Short Circuit Currents (2)

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Power System Protection

Short-Circuit Capacity

- Measures the electrical strength of the bus
- Stated in MVA
- Determines the dimension of bus bars
- Definition

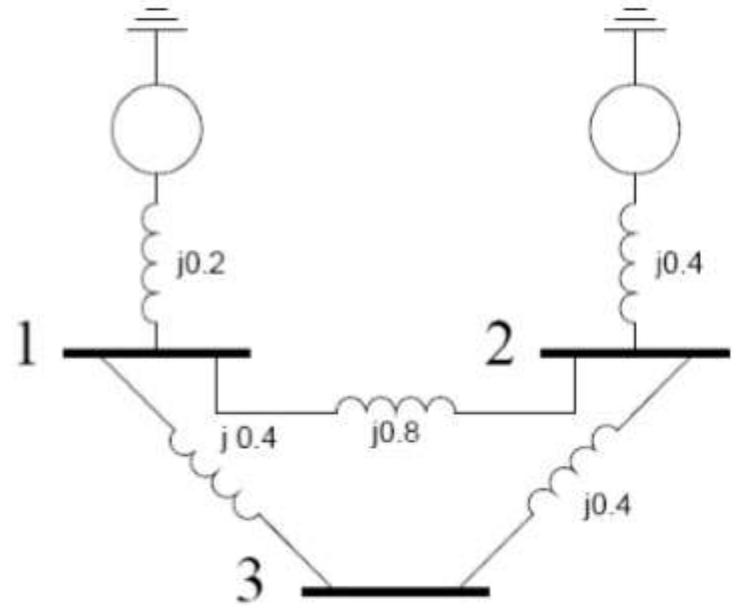
$$SCC = \sqrt{3}\, V_{L-L,k}^{[\text{pre-f}]}\, I_k^{[\text{f}]}$$

$$I_k^{[\text{f}]} = \frac{V_k^{[\text{pre-f}]}}{X_{kk}}$$

$$SCC = \frac{S_B}{X_{kk}}$$

Short-Circuit Capacity

- **Find the SCC for bus #3**



$$Z_{33} = j0.34$$

$$S_{base} = 100 \text{ MVA}$$

$$SCC_3 = \frac{S_{base}}{|Z_{33}|} = \frac{100 \text{ MVA}}{0.34} = 294 \text{ MVA}$$

Types of fault duty

- For respective applications, short-circuit currents have to be calculated carefully as they vary considerably during a fault
  - Rapid drop of the current due to the armature reaction of the synchronous machines
  - Extinction of an electrical arc is never achieved instantaneously
- ANSI/IEEE Standards C37 and IEC 6090 refer to duty types defined as first cycle or momentary peak, interrupting or breaking, and time-delayed or steady-state currents.

Types of fault duty – first cycle current

- First cycle currents, also called momentary currents, are the currents present one half of a cycle after fault initiation (*I''*).
- These are the currents that are sensed by circuit breaker protection equipment when a fault occurs.
- They are calculated with DC offset but no AC decrement in the sources, and using the machine subtransient reactance.
- Peak currents correspond to the maximum currents during the first cycle after the fault occurs and differ from the first cycle currents that are totally asymmetrical rms currents.

Types of fault duty – Interrupting & Time-delayed currents

- Interrupting currents, also known as contact parting currents, are the values that have to be cleared by interrupting equipment.
  - Called breaking currents and typically are calculated in the range from three to five cycles.
  - Currents contain DC offset and some decrement of the AC current.
- Time-delayed or steady-state short-circuit currents correspond to the values obtained between 6 and 30 cycles.
  - Currents should not contain DC offset, and synchronous and induction contributions should be neglected and transient reactance or higher values should be used in calculating the currents.
- Asymmetrical values are calculated as the square root of the sum of the squares of the DC component and the rms value of the AC current

$$I_{\mathrm{rms}} = \sqrt{I_{\mathrm{DC}}^2 + I_{\mathrm{AC}}^2}$$

Calculation of fault duty values

- Typically, the AC and DC components decay to 90% of their initial values after the first half cycle.
- From this, the value of the rms current would then be

$$
\begin{aligned}
I_{\text{rms.asym.closing}} &= \sqrt{I_{\text{DC}}^2 + I_{\text{AC.rms.sym.}}^2} \\
&= \sqrt{\left(\frac{0.9\sqrt{2}V}{X_{\text{d}}''}\right)^2 + \left(\frac{0.9V}{X_{\text{d}}''}\right)^2} \\
&= \frac{1.56V}{X_{\text{d}}''} = 1.56 I_{\text{rms.sym.}}
\end{aligned}
$$

Usually a factor of 1.6 is used by manufacturers

Calculation of fault duty values

- Considering the specification for the switchgear opening current, the rms value of interrupting current is used

$$I_{\text{rms.asym.int.}} = \sqrt{I_{\text{DC}}^2 + I_{\text{AC.rms.sym.int.}}^2}$$

Replacing the DC component by its exponential expression gives

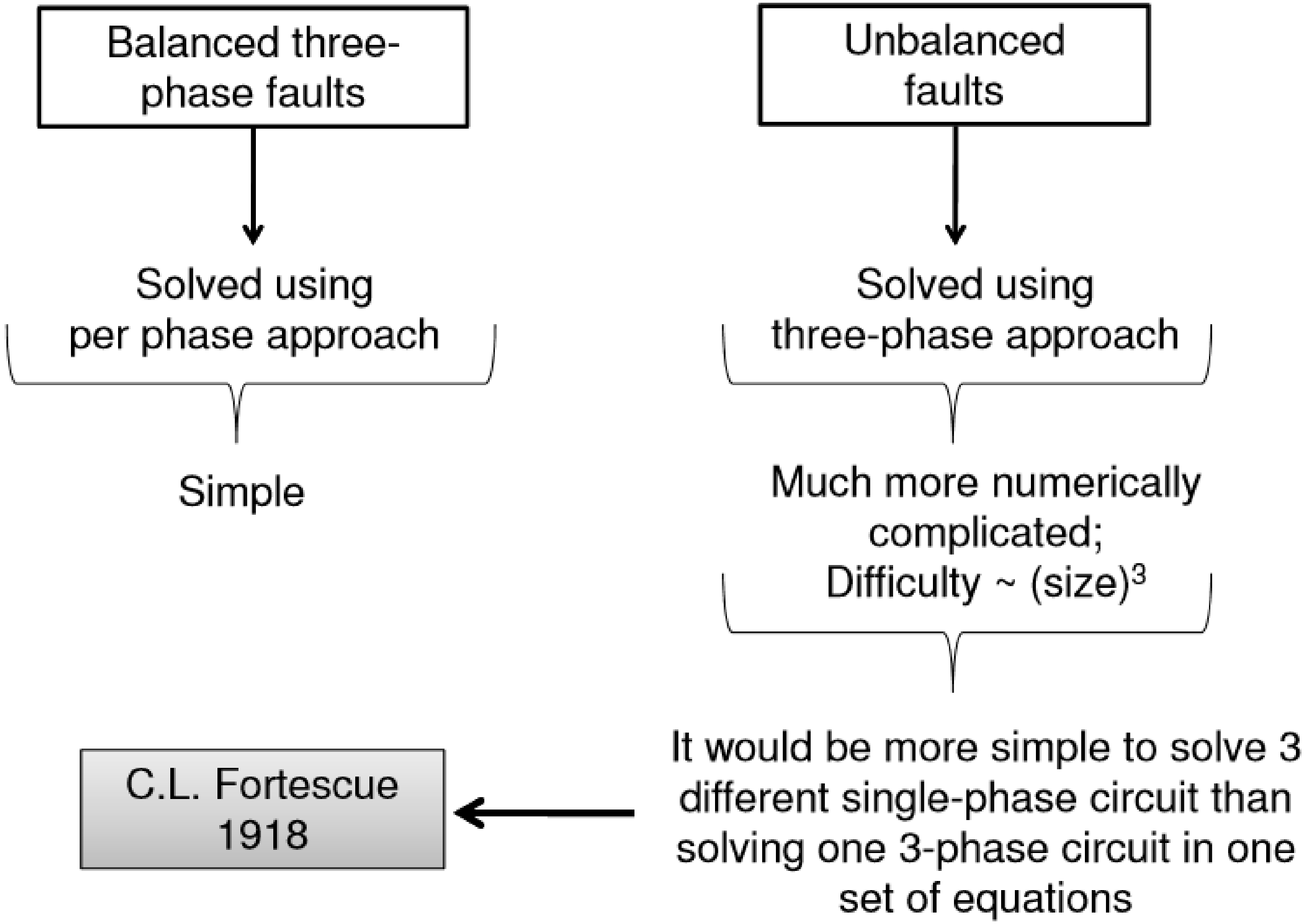
$$I_{\text{rms.asym.int.}} = \sqrt{\left(\sqrt{2}I_{\text{rms.sym.int.}}\,\mathrm{e}^{-(R/L)t}\right)^2 + I_{\text{rms.sym.int.}}^2}$$

$$= I_{\text{rms.sym.int.}}\sqrt{2\mathrm{e}^{-2(R/L)t} + 1}$$

Methods for calculating short-circuit currents

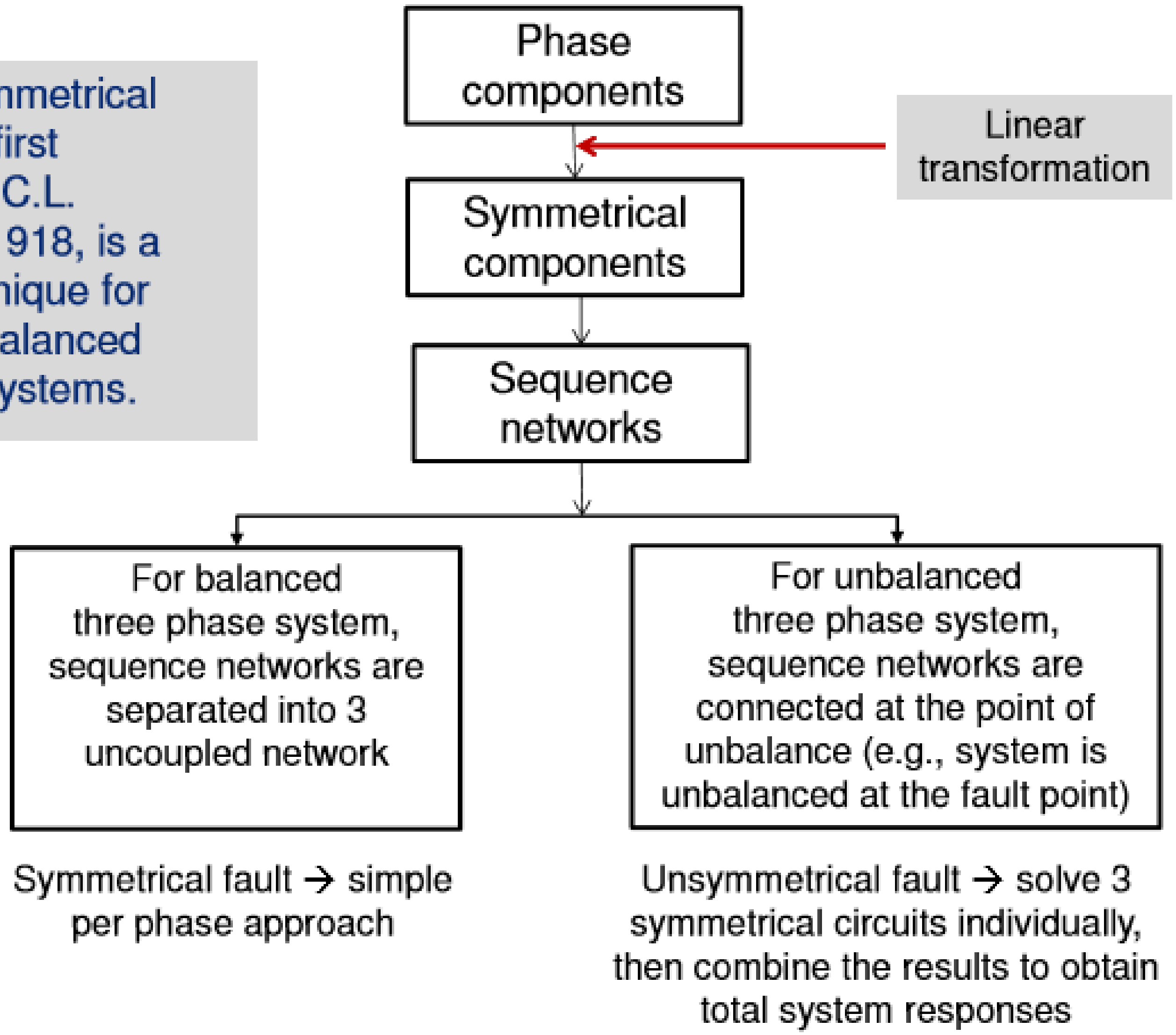
- Symmetrical faults can be treated by using a single-phase representation as it leave the electrical system balanced, i.e. three-phase faults and three-phase-to-earth faults.
- Symmetry is lost during asymmetrical faults (line-to-earth, line-to-line and line-to-line-to-earth) and faults are analyzed through method of symmetrical components
- When considering a three-phase system, each vector quantity, voltage or current, is replaced by three components so that a total of nine vectors uniquely represent the values of the three phases.

Why Symmetrical Components?



Symmetrical components

Method of symmetrical components, first developed by C.L. Fortescue in 1918, is a powerful technique for analyzing unbalanced there-phase systems.



Methods for calculating short-circuit currents

The three-system balanced phasors are designated as:

1. Positive-sequence components, which consist of three phasors of equal magnitude, spaced 120º apart, and rotating in the same direction as the phasors in the power system under consideration, i.e. the positive direction.
2. Negative-sequence components, which consist of three phasors of equal magnitude, spaced 120º apart, rotating in the same direction as the positive sequence phasors but in the reverse sequence.
3. Zero-sequence components, which consist of three phasors equal in magnitude and in phase with each other, rotating in the same direction as the positive sequence phasors.

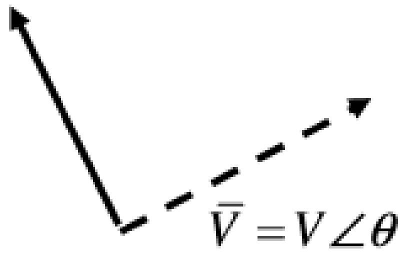
Definition

- We need a vector $a = 1\angle 120^o$ called "a operator" similar to the "j operator"

The "j" operator

$$j = 1\angle 90^0$$

$$j \cdot \bar{V} = V\angle\theta + 90^0$$

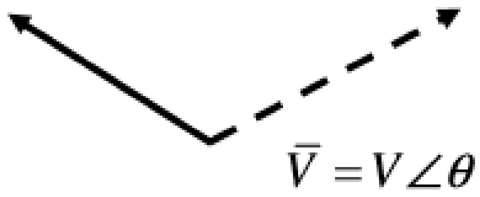


multiplication causes forward rotation of 90^0

The "a" operator

$$a = 1\angle 120^0$$

$$a \cdot \bar{V} = V\angle\theta + 120^0$$



multiplication causes forward rotation of 120^0

With this arrangement, voltage values of any three-phase system, V_a, V_b and V_c, can be represented as follows:

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

It can be demonstrated that

$$V_b = V_{a0} + a^2 V_{a1} + a V_{a2}$$
$$V_c = V_{a0} + a V_{a1} + a^2 V_{a2}$$

where a is a so-called operator that gives a phase shift of 120° clockwise and a multiplication of unit magnitude, i.e. $a = 1\angle 120°$, and a^2 similarly gives a phase shift of 240°, i.e. $a^2 = 1\angle 240°$.

Therefore, the following matrix relationship can be established:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \times \begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix}$$

Inverting the matrix of coefficients, we get

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

From the above matrix, it can be deduced that

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

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

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

$$I_a = I_{a0} + I_{a1} + I_{a2}$$
$$I_b = I_{a0} + a^2 I_{a1} + aI_{a2}$$
$$I_c = I_{a0} + aI_{a1} + a^2 I_{a2}$$

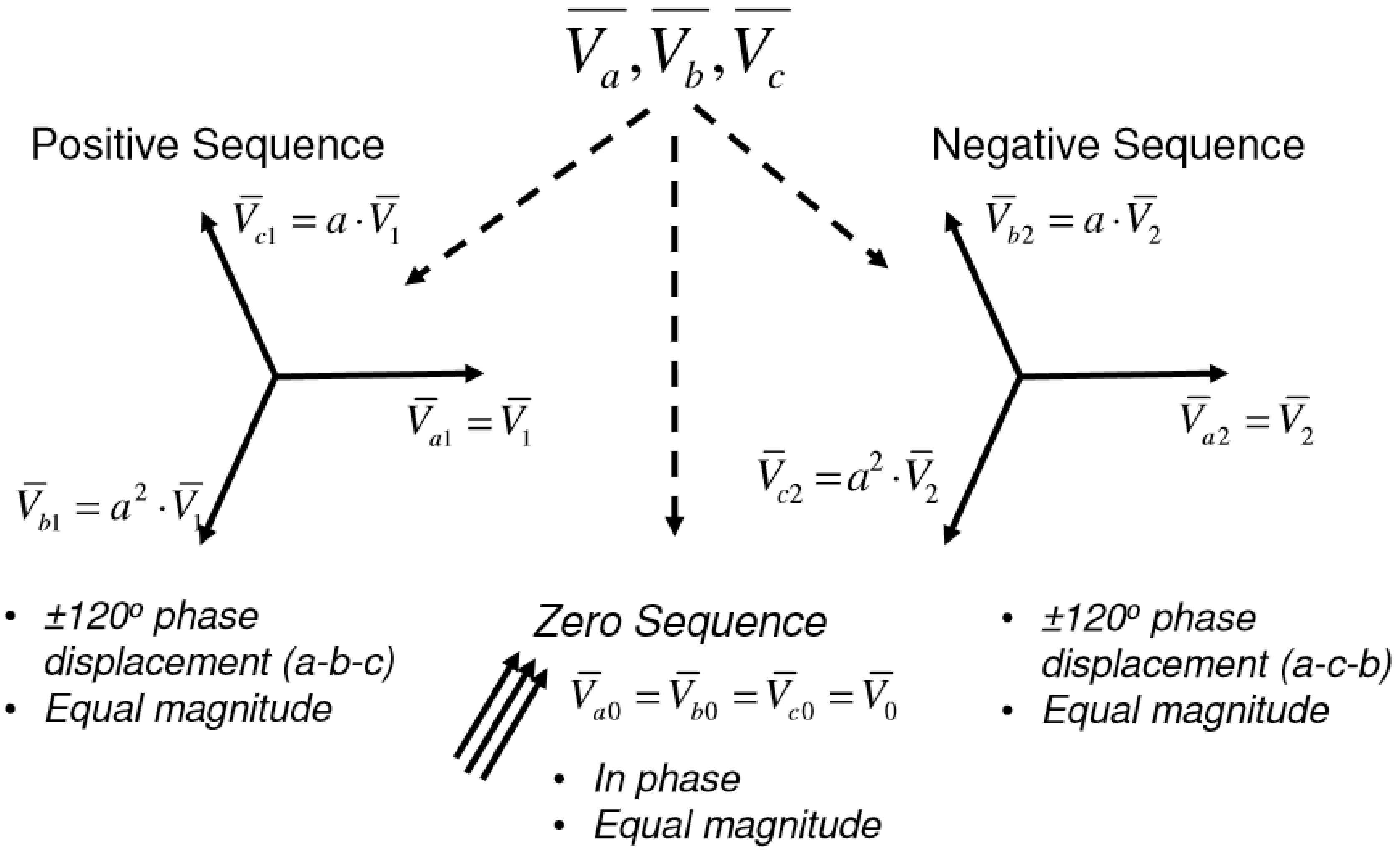
Therefore

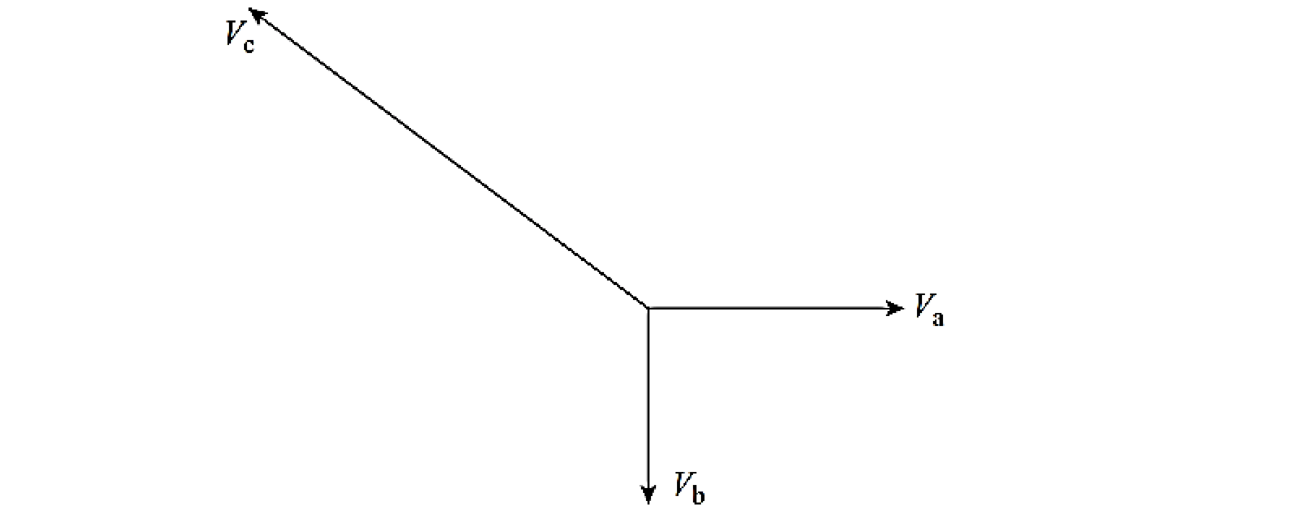
$$I_{a0} = \frac{1}{3}(I_a + I_b + I_c)$$
$$I_{a1} = \frac{1}{3}(I_a + aI_b + a^2 I_c)$$
$$I_{a2} = \frac{1}{3}(I_a + a^2 I_b + aI_c)$$

In three-phase systems, the neutral current is equal to $I_n = I_a + I_b + I_c$ and, therefore, $I_n = 3I_{a0}$.

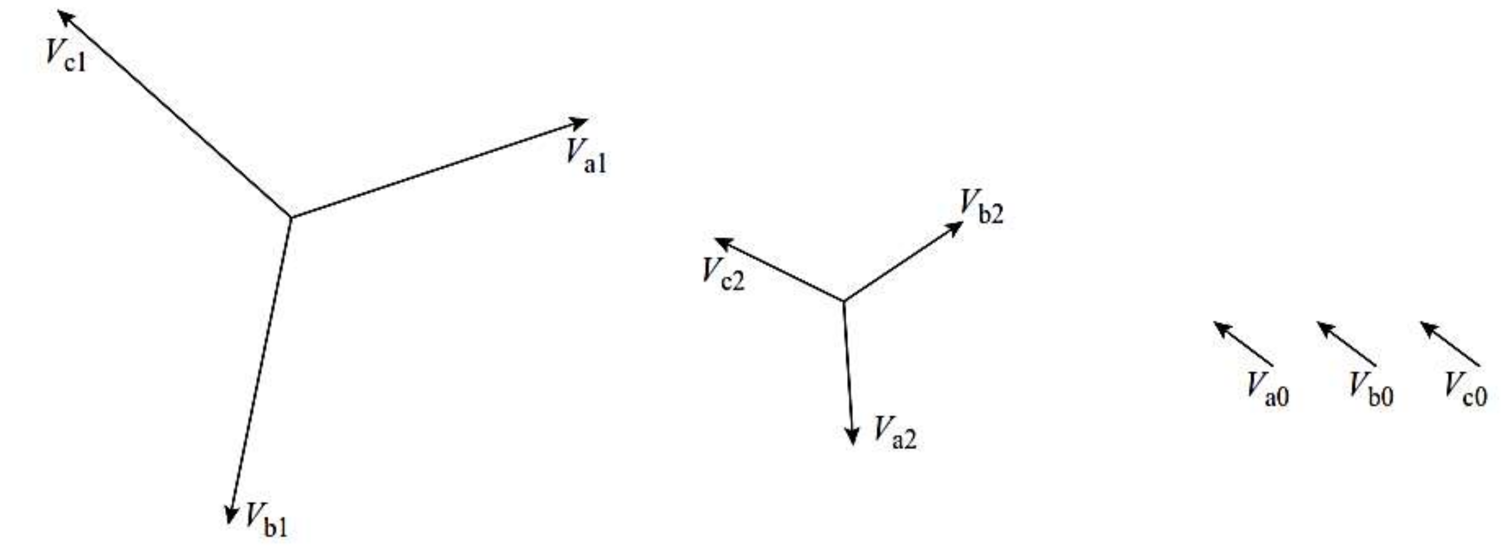
Definition

- Breaking up asymmetrical three-phase voltages and currents into three sets of symmetrical components.





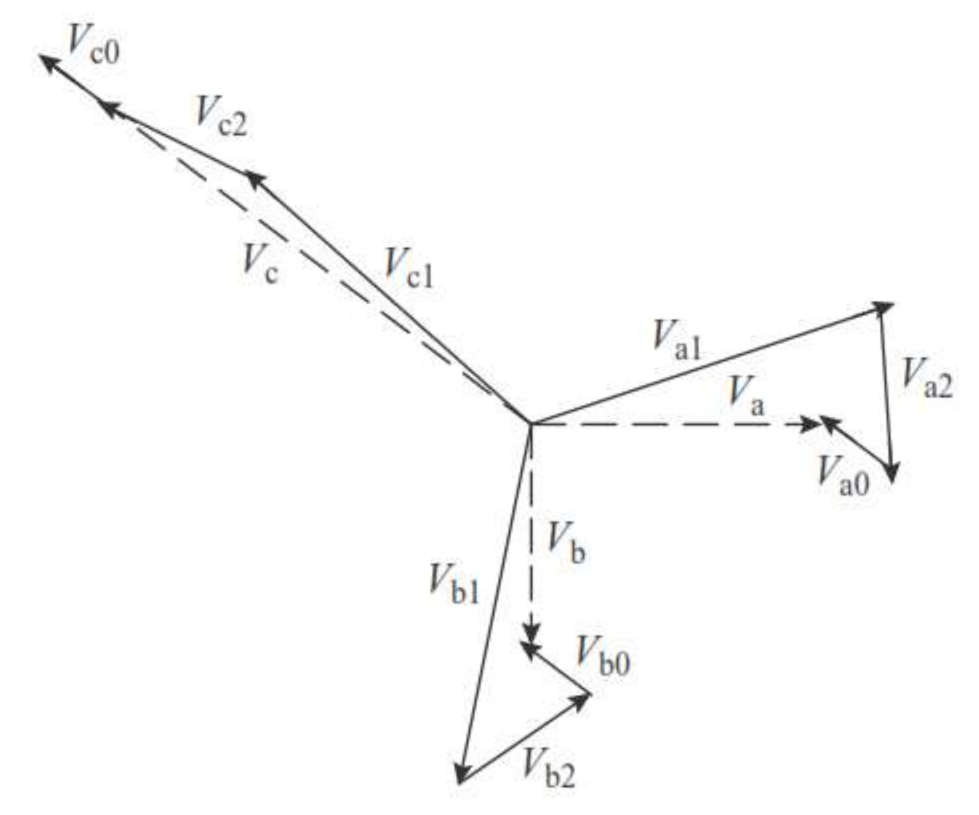
$V_a = 8.0\ \angle 0°$ $V_b = 6.0 \angle -90°$ $V_c = 16.0 \angle 143.1°$



$V_{a1} = 9.8\ \angle 18.4°$
$V_{b1} = 9.8\ \angle -101.6°$
$V_{c1} = 9.8\ \angle 138.4°$

$V_{a2} = 4.3\ \angle -86.2°$
$V_{b2} = 4.3\ \angle 33.8°$
$V_{c2} = 4.3\ \angle -206.2°$

$V_{a0} = 2.0\ \angle 143.1°$
$V_{b0} = 2.0\ \angle 143.1°$
$V_{c0} = 2.0\ \angle 143.1°$



Assignment

Calculate the sequence components of the following balanced line to neutral voltage with a-b-c sequence.

$$V_p = \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} 277\angle 0^\circ \\ 277\angle -120^\circ \\ 277\angle +120^\circ \end{bmatrix} \text{ (Volts)}$$

Assignment

A 3ϕ line feeding a balanced Y-connected load has one of its phases (phase b) open. The load neutral is grounded, and the unbalanced line currents are

$$I_p = \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 10\angle 0^\circ \\ 0 \\ 10\angle 120^\circ \end{bmatrix} \quad \text{(Amps.)}$$

Find $[I_s]$ and $I_{neutral}$

Sequence Networks

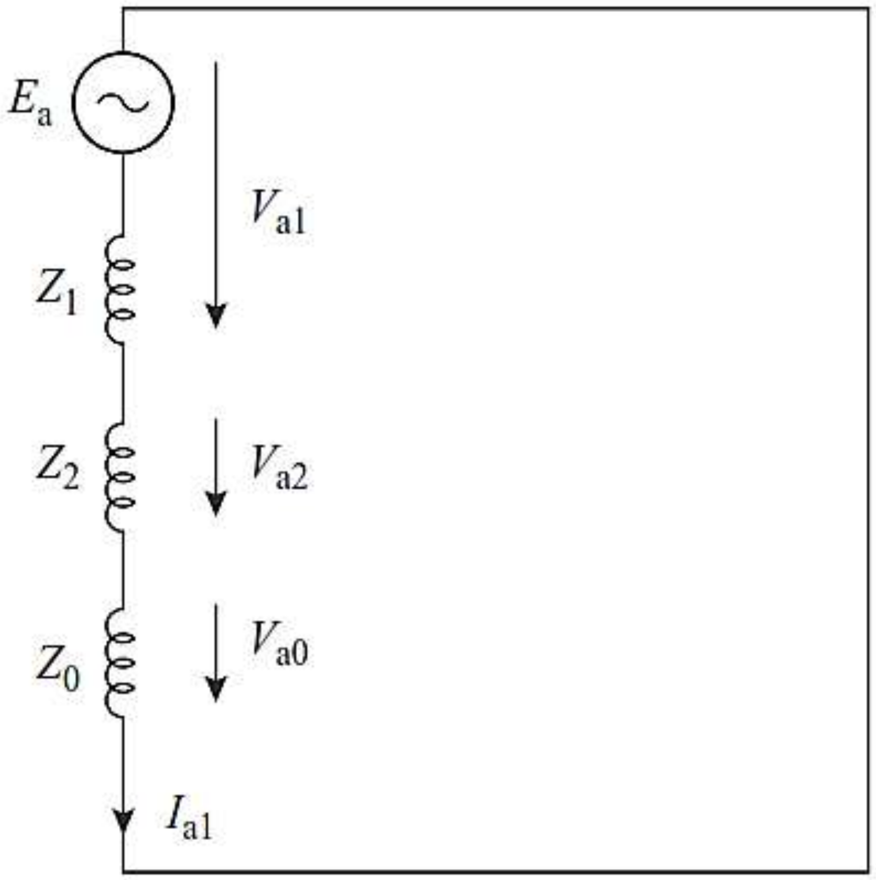
- Impedance of circuit in which positive, negative or zero sequence currents are circulating are called the positive, negative and zero sequence impedances, respectively.
  - These sequence impedances are designated as Z_1, Z_2 and Z_0.
- Generators are designed to supply balanced voltages and therefore of positive sequence only.
  - positive-sequence network is composed of an e.m.f. source in series with the positive-sequence impedance
  - Negative- and zero-sequence networks do not contain e.m.f.s but only include impedances to the flow of negative- and zero-sequence currents, respectively.

Line-to-earth fault

- Conditions for a solid fault from line a to earth

$$I_b = 0,\ I_c = 0 \text{ and } V_a = 0$$

$$I_{a1} = I_{a2} = I_{a0} = E_a/(Z_1+Z_2+Z_0)$$



Line-to-line fault

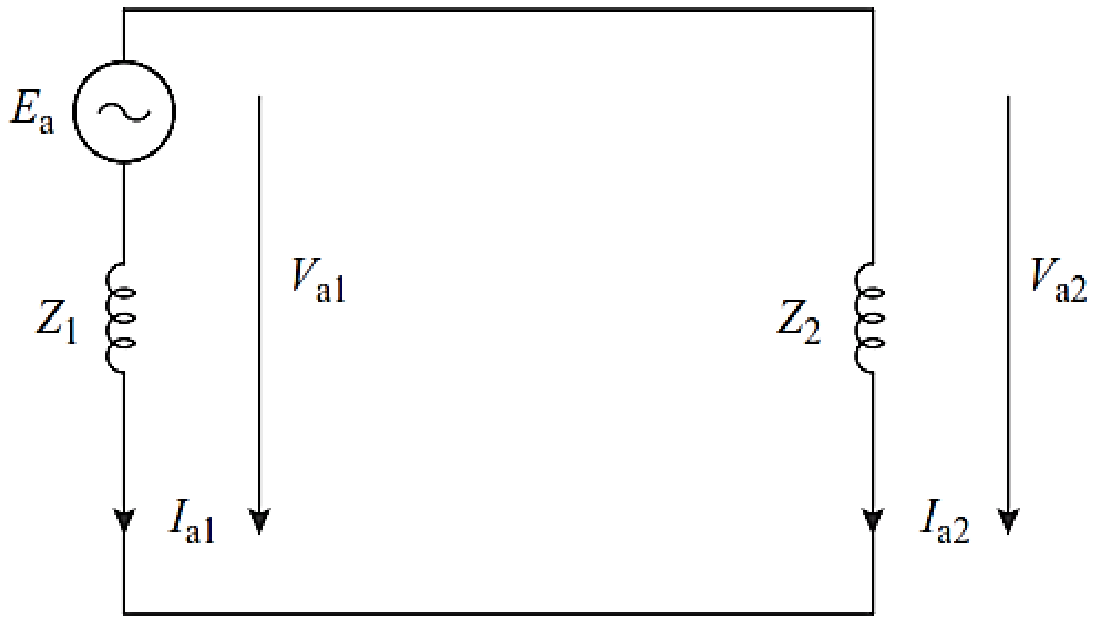
- Conditions for a solid fault between lines b and c are represented as

$$I_a = 0,\ I_b = -I_c \text{ and } V_b = V_c.$$

$$I_{a0} = 0$$

$$I_{a1} = E_a/(Z_1 + Z_2) = -I_{a2}.$$

no zero-sequence current

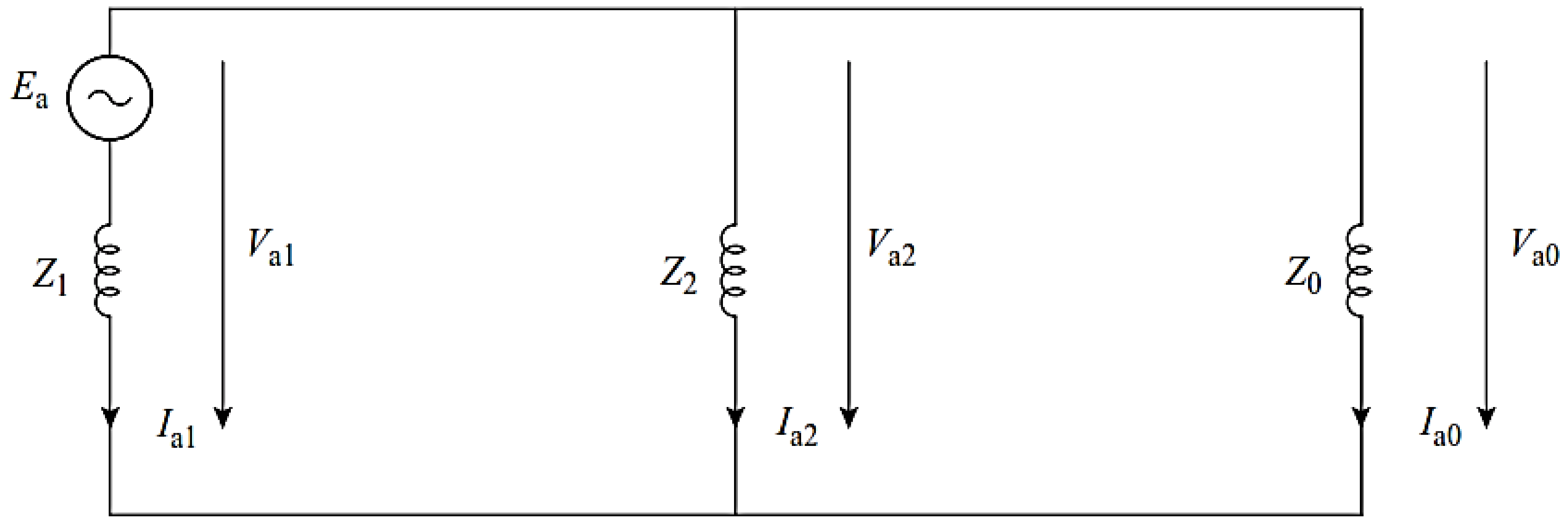


Line-to-line-to-earth fault

- Conditions for a fault between lines b and c and earth are represented

$I_a = 0$ and $V_b = V_c = 0$

$$I_{a1} = \frac{E_a}{Z_1 + [Z_0 Z_2/(Z_0 + Z_2)]}$$



Supplying the current and voltage signals to protection systems

- Current transformers (CTs) circulate current proportional to the fault current to the protection equipment without distinguishing between the vectorial magnitudes of the sequence components
  - Relays usually only operate using the summated
- Relays are available that can operate with specific values of some of the sequence components.
  - achieved by using filters
- Relays for earth fault protection require this type of filter