Journal of the Korean Institute of Illuminating and Electrical Installation Engineers Vol. 16, No.1, pp. 76~84 January 2002 논문 16-1-11

배전선로 고장에 의한 Voltage Sag의 특성 해석

(Characteristic Analysis of Voltage Sags Due to Faulted Distribution Lines)

김성덕* · Madhat M. Morcos**
(Sung Duck, Kim · Madhat M. Morcos)

요 약

송전선과 배전선의 고장에 의한 voltage sag는 산업 수용가와 전력회사에 당면한 가장 중요한 전력품질(power quality) 문제들 중 하나가 되었다. voltage sag는 일반적으로 진폭과 지속시간 특성으로 기술되지만 voltage sag 현상을 규명하여 그 대책을 찾는데는 위상변위 특성을 반드시 고려해야 한다. 이 논문에서는 3상지락, 단선지락, 및 선간단락 사고가 발생하였을 경우에, 고장임피던스의 변화에 의한 voltage sag를 symmetrical components 해석을 이용하여 특성해석을 하였다. 이 때, voltage sag와 이들이 진폭과 위상에 미치는 효과를 고찰하였다. 3상지락과 같은 평형 고장은 모든 상에서 전압과 전류가 동일한 값으로 변화되고 또한 영상성분들은 영이 되었다. 그렇지만, 단선지락과 선간단락 고장과 같은 불평형 고장으로 인한 voltage sag는 진폭과 위상이 각 상마다 다르게 변화되었다. 해석결과를 확인하기 위하여 전력회로 모델들을 토대로 시뮬레이션을 수행하고 그 결과들도 검토되었다.

Abstract

Voltage sags caused by line faults in transmission and distribution lines have become one of the most important power quality problems facing industrial customers and utilities. Voltage sags are normally described by characteristics of both magnitude and duration, but phase angle shifts should be taken account in identifying sag phenomena and finding their solutions. In this paper, voltage sags due to line faults such as three phase-to-ground, single line-to-ground, and line-to-line faults are characterized by using symmetrical component analysis, for fault impedance variations. Voltage sags and their effect on the magnitude and phase angle are examined. Balanced sags of three phase-to-ground faults show that voltages and currents are changed with equivalent levels to all phases and the zero sequence components become zero. However, for unbalanced faults such as single line-to-ground and line-to-line faults, voltage sags give different magnitude variations and phase angle shifts for each phase. In order to verify the analyzed results, some simulations based on power circuit models are also discussed.

Key Words : Voltage sags, balanced and unbalanced faults, fault impedance, power quality

* 주저자 : 국립한밭대학교 전기 · 전자 · 제어공학부 교수
Tel : 042-821-1135, Fax : 042-821-1128
E-mail : sdkim@hanbat.ac.kr
** Professor, Dept. of Electrical and Computer Eng., Kansas State University. USA
접수일자 : 2001년 10월 25일
1차심사 : 2001년 10월 30일 2차심사 : 12월 10일
심사완료 : 2001년 12월 28일

1. Introduction

As the proliferation of sensitive electronic loads such as adjustable speed motors and micro-processor-based equipment, power quality (PQ) has become an increasing concern to facility manufacturers, customers, and electric power companies for the past decade [1]. The ultimate goal to deal with PQ problems is not only to find disturbance characteristics from PQ events but also to provide a suitable solution to both utilities and users.

There are various types of disturbances influenced on maintaining power utilities and facilities reliable, but voltage sag of all power disturbances are considered to be the major cause of more than 80 % of the PQ problems. Voltage sags are usually caused by sources such as operating motors or transformers, shortening power lines or circuits, and inducing direct lightning strokes. Especially, short-duration voltage sags due to short circuits or fault lines are recognized as an important problem in PQ [2]. Voltage sag is a sudden drop while the load remains connected to the power source. This sometimes leads to mal-operation or failure of customers facilities extremely sensitive to small magnitude changes. Many studies have shown that all voltage variations were caused by current flowing to short circuits either within the power systems or on utility lines in the same feeders [3].

Voltage sag characteristics are usually described by using magnitude and duration; voltage sag magnitude is the rms voltage in percent or per unit whereas duration is the time interval lasting voltage sag. According to the IEEE Standard 1159[4], voltage sag is a reduction in the rms value in the range of 0.1 and 0.9 pu for the rated voltage and its duration from 0.5 cycle to 1 minute. Sag magnitude and phase angle shift are normally affected on various factors consisting of power system such as line and load impedance, transformer connection, and fault impedance. However, voltage sag duration mainly depends on characteristics like fault clearing time, characteristics of transformer energizing, or motor starting.

Voltage sags associated with fault clearing show various characteristics, but it is possible to predict the magnitude for individual fault by calculating the voltage drop at the critical load. Of course, sag waveform is dependent on cause and source of line faults, however, the sag magnitude at a special location entirely relies on system configuration, circuit components, fault impedance, transformer connections, and the pre-fault voltage levels. A fault on one feeder drops the voltage on all other feeders within the same power system. In order to find any solutions for voltage sag problems due to line faults such as three phase-to-ground (3ϕ), single line-to-ground (SLG), or line-to-line (LL) faults, it is necessary to identify characteristics of magnitude variation and phase angle shift.

2. Balanced Faults

2.1 Line Fault and Voltage Sag

To characterize a voltage dip and phase angle shift due to a line fault, first, consider a 3ϕ fault as one of balanced faults, and use an analytical model as shown in Fig. 1. It is assumed that a fault occurred at position, F, where Z_a is the equivalent impedance of transformer and lines in front of the fault position while Z_b is the impedance between the fault point and the load, and further Z_L is the impedance of a static load.

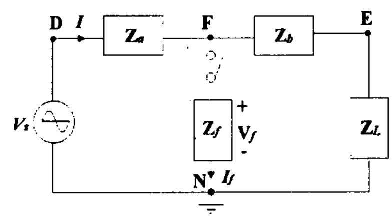


Fig. 1 Circuit diagram for a balanced fault

The voltage, V_F, in the pre-fault condition is given by

$$V_F = \frac{Z_b + Z_L}{Z_a + Z_b + Z_L} V_S \quad (1)$$

where V_S is the source voltage. Under a line fault, the voltage at this point becomes

$$V_f = \frac{Z_f \| Z_{bL}}{Z_a + Z_f \| Z_{bL}} V_S \quad (2)$$

where Z_f is the fault impedance, which is assumed to be resistance, R_f, and $Z_f \| Z_{bL}$ denotes the equivalent impedance of Z_f in parallel with $Z_{bL} (\equiv Z_b + Z_L)$.

Applying Eqn. (1) to Eqn. (2) results in

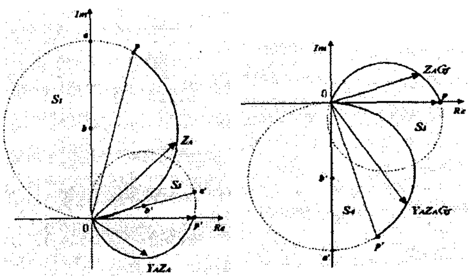
$$V_f = \frac{G - jB}{G + G_f - jB} V_F \quad (3)$$

where $G(\equiv G_a + G_{bL})$ and $B(\equiv B_a + B_{bL})$ are the conductances and suceptances for the correspondent impedances, respectively, and G_f is the fault conductance. Assuming that the voltage at the observation point is 1.0 pu, V_F in Eqn. (1) and (3) is considered as the reference vector. Hence, most phasor diagrams below can be given, based on unit circles. As Eqn. (3) represents voltage change at the fault point, it is easily seen that both magnitude variation and phase angle shift are dependent on circuit components such as G, B, and G_f.

Under the assumption that G_f varies from zero (pre-faulted condition) to infinity (zero fault impedance), voltage changes due to a line fault can be characterized by Eqn. (3). In order to deal phasor diagrams easily, let Eqn. (3) rewrite as

$$V_f = Z_A Y_A \quad (4)$$

where $Z_A = 1/(G + G_f - jB)$ and $Y_A = G - jB$. The phasor diagram for $Z_A Y_A$ corresponding to the fault resistance variation can be represented as Fig. 2(a).



(a) fault voltage (b) fault current

Fig. 2 Phasor diagrams when varying fault impedance

In Fig. 2(a), the phasor plot for Z_A demonstrates an arc on the circle, S_1, with its center, $j1/(4B)$. Hence, the phasor, $Z_A Y_A$, can be obtained as multiplying Z_A by Y_A, i.e., $Z_A Y_A$ shows a vector that its magnitude and phase angle are changed by Z_A. In this case, the center of the vector trajectory S_2 is $1/2 + jG/(2B)$. As a result, the phasor diagram S_1 can be transformed to S_2 where $\overline{op'}$=1.0 pu.

As the phasor diagram S_2 is equivalent to that of the voltage due to fault, magnitude and phase angle of fault voltage can be directly determined by a specified value of R_f. Furthermore, it is seen that the fault voltages for R_f=0 and ∞ become 1.0 pu and zero, respectively. Especially, the fault voltage when R_f=0 lags the reference vector by 90o. Corresponding to the fault impedance, the voltage changes magnitude, 0 to V_F, and phase angles between 0o and -90o. If the fault impedance is small or negligible, the phase angle shift approaches 90o, in regard to the pre-fault voltage.

Using Eqn. (3), the fault current I_f is given by

$$I_f = \frac{G_f(G-jB)}{G+G_f-jB} \tag{5}$$

Applying Eqn. (4) to Eqn. (5), it can be written as $I_f = Z_A Y_A G_f$ since the phasor plot for $Z_A G_f$ is given by S_3 in Fig. 2(b), where the circle is centered at $1/2 - j\ G/(2B)$. Therefore, an arc on the circle S_4 represented by the vector, $Z_A Y_A G_f$, has its center, $-j(G^2+B^2)/(2B)$. If $R_f = 0$, the fault current is $I_f = \sqrt{G^2+B^2} = \sqrt{G_a^2+B_a^2}\,V_S$ and it always lags the reference vector, V_F. As we can see in Fig. 2(b), fault current also depends on fault impedance and it is shown the largest value when $R_f = 0$, but not infinity.

Using Eqn. (3) and Eqn (5), the line current becomes

$$I = \frac{G_f + G_{bL} - jB_{bL}}{G+G_f-jB}(G-jB) \tag{6}$$

For a small Y_{bL}, it is seen that the phasor diagram for the line current can be similar to that of the fault current.

If the voltage and current at fault point are determined, those at position D or E can be easily calculated without any difficulty. Such results show similar characteristics to those at fault position but details are not given here.

2.2 Three Phase-to-Ground Fault

The results given in Sec. 2.1 can be directly applied to characterize any balanced faults like 3ϕ faults under the assumption that all loads and line impedances are balanced for each phase. In this case, the phase and line voltages at fault position have the same magnitudes, and their phase angle differences are exactly 120o. Based on the results determined in Sec. 2.1, the phasor plot for the three phase voltages at fault point can be obtained as in Fig. 3. Note that for most phase diagrams below, positions, p, q, and r are coordinates for $R_f = 0$ and p', q', r', or o for $R_f = \infty$.

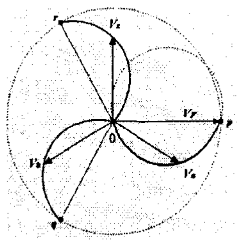


Fig. 3 Phase voltage diagram for a 3ϕ fault

The general goal to analyze voltage and current characteristics caused by line faults is to find solutions in maintaining the reliability of power system. In particular, the zero sequence components are very important in designing circuit breakers, relays, or safeguard devices [5]. These levels are normally dependent on transformer, load connections, or grounding types, however, it is assumed that the power line is directly grounded to earth for the simplicity of analysis. Under this condition, the zero sequence components for a 3ϕ fault are always zero, independently of fault impedance.

3. Unbalanced Faults

3.1 Single Line-to-Ground Fault

Symmetrical components are one of the basic tools available to analyze power system phenomena, especially, voltage sag analysis such unbalanced phenomena as SLG and LL faults [6~8]. The three phase voltage sags from an unbalanced faulted system generally give different magnitudes and phase angle shifts. Furthermore, the three phase quantities may show different changes as moving through various types of power equipment like transformers or loads. Based on the two-component method for solving unbalanced system conditions, the three phase voltages at the fault position, can be described in matrix form as

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 0 \\ 1 & -1/2 & -j\sqrt{3}/2 \\ 1 & -1/2 & j\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_{a0} \\ V_{a\Sigma} \\ V_{a\Delta} \end{bmatrix} \quad (7)$$

where $V_{a\Sigma} = V_{a1} + V_{a2}$ and $V_{a\Delta} = V_{a1} - V_{a2}$. Here, V_{a0}, V_{a1}, and V_{a2} are the zero, positive, and negative sequence voltages, respectively.

Assuming that there is a SLG fault on phase-a at position F, the three phase voltages can be written by

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 \\ a^2 \\ a \end{bmatrix} - \frac{1}{Z_0 + 2Z_1 + 3Z_f} \begin{bmatrix} Z_0 - 2Z_1 \\ Z_0 - Z_1 \\ Z_0 - Z_1 \end{bmatrix} \quad (8)$$

In Eqn. (8), Z_0 and Z_1 represent the zero and positive sequence impedance, and they are given as $Z_0 = Z_a$ and $Z_1 = Z_a \| Z_{bL}$ in Fig. 1, where a is a vector rotational operator defined as $-1/2 + j\sqrt{3}/2$. Rearranging V_a in Eqn. (8), it is equivalent to Eqn. (3) of balanced fault, and moreover, V_a and V_c shows alternative vectors to the fault current I_f multiplied by Z_a and added to them by a and a^2, respectively. These voltage vectors are shown in Fig. 4(a).

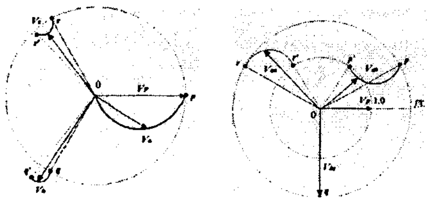

(a) phase voltage (b) line voltage

Fig. 4 Vector diagram for a SLG fault

Contrary to the case of a 3ϕ fault, the line voltages of a SLG fault may be affected by the fault voltage on phase-a. From Eqn. (8), the line voltages are easily obtained by

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = \begin{bmatrix} 1 \\ a^2 \\ a \end{bmatrix} \sqrt{3} e^{\pi/6} - \frac{1}{Z_0 + 2Z_1 + 3Z_f} \begin{bmatrix} 3Z_1 \\ 0 \\ -3Z_1 \end{bmatrix} \quad (9)$$

It is noted that the voltage V_{bc} unlike V_{ab} and V_{ca} does not influence on circuit parameters despite of occurring a fault on phase-a. If $Z_1 (= Z_a)$ in Eqn. (9) is negligible, V_{ab} can be approximated by

$$V_{ab} \doteqdot \sqrt{3} e^{\pi/6} - \frac{G_f}{G + G_f - jB} \quad (10)$$

Since the second term on the right side of Eqn. (10) equals the vector, $Z_A G_f$, it is given as a reversed vector to the phasor, S_3, in Fig. 2(b). As a result, the line voltages can be shown in Fig. 4(b). Note that for R_f = 0, the phase angle shifts of V_{ab} and V_{ca} approach 30o and -30o, respectively, and their magnitudes are both units.

The zero sequence components for a 3ϕ fault are zero, however, those are not zero for a SLG fault. Hence, the zero sequence components for a small Z_a, are given by

$$V_0 \doteqdot -\frac{1}{3} \frac{Z_a G_f (G - jB)}{G + G_f - jB} \quad (11)$$

$$I_0 \doteqdot \frac{G_f (G - jB)}{G + G_f - jB} \quad (12)$$

Finally, the zero sequence voltage is $V_0 = -Z_a I_f / 3$ and the zero sequence current is approximately equivalent to the fault current. The vector diagram for the zero sequence voltage can be directly obtained as rotating I_f to 90o since the resistance of Z_a is nearly negligible. If load is delta-connected, the zero sequence components can be ignored, however, for a wye-connected load, the zero sequence current flows into the neutral line in the power system.

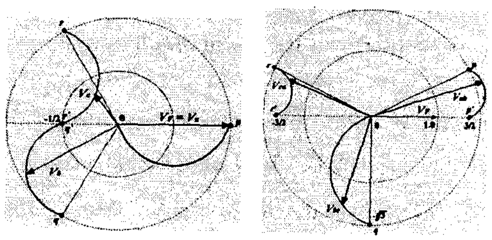
3.2 Line-to-Line Fault

Assuming that there is a LL fault between phase-b and c, it causes two phase voltages to move toward each other, while the phase-a voltage does not change at all. In this case, the phase and line voltages at fault point are described by

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 \\ -1/2 \\ -1/2 \end{bmatrix} + \frac{Z_f}{2Z_1+Z_f} \begin{bmatrix} 0 \\ -j\sqrt{3}/2 \\ j\sqrt{3}/2 \end{bmatrix} \quad (13)$$

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = \begin{bmatrix} 3/2 \\ 0 \\ -3/2 \end{bmatrix} + \frac{Z_f}{2Z_1+Z_f} \begin{bmatrix} j\sqrt{3}/2 \\ -j\sqrt{3} \\ j\sqrt{3}/2 \end{bmatrix} \quad (14)$$

Fig. 5 shows the phasor diagrams for phase and line voltages due to a LL fault. Although the fault impedance in most LL faults are not high, magnitudes and phase angles of the voltages at fault point vary irregularly with fault impedance.



(a) phase voltage (b) line voltage

Fig. 5 Voltage phase diagrams due to LL fault

Especially, if fault impedance is zero, the phase voltages are given as $V_a = V_F$, $V_b = -V_F/2$, and $V_c = -V_F/2$ (points, p', q', and r' in Fig. 5(a)). In addition, the line voltages are given as $V_{ab} = 3/2$, $V_{bc} = 0$, and $V_{ca} = -3/2$, (points, p', q', and r' in Fig. 5(b)) from Eqn. (14). However, the zero sequence components for this case become $V_0 = I_0 = 0$, independently of fault impedance.

4. Simulation and Discussion

4.1 Fault System Model

Simulations for 3ϕ, SLG, and LL faults are performed in order to verify the analytical results described in Sec. 2 and 3. A fault model under study is assumed to be a power system as shown in Fig. 6.

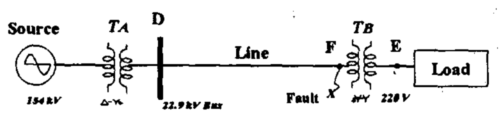


Fig. 6 Simulation model for fault analysis

Table 1. Specifications for simulation network

Components	Features
Source	20 MVA, 154 kV, Z_s = j0.004 pu
Transformer A	25 MVA, 154/22.9 kV, Z_{TA} = 0.001+j0.045 pu
Transformer B	20 MVA, 22.9 kV/220V, Z_{TB} = 0.001+j0.030 pu
Load	S = 14.4+j10.8 MVA, Static Load
Line	Z_l = 0.4+j1.06/km, 3 km

Distribution lines have shorter length, but their impedance is higher than that in transmission lines. There are many step-down transformers to supply low voltages to loads, but for the simplicity of analysis, only one transformer is considered. Table 1 shows system parameters used for simulation. Distribution networks are modeled using the power system blockset package contained in MATLAB. It is assumed that a fault is happened at position, F, on the primary side of transformer, TB, and the fault lasts for 5 cycles.

4.2 Three Phase-to-Ground Fault

First, assuming that the fault impedance is Z_f = 1Ω, the phase voltages and phase angles at the fault position due to a 3ϕ fault are given in Fig. 7, where the rms value of the reference voltage of the pre-fault condition is assumed to be 1.0 pu.

All phase voltages reduce up to 0.23 pu for the pre-fault voltage and lag the reference voltage by 59.7o. The voltage sags show rectangular shapes and their dips may depend on fault impedance and other components of the network. All voltage changes and their phase angle shifts hold balanced levels. Lagging characteristics of the phase angles show that the distribution network dominants inductive components, independently of fault impedance.

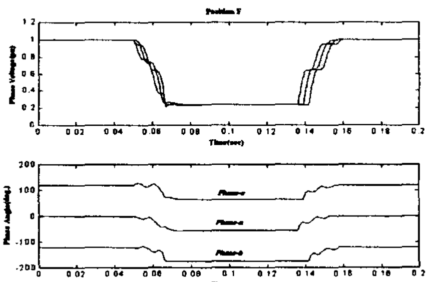
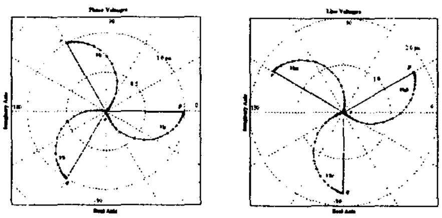


Fig. 7 Balanced voltage sags for a 3ϕ fault

Voltage sags are usually determined by system components such as transformers, line impedance, load characteristic, and fault impedance, however, in this research, any influence of fault impedance on voltage sag is examined under the assumption that only the fault impedance is changed. Fig. 8 shows voltage phasor diagrams at fault point. All phase voltages are semi-circled diagrams as shown in Fig. 8(a). Of course, sag magnitude and phase angle shift for each phase are dependent on fault impedance. In particular, if the fault impedance is zero, the phase angle shifts become all 90o lagging for the pre-fault voltages. In addition, the line voltages, Fig. 8(b), also show similar sag phenomena to the phase voltages. In a balanced fault like a 3ϕ fault, the zero sequence components are zero, independently of fault impedance.



(a) phase voltage (b) line voltage

Fig. 8 Phasor diagrams for a 3ϕ fault

4.3 Unbalanced Faults

When a SLG fault is happened on phase-a at F, line voltage characteristics are given in Fig. 9. The voltage, V_{bc} remains pre-fault level but V_{ab} and V_{ca} show magnitudes of 0.54 and 0.70 pu, and phase angle changes of 17.67 and 28.44o, respectively. Similar characteristics for magnitudes and phase angles changes due to a SLG fault were shown on all feeders in the same power line.

Unlike a balanced fault, voltage sags for a SLG fault are demonstrated different characteristics in magnitudes and phase angles. Fig. 10 shows phasor diagrams of the phase and line voltages for fault impedance variation. In this case, the phase voltages, V_b and V_c hardly change their values and the line voltage, V_{bc}, does not change at all. Even for $R_f = 0$, the phase-a voltage drops nearly to zero, however, the phases-b and c voltages normally remain pre-fault levels, as shown in Sec. 2.1. Especially, note that the phase angle shifts for V_{ab} and V_{ca} approach 30 and -30o, respectively, and their magnitudes are both 1.0 pu. For fault impedance variation, all results show similar characteristics given in Sec. 3.1.

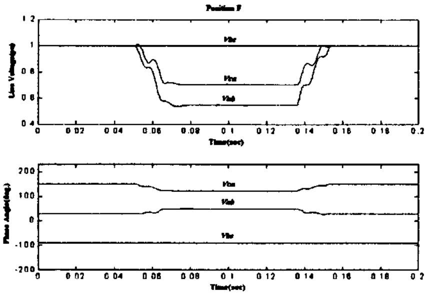
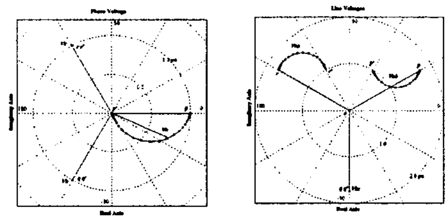


Fig. 9 Unbalanced voltage sag for a SLG fault



(a) phase voltage (b) line voltage

Fig. 10 Voltage phasor for a SLG fault

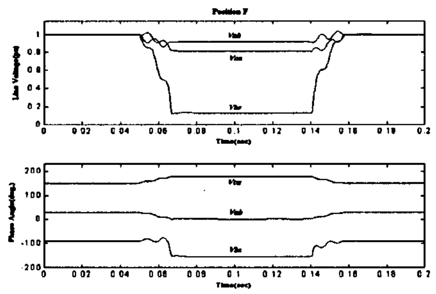
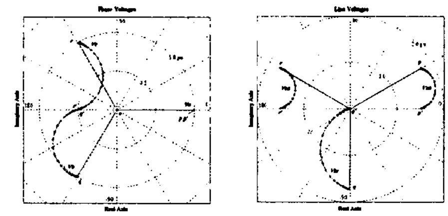


Fig. 11 Unbalanced voltage sag for a LL fault

A LL fault is also one of causes occurring voltage sag, however, characteristics for magnitude changes and phase angle shifts are not similar to those of a SLG fault. Fig. 11 show magnitude and phase angle characteristics for all line voltages due to a LL fault between phases-b and c for $R_f = 1$ Ω. All magnitudes and phase angles vary irregularly with fault impedance. The line voltages drop magnitudes up to 0.92, 0.13, and 0.81 pu, and the phase angle shifts are -28.10, 61.15, and 27.89o, respectively.



(a) phase voltage (b) line voltage

Fig. 12 Phasor diagrams for a LL fault

When fault impedance is changed, phasor diagrams for phase and line voltages are given in Fig. 12. In Fig. 12(a), magnitudes and phase angles of the phase-b and c voltages vary with different values but the phase-a voltage remains unchanged. For $R_f = 0$ Ω, $V_b = V_c$(points, q′ and r′) and they have magnitudes, $1/2V_a$ and phase angles, -180o. In addition, the line voltages in Fig. 12(b) are $V_{ab} = 1.5$ (point p′), $V_{ca} = -1.5$ (point r′), and $V_{bc} = 0$ (point q′), respectively. Although all line voltages changes their magnitudes and phase angles to different values, the zero sequence components are always zero as expected.

5. Conclusions

Power line fault is a major cause to occur voltage sags, which sometimes lead sensitive loads to mal-operation or failure. In this research, voltage sags caused by balanced and unbalanced faults such as three phase-to-ground, single line-to-ground, and line-to-line faults are characterized using symmetrical components analysis. Magnitude variation and phase angle shift of voltage sag are analyzed in detail for fault impedance variation. If fault impedance is zero, the voltage shows its phase-angle shift to 90o for that of pre-fault voltage, independently of balanced or unbalanced faults. Several characteristics for magnitude changes and phase angle shifts due to such faults are also discussed. Through simulations based on distribution line models, the results presented by symmetrical components analysis are verified.

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본 연구는 2001년도 한밭대학교의 교수 해외연수지원에 의하여 수행되었습니다.

◇Authors◇

김 성 덕(Sung-Duck Kim)

He received the B.E., M.S. and Ph. D. degrees from the Han-yang University, Korea, in 1978, 1980 and 1988, respectively, in the Department of Electrical Engineering. He was a visiting professor in the Australian National University during 1990~1991, and the Kansas State University during 2000~2001. Dr. Kim is a professor in the School of Electrical, Electronic and Control Eng. in the Hanbat National University, since 1980. His interest research fields are adaptive control theory, automation, signal processing, sensor applications, and power system diagnosis.

Madhat M. Morcos

He is a professor of electrical and computer engineering and University Distinguished Teaching Scholar at Kansas State University. He received the Ph. D. degree from the University of Wateroo, Ontario, Canada, in 1984. Dr. Morcos is a member of Components and systems. His current research includes artificial intelligence applications in power quality and power systems protection, power electronics, and insulation systems.