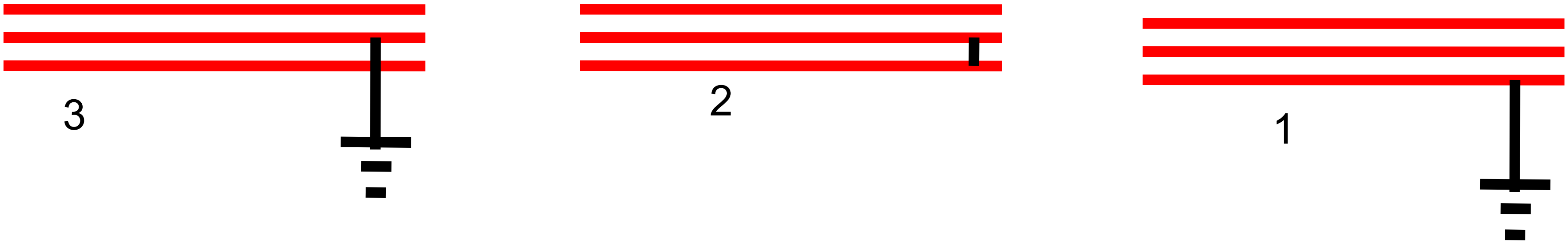
SKEE 4443
POWER SYSTEM ANALYSIS

CHAPTER 4 Cont'd

Unsymmetrical Components

Unsymmetrical Components

- Most faults are unsymmetrical faults, which result in unbalanced currents.
- Require symmetrical components to solve for the voltages and currents during the faults.
- Three major types are:
  1. Single line-to-ground
  2. Line-to-line
  3. Double-line-to-ground



$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} \quad \Rightarrow \quad \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = A \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix}$$

A

The symmetrical components of the unbalanced three-phase voltage can be expressed as

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = A^{-1} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix}$$

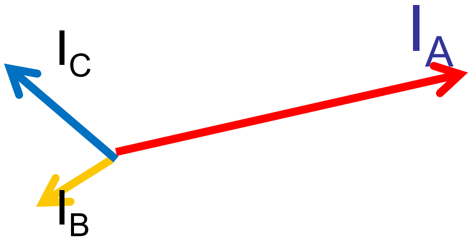
$$A^{-1} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}^{-1} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}$$

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix}$$

Symmetrical components of an unbalanced three-phase current

$I_C = I_{C1}+I_{C2}+I_{C0}$

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



$I_A = I_{A1}+I_{A2}+I_{A0}$

$I_A = I_1+I_2+I_0$

$I_B = I_{B1}+I_{B2}+I_{B0}$

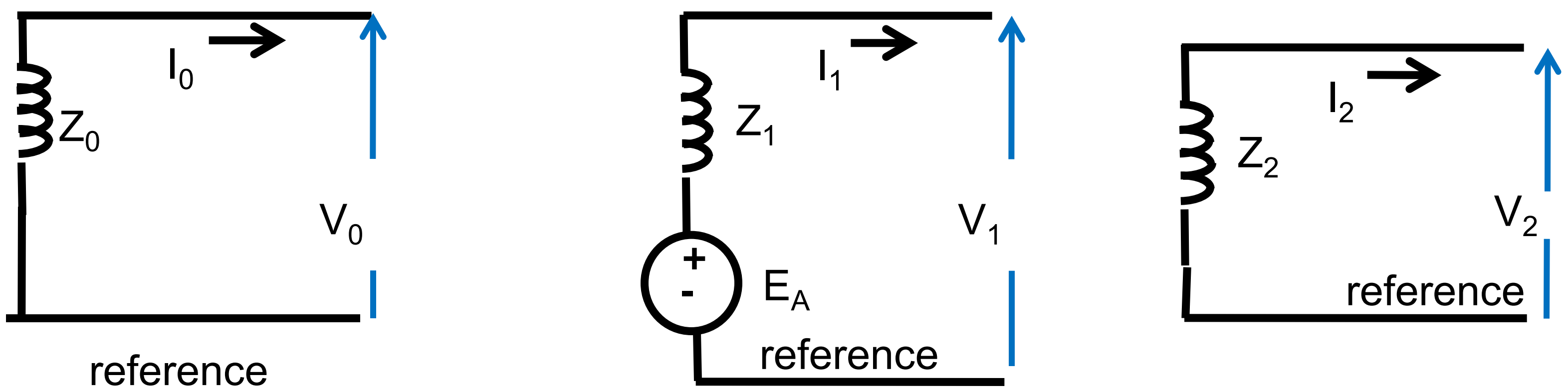
$I_B = a^2I_1+aI_2+I_0$

$$\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix}$$

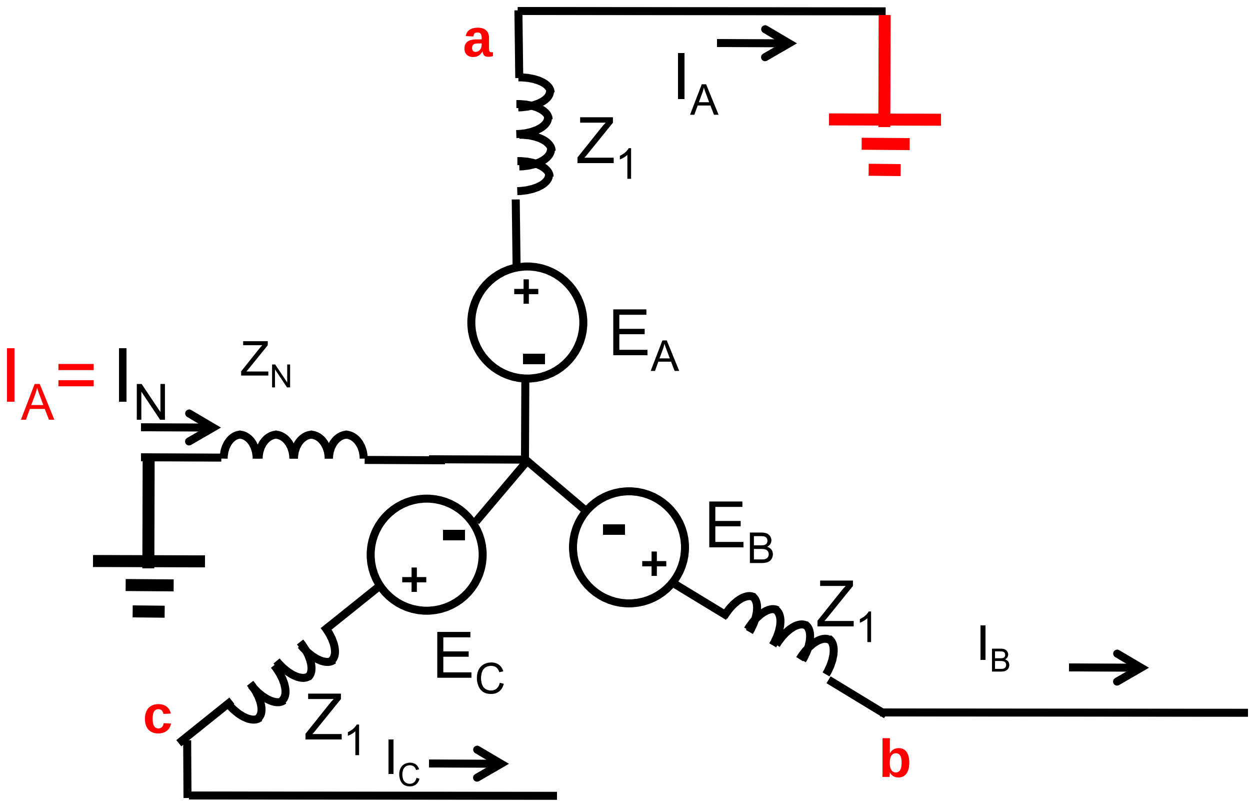
The following equations will be used in the analysis:

$$\begin{bmatrix} \bar{V}_0 \\ \bar{V}_1 \\ \bar{V}_2 \end{bmatrix} = \begin{bmatrix} 0 \\ E_A \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} \bar{I}_0 \\ \bar{I}_1 \\ \bar{I}_2 \end{bmatrix}$$



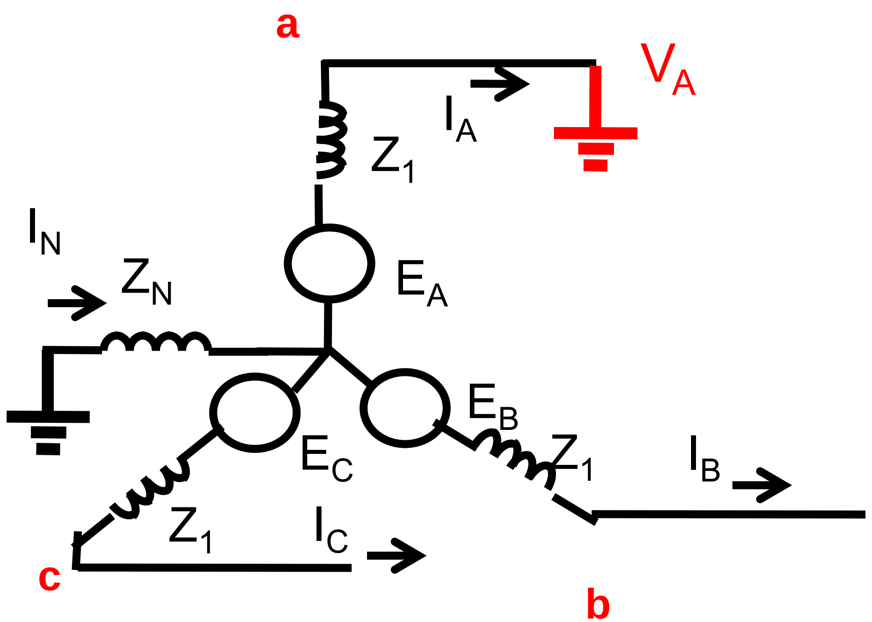
Thevenin equivalents of the sequence networks as seen from the fault point F

Unloaded generator with single line-to-ground fault



Unloaded generator grounded through a reactor (impedance Z_N)

When the fault occur

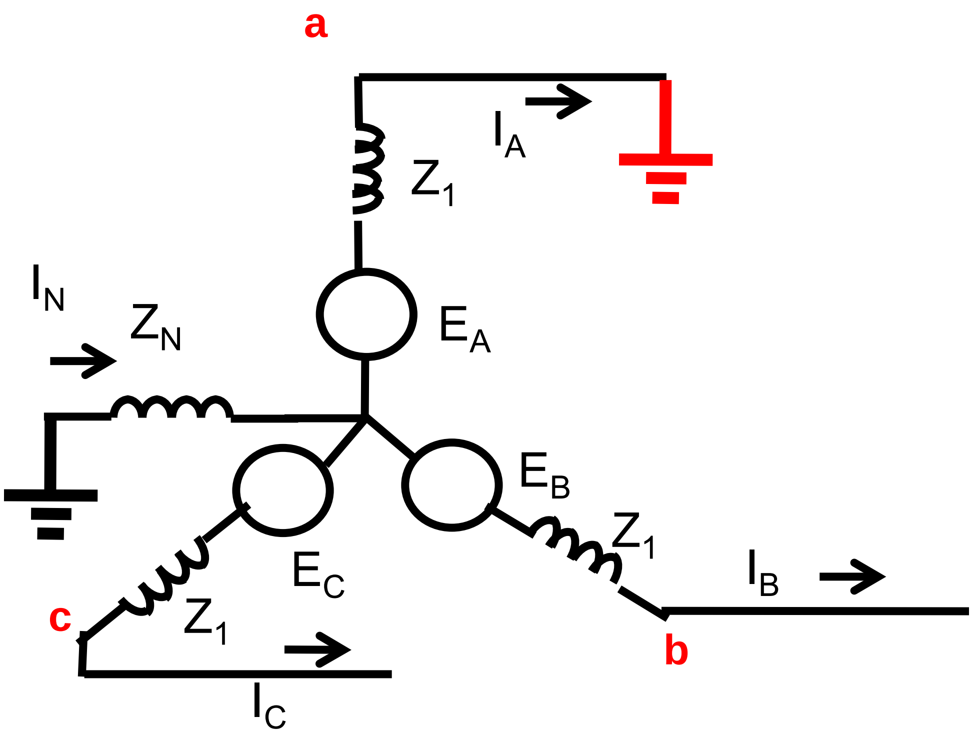


$$I_B = I_C = 0 \qquad V_A = 0$$

Symmetrical components of the fault currents can be found from

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} I_A \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_A \\ 0 \\ 0 \end{bmatrix}$$



$$I_0 = I_1 = I_2 = I_A / 3$$

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 0 \\ E_A \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix}\begin{bmatrix} I_0 = I_1 \\ I_1 \\ I_2 = I_1 \end{bmatrix}$$

Hence:

$$V_0 = -I_1 Z_0$$

$$V_1 = E_A - I_1 Z_1$$

$$V_2 = -I_1 Z_2$$

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 0 \\ E_A \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} I_1 \\ I_1 \\ I_1 \end{bmatrix}$$

And

$$V_A = V_1 + V_2 + V_0$$

$$= E_A - I_1 Z_1 - I_1 Z_2 - I_1 Z_0$$

$$V_A = E_A - I_1 Z_1 - I_1 Z_2 - I_1 Z_0$$

However $V_A = 0$ hence

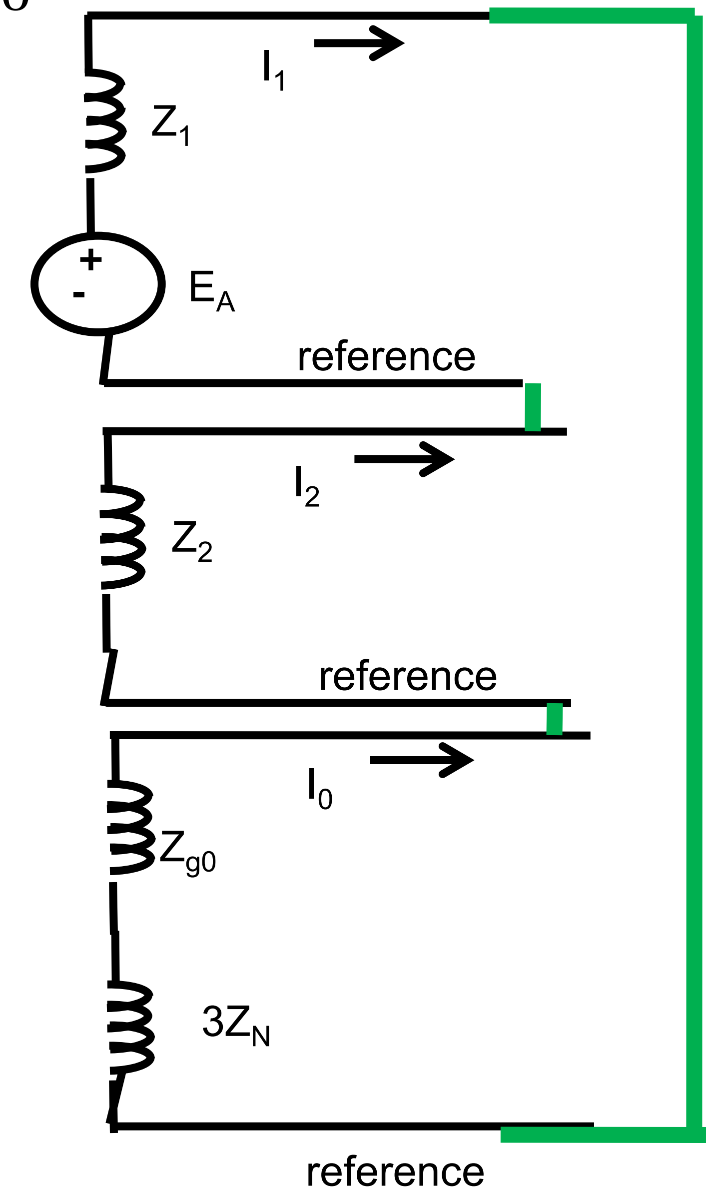
$$I_1 (Z_1 + Z_2 + Z_0) = E_A$$

$$I_1 = \frac{E_A}{(Z_1 + Z_2 + Z_0)}$$

So,

$$I_A = I_0 + I_1 + I_2 = 3 \times I_1$$

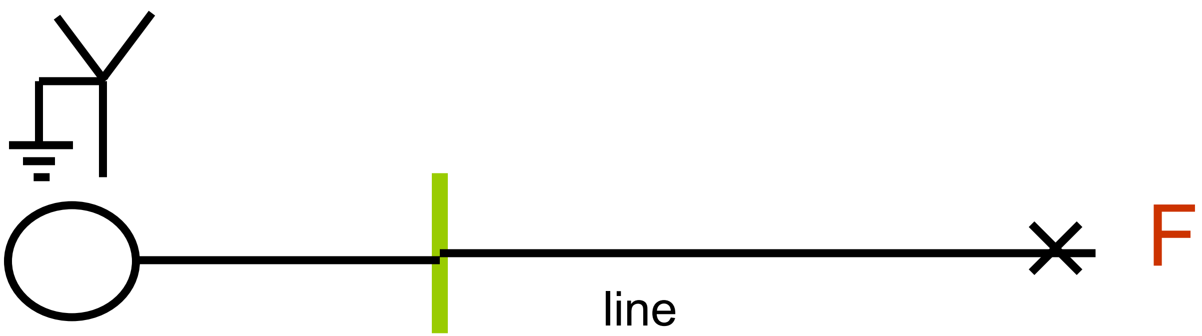
This is equivalent to connecting the three sequence networks in series



Example

- A 150 MVA, 13.8 kV, Y connected synchronous generator has a synchronous, negative and zero sequence reactances 20%, 10%, and 5% respectively. The neutral of the generator is solidly grounded. Generator is connected to short transmission line with positive and negative sequence reactances of 10%, and zero sequence impedance of 30%. The generator was unloaded when a single-line-to-ground fault occurs on phase a at the end of the line. Find the fault currents and the voltage at fault point and at the generator terminals.

Solution



150 MVA,

13.8 kV

X_s=0.20 pu

X_2 = 0.10 pu

X_0= 0.05 pu

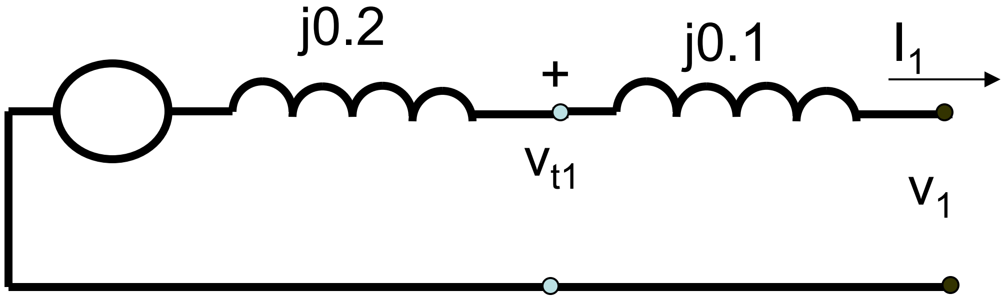
line

X_1=X_2 = 0.10 pu

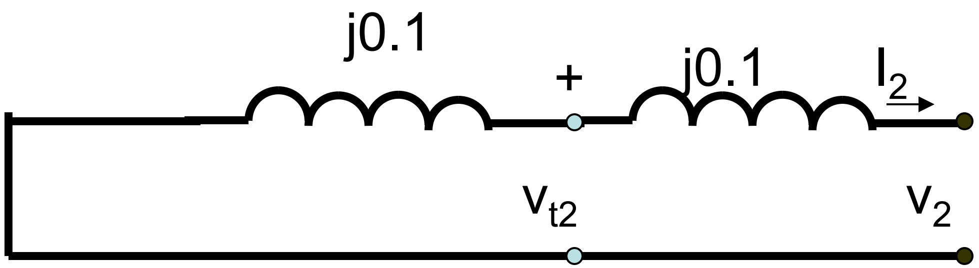
X_0= 0.30 pu

One line diagram

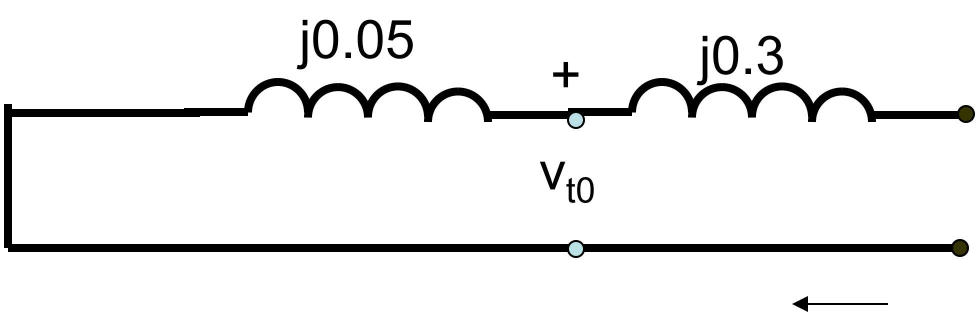
Draw positive sequence network



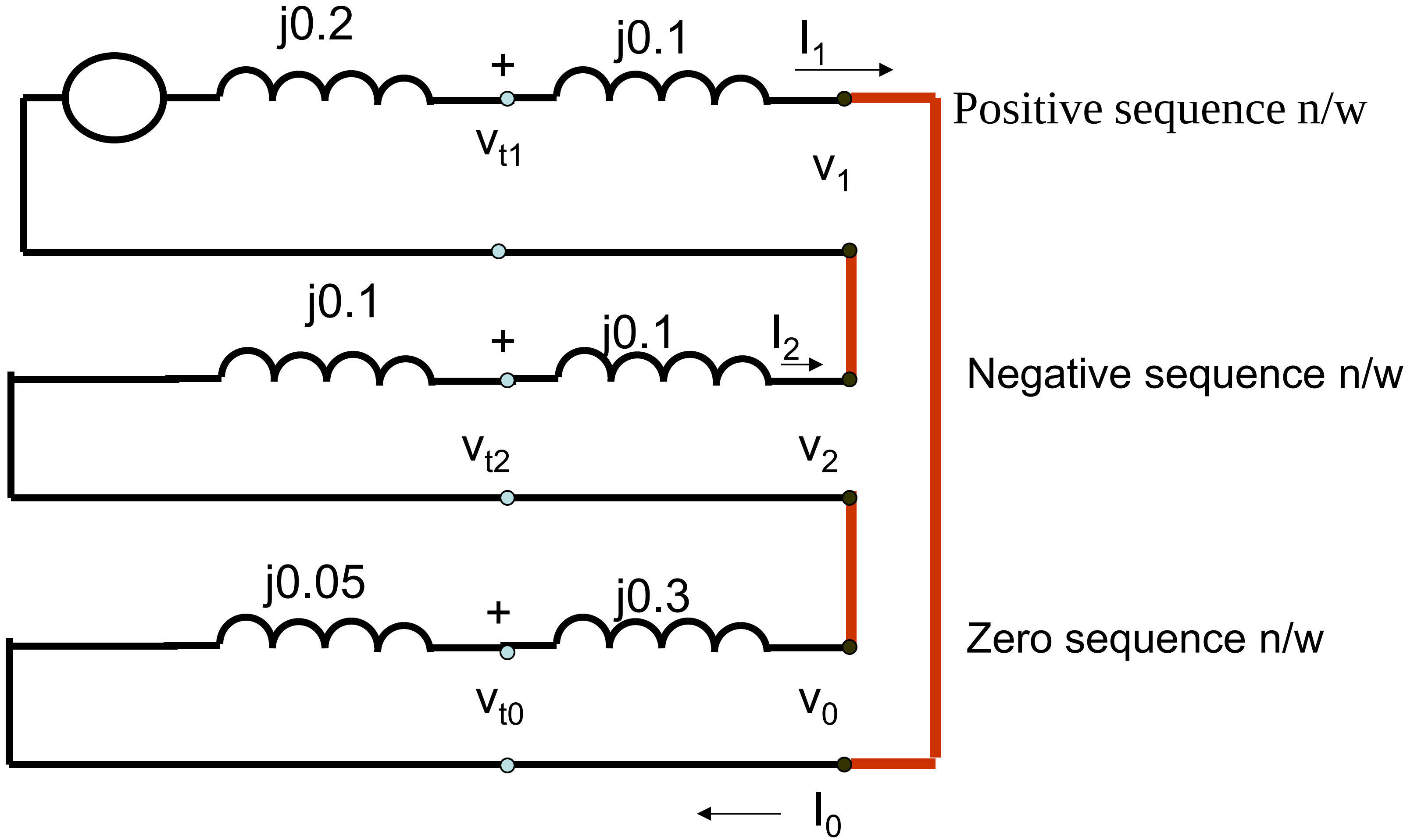
Draw negative sequence network



Draw zero sequence network



Connection for single-line-to-ground fault



$$I_1 = \frac{E_A}{(Z_1 + Z_2 + Z_0)}$$

$$E_a = 1.0\angle 0°$$

$$I_1 = \frac{1\angle 0^\circ}{(Z_1 + Z_2 + Z_0)}$$

$$= \frac{1\angle 0^\circ}{j(0.3 + 0.2 + 0.35)}$$

$$= \frac{1\angle 0^\circ}{j(0.85)}$$

$$= 1.176\angle -90^\circ$$

$$= -j1.176$$

$$I_1 = I_2 = I_0$$

$$= 1.176\angle -90^\circ$$

$$I_a = 3I_1$$

$$= 3 \times 1.176\angle -90^\circ$$

$$= 3.528\angle -90^\circ \, pu$$

Phase currents

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} 1.176\angle -90^\circ \\ 1.176\angle -90^\circ \\ 1.176\angle -90^\circ \end{bmatrix}$$

$$= \begin{bmatrix} 3.528\angle -90^\circ \\ 0 \\ 0 \end{bmatrix} pu$$

I_{base} at the fault

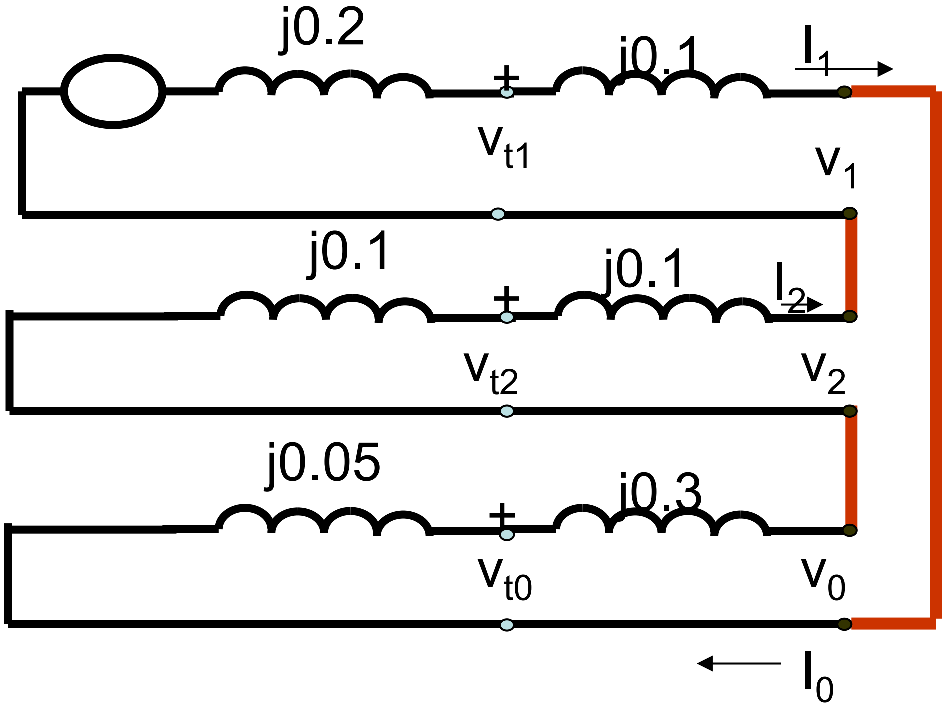
$$I_{\text{base}} = \frac{150{,}000}{13.8\sqrt{3}} = 6276 \quad A$$

$$I_{\text{a}} = 3.528 \times 6276 = 22{,}140 \quad A$$

$$I_{\text{b}} = 0 \quad A$$

$$I_{\text{c}} = 0 \quad A$$

Voltage at the terminals of the generator (symmetrical components)



$$\begin{aligned} V_{t0} &= -j0.05\, I_0 \\ &= -j0.05 \times -j1.176 \\ &= -0.0588 \quad pu \end{aligned}$$

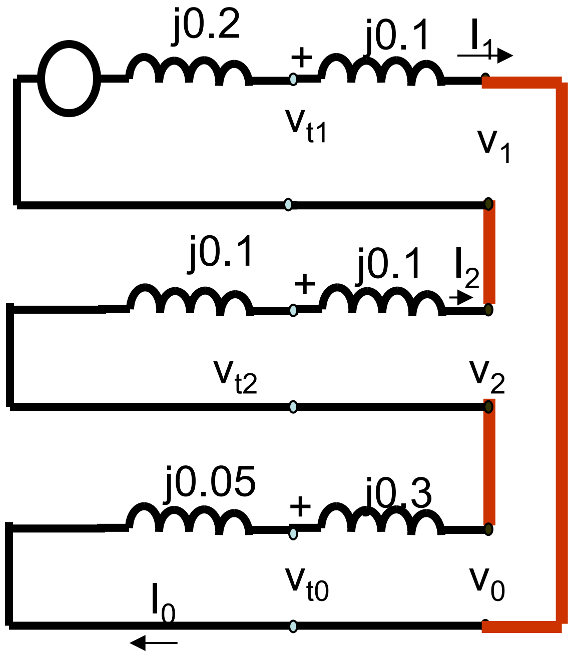
Voltage at the terminals of the generator

$$V_{t1} = E_a - j0.20 \times I_1$$
$$= 1.0\angle 0° - (j0.20)(-j1.176)$$
$$= 0.7648 \quad pu$$

$$V_{t2} = -j0.10 \times I_2$$
$$= -(j0.10)(-j1.176)$$
$$= -0.1176 \quad pu$$

$$V_{t0} = -j0.05\, I_0$$
$$= -j0.05 \times -j1.176$$
$$= -0.0588 \quad pu$$

Phase voltage (line to ground) at the terminals

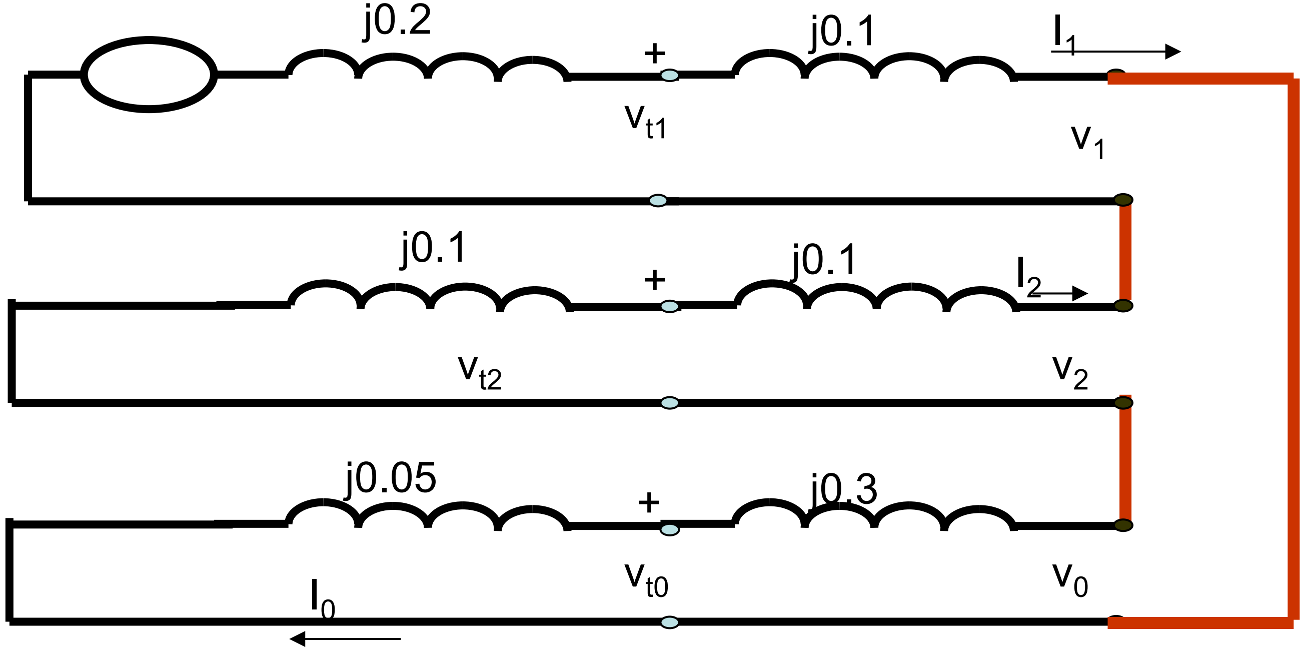


$$\begin{bmatrix} V_{ta} \\ V_{tb} \\ V_{tc} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_{t0} \\ V_{t1} \\ V_{t2} \end{bmatrix}$$

$$\begin{bmatrix} V_{ta} \\ V_{tb} \\ V_{tc} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} -0.0588 \\ 0.7648 \\ -0.1176 \end{bmatrix}$$

$$= \begin{bmatrix} 0.588\angle 0^\circ \\ 0.855\angle -117^\circ \\ 0.855\angle 117^\circ \end{bmatrix} pu$$

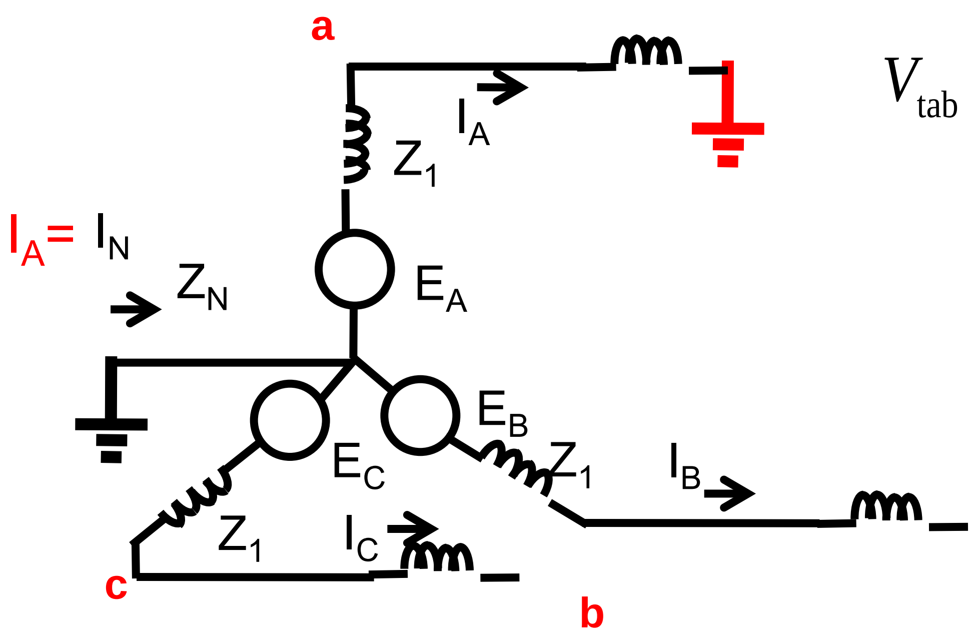
Phase voltage at the terminals



$$\begin{bmatrix} V_{ta} \\ V_{tb} \\ V_{tc} \end{bmatrix} = \begin{bmatrix} 0.588\angle 0^\circ \\ 0.855\angle -117^\circ \\ 0.855\angle 117^\circ \end{bmatrix} \left(\frac{13.8}{\sqrt{3}} kV\right)$$

$$= \begin{bmatrix} 4.685\angle 0^\circ \\ 6.812\angle -117^\circ \\ 6.812\angle 117^\circ \end{bmatrix} kV$$

Since the generated voltage to neutral E_A was taken as 1 p.u, the line to line voltages are expressed in p.u, of the base voltage to neutral. Expressed in volts, the post fault line voltages are



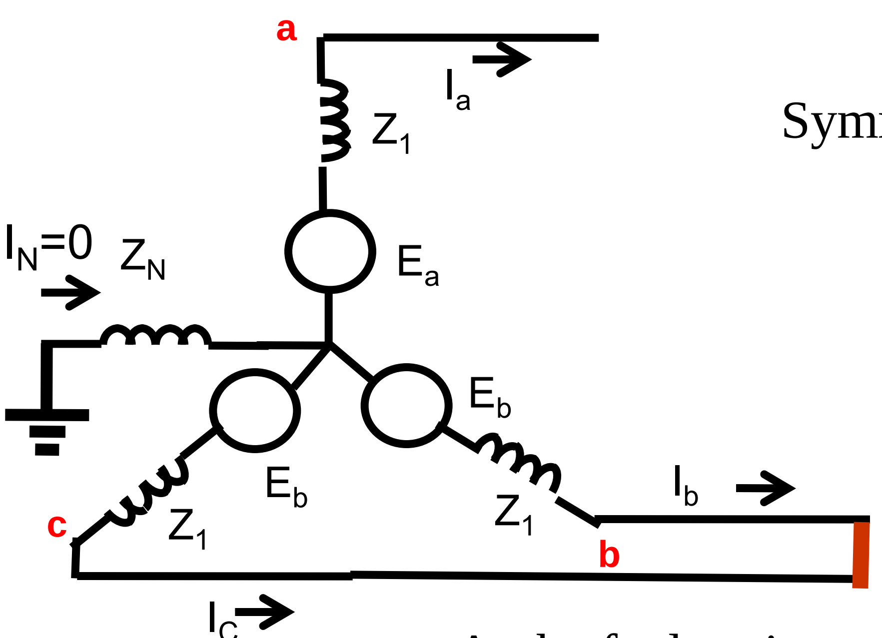
$$V_{tab} = V_{ta} - V_{tb}$$
$$= 4.685 + j0 - (-3.0926 - j6.0695)$$
$$= 9.8656\angle 37.97 \quad kV$$

$$V_{tbc} = V_{tb} - V_{tc}$$
$$= (-3.0926 - j6.0695) - (-3.0926 + j6.0695)$$
$$= -j12.1391$$
$$= 12.1391\angle -90 \quad kV$$

Line voltage at the terminals

$$V_{tca} = \mathrm{V}_{tc} - \mathrm{V}_{ta}$$
$$= (-3.0926 + j6.0695) - 4.685$$
$$= -7.7776 + j6.0695$$
$$= 9.8656\angle 142.03 \quad kV$$

Line-to-line fault on an unloaded generator



At the fault point

$$I_a = 0 \quad V_b = V_c \quad I_b = -I_c$$

Symmetrical components

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

$$V_1 = V_2$$

As, $I_b = -I_c \quad \bar{I}_a = 0$

The symmetrical components of current

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} 0 \\ -I_c \\ I_c \end{bmatrix}$$

so, $I_0 = 0$

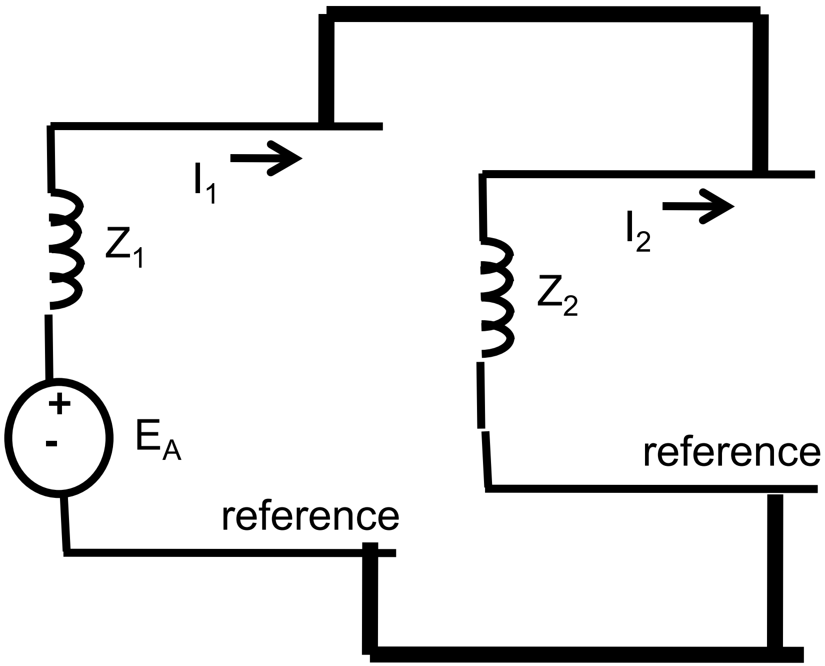
The zero sequence network is unconnected: $I_2 = -I_1$

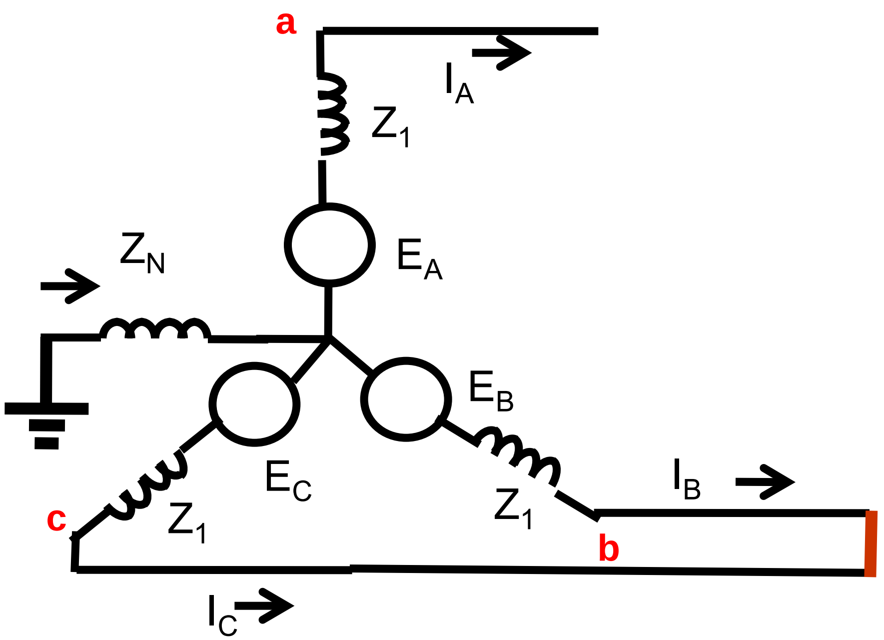
$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} 0 \\ I_1 \\ -I_1 \end{bmatrix}$$

$V_0 = 0 \qquad V_1 = E_a - I_1 Z_1 \qquad V_2 = I_1 Z_2$

But, $V_1 = V_2$ $I_1 Z_2 = E_a - I_1 Z_1$ $\Rightarrow$ $I_1 = \dfrac{E_a}{Z_1 + Z_2}$

The positive and negative sequence networks are connected in parallel:





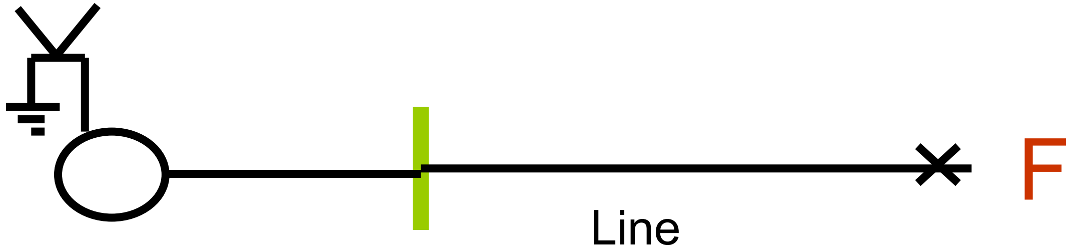
$$I_1 = \frac{E_a}{Z_1 + Z_2}$$

Example

- A 150 MVA, 13.8 kV, Y connected synchronous generator has a synchronous reactance, negative sequence reactance and zero sequence reactance 20%, 10%, and 5% respectively. The neutral of the generator is solidly grounded.
- Generator is connected to short transmission line with positive and negative sequence reactance of 10%, and zero sequence impedance of 30%.
- The generator was unloaded when a line-to-line fault occurs on phase b and c at the end of the line. Find the voltages and fault currents at the fault point and at the generator terminals.

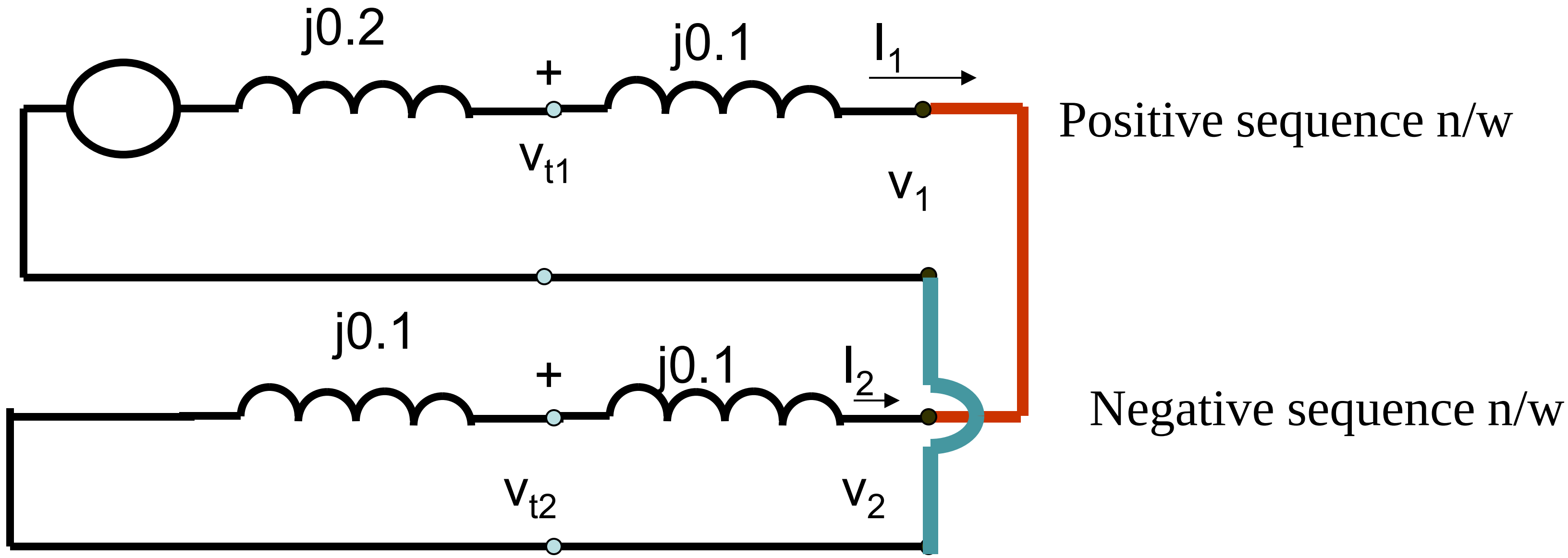
Solution

150 MVA, 13.8 Kv, X_s=0.20 pu, X_2 = 0.10 pu, X_0= 0.05 pu



$X_1 = X_2 = 0.10$ pu

$X_0 = 0.30$ pu



$$E_a = 1.0\angle 0^\circ$$

$$I_1 = \frac{1\angle 0^\circ}{(Z_1 + Z_2)} = \frac{1\angle 0^\circ}{j(0.3 + 0.2)}$$

$$= \frac{1\angle 0^\circ}{j(0.5)} = 2\angle -90^\circ = -j2.0\ pu$$

$$I_0 = 0\ pu$$

$$I_2 = -I_1 = 2\angle 90^\circ = j2.0\ pu$$

Phase currents

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} 0 \\ -j2 \\ j2 \end{bmatrix}$$

$$= \begin{bmatrix} 0 \\ -3.46 \\ 3.46 \end{bmatrix} pu = \begin{bmatrix} 0 \\ -21.74 \\ 21.74 \end{bmatrix} kA$$

Phase terminal voltages

$$V_{t0} = 0$$

$$V_{t1} = E_a \text{ - } j0.20 \times I_1$$

$$= 1.0\angle 0° - (j0.20)(-j2.0)$$

$$= 0.6\angle 0° \quad pu$$

Phase terminal voltages

$$
\begin{aligned}
V_{t2} &= -j0.10 \times I_2 \\
&= -(j0.10)(j2.0) \\
&= 0.2\angle 0^\circ \quad pu
\end{aligned}
$$

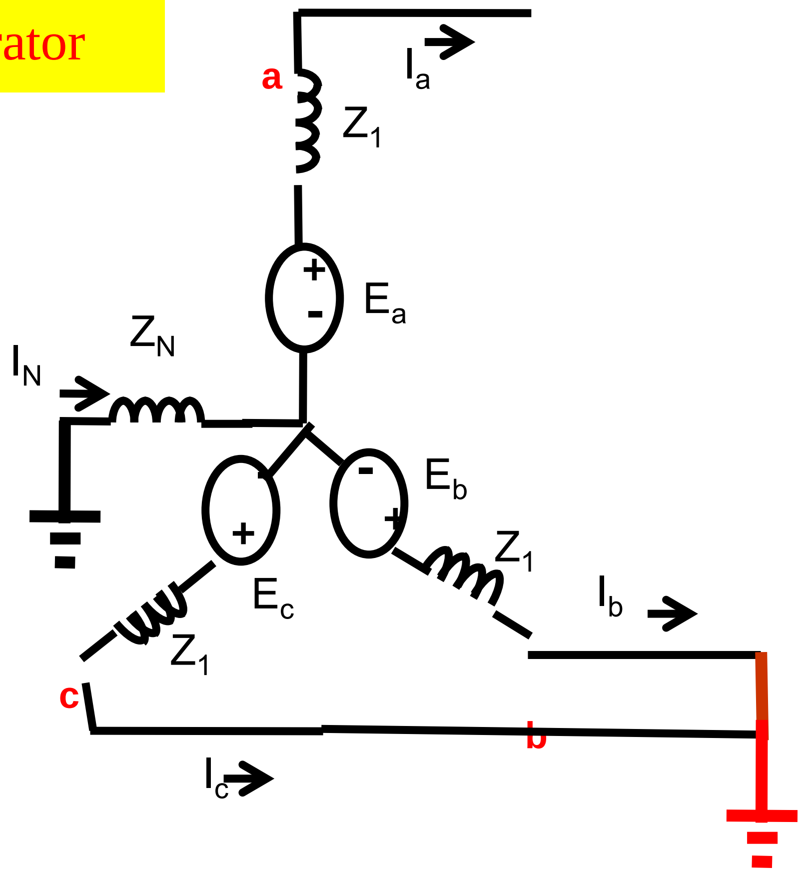
$$
\begin{bmatrix} V_{ta} \\ V_{tb} \\ V_{tc} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} 0.0 \\ 0.6 \\ 0.2 \end{bmatrix}
$$

$$
= \begin{bmatrix} 0.8\angle 0^\circ \\ 0.53\angle -139^\circ \\ 0.53\angle 139^\circ \end{bmatrix} pu = \begin{bmatrix} 6.37\angle 0^\circ \\ 4.22\angle -139^\circ \\ 4.22\angle 139^\circ \end{bmatrix} kV
$$

Double line-to-ground fault of an unloaded generator

At the fault location: $I_a = 0$

$$V_b = 0 \qquad V_c = 0,$$



Symmetrical components becomes:

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_a \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{aligned} V_{a0} &= V_{a1} \\ &= V_{a2} \\ &= V_a / 3 \end{aligned}$$

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

$$\mathrm{V}_0 = \mathrm{V}_1 = \mathrm{V}_2 = {\mathrm{V}_\mathrm{a}}/{3}$$

$$\begin{bmatrix} E_a - I_1 Z_1 \\ E_a - I_1 Z_1 \\ E_a - I_1 Z_1 \end{bmatrix} = \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

$$Z = \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix}$$

$$Z^{-1} = \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix}^{-1} = \begin{bmatrix} \frac{1}{Z_0} & 0 & 0 \\ 0 & \frac{1}{Z_1} & 0 \\ 0 & 0 & \frac{1}{Z_2} \end{bmatrix}$$

$$\begin{bmatrix} E_a - I_1 Z_1 \\ E_a - I_1 Z_1 \\ E_a - I_1 Z_1 \end{bmatrix} = \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

$$[Z]^{-1} \begin{bmatrix} E_a - I_1 Z_1 \\ E_a - I_1 Z_1 \\ E_a - I_1 Z_1 \end{bmatrix} = [Z]^{-1} \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - [Z]^{-1}[Z] \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

$$[Z]^{-1}\begin{bmatrix} E_a - I_1 Z_1 \\ E_a - I_1 Z_1 \\ E_a - I_1 Z_1 \end{bmatrix} = [Z]^{-1}\begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

$$Z^{-1} = \begin{bmatrix} \frac{1}{Z_0} & 0 & 0 \\ 0 & \frac{1}{Z_1} & 0 \\ 0 & 0 & \frac{1}{Z_2} \end{bmatrix}$$

$$\begin{bmatrix} \frac{1}{Z_0} & 0 & 0 \\ 0 & \frac{1}{Z_1} & 0 \\ 0 & 0 & \frac{1}{Z_2} \end{bmatrix}\begin{bmatrix} E_a - I_1 Z_1 \\ E_a - I_1 Z_1 \\ E_a - I_1 Z_1 \end{bmatrix} = \begin{bmatrix} \frac{1}{Z_0} & 0 & 0 \\ 0 & \frac{1}{Z_1} & 0 \\ 0 & 0 & \frac{1}{Z_2} \end{bmatrix}\begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

Solving the equation gives:

$$\frac{\mathbf{E_a - I_1 Z_1}}{\mathbf{Z_0}} = -\mathbf{I_0} \qquad \frac{\mathbf{E_a - I_1 Z_1}}{\mathbf{Z_2}} = -\mathbf{I_2}$$

$$\frac{E_a - I_1 Z_1}{Z_1} = \frac{E_a}{Z_1} - I_1 \qquad I_a = I_0 + I_1 + I_2 = 0$$

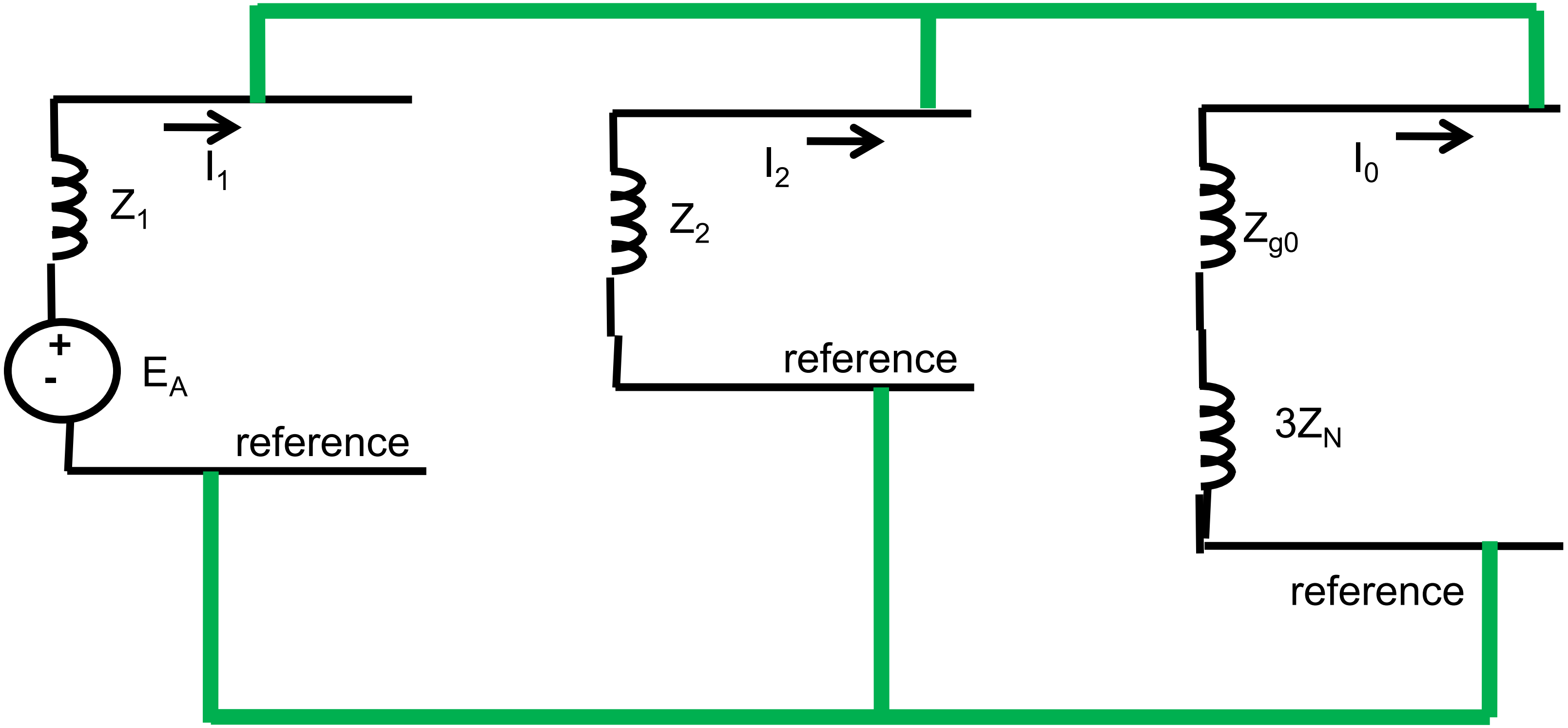
$$-\frac{E_a}{Z_0} + I_1 \frac{Z_1}{Z_0} + I_1 - \frac{E_a}{Z_2} + I_1 \frac{Z_1}{Z_2} = 0$$

$$I_1\left(1 + \frac{Z_1}{Z_0} + \frac{Z_1}{Z_2}\right) = \frac{E_a\left(Z_2 + Z_0\right)}{Z_2 Z_0}$$

$$I_1 = \frac{E_a\left(Z_2 + Z_0\right)}{Z_2 Z_1 + Z_2 Z_0 + Z_1 Z_0}$$

$$I_1 = \frac{E_a}{Z_1 + \dfrac{Z_2 Z_0}{Z_2 + Z_0}}$$

Networks connection becomes:



$$I_1 = \frac{E_a}{Z_1 + \dfrac{Z_2 Z_0}{Z_2 + Z_0}}$$

Example

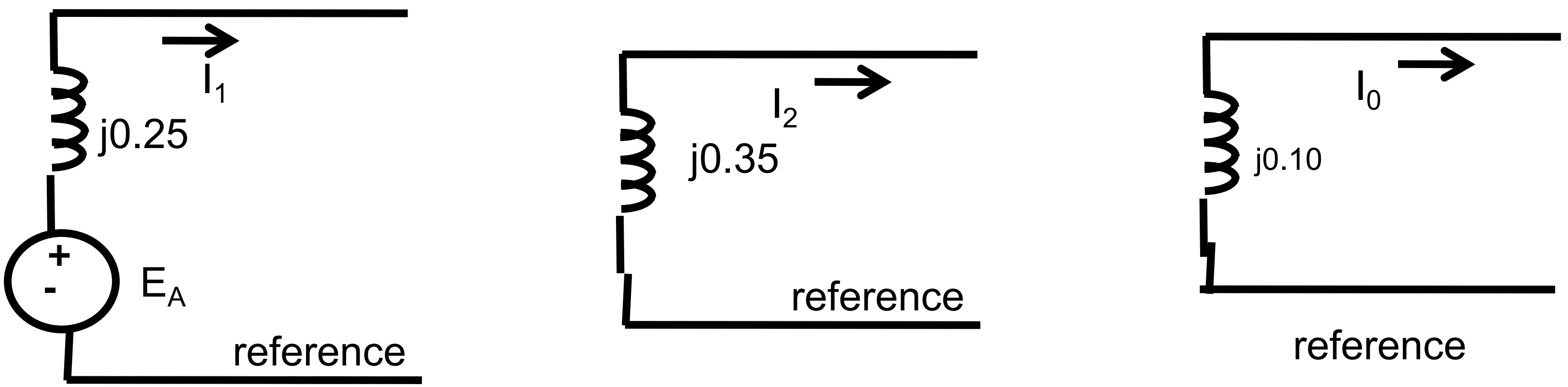
A 20 MVA, 13.8 kV, undamped salient pole synchronous generator, has the following data: $X_d''=0.25$ pu. $X_2=0.35$ pu, $X_0=0.10$ pu

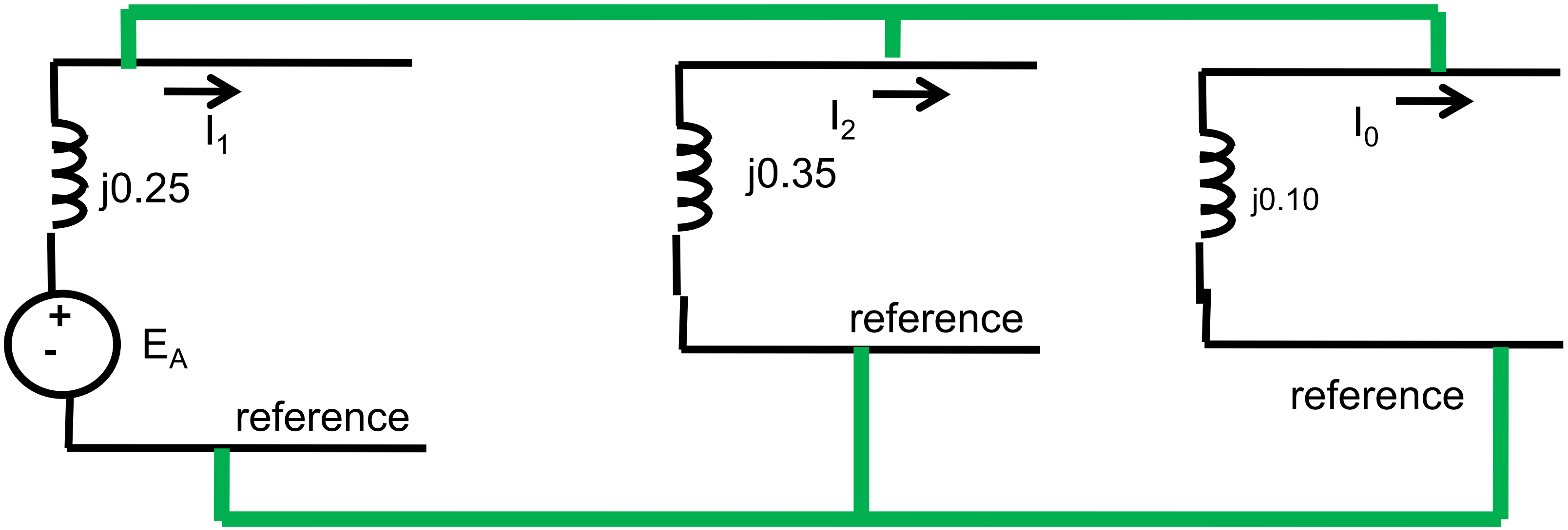
Neutral is solidly grounded.

Calculate subtransient fault current and line voltages when a double-line-to fault occurs at its terminal.

Solution

Sequence networks for the generator:



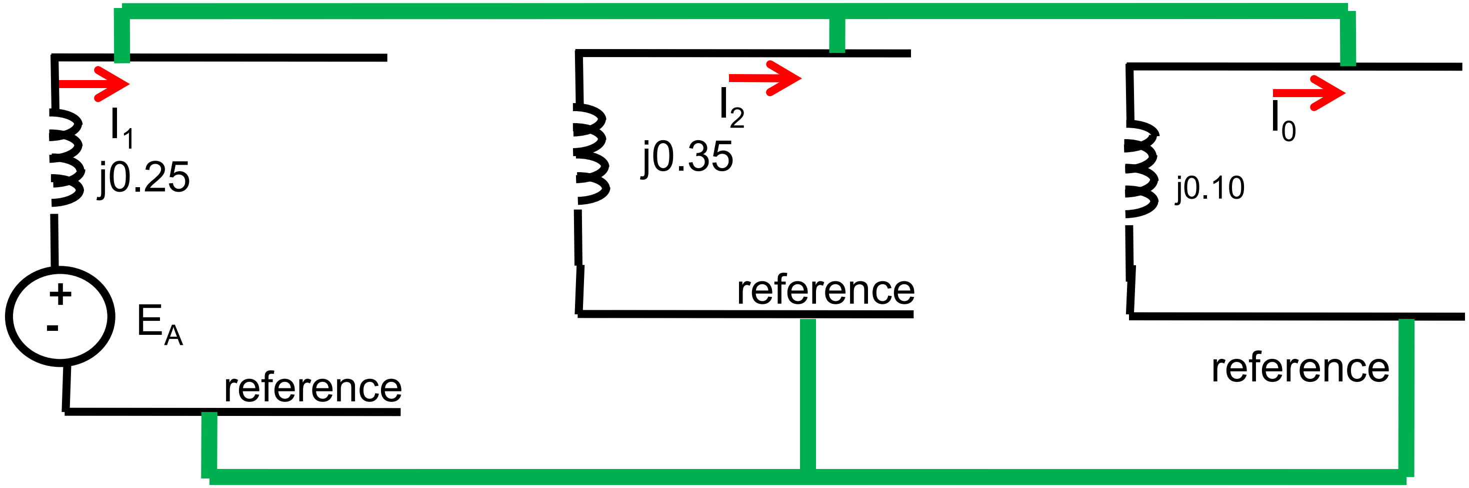


$$I_1 = \frac{E_a}{Z_1 + \frac{Z_2 Z_0}{Z_2 + Z_0}} = \frac{1.0 + j0}{j0.25 + (j0.35 \times j0.10)/(j035 + j0.10)}$$

$$= \frac{1.0}{j0.3278} = \text{-}j3.0506 \text{ pu}$$

$$V_0 = V_1 = V_2 = E_a - I_1 Z_1$$

$$= 1 - (-j3.05)(j0.25) = 0.237 \text{ pu}$$



I_1 = -j3.0506 pu

$$I_2 = -\frac{V_2}{Z_2} = -\frac{0.237}{j0.35} = j0.68 \text{ pu}$$

$$I_0 = -\frac{V_2}{Z_0} = -\frac{0.237}{j0.10} = j2.37 \text{ pu}$$

$$I_a = I_0 + I_1 + I_2$$
$$= -j3.05 + j0.68 + j2.37 = 0$$

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

$$= (-0.5 - j0.866) I_1 + (-0.5 + j0.866) I_2 + I_0$$

$$= -3.230 + j3.555$$

$$= 4.80 \angle 132.3° pu$$

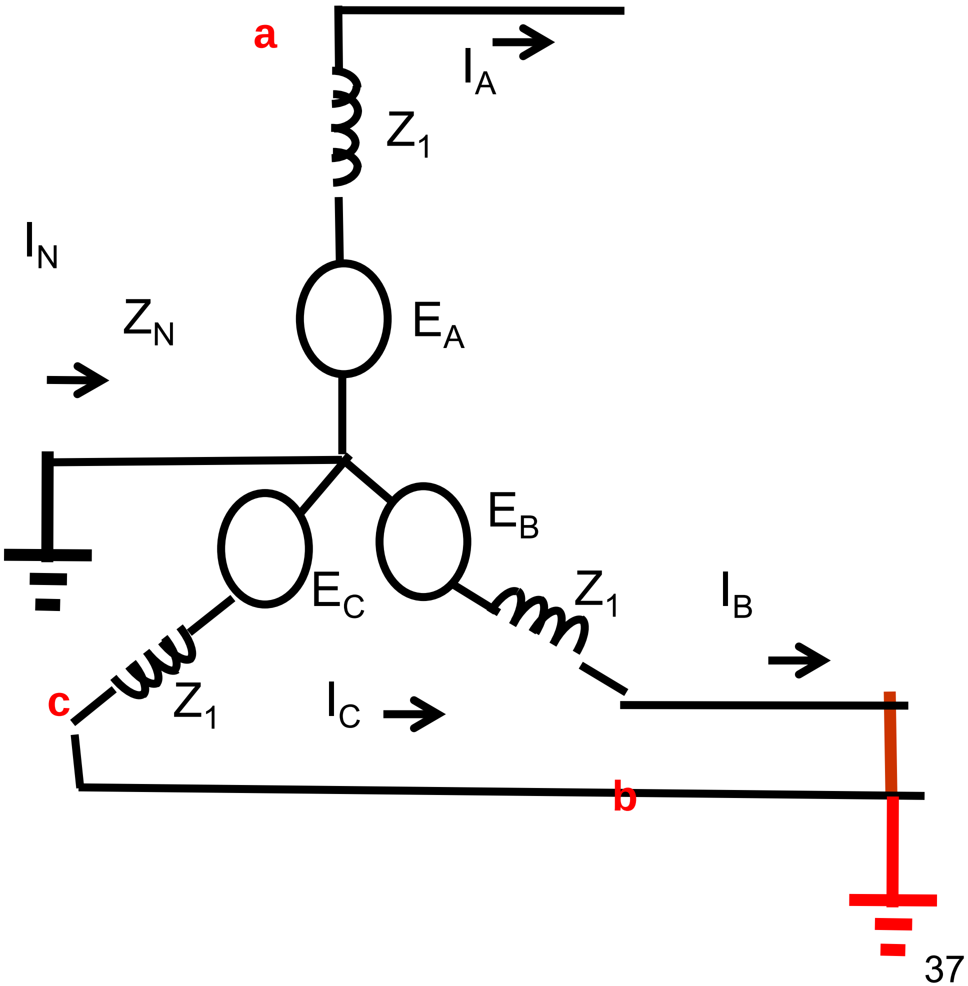
$$I_c = aI_1 + a^2 I_2 + I_0$$

$$= (-0.5 + j0.866)\bar{I}_1 +$$

$$(-0.5 - j0.866)\bar{I}_2 + \bar{I}_0$$

$$= 3.230 + j3.555$$

$$= 4.80 \angle 47.7° pu$$



$$I_N = I_b + I_c$$
$$= -3.23 + j3.555 + 3.236 + j3.555$$
$$= j7.11\,\text{pu}$$

$$V_a = V_1 + V_2 + V_0$$
$$= 3\overline{V}_1 = 3 \times 0.237 = j0.711\ \text{pu}$$

$$V_b = V_c = 0$$
$$V_{ab} = V_a - V_b = 0.711\,\text{pu}$$

$$V_{bc} = 0$$
$$V_{ca} = V_c - V_a = -0.711\,\text{pu}$$

In amperes,

$$\mathbf{I_a = O}$$

$$I_b = 837 \times 4.80\angle 132.3° = 4017\angle 132.3°$$

$$I_c = 837 \times 4.80\angle 47.7° = 4017\angle 47.7°$$

$$I_N = 837 \times 7.11\angle 90° = 5951\angle 90° \text{A}$$

$$V_{ab} = 0.711 \times \frac{13.8}{\sqrt{3}} = 5.66\angle 0° \text{kV}$$

$$V_{bc} = 0$$

$$V_{ca} = -0.711 \times \frac{13.8}{\sqrt{3}} = 5.66\angle 180° \text{kV}$$

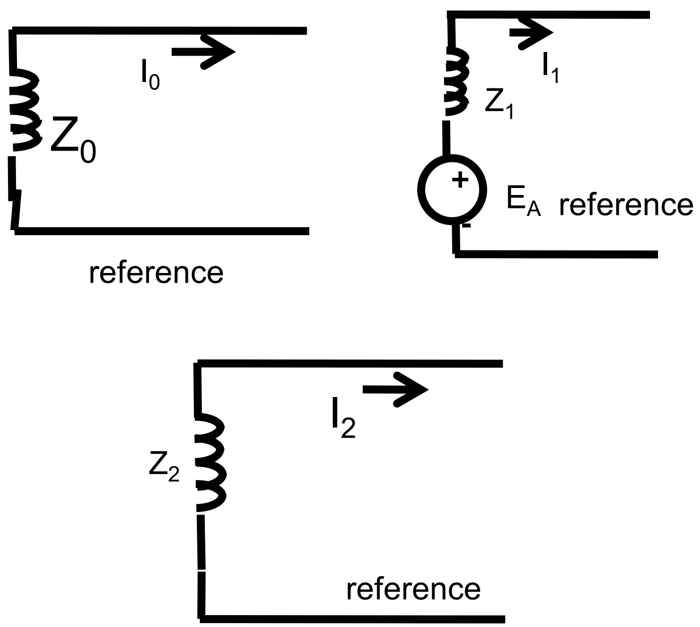
Unsymmetrical Fault in a Power System: the assumptions

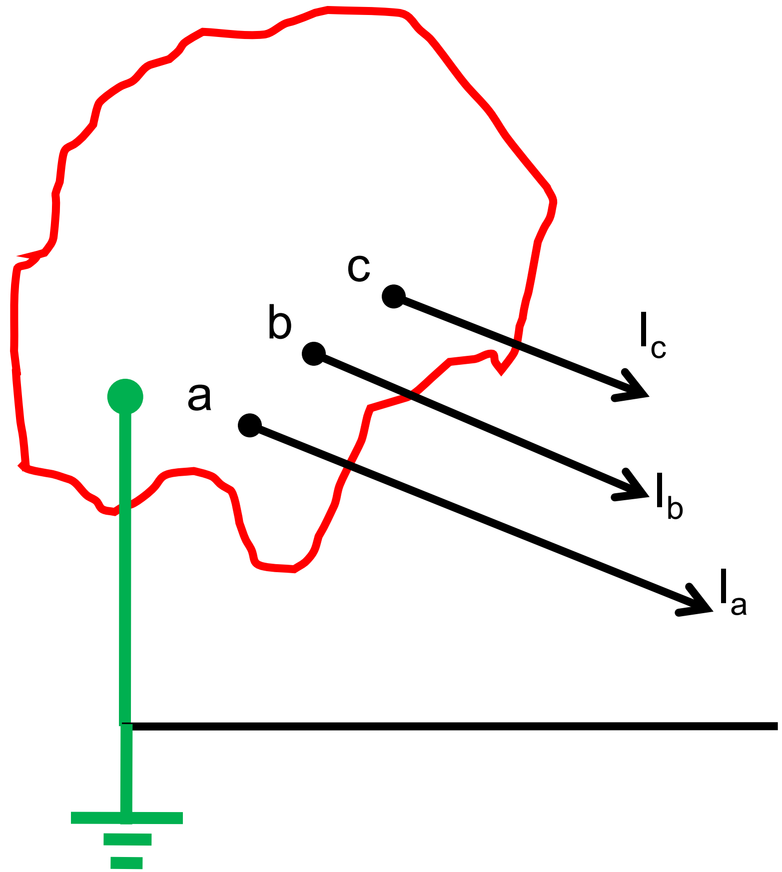
- Power system operates under balanced steady-state conditions before fault.
- Pre fault load current is neglected. Pre fault voltage at each bus in the positive-sequence network equals V_0.
- transformer winding resistance and shunt admittances are neglected.
- Transmission-line series resistance and shunt admittances are neglected.
- synchronous machine armature resistance, saliency and saturation are neglected.
- All non rotating impedance loads are neglected.
- Induction motors are either neglected or represented as synchronous machines.

General three-phase bus:

Terminals abc, denoted the fault terminals, are brought out in order to make external connections that represent faults.

Sequence networks:





Thevenin equivalents as viewed from faults terminals

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

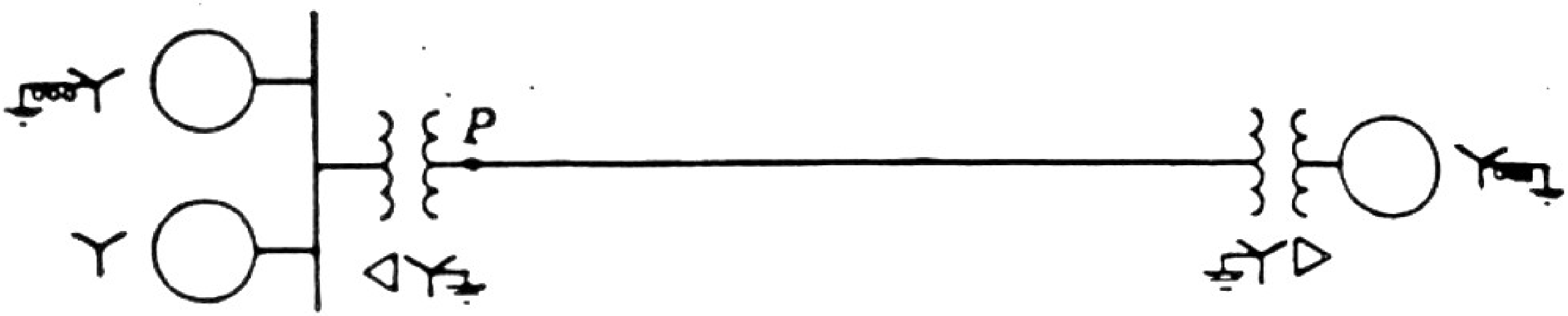
$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

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

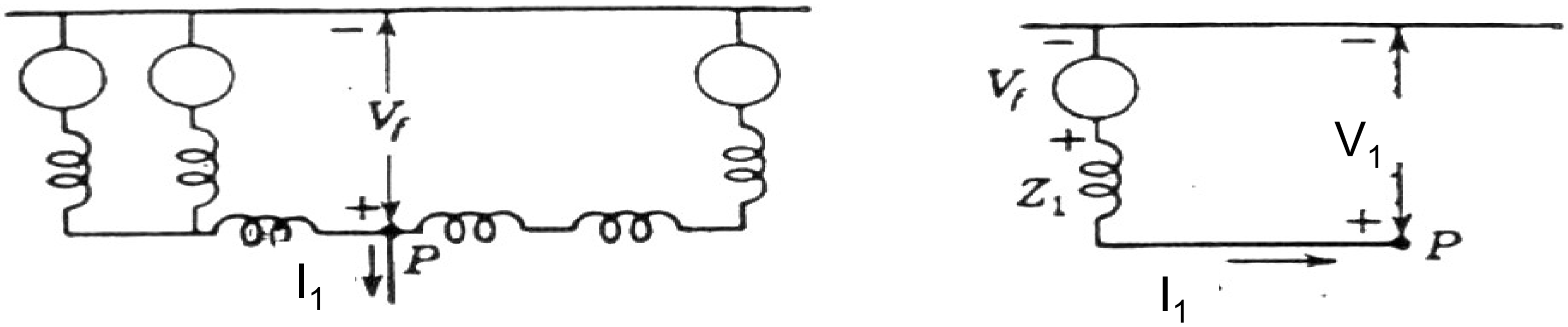
$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix}$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

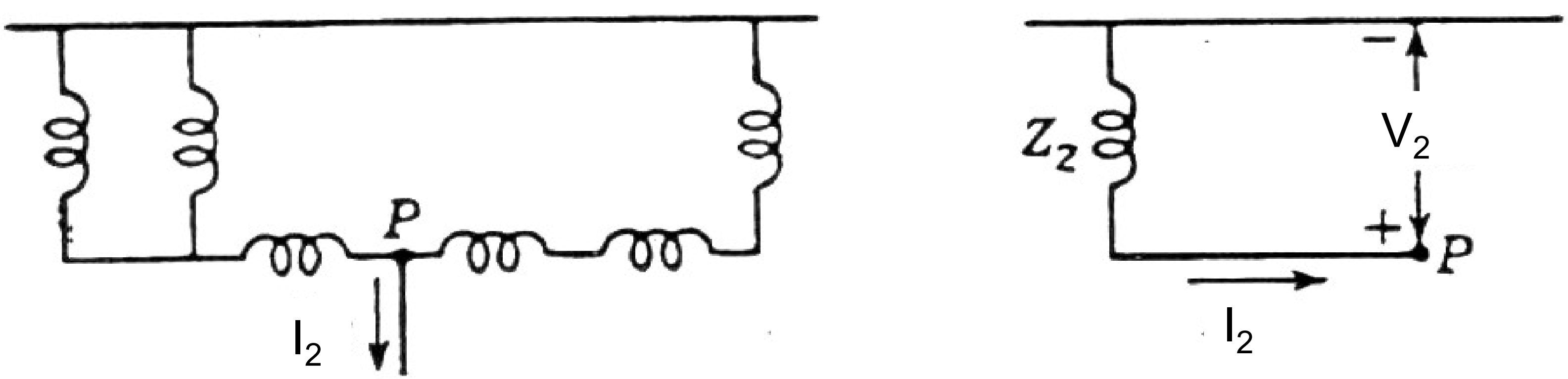
Three phase power system with fault at point **P**



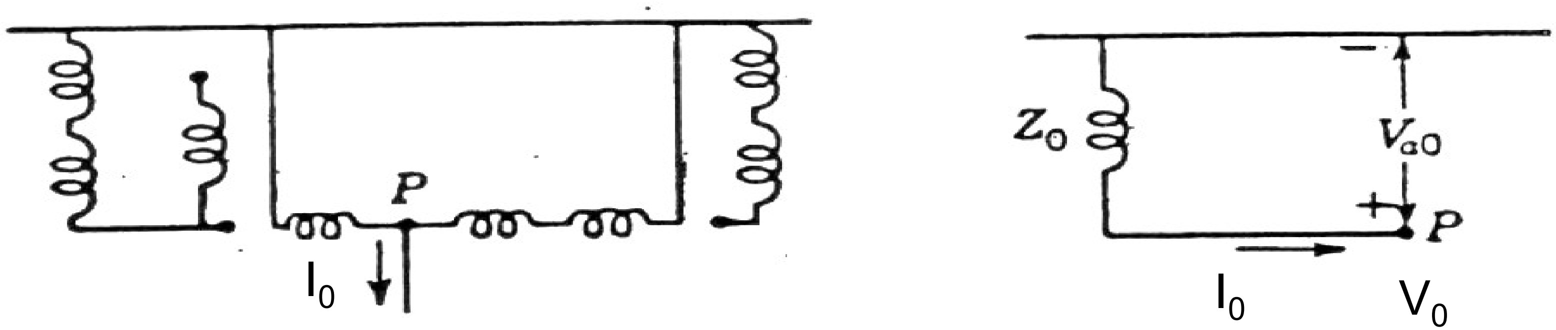
Single-line diagram of a balanced power system



Positive sequence network and thevenin equivalent



Negative sequence network and thevenin equivalent



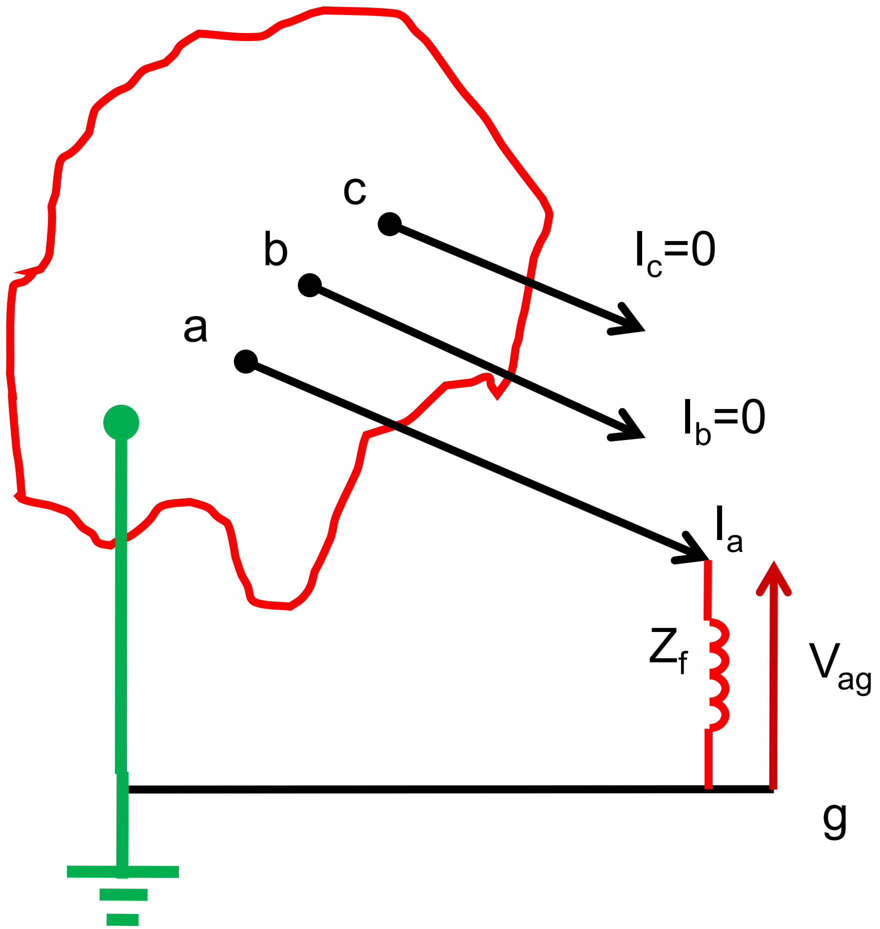
Zero sequence network and thevenin equivalent

Sequence Voltages for phase a are:

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

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

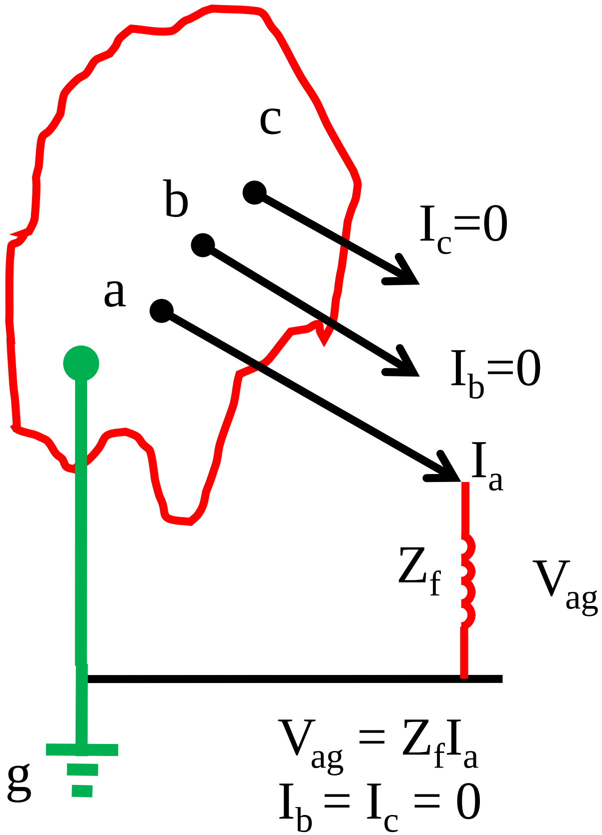
Single line-to-ground Fault:



Fault conditions in phase domain:

$$I_b = I_c = 0$$

$$V_{ag} = Z_f I_a$$



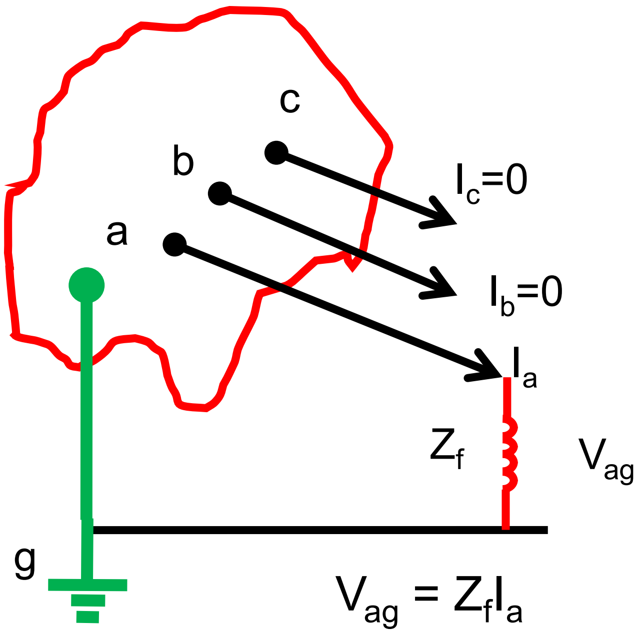
$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} I_a \\ 0 \\ 0 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} I_a \\ I_a \\ I_a \end{bmatrix}$$

$$I_0 = I_1 = I_2$$

$$\underbrace{\left(V_0 + V_1 + V_2\right)}_{V_{ag}} = Z_f \underbrace{\left(I_0 + I_1 + I_2\right)}_{I_a}$$

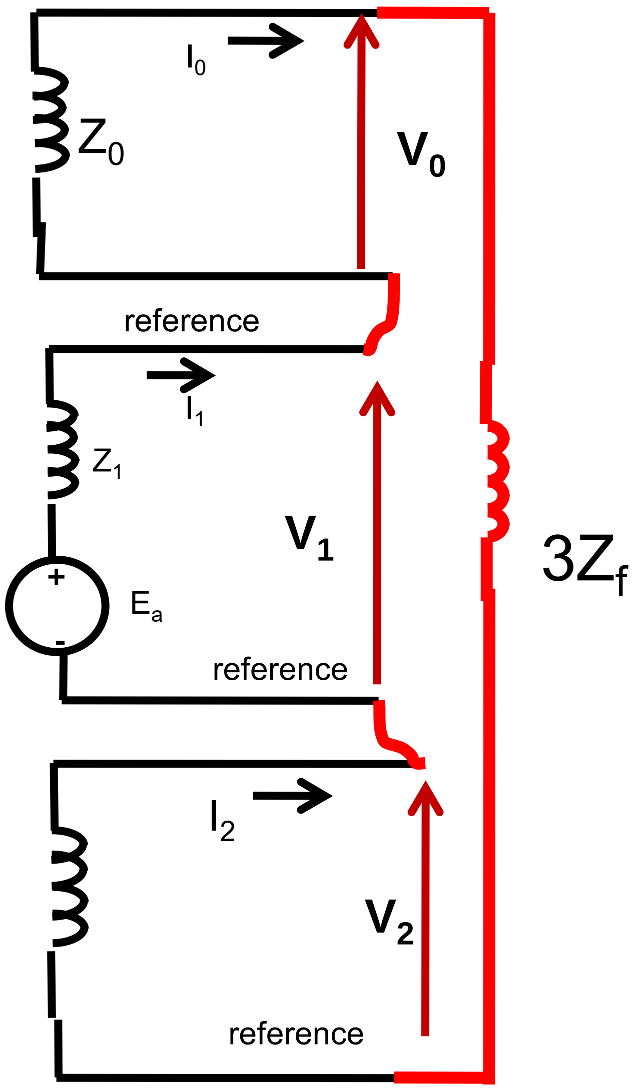
$$\left(V_0 + V_1 + V_2\right) = 3Z_f \left(I_1\right)$$

The equations can be satisfied by interconnecting the sequence network in series at the fault terminals through the impedance $3Z_f$



Prove this your self

Interconnected sequence network



$$\bar{I}_1 = \bar{I}_2 = \bar{I}_0$$

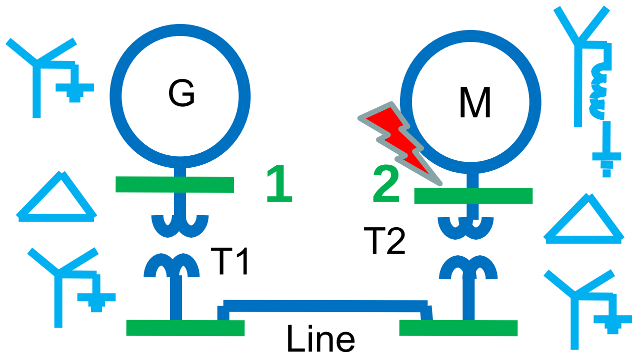
$$(V_0 + V_1 + V_2) = 3Z_f (I_1)$$

$$\bar{I}_1 = \frac{E_a}{Z_0 + Z_1 + Z_2 + (3Z_f)}$$

$$\bar{I}_a = \frac{3E_a}{Z_0 + Z_1 + Z_2 + (3Z_f)}$$

Example

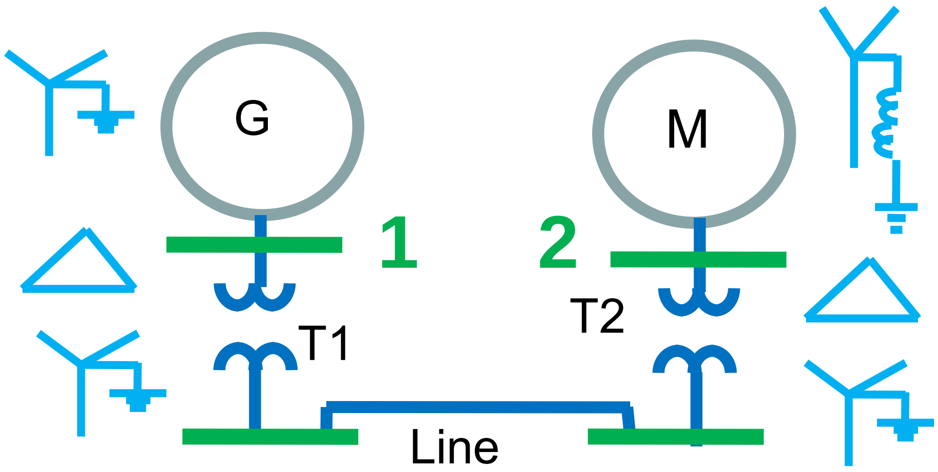
- Calculate the subtransient fault current in per-unit and in kA for a **bolted single line-to-ground short circuit** from phase a to ground at bus 2.
- Calculate the per-unit line-to-ground voltages at bus 2



	MVA	kV	X1	X"	X2	X0	Xn
G	100	13.8		0.15	0.17	0.05	
T1	100	13.8/138	0.10		0.10	0.10	
T2	100	138/13.8	0.10		0.10	0.10	
M	100	13.8		0.20	0.21	0.10	0.05
Line			20Ω		20Ω	60Ω	

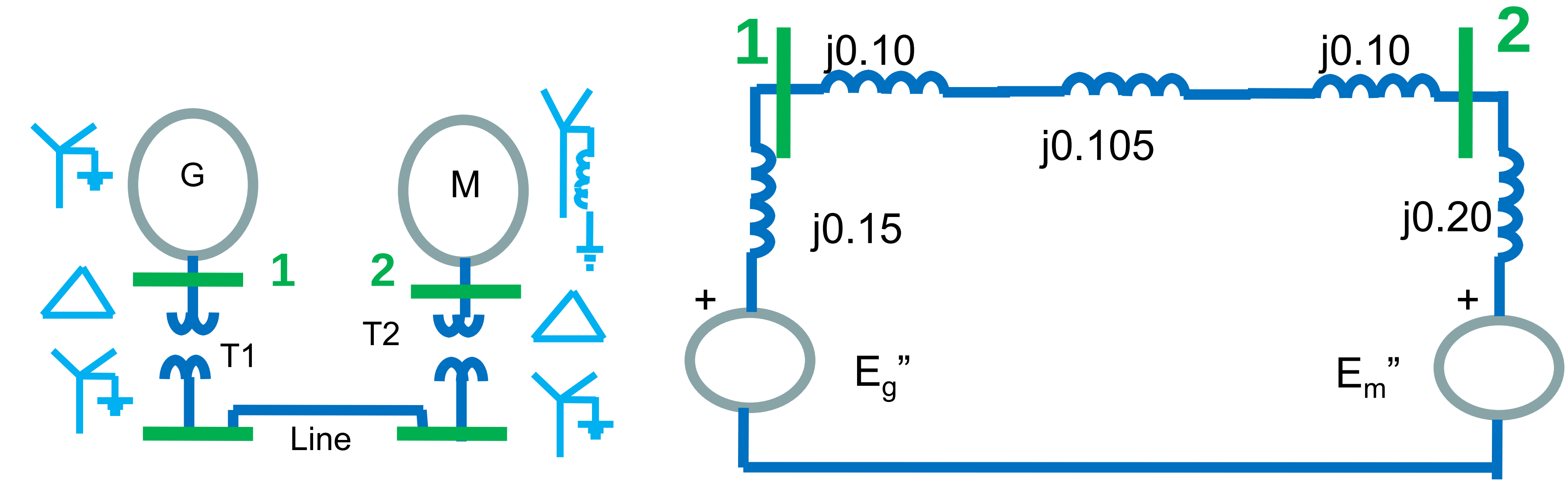
Solution

Draw positive, negative and zero sequence networks of the given system

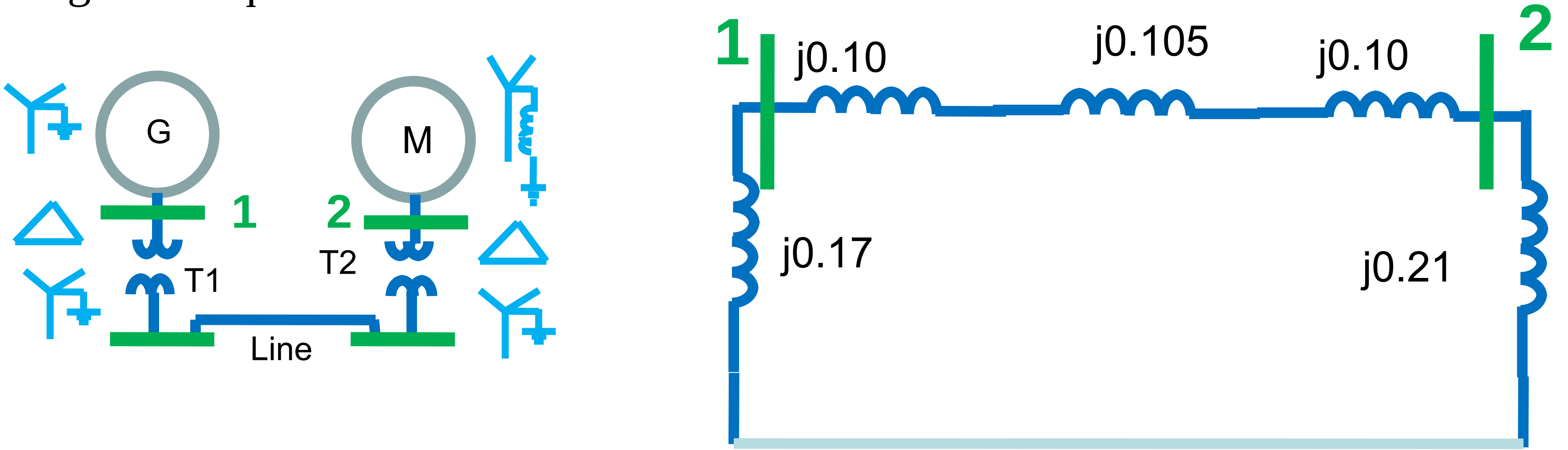


	MVA	kV	X1	X”	X2	X0	Xn
G	100	13.8		0.15	0.17	0.05	
T1	100	13.8/138	0.10		0.10	0.10	
T2	100	138/13.8	0.10		0.10	0.10	
M	100	13.8		0.20	0.21	0.10	0.05
Line			20Ω		20Ω	60Ω	

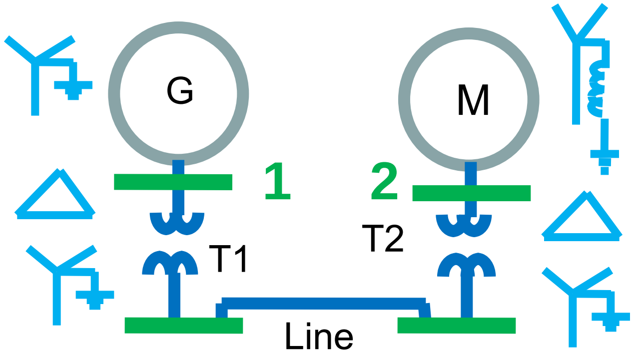
Positive sequence network

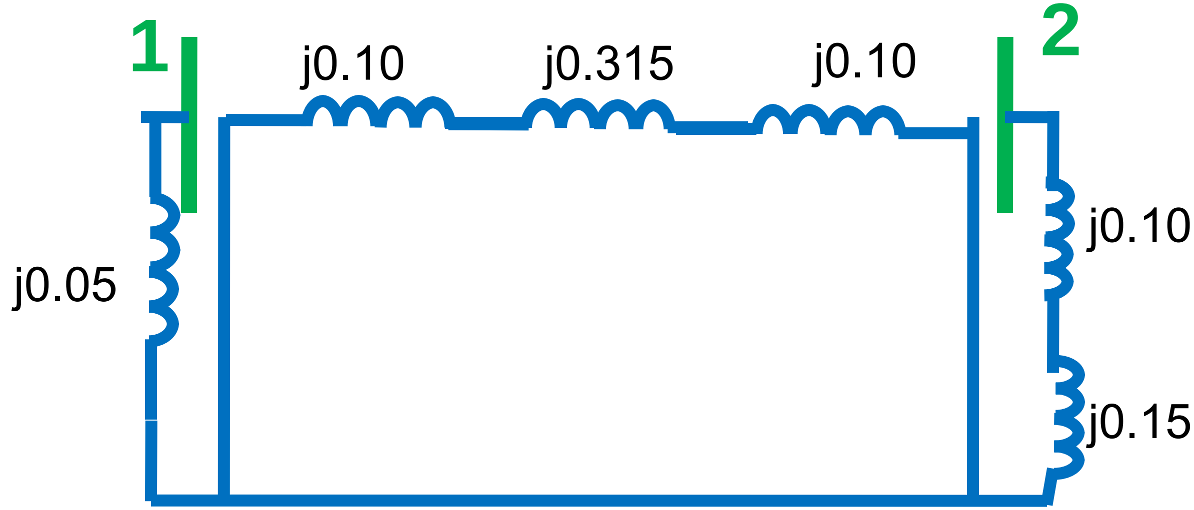


Negative sequence network

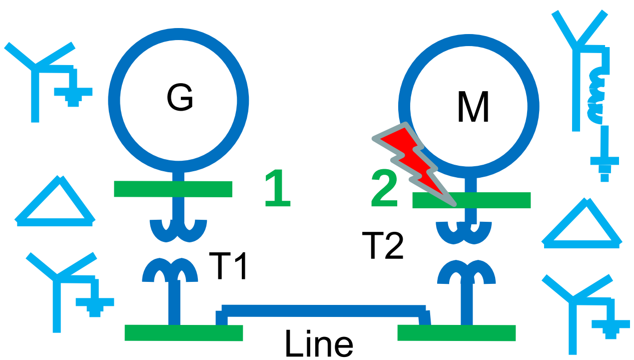


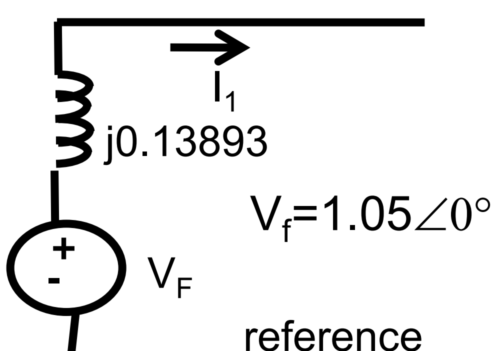
Zero sequence network

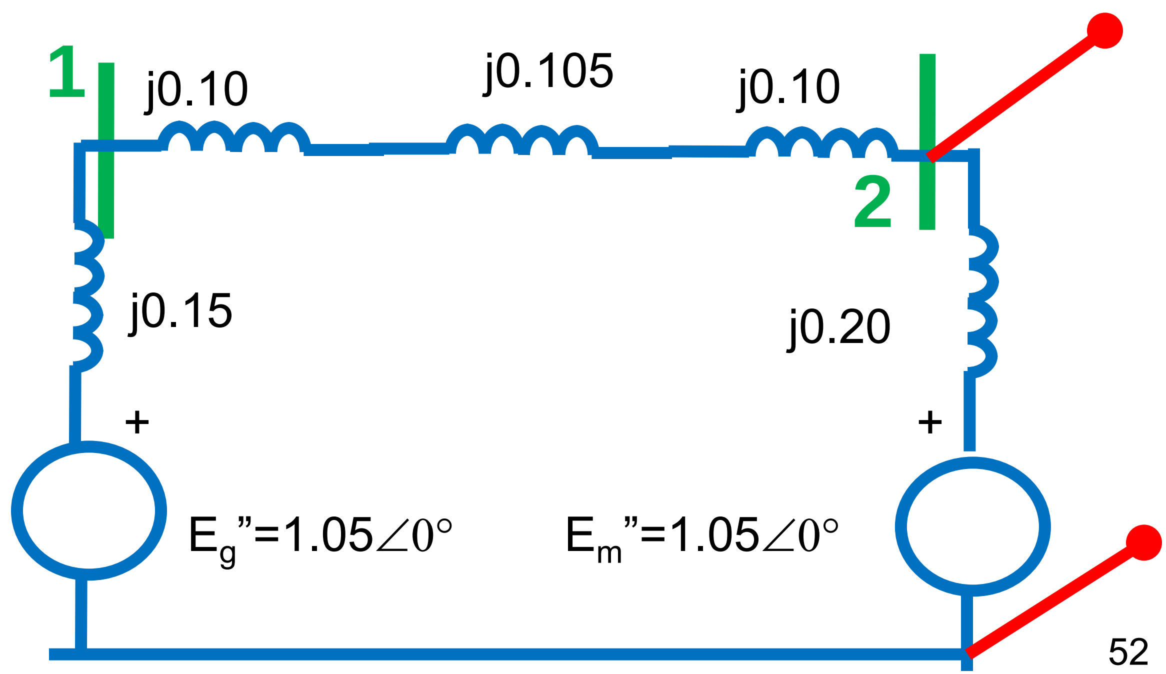




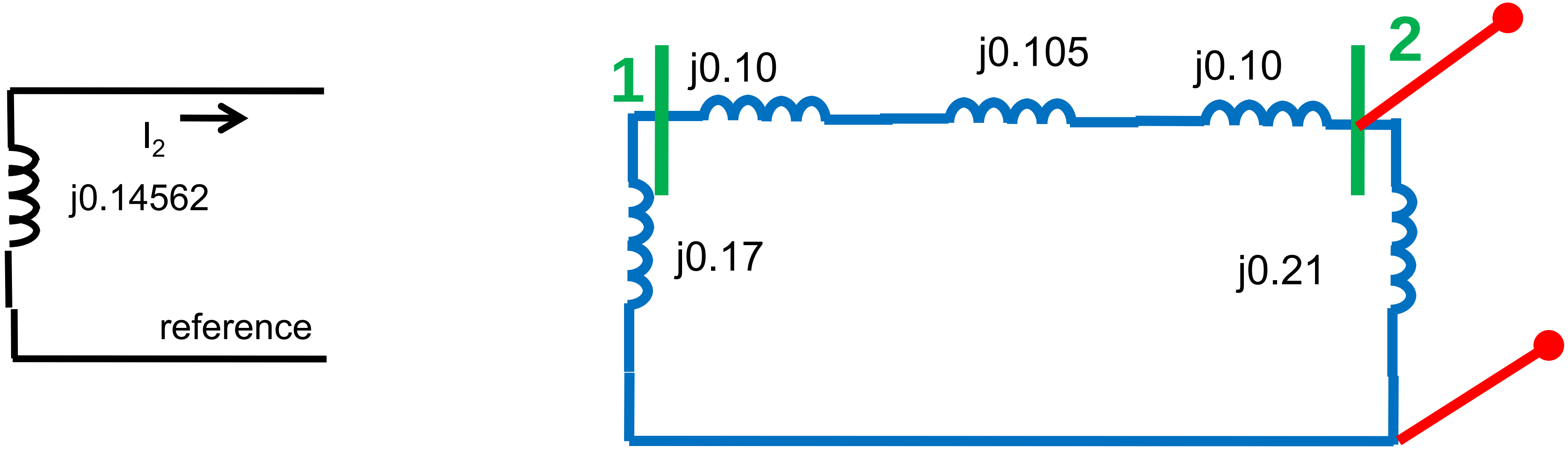
Positive sequence network for fault at bus 2



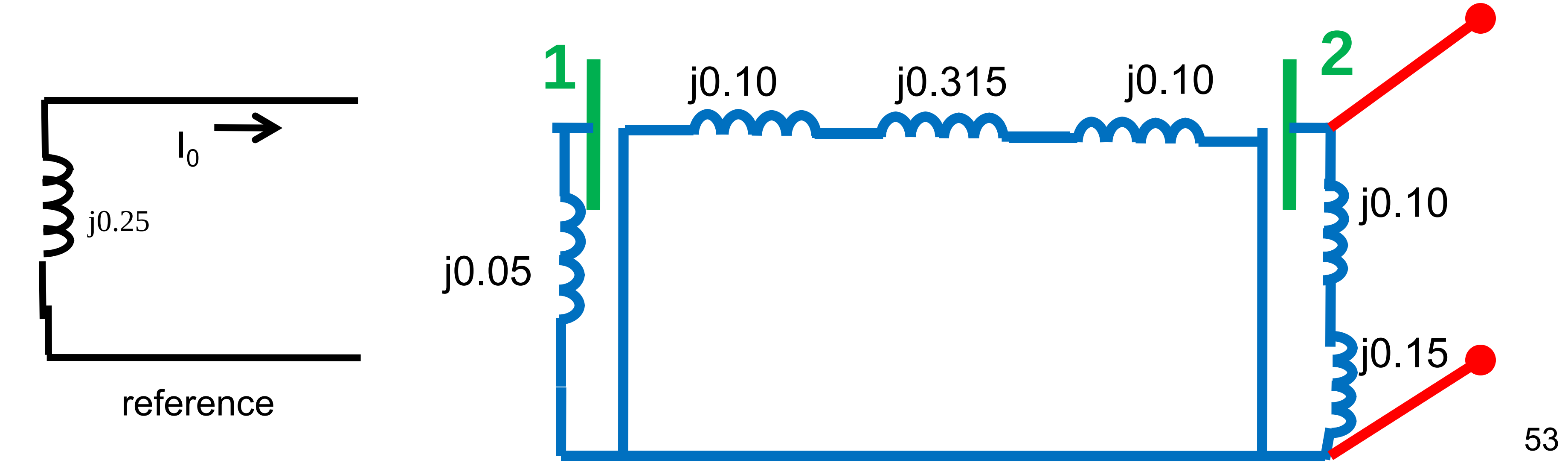




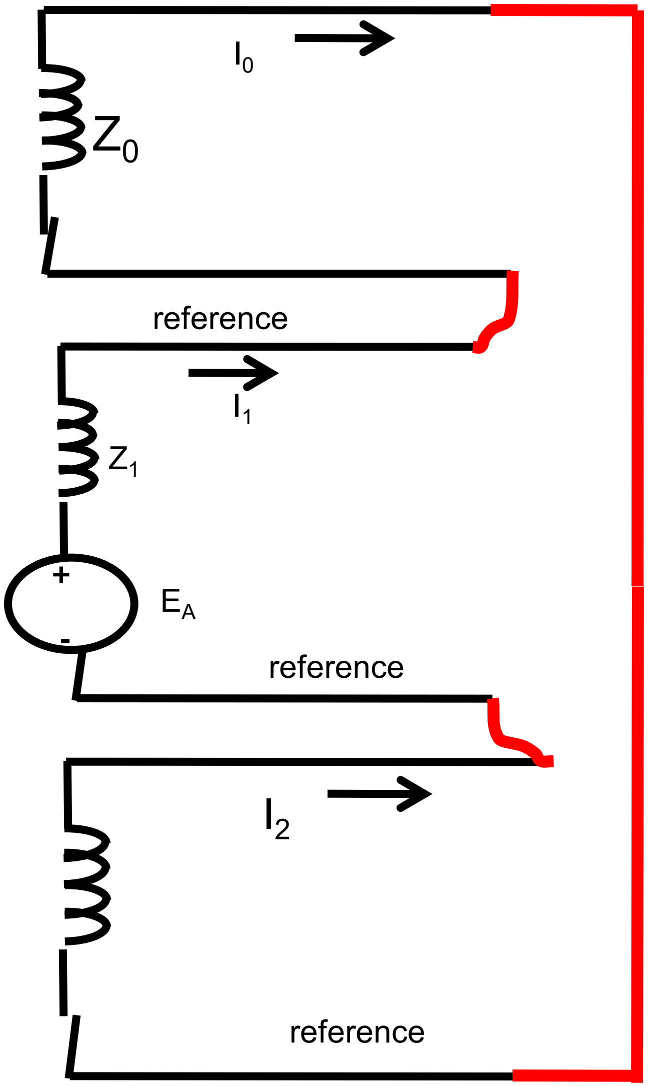
Negative sequence network



Zero sequence network



Interconnected sequence network



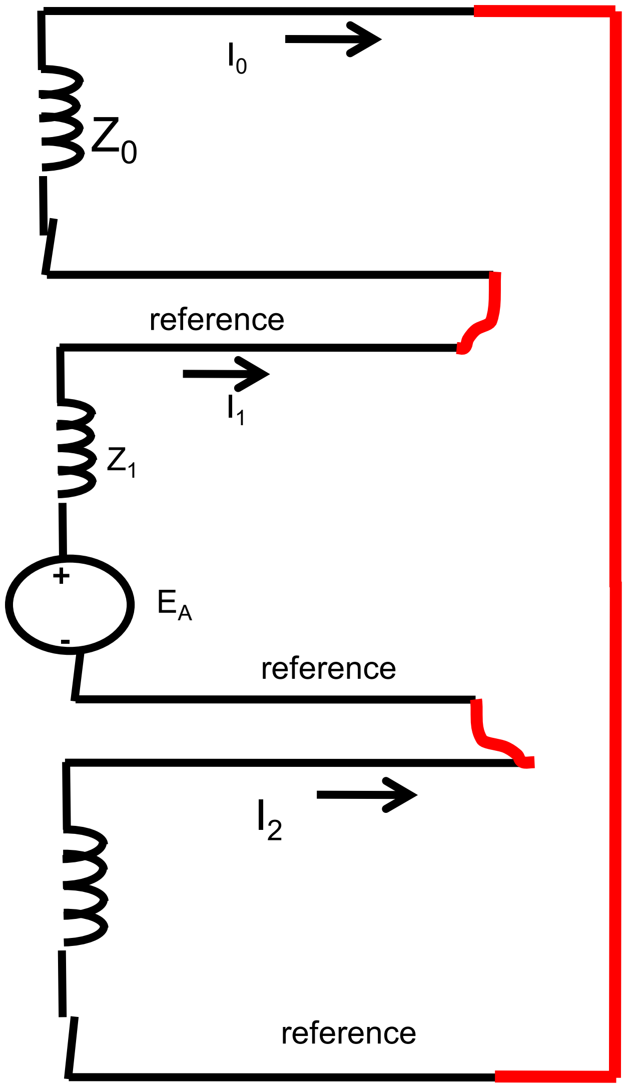
$$\bar{I}_1 = \bar{I}_2 = \bar{I}_0$$

$$\bar{I}_1 = \frac{E_f}{Z_0 + Z_1 + Z_2}$$

$$= \frac{1.05\angle 0}{j(0.25 + 0.13893 + 0.14562)}$$

$$= \frac{1.05}{j0.53455} = -j1.96427\ pu$$

Interconnected sequence network



$$\bar{I}_a = 3(-j1.96427)$$
$$= -j5.8928\ pu$$

$$I_{base} = \frac{100}{\sqrt{3} \times 13.8}$$
$$= 4.1837\ kA$$

$$\bar{I}_a = -j5.8928 \times 4.1837$$
$$= 24.65\ kA$$

The sequence components of the voltages at the fault are

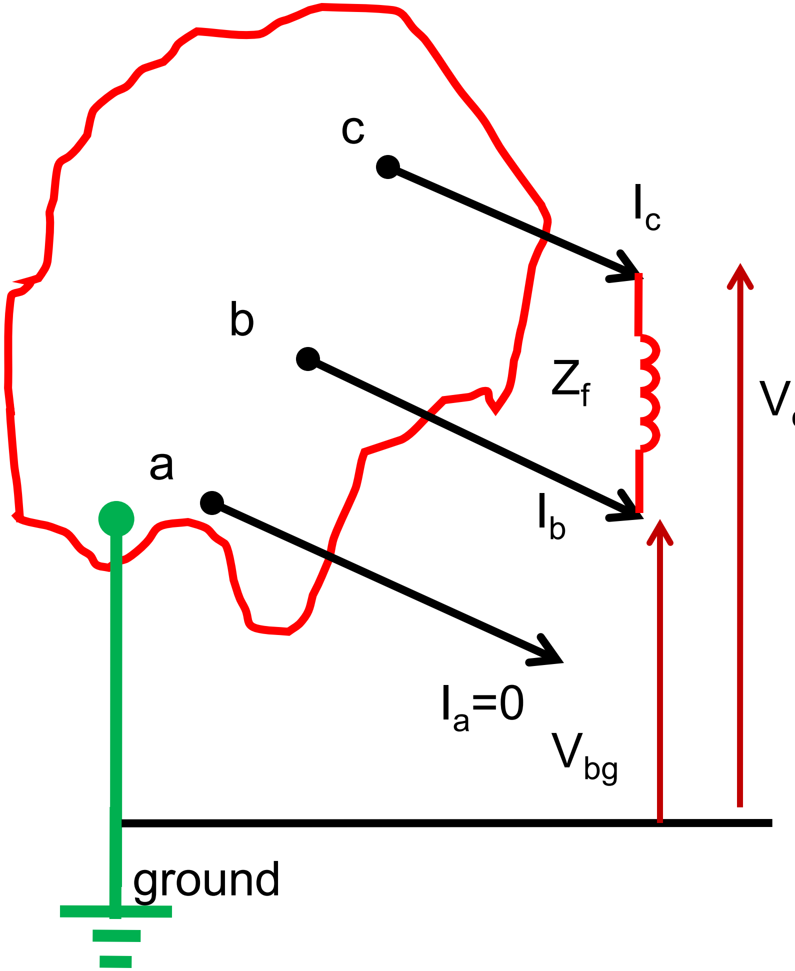
$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 1.05\angle 0 \\ 0 \end{bmatrix} - \begin{bmatrix} j0.25 & 0 & 0 \\ 0 & j0.13893 & 0 \\ 0 & 0 & j0.14562 \end{bmatrix} \begin{bmatrix} -j1.96427 \\ -j1.96427 \\ -j1.96427 \end{bmatrix}$$

$$= \begin{bmatrix} -0.49107 \\ 0.77710 \\ -0.28604 \end{bmatrix} pu$$

The line-to-ground voltage at faulted bus 2 are

$$\begin{bmatrix} V_{ag} \\ V_{bg} \\ V_{cg} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} -0.49107 \\ 0.77710 \\ -0.28604 \end{bmatrix} = \begin{bmatrix} 0 \\ 1.179\angle 231.3 \\ 1.179\angle 128.7 \end{bmatrix} pu$$

Line-to- line Fault:



Fault conditions in phase domain:

$I_b = -I_c$

$I_a = 0$

$V_{bg} - V_{cg} = Z_f I_b$

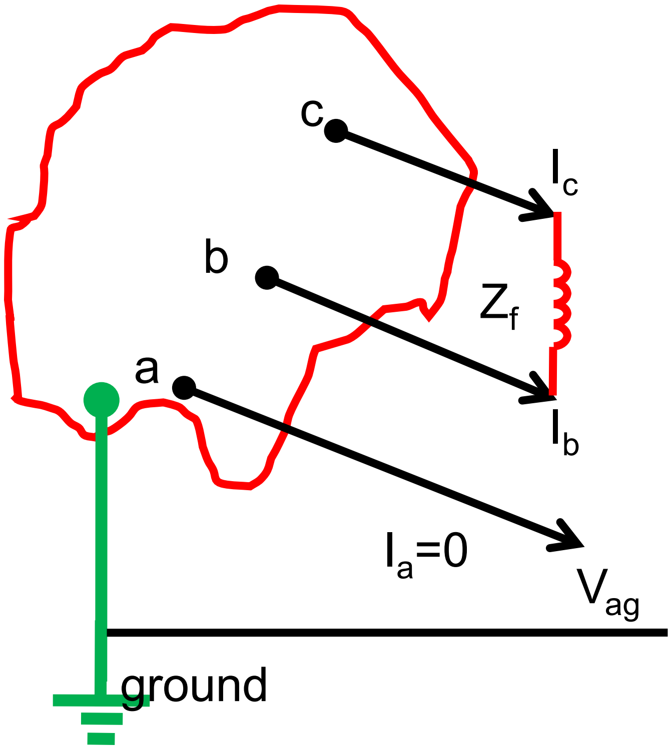
$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} 0 \\ I_b \\ -I_b \end{bmatrix} = \begin{bmatrix} 0 \\ \frac{1}{3}\left(a-a^2\right)I_b \\ \frac{1}{3}\left(a^2-a\right)I_b \end{bmatrix} pu$$

$V_{bg} - V_{cg} = Z_f I_b$

V_{bg} V_{cg} I_b

$$\left(V_0 + a^2 V_1 + a V_2\right) - \left(V_0 + a V_1 + a^2 V_2\right) = Z_F\left(I_0 + a^2 I_1 + a I_2\right)$$

$I_0 = 0$ $I_2 = - I_1$

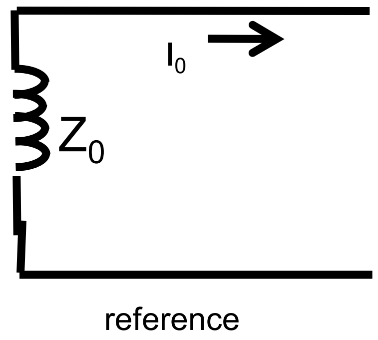


Simplifies to

$$\left(a^2 - a\right)V_1 - \left(a^2 - a\right)V_2 = Z_F\left(a^2 - a\right)I_1$$

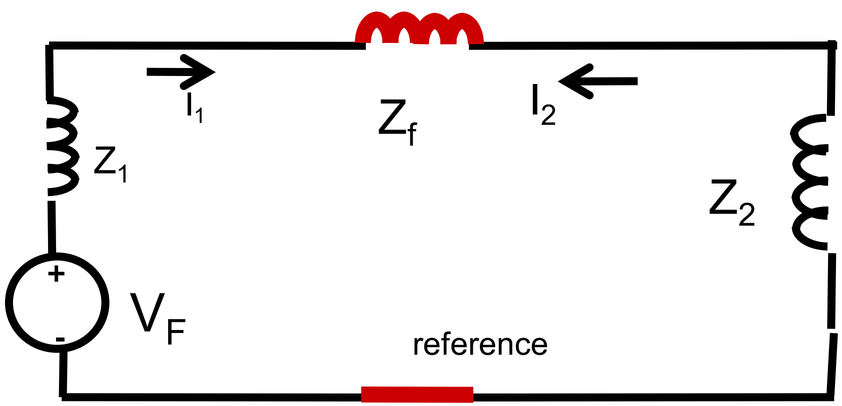
$$V_1 - V_2 = Z_F I_1$$

Fault conditions in sequence domain



$$I_0 = 0 \qquad I_2 = -I_1 \qquad V_1 - V_2 = Z_F I_1$$

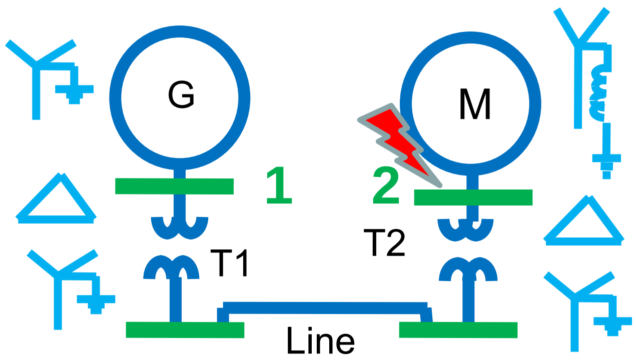
These equations are satisfied by connecting the positive sequence and negative sequence networks in parallel at the fault terminals through the fault impedance Z_f



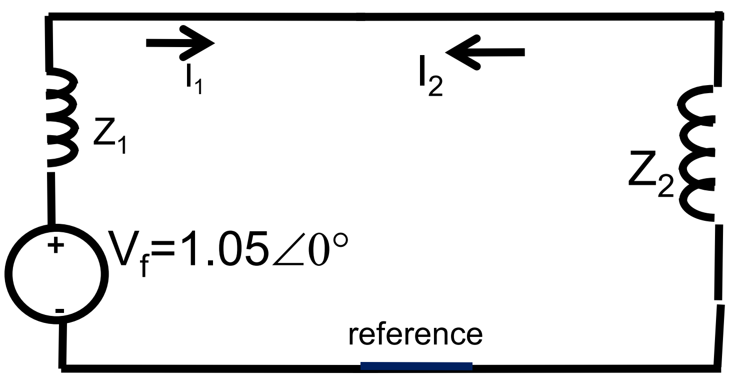
$$I_1 = -I_2 = \frac{V_F}{\left(Z_1 + Z_2 + Z_F\right)}$$

Example

- Calculate the subtransient fault current in per-unit and kA for a bolted line-to-line fault from phase b to c at bus 2



Fault conditions in sequence domain



$$I_1 = -I_2 = \frac{V_F}{(Z_1 + Z_2 + Z_F)}$$

$$= \frac{1.05\angle 0}{j(0.13893 + 0.14562)}$$

$$= 3.690\angle -90$$

$$I_0 = 0$$

$$I_a'' = 0$$

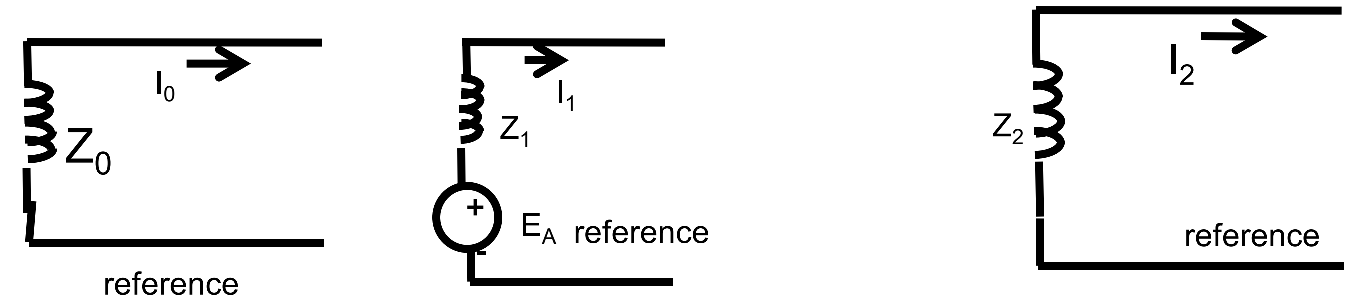
$$I_b'' = 6.391\angle 180 \; pu$$

$$= 26.74 \, kA$$

$$I_c'' = 6.391\angle 0 \; pu$$

$$= 26.74 \, kA$$

Sequence networks:



Thevenin equivalents as viewed from faults terminals

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

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

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

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

Revision

1. Write equation expressing phase and sequence voltages

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

2. Write equation expressing sequence and phase voltages

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

Revision

1. Write equation expressing phase and sequence currents

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

2. Write equation expressing sequence and phase currents

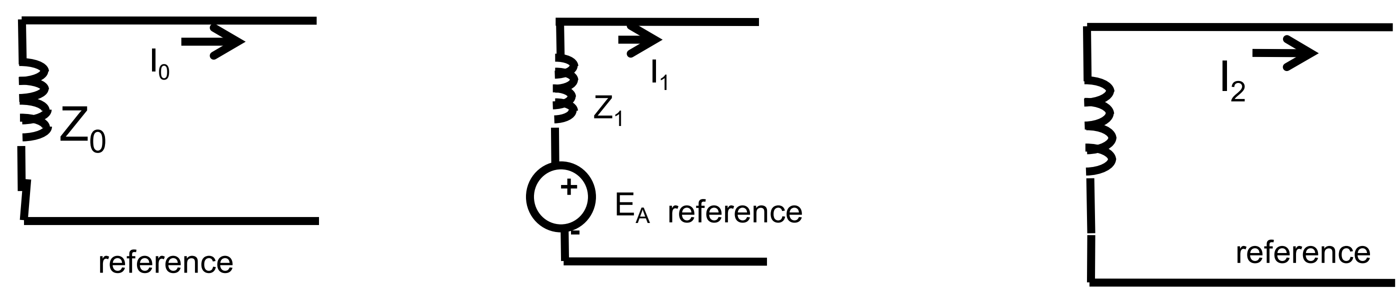
$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

Revision

1. Write equation expressing sequence networks

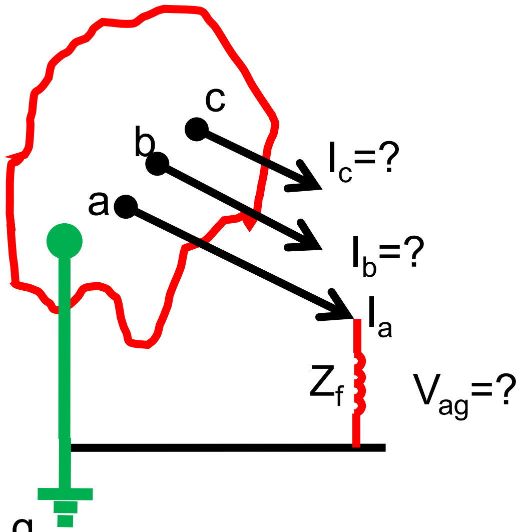
$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

2. Draw sequence networks

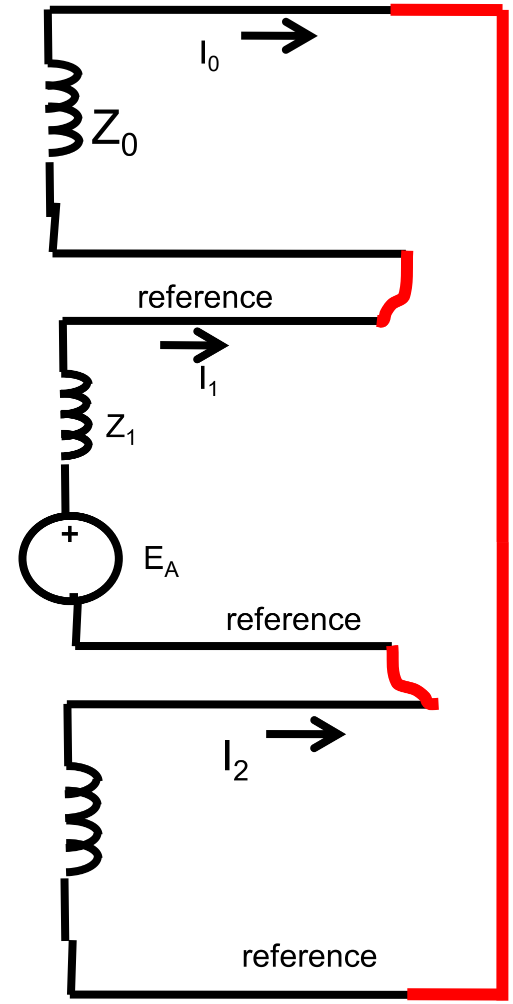


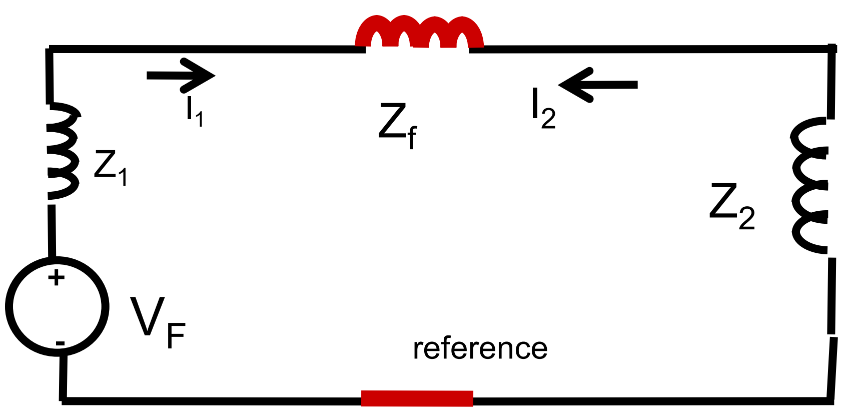
Revision

Interconnected sequence network



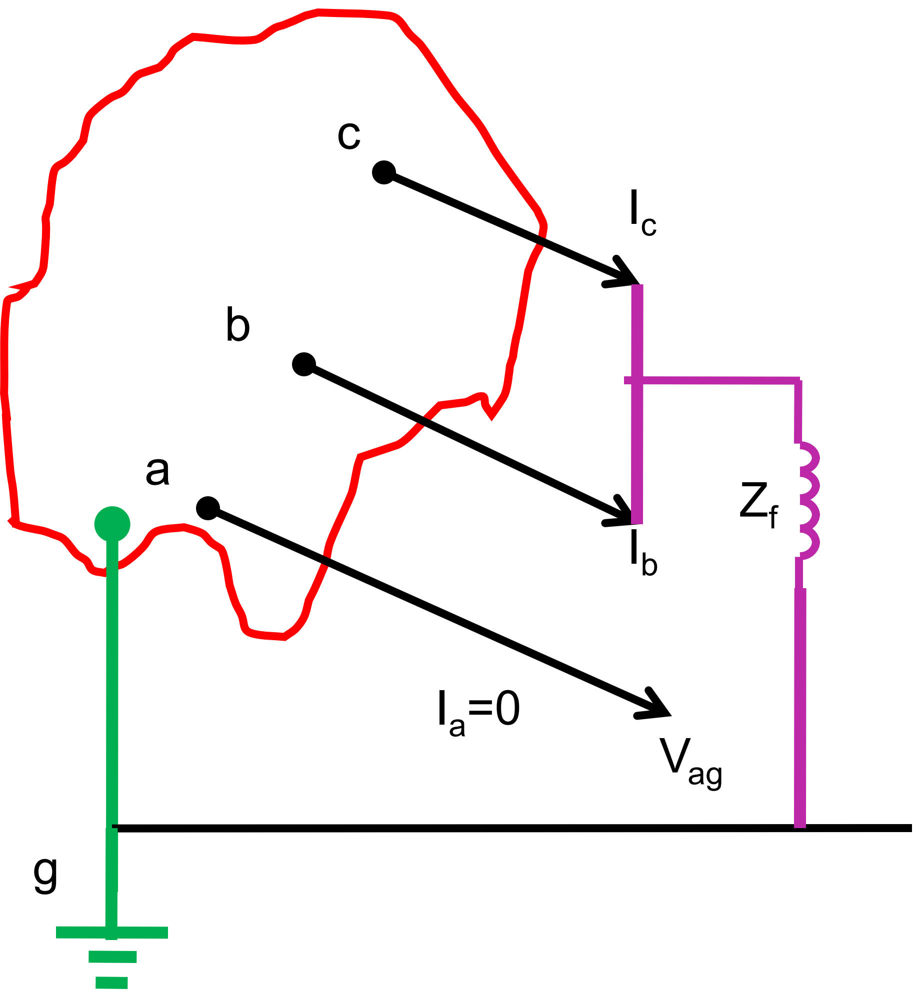
$$V_{ag} = Z_f I_a$$
$$I_b = I_c = 0$$





Double Line-to- Ground Fault:

Fault conditions in phase domain:



$I_a = 0$

$V_{bg} = V_{cg} = Z_f(I_b + I_c)$

$V_{bg} = V_{cg}$ **? ?**

$$\left(V_0 + a^2 V_1 + a V_2\right) = \left(V_0 + a V_1 + a^2 V_2\right)$$

$$\left(-a^2 + a\right) V_2 = \left(-a^2 + a\right) V_1$$

$$V_2 = V_1$$

$$V_{bg} = Z_F(I_b + I_c)$$

$$(V_0 + a^2 V_1 + aV_2) = Z_F(I_0 + a^2 I_1 + aI_2 + I_0 + aI_1 + a^2 I_2)$$

$$(V_0 - V_1) = Z_F(2I_0 - I_1 - I_2) \quad ?$$

$$(V_0 - V_1) = 3Z_F I_0 \quad ?$$

$I_a = 0$

$$(I_0 + I_1 + I_2) = 0$$

$$I_0 = -(I_1 + I_2)$$

$$(a^2 + a) = -1$$

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 0 \\ V_f \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

$I_a = 0$

$V_{bg} = V_{cg} = Z_f(I_b + I_c)$

$$(a^2 + a) = -1$$

$$(V_0 - V_1) = 3Z_F I_0$$

$$(I_0 + I_1 + I_2) = 0$$

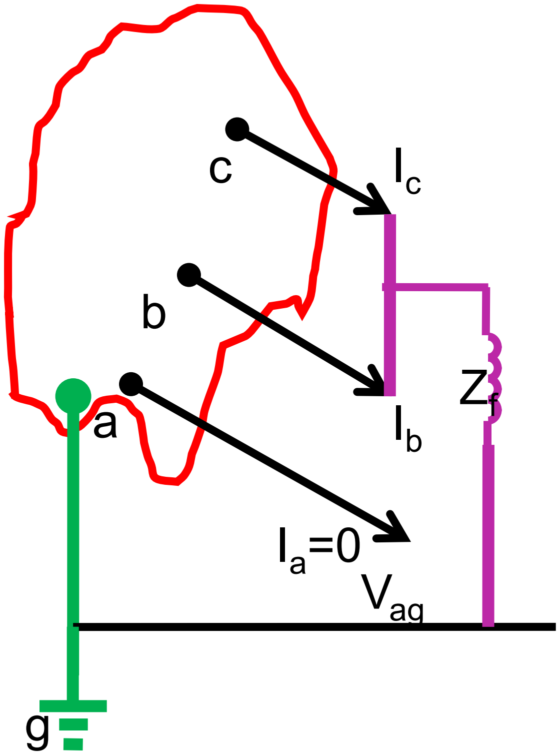
$$(-Z_0 I_0) - (V_f - I_1 Z_1) = 3Z_F I_0$$

$$I_0 = -\frac{V_F - Z_1 I_1}{Z_0 + 3Z_f} \quad ?$$

$$V_2 = V_1$$

$$(-I_2 Z_2) = V_f - Z_1 I_1$$

$$I_2 = -\frac{V_F - Z_1 I_1}{Z_2} \quad ?$$



$$V_2 = V_1$$

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 0 \\ V_f \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

$$\left(V_0 - V_1\right) = 3Z_F I_0$$

$$\left(I_0 + I_1 + I_2\right) = 0$$

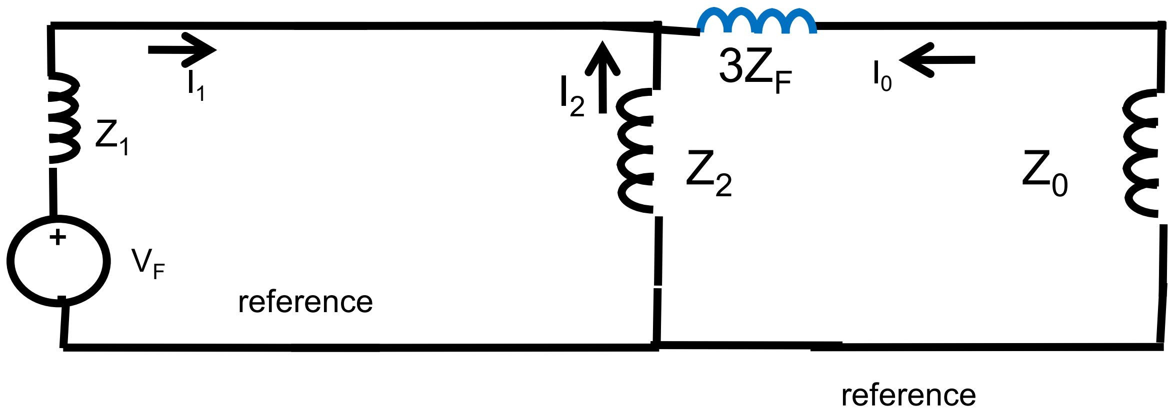
$$I_0 = -\frac{V_F - Z_1 I_1}{Z_0 + 3Z_f}$$

$$I_2 = -\frac{V_F - Z_1 I_1}{Z_2}$$

Substituting for I_0 and I_2 and solving for I_1 gives

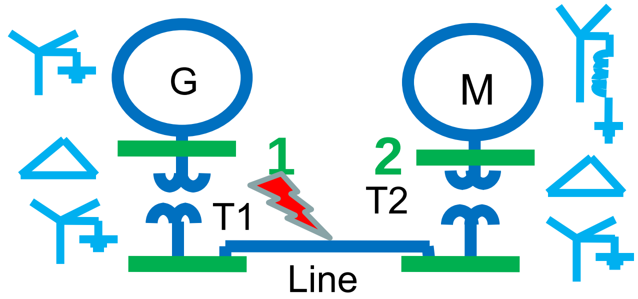
?

$$I_1 = \frac{V_F}{Z_1 + \left[Z_2 \| \left(Z_0 + 3Z_F\right)\right]} = \frac{V_F}{Z_1 + \left[\dfrac{Z_2\left(Z_0 + 3Z_F\right)}{Z_2 + Z_0 + 3Z_F}\right]}$$



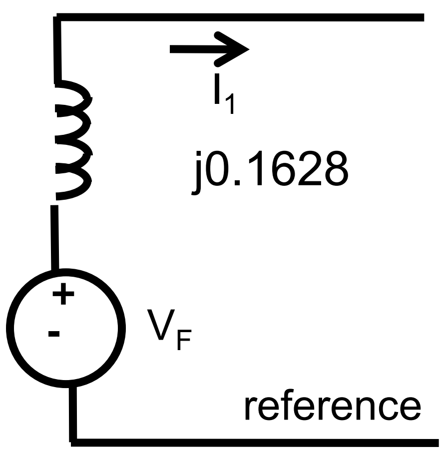
$$I_1 = \frac{V_F}{Z_1 + \left[Z_2 \| (Z_0 + 3Z_F) \right]} = \frac{V_F}{Z_1 + \left[\dfrac{Z_2 (Z_0 + 3Z_F)}{Z_2 + Z_0 + 3Z_F} \right]}$$?

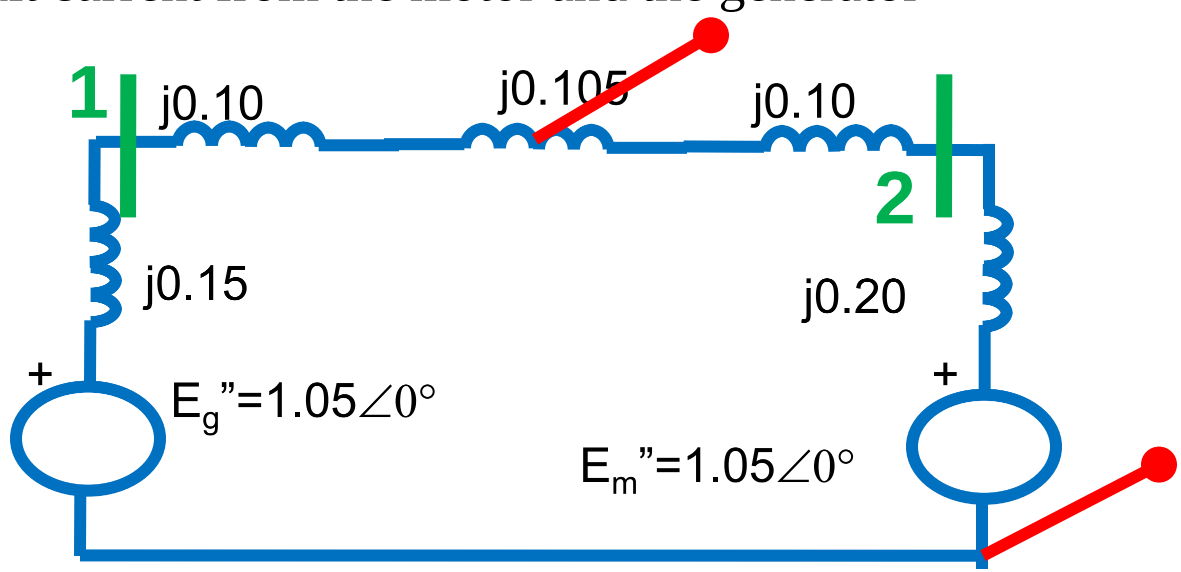
$$I_2 = (-I_1) \frac{(Z_0 + 3Z_F)}{Z_2 + Z_0 + 3Z_F} \qquad I_0 = (-I_1) \frac{Z_2}{Z_2 + Z_0 + 3Z_F}$$?



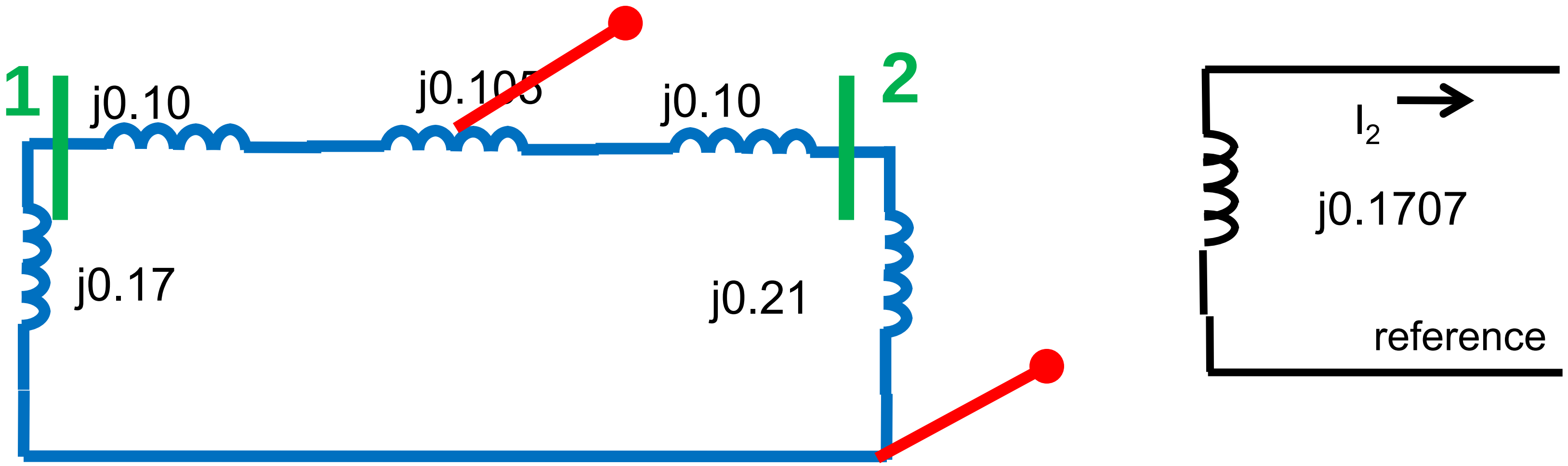
Exercise

- Calculate the subtransient fault current in each phase, in per-unit and kA, for a bolted double line-to-ground fault from phase b to c in the middle of transmission line
- Neutral fault current
- Contribution to the fault current from the motor and the generator

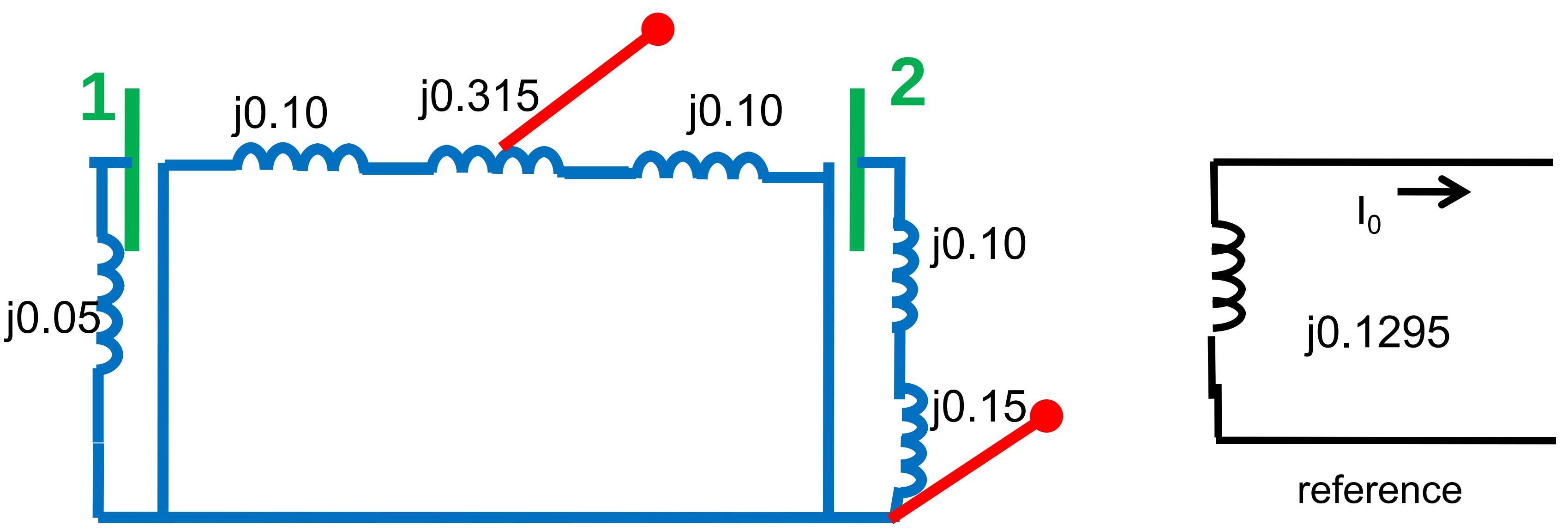




Negative sequence network



Zero sequence network



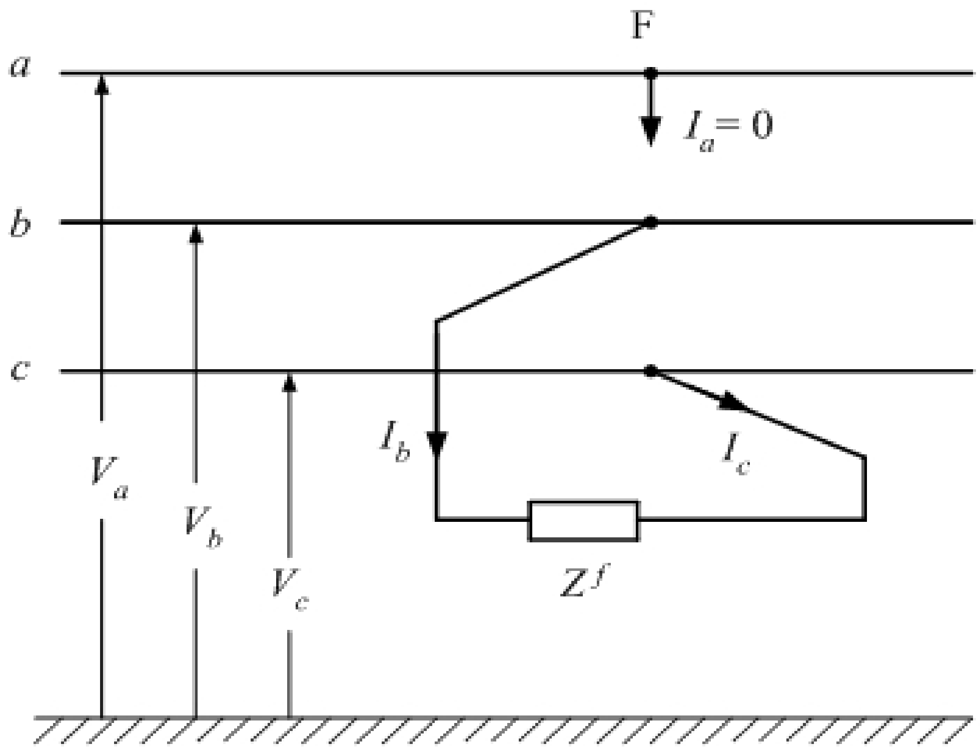
Example

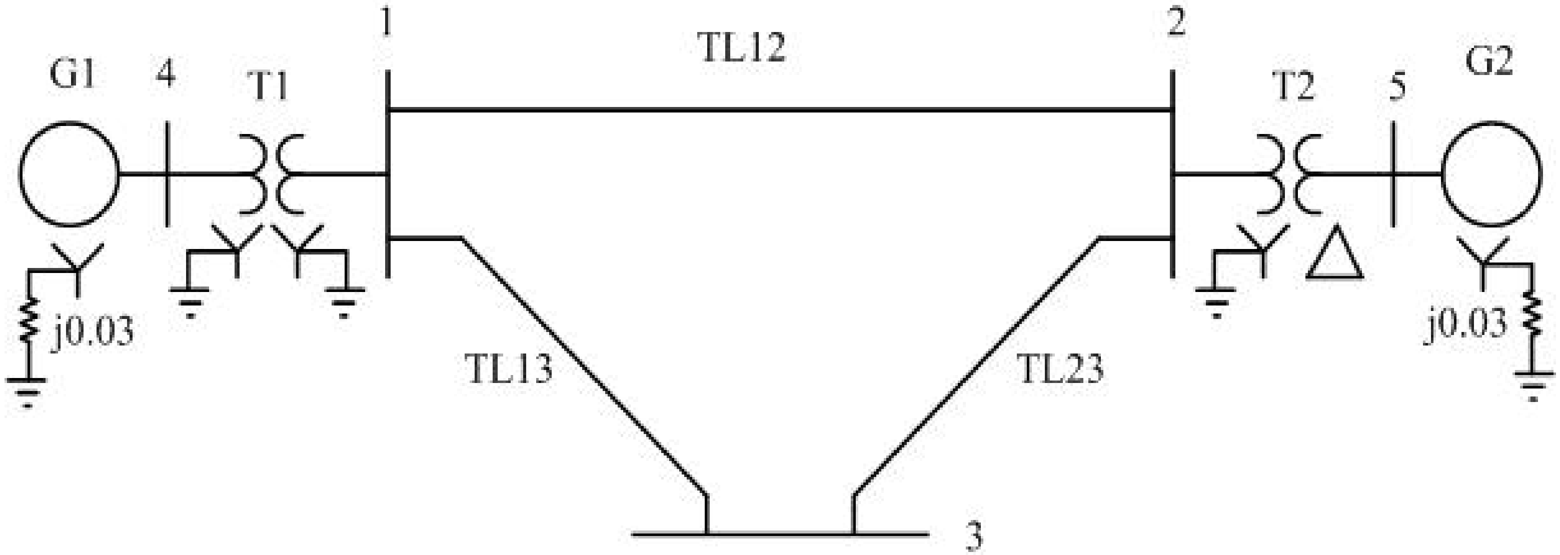
Q3. Explain how methods of symmetrical components is used to analyze unbalanced power systems.**(5 marks)**

What are symmetrical components? Why are they used? **(5 marks)**

Q4. Show that the fault currents in a single line-to-ground fault of an unloaded generator can be calculated by connecting the three sequence networks in series so that $I_{A1} = I_{A2} = I_{A0}$. Where I_{A1}, I_{A2}, and I_{A0} are the positive, negative and zero sequence currents respectively. **(6 marks)**

Figure Q3(a) shows a line to line fault at F in a power system on phases b and c through a fault impedance Z^f. Assume that the system is operating at no load before the occurrence of the fault. Show that the fault current can be calculated by connecting the positive sequence network and negative sequence network in parallel through a series impedance Z^f. **[10 Marks]**



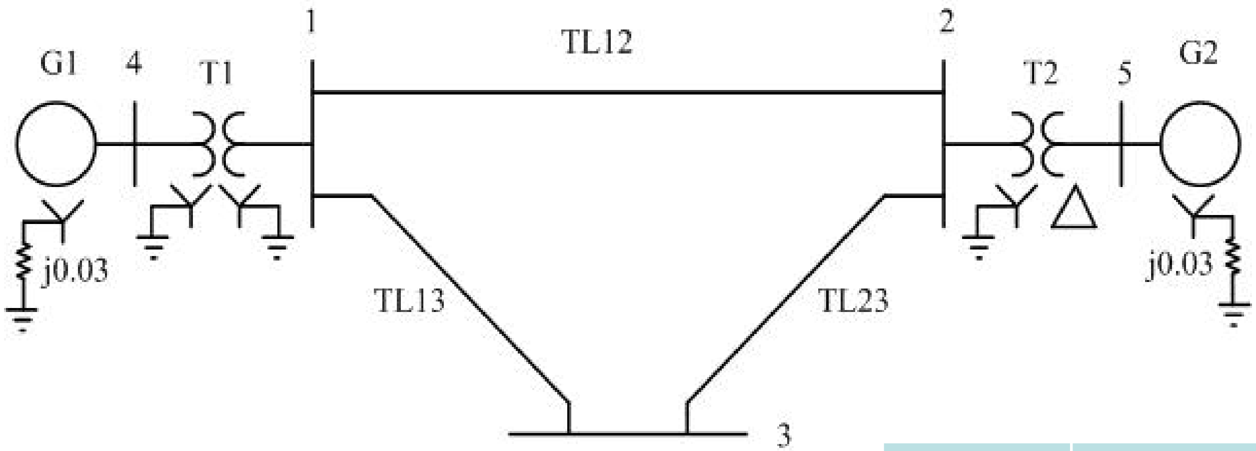


Synchronous generators				
G1	100 MVA	25 kV	$X_1 = X_2 = 0.2$	$X_0 = 0.05$
G2	100 MVA	13.8 kV	$X_1 = X_2 = 0.2$	$X_0 = 0.05$
Transformers				
T1	100 MVA	25/230 kV	$X_1 = X_2 = X_0 = 0.05$	
T2	100 MVA	13.8/230 kV	$X_1 = X_2 = X_0 = 0.05$	

TL12	$X_1 = X_2 = 0.1$	$X_0 = 0.3$
TL13	$X_1 = X_2 = 0.1$	$X_0 = 0.3$
TL23	$X_1 = X_2 = 0.1$	$X_0 = 0.3$

All the reactances are based on 100 MVA and 230 kV at the transmission lines. Compute fault current and voltages for double line to ground fault at the midpoint of transmission line TL12.

[20 marks]

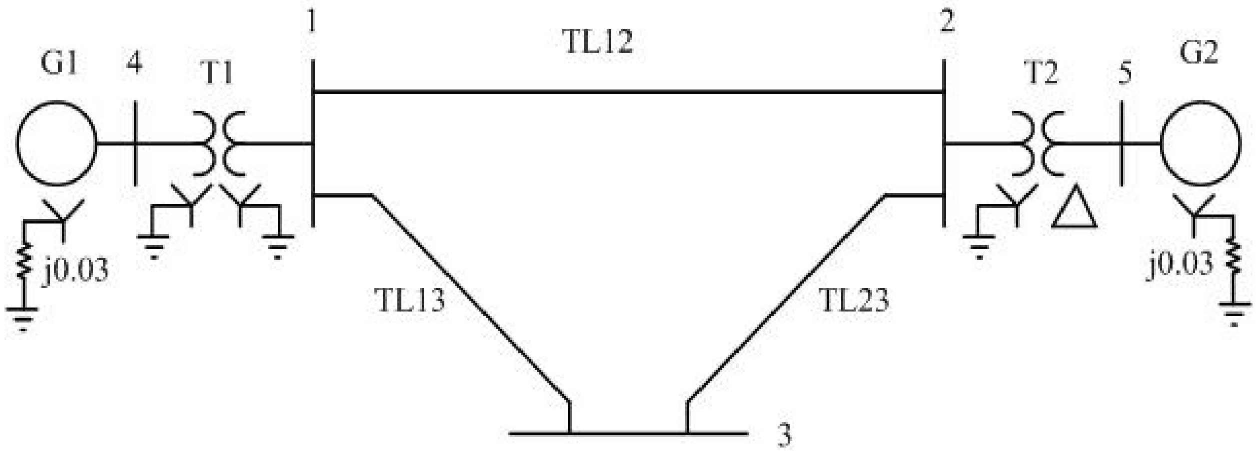


TL12	$X_1 = X_2 = 0.1$	$X_0 = 0.3$
TL13	$X_1 = X_2 = 0.1$	$X_0 = 0.3$
TL23	$X_1 = X_2 = 0.1$	$X_0 = 0.3$

Synchronous generators				
G1	100 MVA	25 kV	$X_1 = X_2 = 0.2$	$X_0 = 0.05$
G2	100 MVA	13.8 kV	$X_1 = X_2 = 0.2$	$X_0 = 0.05$
Transformers				
T1	100 MVA	25/230 kV	$X_1 = X_2 = X_0 = 0.05$	
T2	100 MVA	13.8/230 kV	$X_1 = X_2 = X_0 = 0.05$	

All the reactances are based on 100 MVA and 230 kV at the transmission lines.

Draw positive, negative and zero sequence network



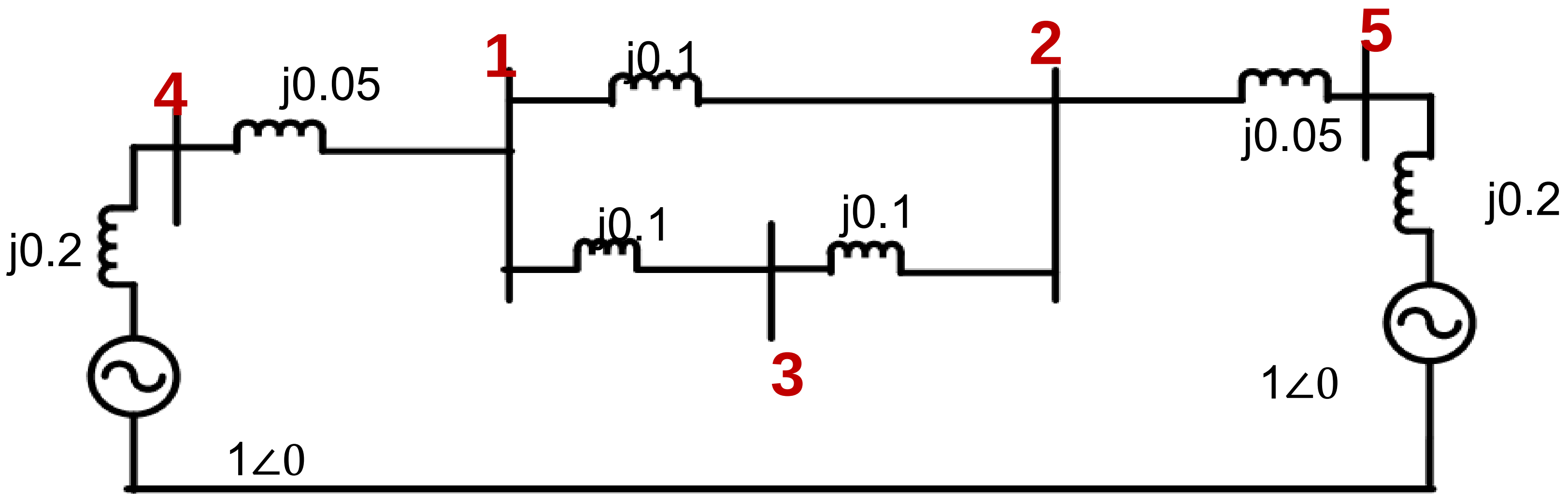
Synchronous generators				
G1	100 MVA	25 kV	$X_1 = X_2 = 0.2$	$X_0 = 0.05$
G2	100 MVA	13.8 kV	$X_1 = X_2 = 0.2$	$X_0 = 0.05$
Transformers				
T1	100 MVA	25/230 kV	$X_1 = X_2 = X_0 = 0.05$	
T2	100 MVA	13.8/230 kV	$X_1 = X_2 = X_0 = 0.05$	

TL12	$X_1 = X_2 = 0.1$	$X_0 = 0.3$
TL13	$X_1 = X_2 = 0.1$	$X_0 = 0.3$
TL23	$X_1 = X_2 = 0.1$	$X_0 = 0.3$

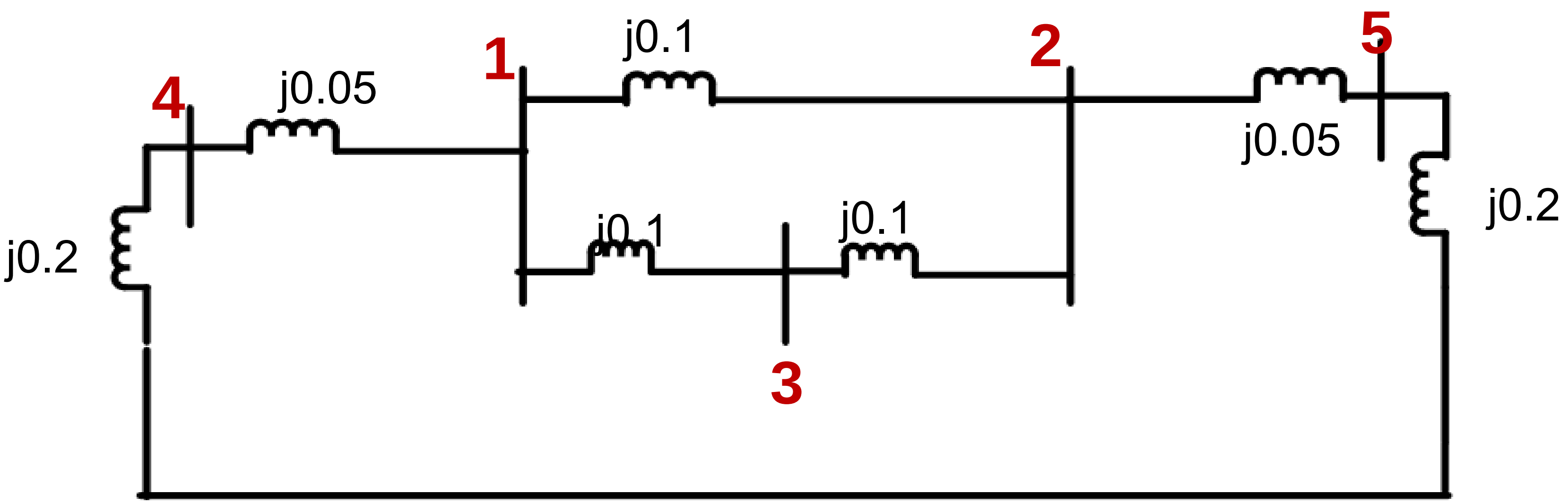
All the reactances are based on 100 MVA and 230 kV at the transmission lines.

Draw positive, negative and zero sequence network

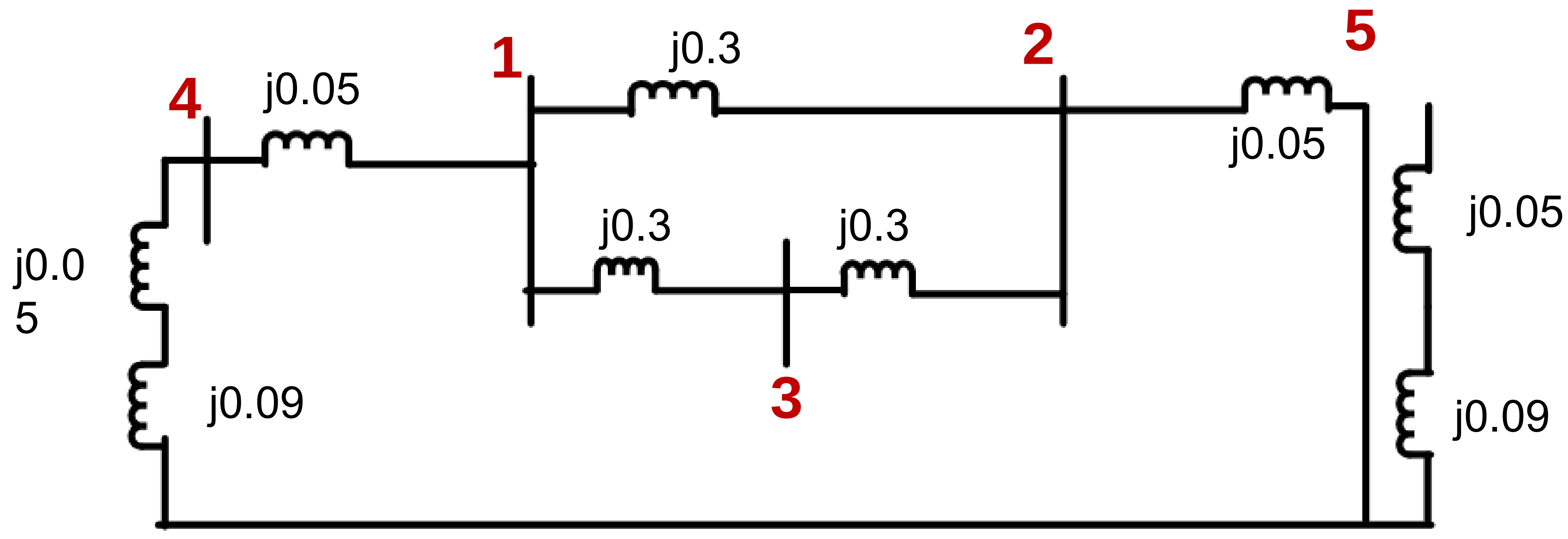
Positive sequence network



Negative sequence network



Zero sequence network



- Reduce the network to their Thevenin equivalents looking at **bus 1**
- **Neglect phase shifts, compute:**
- **Fault currents for a double line to earth fault at bus 1**