}(V_a + aV_b + a^2V_c)$$
$$V_2 = \frac{1}{3}(V_a + a^2V_b + aV_c)$$

$$I_0 = \frac{1}{3}(I_a + I_b + I_c)$$
$$I_1 = \frac{1}{3}(I_a + aI_b + a^2I_c)$$
$$I_2 = \frac{1}{3}(I_a + a^2I_b + aI_c)$$

$$V_a = V_0 + V_1 + V_2$$
$$V_b = V_0 + a^2V_1 + aV_2$$
$$V_c = V_0 + aV_1 + a^2V_2$$

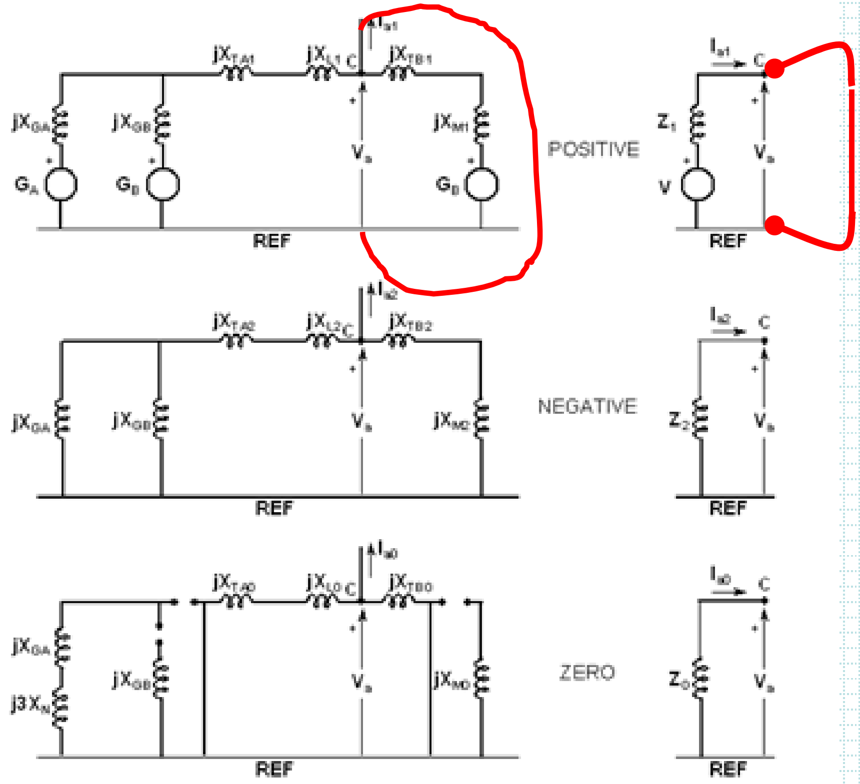
$$I_a = I_0 + I_1 + I_2$$
$$I_b = I_0 + a^2I_1 + aI_2$$
$$I_c = I_0 + aI_1 + a^2I_2$$

# Fault Analysis Using Symmetrical Components
## 3-Phase (3PH) Fault



$$V_a = V_b = V_c = 0$$

$$I_a = I_b = I_c$$



$$I_{a1} = \frac{V}{Z_1}$$

# Fault Analysis Using Symmetrical Components
## 3-Phase (3PH) Fault

Three-phase fault. Compare to example (8.1)

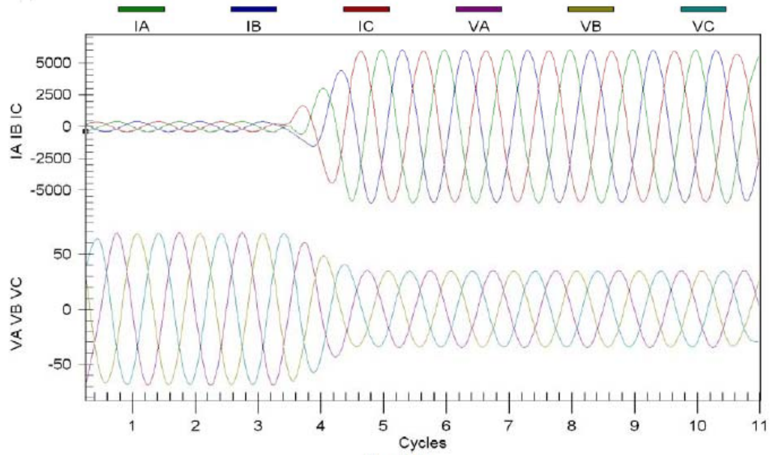


Fig 9.1a

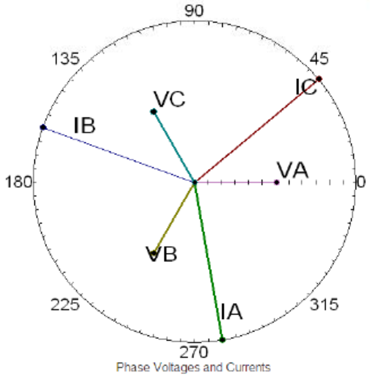


Fig 9.1b

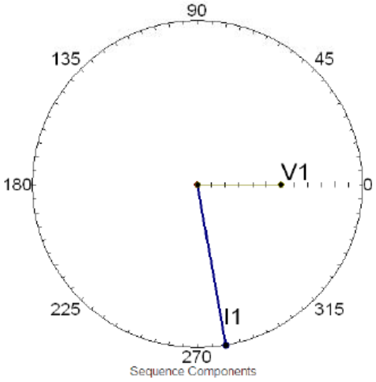


Fig 9.1c

$$I_a = I_b = I_c$$

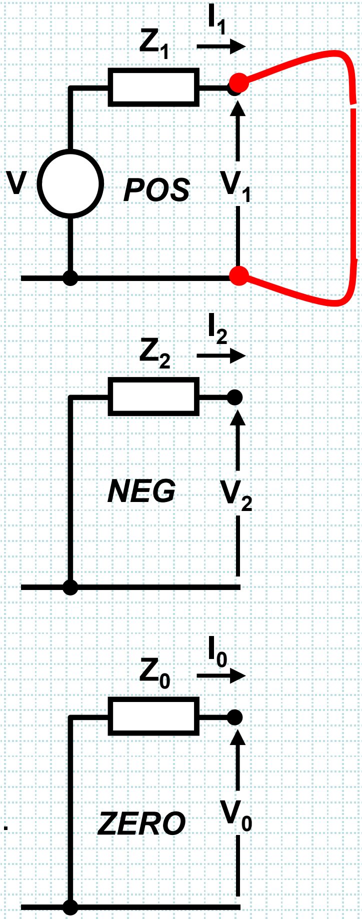
$$V_a = V_b = V_c = 0$$

$$V_1 \approx 0$$

$$V_0 = V_2 = 0$$

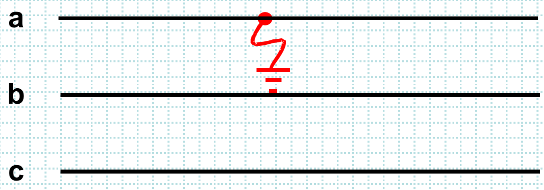
$$I_0 = I_2 = 0$$

Notice there is a extra component of V1 and I1 present because of load current and source impedance.



*The above fault record is from Washington State University's March 2011 Hands-On Relay School*

# Fault Analysis Using Symmetrical Components
# Single-Line-to-Ground (SLG) Fault



At the fault point $V_a = 0$ and $I_b = I_c = 0$

Since $V_a = 0$ $V_0 + V_1 + V_2 = 0$

Since $I_b = I_c = 0$ $I_0 + a^2 I_1 + a I_2 = 0$ and $I_0 + a I_1 + a^2 I_2 = 0$

Which simplifies to $I_0 = I_1 = I_2$

These relationships suggest that all three sequence networks are connected in series at the fault point.

**REFERENCE EQUATIONS**

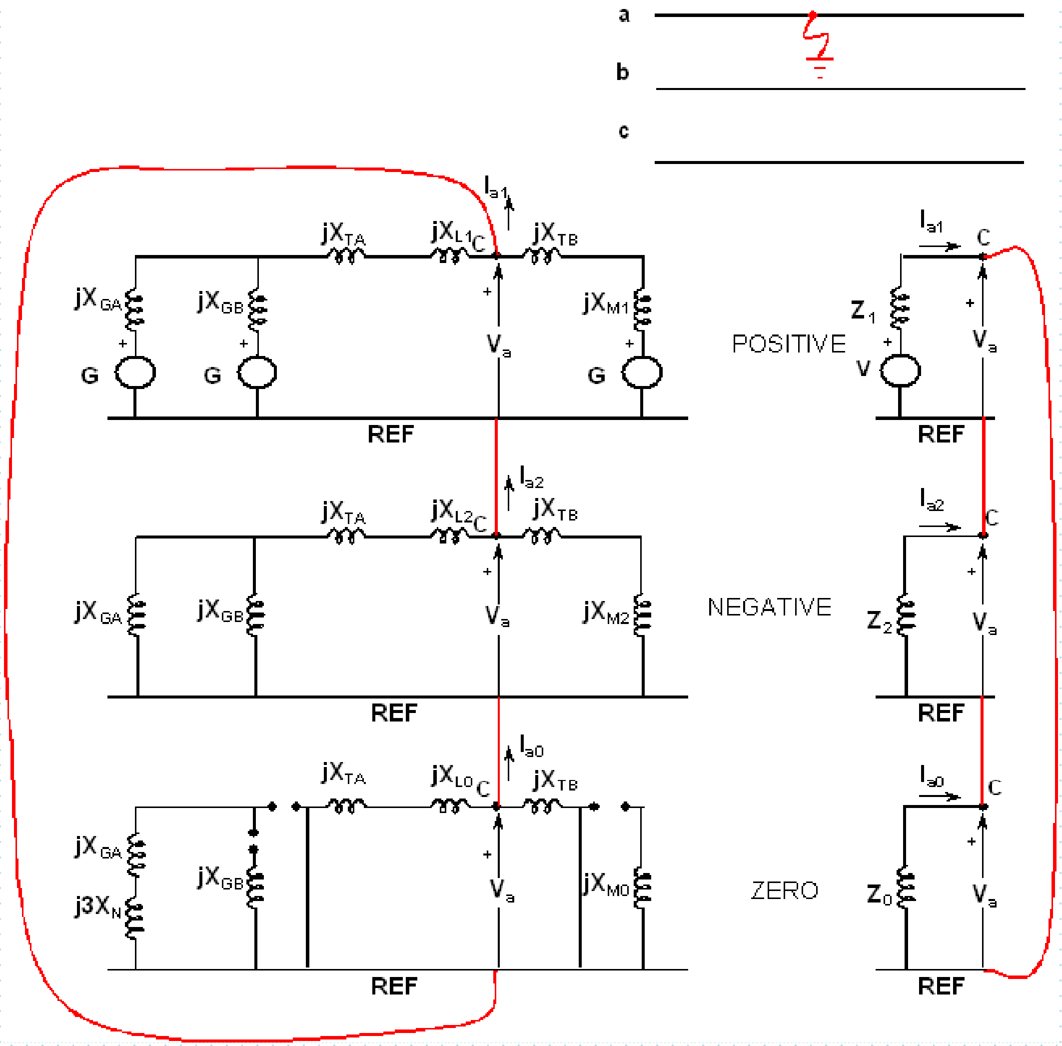
$$V_0 = \frac{1}{3}\left(V_a + V_b + V_c\right)$$
$$V_1 = \frac{1}{3}\left(V_a + aV_b + a^2V_c\right)$$
$$V_2 = \frac{1}{3}\left(V_a + a^2V_b + aV_c\right)$$

$$I_0 = \frac{1}{3}\left(I_a + I_b + I_c\right)$$
$$I_1 = \frac{1}{3}\left(I_a + aI_b + a^2I_c\right)$$
$$I_2 = \frac{1}{3}\left(I_a + a^2I_b + aI_c\right)$$

$$\boxed{V_a = V_0 + V_1 + V_2}$$
$$V_b = V_0 + a^2V_1 + aV_2$$
$$V_c = V_0 + aV_1 + a^2V_2$$

$$I_a = I_0 + I_1 + I_2$$
$$\boxed{\begin{aligned} I_b &= I_0 + a^2I_1 + aI_2 \\ I_c &= I_0 + aI_1 + a^2I_2 \end{aligned}}$$

# Fault Analysis Using Symmetrical Components
## Single-Line-to-Ground (SLG) Fault



$$V_a = 0$$

$$I_b = I_c = 0$$

$$I_{a1} = I_{a2} = I_{a0} = \frac{V}{Z_1 + Z_2 + Z_0}$$

$$I_a = I_{a1} + I_{a2} + I_{a0} = 3I_{a0} = \frac{3V}{Z_1 + Z_2 + Z_0}$$

# Fault Analysis Using Symmetrical Components
# Single-Line-to-Ground (SLG) Fault

Single Line-to-Ground fault. Compare to example (8.2)

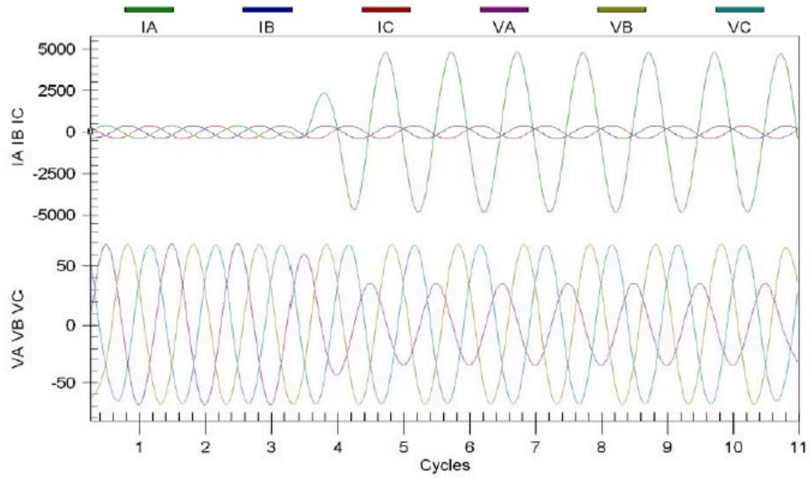
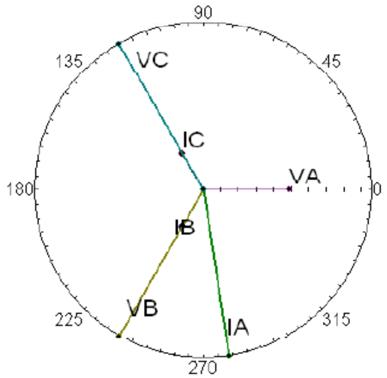
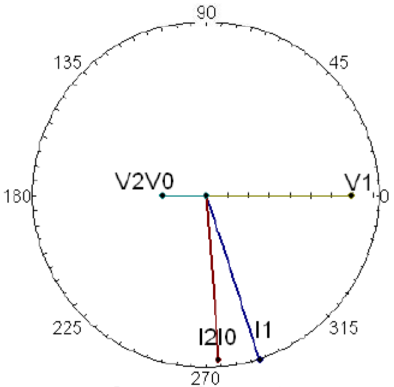


Fig 9.2a



Phase Voltages and Currents

Fig 9.2b



Sequence Components

Fig 9.2c

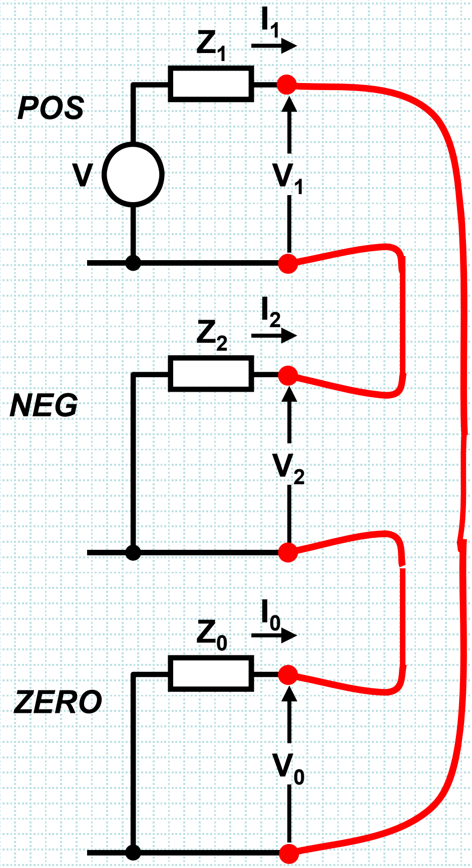
$$V_a = 0$$

$$I_b = I_c = 0$$

$$V_0 + V_1 + V_2 \approx 0$$

$$I_0 \approx I_1 \approx I_2$$

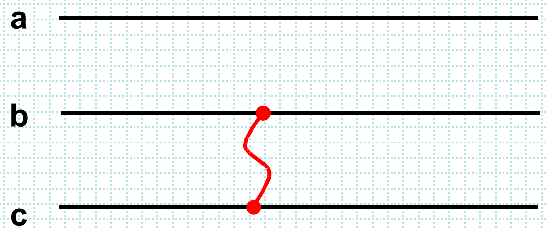
Notice there is a extra component of V1 and I1 present because of load current and source impedance.



*The above fault record is from Washington State University's March 2011 Hands-On Relay School*

# Fault Analysis Using Symmetrical Components
# Line-to-Line (LL) Fault

At the fault point $I_a = 0$ and $I_b = -I_c$ and $V_b = V_c$



Since $V_b = V_c$ $V_0 + a^2V_1 + aV_2 = V_0 + aV_1 + a^2V_2$
Which simplifies to $V_1 = V_2$

Since $I_b = -I_c$ $I_0 + a^2I_1 + aI_2 = -(I_0 + aI_1 + a^2I_2)$
Which simplifies to $I_1 = -I_2$

Since $I_a = 0$ $I_0 + I_1 + I_2 = 0$ where $I_1 = -I_2$
Which simplifies to $I_0 = 0$

These relationships suggest the positive and negative sequence networks are connected in parallel at the fault point.

**REFERENCE EQUATIONS**

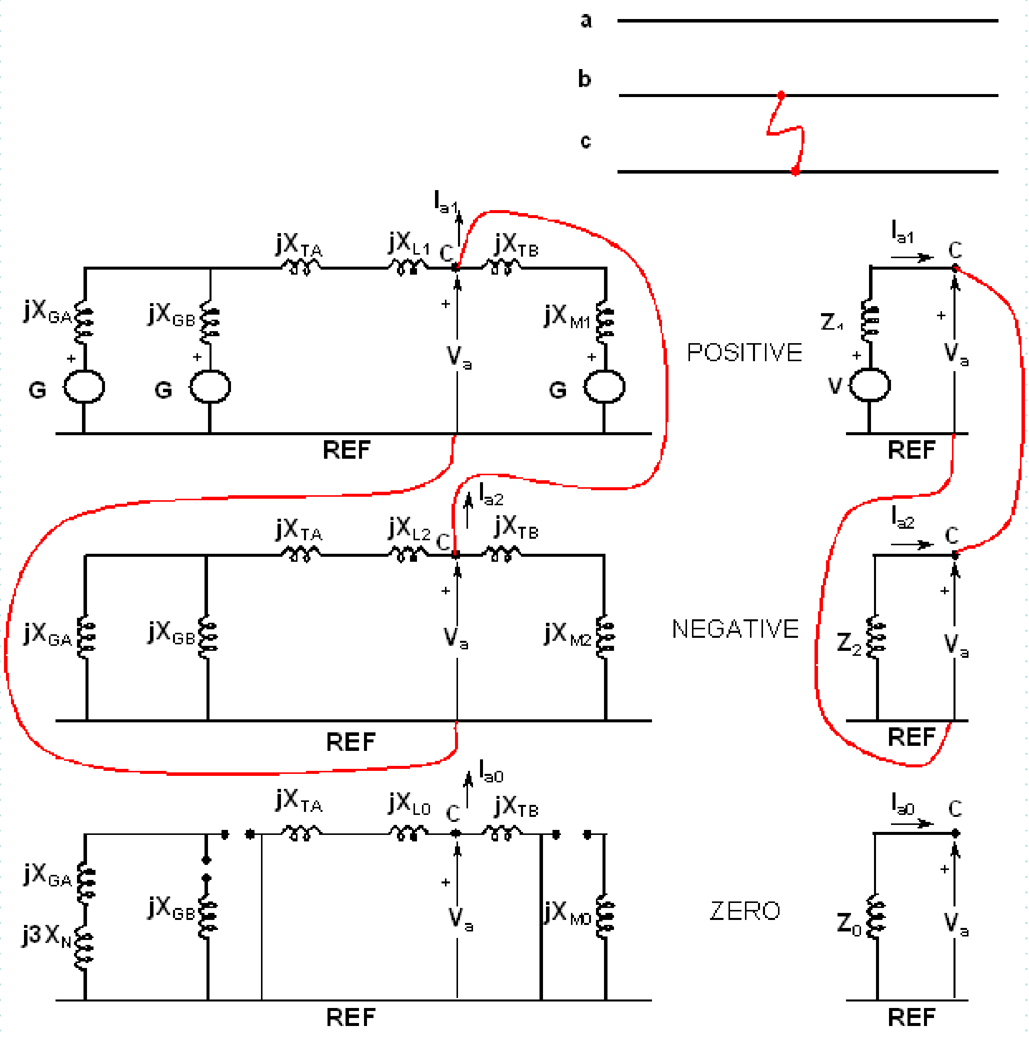
$$V_0 = \frac{1}{3}(V_a + V_b + V_c)$$
$$V_1 = \frac{1}{3}(V_a + aV_b + a^2V_c)$$
$$V_2 = \frac{1}{3}(V_a + a^2V_b + aV_c)$$

$$I_0 = \frac{1}{3}(I_a + I_b + I_c)$$
$$I_1 = \frac{1}{3}(I_a + aI_b + a^2I_c)$$
$$I_2 = \frac{1}{3}(I_a + a^2I_b + aI_c)$$

$$V_a = V_0 + V_1 + V_2$$
$$\boxed{\begin{aligned} V_b &= V_0 + a^2V_1 + aV_2 \\ V_c &= V_0 + aV_1 + a^2V_2 \end{aligned}}$$

$$\boxed{I_a = I_0 + I_1 + I_2}$$
$$\boxed{\begin{aligned} I_b &= I_0 + a^2I_1 + aI_2 \\ I_c &= I_0 + aI_1 + a^2I_2 \end{aligned}}$$

# Fault Analysis Using Symmetrical Components
# Line-to-Line (LL) Fault



$$I_a = 0$$

$$I_b = -I_c$$

$$V_b = V_c$$

$$I_{a1} = -I_{a2} = \frac{V}{Z_1 + Z_2}$$

$$V_{a1} = V_{a2}$$

# Fault Analysis Using Symmetrical Components
# Line-to-Line (LL) Fault

Line-to-Line fault. Compare to example (8.3)

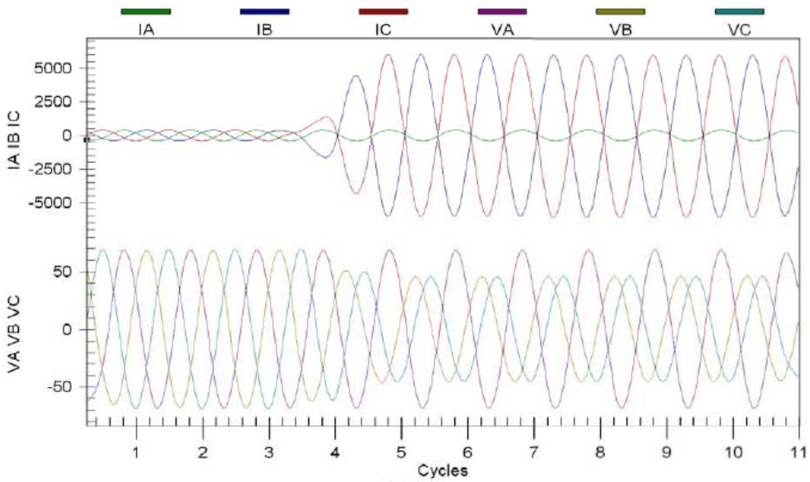
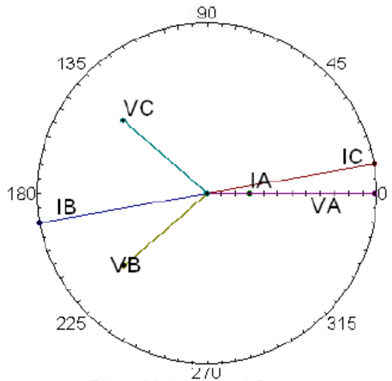
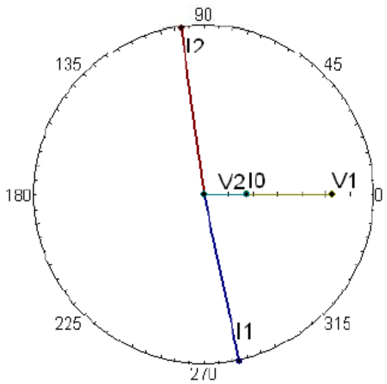


Fig 9.3a



Phase Voltages and Currents

Fig 9.3b



Sequence Components

Fig 9.3c

$$I_a = 0$$

$$I_b = -I_c$$

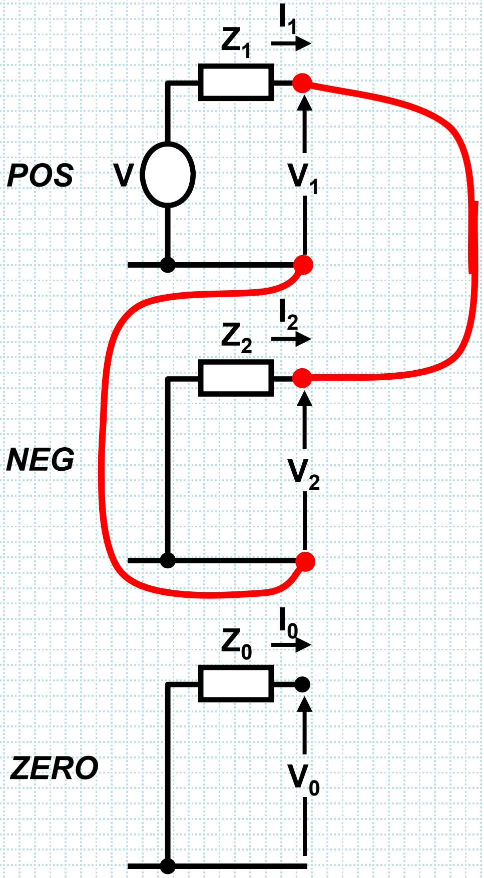
$$V_b = V_c$$

Notice there is a extra component of V1 and I1 present because of load current and source impedance.

$$V_1 \approx V_2$$

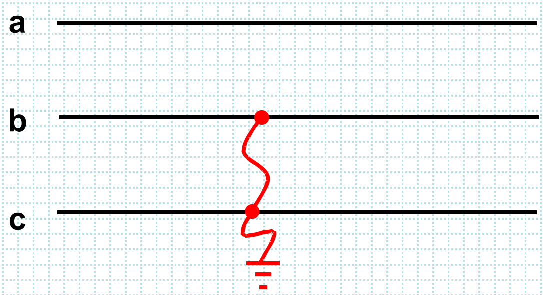
$$I_0 \approx 0$$

$$I_1 \approx -I_2$$



*The above fault record is from Washington State University's March 2011 Hands-On Relay School*

# Fault Analysis Using Symmetrical Components
# Double Line-to-Ground (DLG) Fault



At the fault point $I_a = 0$ and $V_b = V_c = 0$

Since $V_b = V_c = 0$ $V_0 + a^2V_1 + aV_2 = 0$ and
$V_0 + aV_1 + a^2V_2 = 0$

Which simplifies to $V_0 = V_1 = V_2$

Since $I_a = 0$ $I_0 + I_1 + I_2 = 0$

Or rewritten as $I_1 = -(I_0 + I_2)$

These relationships suggest the zero, positive and negative sequence networks are all connected in parallel at the fault point.

**REFERENCE EQUATIONS**

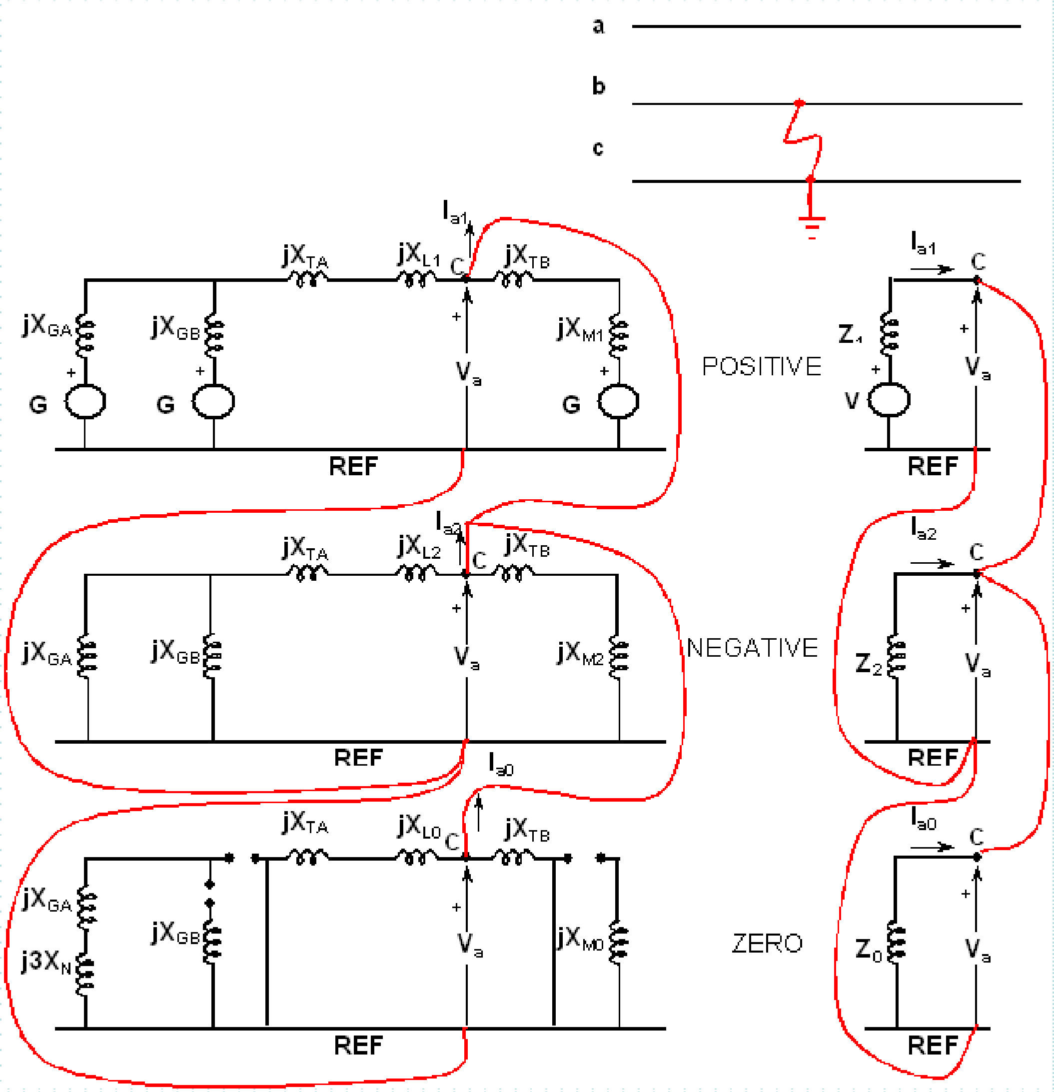
$$V_0 = \frac{1}{3}(V_a + V_b + V_c)$$
$$V_1 = \frac{1}{3}(V_a + aV_b + a^2V_c)$$
$$V_2 = \frac{1}{3}(V_a + a^2V_b + aV_c)$$

$$I_0 = \frac{1}{3}(I_a + I_b + I_c)$$
$$I_1 = \frac{1}{3}(I_a + aI_b + a^2I_c)$$
$$I_2 = \frac{1}{3}(I_a + a^2I_b + aI_c)$$

$$V_a = V_0 + V_1 + V_2$$
$$\boxed{\begin{aligned} V_b &= V_0 + a^2V_1 + aV_2 \\ V_c &= V_0 + aV_1 + a^2V_2 \end{aligned}}$$

$$\boxed{I_a = I_0 + I_1 + I_2}$$
$$I_b = I_0 + a^2I_1 + aI_2$$
$$I_c = I_0 + aI_1 + a^2I_2$$

# Fault Analysis Using Symmetrical Components
# Double Line-to-Ground (DLG) Fault



$$I_a = 0$$

$$V_b = V_c = 0$$

$$V_{a1} = V_{a2} = V_{a0}$$

$$I_{a1} = \frac{V}{Z_1 + \left[\dfrac{Z_2 Z_0}{Z_2 + Z_0}\right]}$$

# Fault Analysis Using Symmetrical Components
# Double Line-to-Ground (DLG) Fault

Double Line-to-Ground fault. Compare to example (8.4)

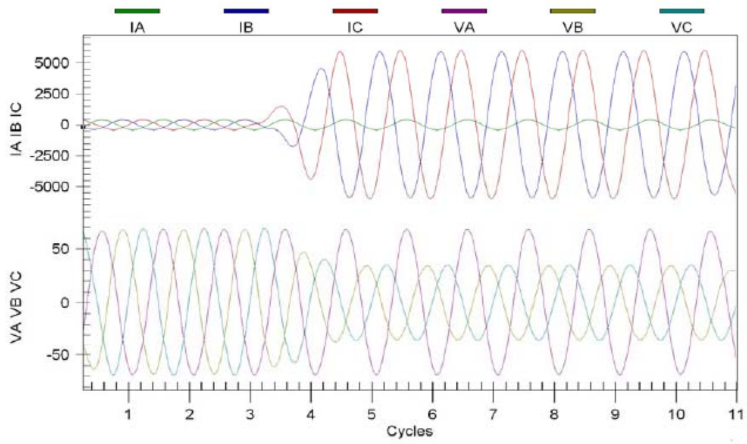
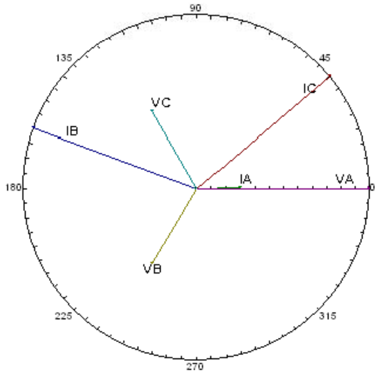
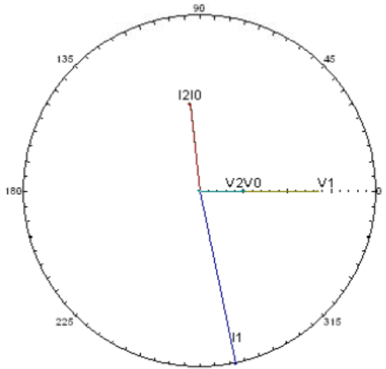


Fig 9.1a



Phase Voltages and Currents
Fig 9.4b



Sequence Components
Fig 9.4c

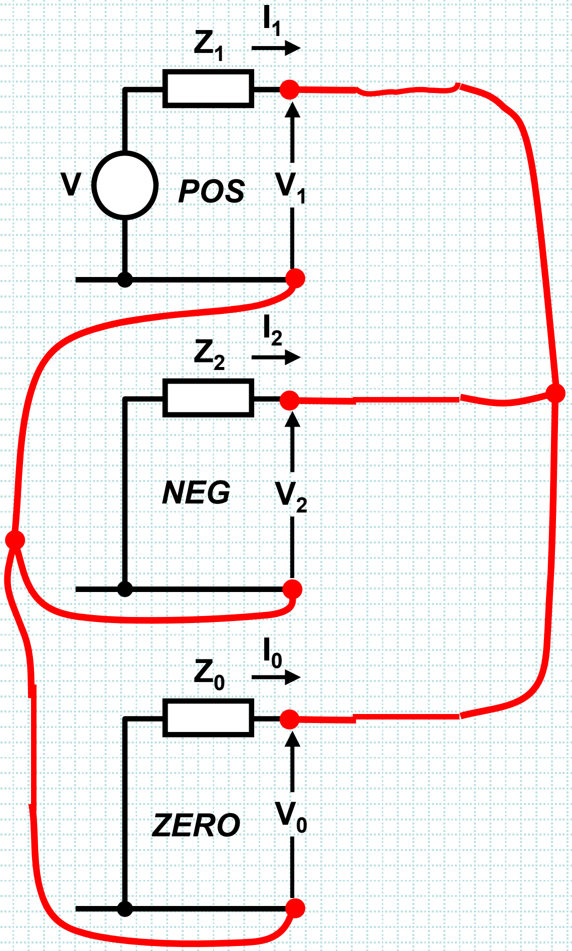
$$I_a = 0$$

$$V_b = V_c = 0$$

$$V_0 \approx V_1 \approx V_2$$

$$I_1 \approx -(I_0 + I_2)$$

Notice there is a extra component of V1 and I1 present because of load current and source impedance.



*The above fault record is from Washington State University's March 2011 Hands-On Relay School*

# Fault Analysis Using Symmetrical Components
# Phase Shifting Across Delta-Wye Transformers

For this example HV leads LV by 30°. Let the system voltage ratio (N) equal 1. Consequently, the turns ratio (n) must be 1/√3. We know that

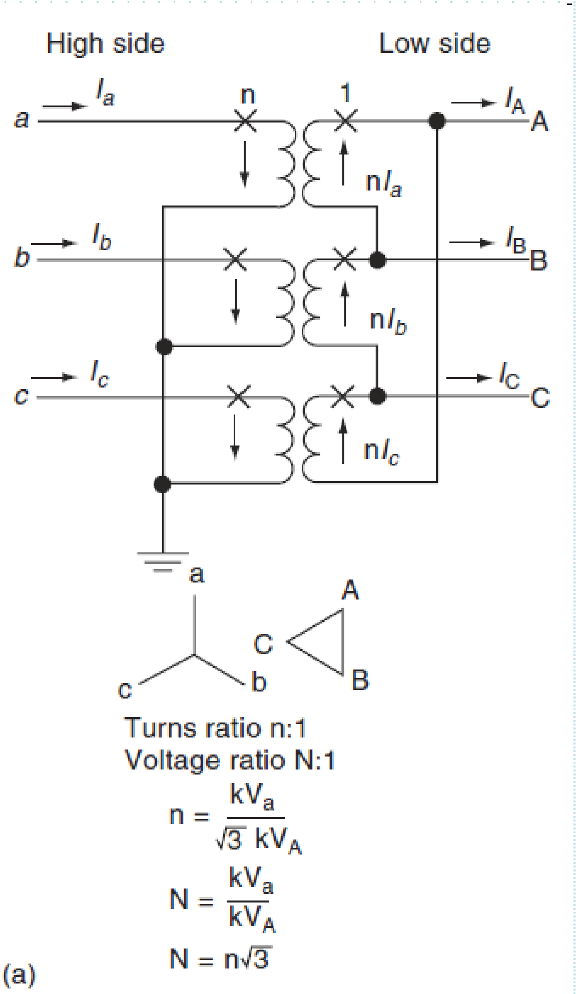
$$I_A = n(I_a - I_c) \text{ and } V_a = n(V_A - V_B).$$

Because the sequence networks are independent, we can apply them individually adding the results by superposition.

Starting with positive sequence values we get the following for voltage and current.

$$\begin{aligned} I_{A1} &= n(I_{a1} - aI_{a1}) = n(1-a)I_{a1} \\ &= \sqrt{3}nI_{a1}\,\underline{/-30^\circ} = NI_{a1}\,\underline{/-30^\circ}, \qquad \text{(A4.3-1)} \end{aligned}$$

$$\begin{aligned} V_{a1} &= n(V_{A1} - a^2V_{A1}) = n(1-a^2)V_{A1} \\ &= \sqrt{3}nV_{A1}\,\underline{/+30^\circ} = NV_{A1}\,\underline{/+30^\circ}. \qquad \text{(A4.3-2)} \end{aligned}$$



Turns ratio n:1
Voltage ratio N:1

$$n = \frac{kV_a}{\sqrt{3}\,kV_A}$$

$$N = \frac{kV_a}{kV_A}$$

$$N = n\sqrt{3}$$

*Pictures and equations are from Appendix 4.3 in Blackburn.*

# Fault Analysis Using Symmetrical Components
# Phase Shifting Across Delta-Wye Transformers

Recall from before that

$$I_A = n(I_a - I_c) \text{ and } V_a = n(V_A - V_B).$$

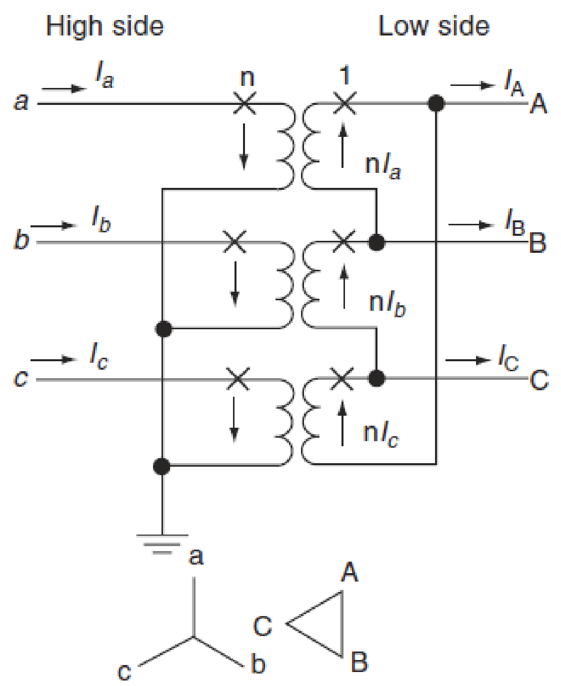
Next applying negative sequence values we get the following for voltage and current.

$$I_{A2} = n(I_{a1} - a^2 I_{a1}) = n(1 - a^2)I_{a2}$$

$$= \sqrt{3} n I_{a2} \underline{/+30^\circ} = N I_{a2} \underline{/+30^\circ}, \qquad \text{(A4.3-3)}$$

$$V_{a2} = n(V_{A2} - aV_{A2}) = n(1 - a)V_{A2}, \qquad \text{(A4.3-4)}$$

$$= \sqrt{3} n V_{A2} \underline{/-30^\circ} = N V_{A2} \underline{/-30^\circ}. \qquad \text{(A4.3-5)}$$



Turns ratio n:1
Voltage ratio N:1

$$n = \frac{kV_a}{\sqrt{3}\, kV_A}$$

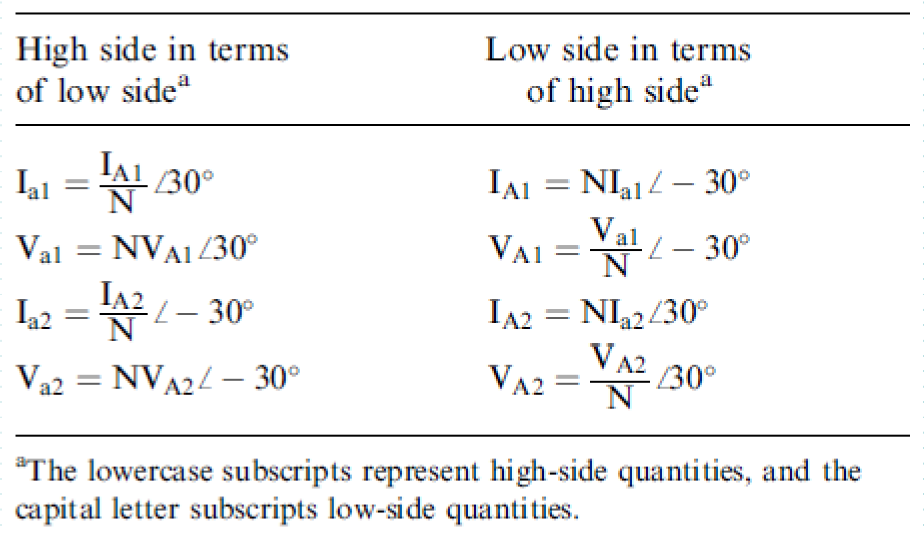
$$N = \frac{kV_a}{kV_A}$$

$$N = n\sqrt{3}$$

(a)

*Pictures and equations are from Appendix 4.3 in Blackburn.*

# Fault Analysis Using Symmetrical Components
# Phase Shifting Across Delta-Wye Transformers

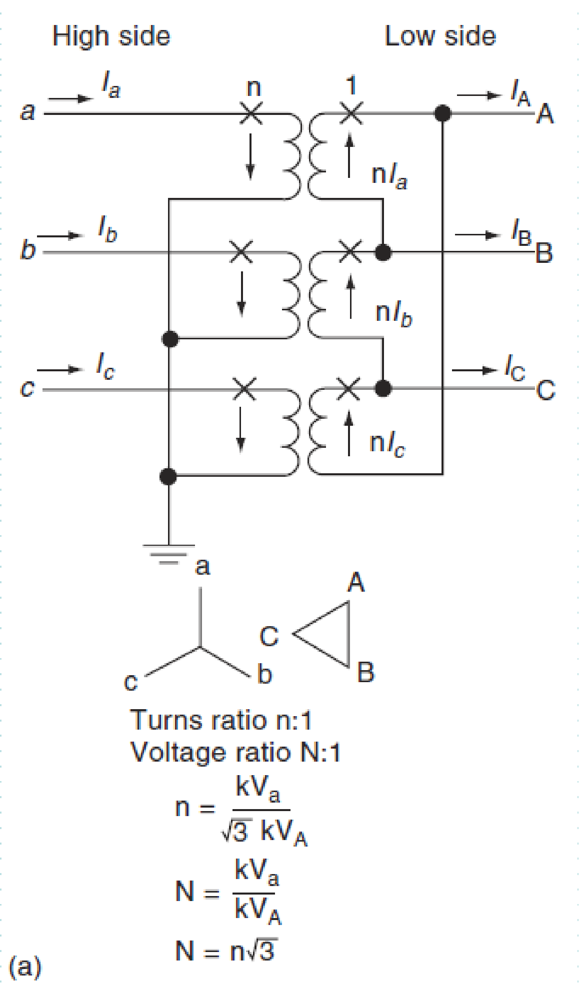


| High side in terms of low side[a] | Low side in terms of high side[a] |
|---|---|
| $I_{a1} = \frac{I_{A1}}{N}\angle 30^\circ$ | $I_{A1} = NI_{a1}\angle -30^\circ$ |
| $V_{a1} = NV_{A1}\angle 30^\circ$ | $V_{A1} = \frac{V_{a1}}{N}\angle -30^\circ$ |
| $I_{a2} = \frac{I_{A2}}{N}\angle -30^\circ$ | $I_{A2} = NI_{a2}\angle 30^\circ$ |
| $V_{a2} = NV_{A2}\angle -30^\circ$ | $V_{A2} = \frac{V_{A2}}{N}\angle 30^\circ$ |

[a] The lowercase subscripts represent high-side quantities, and the capital letter subscripts low-side quantities.

- Blackburn Appendix 4.3 provides a second transformer, Example (b), which has a high side delta, low side wye with the HV side similarly leading the low side by 30°.

- The process for determining the positive and negative sequence shift angles is the same as Example (a) as are the actual shift angles.



Turns ratio n:1
Voltage ratio N:1

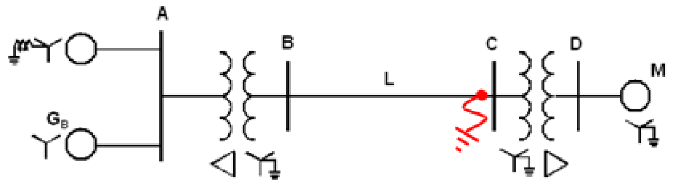
$$n = \frac{kV_a}{\sqrt{3}\,kV_A}$$

$$N = \frac{kV_a}{kV_A}$$

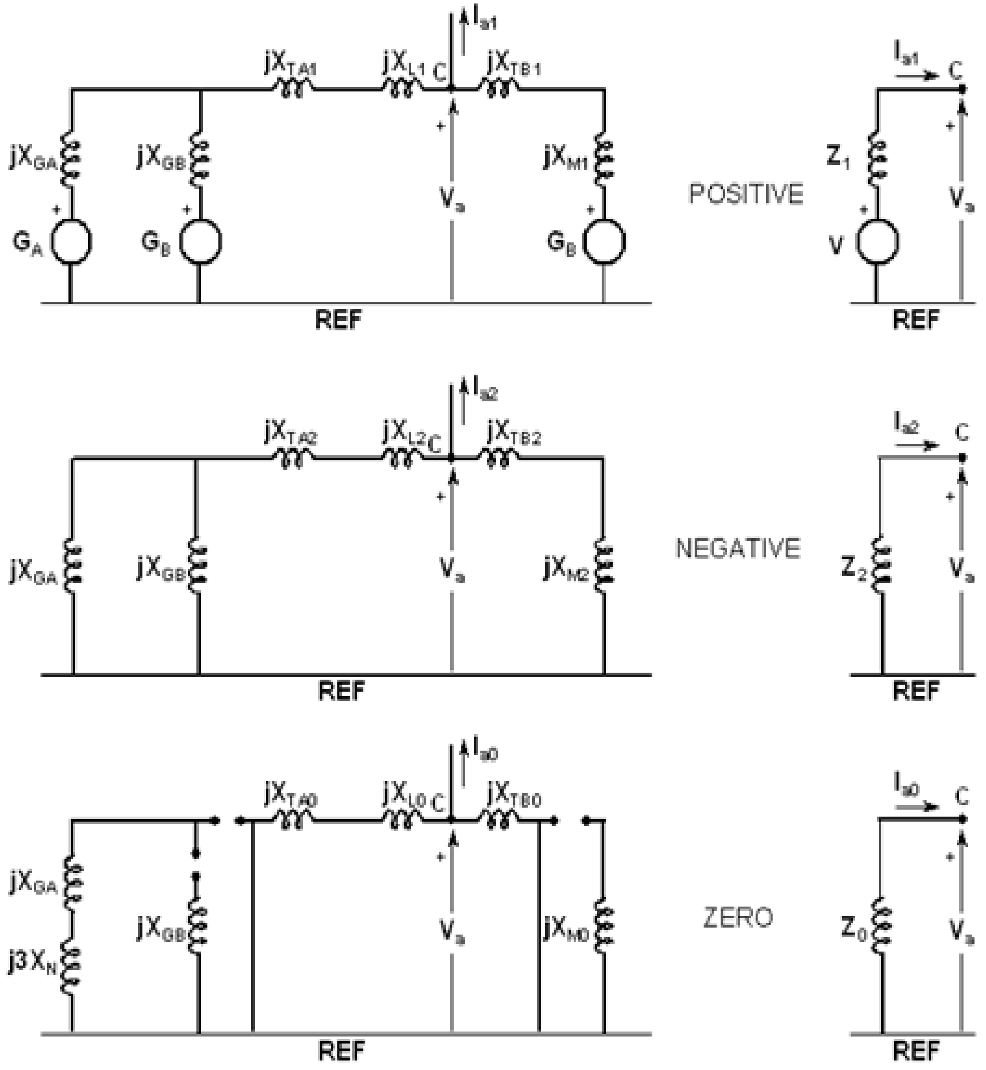
$$N = n\sqrt{3}$$

(a)

# Fault Analysis Using Symmetrical Components
Example System (Fault at Bus C)



- After interconnecting the sequence networks to model the particular fault type and solving the network to determine the fault current, you likely want to determine other internal values for particular elements – say the current through Generator GB and the voltage behind its reactance.
- You simply determine the current through GB in each network ($I_{GB0}$, $I_{GB1}$ and $I_{GB2}$) as well as the 3 voltages across GB ($V_{GB0}$, $V_{GB1}$ and $V_{GB2}$). Recall that
  - $I_{GBA} = I_{GB0} + I_{GB1} + I_{GB2}$, and
  - $V_{GBA} = V_{GB0} + V_{GB1} + V_{GB2}$.
- You similarly determine $V_{GBB}$ and $V_{GBC}$.



# Questions?