Power Systems Analysis
ET-321

References

- **Elements of power system analysis**
  (William Stevenson)

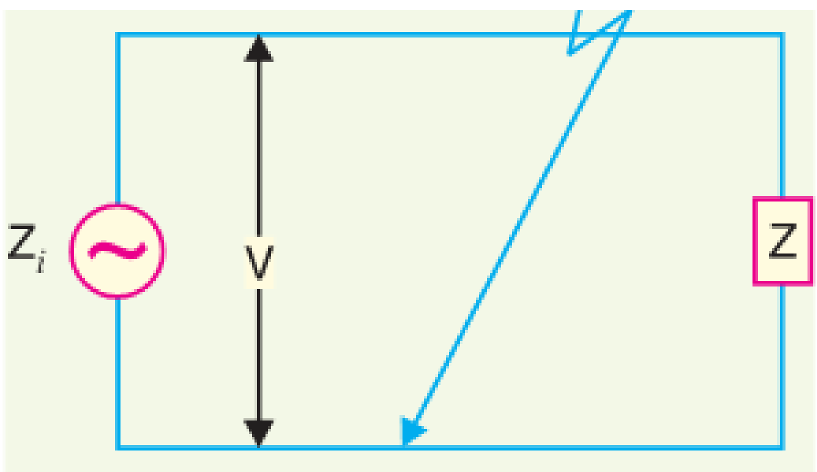
- **Power system analysis**
  (Hadi Sadaat)

FAULT ANALYSIS – UNBALANCED FAULTS

Short-Circuit

- Whenever a fault occurs on a network such that a large current flows in one or more phases, a short-circuit is said to have occurred.
- When a short circuit occurs, a heavy current called short circuit current flows through the circuit.

- This can be beautifully illustrated by referring to Fig. where a single phase generator of voltage V and internal impedance Zi is supplying to a load Z. Under normal conditions, the current in the circuit is limited by *load impedance Z. However, if the load terminals get shorted due to any reason, the circuit impedance is reduced to a very low value ; being Zi in this case. As Zi is very small, therefore, a large current flows through the circuit. This is called short-circuit current.



Causes of short-circuit

- A short circuit in the power system is the result of some kind of abnormal conditions in the system. It may be caused due to internal and/or external effects.
- Internal effects are caused by breakdown of equipment or transmission lines, from deterioration of insulation in a generator, transformer etc. Such troubles may be due to ageing of insulation, inadequate design or improper installation

- External effects causing short circuit include insulation failure due to lightning surges, overloading of equipment causing excessive heating; mechanical damage by public etc.

Effects of short-circuit

- When a short-circuit occurs, the current in the system increases to an abnormally high value while the system voltage decreases to a low value.

Effects of short-circuit

- The heavy current due to short-circuit causes excessive heating which may result in fire or explosion. Sometimes short-circuit takes the form of an arc and causes considerable damage to the system.
- For example, an arc on a transmission line not cleared quickly will burn the conductor severely causing it to break, resulting in a long time interruption of the line.

Effects of short-circuit

- The low voltage created by the fault has a very harmful effect on the service rendered by the power system. If the voltage remains low for even a few seconds, the consumers' motors may be shut down and generators on the power system may become unstable.
- Due to effects of short-circuit, it is desirable and necessary to disconnect the faulty section and restore normal voltage and current conditions as quickly as possible.

Faults in a Power System

- A fault occurs when two or more conductors that normally operate with a potential difference come in contact with each other. These faults may be caused by sudden failure of a piece of equipment, accidental damage or short-circuit to overhead lines or by insulation failure resulting from lightning surges.
- Irrespective of the causes, the faults in a 3-phase system can be classified into two main categories viz

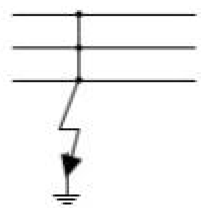
(i) Symmetrical faults (ii) Unsymmetrical faults

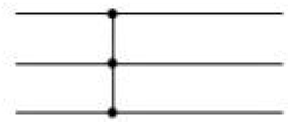
- Symmetrical faults. That fault which gives rise to symmetrical fault currents (i.e. equal faults currents with 120 degree displacement) is called a symmetrical fault.
- The most common example of symmetrical fault is when all the three conductors of a 3-phase line are brought together simultaneously into a short-circuit condition.

- Unsymmetrical faults. Those faults which give rise to unsymmetrical currents (i.e. unequal line currents with unequal displacement) are called unsymmetrical faults.
- The unsymmetrical faults may take one of the following forms :
- (a) Single line-to-ground fault (b) Line-to-line fault (c) Double line-to-ground fault.
- The great majority of faults on the power system are of unsymmetrical nature; the most common type being a short-circuit from one line to ground. The calculations of such fault currents are made by "symmetrical components" method.

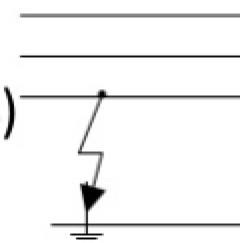
Fault Analysis

- **Fault types:**
  - balanced faults (<5%)
    - three-phase to ground

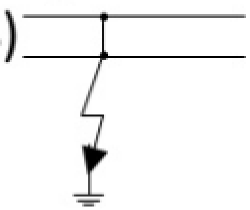




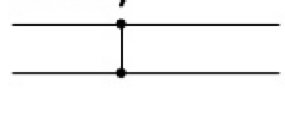
    - Three-phase
  - unbalanced faults
    - single-line to ground (60%-75%)



    - double-line to ground (15%-25%)



    - line-to-line faults (5%-15%)



Introduction:

Technical definition:

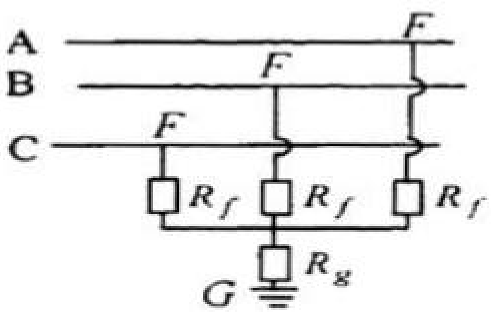
- The fault on the power system which gives rise to the symmetrical fault currents i.e. equal fault currents in the line with 120^0 phase displacement is called a symmetrical fault.

Due to balance nature of fault, for the analysis of the fault only one phase is to be considered as faults in other two cases will be identical.

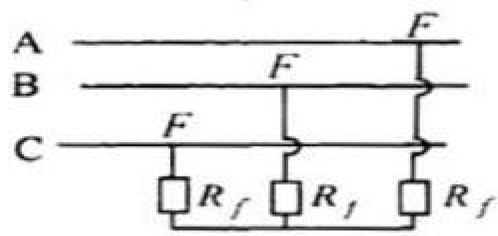
The following points should be particularly noted:

- This type of fault occurs rarely in practice.
- This type of fault is the most severe type of all faults and it imposes more heavy duty on the circuit breakers.

Three-phase-to-ground fault



Three-phase fault



- Knowing the magnitude of the fault current is important when selecting protection equipment (type, size, etc..)

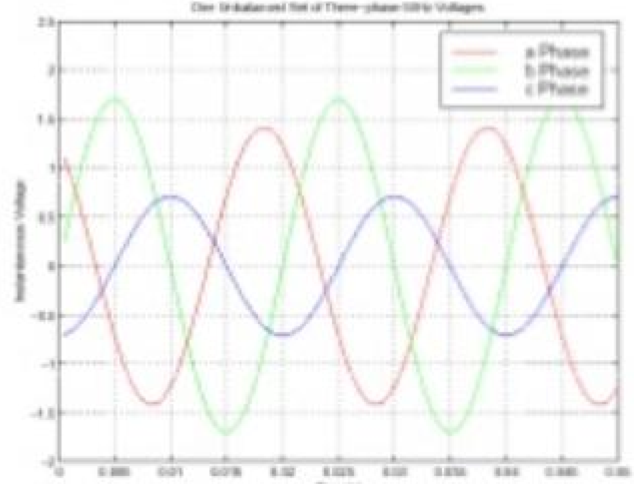
CAUSES OF POWER SYSTEM FAULTS

The causes of faults are numerous, e.g.

- Lightning
- Heavy winds
- Trees falling across lines
- Vehicles colliding with towers or poles
- Birds shorting lines
- Aircraft colliding with lines
- Vandalism
- Small animals entering switchgear
- Line breaks due to excessive loading

Symmetrical Components

- Three phase voltage or current is in a balance condition if it has the following characteristic:
  - Magnitude of phase *a*,*b*, and *c* is all the same
  - The system has sequence of *a*,*b*,*c*
  - The angle between phase is displace by 120 degree
- If one of the above is character is not satisfied, unbalanced occur. Example:



Symmetrical Components

- For unbalanced system, power system analysis cannot be analyzed using per phase as in Load Flow analysis or Symmetrical fault ->Symmetrical components need to be used.

- Symmetrical component allow unbalanced phase quantities such as current and voltages to be replaced by three separate balanced symmetrical components.

EFFECTS OF POWER SYSTEM FAULTS

Faults may lead to fire breakout that consequently results into loss of property, loss of life and destruction of a power system network. Faults also leads to cut of supply in areas beyond the fault point in a transmission and distribution network leading to power blackouts; this interferes with industrial and commercial activities that supports economic growth, stalls learning activities in institutions, work in offices, domestic applications and creates insecurity at night.

All the above results into retarded development due to low gross domestic product realised.

It is important therefore to determine the values of system voltages and currents during faulted conditions, so that protective devices may be set to detect and minimize the harmful effects of such contingencies

THEVENIN'S EQUIVALENT CIRCUIT

Thevenin's theorem states that any linear network containing any number of voltage sources and impedances can be replaced by a single emf and an impedance.

The emf is the open circuit voltage as seen from the terminals under consideration and the impedance is the network impedance as seen from these terminals.

This circuit consisting of a single emf and impedance is known as Thevenin's equivalent circuit.

The calculation of fault current can then be very easily done by applying this theorem after obtaining the open circuit emf and network impedance as seen from the fault point.

SYMMETRICAL COMPONENTS

The majority of faults in power systems are asymmetrical. To analyse an asymmetrical fault, an unbalanced 3- phase circuit has to be solved. Since the direct solution of such a circuit is very difficult, the solution can be more easily obtained by using symmetrical components since this yields three (fictitious) single phase networks, only one of which contains a driving emf.

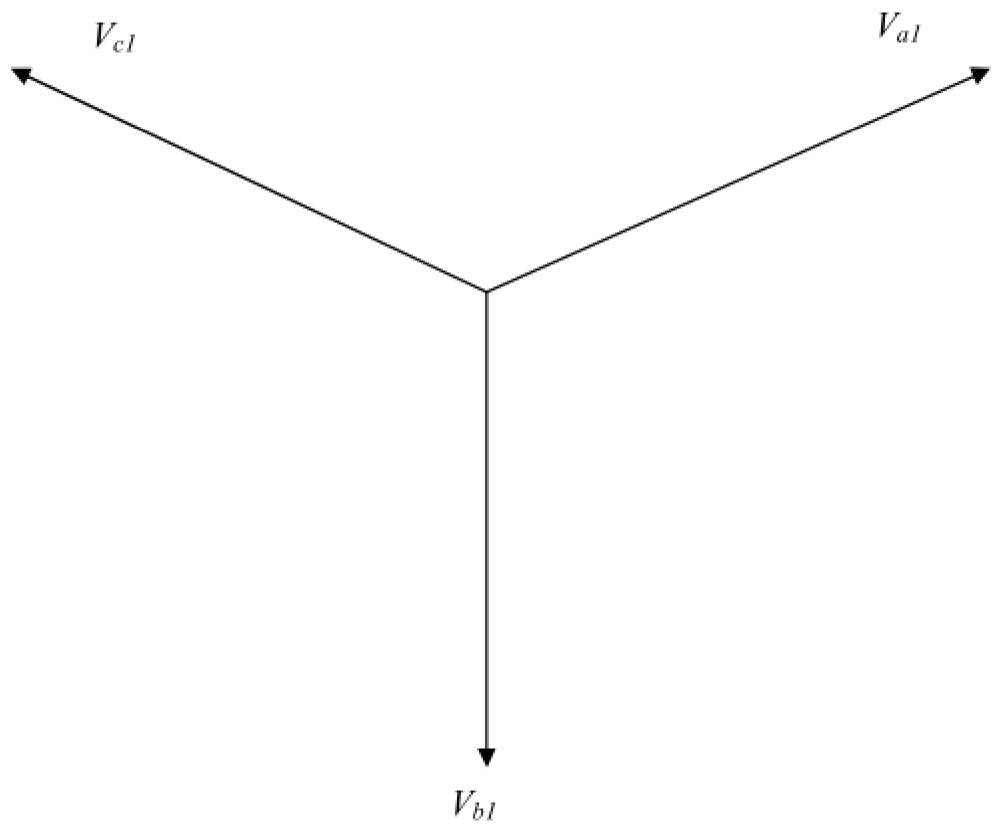
Since the system reactances are balanced the thee fictitious networks have no mutual coupling between them, a fact that is making this method of analysis quite simple.

General principles

Any set of unbalanced 3-phase voltages (or current) can be transformed into 3 balanced sets. These are:

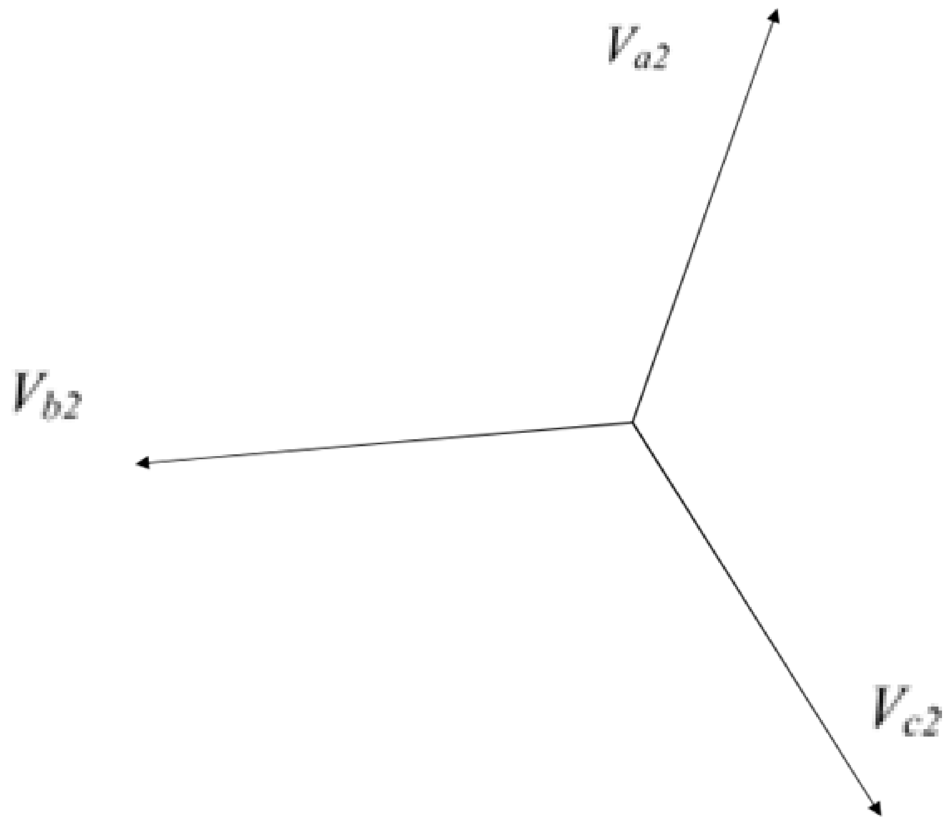
Positive Sequence

A positive sequence set of three symmetrical voltages (i.e. all numerically equal and all displaced from each other by $120^{0)}$ having the same phase sequence *abc* as the original set and denoted by V_{a1}, V_{b1}, V_{c1} as shown in the fig(1a)



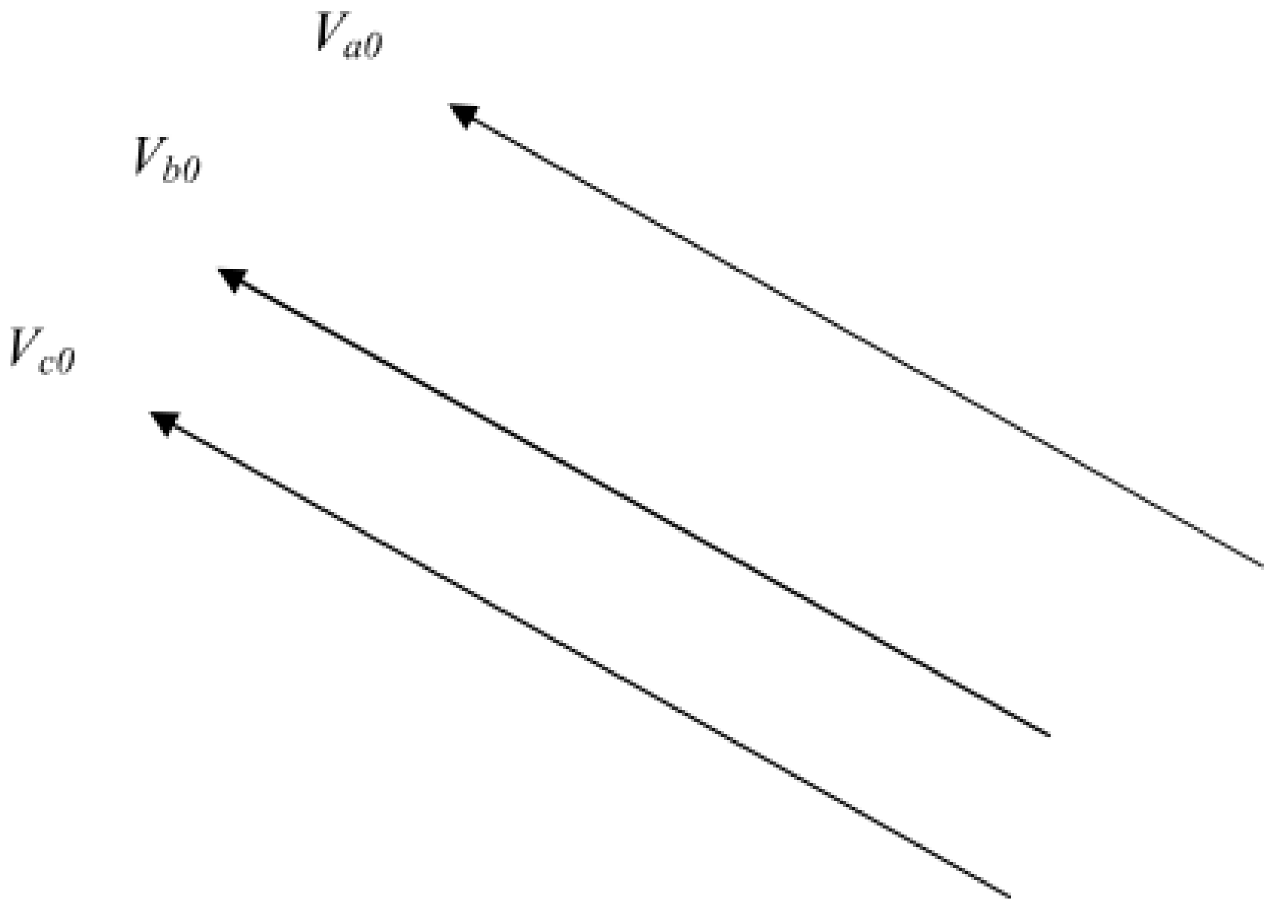
Negative Sequence

A negative sequence set of three symmetrical voltages having the phase sequence opposite to that of the original set and denoted by V_{a2}, V_{b2}, V_{c2} as shown in fig(1b)



Zero Sequence

3. A zero sequence set of three voltages, all equal in magnitude and in phase with each other and denoted by V_{a0}, V_{b0}, V_{c0} as shown in fig (1c) below:



The positive, negative and zero sequence sets above are known as symmetrical components.

Thus we have,

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

$V_b = V_{b1} + V_{b2} + V_{b0}$

$V_c = V_{c1} + V_{c2} + V_{c0}$

The symmetrical components application to power system analysis is of fundamental importance since it can be used to transform arbitrarily unbalanced condition into symmetrical components, compute the system response by straightforward circuit analysis on simple circuit models and transform the results back to the original phase variables.

Generally the subscripts 1, 2 and 0 are used to indicate positive sequence, negative sequence and zero sequence respectively.

The “a” operator

The operator “a” as used in symmetrical components is one in which when multiplied to a vector, rotates the vector through 120^0 in a positive (anticlockwise) direction without changing the magnitude.

The operator “a” is defined as $1\angle 120^0$

THREE-SEQUENCE IMPEDANCES AND SEQUENCE NETWORKS

Positive sequence currents give rise to only positive sequence voltages, the negative sequence currents give rise to only negative sequence voltages and zero sequence currents give rise to only zero sequence voltages, hence each network can be regarded as flowing within in its own network through impedances of its own sequence only.

In any part of the circuit, the voltage drop caused by current of a certain sequence depends on the impedance of that part of the circuit to current of that sequence.

The impedance of any section of a balanced network to current of one sequence may be different from impedance to current of another sequence.

The impedance of a circuit when positive sequence currents are flowing is called impedance, When only negative sequence currents are flowing the impedance is termed as negative sequence impedance.

With only zero sequence currents flowing the impedance is termed as zero sequence impedance.

The analysis of unsymmetrical faults in power systems is carried out by finding the symmetrical components of the unbalanced currents. Since each sequence current causes a voltage drop of that sequence only, each sequence current can be considered to flow in an independent network composed of impedances to current of that sequence only.

The single phase equivalent circuit composed of the impedances to current of any one sequence only is called the sequence network of that particular sequence.
The sequence networks contain the generated emfs and impedances of like sequence.

Therefore for every power system we can form three- sequence network s. These sequence networks, carrying current I_{a1}, I_{a2} and I_{a0} are then inter-connected to represent the different fault conditions.

Symmetrical Components

→ Fortescue's Theorem

☐ 3 unbalanced phasors of a 3-phase system can be resolved into 3 balanced systems of phasors. The balanced sets of components are:

① Positive-sequence components

+ 3 balanced phasors

⇨ equal in magnitude

⇨ displaced from each other by 120°

⇨ same phase sequence as the original phasors (for example a-b-c)

② Negative-sequence components

− 3 balanced phasors

⇨ equal in magnitude

⇨ displaced from each other by 120°

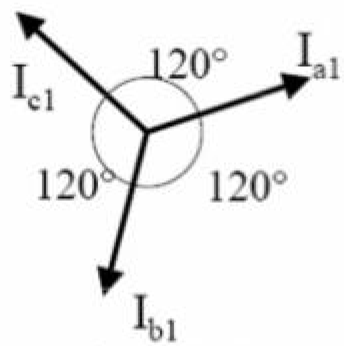
⇨ opposite phase sequence to the original phasors (for example a-c-b)

⓪ Zero-sequence components

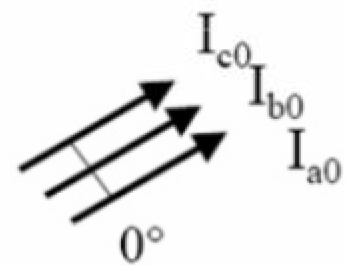
0 3 equal phasors

⇨ equal in magnitude

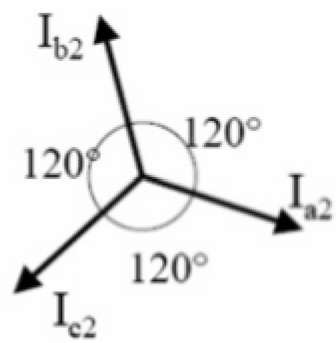
⇨ zero phase displacement from each other



abc sequence
positive sequence



zero sequence



acb sequence
negative sequence

PHYSICAL SIGNIFICANCE OF SEQUENCE COMPONENTS

This is achieved by considering the fields which results when these sequence voltages are applied to the stator of a 3-phase machine e.g. an induction motor.

If a positive sequence set of voltages is applied to the terminals a, b, c of the machine, a magnetic field revolving in a certain direction will be set up. If now the voltages to the terminals band c are changed by interchanging the leads to terminals b and c, it is known from induction motor theory that the direction of magnetic field would be reversed.

It is noted that for this condition, the relative phase positions of the voltages applied to the motor are the same as for the negative sequence set.

Hence, a negative sequence set of voltages produces a rotating field rotating in an opposite direction to that of positive sequence.

For both positive and negative sequence components, the standard convention of counter clockwise rotation is followed.

The application of zero sequence voltages does not produce any field because these voltages are in phase and the three -phase windings are displaced by 120^0.The positive and the negative sequence set are the balanced one. Thus, if only positive and negative sequence currents are flowing, the phasor sum of each will be zero and there will be no residual current. However, the zero sequence components of currents in the three phases are in phase and the residual current will be three times the zero sequence current of one phase. In the case of a fault involving ground, the positive and negative sequence currents are in equilibrium while the zero sequence currents flow through the ground and overhead ground wires.