Sakarya University Journal of Science

ISSN 1301-4048 | e-ISSN 2147-835X | Period Bimonthly | Founded: 1997 | Publisher Sakarya University | http://www.saujs.sakarya.edu.tr/

Title: A Study Of Symmetrical And Unsymmetrical Short Circuit Fault Analyses İn Power Systems

Authors: Faruk Yalçın, Yılmaz Yıldırım

Recieved: 2019-03-15 19:14:15

Accepted: 2019-04-19 15:28:14

Article Type: Research Article
Volume: 23
Issue: 5
Month: October
Year: 2019
Pages: 879-895

How to cite
Faruk Yalçın, Yılmaz Yıldırım; (2019), A Study Of Symmetrical And Unsymmetrical Short Circuit Fault Analyses İn Power Systems. Sakarya University Journal of Science, 23(5), 879-895, DOI: 10.16984/saufenbilder.540294
Access link
http://www.saujs.sakarya.edu.tr/issue/44066/540294

Sakarya University Journal of Science 23(5), 879-895, 2019

SAKARYA UNIVERSITY

A Study of Symmetrical and Unsymmetrical Short Circuit Fault Analyses in Power Systems

Faruk Yalçın*[1], Yılmaz Yıldırım[2]

Abstract

In this study, the common symmetrical and unsymmetrical short circuit faults in power systems are analyzed detailed. Unlike the similar studies in the literature, metallic fault conditions for unsymmetrical faults are also given in the paper additionally. For this aim, a short circuit analysis algorithm is created for the analysis of both three phase short circuit, line-to-line short circuit with fault impedance, metallic line-to-line short circuit, double line-to-ground short circuit with fault impedance, metallic double line-to-ground short circuit, line-to-ground short circuit with fault impedance and metallic line-to-ground short circuit. The obtained algorithm is established as software in MATLAB. The algorithm is applied on a sample power test system and the results are given.

Keywords: electric power system, short circuit analysis, symmetrical components, symmetrical faults, unsymmetrical faults

1. INTRODUCTION

The providing of the electrical energy continuously and healthy is very important for both the consumers and the power system. This situation depends on the continuity of the system operation in normal operation conditions [1]. The removing of all of the effects that force the system operate in abnormal operation conditions from the system as soon as possible is very important [2]. There are many situations that force a power system operate in abnormal operation conditions. The significant ones of these are the short circuit faults [3]. Any short circuit fault causes many undesirable situations in power systems such as thermal-mechanic forces and power system instability [4]. Thus, it is required to remove the short circuit fault from the system as soon as possible. Removing of the short circuit faults from the systems is provided by the circuit breakers in power systems. The circuit breakers remove the short circuit currents caused by the short circuit faults from the system by opening via the relays [5]. The amplitude of the short circuit current occurred by a fault in any point of the system depends on the system parameters, the fault point and the fault type [6]. So, the short circuit

* Corresponding Author: farukyalcin@subu.edu.tr / farukyalcin@sakarya.edu.tr

[1] Sakarya Uni. of Appl. Sciences, Mechatronics Engineering, Sakarya, Turkey. ORCID: 0000-0003-2672-216X

[2] Sakarya Uni. of Appl. Sciences, Graduate Education Institute, Sakarya, Turkey. ORCID: 0000-0002-8114-6399

analyses in power systems are too important to determine the short circuit powers of the circuit breakers that are located in power systems [7]. On the other hand, it is required to know the voltage values in the buses where there is no fault during the short circuit fault. Because of these reasons, short circuit analyses in power systems are essential in terms of system security and control [8-10].

Different type short circuit faults occur in three phase power systems. These faults are generally divided into two types as symmetrical faults and unsymmetrical faults. [11,12]. Three phase short circuit is a symmetrical fault [13]. The faults through metallic or a fault impedance, line-to-line short circuit, double line-to-ground short circuit and line-to-ground short circuit are unsymmetrical faults [14-16]. In the literature, the short circuit calculations are generally done considering the power systems operate in balanced operation conditions before a fault occurs. Although the positive, negative and zero sequence circuits are independent in balanced normal operation conditions, during a short circuit fault, more precisely during unsymmetrical faults, the sequence circuits connect to each other in the fault point and they cannot be independent. [17]. So, symmetrical components method is useful and essential in short circuit analyses [18].

In this study, the analysis of the short circuit faults in electric power systems is aimed considering the general assumptions used in the literature [19]. For this aim, an algorithm that can calculate the short circuit currents in the fault point and the voltage values in the buses where there is no fault during fault condition by analyzing all of the symmetrical and unsymmetrical faults in power systems mentioned above is built. A software is done in MATLAB for the algorithm. The algorithm is applied on a sample test power system and all of the short circuit faults mentioned above are analyzed.

2. THE SHORT CIRCUIT FAULTS

2.1. General Short Circuit Model

All kind of short circuit faults can be analyzed through the Thevenin equivalent sequence circuits seen from the fault point in power systems. These Thevenin equivalent sequence circuits in a balanced three phase power system can be given in Fig. 1 [19].

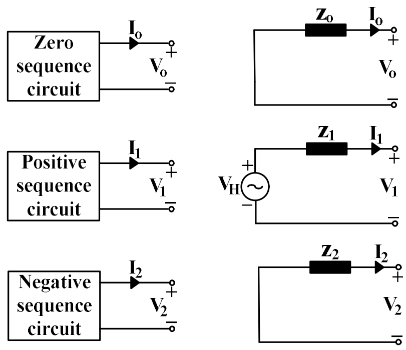

Figure 1. Thevenin equivalent sequence circuits in balanced three phase power system

In Fig. 1, V_o, V_1 and V_2 define the sequence voltages (zero, positive and negative, respectively). I_o, I_1 and I_2 define the sequence currents (zero, positive and negative, respectively). V_H defines the Thevenin voltage seen from the fault point. In this study, as the short circuit analyses are considered in balanced power systems, only the positive sequence circuit includes a voltage source. On the other hand, the load currents prior to short circuit faults are ignored in fault analysis. And, as the synchronous generators generate balanced EMFs, V_H equals to EMF value of the synchronous generators. As “n” represents the bus number of the fault point in the system, z_o, z_1 and z_2 define the (n,n) components of the sequence bus impedance matrices (zero, positive and negative bus impedance matrices, respectively).

The sequence voltages at the fault point can be generalized from Fig. 1 as;

$$\begin{bmatrix} V_o \\ V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 0 \\ V_H \\ 0 \end{bmatrix} - \begin{bmatrix} z_o & 0 & 0 \\ 0 & z_1 & 0 \\ 0 & 0 & z_2 \end{bmatrix} \begin{bmatrix} I_o \\ I_1 \\ I_2 \end{bmatrix} \quad (1)$$

In symmetrical short circuit faults, the sequence circuits given in Fig.1 keep independent. But in unsymmetrical short circuit faults, the sequence circuits connect to each other at the fault point.

2.2. Symmetrical Faults

The metallic three phase short circuit fault in a power system is a symmetrical fault. Although three phase short circuit is balanced, symmetrical components method is useful to analyze this short circuit.

2.2.1. Three Phase Short Circuit

The metallic three phase short circuit in a power system is given as schematic in Fig. 2 [20].

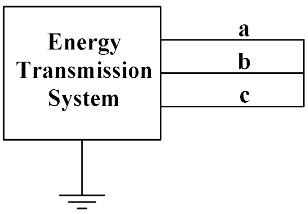

Figure 2. Schematic representation of three phase short circuit fault in power system

In Fig. 2, a, b and c represent the three phases. As seen in Fig. 2, the fault is symmetrical when a direct metallic short circuit occurs between the three phases (a, b, c) in any point of the power system. Thus, the phase voltages at the fault point are equal and zero.

$$V_a = V_b = V_c = 0 \quad (2)$$

Considering the phase "a" as reference, the sequence voltages of this phase can be given as;

$$\begin{bmatrix} V_o \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \quad (3)$$

By using the results of Eq. (3) in Eq. (1), the sequence currents are derived as;

$$\begin{bmatrix} I_o \\ I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} 0 \\ \dfrac{V_H}{z_1} \\ 0 \end{bmatrix} \quad (4)$$

By using the results of Eq. (4) in Fig. 1, the sequence circuits connections for three phase short circuit fault can be given in Fig. 3 [21].

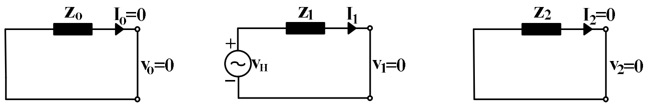

Figure 3. Sequence circuits connections for three phase short circuit fault in power system

The phase currents flowing through phase "a", "b" and "c" at the fault point can be derived using Eq. (4) as;

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 0 & a & a^2 \end{bmatrix} \begin{bmatrix} I_o \\ I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} \dfrac{V_H}{z_1} \\ a^2 \dfrac{V_H}{z_1} \\ a \dfrac{V_H}{z_1} \end{bmatrix} \quad (5)$$

The sequence voltage values of the buses where there is no fault can be derived as [21];

$$\begin{bmatrix} V_{o-k} \\ V_{1-k} \\ V_{2-k} \end{bmatrix} = \begin{bmatrix} 0 \\ V_H \\ 0 \end{bmatrix} - \begin{bmatrix} z_{o-kn} & 0 & 0 \\ 0 & z_{1-kn} & 0 \\ 0 & 0 & z_{2-kn} \end{bmatrix} \begin{bmatrix} I_{o-n} \\ I_{1-n} \\ I_{2-n} \end{bmatrix} \quad (6)$$

In Eq. (6), "k" represents the bus number where there is no fault. z_{o-kn}, z_{1-kn} and z_{2-kn} define the (k,n) components of the sequence bus impedance matrices (zero, positive and negative bus impedance matrices, respectively). The phase voltage values of the buses where there is no fault can be derived from Eq. (6) as;

$$\begin{bmatrix} V_{a-k} \\ V_{b-k} \\ V_{c-k} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_{o-k} \\ V_{1-k} \\ V_{2-k} \end{bmatrix} \tag{7}$$

2.3. Unsymmetrical Faults

The faults in three phase power systems through metallic or a fault impedance, line-to-line short circuit, double line-to-ground short circuit and line-to-ground short circuit are unsymmetrical faults. The sequence circuits cannot be independent and connect to each other according to the fault type when a short circuit fault occurs in a balanced three phase power system.

2.3.1. Line-to-Line Short Circuit with Fault Impedance

The line-to-line short circuit with a fault impedance in a power system is given as schematic in Fig. 4 [22].

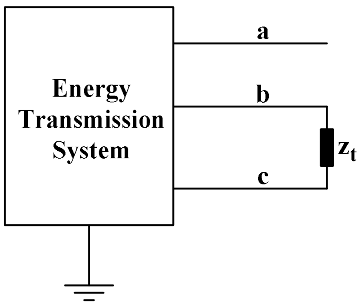

Figure 4. Schematic representation of line-to-line short circuit with a fault impedance in power system

In Fig. 4, z_t defines the fault impedance. From Fig. 4, the phase voltages and currents equations at the fault point can be derived as below:

$$V_b - V_c = z_t I_b \tag{8}$$

$$I_c = -I_b \tag{9}$$

$$I_a = 0 \tag{10}$$

Considering the phase "a" as reference, sequence currents can be defined from Eq. (9) and (10) as;

$$\begin{bmatrix} I_o \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} 0 \\ I_b \\ -I_b \end{bmatrix} = \begin{bmatrix} 0 \\ \frac{1}{3}\left(a - a^2\right) I_b \\ \frac{1}{3}\left(a^2 - a\right) I_b \end{bmatrix} \tag{11}$$

From Eq. (11), the sequence currents can be written as;

$$I_o = 0, \quad I_2 = -I_1 \tag{12}$$

Considering the phase "a" as reference, sequence voltages can be defined from Eq. (8) as;

$$\left(V_o + a^2 V_1 + a V_2\right) - \left(V_o + a V_1 + a^2 V_2\right) = z_t \left(I_o + a^2 I_1 + a I_2\right) \tag{13}$$

From Eq. (12) and (13), the equation below is derived:

$$V_1 - V_2 = z_t I_1 \tag{14}$$

By using the results of Eq. (12) and (14), the sequence circuits connections for the line-to-line short circuit with a fault impedance can be given in Fig. 5 [23].

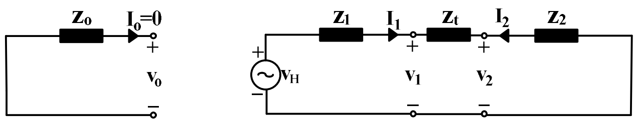

Figure 5. Sequence circuits connections for line-to-line short circuit with a fault impedance in power system

From Fig. 5, the sequence currents can be calculated as below;

$$I_o = 0 \tag{15}$$

$$I_1 = -I_2 = \frac{V_H}{\left(z_1 + z_2 + z_t\right)} \tag{16}$$

By using Eq. (15) and (16), the short circuit phase currents flowing through phase "b" and "c" at the fault point can be derived as;

$$I_b = I_o + a^2 I_1 + aI_2 = \left(a^2 - a\right) I_1 = -\frac{j\sqrt{3}V_H}{\left(z_1 + z_2 + z_t\right)} \quad (17)$$

$$I_c = I_o + aI_1 + a^2 I_2 = \left(a - a^2\right) I_1 = -I_b = \frac{j\sqrt{3}V_H}{\left(z_1 + z_2 + z_t\right)} \quad (18)$$

The sequence and phase voltage values of the buses where there is no fault can be derived from Eq. (6) and (7) respectively given before.

2.3.2. Metallic Line-to-Line Short Circuit

The metallic line-to-line short circuit fault in a power system is given as schematic in Fig. 6.

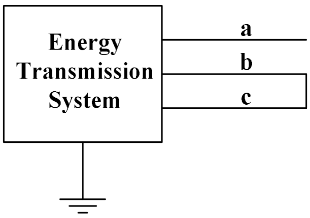

Figure 6. Schematic representation of metallic line-to-line short circuit fault in power system

From Fig. 6, the phase voltages and currents equations at the fault point can be derived as below:

$$V_b = V_c \quad (19)$$

$$I_c = -I_b \quad (20)$$

$$I_a = 0 \quad (21)$$

Considering the phase "a" as reference, sequence currents can be defined from Eq. (20) and (21) as;

$$\begin{bmatrix} I_o \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} 0 \\ I_b \\ -I_b \end{bmatrix} = \begin{bmatrix} 0 \\ \frac{1}{3}\left(a - a^2\right) I_b \\ \frac{1}{3}\left(a^2 - a\right) I_b \end{bmatrix} \quad (22)$$

From Eq. (22), the sequence currents can be written as;

$$I_o = 0, \quad I_2 = -I_1 \quad (23)$$

Considering the phase "a" as reference, sequence voltages can be defined from Eq. (19) as;

$$\left(V_o + a^2 V_1 + aV_2\right) = \left(V_o + aV_1 + a^2 V_2\right) \Longrightarrow \left(a^2 - a\right) V_1 = \left(a^2 - a\right) V_2 \quad (24)$$

From Eq. (24), the equation below is derived:

$$V_1 - V_2 = 0 \quad (25)$$

By using the results of Eq. (23) and (25), the sequence circuits connections for the metallic line-to-line short circuit fault can be given in Fig. 7.

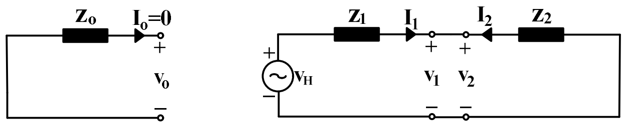

Figure 7. Sequence circuits connections for metallic line-to-line short circuit fault in power system

From Fig. 7, the sequence currents can be calculated as below;

$$I_o = 0 \quad (26)$$

$$I_1 = -I_2 = \frac{V_H}{\left(z_1 + z_2\right)} \quad (27)$$

By using Eq. (26) and (27), the short circuit phase currents flowing through phase "b" and "c" at the fault point can be derived as;

$$I_b = I_o + a^2 I_1 + aI_2 = \left(a^2 - a\right) I_1 = -\frac{j\sqrt{3}V_H}{\left(z_1 + z_2\right)} \quad (28)$$

$$I_c = I_o + aI_1 + a^2 I_2 = \left(a - a^2\right) I_1 = -I_b = \frac{j\sqrt{3}V_H}{\left(z_1 + z_2\right)} \quad (29)$$

The sequence and phase voltage values of the buses where there is no fault can be derived from Eq. (6) and (7) respectively given before.

2.3.3. Double Line-to-Ground Short Circuit with Fault Impedance

The double line-to-ground short circuit with fault impedance in a power system is given as schematic in Fig. 8 [24].

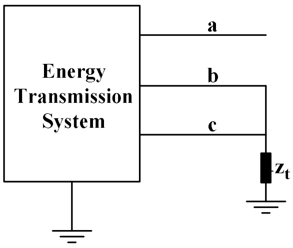

Figure 8. Schematic representation of double line-to-ground short circuit with a fault impedance in power system

From Fig. 8, the phase voltages and currents equations at the fault point can be derived as below:

$$V_b = V_c = z_t\left(I_b + I_c\right) \quad (30)$$

$$I_a = 0 \quad (31)$$

Considering the phase “a” as reference, the relation between the sequence currents can be defined from Eq. (31) as;

$$I_a = I_o + I_1 + I_2 = 0 \text{===>} -I_1 - I_2 = I_o \quad (32)$$

Considering the phase “a” as reference, sequence voltages can be defined from Eq. (30) as;

$$\begin{aligned}&\left(V_o + a^2V_1 + aV_2\right) = \left(V_o + aV_1 + a^2V_2\right)\\ &\text{===>}\left(a^2 - a\right)V_1 = \left(a^2 - a\right)V_2 \text{===>} V_1 = V_2\end{aligned} \quad (33)$$

By reorganizing Eq. (33), the equation below can be written:

$$V_1 - V_2 = 0 \quad (34)$$

Eq. (30) can also be rewritten as;

$$\begin{aligned}&\left(V_o + a^2V_1 + aV_2\right)\\ &= z_t\left(I_o + a^2I_1 + aI_2 + I_o + aI_1 + a^2I_2\right)\end{aligned} \quad (35)$$

By using Eq. (34) in Eq. (35), the equation below can be derived;

$$\left(V_o - V_1\right) = z_t\left(2I_o - I_1 - I_2\right) \quad (36)$$

By using Eq. (32) in Eq. (36), the equation below can be derived;

$$\left(V_o - V_1\right) = 3z_tI_o \quad (37)$$

By using the results of Eq. (32), (34) and (37), the sequence circuits connections for the double line-to-ground short circuit with fault impedance can be given in Fig. 9 [25].

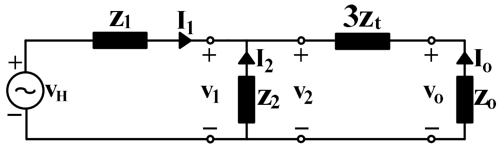

Figure 9. Sequence circuits connections for double line-to-ground short circuit with a fault impedance in power system

From Fig. 9, the positive sequence current can be calculated as;

$$\begin{aligned}I_1 &= \frac{V_H}{z_1 + \left[z_2 // \left(z_o + 3z_t\right)\right]}\\ &= \frac{V_H}{z_1 + \left[\dfrac{z_2\left(z_o + 3z_t\right)}{z_2 + z_o + 3z_t}\right]}\end{aligned} \quad (38)$$

By applying the current divider formula to the circuit given in Fig. 9, the zero and negative sequence currents can be derived as below;

$$\begin{aligned}I_o &= \left(-I_1\right)\left(\frac{z_2}{z_2 + z_o + 3z_t}\right)\\ &= -\frac{V_H}{\left[z_1 + \left(\dfrac{z_2\left(z_o + 3z_t\right)}{z_2 + z_o + 3z_t}\right)\right]\left(\dfrac{z_2 + z_o + 3z_t}{z_2}\right)}\end{aligned} \quad (39)$$

$$I_2 = (-I_1)\left(\frac{z_o + 3z_t}{z_2 + z_o + 3z_t}\right) = -\frac{V_H}{\left[z_1 + \left(\frac{z_2(z_o + 3z_t)}{z_2 + z_o + 3z_t}\right)\right]\left(\frac{z_2 + z_o + 3z_t}{z_o + 3z_t}\right)} \quad (40)$$

By using Eq. (38)-(40), the short circuit phase currents flowing through phase "b" and "c" at the fault point can be derived as;

$$I_b = -\frac{V_H}{\left[z_1 + \left(\frac{z_2(z_o + 3z_t)}{z_2 + z_o + 3z_t}\right)\right]\left(\frac{z_2 + z_o + 3z_t}{z_2}\right)} + a^2 \frac{V_H}{z_1 + \left[\frac{z_2(z_o + 3z_t)}{z_2 + z_o + 3z_t}\right]} - a \frac{V_H}{\left[z_1 + \left(\frac{z_2(z_o + 3z_t)}{z_2 + z_o + 3z_t}\right)\right]\left(\frac{z_2 + z_o + 3z_t}{z_o + 3z_t}\right)} \quad (41)$$

$$I_c = -\frac{V_H}{\left[z_1 + \left(\frac{z_2(z_o + 3z_t)}{z_2 + z_o + 3z_t}\right)\right]\left(\frac{z_2 + z_o + 3z_t}{z_2}\right)} + a \frac{V_H}{z_1 + \left[\frac{z_2(z_o + 3z_t)}{z_2 + z_o + 3z_t}\right]} - a^2 \frac{V_H}{\left[z_1 + \left(\frac{z_2(z_o + 3z_t)}{z_2 + z_o + 3z_t}\right)\right]\left(\frac{z_2 + z_o + 3z_t}{z_o + 3z_t}\right)} \quad (42)$$

The sequence and phase voltage values of the buses where there is no fault can be derived from Eq. (6) and (7) respectively given before.

2.3.4. Metallic Double Line-to-Ground Short Circuit

The metallic double line-to-ground short circuit fault in a power system is given as schematic in Fig. 10.

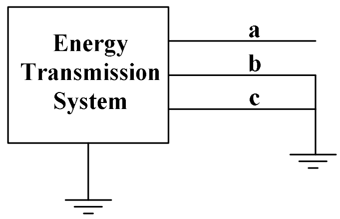

Figure 10. Schematic representation of metallic double line-to-ground short circuit fault in power system

From Fig. 10, the phase voltages and currents equations at the fault point can be derived as below:

$$V_b = V_c = 0 \quad (43)$$

$$I_a = 0 \quad (44)$$

Considering the phase "a" as reference, the relation between the sequence currents can be defined from Eq. (44) as;

$$I_a = I_o + I_1 + I_2 = 0 \quad (45)$$

Considering the phase "a" as reference, sequence voltages can be defined from Eq. (43) as;

$$\left(V_o + a^2V_1 + aV_2\right) = \left(V_o + aV_1 + a^2V_2\right) \Longrightarrow \left(a^2 - a\right)V_1 = \left(a^2 - a\right)V_2 \Longrightarrow V_1 = V_2 \quad (46)$$

By reorganizing Eq. (46), the equation below can be written:

$$V_1 - V_2 = 0 \quad (47)$$

By considering the equations given by Eq. (47) and (43) together, the equation below is derived;

$$\left(V_o + a^2V_1 + aV_2\right) = V_o + \left(a^2V_1 + aV_1\right) = V_o - V_1 = 0 \Longrightarrow V_o = V_1 \quad (48)$$

From Eq. (46) and (48), the relation between the sequence voltages can be derived as;

$$V_o = V_1 = V_2 \quad (49)$$

By using the results of Eq. (45) and (49), the sequence circuits connections for the metallic double line-to-ground short circuit fault can be given in Fig. 11.

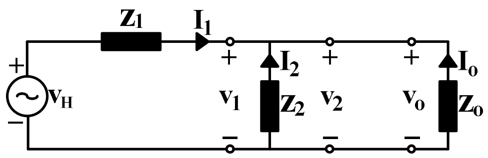

Figure 11. Sequence circuits connections for metallic double line-to-ground short circuit fault in power system

From Fig. 11, the positive sequence current can be calculated as;

$$I_1 = \frac{V_H}{z_1 + (z_2 // z_o)} = \frac{V_H}{z_1 + \frac{z_2 z_o}{z_2 + z_o}} \quad (50)$$

By applying the current divider formula to the circuit given in Fig. 11, the zero and negative sequence currents can be derived as below;

$$I_o = (-I_1)\left(\frac{z_2}{z_2 + z_o}\right) = -\frac{V_H}{\left(z_1 + \frac{z_2 z_o}{z_2 + z_o}\right)\left(\frac{z_2 + z_o}{z_2}\right)} \quad (51)$$

$$I_2 = (-I_1)\left(\frac{z_o}{z_2 + z_o}\right) = -\frac{V_H}{\left(z_1 + \frac{z_2 z_o}{z_2 + z_o}\right)\left(\frac{z_2 + z_o}{z_o}\right)} \quad (52)$$

By using Eq. (50)-(52), the short circuit phase currents flowing through phase "b" and "c" at the fault point can be derived as;

$$I_b = -\frac{V_H}{\left(z_1 + \frac{z_2 z_o}{z_2 + z_o}\right)\left(\frac{z_2 + z_o}{z_2}\right)} + a^2 \frac{V_H}{z_1 + \frac{z_2 z_o}{z_2 + z_o}} - a \frac{V_H}{\left(z_1 + \frac{z_2 z_o}{z_2 + z_o}\right)\left(\frac{z_2 + z_o}{z_o}\right)} \quad (53)$$

$$I_c = -\frac{V_H}{\left(z_1 + \frac{z_2 z_o}{z_2 + z_o}\right)\left(\frac{z_2 + z_o}{z_2}\right)} + a \frac{V_H}{z_1 + \frac{z_2 z_o}{z_2 + z_o}} - a^2 \frac{V_H}{\left(z_1 + \frac{z_2 z_o}{z_2 + z_o}\right)\left(\frac{z_2 + z_o}{z_o}\right)} \quad (54)$$

The sequence and phase voltage values of the buses where there is no fault can be derived from Eq. (6) and (7) respectively given before.

2.3.5. Line-to-Ground Short Circuit with Fault Impedance

The line-to-ground short circuit with fault impedance in a power system is given as schematic in Fig. 12 [26].

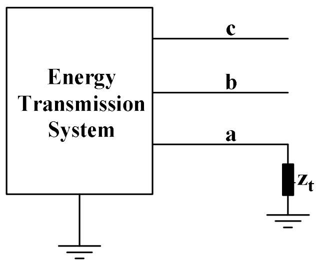

Figure 12. Schematic representation of line-to-ground short circuit with a fault impedance in power system

From Fig. 12, the phase voltages and currents equations at the fault point can be derived as below:

$$V_a = z_t I_a \tag{55}$$

$$I_b = I_c = 0 \tag{56}$$

Considering the phase "a" as reference, the relation between the sequence currents can be defined from Eq. (56) as;

$$\begin{bmatrix} I_o \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_a \\ 0 \\ 0 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} I_a \\ I_a \\ I_a \end{bmatrix} \tag{57}$$

From Eq. (57), the sequence currents are derived as below;

$$I_o = I_1 = I_2 \tag{58}$$

Considering the phase "a" as reference, the relation between the sequence voltages can be defined from Eq. (55) as;

$$\left(V_o + V_1 + V_2\right) = z_t\left(I_o + I_1 + I_2\right) \tag{59}$$

By using Eq. (58) in Eq. (59), the equation below can be derived;

$$\left(V_o + V_1 + V_2\right) = 3 z_t I_1 \tag{60}$$

By using the results of Eq. (58) and (60), the sequence circuits connections for the line-to-ground short circuit with fault impedance can be given in Fig. 13 [27].

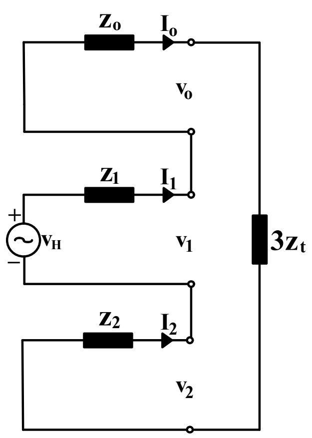

Figure 13. Sequence circuits connections for line-to-ground short circuit with a fault impedance in power system

The sequence currents can be calculated from Fig. 13 as;

$$I_o = I_1 = I_2 = \frac{V_H}{z_o + z_1 + z_2 + 3z_t} \tag{61}$$

By using Eq. (61), the short circuit phase current flowing through phase "a" at the fault point can be derived as;

$$I_a = \frac{3V_H}{z_o + z_1 + z_2 + 3z_t} \tag{62}$$

The sequence and phase voltage values of the buses where there is no fault can be derived from Eq. (6) and (7) respectively given before.

2.3.6. Metallic Line-to-Ground Short Circuit

The metallic line-to-ground short circuit fault in a power system is given as schematic in Fig. 14.

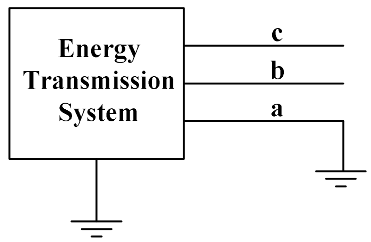

Figure 14. Schematic representation of metallic line-to-ground short circuit fault in power system

From Fig. 14, the phase voltages and currents equations at the fault point can be derived as below:

$$V_a = 0 \tag{63}$$

$$I_b = I_c = 0 \tag{64}$$

Considering the phase "a" as reference, the relation between the sequence currents can be defined from Eq. (64) as;

$$\begin{bmatrix} I_o \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_a \\ 0 \\ 0 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} I_a \\ I_a \\ I_a \end{bmatrix} \tag{65}$$

From Eq. (65), the sequence currents are derived as below;

$$I_o = I_1 = I_2 \tag{66}$$

Considering the phase "a" as reference, the relation between the sequence voltages can be defined from Eq. (63) as;

$$\left(V_o + V_1 + V_2\right) = 0 \tag{67}$$

By using the results of Eq. (66) and (67), the sequence circuits connections for the metallic line-to-ground short circuit fault can be given in Fig. 15.

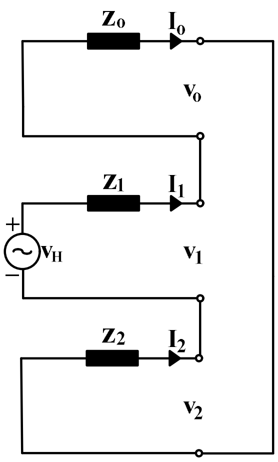

Figure 15. Sequence circuits connections for metallic line-to-ground short circuit fault in power system

The sequence currents can be calculated from Fig. 15 as;

$$I_o = I_1 = I_2 = \frac{V_H}{z_o + z_1 + z_2} \tag{68}$$

By using Eq. (68), the short circuit phase current flowing through phase "a" at the fault point can be derived as;

$$I_a = \frac{3V_H}{z_o + z_1 + z_2} \tag{69}$$

The sequence and phase voltage values of the buses where there is no fault can be derived from Eq. (6) and (7) respectively given before.

3. THE SHORT CIRCUIT ANALYSIS ALGORITHM

In this section, a short circuit analysis algorithm that can analyze all of the short circuit faults given in section 2. The algorithm is written as software in MATLAB. The algorithm can calculate the short currents and the voltage values of the buses where there is no fault in power systems by analyzing the short circuit faults. The schematic representation of the proposed algorithm is given in Fig. 16 and the details of the steps in Fig. 16 are given below the figure.

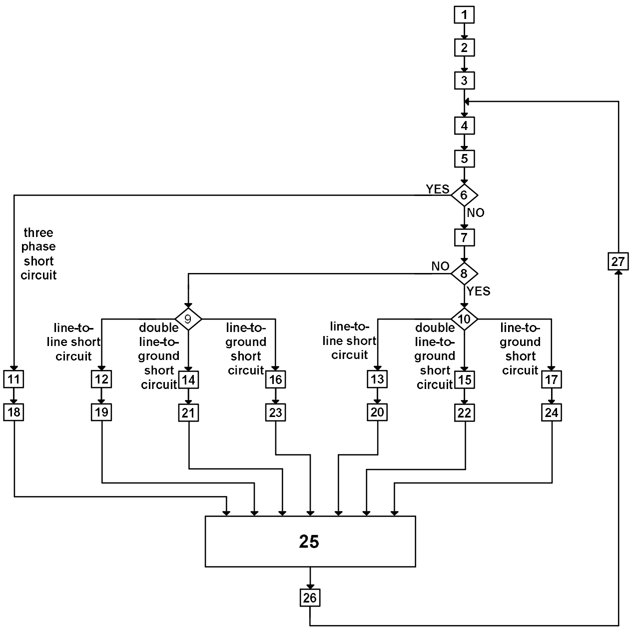

Figure 16. Schematic representation of the proposed short circuit analysis algorithm

Step 1: Read the p.u. values of the power system parameters that are used in the short circuit analysis (Read the Thevenin equivalent voltage value at the fault point, sequence impedances of all of the synchronous generators, sequence impedances of the synchronous and asynchronous motors that have higher powers than 40 kW, serial sequence impedances and the neutral-ground impedances that are in the wye side of the transformers and the serial sequence impedances of the transmission lines. Consider only the reactance values and ignore the resistance values of the read ones).

Step 2: Create the sequence bus admittance matrices (y_{bus-o} , y_{bus-1} and y_{bus-2}) by using the read values in step 1.

Step 3: Create the sequence bus impedance matrices (z_{bus-o} , z_{bus-1} and z_{bus-2}) by inversing the sequence admittance matrices derived in step 2.

Step 4: Enter the bus number where the short circuit fault occurs.

Step 5: Select the short circuit fault type that is required to analyze (three phase short circuit fault? line-to-line short circuit fault? double line-to-ground short circuit fault? line-to-ground short circuit fault?).

Step 6: Is the selected fault in step 5 three phase short circuit fault?

Step 7: Enter the value of the short circuit fault impedance z_t .

Step 8: Is the value of the short circuit fault impedance $z_t = 0$?

Step 9: Is the selected fault type line-to-line short circuit fault, double line-to-ground short circuit fault or line-to-ground short circuit fault?

Step 10: Is the selected fault type line-to-line short circuit fault, double line-to-ground short circuit fault or line-to-ground short circuit fault?

Step 11: Calculate the short circuit currents I_a , I_b ve I_c that occur at the fault point by using Eq. (5).

Step 12: Calculate the short circuit currents I_b and I_c that occur at the fault point by using Eq. (17) and (18).

Step 13: Calculate the short circuit currents I_b and I_c that occur at the fault point by using Eq. (28) and (29).

Step 14: Calculate the short circuit currents I_b and I_c that occur at the fault point by using Eq. (41) and (42).

Step 15: Calculate the short circuit currents I_b and I_c that occur at the fault point by using Eq. (53) and (54).

Step 16: Calculate the short circuit current I_a that occurs at the fault point by using Eq. (62).

Step 17: Calculate the short circuit current I_a that occurs at the fault point by using Eq. (69).

Step 18: Calculate the sequence currents at the fault point by using Eq. (4).

Step 19: Calculate the sequence currents at the fault point by using Eq. (11).

Step 20: Calculate the sequence currents at the fault point by using Eq. (22).

Step 21: Calculate the sequence currents at the fault point by using Eq. (38)-(40).

Step 22: Calculate the sequence currents at the fault point by using Eq. (50)-(52).

Step 23: Calculate the sequence currents at the fault point by using Eq. (57).

Step 24: Calculate the sequence currents at the fault point by using Eq. (65).

Step 25: Calculate the sequence and phase voltage values of the buses where there is no fault by using Eq. (6) and (7).

Step 26: Calculate the real values of the short circuit phase currents and the phase voltage values of the buses where there is no fault through the p.u. values of them calculated in the previous steps.

Step 27: Return to step 4 for a new short circuit analysis.

4. RESULTS

The proposed short circuit analysis algorithm given in section 3 is applied to a sample 14-bus test power system given in Fig. 17.

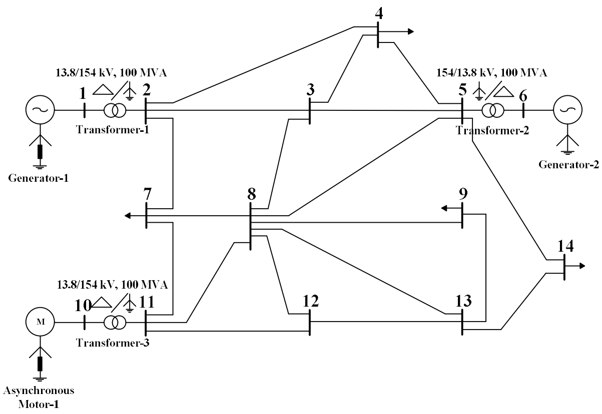

Figure 17. The 14-bus sample test power system

The system parameters of the test system shown in Fig. 17 are given in Table 1, 2 and 3.

Table 1. Transmission line parameters of the 14-bus sample test power system

Transmission Line bus-(i)	– bus-(j)	x_{h-o} (p.u.)	x_{h-1} (p.u.)	x_{h-2} (p.u.)
2	3	0.69	0.23	0.23
2	4	2.13	0.71	0.71
2	7	1.74	0.58	0.58
3	4	2.52	0.84	0.84
3	5	1.08	0.36	0.36
3	8	1.41	0.47	0.47
4	5	2.79	0.93	0.93
5	8	1.98	0.66	0.66
5	14	2.07	0.69	0.69
7	8	0.87	0.29	0.29
7	11	2.70	0.90	0.90
8	9	2.31	0.77	0.77
8	11	2.43	0.81	0.81
8	12	1.77	0.59	0.59
8	13	1.26	0.42	0.42
9	13	1.17	0.39	0.39
11	12	1.95	0.65	0.65
12	13	0.87	0.29	0.29
13	14	1.05	0.35	0.35

Table 2. Rotating machine parameters of the 14-bus sample test power system

Rotating Machine	x_{g-o} (p.u.)	x_{g-1} (p.u.)	x_{g-2} (p.u.)	x_t (p.u.)
Generator-1	0.035	0.95	0.95	0.045
Generator-2	0.045	0.98	0.98	0
Asynchronous Motor-1	0.04	1.00	1.00	0.05

Table 3. Transformer parameters of the 14-bus sample test power system

Transformer	x_{t-o} (p.u.)	x_{t-1} (p.u.)	x_{t-2} (p.u.)
Transformer -1	0.035	0.95	0.95
Transformer -2	0.045	0.98	0.98
Transformer -3	0.04	1.00	1.00

The proposed algorithm is applied to the test system to analyze a three phase short circuit fault at bus 4. The short circuit currents I_a, I_b and I_c at the fault point (bus-4) and the phase voltages at the buses where there is no fault are given in Table 4. Thevenin equivalent voltage value at the fault point is considered as $v_H=1.02\angle 0^o$. The base power is considered as S_{base}=100 MVA.

Table 4. The analysis results for three phase short circuit fault at bus 4

Bus No.	Short Current Currents (kA)		
	I_a	I_b	I_c
4 (fault point)	0.5574	0.5574	0.5574
Bus No.	**Bus Voltages (kV)**		
	V_a	V_b	V_c
1	6.6659	6.6659	6.6659
2	62.2017	62.2017	62.2017
3	58.3281	58.3281	58.3281
5	66.9003	66.9003	66.9003
6	6.8765	6.8765	6.8765
7	72.2971	72.2971	72.2971
8	71.8567	71.8567	71.8567
9	72.8860	72.8860	72.8860
10	8.7033	8.7033	8.7033
11	89.3293	89.3293	89.3293
12	76.6800	76.6800	76.6800
13	73.4073	73.4073	73.4073
14	71.2174	71.2174	71.2174

The proposed algorithm is applied to the test system to analyze a line-to-line short circuit with a fault impedance at bus 7. The short circuit currents I_b and I_c at the fault point (bus-7) and the phase voltages at the buses where there is no fault are given in Table 5. Thevenin equivalent voltage value at the fault point is considered as $v_H=1.05\angle 0^o$. The fault impedance is selected as $z_f=(0.01+j0.025)$ (p.u.). The base power is considered as $S_{base}=100$ MVA.

To compare the results of the line-to-line short circuit with a fault impedance with the metallic line-to-line short circuit fault, the proposed algorithm is applied to the test system to analyze a metallic line-to-line short circuit fault considering the same fault point and the parameters of the previous analysis for the line-to-line short circuit with a fault impedance. So, for the metallic line-to-line short circuit fault analysis, the fault point is selected as bus 7, Thevenin equivalent voltage value at the fault point is considered as $v_H=1.05\angle 0^o$ and the base power is considered as $S_{base}=100$ MVA. The short circuit currents I_b and I_c at the fault point (bus-7) and the phase voltages at the buses where there is no fault for the metallic line-to-line short circuit fault analysis are given in Table 6.

Table 5. The analysis results for line-to-line short circuit with a fault impedance at bus 7

Bus No.	Short Current Currents (kA)		
	I_a	I_b	I_c
7 (fault point)	0	0.5838	0.5838
Bus No.	Bus Voltages (kV)		
	V_a	V_b	V_c
1	14.4900	9.1372	9.0408
2	161.7000	95.5293	94.2098
3	161.7000	94.9664	93.6225
4	161.7000	96.3633	95.0788
5	161.7000	99.1421	97.9664
6	14.4900	9.3679	9.2790
8	161.7000	88.7399	87.0778
9	161.7000	90.1935	88.6157
10	14.4900	9.0312	8.9312
11	161.7000	95.0676	93.7282
12	161.7000	91.2428	89.7214
13	161.7000	90.9767	89.4413
14	161.7000	93.4855	92.0748

Table 6. The analysis results for metallic line-to-line short circuit fault at bus 7

Bus No.	Short Current Currents (kA)		
	I_a	I_b	I_c
7 (fault point)	0	0.5966	0.5966
Bus No.	Bus Voltages (kV)		
	V_a	V_b	V_c
1	14.4900	8.9962	8.9962
2	161.7000	93.8457	93.8457
3	161.7000	93.2757	93.2757
4	161.7000	94.6911	94.6911
5	161.7000	97.5146	97.5146
6	14.4900	9.2318	9.2318
8	161.7000	87.0248	87.0248
9	161.7000	88.4724	88.4724
10	14.4900	8.8881	8.8881
11	161.7000	93.3782	93.3782
12	161.7000	89.5228	89.5228
13	161.7000	89.2560	89.2560
14	161.7000	91.7792	91.7792

The proposed algorithm is applied to the test system to analyze a double line-to-ground short circuit with a fault impedance at bus 10. The short circuit currents I_b and I_c at the fault point (bus-10) and the phase voltages at the buses where there is no fault are given in Table 7. Thevenin equivalent voltage value at the fault point is considered as $v_H=1.03\angle 0^o$. The fault impedance is selected as $z_f=(j0.03)$ (p.u.). The base power is considered as $S_{base}=100$ MVA.

Table 7. The analysis results for double line-to-ground short circuit with a fault impedance at bus 10

Bus No.	Short Current Currents (kA)		
	I_a	I_b	I_c
10 (fault point)	0	9.1924	9.1924
Bus No.	Bus Voltages (kV)		
	V_a	V_b	V_c
1	11.3247	9.1351	9.1351
2	121.6260	93.8962	93.8962
3	118.9253	89.3844	89.3844
4	120.5505	92.0936	92.0936
5	120.9413	92.7477	92.7477
6	11.2059	8.9328	8.9328
7	109.6299	74.3261	74.3261
8	109.8653	74.6960	74.6960
9	109.3119	73.8273	73.8273
11	90.2851	47.8193	47.8193
12	104.9267	67.0965	67.0965
13	109.0316	73.3888	73.3888
14	113.0397	79.7503	79.7503

Table 8. The analysis results for metallic double line-to-ground short circuit fault at bus 10

Bus No.	Short Current Currents (kA)		
	I_a	I_b	I_c
10 (fault point)	0	9.9872	9.9872
Bus No.	Bus Voltages (kV)		
	V_a	V_b	V_c
1	10.7538	8.9610	8.9610
2	114.3163	91.5714	91.5714
3	111.0820	86.8250	86.8250
4	113.0284	89.6771	89.6771
5	113.4963	90.3647	90.3647
6	10.6116	8.7495	8.7495
7	99.9500	70.8321	70.8321
8	100.2318	71.2285	71.2285
9	99.5691	70.2972	70.2972
11	76.7828	41.5058	41.5058
12	94.3174	63.0356	63.0356
13	99.2334	69.8266	69.8266
14	104.0334	76.6247	76.6247

To compare the results of the double line-to-ground short circuit with a fault impedance with the metallic double line-to-ground short circuit fault, the proposed algorithm is applied to the test system to analyze a metallic double line-to-ground short circuit fault considering the same fault point and the parameters of the previous analysis for the double line-to-ground short circuit with a fault impedance. So, for the metallic double line-to-ground short circuit fault analysis, the fault point is selected as bus 10, Thevenin equivalent voltage value at the fault point is considered as $v_H=1.03\angle 0^o$ and the base power is considered as S_{base}=100 MVA. The short circuit currents I_b and I_c at the fault point (bus-10) and the phase voltages at the buses where there is no fault for the metallic double line-to-ground short circuit fault analysis are given in Table 8.

The proposed algorithm is applied to the test system to analyze a line-to-ground short circuit with a fault impedance at bus 13. The short circuit current I_a at the fault point (bus-13) and the phase voltages at the buses where there is no fault are given in Table 9. Thevenin equivalent voltage value at the fault point is considered as $v_H=1.04\angle 0^o$. The fault impedance is selected as $z_t=(0.012+j0.035)$ (p.u.). The base power is considered as S_{base}=100 MVA.

Table 9. The analysis results for line-to-ground short circuit with a fault impedance at bus 13

Bus No.	Short Current Currents (kA)		
	I_a	I_b	I_c
13 (fault point)	0.5637	0	0
Bus No.	Bus Voltages (kV)		
	V_a	V_b	V_c
1	10.2111	13.4037	13.4701
2	104.9152	149.1129	149.8948
3	94.0718	150.0880	150.7865
4	99.3828	149.2976	150.0634
5	98.0165	148.6847	149.5045
6	9.6931	13.3030	13.3783
7	80.9176	151.9723	152.5195
8	63.7993	154.7565	155.0999
9	26.9525	161.9901	161.8861
10	9.6352	13.2920	13.3683
11	96.8210	148.4980	149.3345
12	42.7253	158.5593	158.6549
14	38.4504	159.4778	159.5180

To compare the results of the line-to-ground short circuit with a fault impedance with the metallic line-to-ground short circuit fault, the proposed algorithm is applied to the test system to analyze a metallic line-to-ground short circuit fault considering the same fault point and the parameters of the previous analysis for the line-to-ground short circuit with a fault impedance. So, for the metallic line-to-ground short circuit fault analysis, the fault point is selected as bus 13, Thevenin equivalent voltage value at the fault point is considered as $v_H=1.04\angle 0^o$ and the base power is considered as S_{base}=100 MVA. The short circuit current I_a at the fault point (bus-13) and the phase voltages at the buses where there is no fault for the metallic line-to-ground short circuit fault analysis are given in Table 10.

Table 10. The analysis results for metallic line-to-ground short circuit fault at bus 13

Bus No.	Short Current Currents (kA)		
	I_a	I_b	I_c
13 (fault point)	0.5938	0	0
Bus No.	Bus Voltages (kV)		
	V_a	V_b	V_c
1	9.9888	13.3951	13.3951
2	101.9482	149.0227	149.0227
3	90.5206	149.9878	149.9878
4	96.1178	149.2051	149.2051
5	94.6779	148.6004	148.6004
6	9.4429	13.2958	13.2958
7	76.6561	151.8655	151.8655
8	58.6090	154.6650	154.6650
9	19.7048	162.0350	162.0350
10	9.3819	13.2850	13.2850
11	93.4180	148.4167	148.4167
12	36.3768	158.5252	158.5252
14	31.8628	159.4626	159.4626

5. CONCLUSION

This paper presents a study to analyze the common symmetrical and unsymmetrical short circuit faults in electric power systems. For this aim, all kind of short circuit faults are studied detailed and their short circuit fault models are derived considering the assumptions commonly used in the literature. Apart from the similar studies in the literature, metallic fault conditions for unsymmetrical short circuit faults are also analyzed in the study additionally. Then, an algorithm for the power systems to analyze these short circuit fault types to determine the short circuit currents at the fault points and the voltages of the buses where there is no fault in the system. A software is created for the proposed algorithm in MATLAB. The proposed short circuit analysis algorithm is applied to a sample 14-bus test power system and each symmetrical and unsymmetrical short circuit faults are analyzed. The obtained results have shown that the algorithm is efficient and accurate.

REFERENCES

[1] Y. Shu and Y. Tang, "Analysis and recommendations for the adaptability of China's power system security and stability relevant standards," CSEE Journal of Power and Energy Systems, vol. 3, no. 4, pp. 334–339, 2017.

[2] W. Du, Q. Fu, and Y. Wang, "Small-signal stability of an AC/MTDC power system as affected by open-loop modal coupling between the VSCs," IEEE Transactions on Power Systems, vol. 33, no. 3, pp. 3143–3152, 2018.

[3] C. Huang, B. Zhang, Y. Ma, F. Zhou, and J. He, "Analysis of short-circuit current characteristics and its distribution of artificial grounding faults on DC transmission lines," IEEE Transactions on Power Delivery, vol. 33, no. 1, pp. 520–528, 2018.

[4] J. Ma, S. Wang, Y. Qiu, Y. Li, Z. Wang, and J. S. Thorp, "Angle stability analysis of power system with multiple operating conditions considering cascading failure," IEEE Transactions on Power Systems, vol. 32, no. 2, pp. 873–882, 2017.

[5] P. M. Anderson, Power System Protection, IEEE Press Marketing, 1999.

[6] J. Teng, "Systematic short-circuit-analysis method for unbalanced distribution systems," IEE Proceedings - Generation, Transmission and Distribution, vol. 152, no. 4, pp. 549–555, 2005.

[7] R. M. Ciric, L. F. Ochoa, A. Padilla-Feltrin, and H. Nouri, "Fault analysis in four-wire distribution networks," IEE Proceedings - Generation, Transmission and Distribution, vol. 152, no. 6, pp. 977–982, 2005.

[8] G. H. Kjolle, O. Gjerde, B. T. Hjartsjo, H. Engen, L. Haarla, L. Koivisto, and P. Lindblad, "Protection system faults -- a comparative review of fault statistics," International Conference on Probabilistic

Methods Applied to Power Systems, Stockholm, pp. 1–7, 2006.

[9] Y. Zhang, J. Zhang, J. Ma, and Z. Wang, "Fault detection based on discriminant analysis theory in electric power system," International Conference on Sustainable Power Generation and Supply, Nanjing, pp. 1–5, 2009.

[10] C. I. Ciontea, C. Leth Bak, F. Blaabjerg, K. K. Madsen, and C. H. Sterregaard, "Fault analysis for protection purposes in maritime applications," 13th International Conference on Development in Power System Protection, Edinburgh, pp. 1–6, 2016.

[11] B. Mahamedi and J. G. Zhu, "A novel approach to detect symmetrical faults occurring during power swings by using frequency components of instantaneous three-phase active power," IEEE Transactions on Power Delivery, vol. 27, no. 3, pp. 1368–1376, 2012.

[12] E. H. Badawy and M. K. El-Sherbiny, A. A. Ibrahim, and M. S. Farghaly, "A method of analyzing unsymmetrical faults on six-phase power systems," IEEE Transactions on Power Delivery, vol. 6, no. 3, pp. 1139–1145, 1991.

[13] D. Dufournet and G. Montillet, "Three-phase short circuit testing of high-voltage circuit breakers using synthetic circuits," IEEE Transactions on Power Delivery, vol. 15, no. 1, pp. 142–147, 2000.

[14] S. Wang, Y. Sun, Z. Huang, and S. Mu, "Analysis of stator internal phase-to-phase short circuit in the 12-phase synchronous generator with rectifier-load system," IEEE Transactions on Energy Conversion, vol. 33, no. 1, pp. 299–311, 2018.

[15] R. Korab and E. Siwy, "Statistical analysis of the double line-to-ground short-circuit current in MV urban network for the power cable metallic screen rating," International Conference on Probabilistic Methods Applied to Power Systems, Stockholm, pp. 1–6, 2006.

[16] S. Shimizu, H. Kado, Y. Uriu, and T. Ishigohka, "Single-line-to-ground fault test of a 3-phase superconducting fault current limiting reactor," IEEE Transactions on Magnetics, vol. 28, no.1, pp. 442–445, 1992.

[17] L. Shi, C. Shan, X. Wu, and H. Wang, "Short circuit current calculation and analysis of shipboard medium frequency power system," International Conference on Electrical Machines and Systems, Beijing, pp. 1–5, 2011.

[18] S. Kulkarni, A. B. Parit, Pulavarthi, B. V R S V, and S. S. Patil, "Comparative analysis of three phase, five phase and six phase symmetrical components with MATLAB," International Conference on Data Management, Analytics and Innovation, Pune, pp. 182–186, 2017.

[19] J. D. Glover, M. S. Sarma, and T. J. Overbye, Power System Analysis and Design, Cengage Learning, 2012.

[20] A. A. Sallam and O. P. Malik, Electric Distribution Systems, Wiley-IEEE Press, 2019.

[21] U. Arifoglu, Güç Sistemlerinin Bilgisayar Destekli Analizi, Alfa Yayınları, 2002.

[22] M. S. Choi, S. J. Lee, S. I. Lim, D. S. Lee, and X. Yang, "A direct three-phase circuit analysis-based fault location for line-to-line fault," IEEE Transactions on Power Delivery, vol. 22, no. 4, pp. 2541–2547, 2007.

[23] M. Alwash, M. Sweet, and E. M. S. Narayanan, "Analysis of voltage source converters under DC line-to-line short-circuit fault conditions," IEEE 26th International Symposium on Industrial Electronics, Edinburgh, pp. 1801–1806, 2017.

[24] S. N. Pashkovskiy, R. A. Vainstein, and S. M. Yudin, “Transformation of zero-sequence electric quantities for protection against line-to-ground fault in the networks with various neutral grounding modes,” 2nd International Conference on Industrial Engineering, Applications and Manufacturing, Chelyabinsk, pp. 1–5, 2016.

[25] A. Dubey, H. Sun, D. Nikovski, T. Takano, Y. Kojima, and T. Ohno, “Locating double-line-to-ground faults using hybrid current profile approach,” IEEE Power & Energy Society Innovative Smart Grid Technologies Conference, Washington, pp. 1–5, 2015.

[26] A. Birajdar and S. Tajane, “Modelling and simulation of transmission line to detect single line to ground fault location,” IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems, Delhi, pp. 1–4, 2016.

[27] X. Liang, S. A. Wallace, and X. Zhao, “A technique for detecting wide-area single-line-to-ground faults,” IEEE Conference on Technologies for Sustainability, Portland, pp. 121–124, 2011.