

SWITCHGEAR & PROTECTIVE DEVICES

UNIT-I

INTRODUCTION

Importance of protective schemes for electrical apparatus and power system

1. What is meant by switchgear? (M/J-06)

Switchgear is a general term covering switching devices and their combinations with associated control, measuring and protective equipments.

2. What are the consequences of a short circuit?

The consequences of a short circuit are

1. A reduction in the line voltage over a major part of the power system.
2. Damage to the equipments due to overheating.
3. A single line to ground fault in an ungrounded system gives rise to arching grounds and also the voltages of the other lines are increased by 3 times the original value which may stress the insulation of the equipments.
4. The stability of the power system is affected.

3. Define – Protective Zone

Protective zone is defined as a part of the system protected by a certain protective scheme.

The entire power system is covered by several protective zones and no part of the system is left unprotected. Neighbouring zones are overlapped so that no dead spots are left in the protected system. The boundary of the protective zone is determined by the location of current transformers which detects and isolates the system by the circuit breakers during abnormal operation.

4. What are unit system and non-unit system?

A unit protective system is one in which the protection scheme responds to faults in the protected zone alone whereas non-unit system does not have exact zone boundaries. Each zone has certain protective scheme and each protective scheme has several protective systems.

5. What is primary protection?

Primary protection is the main protection provided for protecting the equipments. The primary protection is the first to act and if the primary protection fails, then the backup protection comes into action and removes the faulty part from the healthy system.

6. What is backup protection?

Secondary protection is the second line of defence which operates if the primary protection fails to activate within a definite time period. The methods of backup are classified as relay backup, breaker backup and remote backup.

7. Distinguish between primary protection scheme and secondary protection scheme.

Main or primary protection can fail due to non-functioning of one of its components in the protective scheme such as relay, CT, PT, trip circuit or circuit breaker. If the primary protection fails, then there must be an additional protection, otherwise the fault may remain uncleared which may result into a disaster. The backup protection is provided either by time grading principle or by duplication principle to protect the power system.

Sequence Components and Fault Analysis

Sequence Components

Objectives

In this lecture we will

- Introduce sequence components.
- Extract positive, negative and zero sequence components from 3ϕ unbalanced phasors.
- Synthesize a 3ϕ unbalanced phasor using sequence components.
- Analyze 3ϕ , S-L-G, L-L and L-L-G faults using sequence components.

1.1 Introduction

Electrical systems occasionally experience short circuits. These short circuits are hazardous to the safety of both equipment and people. Though the protective devices will isolate the faults safely, the parts of the system should withstand the resulting mechanical and thermal stresses. Fault impedance and fault current estimates also form input for the setting and coordination of protective devices like overcurrent relay, distance relay etc. Hence it is very important to estimate the magnitude of the fault currents. The equipment rating are decided based on this value. Fault currents can be estimated either by hand calculation or by fault analysis program.

Sources of Fault Current

The fault current in a system can be contributed by any of the following.

- Synchronous Motors and Condensers
- Induction Machines
- Synchronous Generators
- Electrical Utility System
- Distributed Generation

1.2 Sequence Components

Faults in a 3 phase system can be single line to ground, double line to ground, line to line or three phase. Power system operation during any of these faults can be analyzed using sequence components. The method of sequence component was discovered by Charles L. Fortescue in 1918. He came up with the following intuition that any 3ϕ unbalanced system has 6 degrees of freedom; whereas, a 3ϕ balanced system has only 2 degrees of freedom. Hence an unbalanced 3ϕ system having 6 degrees of freedom can be synthesized by 3 sets of balanced system each having 2 degrees of freedom.

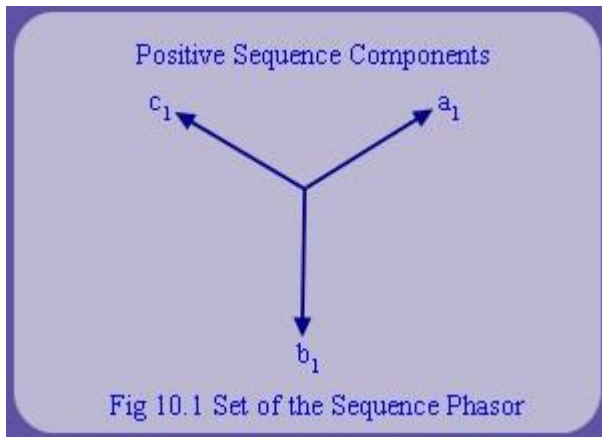
Note: This idea can be easily extended to N-phase system where $N \geq 3$.

For a three phase system with phase sequence a-b-c, the three sets of balanced phasors are called positive, negative and zero sequences.

1.2 Sequence Components (contd..)
1.2.1 Positive Sequence Component

It represents a set of balanced phasors $\vec{V}_{a1}, \vec{V}_{b1}$ and \vec{V}_{c1} . If we choose 'a' phase as reference phasor.

- (1) $\vec{V}_{b1} = \alpha^2 \vec{V}_{a1}$
 $\vec{V}_{c1} = \alpha \vec{V}_{a1}$
- (2) Where $\alpha = e^{j2\pi/3}$



'a' is cubic root of unity. Multiplying a phasor by 'a' causes a rotation of 120° direction (lead of 120° 240° in the anticlockwise direction or equivalently a lag of 120° . The positive sequence of phasors is the same balanced set of phasors that we expect in steady operation of an ideal power system. Thus, a, b and c phasors are nothing but V_{a1}, V_{b1} and V_{c1} .

The sequence phasors are shown in fig 10.1. If the stator of an induction motor is subjected to positive sequence voltage, it should cause rotation in anticlockwise direction. Note that placement of V_{a1} can be done arbitrarily in the x-y plane. But once, V_{a1} is fixed both V_{b1} and V_{c1} are fixed in the anticlockwise direction. Similar usage of a^2 results in V_{c1} and V_{b1} respectively.

Thus, a positive sequence set of phasors have 2 degrees of freedom i.e. we can decide placement of $|V_{a1}|$ (magnitude) and $\angle V_{a1}$ arbitrarily.

1.2 Sequence Components (contd..)

1.2.2 Negative Sequence Component

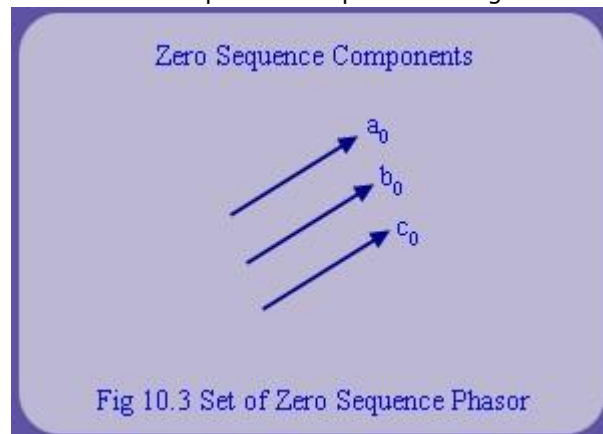
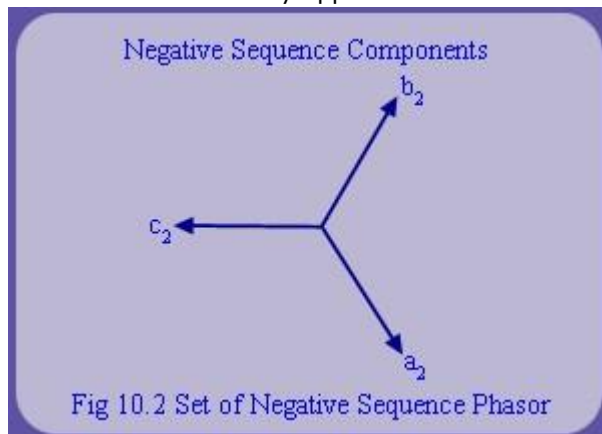
Negative sequence phasors are used to represent a balanced set of phasors (each of equal magnitude and phase difference of 120°) but in which the order of Vb and Vc has been reversed with respect to the positive sequence phasor. Thus,

$$\vec{V}_{b2} = a \vec{V}_{a2} \quad (3)$$

$$\vec{V}_{c2} = a^2 \vec{V}_{a2} \quad (4)$$

This is illustrated in fig 10.2. Note that placement of Va2 in x – y plane can be done arbitrarily. However, once Va2 is fixed both Vb2 and Vc2 are automatically fixed. Thus, negative sequence component have exactly two degrees of freedom which is to fix magnitude and angle of Va2.

If stator of a 3ϕ induction motor is subject to negative sequence voltage the rotor will rotate in a clockwise direction. i.e. in exactly opposite direction to that obtained with the positive sequence voltage.



1.2.3 Zero Sequence Component

The zero sequence phasors Va0, Vb0 and Vc0 are a set of balanced phasors defined as follows.

$$\vec{V}_{a0} = \vec{V}_{b0} = \vec{V}_{c0} \quad (5)$$

1.2 Sequence Components (contd..)

1.2.2 Zero Sequence Component (contd..)

Again there are two degrees of freedom in placing the zero sequence phasors. Application of zero sequence does not create any rotation to the rotor of an induction machine. This is because the net mmf induced in the air gap is zero.

An unbalanced set of phasors can be synthesized by linear combination (superposition of positive, negative and zero sequence phasors).

For example,

1.3 Mathematical description of sequence components

So far we have seen that,

$$\vec{V}_a = \vec{V}_{a1} + \vec{V}_{a2} + \vec{V}_{a0}$$

$$\vec{V}_b = \vec{V}_{b1} + \vec{V}_{b2} + \vec{V}_{b0}$$

$$\vec{V}_c = \vec{V}_{c1} + \vec{V}_{c2} + \vec{V}_{c0}$$

Using equation (1) to (5), we get

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} \quad (6)$$

or stated more compactly,

$$[V^{abc}] = [T][V_a^{012}] \text{ where } T = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \text{ and } \alpha = e^{j2\pi/3}$$

Matrix [T] defines a linear transformation of

phasors from sequence domain to phase domain. Matrix [T]

enjoys some interesting properties. For example, every pair of rows or columns of matrix [T] are orthogonal.

For example,

$$\text{If } c_1 = (1, 1, 1)^t \text{ and } c_2 = (1, \alpha^2, \alpha)^t$$

Then, $(c_1)^H c_2 = (c_2)^H c_1 = 0$ where H is Hermitian operator defined as transpose and conjugate of a vector or matrix.

Similarly,

In other words, $T^H T = T T^H = D$, where D is a diagonal matrix

$$D = \begin{bmatrix} 3 & 0 & 0 \\ 0 & 3 & 0 \\ 0 & 0 & 3 \end{bmatrix}$$

With

It can be verified that

$$T^{-1} = \frac{1}{3} T^H = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix}$$

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad \text{and(7)}$$

1.3 Mathematical description of sequence components (contd..)

1.3.1 Geometrical interpretation

We illustrate the inverse transformation for phase to sequence domain by geometrical method. We are given a set of unbalanced phasors and we have to compute the sequence components from it. Algebraically, it is simply application of equation (7). Geometrically, it can be interpreted by noting that 'a' represents 120° rotation of phasor in anticlockwise direction and α^2 is 240° rotation of phasor in anticlockwise direction.

1.3 Mathematical description of sequence components (contd..)

1.3.2 Significance of Transformation

One should understand the significance of linearity in sequence component transformation clearly.

Sequence transformation matrix [T] provides a methodology to convert sequence domain phasors to phase domain

phasors.

- Conversely, inverse transformation matrix [T⁻¹] provides a mechanism to convert phasors in a-b-c domain to sequence domain. This is typically required for analysis purpose. Also, the mapping between phase domain and sequence domain is 1:1.

There is no loss of information in either domain. In other words, both domains have identical information content.

- The transformations [T] and [T⁻¹] are linear i.e. if V_x^{abc} and V_y^{abc} are two sets of three phase phasors in a-b-c domain,

then superposition V_x^{abc} and V_y^{abc} in phase domain is equivalent to corresponding superposition in sequence domain. Conversely, if we superpose phasors in sequence domain, then in a-b-c domain also it amounts to equivalent superposition of phasors. Thus,

$$T^{-1} (\alpha V_x^{abc} + \beta V_y^{abc}) = \alpha T^{-1}(V_x^{abc}) + \beta T^{-1} V_y^{abc}$$

are $\alpha V_x^{012} + \beta V_y^{012}$ complex numbers.

Where $V_x^{012} = [V_x^0, V_x^1, V_x^2]$, $V_y^{012} = [V_y^0, V_y^1, V_y^2]$ and α and β

$$\text{Similarly, } T(\alpha V_x^{012} + \beta V_y^{012}) = \alpha T(V_x^{012}) + \beta T(V_y^{012})$$

$$= \alpha V_x^{abc} + \beta V_y^{abc}$$

Sequence components provide a methodology to view unbalanced phasors as a set of balanced phasors. If a network is balanced,

then the resulting analysis gets extremely simplified. This is because we are able to break a three phase network into three decoupled sequence networks (under some acceptable symmetry assumptions). We now elaborate on this concept of decoupled sequence networks.

1.4 Modeling Network in Sequence Components

We now show that corresponding network modeling can also be simplified in sequence domain. If the three phase network elements enjoy a particular symmetry (circulant structure) then, application of sequence component transformation diagonalizes three phase impedance or admittance matrix. Thus, we achieve decoupling in positive, negative and zero sequence networks, provided that network is balanced. Hence, sequence component analysis is used when network is balanced but phasors or loads are unbalanced. To begin with, consider a transposed transmission line whose three phase model is given by the following equation. Z_s is the self impedance of transmission line and Z_m is the mutual impedance between two phases. These quantities

can be evaluated from GMD and GMR of transmission line. ΔV_a ,

$$\Delta V_b \text{ and } \Delta V_c$$

is the drop in phase voltage across the line due to currents I_a, I_b and I_c respectively then,

$$(8) \quad \underbrace{\begin{bmatrix} \Delta V_a \\ \Delta V_b \\ \Delta V_c \end{bmatrix}}_{\Delta V^{abc}} = \begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix} \underbrace{\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}}_{I^{abc}}$$

Applying the transformation,

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = [T] \begin{bmatrix} I_a^0 \\ I_a^1 \\ I_a^2 \end{bmatrix}$$

and

$$\text{with phase 'a'} \quad \begin{bmatrix} \Delta V_a \\ \Delta V_b \\ \Delta V_c \end{bmatrix} = [T] \begin{bmatrix} \Delta V_a^0 \\ \Delta V_a^1 \\ \Delta V_a^2 \end{bmatrix} \quad \text{as reference phasor.}$$

$$\text{we get,} \quad [\Delta V^{012}] = [T^{-1}] [Z] [T] [I^{012}]$$

$$\text{Where} \quad [T] = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \quad \text{And } a = e^{j2\pi/3}$$

Hence,

$$\begin{bmatrix} \Delta V_a^0 \\ \Delta V_a^1 \\ \Delta V_a^2 \end{bmatrix} = \begin{bmatrix} Z_s + 2Z_m & 0 & 0 \\ 0 & Z_s - Z_m & 0 \\ 0 & 0 & Z_s - Z_m \end{bmatrix} \begin{bmatrix} I_a^0 \\ I_a^1 \\ I_a^2 \end{bmatrix} \quad (9)$$

1.4 Modeling Network in Sequence Components (contd..)

$$\text{Let } Z_0 = Z_s + 2Z_m$$

$$Z_1 = Z_s - Z_m$$

$$Z_2 = Z_s - Z_m$$

Then equation (8) can be decoupled into three separate equations one for each sequence component as follows.

$$\Delta V_0 = Z_0 I_0, \quad \Delta V_1 = Z_1 I_1 \quad \text{and} \quad \Delta V_2 = Z_2 I_2$$

Also, note that Z_0 , Z_1 and Z_2 are the eigen values of the phase-impedance matrix Z_{abc} .
Reference

phasor subscript 'a' has been dropped for convenience.

Thus, we see that positive, negative and zero sequence networks are decoupled. In general, if Z matrix has following circulant symmetry we can decouple the positive, negative and zero sequence networks by sequence transformation T. It can be shown that if,

$$Z_{012} = T^{-1} [Z_{abc}] T, \quad \text{then} \quad Z_{012} = \begin{bmatrix} Z_0 & & \\ & Z_1 & \\ & & Z_2 \end{bmatrix}$$

$$Z_{abc} = \begin{bmatrix} Z_s & Z_{m1} & Z_{m2} \\ Z_{m2} & Z_s & Z_{m1} \\ Z_{m1} & Z_{m2} & Z_s \end{bmatrix}$$

$$\text{where } Z_0 = Z_s + Z_{m1} + Z_{m2}$$

$$Z_1 = Z_s + a^2 Z_{m1} + a Z_{m2} = \begin{bmatrix} Z_0 \\ Z_1 \\ Z_2 \end{bmatrix}$$

$$Z_2 = Z_s + a Z_{m1} + a^2 Z_{m2}$$

(10)

Thus, all the sequence components can be determined from the above equations.

1.4.1 Advantages of Sequence Transformation

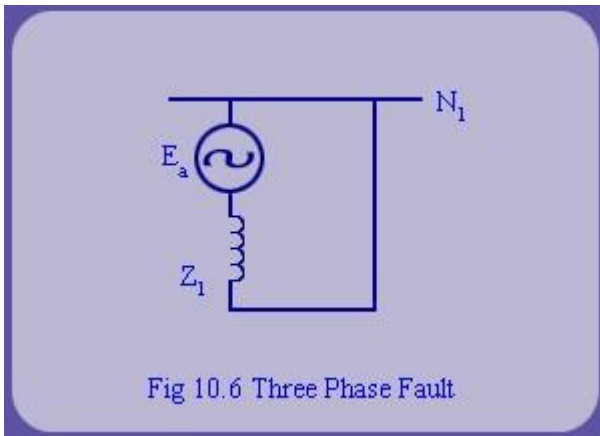
- It is used when the network is balanced. For a n - node system a $3n \times 3n$ linear system solver $I^{abc} = Y^{abc} V^{abc}$ can be decoupled into three $n \times n$ linear system solvers, $I_0 = Y_0 V_0$, $I_1 = Y_1 V_1$ and $I_2 = Y_2 V_2$. Hence it provides decoupling of the network.
- It can be applied for both balanced and unbalanced loads. However, simplicity and elegance of sequence component approach reduces when network is unbalanced.
- Zero sequence current is used to provide sensitive earth fault detection technique.

1.5 Fault Current Calculation in Sequence Domain

Consider a transposed transmission line connected to an ideal voltage source E . The fault appears at the remote end of transmission line. We now derive sequence network interconnections for different fault types. We begin with a three phase fault.

1.5.1 Three phase fault: Three phase faults are considered to be symmetrical and hence

sequence components are not necessary for their calculation.



It can be easily shown that for a three phase fault, fault currents are balanced with,

$$I = I_0 + I_1 + I_2$$

(Hint : $I^{012} = aI_a$).

$$I = I_0 = 0 \text{ and } I_1 = I_a$$

$$= T^{-1} I^{abc} \text{ with } I_b = a^2 I_a \text{ and } I_c$$

- $I_1 = \frac{E_a}{Z_1}$
- $I_1 = \frac{E_a}{Z_1 + Z_f}$

Thus, for a Three Phase Fault only Positive Sequence Network is considered. The fault currents are given by the following equations

(solid fault)

(Fault through impedance)

10.5.2 Single Line to Ground Fault (SLG):

On an unloaded system (fig 10.7), let there be 'a' phase to ground fault with a fault impedance Z_f . Then, the faulted system is described by, $I_a = I_f$, $I_b = 0$ and $I_c = 0$. Applying sequence transformation, we get

Thus, $I_0 = I_1 = I_2 = I_a/3$. Let V_f represent the voltage of the transmission line at the receiving end of the line where fault is created.

Further, from equation,

1.5

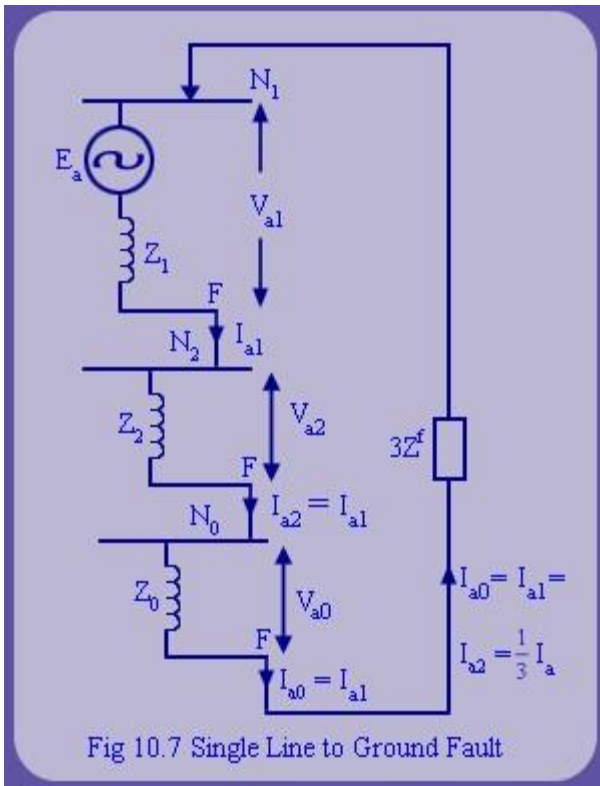


Fig 10.7 Single Line to Ground Fault

$$V_0 = -Z_0 I_0$$

$$V_1 = E_a - Z_1 I_1$$

$$V_2 = -Z_2 I_2$$

we get,

$$Z_f I_a = E_a - Z_1 I_1 - Z_2 I_2 - Z_0 I_0$$

$$Z_f 3I_1 = E_a - (Z_1 + Z_2 + Z_0) I_1$$

$$I_1 = I_2 = I_0 = \frac{E_a}{Z_1 + Z_2 + Z_0 + 3Z_f}$$

The SLG fault can be visualized by a series connection of positive, negative and zero sequence networks with three times the fault impedance.

The positive sequence, negative sequence and Zero sequence fault currents are given by following equations.

- $I_1 = I_2 = I_0 = \frac{E_a}{Z_1 + Z_2 + Z_0}$ (Solid Fault)

- $I_1 = I_2 = I_0 = \frac{E_a}{Z_1 + Z_2 + Z_0 + 3Z_f}$

- $I_{aF} = I_1 + I_2 + I_0 = 3I_1 = 3I_2 = 3I_0$ (Fault through impedance Z_f)

On similar lines following equations can be derived for LL and LLG faults.

LL fault:

The Zero Sequence Data is not required for this fault.

$$\begin{bmatrix} V_f^a \\ V_f^b \\ V_f^c \end{bmatrix} = \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} - \begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

Equivalent in the sequence domain we get by premultiplying (9) by T^{-1}

i.e.

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

or

(11)

(12)

(13)

Fault Current Calculation in Sequence Domain

$V_{a1} + V_{a2} + V_{a0} = V_a = Z_f I_a$ Since for SLG fault at phase 'a' we can add equations 11, 12 and 13. In addition when we invoke the condition that $I_0 = I_1 = I_2 = I_a/3$

Domain

$$V_f^a$$

(contd..)

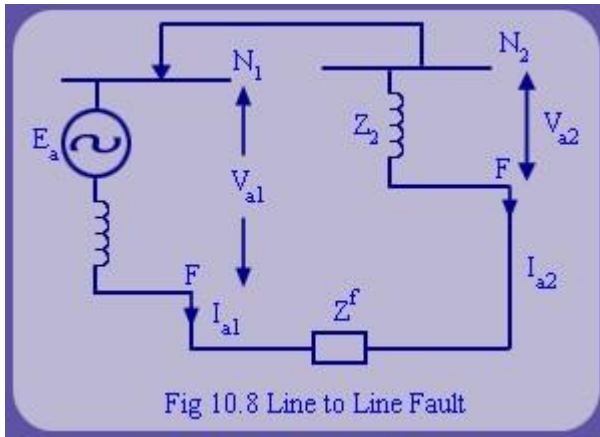


Fig 10.8 Line to Line Fault

(solid fault)

$$I_1 = -I_2 = \frac{E_a}{Z_1 + Z_2}$$

$$I_1 = -I_2 = \frac{E_a}{Z_1 + Z_2 + Z_f} \quad (\text{fault through impedance } Z_f)$$

Z_f)

$$I_F = I_b = -I_c = (a^2 - a)I_1 = -j\sqrt{3}(I_1)$$

1.5 Fault Current Calculation in Sequence Domain (contd..)

1.5.3 Line to Line Ground Fault (LLG):

1. Bolted Fault:

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

$$I_2 = -I_1 \frac{Z_0}{Z_2 + Z_0}$$

$$I_0 = -I_1 \frac{Z_2}{Z_2 + Z_0}$$

2. Fault current through impedance Z_f

$$I_1 = \frac{E_a}{Z_1 + \frac{Z_f}{2} + \frac{\left(Z_2 + \frac{Z_f}{2}\right)\left(Z_0 + \frac{Z_f}{2} + 3Z_{FG}\right)}{Z_2 + Z_0 + Z_f + 3Z_{FG}}}$$

$$I_2 = -I_1 \frac{\left(Z_0 + \frac{Z_f}{2} + 3Z_{FG}\right)}{Z_2 + Z_0 + Z_f + 3Z_{FG}}$$

$$I_0 = -I_1 \frac{\left(Z_2 + \frac{Z_f}{2}\right)}{Z_2 + Z_0 + Z_f + 3Z_{FG}}$$

Fault current in phases b and c:

$$I_b = I_0 + a^2 I_{a1} + a I_{a2}$$

$$I_c = I_0 + a I_{a1} + a^2 I_{a2}$$

$$I_F = I_b + I_c = 3I_0$$

Z_f is fault impedance between the lines, while Z_{FG} is the fault impedance to Ground.

Review Questions

1. What are sequence components?

2. Derive the sequence transformation matrix using 'c' phase as reference phasor.

3. Show that sequence transformation is linear.

If Z_s is the self impedance and Z_m mutual impedance of a transmission line, show that $Z_0 = Z_s + 2Z_m$

4. and Z_1 and

$$Z_2 = Z_s - Z_m.$$

5. Derive the equation for fault current in (a) L-L fault with fault impedance Z_f . (b) L-L-G fault.

6. If we do not want to lose information during a transformation 'f' from domain say A to B, then it is required that 'f' should be invertible. In addition, to simplify analysis, we prefer linear transformations. List out some other transformations that you have come across in electrical engineering.

7. Clarke's transformation with 'a' phase as reference phasor is defined as follows:

$$\begin{bmatrix} I_0 \\ I_\alpha \\ I_\beta \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

Show that the transformation matrix is invertible. Hence, define the inverse transformation from Clarke's components to phase components.

8. Using Clarke's transformation show that

1) for a - g fault

$$I_\alpha = 2I_0$$

$$I_\beta = 0$$

2) b - c - g fault

$$I_\alpha = -I_0$$

3) b - c fault

$$I_\alpha = 0 \quad I_0 = 0$$

4) 3 - phase fault

$$I_0 = 0$$

9. Suppose that in an DSP implementation of relay, we have to choose between the sequence transformation and Clarke's transformation suggest your choice and justify it from computational requirement and ability to correctly detect a fault.

Recap

In this lecture we have learnt the following:

- Sources of fault current.
- Method to extract sequence components from unbalanced phasor.
- Advantages of sequence transformation.
- Derivation of sequence transformation matrix.

Fault current formulae and interconnection of sequence network for three phase, S-L-G, L-L and L-L-G • faults