Analysis of Voltage Sag on Transmission System Under Fault Conditions

EE5200 - Advanced Power System Analysis

Term Project

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Statement of Contribution

This was the collaborative effort from both team members with first draft responsibility of individual sections of the report split equally between team members. The MATLAB SimPowerSystem file development was a collaborative effort as well as including the Simulink control blocks and test case parameters.

Disclaimer

This case study report aims to evaluate and reproduce important functionalities of “Factor Affecting Characteristics of Voltage Sag due to Fault in the Power System” presented in paper. All the methods, analyses, results, discussions and conclusion presented in this report is the reproduction of those developed in paper.

Signed in Agreement by All

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Executive Summary

With the growth of need of electrical energy in the technological societies, the demand for receiving the high-quality electrical energy is being increased. This report introduces a voltage sag (dips) characterization based on instantaneous voltage and current through the analysis of these quantities. The factors which affects the characteristics of voltage sag such as type of fault in the system, location of the fault in the system, X/R ratio of transmission lines with respect to symmetrical and unsymmetrical faults for balanced and unbalanced voltage sag are obtained.

Voltage sags have been characterized by their magnitude and duration of the sag. In order to completely characterize the event as well as predicting the behavior of sensitive equipment's like ASD (Adjustable Speed Drives), PLC (Programmable Logic Controllers) and computers more parameters are required in case of three phase unbalanced faults.

Out of the different power quality problems such as transients, voltage fluctuations, harmonics, inter-harmonics, voltage unbalance, waveform distortion, dc offset, noise and notches voltage sag is considered to be one of the most harmful power quality disturbance due to its impact on sensitive loads. Voltage sags or Voltage dips are also called as short duration under-voltages. According to the IEEE Standard 1159-1995, sag is defined as a decrease in rms voltage to values in between 0.1 and 0.9 pu for durations of 0.5 cycles to 1 min. Three methods have been developed for the assessment of voltage sag due to faults such as the method of critical distances, the method of fault positions and the Monte Carlo Method.

The method of fault positions is applied to the model as shown in the base paper as system under study. Using this system, performance of some selected busbars regarding voltage sags is estimated by performing both symmetrical and unsymmetrical faults. Also, the analysis is carried out for the location of fault and its influence on the magnitude as well as the phase angle of the sag at the respective busbars. Performance analysis of magnitude and duration of sag has been carried out by changing the X/R ratio of the line as well as by considering the single/ double circuit lines. Simulation results for positive, negative and zero sequence components for various types of faults are implemented in MATLAB/Simulink. All results are also compared to the base paper in [1] to confirm the theoretical calculations as well as simulation results. Moreover, further investigations can be carried out in terms of different sag indices and few more parameters like phase angle jump, conductor area with overhead and underground cables. Additionally to improve the dynamics of the system some proposals and mitigation techniques can be incorporated to further analyze the system.

Introduction

1.1. Problem Description

Today’s power systems have become very complicated electric network because it consists of thousands of generating stations and load centers which are interconnected to high voltage transmission lines. Power quality problems exhibits deviation in voltage, current, or frequency which results in failure of equipment’s, which are sensitive to power quality variations. There is a continuous growth in the application of devices integrated with power electronics and microprocessor control to improve the efficiency in the power system as load equipment’s are very sensitive to power quality variations. Among the different disturbances such as voltage fluctuations , voltage unbalance, transients, harmonics, inter harmonics, dc offset, noise, notches etc which affect the power quality, voltage sag is considered as the most important power quality problem in the transmission and distribution system and equipment’s like PLC, ASD which needs to be fully analyzed and investigated.

1.2. Motivation for the project

Until the 1960’s, the continuity of the supply was the main concern of the consumers for electricity, that is reliability of the supply. Now a days, a consumer not only require reliability, but also on the power quality. For example, a consumer may face an unexpected voltage reduction every time there is a fault at some part of the power system which affects the sensitive loads. A voltage may lead to a failure or disconnection of the loads or of the entire plant which depends on the sensitivity of the consumer’s loads. Although the supply is not disrupted, but it causes an outage of the plant because of the disturbance experienced by a consumer. Examples of very sensitive end users’ loads are hospitals, manufacturing industries, air traffic control towers, and financial institutions which require reliable and high-quality electrical supply.

The location of the source of the disturbance or fault plays an important role in deciding about financial penalties and responsibilities. This information plays a critical role in considering the new power system management in deregulated environments, where may transmission and distribution companies exchange electric energy and also power quality disturbances.

1.3. Project Overview

In this project, a theoretical analysis and simulation results were developed. The theoretical study regarding the determination of voltage sag and also phase voltage of various types of faults such as single line to ground fault, line to line fault, double line to ground fault and three phase faults are explained. The results of this theoretical study are further demonstrated with a simulation on a model system, which is used to reproduce the results obtained in the base paper are attached herewith.

This paper contains the key sections addressing various types of faults, characteristics of voltage sag and factors power system factors affecting the performance of the voltage sag. In the background section the power quality problems and characteristics of the voltage sag are explained. In proposed approach and implementation, the simulation for various types of faults were considered and analysis was done on the performance of the voltage sag due to the parameter changes in the power system. The simulation was carried out in MATLAB/Simulink, followed by the results section which provides a discussion of results in the simulation. The conclusion and recommendations for continued work section provides an outline of what was achieved in the project and the recommendations are provided for further development of the topic.

Background

2.1. Literature Survey of Power Quality Problems

Power Quality has become the most important issue in the recent years. Any power problem exhibited in voltage, current or frequency deviation will result in failure or non-operation of customer equipment is a Power Quality problem. The load equipment are more sensitive than the equipment used before, to power quality variation in recent case scenario. This is because there is an advance development to improve the efficiency of the power system with the application of the devices like microprocessor and control in power electronics. [1]. Out of various power quality problems, such as transients, voltage fluctuations, harmonics, inter-harmonics, voltage unbalance, waveform distortion, DC offset, noise, notches etc. voltage sag is considered as the most important one [2],[3].

Table I: Power Quality Problems and their causes [4]

Broad Categories	**Specific Categories**	**Methods of Characterization**	**Typical Causes**
Transients	Impulsive	Peak magnitude, rise time and duration	Lightning strike, transformer energization, capacitor switching
	Oscillatory	Peak Magnitude, frequency components	Line or capacitor or load switching
Short duration voltage variation	Sag	Magnitude, duration	Ferro-resonant transformers, single line-to-ground faults
	Swell	Magnitude, duration	Ferro-resonant transformers, single line-to-ground faults
	Interruption	Duration	Temporary (self-clearing) faults
Long duration voltage variation	Undervoltage	Magnitude, duration	Switching on loads, capacitor de-energization
	Overvoltage	Magnitude, duration	Switching on loads, capacitor energization
	Sustained	Duration	Faults
Voltage Imbalance		Symmetrical Components	Single-phase loads, single-phasing condition
Waveform Distortion	Harmonics	THD, Harmonic spectrum	Adjustable speed drives and other non-linear loads
	Notching	THD, Harmonic spectrum	Power electronics Converter
	DC Offset	Volts, Amps	Geo-magnetic disturbance, half wave rectification
Voltage Flicker		Frequency of occurrence, modulating frequency	Arc furnace, arc lamps

Severe voltage sag may cause tripping of equipment which will result in stopping of the process which leads to financial losses. Power system study says that sags are more severe than interruptions as they are more frequent in the power system. Voltage sags are usually associated with system faults, energizing of heavy loads or starting of a large induction motor; but faults in the system are the most frequent cause of voltage sags. Majority of equipment trips are caused because of voltage sags has severe effects on various types of machines such as synchronous motors, induction motor, DC motor and different types of drives. [1]. The characteristics of voltage sag are defined by magnitude of the sag, duration, phase angle jump and unbalanced [5],[6].

2.2. Analysis of Voltage Sag

2.2.1 Definition of Voltage Sag

Short duration under voltages are called "voltage sags" or "voltage dips". Voltage sag is reduction in supply voltage magnitude followed by voltage recovery after a short period of time. According to the IEEE standard 1159-1995, the terminology sag is defined as a decrease in rms voltage to values between 0.1 to 0.9 pu, for durations of 0.5 cycles to 1 min.

2.2.2 Sag Determination

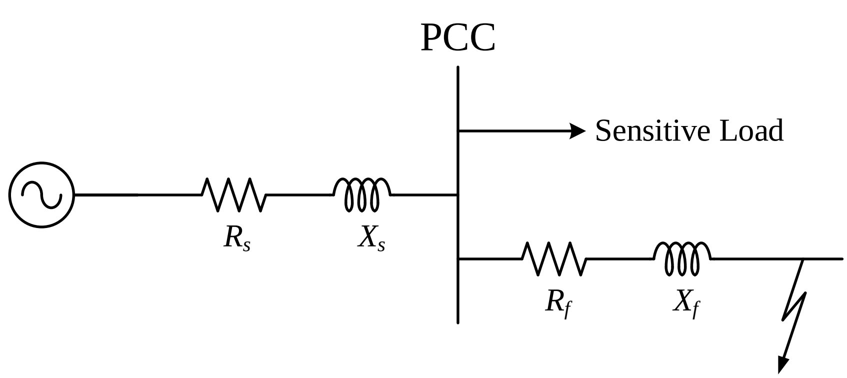

Fig.1. Voltage Divider Model for the determination of voltage sag [1]

The fault analysis is performed on a radial system using voltage divider model in order to determine the voltage sag which is shown in Fig. 1.The voltage sag characteristics at any node can be simulated using information of all impedances such as positive, negative and zero sequence resistances and reactance's of the power components and fault impedances. Z_s which is the sum of the R_s + j X_s is the source impedance at the point of common coupling (PCC). The voltage at the sensitive load terminal is given by

$$\bar{V}_{sag} = \bar{E}\frac{\bar{Z}_f}{\bar{Z}_f + \bar{Z}_s} \quad (1)$$

Assume that the prefault voltage is 1 pu., therefore E = 1. So, equation (1) becomes,

$$\bar{V}_{sag} = \frac{\bar{Z}_f}{\bar{Z}_f + \bar{Z}_s} \quad (2)$$

Feeder Impedance Z_f consists of fault impedance.

Consider $Z_f = zl$, where z is the impedance of the feeder per unit length and l is the distance between the PCC and the fault. Calculation of sag as a function of the distance can be performed using equation (2).

$$\bar{V}_{sag} = \frac{\overline{zl}}{\overline{zl} + \bar{Z}_s} \quad (3)$$

In equation (3) V_{sag}, Z_f, Z_s and zl are complex quantities.

From equation (3), magnitude of the voltage at the PCC terminal will be

$$\lfloor V_{sag} \rfloor = \frac{|zl|}{|zl| + |Z_s|} \quad (4)$$

Phase – angle jump with voltage sag at PCC is given by

$$\Delta\emptyset = arctan\frac{X_f}{R_f} - arctan\frac{X_s + X_f}{R_s + R_f} \quad (5)$$

where $Z_f = X_f + j\,R_f$ and $Z_s = R_s + j\,X_s$

If the X/R ratio of the source and the feeder are different then the phase-angle jump will be present.

2.2.3 Characteristics of voltage sag

Voltage sag is characterized in terms of the following parameters:[2]

1. Magnitude of the Sag
2. Three Phase balance/Unbalanced
3. Duration of the Sag
4. Phase Angle Jump
5. Point of Wave Characteristics
6. Missing Voltage

1. **Magnitude of the sag:**

   One common practice to characterize the sag magnitude is through the lowest per unit rms remaining voltage during the event of the sag. It implies that deep sag is the sag with a low magnitude and shallow sag has a large magnitude.

2. **Three phase balance/Unbalanced:**

   In the power system depending on the type of fault the sag in all the three phases can be balanced and unbalanced. For a three phase short circuit in the system during a fault all three phase sags will be equal in magnitude called balanced sag and if the fault is a single line to ground, line to line or double line to the ground depending on the faulty phase, the sag in all the three phases will be unbalanced in nature.

3. **Duration of the fault:**

   The duration of the sag is mainly determined by the fault clearing time of the protective device. Faster the fault clearing lesser will be the duration of sag and vice versa [7]. For distribution system as the circuit breakers are slower, having large fault clearing time as compared of the breakers to transmission system. The duration of the sag occurring in lower voltage distribution system is larger.

4. **Phase-angle Jump:**

   The phase angle jump manifests itself as a shift in zero crossing of the instantaneous voltage. Phase angle jumps during three phase faults are due to the difference in the X/R ratio between the source and the feeder [8],[9]. Phase-angle jumps are not of concern for most equipment but power electronic converters using phase angle information for switching may be affected.

5. **Point of Wave Characteristics:**

   The voltage sag characteristics such as magnitude, phase angle jump, three phase unbalance are related to the fundamental frequency component of the voltage. In order to determine the more accurate value for the sag duration, it is necessary to determine the start and the ending of the sag with a higher precision.

   5.1 Point on Wave of Sag Initiation:

   The point on wave of sag initiation is the phase angle of the fundamental voltage wave at which the voltage sag starts. This angle corresponds to the angle at which the short circuit fault occurs. Faults are associated with a flashover; they are more likely to occur near voltage maximum than near voltage zero.

5.2 Point on Wave of Voltage Recovery:

The point on wave of voltage recovery is the phase angle of the fundamental voltage wave at which the main recovery takes place.

6. Missing Voltage:

It is a way of describing the change in momentary voltage experienced by the equipment. It is also defined as a complex voltage (a phasor), being the difference in the complex plane between the pre-event voltage and the voltage during the sag.

2.2.4. Theoretical Calculation of Voltage Sag

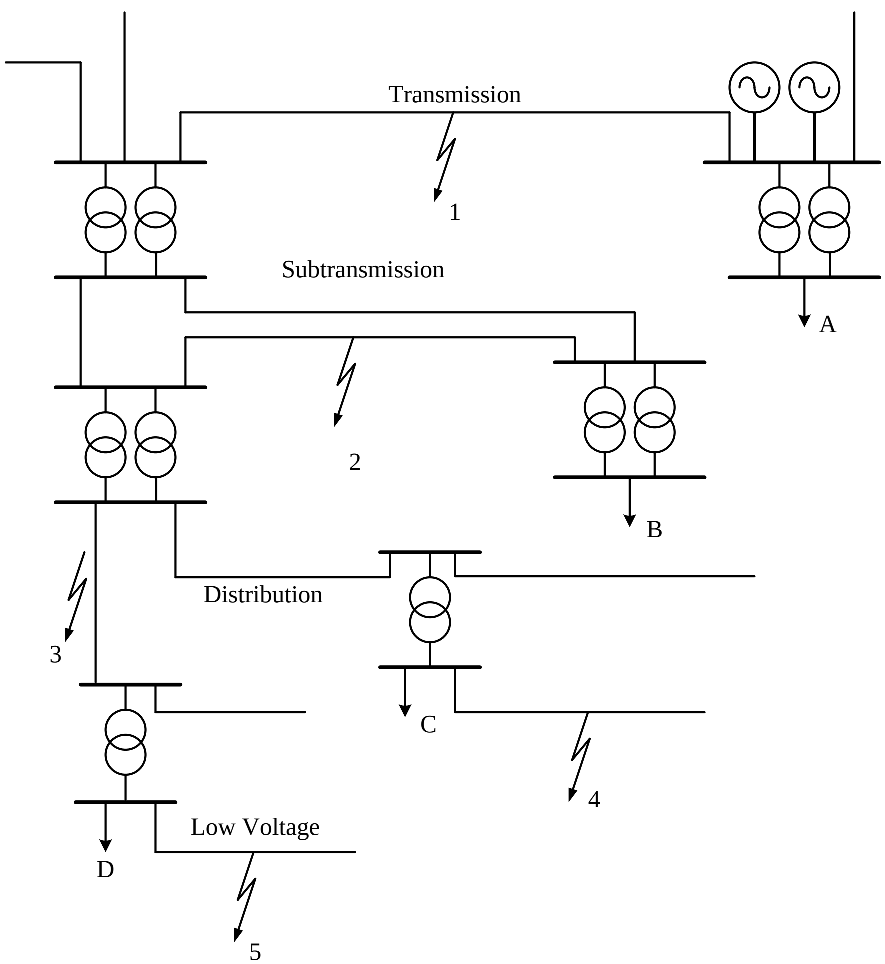

Fig.2 Distribution Network with load positions and fault positions [2]

Consider the power system shown in Fig. 2, where the numbers 1 through 5 indicates the fault positions and the letters A through D indicates the loads. A fault in the transmission line occurs at fault position 1, which will cause a serious sag for both substations bordering the faulted line. This sag is transferred down to all the customers fed from these two substations. There is normally no generation connected at lower voltage levels, there is nothing to keep up the voltage. The result is that a deep sag is experienced by all customers A, B, C, and D. The sag is experienced by A is likely to be less deep, as the generators are connected to that substation will keep up the voltage. A fault at position 2 will not cause much voltage drop for customer A. The impedance of the transformers between the transmission and the sub-transmission system are large enough to considerably limit the voltage drop at high voltage side of the transformer. The sag at customer A is further mitigated by the generators feeding it its local transmission substation. The fault at position 2 will cause a deep sag at both subtransmission substations and for all customers B, C and D.

A fault at position 3 will cause a very deep sag for customer D, followed by a short or long interruption when the protection clears the fault. Customer C will experience a deep sag. Customer C will experience two or more sags shortly after each other for a permanent fault, if fast reclosure is used in the distribution system. Due to the transformer impedance, customer B will experience a shallow sag. This fault will not affect anything for customer A. When the fault occurs at position 4, a deep sag will be experienced by the customer C and a shallow sag for customer D. For the fault at position 5, a deep sag will be experienced by customer D and shallow sag for customer C. Customers A and B will not be influenced at all by the faults at 4 and 5.

Proposed Approach and Implementation

3.1. *Simulation and Analysis in MATLAB*

The system under study is simulated in MATLAB and the analysis regarding various types of faults was performed in MATLAB.

3.1.1 System Under Study

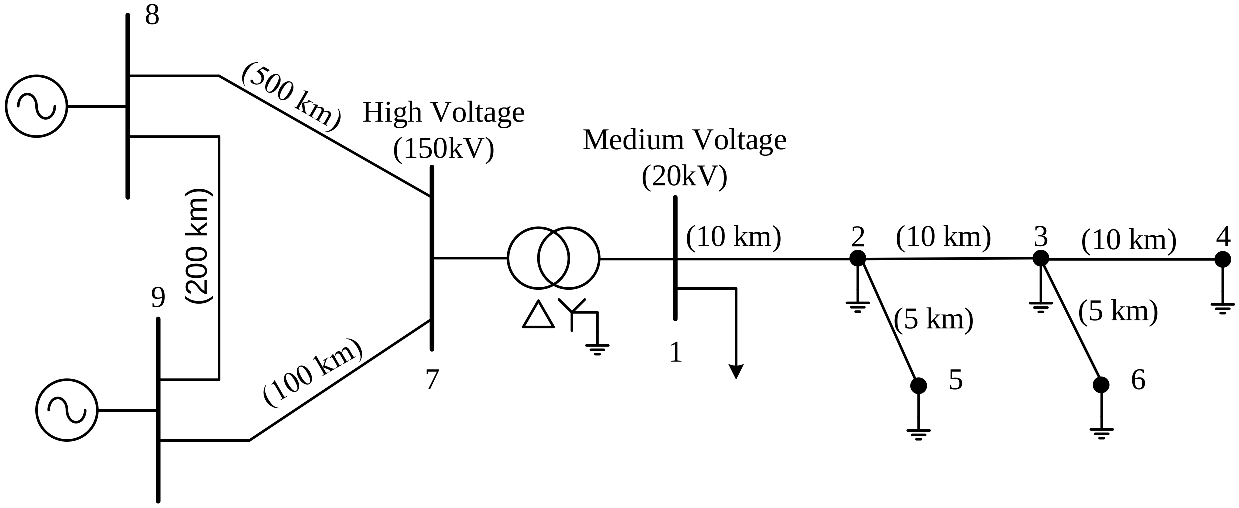

Fig. 3. System Under Study [10]

In order to investigate the performance of the method of fault positions for voltage sag assessment in a large transmission system, a model in Fig. 3 is used. The transmission network having a geographical extension of around 760 kms is connected to six critical industrial customers through a solidly ground delta wye transformer. The transmission network consists of two generators which are about 500 kms and 100 kms away from the bus 7. Generator 1 and generator 2 are connected to each other through transmission line of about 200 kms. The generating voltage is assumed to be 25kV, 60 Hz, star grounded with source resistance 0.8929 ohms and source inductance of 16.58mH. Using two 25kV/150kV Wye-Wye transformer, the transmission lines voltage increased to 150kV. The transmission network consists of three 150kV lines and distribution network is considered at 20kV. The fact that a severe sag occurs if the fault location is at 100 kms away from the industrial customers. MATLAB software package is used to simulate this model with the fault position method. To further analyze the factors affecting the characteristics of the sag, a particular factor is taken into consideration and the system is simulated. Line 8-9 is considered here to study the effect of aforementioned parameters and a fault position is selected near to the sensitive load. Line to ground fault (A-G), Line to line fault (BC), double line to ground fault (BC-G) is plotted to investigate the voltage sag and it is found that for A-G fault the most sagged voltage occurs in phase A, for BC and BC-G fault the most sagged voltage occurs in phase B.

In the simulation studies the required values of positive, negative and zero sequence impedances for each line is shown in Table I.

Table II

Transmission and distribution line impedances

Lines	Positive and Negative sequence impedances (Ω/km)	Zero sequence impedance (Ω/km)
1-2,2-3,3-4	0.22 + j0.37	0.37 +j 1.56
2-5,3-6	1.26 + j0.42	1.37 + j1.67
7-8,8-9,7-9	0.097 + j0.39	0.497 + j2.349

- Type of fault: Depending on the type of the fault sag can be unbalanced or balanced depending on the type of the fault. For ABC-G fault(balanced), the sag is balanced or symmetrical for all three phases whereas for Line to ground fault (A-G), Line to line fault (BC), double line to ground fault (BC-G) which are unbalanced faults, therefore the sag is unbalanced or unsymmetrical in all the three phases.
- Location of the fault: To study about the location of fault effects on sag characteristics, various type of faults is created along the transmission lines and increasing the distance from the fault location. Faults which are occurring near the point of common coupling (PCC) will have prominent effect on sag.
- X/R ratio of the line: The X/R of the transmission line 8-9 is changed to analyze the changes in the magnitude of the voltage where the sensitive load is connected.
- Single/Double circuit transmission: To study the effect of the transmission configuration as a single or double circuit transmission, the configuration of the line 7-8 in the system is changed and with A-G fault on line 8-9 is taken into consideration, the sag magnitude is studied.

3.1.2 Voltage Sag Analysis under different Unsymmetrical Faults

The voltage divider model shown in Fig. 1 was introduced for the three phase faults, where the impedances used are the positive sequence values. But in power systems most of the short circuits faults are the single phase or two phases. For the non-symmetrical faults, the voltage divider model shown in Fig. is split into its three components, a positive sequence network, a negative sequence network and a zero-sequence network. In the figure, V_1, V_2 and V_0 represents the positive, negative and zero sequence voltage respectively at the point of common coupling. Z_{s1}, Z_{s2} and Z_{s0} which is the combination of respective resistance and the reactance's are the source impedance values and Z_{F1}, Z_{F2}, and Z_{F0} which is the combination of respective resistance and the reactance's are the fault impedance values in the three components. I_1, I_2 and I_0 represents the three components of the fault current. The source of the positive sequence is denoted by E. There will be no source in the negative and the zero sequence networks. The three component networks have to be connected into one equivalent circuit at the fault position. All the three networks are shorted at the fault position for a three-phase fault [11], [12].

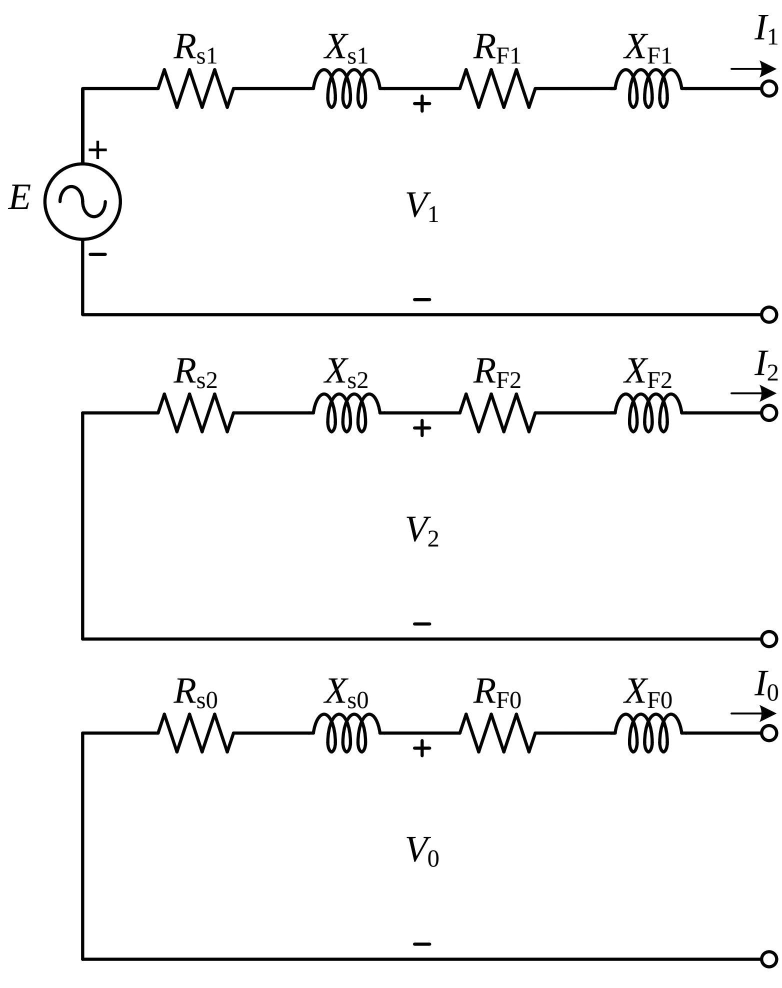

Fig.4 Positive, negative and zero sequence networks for the voltage divider

3.1.2.1. Analysis of Single-Phase Faults

For a single-phase fault, the three networks should be connected in series at the fault position as shown in Fig.4 The resulting circuit diagram for a single-phase fault in phase a is depicted in Fig. 5. Considering the value of the source of the positive sequence E to be 1, the following expressions are derived for the component voltages at the point of common coupling (PCC).

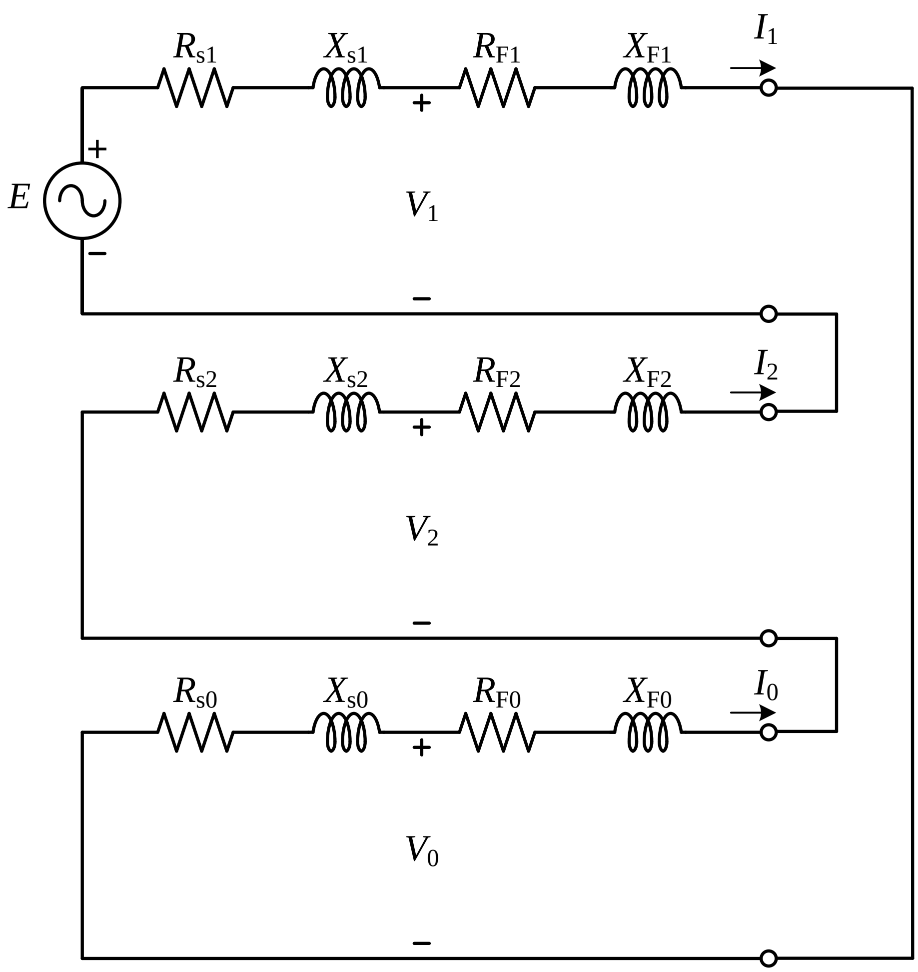

Fig. 5 Equivalent circuit for a single-phase fault.

$$V_1 = \frac{Z_{F1} + Z_{S2} + Z_{F2} + Z_{S0} + Z_{F0}}{(Z_{F1} + Z_{F2} + Z_{F0}) + (Z_{S1} + Z_{S2} + Z_{S0})} \tag{6}$$

$$V_2 = \frac{Z_{S2}}{(Z_{F1} + Z_{F2} + Z_{F0}) + (Z_{S1} + Z_{S2} + Z_{S0})} \tag{7}$$

$$V_0 = \frac{Z_{S0}}{(Z_{F1} + Z_{F2} + Z_{F0}) + (Z_{S1} + Z_{S2} + Z_{S0})} \tag{8}$$

The voltages in the three phases at the pcc during the fault are calculated by transforming back from sequence domain to phasor domain.

$$\begin{aligned} V_a &= V_1 + V_2 + V_0 \\ V_b &= \alpha^2 V_1 + \alpha V_2 + V_0 \\ V_c &= \alpha V_1 + \alpha^2 V_2 + V_0 \end{aligned} \tag{9}$$

For faulted phase voltage V_a we obtained

$$V_a = \frac{Z_{F1} + Z_{F2} + Z_{F0}}{(Z_{F1} + Z_{F2} + Z_{F0}) + (Z_{S1} + Z_{S2} + Z_{S0})} \tag{10}$$

The expression for the three voltages in the non-faulted phases is obtained below

$$\begin{aligned} V_a &= 1 - \frac{Z_{S1} + Z_{S2} + Z_{S0}}{(Z_{F1} + Z_{F2} + Z_{F0}) + (Z_{S1} + Z_{S2} + Z_{S0})} \\ V_b &= \alpha^2 - \frac{\alpha^2 Z_{S1} + \alpha Z_{S2} + Z_{S0}}{(Z_{F1} + Z_{F2} + Z_{F0}) + (Z_{S1} + Z_{S2} + Z_{S0})} \\ V_c &= \alpha - \frac{\alpha Z_{S1} + \alpha^2 Z_{S2} + Z_{S0}}{(Z_{F1} + Z_{F2} + Z_{F0}) + (Z_{S1} + Z_{S2} + Z_{S0})} \end{aligned} \tag{11}$$

The voltage between the two non-faulted phases is

$$V_b - V_c = (\alpha^2 - \alpha)\left[1 - \frac{Z_{S1} - Z_{S2}}{(Z_{F1} + Z_{F2} + Z_{F0}) + (Z_{S1} + Z_{S2} + Z_{S0})}\right] \tag{12}$$

3.1.2.2. Analysis of Phase-to-Phase Faults

As shown in the Fig. the positive and negative sequence networks are connected in parallel for a phase to phase fault.

The sequence voltages at the PCC are

$$V_1 = E - E\frac{Z_{S1}}{(Z_{S1}+Z_{S2})+(Z_{F1}+Z_{F2})}$$
$$V_2 = \frac{Z_{S2}}{(Z_{S1}+Z_{S2})+(Z_{F1}+Z_{F2})} \tag{13}$$
$$V_0 = 0$$

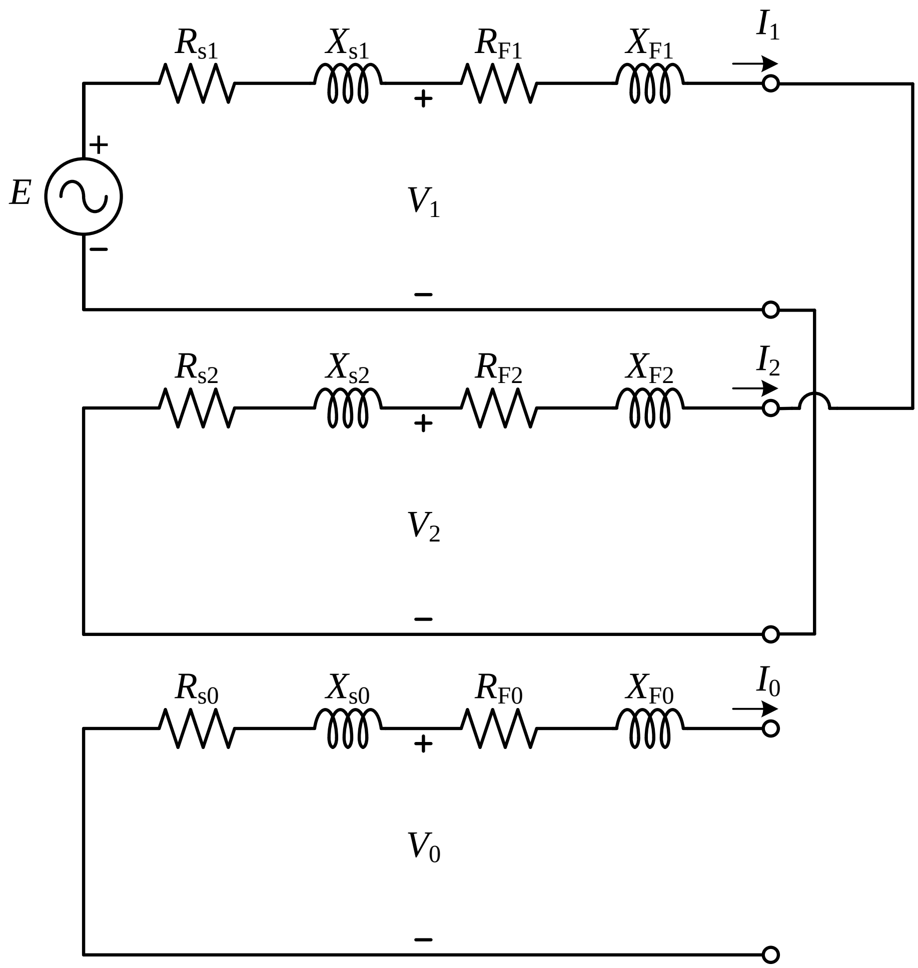

Fig. 6. Equivalent circuit for phase to phase fault

When E=1, the phase voltage obtained are

$$V_a = 1 - \frac{Z_{S1}-Z_{S2}}{(Z_{S1}+Z_{S2})+(Z_{F1}+Z_{F2})} \tag{14}$$

$$V_b = \alpha^2 - \frac{\alpha^2 Z_{S1} - \alpha Z_{S2}}{(Z_{S1} + Z_{S2}) + (Z_{F1} + Z_{F2})}$$

$$V_c = \alpha - \frac{\alpha Z_{S1} - \alpha^2 Z_{S2}}{(Z_{S1} + Z_{S2}) + (Z_{F1} + Z_{F2})}$$

The fault is assumed to be in between phases b and c. Therefore, a is the non-faulted phase, and b and c are the faulted phase. From equation (14), the voltage drop in the non-faulted phase depends on the difference between the positive and negative sequence source impedances. As these faults are normally equal, the voltage in the non-faulted phase will not be influenced by the phase to phase fault and under this assumption $Z_{s1} = Z_{s2}$,

$$V_a = 1$$

$$V_b = \alpha^2 - \frac{(\alpha^2 - \alpha) Z_{S1}}{2Z_{S1} + 2Z_{F1}} \tag{15}$$

$$V_c = \alpha + \frac{(\alpha^2 - \alpha) Z_{S1}}{2Z_{S1} + 2Z_{F1}}$$

The voltage drops in the faulted phases

$$V_b - V_c = (\alpha^2 - \alpha)\left[1 - \frac{Z_{F1} + Z_{F2}}{(Z_{S1} + Z_{S2}) + (Z_{F1} + Z_{F2})}\right] \tag{16}$$

3.1.2.3. Analysis of two Phase-to-Ground Faults

For a two phase to ground fault the three sequence networks are connected in parallel as shown Fig. 7.

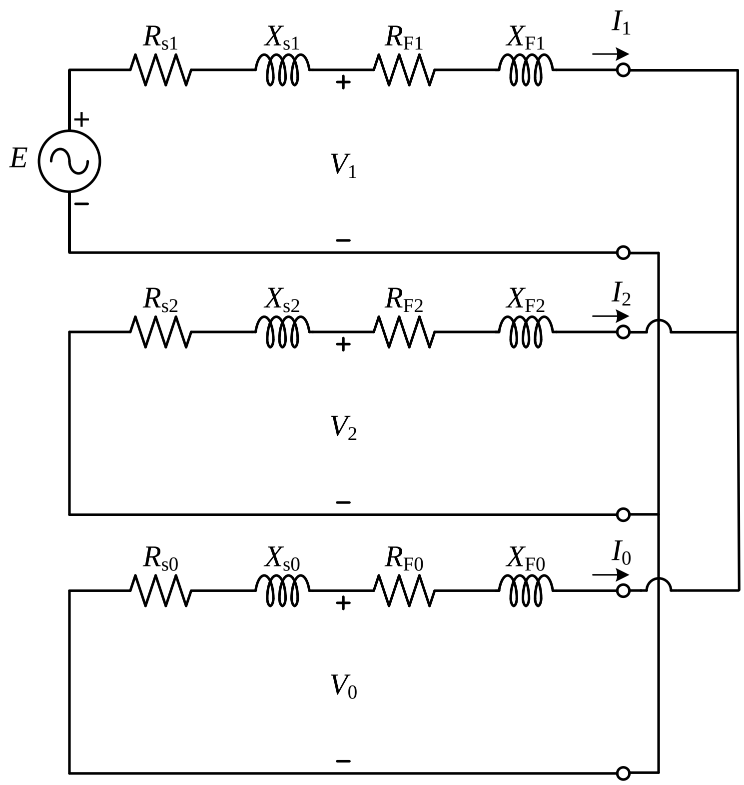

Fig. 7. Equivalent circuit for two phases to ground fault

The sequence voltages at the point of common coupling for a fault between phases b and c and ground are given by the following expressions

$$\begin{aligned} V_1 &= 1 - \frac{Z_{S1}(Z_{S0} + Z_{F0} + Z_{S2} + Z_{F2})}{D} \\ V_2 &= \frac{Z_{S2}(Z_{S0} + Z_{F0})}{D} \\ V_0 &= \frac{Z_{S0}(Z_{S2} + Z_{F2})}{D} \end{aligned} \tag{17}$$

The phase to ground voltages in the three phases are

$$\begin{aligned} V_a &= 1 - \frac{(Z_{S2} - Z_{S1})(Z_{S0} + Z_{F0})}{D} + \frac{(Z_{S0} - Z_{S1})(Z_{S2} + Z_{F2})}{D} \\ V_b &= \alpha^2 + \frac{(\alpha Z_{S2} - \alpha^2 Z_{S1})Z_0}{D} + \frac{(Z_{S0} - \alpha^2 Z_{S1})Z_2}{D} \\ V_c &= \alpha + \frac{(\alpha^2 Z_{S2} - \alpha Z_{s1})Z_0}{D} + \frac{(Z_{S0} - \alpha Z_{S1})Z_2}{D} \end{aligned} \tag{18}$$

Where $D = (Z_{S0} + Z_{F0})(Z_{S1} + Z_{F1} + Z_{S2} + Z_{F2}) + (Z_{S1} + Z_{F1})(Z_{S2} + Z_{F2})$

3.1.3. Effect of power system parameters on voltage sag

Power system parameters such as length of the transmission lines, fault impedance, X/R ratio, cross sectional area of the conductor have an influence on voltage sag.

3.1.3.1. Effect of Line length on voltage sag

The magnitude of the sag increases (sag becomes less severe) when the distance to the fault increases.

3.1.3.2. Effect of fault impedance on voltage sag

The magnitude of the voltage sag increases when the impedance of the fault increases.

3.1.3.3. Effect of X/R ratio on voltage sag

The magnitude of the voltage sag increases when the X/R ratio increases.

Results

4.1. Three Phase to Ground Fault

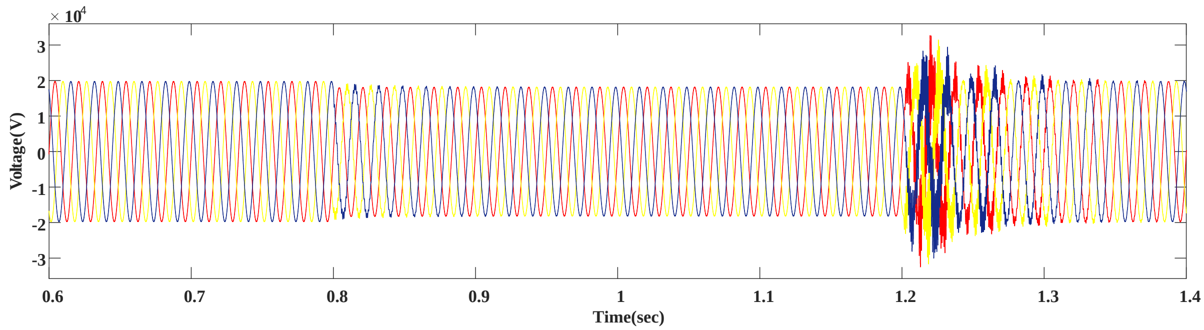

Fig. 8. Voltages at node 9 for ABC-G fault in line 8-9

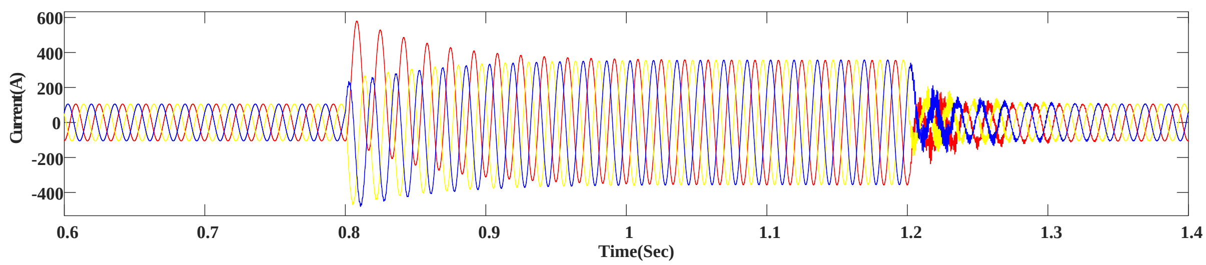

Fig. 9. Current at node 9 for ABC-G fault in line 8-9.

4.1.1. Analysis of Voltage Sag with Respect to line Length(L)

The system is simulated to analyze the voltage sag with respect to line length. The line length is varied from L= 50 kms-500 kms in a step of 50 Kms. It has been observed that voltage sag magnitude increases from 15.743 kV to 19.327kV as the line length increases from 50 kms - 500 kms. When the length of the line (L) is less, sag magnitude is less, and sag is more severe. If the line length is more, sag magnitude is more, and sag is less severe. Various results for line length variations is shown in Table II.

Table III: Sag Magnitude with respect to Line Length

Distance in Kms(L)	**Sag Magnitude(kV)**
50	15.473
100	17.118
150	17.823
200	18.119
250	18.528
300	18.857
350	19.045
400	19.092
450	19.233
500	19.327

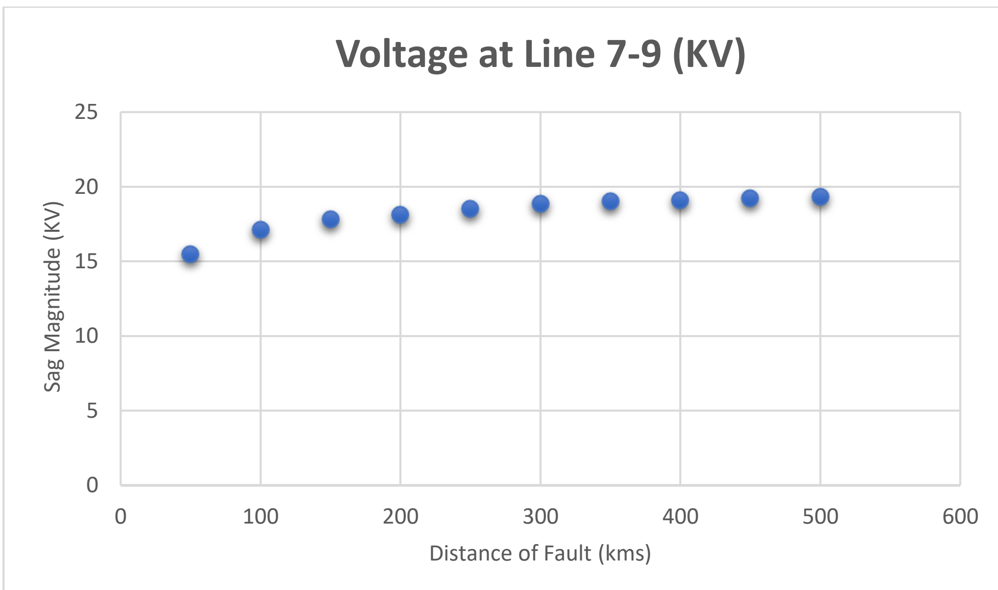

Fig.10. Sag magnitude versus variation in line length

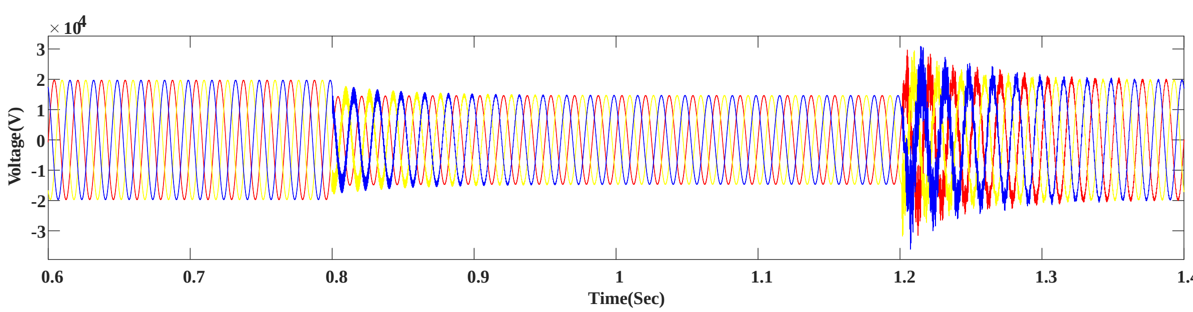

Fig. 11. Voltage at node 9 when distance is 50 Kms

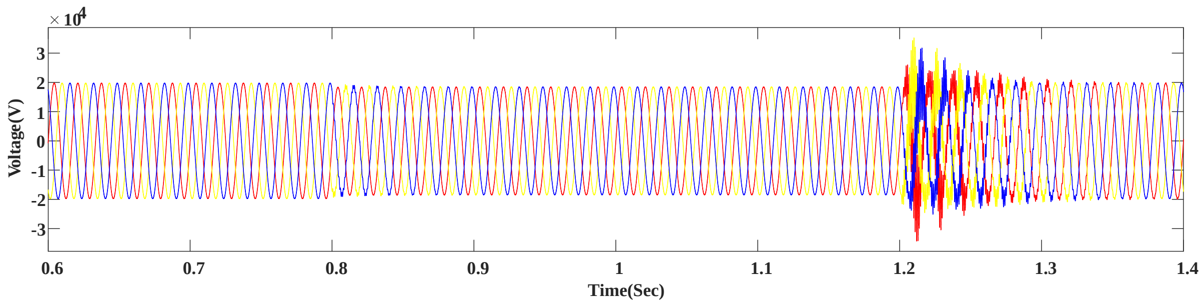

Fig. 12. Voltage at node 9 when distance is 250 Kms

From Fig. 11 and Fig. 12, depicts the voltage at node by considering the distance from fault position as 50 kms and 250 kms respectively. It is seen that, as the distance increases the magnitude of voltage sag increases and the sag becomes less severe. The magnitude of voltage is 15.473 kV, when the distance is considered as 50 kms whereas when the distance is considered as 250 kms, the magnitude of the voltage is 18.528kV.

4.1.2. Analysis of Voltage Sag with Respect to Fault Impedance (Z_F)

The system is simulated to analyze the voltage sag with respect to fault impedance. The fault impedance is varied from Z_F=1Ω-10Ω. It has been observed that voltage sag magnitude increases from 18.105kV to 19.303 kV as the fault impedance increases from 1Ω-10Ω. When the fault impedance (Z_F) is less, sag magnitude is less, and sag is more and severe. If the fault impedance is more, sag magnitude is more, and sag is less severe. Various results for fault impedance variation is shown in Table IV. and Fig. 13.

Table IV: Sag Magnitude with respect to Fault Impedance

Fault Impedance Z_F(Ω)	**Sag Magnitude(kV)**
1	18.105
2	18.341
3	18.481
4	18.669
5	18.716
6	18.811
7	18.998
8	19.139
9	19.223
10	19.303

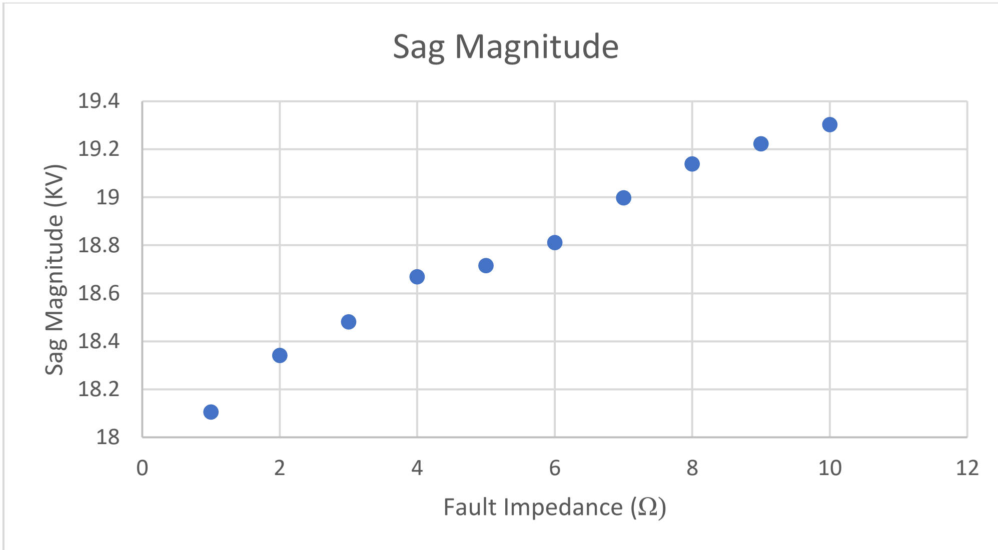

Fig.13. Sag magnitude versus time for variation in fault impedance.

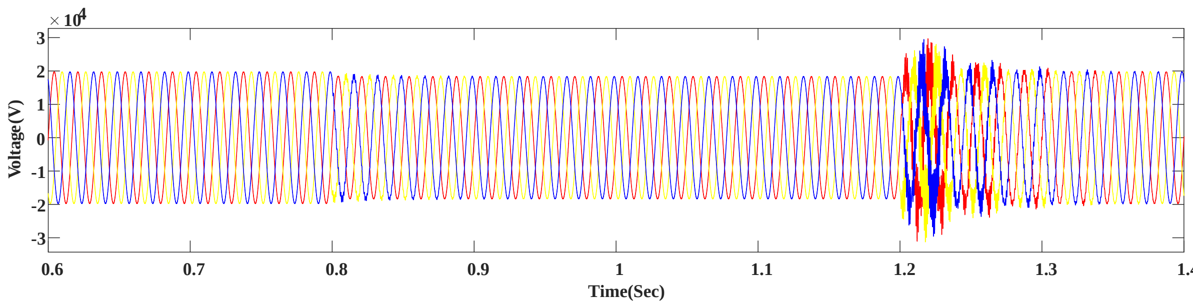

Fig. 14. Voltage at node 9 when the fault resistance is 2Ω.

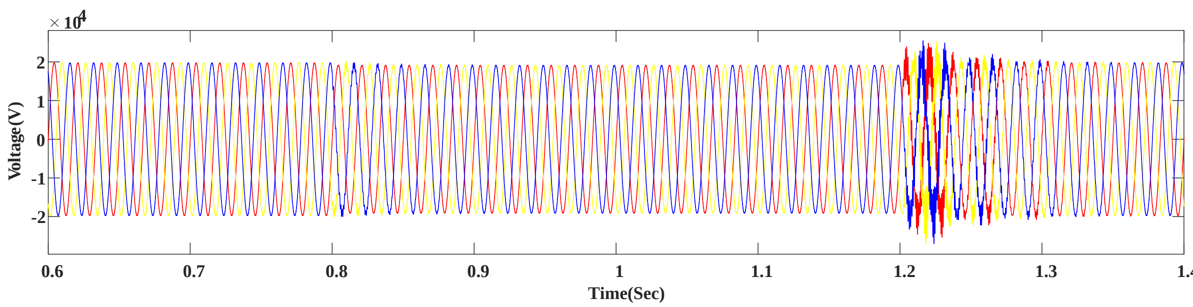

Fig. 15. Voltage at node 9 when the fault resistance is 8Ω.

From Fig. 14 and Fig. 15, depicts the voltage at node by considering the fault resistance as 2Ω and 8Ω kms respectively. It is seen that, as the fault resistance increases, the magnitude of voltage sag increases, and the sag becomes less severe. The magnitude of voltage is 18.341 kV when the fault resistance is considered as 2Ω whereas when the fault resistance is considered as 8Ω, the magnitude of the voltage is 19.139 kV.

4.1.3. Analysis of Voltage Sag with Respect to X/R ratio

The system is simulated to analyze the voltage sag with respect to X/R ratio. The X/R ratio is varied from X/R=1-10. It has been observed that voltage sag magnitude increases from 14.063 kV to 19.162 kV as the X/R ratio increases from 1-10. When the X/R ratio is less, sag magnitude is less, and sag is more and severe. If the X/R ratio is more, sag magnitude is more, and sag is less severe. Various results for X/R ratio variation is shown in Table V. And Fig. 16.

Table V: Sag Magnitude with respect to X/R ratio

X/R ratio	Sag Magnitude(kV)
1	14.063
2	16.718
3	17.635
4	18.105
5	18.387
6	18.692
7	18.810
8	18.927
9	19.045
10	19.162

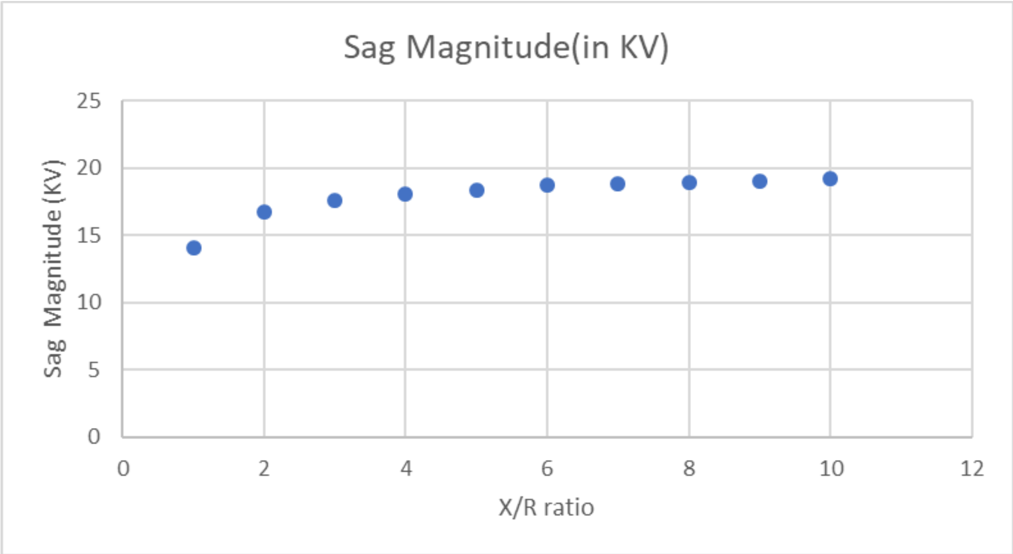

Fig.16. Sag magnitude versus time for variation in X/R ratio

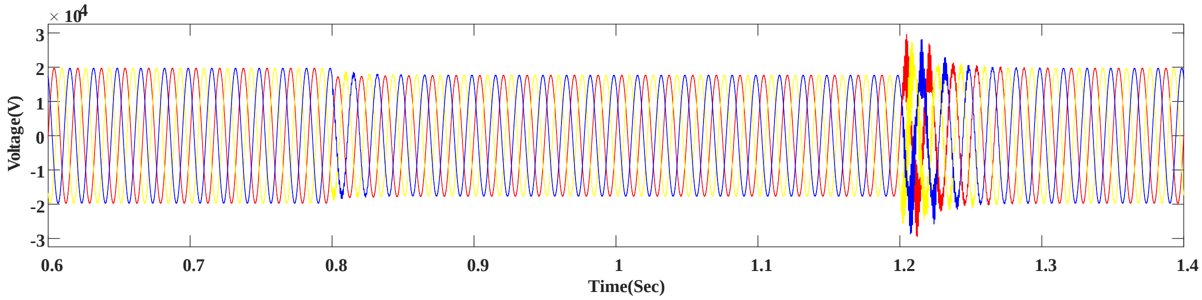

Fig. 17. Voltage at node 9 when the X/R ratio is 3.

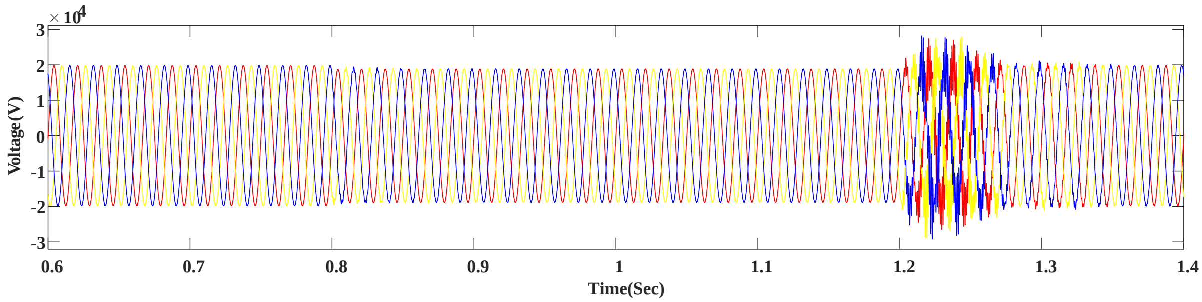

Fig. 18. Voltage at node 9 when the X/R ratio is 7.

From Fig. 17 and Fig. 18, depicts the voltage at node by considering the X/R ratio as 3 and 7 respectively. It is seen that as the X/R ratio increases the magnitude of voltage sag increases and the sag becomes less severe. The magnitude of voltage is 17.635 kV, when the X/R ratio is considered as 3 whereas when the X/R ratio is considered as 7 the magnitude of the voltage is 18.810 kV.

4.2. Single Line to Ground Fault

Fig. 19 and Fig. 20 depicts the fault voltages and fault current of phases a, b and c for single line to ground fault. For single to ground fault which occurs in phase a during the time interval of 0.8 seconds to 1.2 seconds, the phase voltage of phase a will reduce to zero, while the voltages in phase b and phase c will remains constant. Similarly, for phase currents, the current in the phase will increase during the fault interval while the currents in phase b and phase c will be equal to zero.

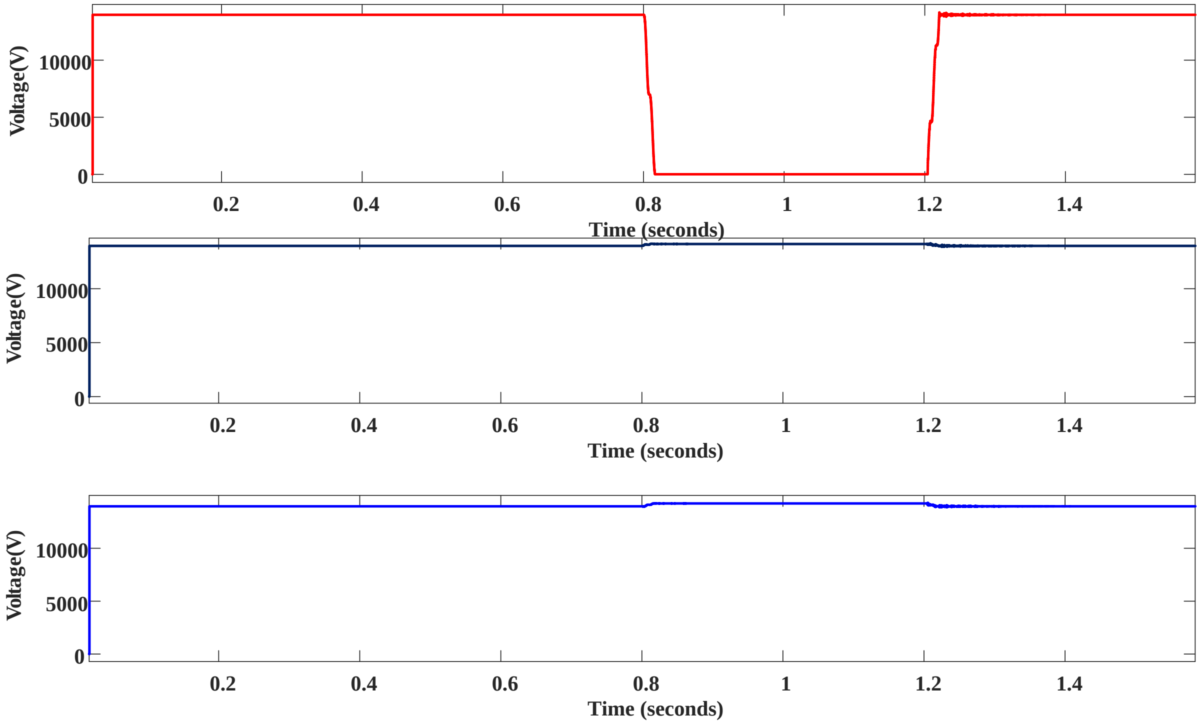

Fig. 19. Fault voltages for a, b and c for A-G fault

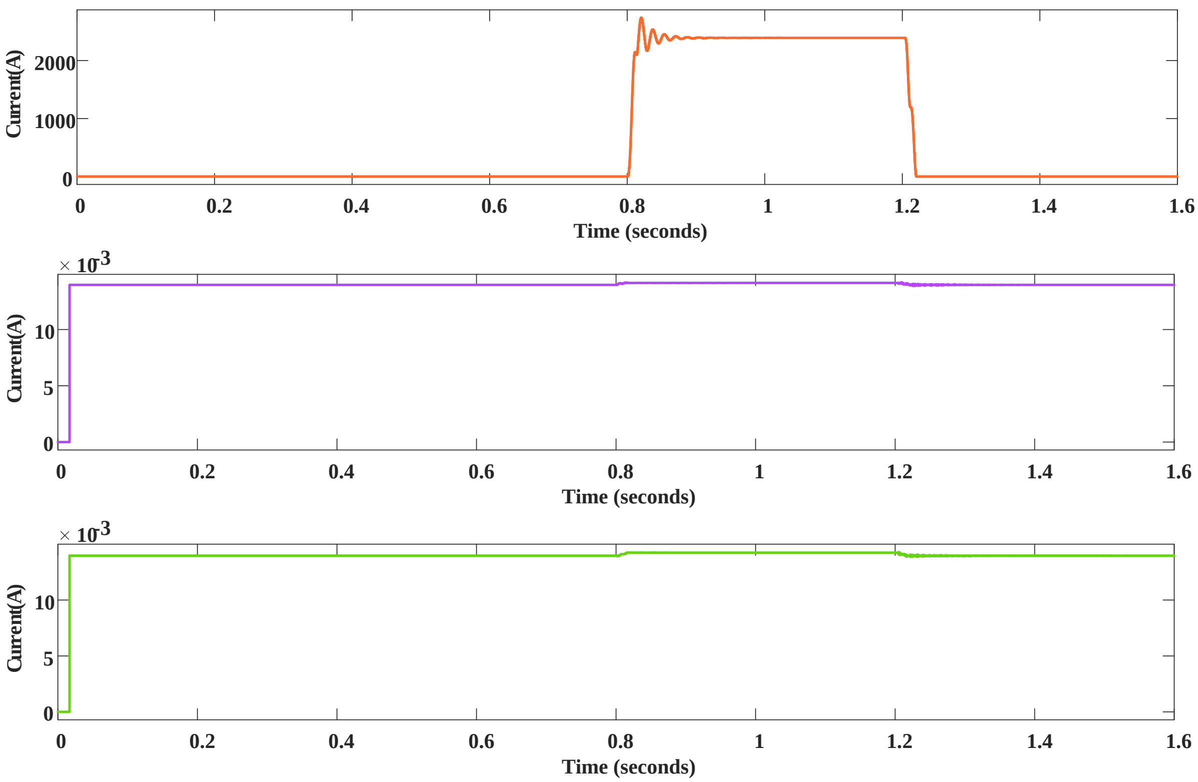

Fig. 20. Fault current for a, b and c for A-G fault

4.3. Line to Line Fault

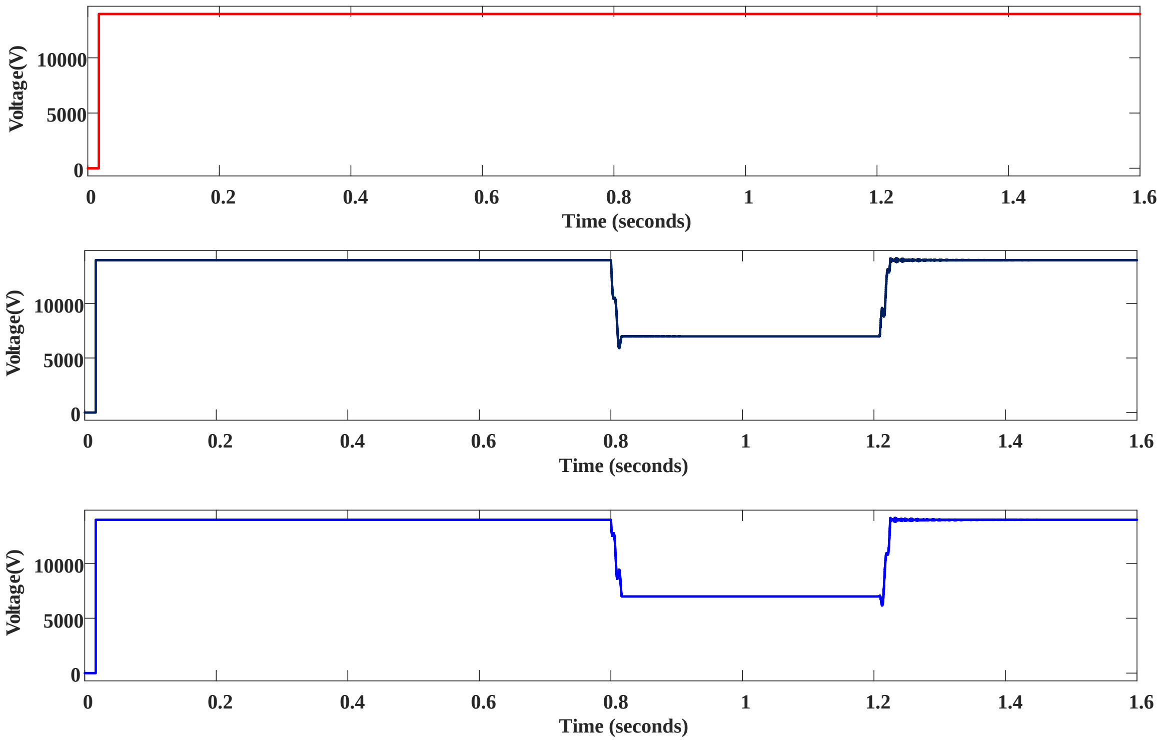

Fig. 21. Fault voltages for a, b and c for B-C fault

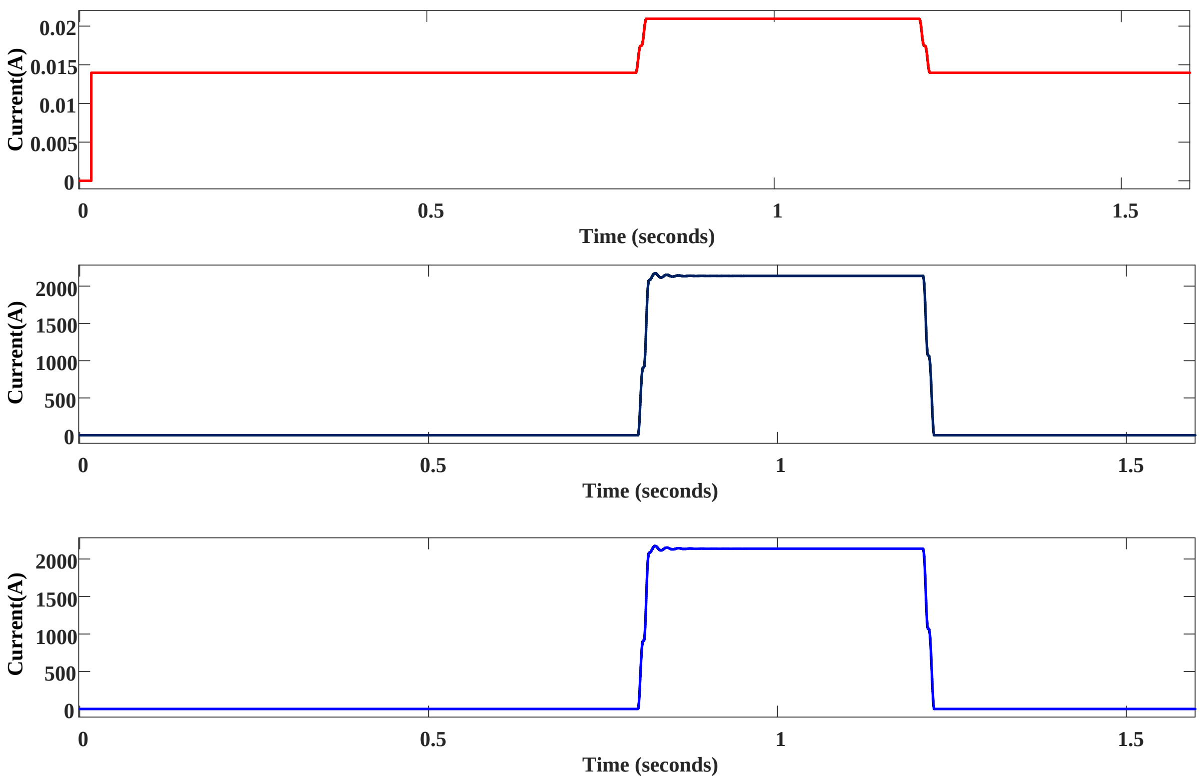

Fig. 22. Fault current for a, b and c for B-C fault

Fig. 21 and Fig. 22 depicts the fault voltages and fault current of phases a, b and c for line to line fault. For line to line fault which occurs in phases b and c during the time interval of 0.8 seconds to 1.2 seconds, the phase voltage of phases b and c(where fault occurs) will reduce around 6000 A. while the voltage in phase a will remains constant. Similarly, for phase currents, the current in the phases b and c will increase during the fault interval whereas the current in phase a will nearly be equal to zero.

4.3. Line to Line to Ground Fault

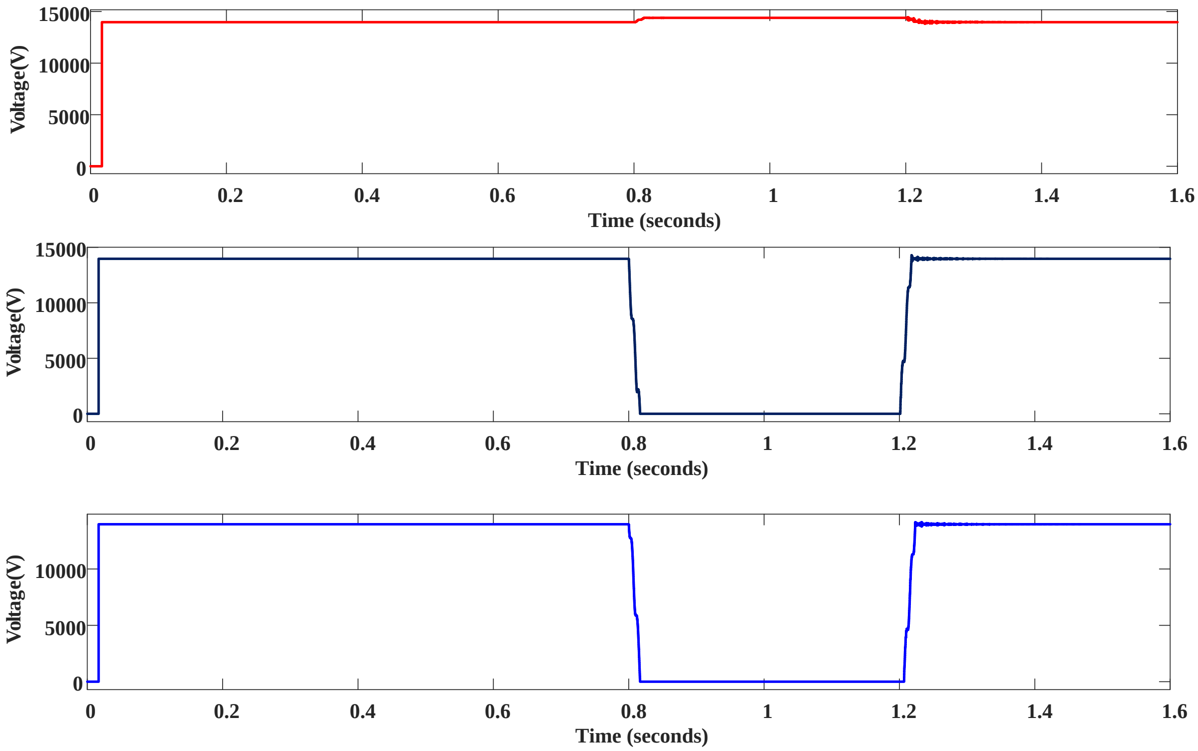

Fig. 23. Fault voltages for a, b and c for BC-G fault

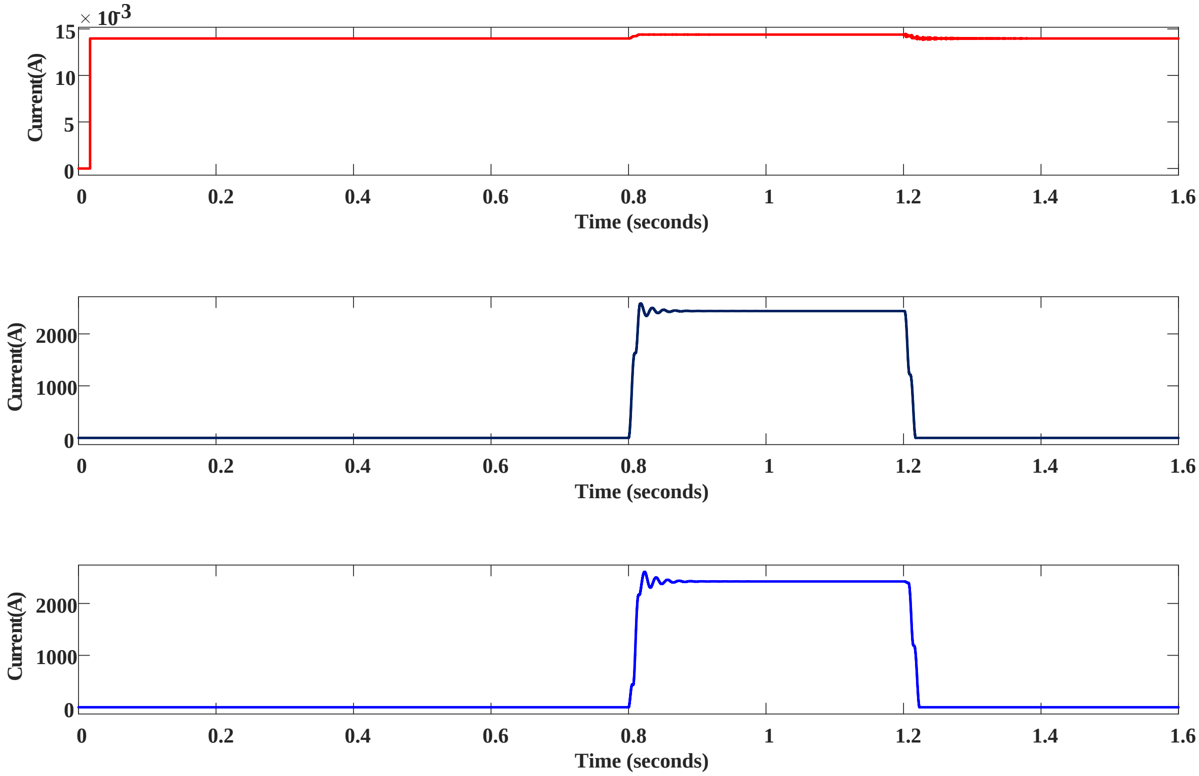

Fig. 24. Fault currents for a, b and c for BC-G fault

Fig. 23 and Fig. 24 depicts the fault voltages and fault current of phases a, b and c for line to line to ground fault. For line to line to ground fault which occurs in phases b and c during the time interval of 0.8 seconds to 1.2 seconds, the phase voltage of phases b and c (where fault occurs) will reduce to zero while the voltage in phase a will remains constant. Similarly, for phase currents, the current in the phases b and c will increase during the fault interval whereas the current in phase a will nearly be equal to zero.

Conclusion

This work discusses the different power quality problems generally arising in distribution system. A special focus has been made on analysis of voltage sag in terms of various power system parameters such as distance of fault from the point of common coupling (PCC), fault impedance and X/R ratio. The detailed performance analysis is carried out and the results are demonstrated. Further, the effect of symmetrical fault and unsymmetrical fault (line to ground, line to line and double line to ground faults) are realized on double circuit transmission line and its comprehensive analysis is provided in terms of sequence components which satisfies the mathematical evaluation.

All the above proposals are verified through an extensive digital simulation in MATLAB/ Simulink.

Recommendations for Future Work

This work successfully demonstrates the analysis of voltage sag in terms of different power system parameters using symmetrical and unsymmetrical faults. However, further it also creates some space for future investigations using new and modified algorithms.

The work analyses the effect of unsymmetrical faults in terms of sequence components. Since, the different types of voltage sag are already proposed, further investigations can be extended towards the unbalance sag analysis for these various types of voltage sag. Also, a critical analysis can be done in terms of different sag indices and few more parameters like phase angle jump, conductor area with overhead and underground cables.

Moreover, the mitigation techniques can also be implemented, and new proposal can be put forward to improve the dynamic performance of the system.

References

[1] Patne N.R and Thakre K.L, "Factor affecting characteristic of voltage sag due to fault in the power system," Serbian Journal of Electrical Engineering, 2008, 5(1),pp. 171-182.

[2] M.H.J. Bollen, "*Understanding Power Quality Problems Voltage sags & Interruptions,*" New York, IEEE Press, 2000.

[3] R.C. Dugan, F. McGranaghan and Beaty H.W, "Electrical Power System Quality, McGraw-Hill,"1996

[4] A. Ghosh and G. Ledwich, "*Power Quality Enhancement using Custom Power Devices*," Kluwer Academic Publishers, 2002.

[5] Martinez. J. A and Martim-Aenedo. J, "Voltage sag studies in Distribution Networks—Part I: System Modeling," *IEEE Trans. Power Delivery*, 2006,21 (3), pp.338-345.

[6] Martinez. J. A and Martim-Aenedo. J, "Voltage sag studies in Distribution Networks— Part II : Voltage Sag Assessment," *IEEE Trans. Power Delivery*, 2006, 21(3), pp. 1679-1688.

[7] Hochgraf. C and Lasseter. R," Statcom control for operation with unbalanced voltages," *IEEE Trans. On Power Delivery*, 1998, 13(2), pp.538-544.

[8] Aeloíza. E. C and Enjeti. P.N, "Analysis and Design of New Voltage Sag Compensator for Critical Loads in Electrical Power Distribution Systems," *IEEE Trans. On Industrial Application*, 2003, 39(4), pp.1143-1149.

[9] Nasiraghdam. H and Jalilian. A, "Balanced and Unbalanced voltage sag mitigation using DSTATCOM with linear & nonlinear loads", World Academy of Science, Engineering & Technology, 2007, pp.20-25.

[10] Moschakis M.N., and Hatziargyriou N.C., "Analytical Calculation and Stochastic Assessment of Voltage Sags," *IEEE Transactions on Power Delivery*, 2006, 21(3), pp. 1727-1734.

[11] Zhang L, Bollen M.H.J, "Characteristics of Voltage Dips (Sags) in Power Systems," *IEEE Transactions on Power Delivery*, 2000, 15(2), pp. 827-832.

[12] P.M. Anderson, "Analysis of Faulted power systems," IEEE press, New York, 1995.