Factor Affecting Characteristic of
Voltage Sag Due to Fault in the Power System

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Abstract: Faults in the power system are the most common reason for the occurrence of important power quality problem, voltage sag in the system. Due to increasing use of sensitive and sophisticated control in almost all modern devices at the industrial and residential consumer level, the Voltage sag which causes severe problems to these devices needs to be analyzed. Factors which affect the characteristics of voltage sag as a type of fault in the system, location of fault in the system, X/R ratio of transmission lines, type of transmission as single or double circuit transmission, Point on wave of sag initiation are studied in this paper. PSCAD/EMTDC is used as a simulation tool.

Keywords: Sag characteristic, Faults, X/R ratio, Point on wave of sag initiation.

1 Introduction

Any power problem manifested in voltage, current, or frequency deviation that results in failure or disoperation of customer equipment is a Power Quality problem. Nowadays load equipment is more sensitive to power quality variations than equipment used before, because in order to improve power system efficiency there is continuous growth in the application of devices with micro-processor and power electronics control. These devices are sensitive to power quality variations and they are the sources of power quality problems.

Out of different power quality problems, such as transients, voltage fluctuations, harmonics, inter-harmonics, voltage unbalance, waveform distor-tion, dc offset, noise, notches etc. voltage sag is the important [1]. Severe voltage sag may cause tripping of equipment which will result in stopping of the process which in tern leads to financial losses. Study says that voltage 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. These voltage sags cause the majority of equipment trips. The characteristic of sag is mainly defined by the magnitude of

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sag and its phase-angle [2]. The factors which affect these characteristics of voltage sag are studied in this paper. In this paper a study system used in [3] is simulated using PSCAD/EMTDC software package as a tool for simulation [4].

2   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. In the IEEE Standard 1159-1995, the term "sag" is defined as a decrease in rms voltage to values between 0.1 to 0.9 p.u., for durations of 0.5 cycles to 1 min. Voltage sag due to faults in power systems are studied in this paper.

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

1. Magnitude of sag
2. Three phase balance
3. Duration of sag
4. Phase-angle jump.

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

2. **Three phase unbalance:** In the power system depending on the type of fault the sag in all three phases can be balanced or unbalanced. For a three phase short circuit in the system during a fault all three phase sags will be of equal magnitude called balanced fault. 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 three phases will be unbalanced in nature.

3. **Duration of fault:** The duration of sag is mainly determined by the fault-clearing time. For fast clearing of the fault, duration of sag will be less and vice-versa.

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 a difference in the *X/R* ratio between the source and the feeder. Phase-angle jumps are not of concern for most equipment but power electronic converters using phase angle information for their switching may be affected.
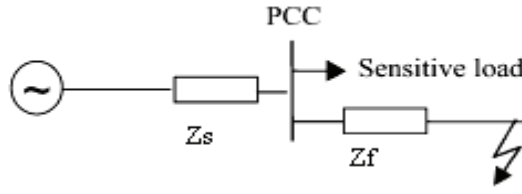
Fig. 1 – *Voltage divider model.*

2 Voltage Sag Determination

The basis of voltage sag determination is fault analysis. With accurate information of all impedances including positive, negative and zero sequence resistances and reactances of the power components, and fault impedances, the system can be simulated to predict the sag characteristic at the node where the sensitive load is connected. To quantify sag in a radial system, the voltage divider model is shown in Fig.1. In this figure Z_s is source impedance at the point of common coupling (PCC) and Z_f is the impedance between PCC and the fault. The PCC is the point from which both the fault and the load is fed. In the voltage divider model the load current before as well as during a fault is neglected. The voltage at the PCC, which is the voltage at the terminal of sensitive equipment, will be as in (1)

$$\overline{V}_{sag} = \overline{E}\,\frac{\overline{Z}_f}{\overline{Z}_f + \overline{Z}_s}. \tag{1}$$

With the assumption that the prefault voltage is 1 pu., $E = 1$. Now the expression of sag will be as (2)

$$\overline{V}_{sag} = \frac{\overline{Z}_f}{\overline{Z}_f + \overline{Z}_s}. \tag{2}$$

Here fault impedance is included in feeder impedance Z_f.

Equation (2) can be used to calculate sag as a function of the distance to the fault. Let $Z_f = zl$, with z as the impedance of the feeder per unit length and l as the distance between the fault and the PCC. Equation (2) will be now,

$$\overline{V}_{sag} = \frac{\overline{zl}}{\overline{zl} + \overline{Z}_s}. \tag{3}$$

In the above equations V_{sag}, Z_f, Z_s and zl are complex quantities.

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

$$\left| V_{sag} \right| = \frac{|zl|}{|zl| + |Z_s|}. \tag{4}$$

And the phase-angle jump associated with voltage sag at PCC is given by

$$\Delta\Phi = \arctan\frac{X_f}{R_f} - \arctan\frac{X_s + X_f}{R_s + R_f}, \tag{5}$$

where $Z_f = X_f + jR_f$ and $Z_s = R_s + jX_s$.

Thus the phase-angle jump will be present if the *X/R* ratio of the source and the feeder are different.

Duration of sag is determined by the fault clearing time which is considered constant for this study.

For the three phase to ground faults, i.e. balanced faults, the voltage sag (during fault voltage) will be balanced in all phases and its calculations can be carried out on a single phase basis using positive sequence values of all parameters.

But for unbalanced faults the voltage divider model has to be split into its three components: a positive-sequence network, a negative-sequence network and a zero sequence network. The three component networks have to be connected into equivalent circuits at the fault position. The connection of the component networks depends on the fault type [2].

3   Factors Affecting Sag Characteristics

1. Type of fault: Type of fault in the power system is the first factor which affects sag characteristic. Depending whether the fault type is balanced or unbalanced, sag will be balanced or unbalanced in all three phases. The magnitude and phase angle of sag will also depend on the type of fault [2].

2. Location of fault: Along with the type, the location of faults in the system have a great impact on the magnitude as well as the phase-angle jump of the sag. The sensitive load is at distribution level but the faults at distribution as well as at hundreds of kilometres away at the transmission level will have an influence on the magnitude as well as the phase-angle of the sag at PCC [2].

3. *X/R* ratio of the lines: With change in the *X/R* ratio of the line there is change in the *X/R* ratio of fault to source impedance which will affect the magnitude as well as phase-angle jump [1]. To study the effect, the *X/R* ratio of one of the lines can be changed and the magnitude and the phase angle jump of voltage at observed node can be analyzed.

4. 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. As most of the faults are associated with a flashover, they are more likely to occur near the voltage maximum than near the voltage zero. Upward crossing of the fundamental voltage is an obvious choice for reference to quantify the point of wave initiation [2]. With change in point on wave of sag initiation it is expected that the phase-angle jump will change more as compared to the magnitude of sag.

5. Single/Double circuit transmission: In the power system it is common practice to have double circuit transmission to improve reliability. Another interesting analysis on studying the influence of disconnection of lines on the sag magnitude and phase angle can be carried out by keeping any the transmission line as a double circuit. The results are compared with single circuit configuration of the same line. With changes in the transmission configuration basically there will be change in X/R ratio of impedances, which will affect the characteristic of sag.

Table 1
Transmission and distribution line impedances.

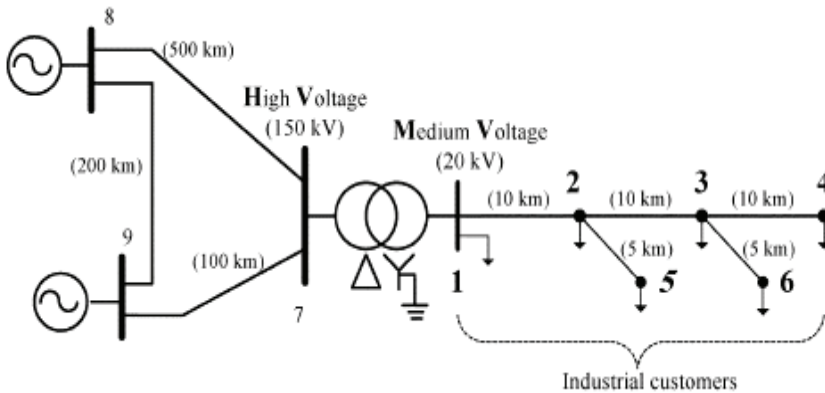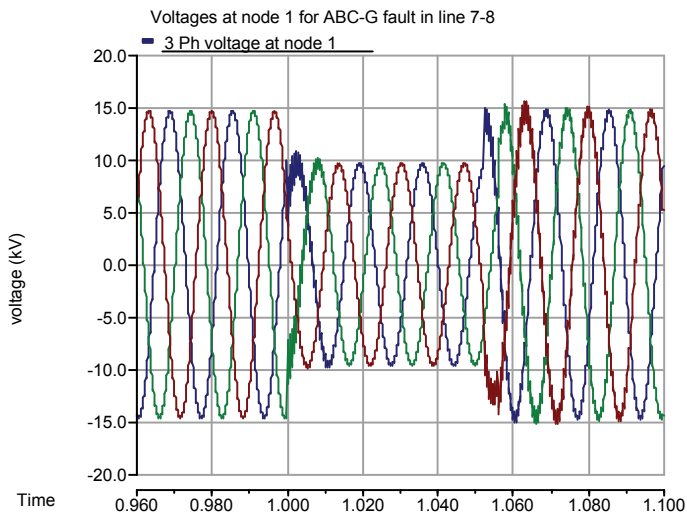| Line(s)	Positive & Negative sequence impedances (Ω/km)	Zero sequence impedance (Ω/km)
1-2,2-3,3-4	0.22+j0.37	0.37+j1.56
2-5.3-6	1.26+j0.42	1.37_j1067
7-8,8-9,7-9	0.097+j0.39	0.497+j2.349

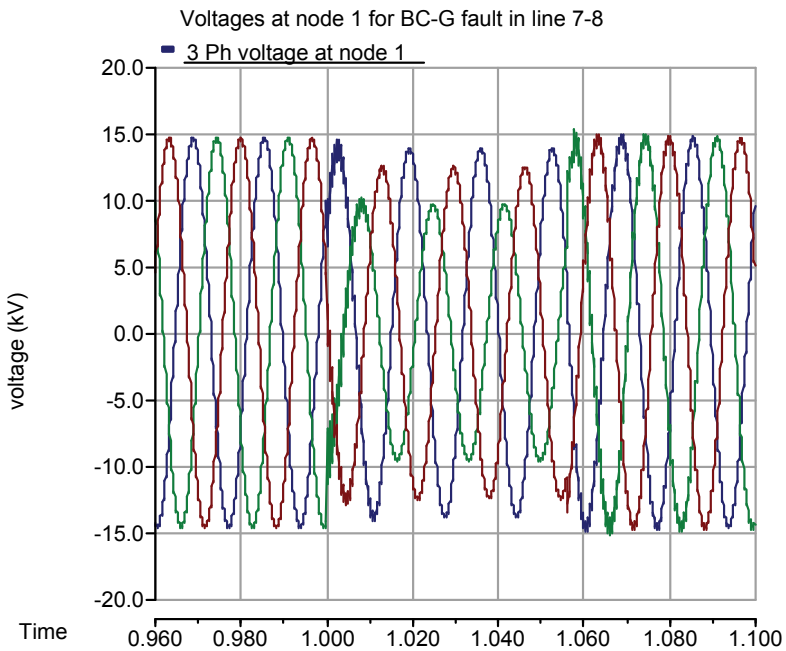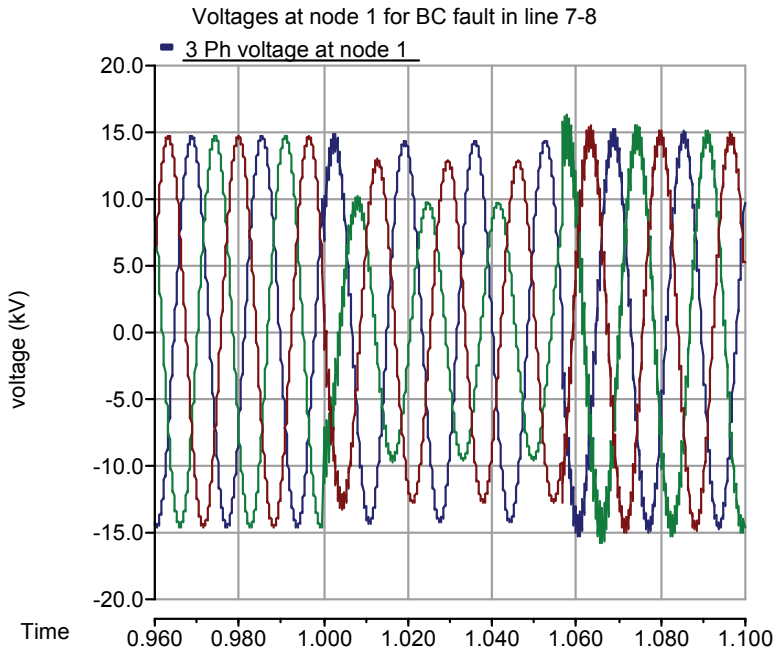**Fig. 2** – *System under study.*

4   Case Study

A diagram of the test system is shown in Fig. 2 [3]. Six critical industrial customers are connected at six nodes of the same 20 kV distribution line(40 km in total length) through a solidly grounded delta-wye transformer. It should be noted that this network represents a typical distribution network with several hundred nodes spread along the main feeder and lateral but only the node supplying the most critical customer needs to be examined. The equivalent transmission system consists of three 150 kV lines and is relatively of large size (800 km in total length) to take into account the fact that faults at 100 km away from the critical customer will cause severe sags. Data for the transmission and distribution lines is as given in **Table 1**. In [3] this system is solved analytically. Here it is simulated using PSCAD/EMTDC software package with the Fault position method. To study the effect of factors affecting the sag characteristic, the system is simulated by taking that particular factor into consideration. In order to study the effect of all the said parameters line 7-8 is taken as the line under consideration and the node 1 voltage is the voltage of interest where the sensitive load is connected. The most sagged voltage for a particular fault is plotted. For an A-G fault the most sagged voltage is of phase A, for BC and BC-G fault the most sagged voltage is of phase B.

1. Type of fault: Depending on the type of fault, sag can be balanced or unbalanced. To study that different faults are created in the line 7-8 at a fixed distance of 50% of its complete length. Naturally for the Three phase to ground (ABC-G) fault the sag is symmetrical (balanced) in all three phases, whereas for unbalanced faults like A-G, B-C, BC-G the sag is unsymmetrical (unbalanced) in all three phases, as shown in Fig. 3.

Voltages at node 1 for ABC-G fault in line 7-8

Voltages at node 1 for BC fault in line 7-8

■ 3 Ph voltage at node 1

Voltages at node 1 for BC-G fault in line 7-8

■ 3 Ph voltage at node 1

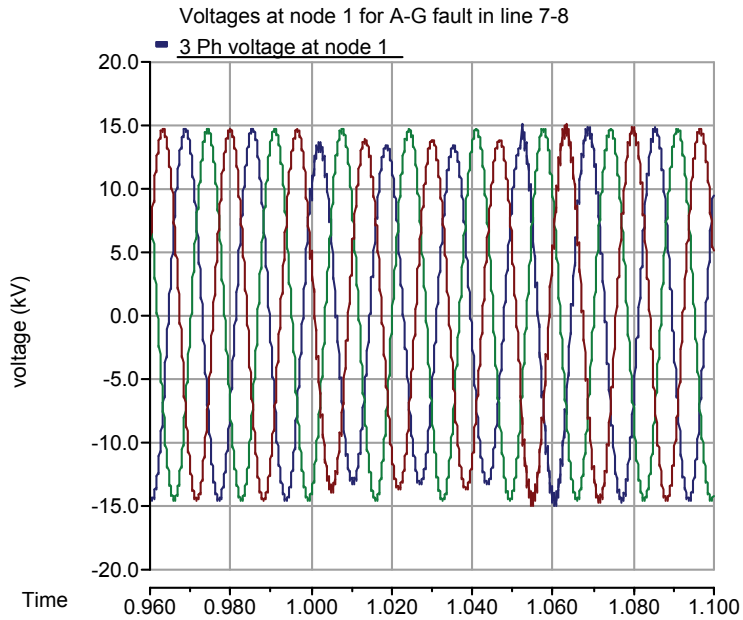Voltages at node 1 for A-G fault in line 7-8

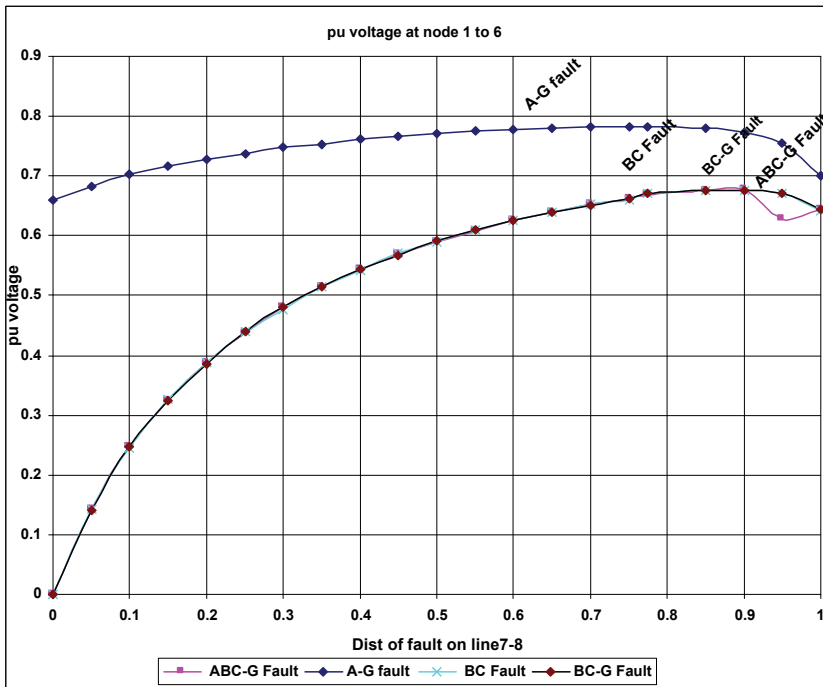**Fig. 3** – *Balanced and unbalanced sags due to faults in line 7-8.*

Fig. 4 – *Magnitude of sag vs. distance of fault for different types of faults.*

2. Location of fault: To study the effect of location of fault on the characteristic of sag, different types of faults are created at different locations along the transmission line 7-8 and the results of sag magnitude and phase-angle jumps are plotted as a function of the distance of that line in Figs. 4 and 5 respectively. Faults near the PCC have prominent effect on sag.

3. *X/R* ratio of the line: To study the effect of changes in *X/R* ratio, the *X/R* ratio of line 7-8 is changed and the magnitude and phase angle jump of voltage at node 1 is as shown in Figs. 6 and 7.

4. Point on wave of sag initiation: To study the effect of this factor, along the line 7-8 the A-G fault is created at two different instants, one near zero crossing of the voltage wave and the second at the maximum value of the voltage. The results of sag magnitude and phase-angle jump are as shown in Figs. 8 and 9 respectively. This factor has more effect on the phase-angle jump compared to the sag magnitude.

5. Single/Double circuit transmission: To study the effect of the transmission configuration as a single or double circuit transmission, the configuration of line 8-9 in the system is changed and with A-G fault on line 7-8 which is under consideration, the sag magnitude and phase-angle jump is studied and is plotted in Figs. 10 and 11 respectively.
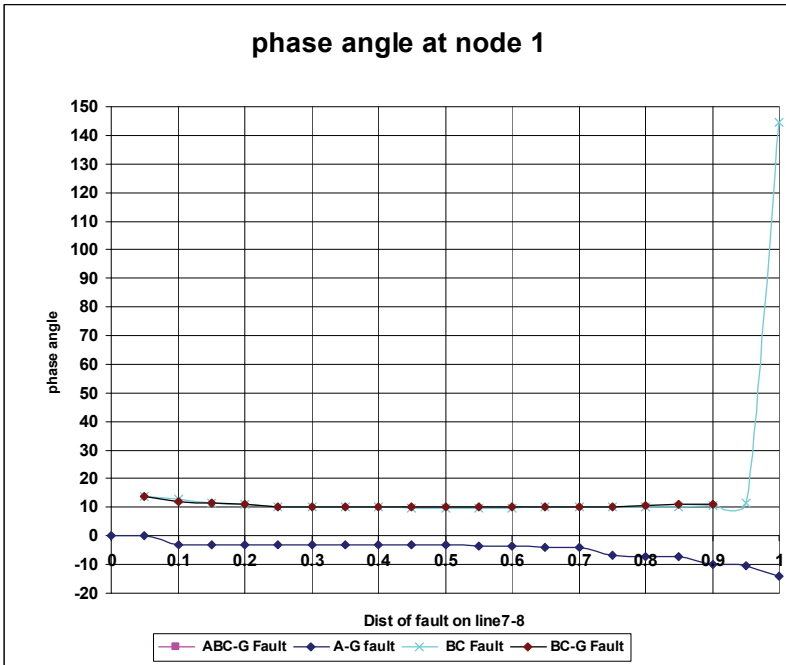

Fig. 5 – *Phase-angle of sag vs. distance of fault for different types of faults.*
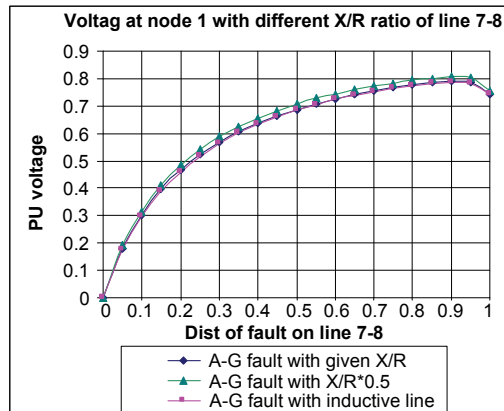
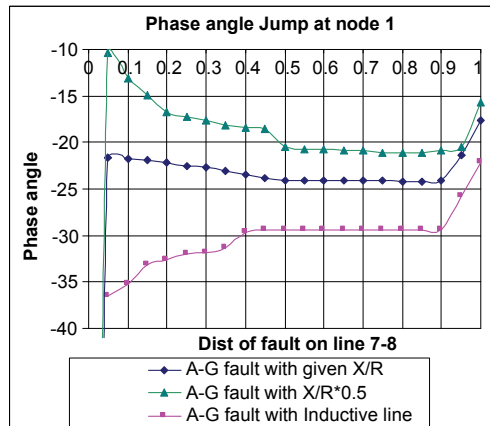**Fig. 6** – *Effect of X/R ratio on the magnitude of sag.*

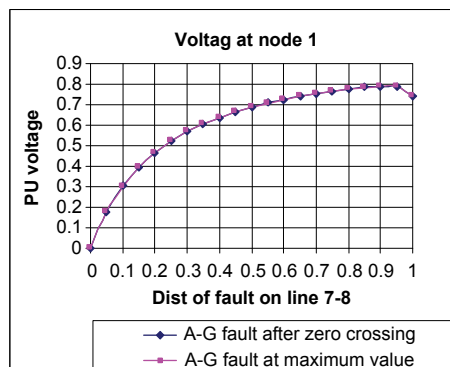**Fig. 7** – *Effect of X/R ratio on the phase-angle jump of sag.*

Fig. 8 – *Effect of points on the wave of sag initiation on the magnitude of sag.*
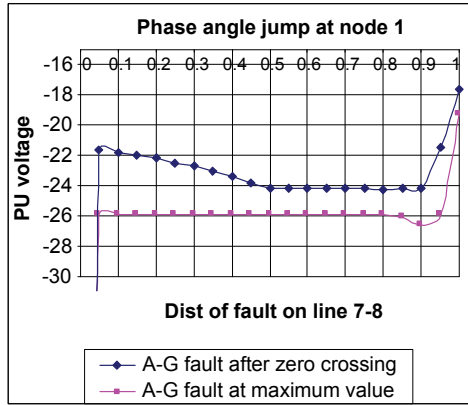
Fig. 9 – *Effect of points on the wave of sag initiation on the phase-angle jump of sag.*
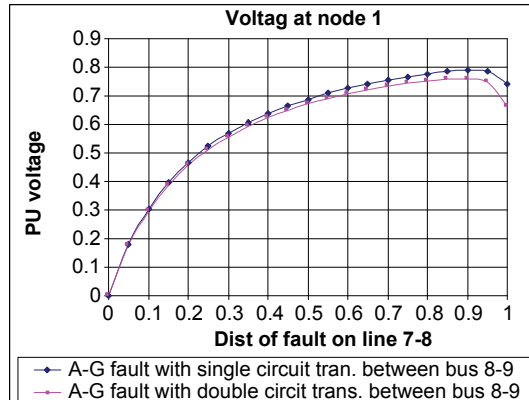
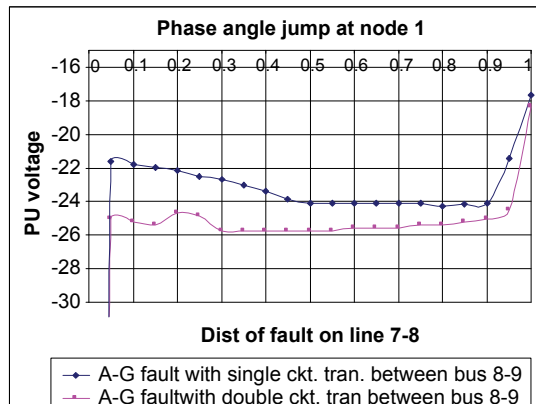**Fig. 10** – *Effect of the transmission configuration on the magnitude of sag.*

Fig. 11 – *Effect of the transmission configuration on the phase-angle jump of sag.*

5 Conclusion

Faults in the system are the main reason for voltage sags in the power system. Along with the type and location of faults in the system characteristics of sag created in the system due to faults depend on the other parameters of circuit configuration, as the *X*/*R* ratio of lines, point on wave of sag initiation, single or double circuit transmission. Sag may cause tripping of sensitive loads if its magnitude is below the critical voltage that equipment can sustain. These factors will also affect that number of trips of the equipment. So it is necessary to take all these factors into account while performing a study related to voltage sag.

6 References

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