MODULE 3

Symmetrical Components

Course Objectives:

1. To explain symmetrical components, their advantages and the calculation of symmetrical components of voltages and currents in un-balanced three phase circuits.
2. To explain the concept of sequence impedance and its analysis in three phase unbalanced circuits.
3. To explain the concept of sequence networks and sequence impedances of an unloaded synchronous generator, transformers and transmission lines.

3.1 INTRODUCTION

The electrical power system normally operates in a balanced three-phase sinusoidal steady-state mode. However, there are certain situations that can cause unbalanced operations. The most severe of these would be a fault or short circuit. Examples may include a tree in contact with a conductor, a lightning strike, or downed power line.

In 1918, Dr. C. L. Fortescue wrote a paper entitled "Method of Symmetrical Coordinates Applied to the Solution of Polyphase Networks." In the paper Dr. Fortescue described how arbitrary unbalanced 3-phase voltages (or currents) could be transformed into 3 sets of balanced 3-phase components, Fig 3.1. He called these components "symmetrical components." In the paper it is shown that unbalanced problems can be solved by the resolution of the currents and voltages into certain symmetrical relations.

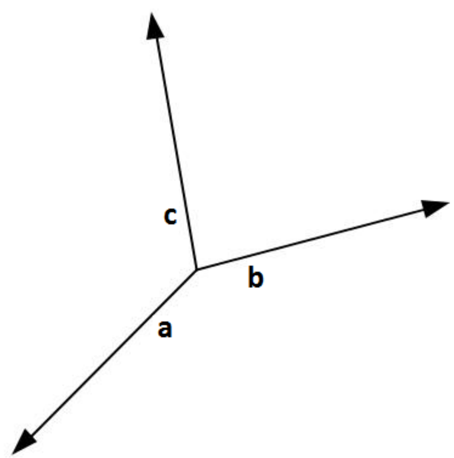


Fig 3.1: Unbalanced Phasor

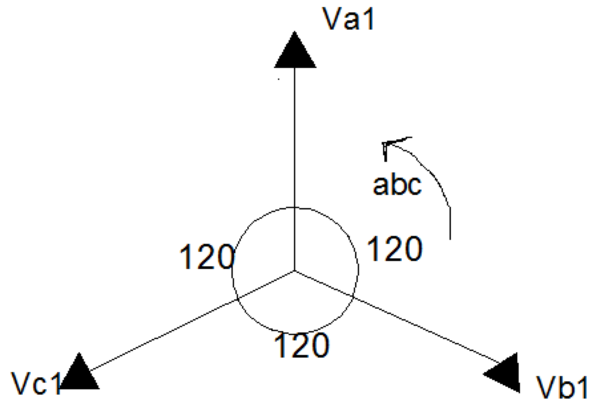


Fig 3.1 a): Positive sequence component

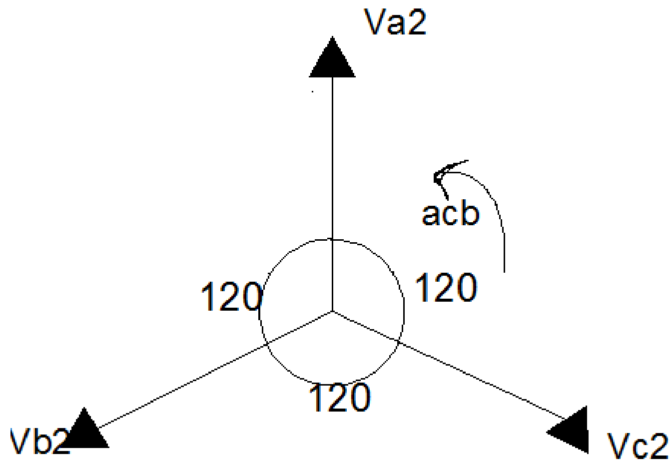


Fig 3.1 b): Negative sequence component

Fig 3.1 c): Negative sequence component

3.2 Symmetrical Component Transformation

a) THE' j' AND 'a' OPERATOR

In polar form, $j = 1\angle 90^o$. Multiplying by j has the effect of rotating a phasor 90^o without affecting the magnitude. In a similar manner the a operator is defined as unit vector at an angle of 120^0, written as $a = 1\angle 120^o$. The operator a^2, is also a unit vector at an angle of 240^0, written $a^2 = 1\angle 240^o$

3.2.1 PROPERTIES OF VECTOR ' a'

$$1 = 1.0 + j0.0$$
$$a = 1\angle 120^o$$
$$a^2 = 1\angle 240^o$$
$$a^3 = 1\angle 360^o = 1\angle 0^o$$
$$1 + a^2 + a = 0$$
$$a + a^2 = -1$$
$$1 + a = 1\angle 60^o$$
$$1 + a^2 = 1\angle -60^o$$
$$a - a^2 = j\sqrt{3}$$
$$a^2 - a = -j\sqrt{3}$$
$$1 - a = \sqrt{3}\angle -30^\circ$$
$$1 - a^2 = \sqrt{3}\angle 30^o$$

3.2.3 THE THREE-PHASE SYSTEM AND THE RELATIONSHIP OF THE $\sqrt{3}$

In a Wye connected system the voltage measured from line to line equals the square root of three, $\sqrt{3}$ times the voltage from line to neutral. The line current equals the phase current

$$V_{LL} = \sqrt{3}V_{LN}$$
$$I_L = I_\Phi$$

In a Delta connected system the voltage measured from line to line equals the phase voltage. The line current will equal the square root of three, times the phase current

$$V_{LL} = V_\Phi$$
$$I_L = \sqrt{3}I_\Phi$$

The power equation, for a three phase system, is

$$S = \sqrt{3}V_{LL}I_L$$
$$P = \sqrt{3}V_{LL}I_L\cos\psi$$
$$Q = \sqrt{3}V_{LL}I_L\sin\psi$$

where S is the apparent power or complex power in volt-amperes (VA). P is the real power in Watts (W, kW, MW). Q is the reactive power in VARS (Vars, kVars, MVars).

S*base*= power base, in VA. Although in principle S*base* may be selected arbitrarily, in practice it is typically chosen to be 100 MVA.

V*base* = voltage base in V. Although in principle V*base* is also arbitrary, in practice V*base* is equal to the nominal line-to-line voltage. The term nominal means the value at which the system was designed to operate under normal balanced conditions.

The base power equation for a three-phase system is:

$$S_{3\Phi base} = \sqrt{3} V_{base} I_{base}$$

Solving for current:

$$I_{base} = \frac{S_{3\Phi base}}{\sqrt{3} V_{base}}$$

Because S3Φbase can be written as kVA or MVA and voltage is usually expressed in kilovolts, or kV, current can be written as:

$$I_{base} = \frac{kVA_{base}}{\sqrt{3} kV_{base}} amperes$$

Solving for base impedance:

$$Z_{base} = \frac{V_{base}}{I_{base}} = \frac{V_{base}^2}{S_{base}}$$

$$Z_{base} = \frac{kV_{base}^2 x1000}{kVA_{base}} ohms$$

$$Z_{base} = \frac{kV_{base}^2}{MVA_{base}} ohms$$

Given the base values, and the actual values: $V = IZ$, then dividing by the base we are able to calculate the *pu* values

$$\frac{V}{V_{base}} = \frac{IZ}{I_{base}Z_{base}} \Rightarrow V_{pu} = I_{pu}Z_{pu}$$

After the base values have been selected or calculated, then the *per-unit* impedance values for system components can be calculated

$$Z_{pu} = \frac{Z(\Omega)}{Z_{base}} = \left(\frac{MVA_{base}}{kV_{base}^2}\right)\cdot Z(\Omega)$$

$$Z_{pu} = \left(\frac{kVA_{base}}{1000\cdot kV_{base}^2}\right)\cdot Z(\Omega)$$

It is also a common practice to express *per-unit* values as percentages (i.e. 1 pu = 100%). (Transformer impedances are typically given in % at the transformer MVA rating.)

$$per-unit = \frac{percent\_value}{100}$$

Then Equation can be written as

$$\%Z = \frac{100MVA_{base}\cdot Z(\Omega)}{kV_{base}^2} = \frac{kVA_{base}Z(\Omega)}{10kV_{base}^2}$$

It is frequently necessary, particularly for impedance values, to convert from one (old) base to another (new) base.

$$Z_{pu}^{new} = Z_{pu}^{old}\left(\frac{Z_{base}^{old}}{Z_{base}^{new}}\right)$$

Substituting for $Z_{old,\ base}$ and $Z_{new,base}$ re-arranging the new impedance in *per-unit* equals:

$$Z_{pu}^{new} = Z_{pu}^{old}\left(\frac{kVA_{base}^{new}}{kVA_{base}^{old}}\right)\left(\frac{kV_{base}^{old}}{kV_{base}^{new}}\right)^2$$

In most cases the turns ratio of the transformer is equivalent to the system voltages, and the equipment rated voltages are the same as the system voltages. This means that the voltage-squared ratio is unity

$$Z_{ohm}^{new} = Z_{ohm}^{old} \cdot \left(\frac{kV_{base}^{new}}{kV_{base}^{old}}\right)^2$$

3.2.4 Numericals

A system has S_{base} = 100 MVA, calculate the base current for

a) V_{base} = 230 kV

b) V_{base} = 525 kV

Then using this value, calculate the actual line current and phase voltage where $I_{pu} = 4.95$, and $V_{pu} = 0.5$ at both 230 kV and 525 kV.

Solution:

$$I_{base} = \frac{kVA_{base}}{\sqrt{3}kV_{base}} amperes$$

a) $$I_{base} = \frac{1000\times100}{\sqrt{3}\times230} amperes = 251A$$

b) $$I_{base} = \frac{1000\times100}{\sqrt{3}\times525} amperes = 110.0A$$

$$I_{actual} = I_{pu} \cdot I_{base}$$
$$V_{actual} = V_{pu} \cdot V_{base}$$

At 230 kV

c) $I_{actual} = (4.95) \cdot (251A) = 1242A$

d) $V_{actual} = (0.5) \cdot (230kV) = 115kV$

At 525 kV

e) $I_{actual} = (4.95) \cdot (110.0A) = 544A$

f) $V_{actual} = (0.5) \cdot (525kV) = 263kV$

2) A 900 MVA 525/241.5 autotransformer has a nameplate impedance of 10.14%

a) Determine the impedance in ohms, referenced to the 525 kV side.

b) Determine the impedance in ohms, referenced to the 241.5 kV side

$$Zpu = \frac{Z\%}{100} = 0.1014$$

$$Z(\Omega) = Z_{pu} \frac{kV_{base}^2}{MVA_{base}}; \text{ therefore}$$

$$\text{a) } Z_{525kV} = 0.1014 \times \frac{525^2}{900}$$
$$= 31.05\Omega$$

$$\text{b) } Z_{241.5kV} = 0.1014 \times \frac{241.5^2}{900}$$
$$= 6.57\Omega$$

3.3 Sequence Impedance and Sequence Networks

There are four conductors to be considered: *a*, *b*, *c* and neutral *n*.

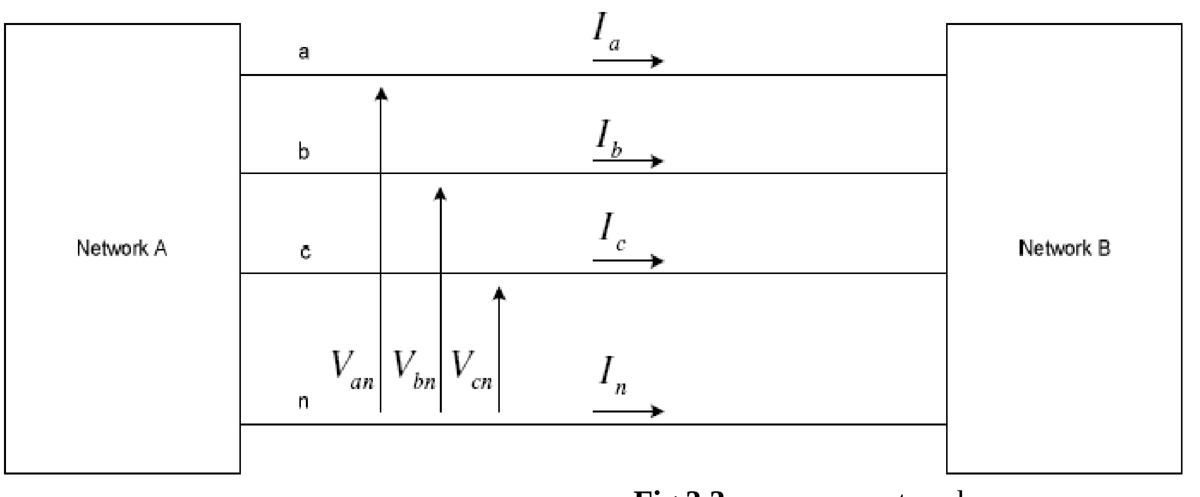


Fig 3.3: sequence network

The phase voltages, V_p , for the balanced 3Φ case with a phase sequence *abc* are

$$V_{an} = V_a = V_p\angle 0^o$$
$$V_{bn} = V_b = V_p\angle -120^o$$
$$V_{cn} = V_c = V_p\angle +120^0 = V_p\angle -240^o$$

The phase-phase voltages, $V\,LL$, are written as

$$V_{ab} = V_a - V_b = V_{LL}\angle 30^o$$
$$V_{bc} = V_b - V_c = V_{LL}\angle -90^o$$
$$V_{ca} = V_c - V_a = V_{LL}\angle 150^o$$

The above equations can be shown in phasor form

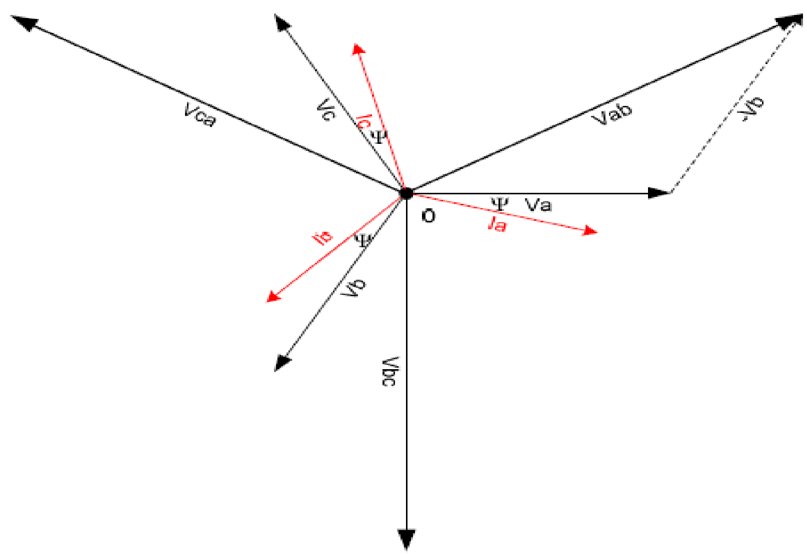


Fig 3.4: Phasor diagram

There are two balanced configurations of impedance connections within a power system. For the wye case and with an impedance connection of $Z\angle\Psi$, the
current can be calculated as

$$I_a = \frac{V}{Z_Y} = \frac{V_P}{Z_Y}\angle 0^o - \psi$$

Where Y is between -90^0 and + 90^0 For Y greater than zero degrees the load would be inductive ($I\ a$ lags $V\ a$). For y less than zero degrees the load would be capacitive
($I\ a$ leads $V\ a$).
The phase currents in the balanced three-phase case are

$$I_a = I_p\angle 0^o - \psi$$

$$I_b = I_p\angle -120^o - \psi$$

$$I_c = I_p\angle -240^o - \psi$$

3.4 SYMMETRICAL COMPONENTS SYSTEMS

The electrical power system operates in a balanced three-phase sinusoidal operation. When a tree contacts a line, a lightning bolt strikes a conductor or two conductors swing into each other we call this a fault, or a fault on the line. When this occurs the system goes from a balanced condition to an unbalanced condition. In order to properly set the protective relays, it is necessary to calculate currents and voltages in the system under such unbalanced operating conditions.

In Dr. C. L. Fortescue's paper he described how symmetrical components can transform an unbalanced condition into symmetrical components, compute the system response by straight forward circuit analysis on simple circuit models, and transform the results back into original phase variables. When a short circuit fault occurs the result can be a set of unbalanced voltages and currents. The theory of symmetrical components resolves any set of unbalanced voltages or currents into three sets of symmetrical balanced phasors. These are known as positive, negative and zero-sequence components. Fig. shows balanced and unbalanced systems.

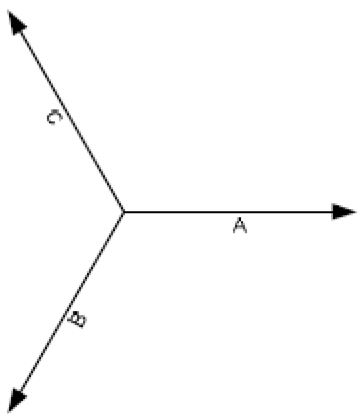


Fig 3.5.1 Balanced system

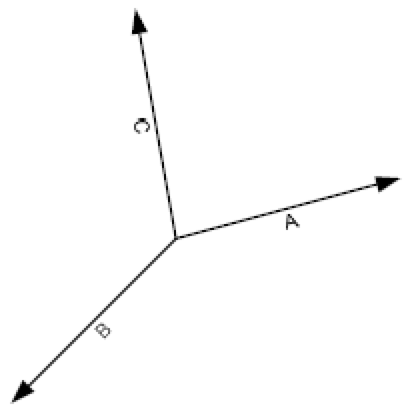


Fig 3.5.2 Unbalanced system

Consider the symmetrical system of phasors. Being balanced, the phasors have equal amplitudes and are displaced 120_o relative to each other. By the definition of symmetrical components, V_{b1} *always lags* V_{a1} by a fixed angle of 120^o and always has the same magnitude as V_{a1} . Similarly V_{c1} leads V_{a1} by 120^o. It follows then that

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

$$V_{b1} = (1\angle 240^o)V_{a1} = a^2 V_{a1}$$

$$V_{c1} = (1\angle 120^o)V_{a1} = aV_{a1}$$

Where the subscript (1) designates the positive-sequence component. The system of phasors is called positive-sequence because the order of the sequence of their maxima occur *abc*.

Similarly, in the negative and zero-sequence components, we deduce

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

$$V_{b2} = (1\angle 120^o)V_{a2} = aV_{a2}$$

$$V_{c2} = (1\angle 240^o)V_{a2} = a^2 V_{a2}$$

$$V_{a0} = V_{a0}$$
$$V_{b0} = V_{a0}$$
$$V_{c0} = V_{a0}$$

Where the subscript (2) designates the negative-sequence component and subscript (0) designates zero-sequence components. For the negative-sequence phasors the order of sequence of the maxima occur *cba*, which is opposite to that of the positive-sequence. The maxima of the instantaneous values for zero-sequence occur simultaneously.

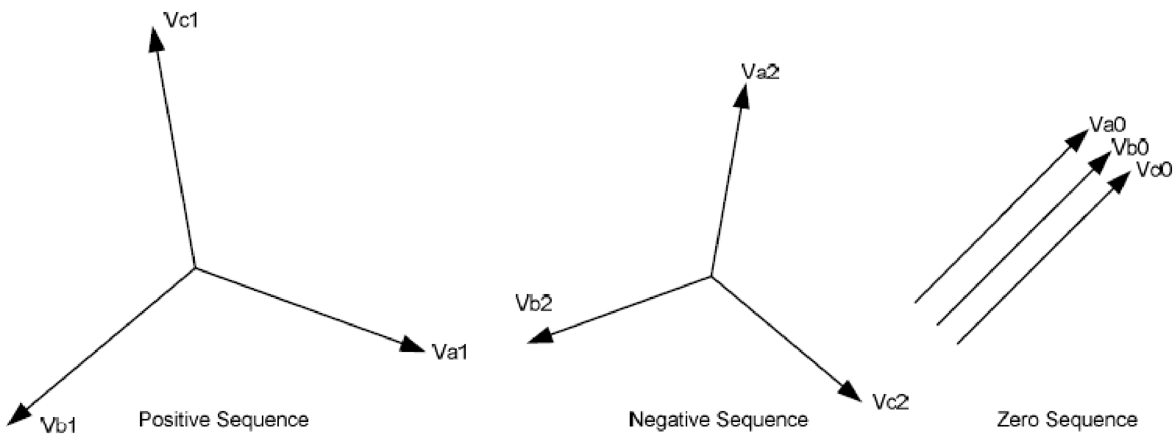


Fig3.6: Sequence networks

In all three systems of the symmetrical components, the subscripts denote the components in the different phases. The total voltage of any phase is then equal to the sum of the corresponding components of the different sequences in that phase. It is now possible to write our symmetrical components in terms of three, namely, those referred to the *a* phase (refer to section 3 for a refresher on the *a* operator).

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

We may further simplify the notation as follows; define

$$V_0 = V_{a0}$$
$$V_1 = V_{a1}$$
$$V_2 = V_{a2}$$

Substituting their equivalent values

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

These equations may be manipulated to solve for V_0 , V_1 , and V_2 in terms of V_a , V_b and V_c .

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

It follows then that the phase currents are

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

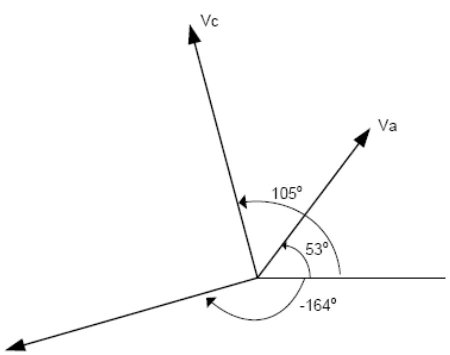
The sequence currents are given by

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

The unbalanced system is therefore defined in terms of three balanced systems may be used to convert phase voltages (or currents) to symmetrical component voltages(or currents) and vice versa

3.4.1 Numericals:

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



Unbalanced condition

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

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

$$= 3.5\angle 122^o$$

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

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

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

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

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

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

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

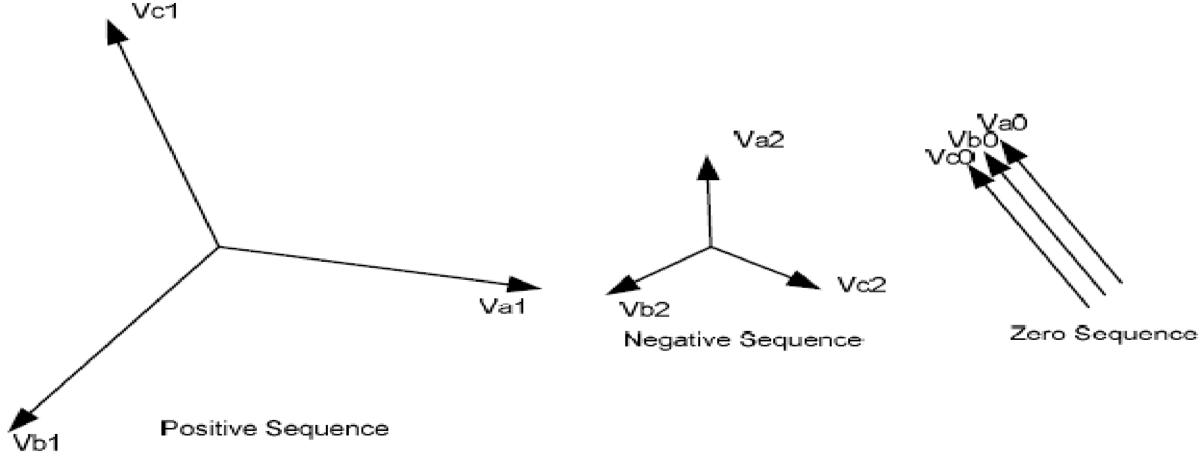
$$V_{a2} = \frac{1}{3}\left(V_a + a^2V_b + aV_c\right)$$

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

$$= 1.9\angle 92^o$$

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

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

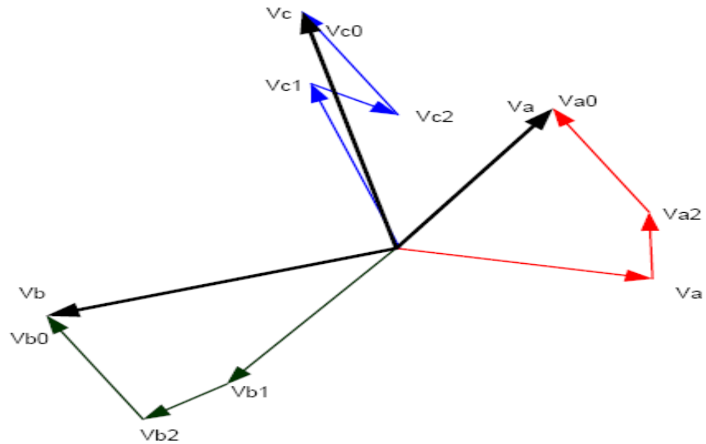


2. Given $V_0 = 3.5\angle 122^o$, $V_1 = 5.0\angle -10^o$, $V_2 = 1.9\angle 92^o$, find the phase sequence components. Shown in the phasor form

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

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

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



3.4.2 SYMMETRICAL COMPONENTS THROUGH A TRANSFORMER

This section will look at current flow through a wye-delta transformer bank. It will be shown in the next chapter that for faults that include ground that zero-sequence quantities will be generated. It can be shown using symmetrical components that zero-sequence components cannot pass through delta-wye transformer banks. If zero-sequence is flowing on the wye side, the currents will be reflected to the other side, but circulate within the delta

$$I_a = \frac{1}{n}(I_A - I_B)$$

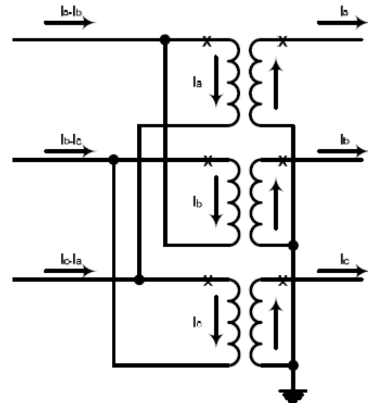


Fig 3.7.1: star delta transformer bank

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

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

$$(I_A - I_B) = (I_{A0} - I_{B0}) + (I_{A1} - I_{B1}) + (I_{A2} - I_{B2})$$

$$(I_A - I_B) = (I_{A1} - I_{B1}) + (I_{A2} - I_{B2})$$

$$(I_{A1} - I_{B1}) = \sqrt{3} I_{A1} \angle 30^o \text{ and } (I_{A2} - I_{B2}) = \sqrt{3} I_{B2} \angle -30^o$$

$$I_a = \frac{1}{n}(\sqrt{3} I_{A1} \angle 30^o) + (\sqrt{3} I_{B2} \angle -30^o)$$

$$I_a = \frac{\sqrt{3}}{n}(I_{A1} \angle 30^o + I_{B2} \angle -30^o)$$

$$I_a = \frac{\sqrt{3}}{n}(I_A \angle 30^o)$$

As can be seen the current will shift by 30^o when transferring through a transformer connected delta-wye. The same can be prove when looking at the voltages.

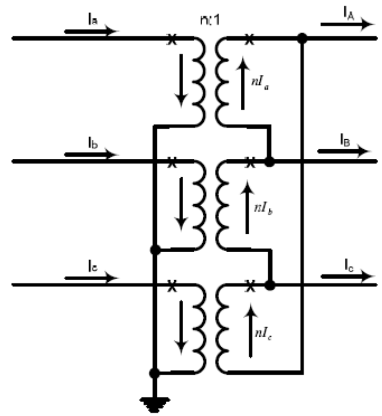


Fig 3.7.2: star delta transformer

$$I_A = n(I_a - I_c)$$
$$(I_A - I_C) = (I_{A0} - I_{C0}) + (I_{A1} - I_{C1}) + (I_{A2} - I_{C2})$$
$$I_a = n(\sqrt{3}I_{A1}\angle -30^o) + (\sqrt{3}I_{C2}\angle 30^o)$$
$$I_a = n\sqrt{3}(I_{A1}\angle -30^o + I_{C2}\angle 30^o)$$
$$I_a = n\sqrt{3}(I_A\angle -30^o)$$

By inspection of the equations above for ANSI standard connected delta-wye transformer banks if the positive-sequence current on one side leads the positive current on the other side by 30^o, the negative-sequence current correspondingly will lag by 30^o. Similarly if the positive-sequence current lags in passing through the bank, the negative-sequence quantities will lead 30^o.

The direction of the phase shifts between the delta-connected winding and the wye-connected winding depends on the winding connections of the transformer.

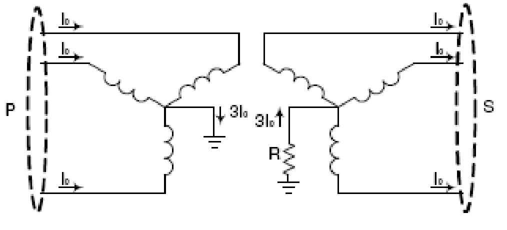
The winding configurations of a transformer will determine whether or not zero-sequence currents can be transformed between windings. Because zero-sequence currents do not add up to zero at a neutral point, they cannot flow in a neutral without a neutral conductor or a ground connection. If the neutral has a neutral conductor or if it is grounded, the zero-sequence currents from the phases will add together to equal 3I0 at the neutral point and then flow through the neutral conductor or ground to make a complete path.

Following are some different transformer winding configurations and their effect on zero-sequence currents

3.4.3 TRANSFORMERS WITH AT LEAST TWO GROUNDED WYE WINDINGS

When a transformer has at least two grounded-wye windings, zero-sequence current can be transformed between the grounded-wye windings. The I0 currents will add up to 3I0 in the neutral and return through ground or the neutral conductor. The I0 currents will be transformed into the secondary windings and flow in the secondary circuit. Any impedance between the transformer neutral points and ground must be represented in the zero-sequence network as three times its value to correctly account for the zero-sequence voltage drop across it.

Below on the left is a three-phase diagram of a grounded-wye, grounded-wye transformer connection with its zero-sequence network model on the right. Notice the resistance in the neutral of the secondary winding is modelled by 3R in the zero-sequence network model.



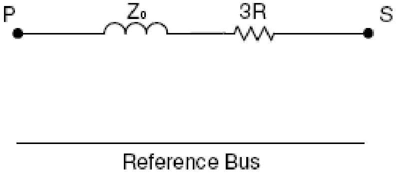


Fig 3.7.3 Three-phase diagram of a grounded-wye, grounded-wye transformer connection with its zero-sequence network model

3.4.4 TRANSFORMERS WITH A GROUNDED-WYE WINDING AND A DELTA WINDING

When a transformer has a grounded-wye winding and a delta winding, zero-sequence currents will be able to flow through the grounded-wye winding of the transformer. The zero-sequence currents will be transformed into the delta winding where they will circulate in the delta without leaving the terminals of the transformer. Because the zero-sequence current in each phase of the delta winding is equal and in phase, current does not need to enter or exit the delta winding. Below on the left is a three-phase diagram of a grounded-wye-delta transformer connection with its zero-sequence network model on the right.

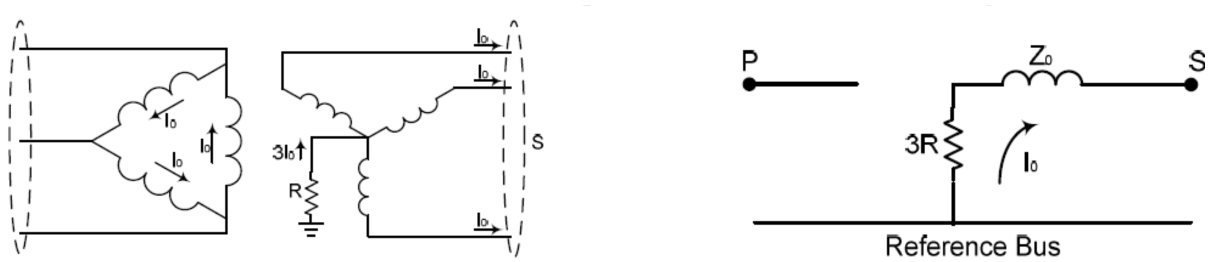


Fig 3.7.4 Three-phase diagram of a grounded-wye-delta transformer connection with its zero-sequence network model

3.4.5 AUTOTRANSFORMERS WITH A GROUNDED NEUTRAL

Autotransformers can transform zero-sequence currents between the primary and secondary windings if the neutral is grounded. Zero-sequence current will flow through both windings and the neutral ground connection. Below on the left is a three-phase diagram of a grounded neutral autotransformer with its zero-sequence network model on the right.

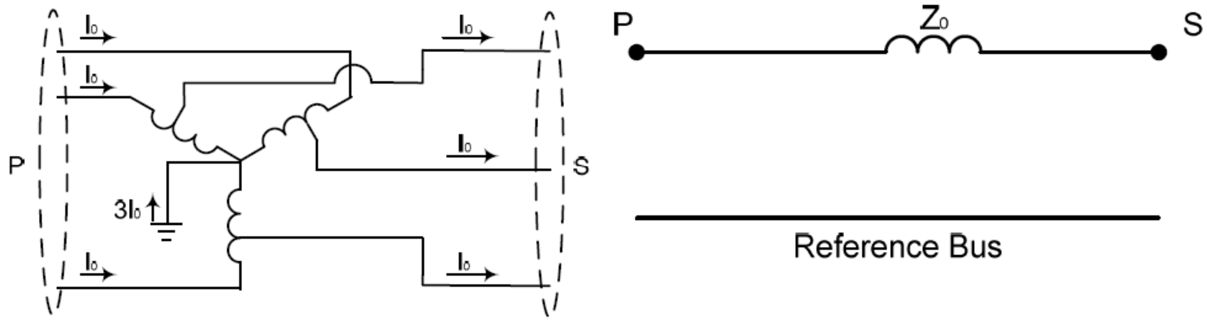


Fig 3.7.5: Three-phase diagram of a grounded neutral autotransformer with its zero-sequence network model

3.4.6 AUTOTRANSFORMERS WITH A DELTA TERTIARY

If an autotransformer has a delta tertiary, zero-sequence current can flow through either the primary or secondary winding even if the other winding is open circuited in the same manner that zero-sequence current can flow in a grounded-wye-delta transformer. If the ground is removed from the neutral, zero-sequence current can still flow between the primary and secondary windings, although there will not be any transformation of currents between the primary and secondary windings—only between the partial winding between the primary and secondary terminals and the delta tertiary. This is not a normal condition though, so it will not be analyzed here.

Note that when modeling three-winding transformers the impedance needs to be broken into the impedance of the individual windings

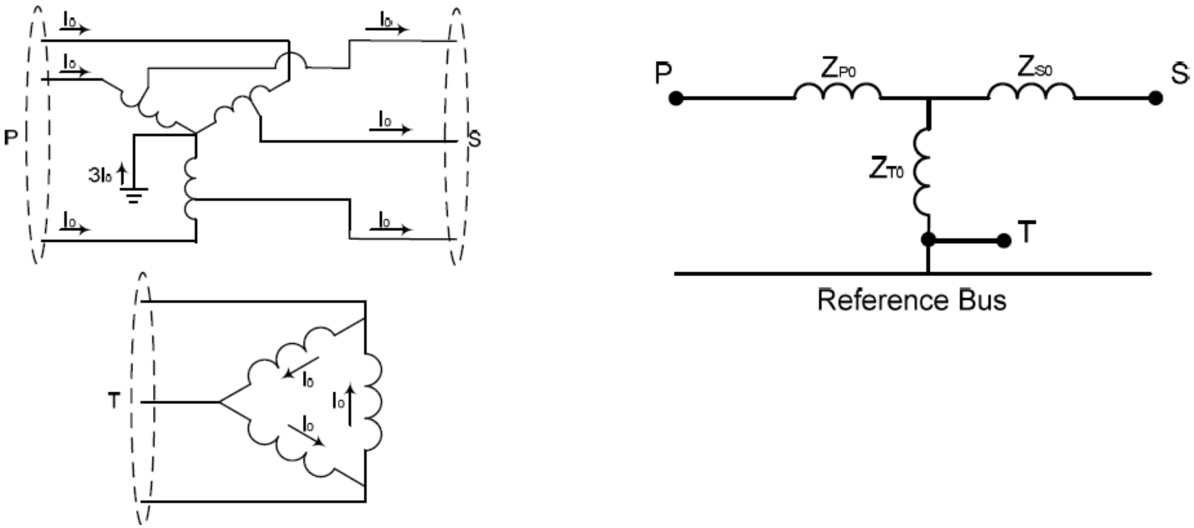
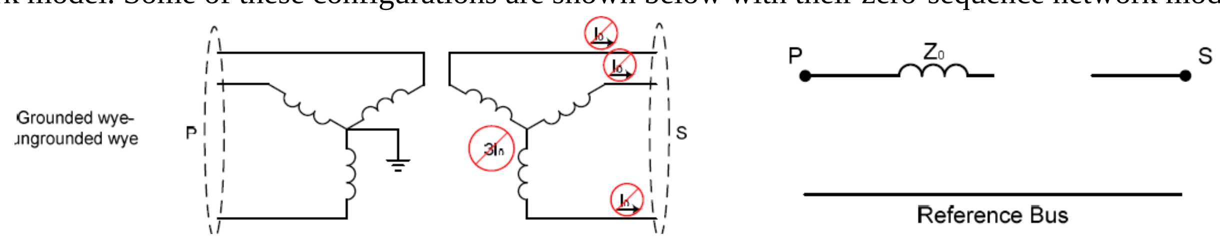


Fig 3.7.6: Autotransformer with delta teritiary

3.4.7 OTHER TRANSFORMERS

Other transformer configurations, such as ungrounded wye-ungrounded wye, grounded wye-ungrounded wye, ungrounded wye-delta, and delta-delta will not allow zero-sequence currents to flow and will have an open path in the zero-sequence network model. Some of these configurations are shown below with their zero-sequence network models



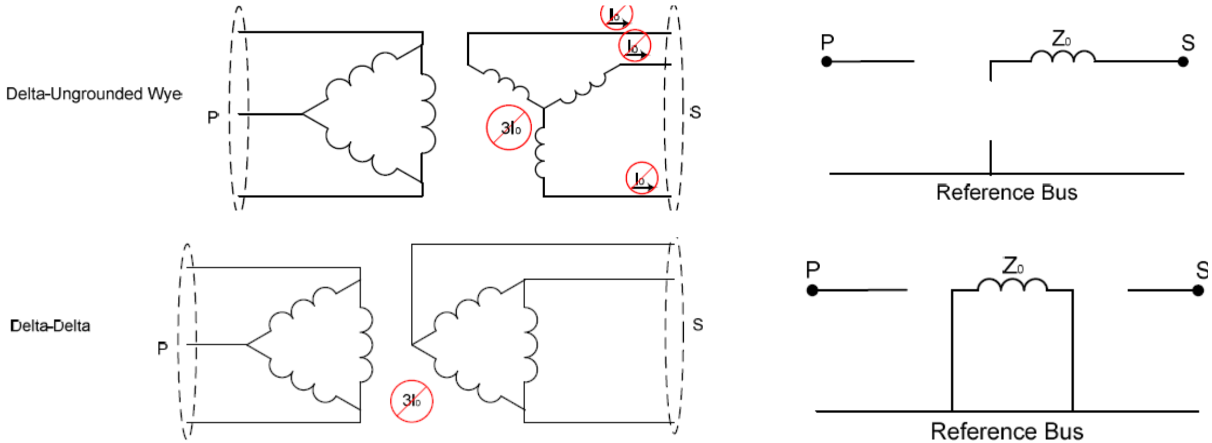


Fig 3.7.7: zero sequence network for different transformer configurations

3.4.8 SYSTEM MODELLING OF TRANSMISSION LINES

Transmission lines are represented on a one-line diagram as a simple line connecting busses or other circuit elements such as generators, transformers etc.

Transmission lines are also represented by a simple line on impedance diagrams, but the diagram will include the impedance of the line, in either ohm or per-unit values. Sometimes the resistive element of the impedance is omitted because it is small compared to the reactive element.

Here is an example of how a transmission line would be represented on an impedance diagram with impedances shown in ohms

Fig 3.8: Modelling of transmission lines

3.5 System Modelling: Sub-transient, Transient, and Synchronous Reactance Of Synchronous Generators

A synchronous generator is modelled by an internal voltage source in series with an internal impedance.

Below is a typical one-line diagram symbol for a generator.

Fig 3.9: Single line diagram symbol of generator

The circle represents the internal voltage source. The symbol to the left of the circle indicates that the three phases of the generator are wye-connected and grounded through a reactance. The symbol for a synchronous motor is the same as a synchronous generator.

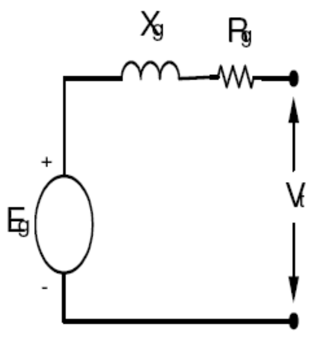


Fig 3.10: A typical impedance diagram representation of a synchronous generator

When modelling the impedance of a synchronous generator (or motor), the resistive component is usually omitted because it is small compared to the reactive component. When a fault is applied to a power system supplied by a synchronous generator, the initial current supplied by the generator will start at a larger value, and over a period of several cycles it will decrease from its initial value to a steady state value. The initial value of current is called the Sub-transient current or the initial symmetrical rms current. Sub-transient current decreases rapidly during the first few cycles after a fault is initiated, but its value is defined as the maximum value that occurs at fault inception.

After the first few cycles of Sub-transient current, the current will continue to decrease for several cycles, but at a slower rate. This current is called the transient current. Although, like the Sub-transient current, it is continually changing, the transient current is defined as its maximum value, which occurs after the first few cycles of Sub-transient current. After several cycles of transient current, the current will reach a final steady state value. This is called the steady state current or the synchronous current.

The reason why the current supplied by the synchronous generator is changing after a fault is because the increased current through the armature of the generator creates a flux that counteracts the flux produced by the rotor. This results in a reduced flux through the armature and therefore a reduced generated voltage. However, because the decrease in flux takes time, the generator voltage will be initially higher and decrease over time. We account for the changing generator voltage in our model by using different values of reactance in series with the internal generator voltage. We use three values of reactance to model the generator during the period after fault inception: the Sub-transient reactance (Xd'') is used during the initial few cycles; the transient reactance (Xd') is used for the period following the initial few cycles until a steady state value is reached; the synchronous reactance (Xd) is used for the steady state period.

The impedance diagrams for a synchronous generator (or motor) during the Sub-transient, transient, and synchronous periods

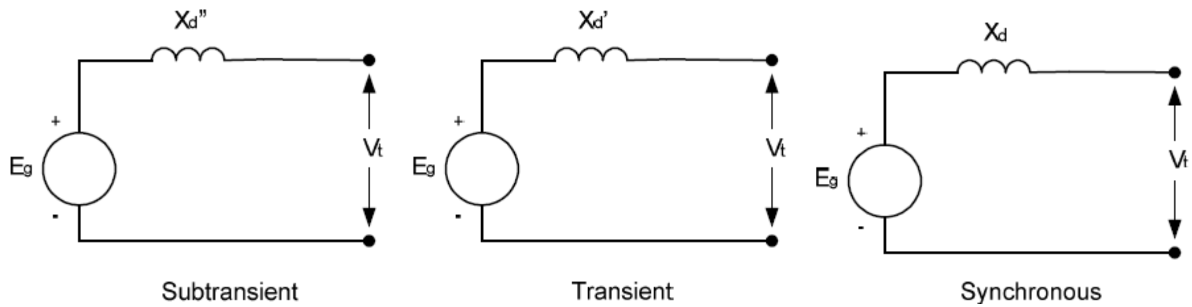


Fig 3.11: Impedance diagrams for a synchronous generator (or motor) during the Sub-transient, transient, and synchronous periods

The reactance of synchronous motors are the same as for synchronous generators. If the line to a synchronous motor develops a three-phase fault, the motor will no longer receive electrical energy from the system, but its field remains energized and the inertia of its rotor and connected load will keep the rotor turning for some time. The motor is then acting like a generator and contributes current to the fault

Course Outcomes

At the end of the module, students will be able to:

Develop un-balanced power system network using symmetrical components.[L3]