International Journal of Engineering & Technology, 7 (4.38) (2018) 23-29

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Estimation of Phase Angle Jump (PAJ) for Different Types of Faults and Unbalancing in Distribution System

Muhammad Fawad Shaikh[1], Madad Ali Shah[2], Sunny Katyara[1], Bhawani Shankar Chowdhry[3]

[1]Electrical Engineering, Sukkur IBA University, Pakistan
(mfawad.be14@iba-suk.edu.pk, VC@bbsutsd.edu.pk, sunny.katyara@iba-suk.edu.pk)
[2]BBSUTSD, Khairpur Mirs, Sindh, Pakistan
[3]Mehran University of Engineering & Technology, Pakistan
**Corresponding author E-mail: dean.feece@admin.muet.edu.pk*

Abstract

Voltage sag caused by the faults in the power system has serious power quality issues and sometimes leads to interruption of power supply. The characteristics of voltage sag are its magnitude, time and phase angle jump (PAJ). This paper represents the estimation of phase angle jump (PAJ) when different types of faults are occurred in distribution system. Since the unbalancing is one of the major issues in distribution system that increases the zero sequence currents, over heats the distribution transformer, causes huge voltage drops in distributor etc. Therefore, the method used in this paper shows the PAJ when distributor is unbalance due to uneven loading or the line parameters of the distributor are unsymmetrical. Simple radial system is used to analyze the PAJ caused by the different types of faults and unbalancing. Different comparisons are made that are associated with PAJ such as PAJ vs fault impedance, zero sequence current and percentage of voltage unbalance. The research work is performed on MATLAB/SIMULINK to analyze the real time results.

Keywords: *Phase angle jump, unevenly loaded lines, unbalancing, zero sequence currents, distributor.*

1. Introduction

When fault occurs in power system, the voltages of the system drastically go down, this sudden reduction in voltage magnitudes is termed as voltage sag and it affects the power quality, particularly on secondary distribution system such voltage sag affects the performance of air conditioners, compressors, lightings and computers [3]. IEEE standard 1159-1995 defines voltage sag as diminishing of voltage magnitude between 90% and 10% of nominal RMS value for more than half cycle duration but less than or equal to sixty seconds [2]. Voltage sag is inherently present in the distribution system and it depends on network topology and line impedances. Voltage sag can be caused by faults in utility network, sudden insertion of heavy reactive loads, energization of bulk induction motor with large starting time and primary protection failure when secondary protection has large time to operate. Different papers are written on voltage sag phenomenon but very few are related to phase angle jump (PAJ). The conventional written papers define the causes of voltage sag and their effects on utilization. They are characterized by voltage sag magnitude and its duration. Since, the inceptions of symmetrical and unsymmetrical faults not only cause the voltage dip magnitude but also affect the phase angle of voltage [1]. Phase angle jump (PAJ) shifts the zero crossing of the three phase system. Hence, power-electronics converters that operates on the instants of phase angle get affected by subsequent magnitude of phase-angle jump (PAJ) [6], [7],[8]. The nature of PAJ for three-phase faults depends upon difference of X/R ratio between the source and the feeder and the transmission of dips to lower tension circuits [4]. In coming sections, we will see the severity of faults through PAJ. Since power system is consist of three phases that carry the balanced three phase voltages and currents. Ideally, all the phase' signals are symmetrical and displaced by 120^0 in balanced system while unbalance condition occurs if the magnitudes are not equal or there is no any 120 degrees symmetry [5]. Unbalancing is also one of the causes that disturbs the symmetry of the three phase system and distorts the power quality. Due to unbalanced system, the phase angle between alternate phases will no longer be 120^o. The major cause of unbalancing in the distribution system is uneven loading of distributor or asymmetry of line parameters of distributor. Unbalancing increases the zero sequence currents, over heats the transformer, reduces the torque and increases the current in induction motor. It also causes fluctuation in illumination of lights and huge voltage drops in line.

This paper comprises of phase angle jump estimation under different types of faults such as L-G fault, L-L-G fault, L-LL-G fault, L-L fault and different open conductor faults. Also PAJ is calculated for different unbalancing conditions. Finally, a comparative analysis is made to see the broader influence of PAJ due to unbalancing and different types of faults.

2. Calculation of Phase Angle Jump

Phase angle jump (PAJ) is related with intensity of voltage sag and system unbalancing. There are several methods to compute the voltage sag proposed in research papers. First method is "*critical distance method [9]*" and second method is *"fault positions method [6]"*. These methods help to calculate the PAJ. The PAJ can be determined by measuring the zero crossing of the fundamental signal and then comparing it with reference signal to get the time difference. Another method of finding the PAJ is Fourier Transform (FT), in which the Fourier Transform of complex signal is known and the instantaneous phase angle difference between three phases is found. In this paper, we majorly focus on critical distance method. This method is only applicable to radial network but not applicable in finding the PAJ for ring or interconnected system. While, the fault position method determines the voltage sag in mesh network. Since, our focus in on radial network, thus we use the critical distance method to find the phase angle jump.

A. The method of critical distances

The critical distance method is a easy technique for determining the voltage sag by using voltage divider model [4]. This method is only used for radial network. The circuit for critical distance method is shown in Fig.1. The sag in voltage at point of common coupling (PCC) due to the fault can be determined by simply applying Voltage Divider Rule (VDR), given by equation (1):

Where $|Z_s| = R_s + jX_s$ and $|Z_f| = R_f + jX_f$ are the source and fault impedances respectively.

$$|V_{sag}| = E_g \cdot \frac{|Z_f|}{|Z_s|+|Z_f|} \quad (1)$$

Since, the analysis of power system is done in per unit (pu) system. So we consider pre-fault voltage is 1 pu and hence $E_g = 1$. Now expression of voltage sag after converting into per unit system is given by equation (2).

$$|V_{sag}| = \frac{|Z_f|}{|Z_s|+|Z_f|} \quad (2)$$

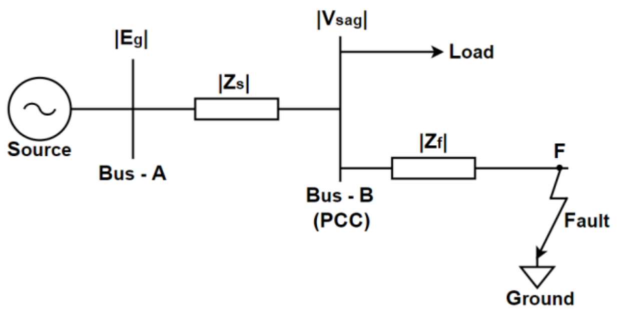


Fig. 1. Shows the network for critical distances method

In complex phasor, the phase angle or argument is found by usingtan$^{-1}\frac{X}{R}$. Since in Fig.1 model, the phase angle jump (PAJ) is needed but not simply phase angle of the system. To find the PAJ pre-fault phase angle is very important which is found by subtracting the phase angle of fault from the phase angle of sum of X/R ratio of source reactance and fault reactance Phase angle jump(PAJ) can be found. Mathematically

$$\Delta\Phi = \arg(|V_{sag}|) = \tan^{-1}\left(\frac{X_f}{R_f}\right) - \tan^{-1}\left(\frac{X_f + X_s}{R_f + R_s}\right) \quad (3)$$

If X/R ratio of fault and supply is same i-e $\frac{X_f}{R_f} = \frac{X_s}{R_s}$then there is no phase angle jump. This condition holds good for faults in transmission lines, but usually not for faults in utility networks [10].The phase-angle jump will thus be associated with system if the X/R ratio of the supply and the utility network are distinct [4]. Through Fig.1 model, different types of faults and their associated PAJ can be found.

In order to find the phase angle jump (PAJ) caused by unbalancing, sequence component analysis is used. The phase is breakdown into its sequence components (positive, negative and zero sequence). By analyzing its sequence components, PAJ can be calculated. However, sequence components analysis is also helpful to find the phase angle jump when various kinds of faults occur in utility network.

1)Single Line-To-Ground Fault

When any single phase of three phase system is grounded then it is called single line-to-ground fault. The sequence components of voltages after fault are defined by equations (4), (5), (6) and (7):

$$V_0 = Z_0 I_0 \quad (4)$$

$$V_1 = V_{pf} - Z_1 I_1 \quad (5)$$

$$V_2 = Z_2 I_2 \quad (6)$$

$$\begin{bmatrix} V_{ag} \\ V_{bg} \\ V_{cg} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} \quad (7)$$

The phase angle jump is calculated by equation (8)

$$\Delta\Phi_{Ph} = \arg(V_{Ph}^{Pf}) - \arg(V_{ph}^{f}) \quad (8)$$

Where $V_{0,1,2}$ are the zero, positive and negative sequence voltages respectively. $Z_{0,1,2}$ are the sequence impedances and I_{012} are sequence currents. V_{Ph}^{Pf} and V_{ph}^{f} are phase pre-fault voltage and phase fault voltage respectively.

2)Double Line-To-Ground Fault

When any two lines of three phase power system are grounded, then it is called double line-to-ground fault. The fault conditions are defined by equations (9), (10), (11) , (12), (13) and (14)

$$V_a = V_a \quad (9)$$

$$V_b = 0 \quad (10)$$

$$V_c = 0 \quad (11)$$

$$I_1 = \frac{V_{pf}}{Z_1 + \frac{Z_2 Z_0}{Z_2 Z_0}} \quad (12)$$

$$I_2 = (-I_1)\frac{Z_0}{Z_0 + Z_2} \quad (13)$$

$$I_2 = (-I_1)\frac{Z_2}{Z_0 + Z_2} \quad (14)$$

The phase angle jump is estimated by equation (15)

$$\Delta\Phi_{Ph} = \arg(V_{Ph}^{Pf}) - \arg(V_{ph}^{f}) \quad (15)$$

3)Double line Fault

When any two of three lines comes in contact with each other without involving ground, it is called the line-to-line fault. The fault conditions are defined by equations (16), (17), (18), (19), (20), (21) and (22):

$$V_b = V_c \quad (16)$$

$$I_2 = -I_1 \quad (17)$$

$$I_0 = 0 \quad (18)$$

$$V_1 = V_2 \quad (19)$$

$$V_0 = 0 \quad (20)$$

$$I_1 = -I_2 = \frac{V_{pf}}{Z_1 + Z_2} \quad (21)$$

$$I_b = -I_c = I_0 + a^2 I_1 + a I_2 \quad (22)$$

The phase angle jump is calculated by equation (23)

$$\Delta\Phi_{Ph} = \arg\left(V_{Ph}^{Pf}\right) - \arg\left(V_{ph}^{f}\right) \quad (23)$$

4)Triple Line-To-Ground Fault

When all three phases come in contact with ground, then it is called triple-line-to-ground fault. This sort of fault is symmetrical fault. The fault conditions are determined by equations (24) and 24,

$$V_a = V_b = V_c = 0 \quad (24)$$

$$I_{a,b,c} = \frac{V_{pf}}{Z_1} \quad (26)$$

5) Calculation Of Three Phase Unbalance System

Phase angle jump (PAJ) is not only caused by the different types of fault but it is also caused by the unbalancing. Unbalancing disturbs the symmetry of phases and it is totally dependent of how much system is unbalanced. Through Fourier Transform, phase angle jump can be found but mathematically PAJ can be found by using sequence component analysis. The unbalanced system is governed by equations (27) , (28) and (29):

$$\boldsymbol{V_s} = \boldsymbol{A^{-1} V_P} \quad (27)$$

$$\boldsymbol{A^{-1}} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \quad (28)$$

Where $\boldsymbol{V_s}$ is the sequence components and $\boldsymbol{V_P}$ is phase voltages. Further opening the eq.(27) it will be

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (29)$$

Phase angle jump (PAJ) of each unbalance phase can be find by using equations (30), (31) and (31):

$$\Delta\Phi_{Ph,a} = \arg\left(V_{Ph,a}^{BU}\right) - \arg\left(V_{ph,a}^{AU}\right) \quad (30)$$

$$\Delta\Phi_{Ph,b} = \arg\left(V_{Ph,b}^{BU}\right) - \arg\left(V_{ph,b}^{AU}\right) \quad (31)$$

$$\Delta\Phi_{Ph,c} = \arg\left(V_{Ph,c}^{BU}\right) - \arg\left(V_{ph,c}^{AU}\right) \quad (32)$$

Where $V_{Ph(a,b,c)}^{BU}$ voltages of any phase before unbalance and $V_{Ph(a,b,c)}^{BU}$ voltages of any phase after unbalance.

4. Simulation

The study of phase angle jump is performed on 4-bus radial system.The SLD is shown below in fig.2

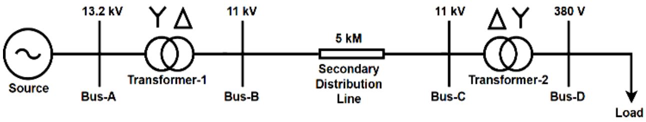


Fig. 2. Shows 4-bus radial network

For the purpose of simplification, transmission line is not included in the model. The substation is fed from 132kV generating station where voltages are stepped down to primary distribution level(11kV) by star/delta transformer-1 and then 5kM feeder is connected to delta/star Transformer2, which is used to further stepdown the voltages up to 380 V three phase and 220 V single phase for power utilization. In this paper, our main focus is on Bus-D because faults and unbalancing occur at this point and it is also called Point of Common Coupling (PCC). The simulation of this model is done on MATLAB/SIMULINK to get the real time results. Table.1 shows the parameters that are used in simulation keeping the system frequency as 50 Hz.

Table.1: Simulation Model Parameters

Sr. No.	***System***	***Description***
01	Supply	50 MVA, 33 kV, X/R=3
02	Transformer-1	30 MVA, 13.2/11 kV, Z%=7.21, X/R=8.471
03	Secondary Distribution Line	Z=0.132+j0.235 Ohm/km
04	Transformer-2	20 MVA, 11kV/380V, Z%=13.10, X/R=8.431
05	Load	11.2 MVA, 0.89 Pf Lagging

A) Simulation Results

1)Single Phase-To-Ground Fault

Single Phase-to-ground fault is occurred at the load terminal. The RMS per unit voltage and PAJ are shown in fig.3. After fault, load terminal voltage is reduced to 0.14 pu and has a phase angle jump of -51^0. The remaining phases are healthy due to proper grounding. The fault is simulated for 0.1 seconds.

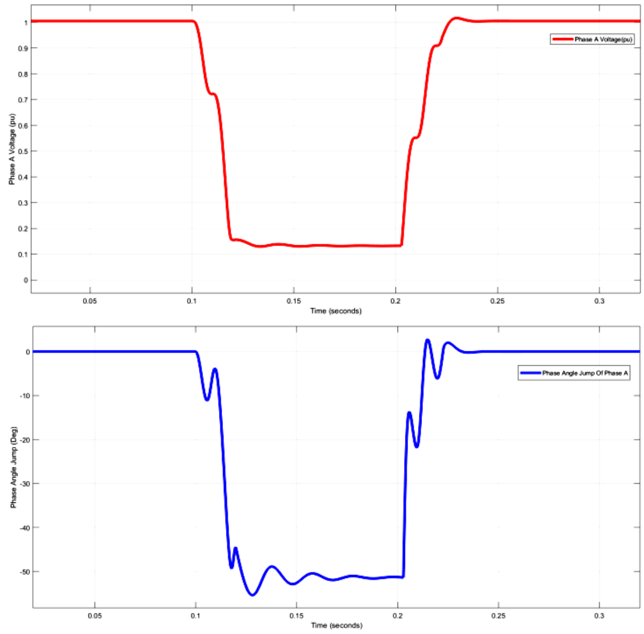
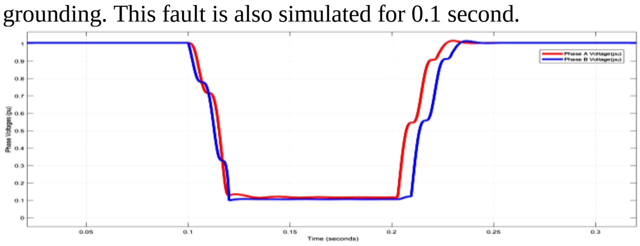


Fig. 3: Shows single line-to-ground fault (a)RMS Voltage(pu) (b)PAJIn Degrees

2) Double Line-To-Ground Fault

Double line to ground fault is simulated at the load terminal. The RMS per unit voltage and PAJ are shown in fig.4. After the fault, the voltages of both faulted phases reduced to 0.12 pu and phase-A has a phase angle jump of -78^0 while phase-B has a phase angle jump of -22^0. The remaining phase-C is healthy due to proper grounding. This fault is also simulated for 0.1 second.



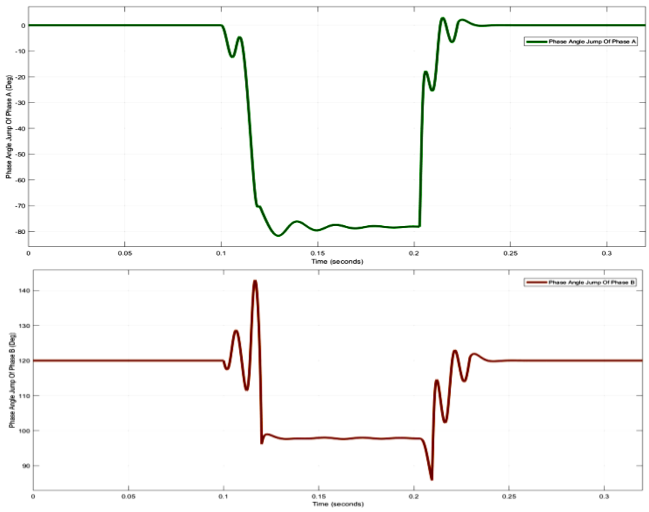


Fig.4: Double line-to-ground fault (a)RMS voltages of phase A, B(pu) (b)PAJ of phase A in degrees (c)PAJ of phase B in degrees

3) Phase to Phase Fault

Phase to phase fault is occurred when any single phase is shorted with other phase. This type of fault is also simulated on load terminals. The RMS per unit voltage and phase angle jump (PAJ) are shown in Fig.5. After the occurrence of fault phase-A has 0.55 pu while Phase-B has sag of 0.45 pu. The Phase Angle Jumps of Phases A, B are -56^0 and 56^0 respectively. However, the remaining Phase-C is healthy due to proper grounding. This fault is also simulated for 0.1 second.

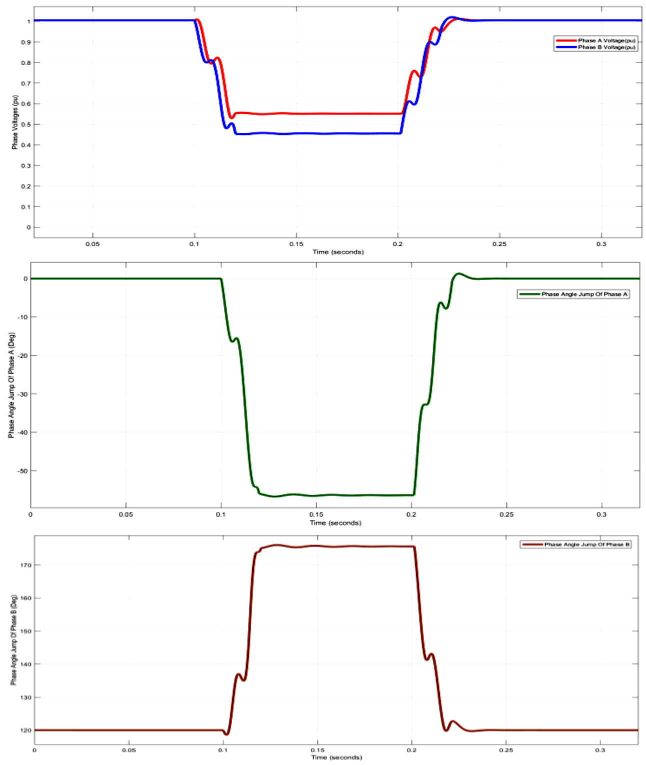


Fig. 5: Line-to-line fault (a) RMS voltages of phase A, B (pu) (b)PAJ of phase A in degrees (c)PAJ of phase B in degrees

4) Three Phase-To-Ground Fault

When all three phases of power system are shorted with ground, the resultant fault is called triple line-to-ground fault. Again this fault is simulated on load terminals. The RMS per unit voltage and phase angle jump (PAJ) are shown in fig.6. After the fault, all the phases have equal sag that is around 0.07 pu as well as all phases have equal phase angle jump of -60^0. This fault is also simulated for 0.1 second.

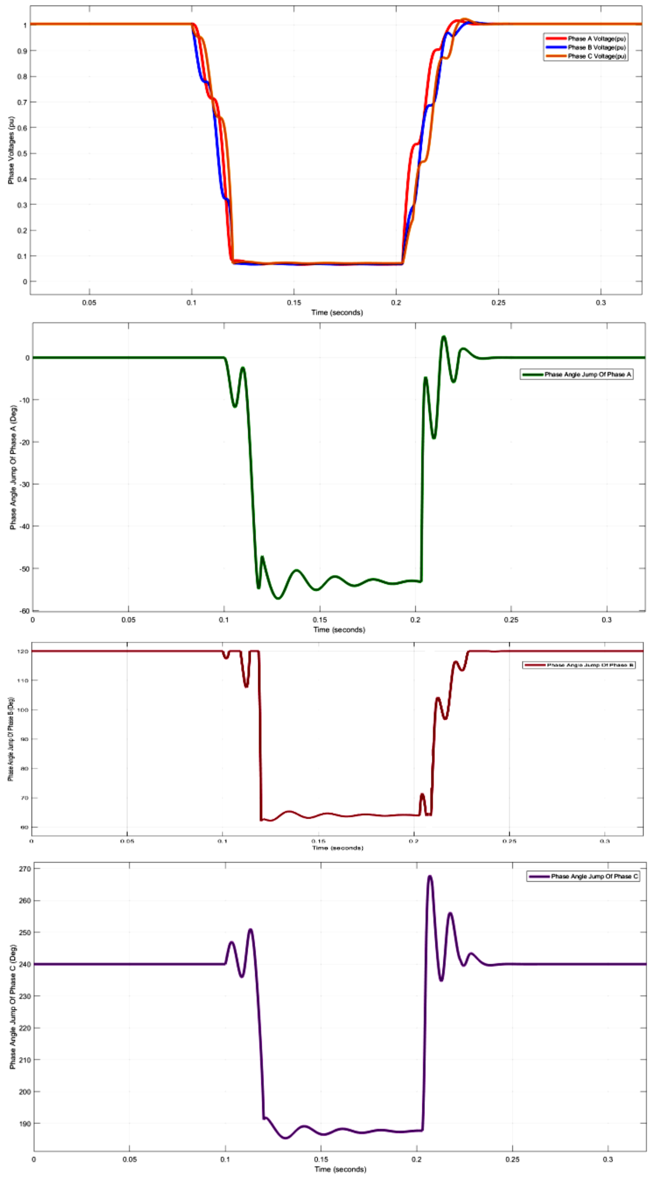


Fig. 6.: Three line-to-ground fault (a) RMS voltages of phase A, B, C(pu) (b)PAJ of phase A in degrees (c)PAJ of phase B in degrees (d) PAJ of phase c in degrees

5) Phase Angle Jump Due To Unbalancing

Unbalancing in the power system disturbs the symmetry of three phase balanced system. Especially in distribution system, where local consumers are connected. There is always some amount of unbalancing in system and practically it is impossible to get balanced secondary distribution system. Due to unbalance in system, the phase angle between alternate phases have no more 120^{0}electrical symmetry but are disturbed by the uneven loads on distributor or even the line parameters of the distributor are unsymmetrical. In simulation, distribution system is unevenly loaded to find out the phase angle jump. Phase-A is overloaded to 23.5 MVA and Phase-B has a load of 15.5 MVA and finally Phase-C has a load of 8.5 MVA. Total voltage unbalance is 25.87%. The Voltage sag of each phase and their corresponding phase angle jump (PAJ) are shown in Fig.7. Phase A, B and C have per unit voltages of 0.695 pu , 0.899 pu and 1.153pu respectively and have a phase angle jumps of -21.73^0, -11.96^0 and 2.01^0 respectively.Unbalancing is simulated for 0.1 second.

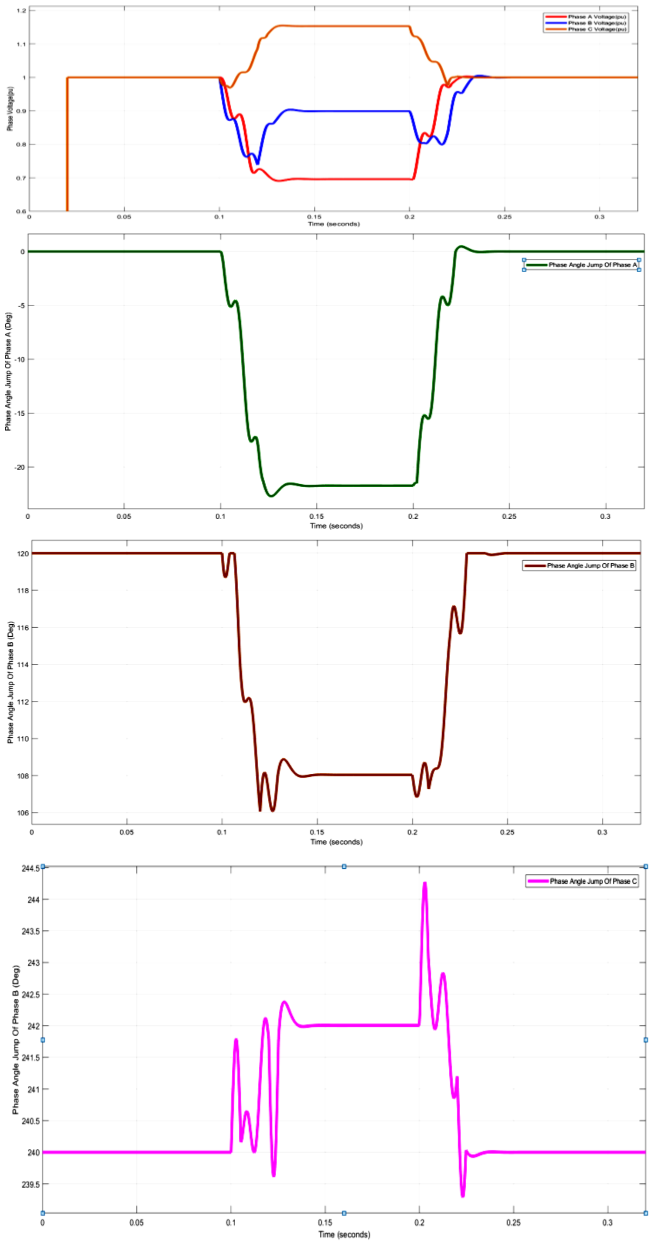


Fig.6: Unbalancing Iin distribution system (a) RMS voltages of phase A, B, C(pu) (b)PAJ of phase A in degrees (c)PAJ of phase B in degrees (d) PAJ Of phase C in degrees

5. Comparisons

After analyzing the phase angle jump (PAJ) caused by the different types of faults and unbalancing, different comparisons are made to broadly see the effect of different parameters on phase angle jump (PAJ). The comparison includes the (a)fault impedance verses phase angle jump, (b)voltage sag verses phase angle jump, (c)fault current verses phase angle jump, (d)power verses phase angle jump and (e)voltage unbalance percentage vs phase angle jump. Finally, the Table.II is drawn which shows the accurate variation of PAJ with different parameters.

B. Fault impedance versus PAJ

It is observed that phase angle jump (PAJ) changes when impedance of fault is varied. When impedance of fault is very low, the PAJ is large, increase of fault impedance greatly reduces the phase angle jump (PAJ) and non-linear effect is observed. Fig.7 shows the graph of fault impedance verses PAJ. The result is obtained from single line-to-ground fault.

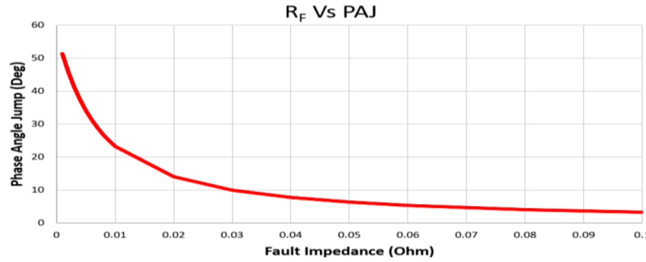


Fig.7: Variation of PAJ when impedance of fault is changed.

C. Voltage sag versus PAJ

Since voltage sag is related to phase angle jump (PAJ). Voltage sag in any phase of distribution system affects the symmetry of three phase and hence phase angle jump (PAJ) occurs. It is found that when the extent of sag is very high, the phase angle jump is also too much high and load voltage linearly reduces the phase angle jump. Fig.8 illustrates the effect of voltage sag on PAJ.

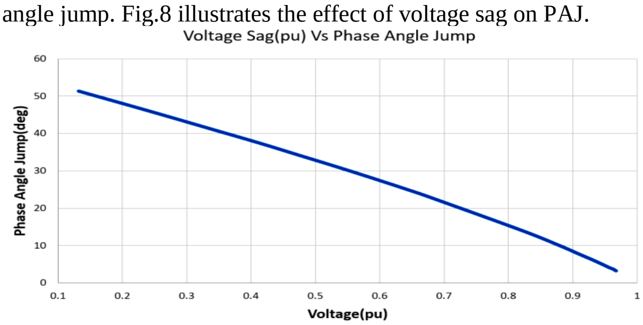
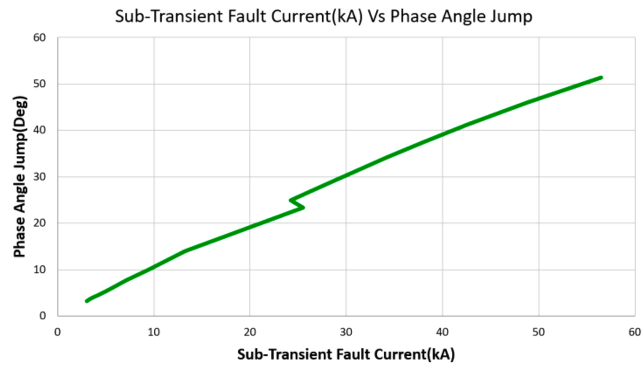
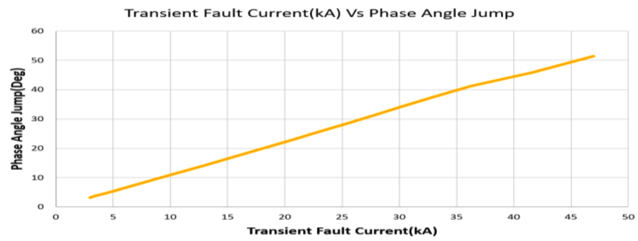


Fig. 8: Variation in PAJ when load voltage is changed (pu).

D. Fault Current versus PAJ

In this section phase angle jump (PAJ) is observed when single line-to-ground fault current is changed. Since any fault occurred in power system is composed of three states: sub-transient, transient and steady state. Sub-transient fault current has highest amount of current value which is dangerous for power system and then after few moments, transient fault current flow in system which is lesser than sub-transient current and sustain for one or two cycles and then steady state fault current flow in system which remain in power system until fault is not cleared. Fig.9 shows the all states of fault current variation with phase angle jump (PAJ).





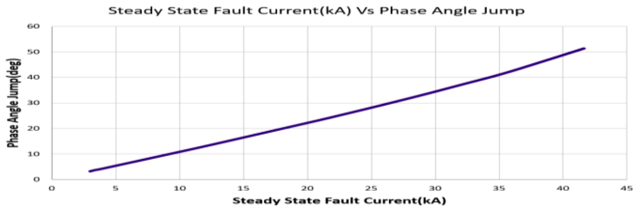


Fig. 9: Variation of PAJ when fault current is changed (a) sub-transient fault current (kA), (b) transient fault current, (c) steady state fault current.

E. Power versus PAJ

When fault occurs in power system, the voltages of the system drastically goes down and huge amount of current flows in the system which causes huge power losses, produce heating and affect the thermal stability of the power system. In this section, power loss is observed when single line to-ground fault occurs in system at various impedances and their associated phase angle jumps. It is observed that power losses vary non-linearly with different value of phase angle jumps (PAJ). Fig.10 shows the variation of PAJ with different values of power losses. Highest power loss is accounted at 24.923^0.

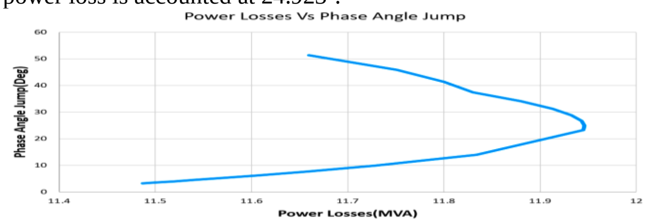


Fig.10. Variation of PAJ with different power losses caused by SLGF fault.

F. Voltage Unbalance Percentage versus phase angle jump

Voltage unbalance also produce phase angle jump (PAJ) as seen in above section. Phase angle jump (PAJ) depends upon that how much the system is unbalance. Fig.11 shows the variation of phase angle jump (PAJ) with respect to the percentage of voltage unbalance. Voltage unbalance percentage is defined by NEMA (National Electrical Manufacturers Association) as:

$$\%LVUR = \frac{Max\ Voltage\ Deviation\ From\ The\ Avg\ Line\ Voltage}{Avg\ Line\ Voltage} \quad (33)$$

Where LVUR is line voltage unbalance rate. The simulation is performed by varying the load of phase-A only and observing the PAJ thus the total voltage unbalance is calculated by equation (33) according to NEMA.

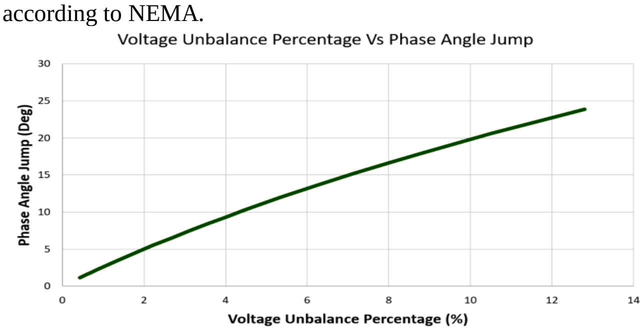


Fig. 11: Variation of PAJ with different percentage of voltage unbalance

Table.2: Variation of Phase Angle Jump with Different Parameters

Phase Angle Jump(Deg)	Voltage Sag(pu)	Sub-Transient Fault Current(kA)	Transient Fault Current(kA)	Sustained Fault Current(kA)	Power (MVA)	Fault Impedance(Ohm)
51.39	0.132	56.471	46.961	41.615	11.66	0.001
45.93	0.244	48.67	41.615	38.157	11.751	0.002
41.33	0.336	42.69	36.27	35.158	11.8	0.003
37.47	0.413	37.977	32.902	32.24	11.83	0.004
34.13	0.476	34.159	30.127	29.715	11.88	0.005
31.3	0.5296	31.013	27.7685	27.498	11.913	0.006
28.87	0.5742	28.378	25.73	25.545	11.932	0.007
26.762	0.612	26.1411	23.951	23.8188	11.943	0.008
24.923	0.6444	24.2202	22.385	22.2878	11.946	0.009
23.306	0.6722	25.541	20.9987	20.92448	11.945	0.01
13.9922	0.8217	13.2633	12.7973	12.78536	11.834	0.02
9.9422	0.8802	9.3507	9.13373	9.129418	11.729	0.03
7.6993	0.91	7.120769	7.086291	7.08413	11.6574	0.04
6.2789	0.9293	5.86477	5.78423	5.782961	11.6067	0.05
5.2996	0.9418	4.940994	4.884694	4.883853	11.5696	0.06
4.5841	0.9507	4.268	4.22651	4.22592	11.541	0.07
4.0385	0.9574	3.75618	3.72426	3.7238	11.519	0.08
3.6881	0.9627	3.35377	3.32849	3.32815	11.502	0.09
3.2618	0.9669	3.029153	3.00864	3.008372	11.487	0.1

6. Conclusion

This paper discussed the method for calculating phase angle jump (PAJ) caused by the symmetrical, unsymmetrical faults as well as for unbalanced system. Equations were defined for better understanding and accurate calculation of PAJ. For the analysis of PAJ, the 4-bus radial system was simulated. Phase angle jump (PAJ) due to different faults was analyzed for SLGF, DLGF, LLLGF and LLF. PAJ for unbalanced system was also analyzed by installing different loads on each phase. It was observed that highest PAJ was caused by the LLGF.
Finally, different comparisons were made to analyze PAJ broadly with different parameters. Comparisons include phase angle jump versus fault impedance, voltage sag, fault current (sub-transient,

transient and steady state), power loss and voltage unbalance percentage. It was observed that some parameter of PAJ varying linearly were voltage sag, fault current and voltage unbalance percentage and for some parameter PAJ varied non-linearly such as with power loss and fault impedance. In the end, table was shown to accurately observe the PAJ with variation of different parameters.

References

[1] Kamble, S. and Thorat, C. (2014) Voltage Sag Characterization in a Distribution Systems: A Case Study. Journal of Power and Energy Engineering, 2, 546-553. http://dx.doi.org/10.4236/jpee.2014.24074

[2] (1995) IEEE Recommended Practice for Monitoring Electric Power Quality. IEEE Std. 1159-1995.

[3] S. Saksena and S. G. Karady, "Effects of voltage sags on household loads," *IEEE Power Engineering Society General Meeting, 2005*, San Francisco, CA, 2005, pp. 2456-2461 Vol. 3. doi: 10.1109/PES.2005.1489404

[4] A. K. Goswami, C. P. Guptaand Girish Kumar Singh, "An Analytical Approach for Stochastic Assessment of Phase-Angle Jumps in Large Systems"

[5] M. H. Albadi, A. S. A. Hinai, A. H. Al-Badi, M. S. A. Riyami, S. M. A. Hinai and R. S. A. Abri, "Unbalance in power systems: Case study," 2015 IEEE International Conference on Industrial Technology (ICIT), Seville, 2015, pp. 1407-1411. doi: 10.1109/ICIT.2015.7125294

[6] M. H. J. Bollen, Understanding Power Quality Problems. Voltage sags and Interruptions: IEEE Press Series on Power Engineering, 2000.

[7] M. H. J .Bollen, P. Wang, and N. Jenkins, "Analysis and consequences of the phase angle associated with a voltage sag," in Conf. Rec. Power systems Computation conf., Aug.1996, Dresden, Germany, pp 316-322.

[8] Elisa .Espinosa Juarez and Araceli Hernandez, " Stochastic assessment of phase-angle jumps caused by voltage sags applying an analytical method" in Proc. 9 th International conference on probabilistic method applied to power systems, KTH, Stockholm, 2006, Sweden, June 11-15, pp 1-6.

[9] M. H. J. Bollen, T. Tayjasanant, and G. Yalcinkaya, "Assessment of the number of voltage sags experienced by a large industrial customer", IEEE Transaction on Industry Applications, Nov/Dec 1997, vol.33, no.6, pp.1465-71.

[10] Leonard L. Grigsby "Electric Power Generation, Transmission, and Distribution, Third Edition"

[11] J Duncan Glover and Thomas Overbye and Mulukutla S Sarma " Power System Analysis and Design 6th Edition"