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Effect of transformer on stochastic estimation of voltage sag due to faults in the power system: a PSCAD/EMTDC simulation

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Abstract

Voltage sags in the electric power system are mostly due to faults in the power system. Voltage sag is characterized by its magnitude (the retained voltage), phase-angle jump, unbalance in the sag in the three phases, and duration. Type of transformers in the electrical system is the important parameter influencing the characteristic of sag at the node where sensitive loads are connected. For sensitive loads it is necessary to estimate how many times in a year the voltage at their terminal will experience sag to avoid tripping of operation. In this paper the effect of transformer on stochastic estimation of voltage sag is studied. Several stochastic methods for the estimation of number of sags have been developed in recent years. Various methods of sag prediction require lengthy programming or calculations. In the present work the PSCAD/EMTDC software package is used to estimate number of sags assuming uniform distribution of faults along the lines.

Key Words: *Faults, voltage sag, type of transformer, PSCAD/EMTDC; uniform fault distribution, number of sags.*

1. Introduction

The Power Quality and Reliability problem affects industry most in terms of financial loss. According to the results of the EPRI Distribution Power Quality (DPQ) study conducted several years ago [1], only 3% of events experienced by distribution grid industrial customers were outages. The vast majority of the offending "events" were found to be short duration disturbances, primarily voltage sags and momentary loss of power.

Voltage sag is a sudden short duration drop of the root mean square (RMS) voltage, followed by a recovery within 1 minute [2, 3]. Voltage sags are generally created on the electric system when faults occur due to lightning, accidental shorting of the phases by trees, animals, birds, human error such as digging underground lines or automobiles hitting electric poles, and failure of electrical equipment. Sags can also occur when large motor loads are started, or due to operation of certain types of electrical equipment such as welders, arc furnaces, smelters, etc. In the case of a fault, the utility would detect the resulting over-current, and perform a feeder breaker re-closure operation that disconnects the down-stream loads from the system, in its attempt to clear the fault and therefore maintain the reliability (availability) of the electric supply to the majority of its customers. Thus the downstream customers experience voltage sag.

Characteristic of voltage sag at the terminals of sensitive equipment in the customer premises will depend upon nature of the fault, distance of the fault from terminals of the sensitive load, and on the type of transformer in between. A power system cannot be imagined without a transformer and the great impact this transformer can have on the sag characteristics. The number of sags experienced by sensitive equipment is highly dependent on the type of transformer [3], [5].

System performance, expressed as the expected number of voltage sags in the site, can be estimated through monitoring the supply or through stochastic prediction methods. Even though monitoring is a direct way to get information about system performance, its important drawback is that it is a very lengthy process [3]. Several stochastic prediction methods have been proposed, like method of critical distance, method of fault position, Monte Carlo method and analytical approach [3, 4, 6–10]. The method of fault position is most suitable for implementation in a software tool [3].

Investigators in [11–13] looked into the scope and advantage of an EMTP-based procedure for voltage sag analysis. In this paper PSCAD/EMTDC [14] has been used to perform the modeling and analysis of power system used in [6] with delta-star transformer, for estimation of number of sags due to different types of faults, on different lines, at the sensitive node in the system for uniform distribution of faults along the lines [4]. Then, to see the effect of the transformer on the estimated number of sags, the system is simulated with other types of transformers [3].

2. PSCAD/EMTDC simuation package

PSCAD/EMTDC is an industry standard simulation tool for studying the transient behavior of electric networks. Its graphical user interface enables all the aspects of the simulation to be conducted within a single integrated environment, including circuit assembly, run-time control, analysis of results, and reporting. Its comprehensive library model supports most ac and dc power plant components and control, in such a way that Power system can be modeled with speed and precision. It provides a powerful resource for assessing the impact of new power technologies in the power network. Simplicity is one of the outstanding features of PSCAD/EMTDC. It integrates many modeling capabilities and highly complex algorithms and methods are transparent to the user, leaving them free to concentrate their efforts on the analysis of results rather than on mathematical modeling. For the purpose of modeling user can either use the large base of build-in components available in PSCAD/EMTDC or their own user-defined models [12, 14].

3. Voltage sag

Short-duration under-voltages are called "Voltage sags" or "Voltage dips." Voltage sag is a reduction in supply voltage followed by voltage recovery after a short period of time. In IEEE Standard 1159-1995, the term "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]. Voltage sag only due to faults in the power system is studied in this paper.

Voltage sag is characterized in terms of the parameters [3]: Magnitude of sag, Three phase balance, Duration of sag, Phase-angle jump.

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

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

Duration of fault: The duration of sag is mainly determined by the fault-clearing time. A fast-clearing fault results in less sag, and a slow-cleared fault results in deeper sag.

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 X/R ratio between the source and the feeder. Phase-angle jumps are not of concern for most equipment, but power electronics converters using phase angle information for their firing instants may be affected.

4. Voltage sag due to fault

The voltage sag induced due to fault in the power system is studied in this paper. In general, voltage sag is characterized by sag magnitude, phase angle jump, duration of sag and three phase balance. The sag magnitude is the lowest per unit RMS remaining voltage during the event of sag i.e. fault in this case. 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 X/R ratio between the source and the feeder. The duration of sag is mainly determined by the fault-clearing time. In the power system depending on the type of fault the sag in all the three phases can be balanced or unbalanced.

The basis of voltage sag determination is fault analysis. With accurate information of all impedances, including the positive, negative and zero sequence resistances and reactances of the power components, and the 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 as shown in Figure 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 fault is neglected. The voltage at the PCC, which is voltage at the terminal of sensitive equipment, will be

$$\overrightarrow{V_{sag}} = \overrightarrow{E} * \overrightarrow{Z_f}/(\overrightarrow{Z_f} + \overrightarrow{Z_s}) \tag{1}$$

With the assumption that prefault voltage is 1 pu., $E = 1$, now the expression of sag is

$$\overrightarrow{V_{sag}} = \overrightarrow{Z_f}/(\overrightarrow{Z_f} + \overrightarrow{Z_s}). \tag{2}$$

Here fault impedance is included in feeder impedance Z_f.

Equation (2) can be used to calculate the 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

$$\overrightarrow{V_{sag}} = \overrightarrow{zl}/(\overrightarrow{Z_s} + \overrightarrow{zl}). \tag{3}$$

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

$$|V_{sag}| = |Z_f| \, / \, |(Z_f + Z_s)| \,, \tag{4}$$

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

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

where $Z_f = R_f + jX_f$ 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 [3].

Duration of sag is determined by fault clearing time, and is considered to be 0.05 seconds in this study.

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

For unbalanced faults the voltage divider model has to be split into three components: a positive-sequence network, a negative-sequence network and a zero-sequence network. The three component networks have to be connected into an equivalent circuit at the fault position. The connection of the component networks depends on the fault type [3].

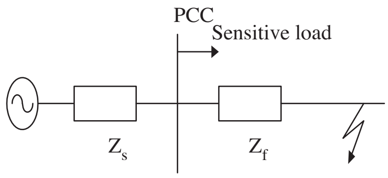

Figure 1. Voltage divider model to quantify sag in a radial system. Z_s is source impedance at the point of common coupling (PCC) and Z_f is the impedance between PCC and the fault.

Faults along transmission lines can be considered using the fault position method. A number of discrete fault positions are selected along the system lines. Consider, for illustration, the transmission line between buses k and j in Figure 2 [7], in which the location at which a fault occurs is identified by means of parameter ψ. This parameter varies from 0 to 1, as fault position moves from bus k to bus j; in this way ψ is defined as

$$\psi = \frac{L_{kp}}{L_{kj}}, \tag{6}$$

where L_{kp} is the distance from bus k to location p, where the fault occurs; and L_{kj} is the length of transmission line k-j.

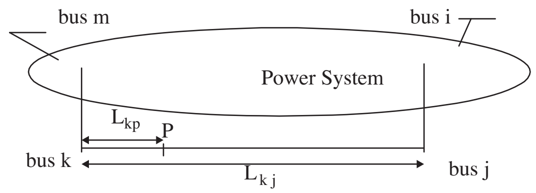

Figure 2. Electrical System transmission line between bus k and bus j.

When the fault takes place at a position p between k and j, the voltage at m will be given by

$$V_m^{012} = V_m^{012pf} - \left[Z_{mp}^{012}\right] I_p^{012}, \tag{7}$$

where

$$V_m^{012} = \begin{bmatrix} V_m^0 \\ V_m^1 \\ V_m^2 \end{bmatrix},$$

where the terms V_m^0, V_m^1, and V_m^2 are zero, positive and negative sequence voltage phasors at m, respectively. For prefault conditions, we also define

$$V_m^{012pf} = \begin{bmatrix} V_m^{0pf} \\ V_m^{1pf} \\ V_m^{2pf} \end{bmatrix},$$

where the terms $V_m^{0\text{pf}}, V_m^{1\text{pf}}$, and $V_m^{2\text{pf}}$ are zero, positive and negative sequence prefault voltage phasors at m, respectively. The transfer complex matrix is

$$\left[Z_{mp}^{012}\right] = \begin{bmatrix} Z_{mp}^o & 0 & 0 \\ 0 & Z_{mp}^1 & 0 \\ 0 & 0 & Z_{mp}^2 \end{bmatrix}$$

where the terms Z_{mp}^0, Z_{mp}^1, and Z_{mp}^2 are the transfer complex impedances between m and fictitious bus p in the Z matrix. The position of p is defined by the value of parameter ψ, where $0 \leq \psi \leq 1$. The current phasor at location p is

$$I_p^{012pf} = \begin{bmatrix} I_p^0 \\ I_p^1 \\ I_p^2 \end{bmatrix}$$

where I_p^0, I_p^1, and I_p^2 are zero, positive and negative sequence fault current phasors at p, respectively.

Expressions relating the transfer and driving point impedances of a location along the transmission line to the transfer and driving point impedances of buses at the end of that transmission line, and of the line impedances in generalized form, are

$$\left[Z_{mp}^{012}\right] = (1-\psi)\left[Z_{mk}^{012}\right] + \psi\left[Z_{mj}^{012}\right] \tag{8}$$

$$\left[Z_{pp}^{012}\right] = (1-\psi)^2\left[Z_{kk}^{012}\right] + \psi^2\left[Z_{jj}^{012}\right] + 2\psi(1-\psi)\left[Z_{kj}^{012}\right] + \psi(1-\psi)\left[Z_{kj}^{012}\right], \tag{9}$$

where $\left[Z_{mk}^{012}\right]$, $\left[Z_{mj}^{012}\right]$, $\left[Z_{kk}^{012}\right]$, and $\left[Z_{kj}^{012}\right]$ are diagonal 3×3 matrices whose diagonal elements are zero, positive, and negative sequence Z-bus impedances corresponding to buses indicated by the subscript.

For a single Line-To-Ground fault,

$$I_p^{012} = \begin{bmatrix} \frac{1}{Z_{pp}^o + Z_{pp}^1 + Z_{pp}^2} \\ \frac{1}{Z_{pp}^0 + Z_{pp}^1 + Z_{pp}^2} \\ \frac{1}{Z_{pp}^0 + Z_{pp}^1 + Z_{pp}^2} \end{bmatrix}. \tag{10}$$

For a Three-Phase fault,

$$I_p^{012} = \begin{bmatrix} I_p^0 \\ I_p^1 \\ I_p^2 \end{bmatrix} = \begin{bmatrix} 0 \\ \frac{1}{Z_{pp}^1} \\ 0 \end{bmatrix}. \tag{11}$$

For a Line-to-Line Fault,

$$I_p^{012} = \begin{bmatrix} I_p^0 \\ I_p^1 \\ I_p^2 \end{bmatrix} = \begin{bmatrix} 0 \\ \frac{1}{Z_{pp}^1 + Z_{pp}^2} \\ -I_p^1 \end{bmatrix}. \tag{12}$$

For a Double-line-to-ground Fault,

$$I_p^{012} = \begin{bmatrix} I_p^0 \\ I_p^1 \\ I_p^2 \end{bmatrix} = \begin{bmatrix} -I_p^1 \frac{Z_{pp}^2}{Z_{pp}^o + Z_{pp}^2} \\ \frac{1}{Z_{pp}^1 + \frac{Z_{pp}^{21} + Z_{pp}^0}{Z_{pp}^0 + Z_{pp}^2}} \\ -I_p^1 \frac{Z_{pp}^0}{Z_{pp}^0 + Z_{pp}^2} \end{bmatrix}. \tag{13}$$

Factors Z_{pp}^0, Z_{pp}^1, and Z_{pp}^2 must be calculated using (4).

Thus voltage at m during fault can be expressed in terms of parameter ψ. Then it is possible to express the remaining voltage (sag magnitude) for each phase as a function of ψ using symmetrical matrix components.

5. Type of transformer and propagation of voltage sag

Transformers come with many different winding connections, but a classification into only three types is sufficient to explain the propagation of three-phase unbalanced sags from one voltage level to another [3]:

1. Type I: Transformers that do not step voltages. In this type of transformer the secondary-side per-unit voltage is equal to the primary side per-unit voltage. The only type of transformer in this category is the star-star transformer with both windings grounded. This type of transformer can be defined mathematically by the simple transformation matrix

   $$\mathbf{T}_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

2. Type II: Transformers that removes the zero-sequence voltage. The per-unit voltage on the secondary equal per-unit voltage on the primary side, minus the zero-sequence component. Transformers with star-star windings and one or both windings ungrounded, and delta-delta winding transformers, are the examples

in this category. Transformers of this type can be defined mathematically by means of transformation matrix

$$\mathbf{T}_2 = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}$$

3. Type III: Transformer that swaps line and phase voltages. For this type of transformer, each secondary-side voltage equals the difference between two primary-side voltages. Examples are delta-star, star-delta transformers and star-zigzag transformers. This type of transformer can be defined mathematically by means of the transformation matrix

$$\mathbf{T}_3 = \frac{j}{\sqrt{3}}\begin{bmatrix} 0 & 1 & -1 \\ -1 & 0 & 1 \\ 1 & -1 & 0 \end{bmatrix}.$$

Within each of these categories there will be transformers with different clock numbers leading to a different phase shift between primary-side and secondary-side voltages. This difference is not of any importance for voltage sags as experienced by the equipment. All that matters is the change between the pre-fault voltages and the during fault voltages, in magnitude and in phase-angle.

In the power system the propagation of sags due to different types of symmetrical and unsymmetrical faults depends on the type of transformer. The voltage sag equations for the different types of faults at the primary and secondary of transformer can be derived. The equations of phase voltages at the fault point and after different types of transformer are given in [3]. From these equations it is clear that magnitude as well as phase angle of voltages undergo change when it is propagated through transformer. Thus the magnitude and phase angle of sag at the terminal of equipment depends on the type, location of fault as well as on the type of transformer. The most-sagged phase for particular type of fault when propagated through Type I, Type II, or Type III transformers are as shown in the Table 1. In this paper, aim is to study the effect of transformer type on stochastic estimation of the number of sags at the terminal of a sensitive load.

6. System of study

The diagram of the test system used in this work is shown in Figure 3 [6]. Six critical industrial customers are connected at six nodes of the same 20 kV distribution line (40 km 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 need to be examined. The equivalent transmission system consists of three 150 kV lines and is relatively of large size(800 km total length) to take into account the fact that fault at 100 km away from the critical customer will cause severe sags. The data of the transmission and distribution lines is as given in Table 2.

In [4] this system is solved analytically. In the present work it is simulated using PSCAD/EMTDC software package by Fault position method [3]. The analytical expressions in general form for the voltage at the node of our interest are given in [4, 6]. In the PSCAD/EMTDC environment there is no need for complex programming. A system is simulated for different types of faults with fault positions at a distance of 5% of the length of the line for all the lines in the system. The voltage at critical node 1 is observed for different types of faults for different fault locations for the complete length of all the lines with type I, Type II and Type III transformer. And graphs are plotted for these voltages versus length of lines.

The sag can be symmetrical or unsymmetrical depending on the type of fault. The unsymmetrical and symmetrical sags are shown in Figure 4 and Figure 5.

Table 1. Most-sagged phase for particular fault types when propagated through Transformer Types I, II and III. transformers.

Type of fault	Type of Transformer	Most sagged phase
ABC_G	Type-I	A/B/C
BC_G		A
BC		B
A-G		B
ABC_G	Type-II	A/B/C
BC_G		A
BC		C
A-G		C
ABC_G	Type-III	A/B/C
BC_G		A
BC		C
A-G		C

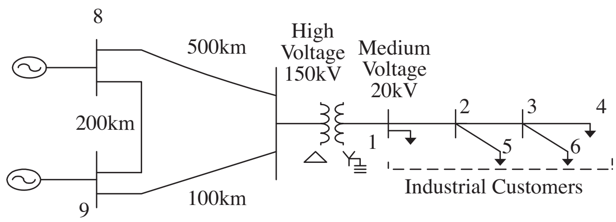

Figure 3. Single line diagram of test system.

Table 2. Transmission and distribution line impedances.

Line(s)	Positive & Negative sequence impedances (ohm/km)	Zero sequence impedance (ohm/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

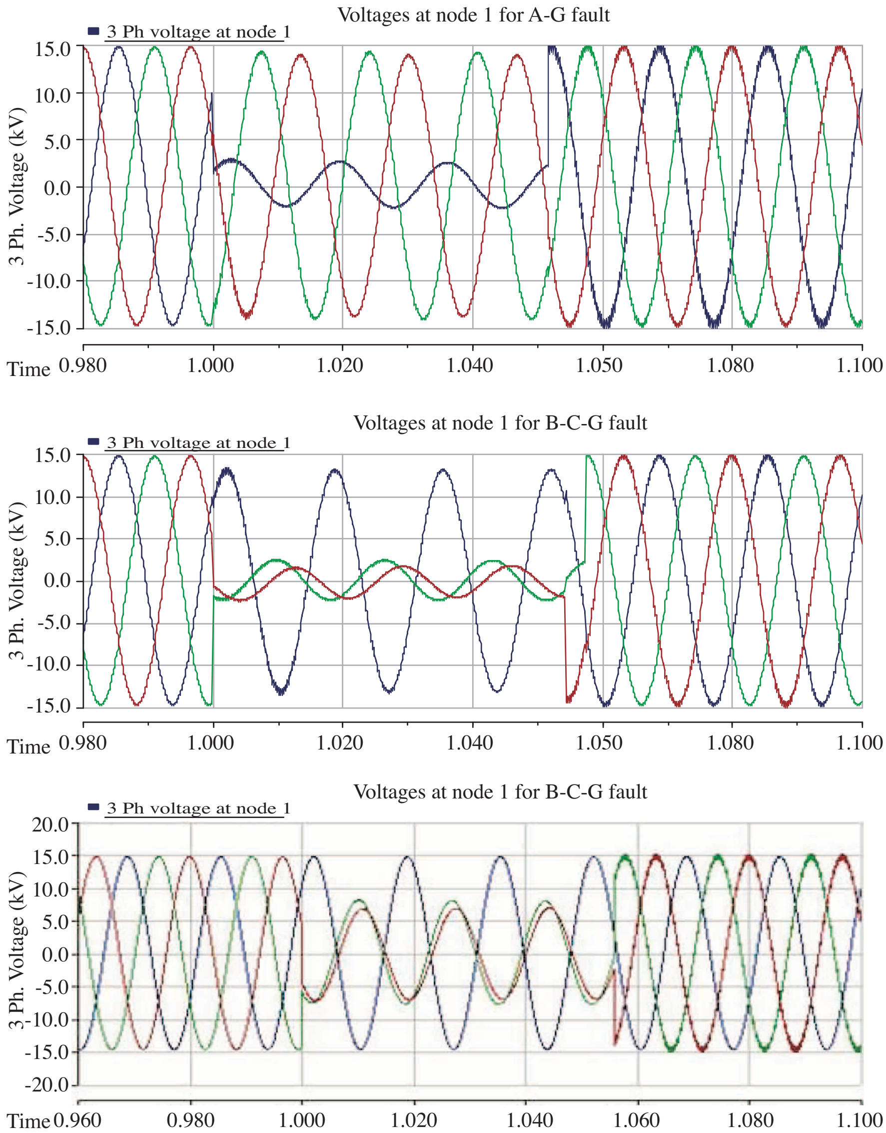

Figure 4. Unsymmetrical faults due to line-to-ground, double-line-to-ground and line-to-line short circuits on line 1-2 at a fractional distance of 5% from node 1 (top to bottom).

The test system is simulated in the PSCAD/EMTDC software package. On all lines, each type of fault is created at $t = 1$ s, at a number of points on all lines, at a fractional distance of 5% from node j, and the fault is cleared in 0.05 sec. The sag magnitude observed at node 1 versus the distance at which the fault occurs on that line, for different types of transformers, are plotted in Figures 6–11. Prefault voltage at node 1 is 1 pu.

The most-sagged phase depends on the type and location of fault and type of transformer and is as shown in Table 1. If the fault is on the transmission side, then transformer type plays an important role. The most-sagged phase voltage at node 1 in each case is plotted as a function of the fractional length of line at which the fault takes place (see Figures 6–11). The sag magnitude at node 1 due to faults in transmission side i.e. on lines 7-8, 8-9, 7-9 will be affected by type of transformer. The variation in the sag magnitude at node 1 due to fault in the line 8-9 will be list affected as compared to line 7-8 and line 7-9. Whereas the sag magnitude at node 1 due to faults on distribution lines i.e. line 1-2-3-4, 2-5, 3-6 is not affected by the type of transformer. These graphs are used for stochastic prediction of number of sag experienced by a sensitive load at node 1.

7. Stochastic estimation of voltage sag

In order to properly assess a system with respect to sensitive load terminals, there is need to know the number of voltage sags, at particular magnitudes at those terminals. In this study, the fault rate is considered as per [6] and fault distribution along the line is assumed as uniform as per [4]. The magnitude of sag at the node of interest depends on both the type and location of fault along the lines. The probability that the sag magnitude at any node a is within the limits V_{low} to V_{up} is given by

$$P^a\left(V_{\text{low}} \leq V \leq V_{\text{up}}\right) = P^a\left(l_{\text{low}} \leq l \leq l_{\text{up}}\right) \int\limits_{l_{\text{low}}}^{l_{\text{up}}} g\left(l\right) dl. \tag{14}$$

Here, $P^a(V_{low} \leq V \leq V_{up})$ is the probability that voltage magnitude at node a is within the limits V_{low} to V_{up} and P^a $(l_{low} \leq l \leq l_{up})$ is probability that fault takes place between the length specified by l_{low} to l_{up} for any particular line, for a particular fault. Values$l$ and V are in per-unit, and $g(l)$ is a probability distribution function. For uniform distribution of faults [5] along the lines $g(l) = 1$, so

$$P^a\left(V_{\text{low}} \leq V \leq V_{\text{up}}\right) = l_{\text{up}} - l_{\text{low}}. \tag{15}$$

Now the number of sags within limits V_{low} to V_{up}, at node a due to fault along any line, with fault distribution uniform along the line, is given by

$$N^a\left(V_{\text{low}} \leq V \leq V_{\text{up}}\right) = \lambda\left(l_{\text{up}} - l_{\text{low}}\right), \tag{16}$$

where λ is the total number of particular faults on that line and $N^a(V_{low} \leq V \leq V_{up})$ is the number of sags/year with voltage magnitude within the limits of V_{low} to V_{up}, for a particular fault along any line.

Thus total number of sags within V_{low} to V_{up} for any one type of fault can be calculated by adding number of sags at node a due to all lines in the system:

$$N^a_{\text{Total}}\left(V_{\text{low}} \leq V \leq V_{\text{up}}\right) = \sum_{\text{Line}} N^a\left(V_{\text{low}} \leq V \leq V_{\text{up}}\right), \tag{17}$$

where $N^a_{\text{Total}}\left(V_{\text{low}} \leq V \leq V_{\text{up}}\right)$ is the total number of sags/year for any particular faults along all the lines.

To estimate number of sags experienced by node 1 in the study system, the probability of fault P_a considered is as shown in Figure 12 [6] and the fault rate is as shown in Table 3.

From the sag magnitude curves for fault on different lines and of different types, for Type I transformers, along with particular fault rate for a sag magnitude of 0.8, the estimated number of sags for A-G fault are calculated and shown in Table 3 as sample calculations. Same calculations are repeated for all other types of faults and for sag magnitude of 0.8, 0.7, 0.6 pu with different types of transformers with the help of the curves of Figures 6–11. Same curves can be plotted for voltage at any other node for the calculation of number of sags experienced by load at that node due to faults of any type along all the lines of the system. The sample calculations are as shown in Table 4.

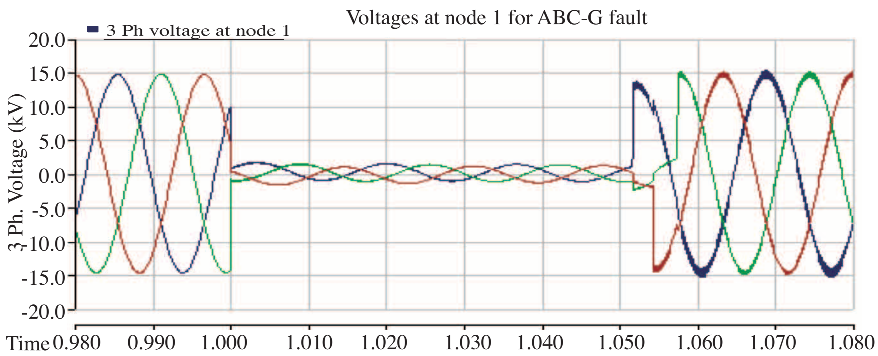

Figure 5. Symmetrical Fault on line 1-2 at a fractional distance of 5% from node 1.

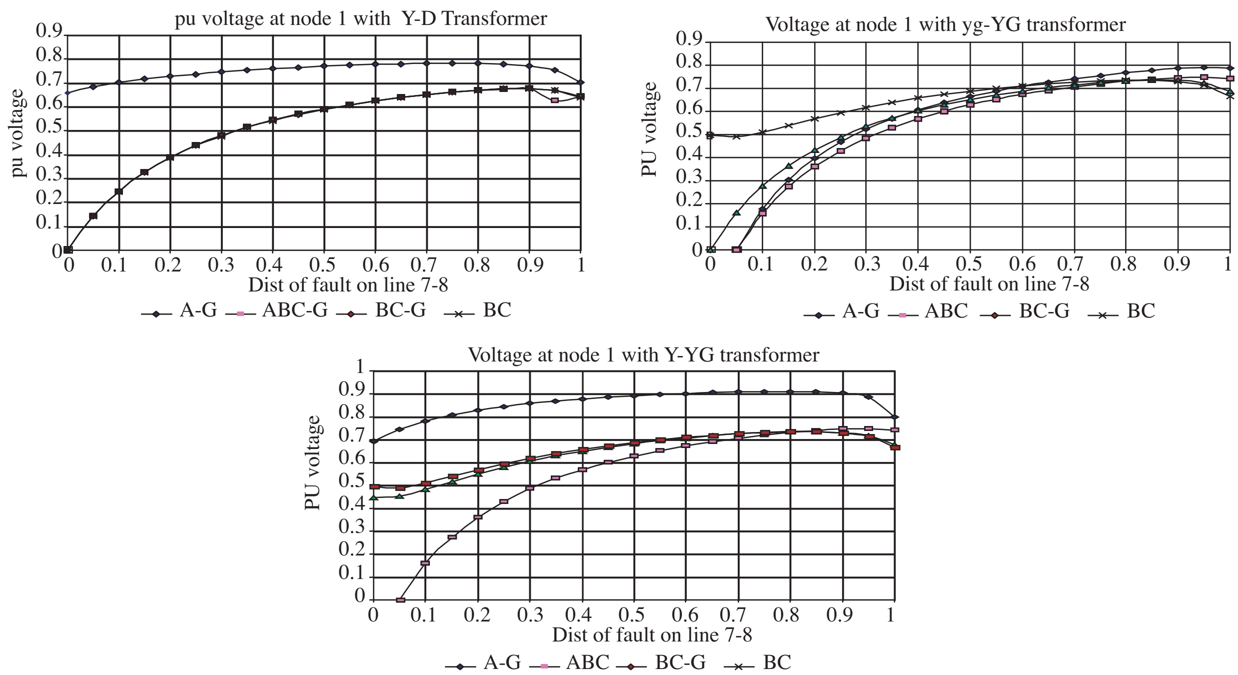

Figure 6. Most-sagged phase voltage at node 1, in pu, due to fault along the 150 kV line 7-9 with length 100 km.

Table 3. Fault rate at each voltage level.

Voltage	Fault rate (events/km/year)	Total Length (km)	Annual expected number of faults
MV (20 kV)	1	40	40
HV (150 kV)	0.1	800	80

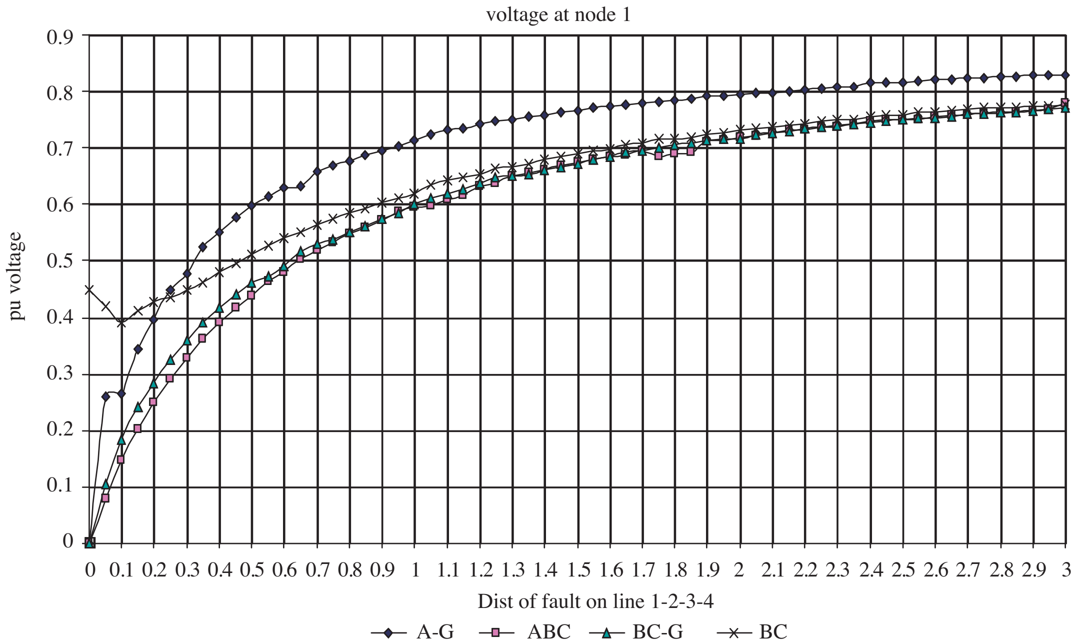

Figure 7. Most-sagged phase voltage at node 1 in pu due to fault along the 20 kV line 1-2-3-4 with length 30 km.

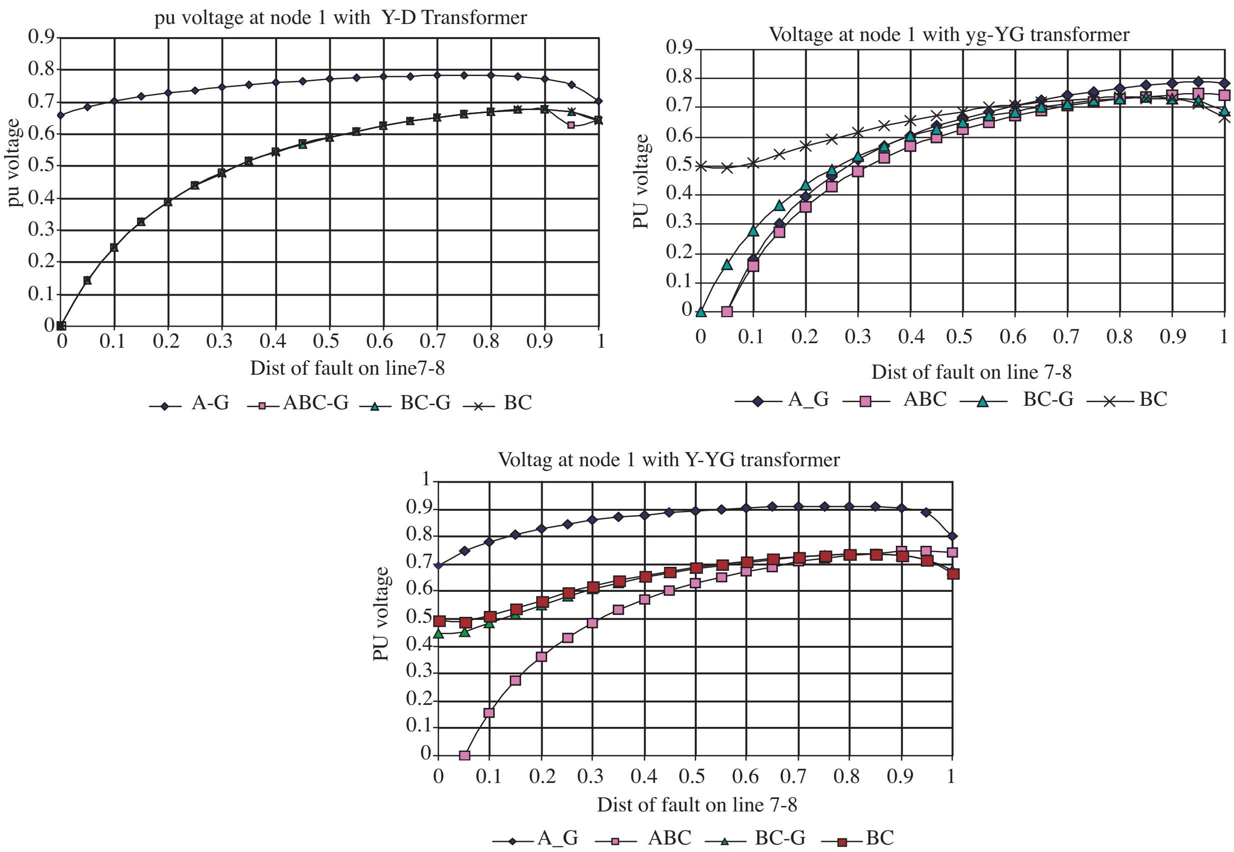

Figure 8. Most-sagged phase voltage at node 1, in pu, due to fault along the 150 kV line 7-8, with length 500 km.

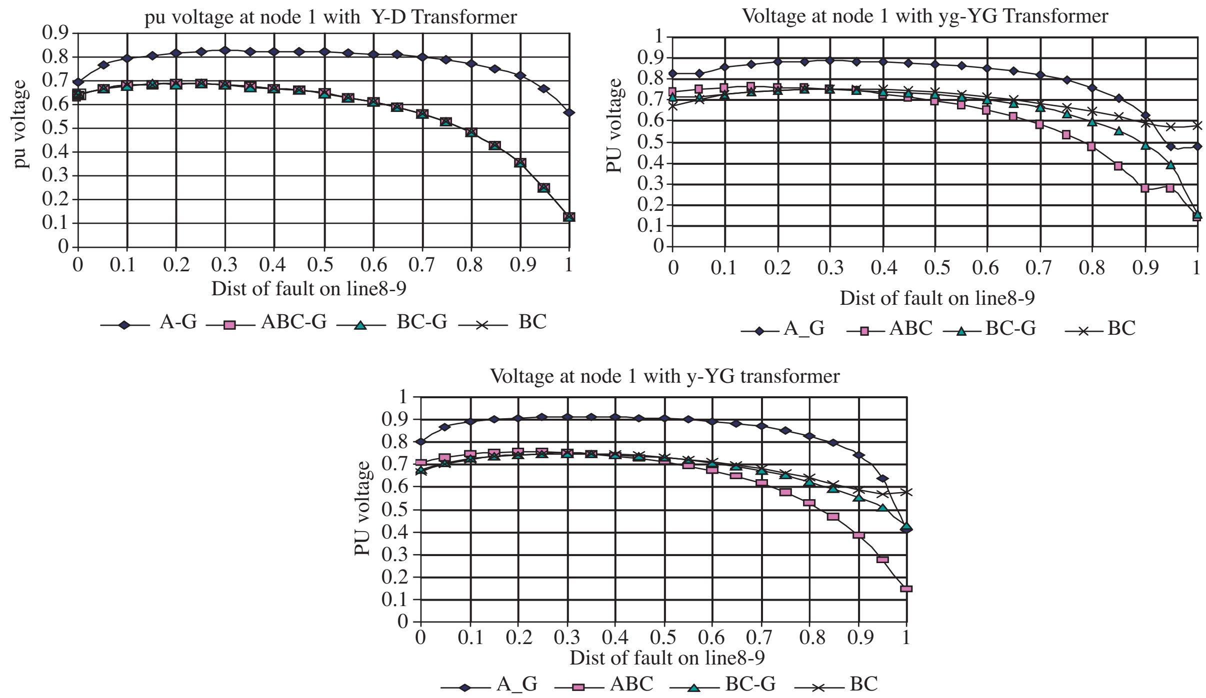

Figure 9. Most-sagged phase voltage at node 1, in pu, due to fault along the 150 kV line 8-9, with length 200 km.

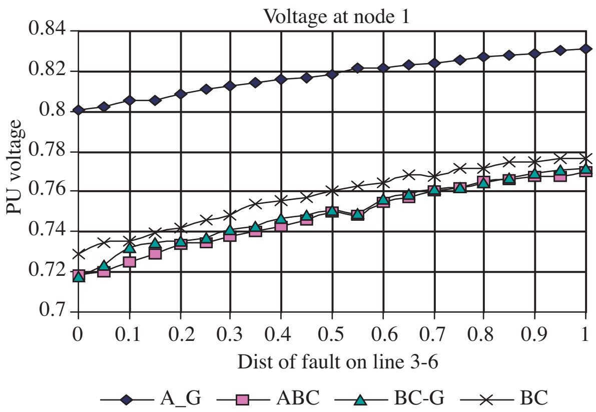

Figure 10. Most-sagged phase voltage at node 1, in pu, due to fault along the 20 kV line 3-6, with length 5 km.

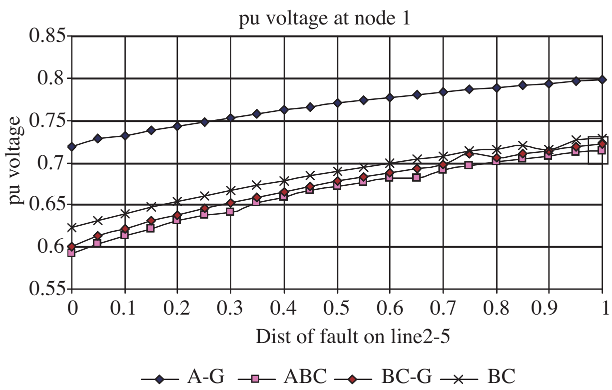

Figure 11. Most-sagged phase voltage at node 1, in pu, due to fault along the 20 kV line 2-5, with length 5 km.

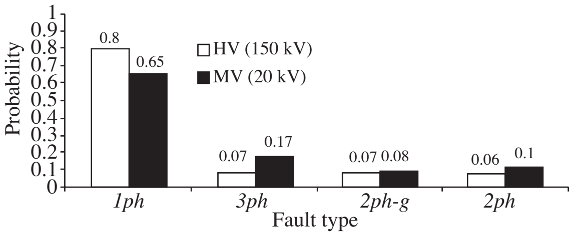

Figure 12. Fault probability, by line type [6].

Table 4. Calculations of expected number of sags for critical sag voltage magnitude 0.8 pu with Y-D transformer (Type III).

Type of Fault	Voltage level	Name of Line	Length of the for which the voltage is less than critical voltage	Total length	Annual expected Fault numbers	Expected No. of sags	Total number of sags at node 1
A-G	HV Level	Line 8-9	0.4×200=80	680	680×0.1=68	68×0.8=54.4	68.7
		Line 7-8	1.0×500=500				
		Line 7-9	1.0×100=100				
	LV Level	Line 1-2-3-4	2.1×10=21	22	22×1=22	22×0.65=14.3	
		Line 2-5	0.1×10=1				
		Line 3-6	0.0×1=0				

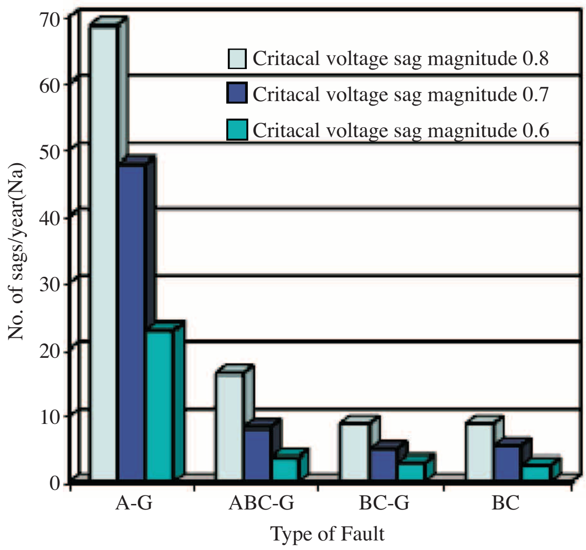

Figure 13. Estimated number of sags at node 1 with Type I Transformer.

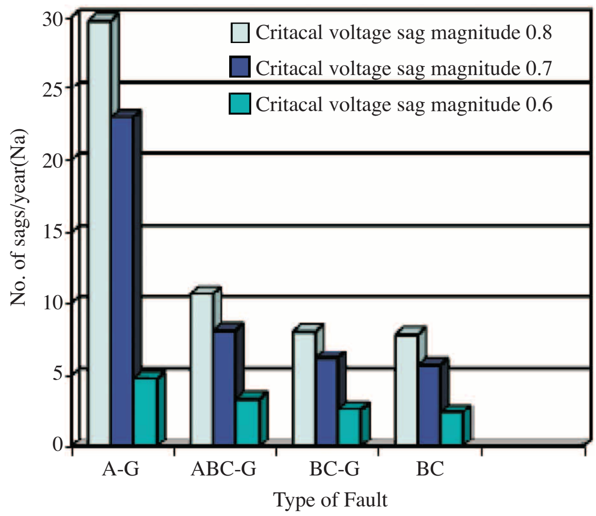

Figure 14. Estimated number of sags at node 1 with Type II Transformer.

Thus number of sags experienced by load at node 1 with transformers of different type is as shown in Figures 13–15. Note how the type of transformer has a remarkable effect on the number of estimated sags.

The study is with only one transformer in the system but in an actual system there could be a number of transformers, each of which, and collectively, will have a different impact on the number of estimated sags. Along with magnitude of sag, the phase angle will also undergo change via the transformer, but this phenomenon is not discussed in this paper.

Estimated number of sags by stochastic method, via power system simulation, can have applications in estimating dip frequency for new industrial customers, as an aid in defining requirements for equipment immunity, to identify locations that may be prone to dips, or as an aid in choosing mitigating methodology [15], among others.

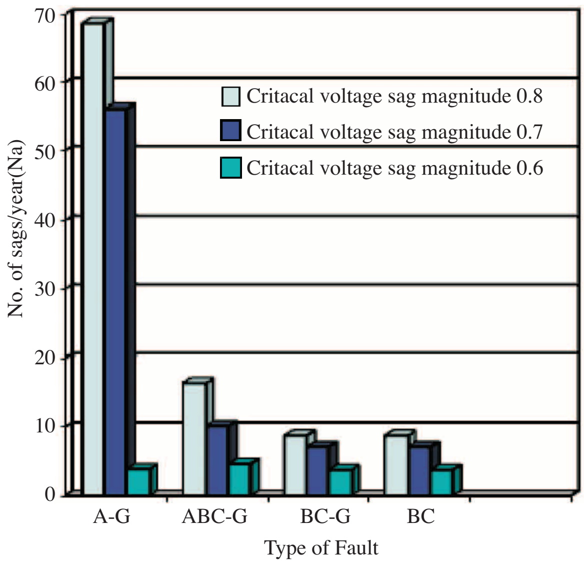

Figure 15. Estimated number of sags at node 1 with Type III transformer.

8. Conclusion

The characteristic of voltage sag, at a sensitive load in the system due to faults in the transmission and distribution system, is greatly affected by type, location of fault and type of transformer between the transmission and distribution system. Transformers are an integral part of any power system. We find that the estimated number of sags experienced by sensitive load at nodes under study is dependent on transformer type. Simulation results of the system via PSCAD/EMTDC clearly indicate this effect. Greater number of sags will be experienced with Type I and Type III transformers than Type II transformer (types of transformers are as explained in Section 5). While designing the power system, emphasis should be given on the type of transformer winding in order to take power quality issues into consideration.

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