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Analysis of Double Line-to-Ground Fault in an Unbalanced-Unloaded Synchronous Generator

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Abstract – Analysis of faults in synchronous generators are so important to protect the generators and the power systems. In this paper, double line-to-ground fault analysis in unloaded synchronous generator is presented. Apart from the similar studies in the literature, the synchronous generator is considered in unbalanced operation in this study. For this aim, new sequence circuits are obtained for synchronous generator. Thus, new equivalent circuit for short circuit consisting of the obtained sequence circuits is obtained to analyze short circuit of double line-to-ground fault in unbalanced and unloaded synchronous generator. The proposed short circuit model is applied to a sample fault system and the obtained results are given.

Keywords – double line-to-ground fault, short circuit, synchronous generator, symmetrical components, sequence circuits

I. Introduction

Fault analyzes of short circuits in electric power systems are very important for the security of the system and the components of it. Because, the sizing and the coordination of the breakers used for clearing the short circuits in fault nodes depend on the short circuit analyzes [1].

Short circuit faults are divided into four types in the literature: three-phase fault, line-to-line fault, double line-to-ground fault and single line-to-ground fault [2-5]. In these faults, three-phase fault is described as symmetrical fault and the others are described as unsymmetrical faults. In terms of the fault node, the fault analysis nodes are divided into two as synchronous generator terminals and the nodes in the power system different from the synchronous generator terminals. Short circuit fault analyzes in the literature are done in the consideration for both balanced synchronous generators and balanced transmission lines [6]. In these short circuit analyzes, especially in unsymmetrical faults, Foretscue's symmetrical components method is used efficiently [7]. The seen equivalent circuit through the fault node is transformed to equivalent positive, negative and zero sequence circuits in the short circuit analyzes used symmetrical components method [8]. Only the positive-sequence circuit includes source in the system that includes balanced synchronous generators and balanced transmission lines. Depending on the fault type, equivalent sequence circuits are connected to each other properly in the fault node [9,10].

In this study, analysis of metallic double line-to-ground short circuit fault in an unloaded synchronous generator is presented. Apart from the existing studies in the literature mentioned above, synchronous generator is considered in unbalanced operation. So, new sequence circuit models are built for short circuit analyzes. By using these sequence models, equivalent short circuit model is obtained for the analysis of double line-to-ground fault. The obtained equivalent short circuit model is applied to a sample unbalanced and unloaded synchronous generator system where a double line-to-ground fault is occurred and the numerical results are obtained.

II. Symmetrical Component Model of Unbalanced-Unloaded Synchronous Generator

In Figure 1, circuit diagram of an unbalanced and unloaded synchronous generator is seen. Generator rotating direction is abc.

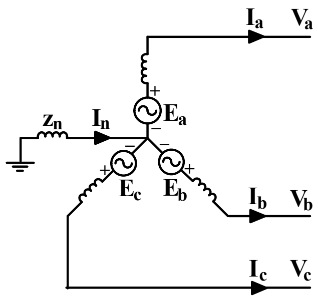

Fig. 1 Circuit diagram of the unbalanced-unloaded synchronous generator where the generator's neutral is grounded through an impedance

z_n is the grounding empedance between the generator's neutral and the earth ground. I_a, I_b, I_c and I_n represent the currents flowing through the generator's phases a, b, c and the current flowing through the generator's neutral, respectively. V_a, V_b ve V_c represent the terminal voltages of the generator's phases a, b and c, respectively. E_a, E_b ve E_c are the induced emf values in the windings of the generator's phases a, b and c, respectively. In this study, the generator is considered in unbalanced operation. So, the induced emf values are not equal and the differences between the phase voltages are different from 120°;

$$|E_a| \neq |E_b| \neq |E_c| \tag{1}$$

$$\angle\phi_{E_a} - \angle\phi_{E_b} \neq 120^o, \qquad \angle\phi_{E_c} - \angle\phi_{E_a} \neq 120^o \tag{2}$$

Symmetrical components of the emf E_a of phase a can be obtained as below:

$$\begin{bmatrix} E_{a0} \\ E_{a1} \\ E_{a2} \end{bmatrix} = \begin{bmatrix} E_0 \\ E_1 \\ E_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \tag{3}$$

E_0 , E_1 ve E_2 defined in Eq. (3) represent the zero, positive and negative sequence values of the emf induced in phase a, respectively. Here, a is a complex number and can be given as below:

$$a = 1\angle 120^o \tag{4}$$

Sequence circuit model of the synchronous generator circuit diagram given in Figure 1 is given in Figure 2. It is clear that zero and negative sequence emf values are different from zero in Eq. (3) as the internal emf values of the generator are unbalanced. So, as seen from Figure 2, all of the zero, positive and negative sequence circuits include sources. It must be noted that only the positive sequence circuit includes source in the balanced synchronous generator models studied in the literature.

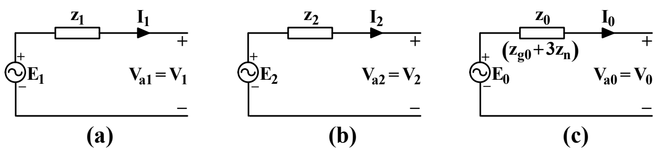

Fig. 2 Unbalanced-unloaded synchronous generator sequence circuit model a) positive sequence circuit b) negative sequence circuit c) zero sequence circuit

In Figure 2, z_0, z_1 and z_2 represent the zero, positive and negative sequence equivalent impedance values of the synchronous generator, respectively. z_{g0} is the zero sequence impedance of the synchronous generator winding. V_0 , V_1 and V_2 represent the zero, positive and negative sequence values of the terminal voltage for phase a, respectively. I_0 , I_1 and I_2 represent the zero, positive and negative sequence values of the current flowing through phase a, respectively. Sequence values of the terminal voltage can be derived from Figure 2 as below:

$$V_0 = E_0 - z_0 I_0 \tag{5}$$

$$V_1 = E_1 - z_1 I_1 \tag{6}$$

$$V_2 = E_2 - z_2 I_2 \tag{7}$$

Thus, sequence values of the terminal voltage can be derived in vector-matrix form as below:

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} E_0 \\ E_1 \\ E_2 \end{bmatrix} - \begin{bmatrix} z_0 & 0 & 0 \\ 0 & z_1 & 0 \\ 0 & 0 & z_2 \end{bmatrix}\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} \tag{8}$$

III. Analysis of Double Line-to-Ground Short Circuit Fault in Unbalanced-Unloaded Synchronous Generator

A metallic double line-to-ground fault that occurs between phase a and b of unbalanced-unloaded synchronous generator shown in Figure 1 is given in Figure 3.

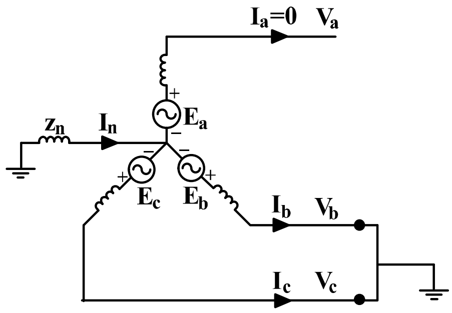

Fig. 3 Double line-to-ground fault in unbalanced-unloaded synchronous generator

As seen from Figure 3, it is clear that no current flows through phase a and the terminal voltage values of phase a and b equal and this value is zero. Thus, the equations can be derived as below:

$$I_a = 0 = I_0 + I_1 + I_2 \tag{9}$$

$$V_b = V_c = 0 \tag{10}$$

From Eq. (10), terminal voltage sequence values can be obtained as below:

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} V_a \\ 0 \\ 0 \end{bmatrix} \tag{11}$$

From Eq. (11), the equation is derived below:

$$V_0 = V_1 = V_2 = \frac{1}{3}\left(V_a + 0 + 0\right) = \frac{1}{3}V_a \tag{12}$$

The sequence circuits of the generator are connected to each other properly when a fault occurs in the unloaded generator. Thus, equivalent short circuit model for double line-to-ground fault in unbalanced-unloaded generator can be given in Figure 4 using the sequence circuit model given in Figure 2, Eq. (9) and Eq. (12).

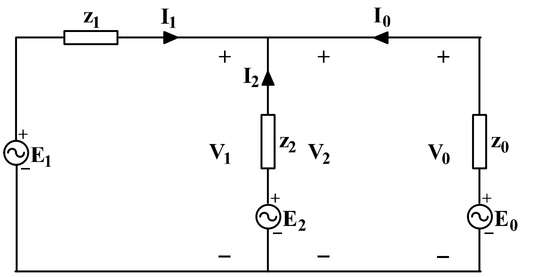

Fig. 4 Equivalent short circuit model for double line-to-ground fault in unbalanced-unloaded synchronous generator

Kirchoff's equations can be derived from Figure 4 as below:

$$E_1 - E_2 - z_1 I_1 + z_2 I_2 = 0 \quad (13)$$

$$E_2 - E_0 - z_2 I_2 + z_0 I_0 = 0 \quad (14)$$

$$I_0 + I_1 + I_2 = 0 \quad (15)$$

Equations (13)-(15) can be written in matrix form as below:

$$\begin{bmatrix} 0 & -z_1 & z_2 \\ z_0 & 0 & -z_2 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} E_2 - E_1 \\ E_0 - E_2 \\ 0 \end{bmatrix} \quad (16)$$

From Eq. (16), phase current sequence values can be obtained as below:

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} 0 & -z_1 & z_2 \\ z_0 & 0 & -z_2 \\ 1 & 1 & 1 \end{bmatrix}^{-1} \begin{bmatrix} E_2 - E_1 \\ E_0 - E_2 \\ 0 \end{bmatrix} \quad (17)$$

Short circuit currents flowing through phase b and c can be calculated through Eq. (17) as below:

$$I_b = I_0 + a^2 I_1 + a I_2 \quad (18)$$

$$I_c = I_0 + a I_1 + a^2 I_2 \quad (19)$$

As seen from Figure 1 and using Eq. (9), (18), (19), the current flowing through generator's neutral can be calculated as below:

$$I_n = I_a + I_b + I_c = I_b + I_c \quad (20)$$

IV. RESULTS

The proposed approach has been applied to sample double line-ground fault occurred in unbalanced-unloaded synchronous generator given in Figure 5. The obtained results are given in Table 1.

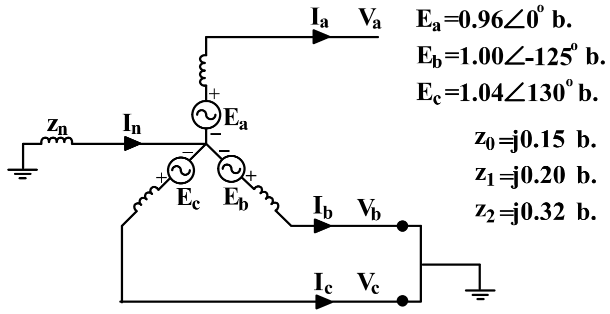

Fig. 5 Sample test system

Table 1. The obtained results for the sample test system

Symmetrical Component Values	I_0 (b.)	I_1 (b.)
	2.6692∟91.38°	3.4392∟-87.58°
	I_2 (b.)	V_0 (b.)
	0.7720∟ 95.99°	0.3062∟0.4°
	V_1 (b.)	V_2 (b.)
	0.3062∟0.4°	0.3062∟0.4°
Real Values	I_a (b.)	I_b (b.)
	0	5.3349∟134.46°
	I_c (b.)	I_n (b.)
	5.4941∟49.82°	8.0075∟91.38°

V. CONCLUSION

In this study, double line-to-ground short circuit fault in an unloaded synchronous generator is analyzed in unbalanced operation apart from the similar studies in the literature. New sequence circuits are obtained for the unbalanced synchronous generator. So, new sequence short circuit model composed of the obtained generator's sequence circuits is obtained for the short circuit analysis. The obtained results show that the proposed approach is applicable.

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