Voltage Sag Assessment in a Large Chemical Industry

A. K. Goswami, *Member, IEEE*, C. P. Gupta, *Member, IEEE*, and G. K. Singh

Abstract—This paper presents a method for the assessment of voltage sags caused by short-circuit faults in a large chemical industry. The supply arrangement for the industry is discussed. The connected equipment of the industry is fed from the 6.6-kV bus. The voltage sag analysis is performed for faults at different voltage levels in the power supply network. For every voltage level, the critical distance and expected number of voltage sags have been calculated. Since the industry has its own generator, thus the influence of local generation in voltage sag analysis is also investigated.

Index Terms—Critical distance, industrial power supply, power quality, voltage sag.

NOMENCLATURE

V_{Sag}	Voltage sag at the point of common coupling (PCC).
z	Feeder impedance per unit length.
L	Distance of the fault position from the PCC.
L_{Crit}	Critical distance.
α	Impedance angle.
Z_s	Source impedance.
Z_F	Feeder impedance.
Z_1	Impedance of the local generator.
Z_2	Impedance between the fault and the PCC.
Z_3	Impedance between the generator bus and the PCC.
Z_4	Source impedance at the PCC.

I. INTRODUCTION

VOLTAGE SAGS are defined as a sudden reduction of the supply root-mean-square voltage between 10% and 90% of the nominal voltage at the power frequency [1]–[4].

Voltage sags are the most frequent among various types of power-quality disturbances (e.g., voltage sag, voltage swells, overvoltages, interruptions, transients, voltage unbalance, voltage flickers, and harmonics) [5], [6]. The ability of modern industrial process equipment to ride through voltage sags is becoming more and more important as never before. As plant operation and process are becoming more automated, the need to keep equipment operation running is of utmost importance. Any downtime can be directly correlated to lost production, revenue, and profits. The equipment used in modern industrial process (e.g., programmable logic controllers (PLCs), adjustable-speed drives (ASDs), computers, and motor contactors) is highly sensitive to voltage sags. When the number of voltage sags at a plant bus is too large, mitigation methods are needed. Several methods of mitigation have been proposed in the literature [7]–[19] mainly emphasizing on the improvement of equipment ride through and installation of mitigation devices.

Before making a decision about which mitigation method to choose, the information is needed about the actual number of voltage sags experienced at the load point of interest, and then, the study about the effectiveness of various mitigation methods can be performed. It is therefore essential to estimate the expected number of voltage sags that will cause tripping of the sensitive equipment.

In this paper, a method for the assessment of the number of voltage sags experienced by a large chemical industry in India is described. In chemical industry systems, customers are often classified as small with 0–2-MW power requirement, medium with 2–15-MW power requirement, and large industrial customers with power requirement more than 15 MW. The industry is located in the north of New Delhi, India, and is fed from the 132-kV Bajpur substation of Uttarakhand Power Corporation Ltd. (UPCL). The industry is manufacturing chemicals (like bio-glycols, bio-ethoxylates, bio-glycol ethens, and acetates), spirits (extra neutral alcohol (ENA)/potable alcohol), gases [cryogenic gases (O2, N2)], food-grade CO_2, and herbal products which are widely used in the industry. The industry is working toward the reduction of greenhouse-gas emission by thermal energy generation from a biomass-fired boiler (cane juice unit) which produces 25 000 MT of CO_2 emission reductions per annum. Also, the utilization of effluent/waste (spent wash) in the boiler as fuel after evaporation produces 100 000 MT of CO_2 emission reduction per annum. The industry has its own captive power plant consisting of four diesel generators of 4 MW each, which are using the by-product of the industry as fuel as shown in Fig. 1. The total power requirement of the plant is 34 MW, so the rest of the 18 MW is supplied by UPCL. Authority of the chemical industry complained about the frequent tripping of their sensitive equipment like PLCs, ASDs, and compressors which caused the automatic plant to trip. They have 50 HT motors of various capacities ranging
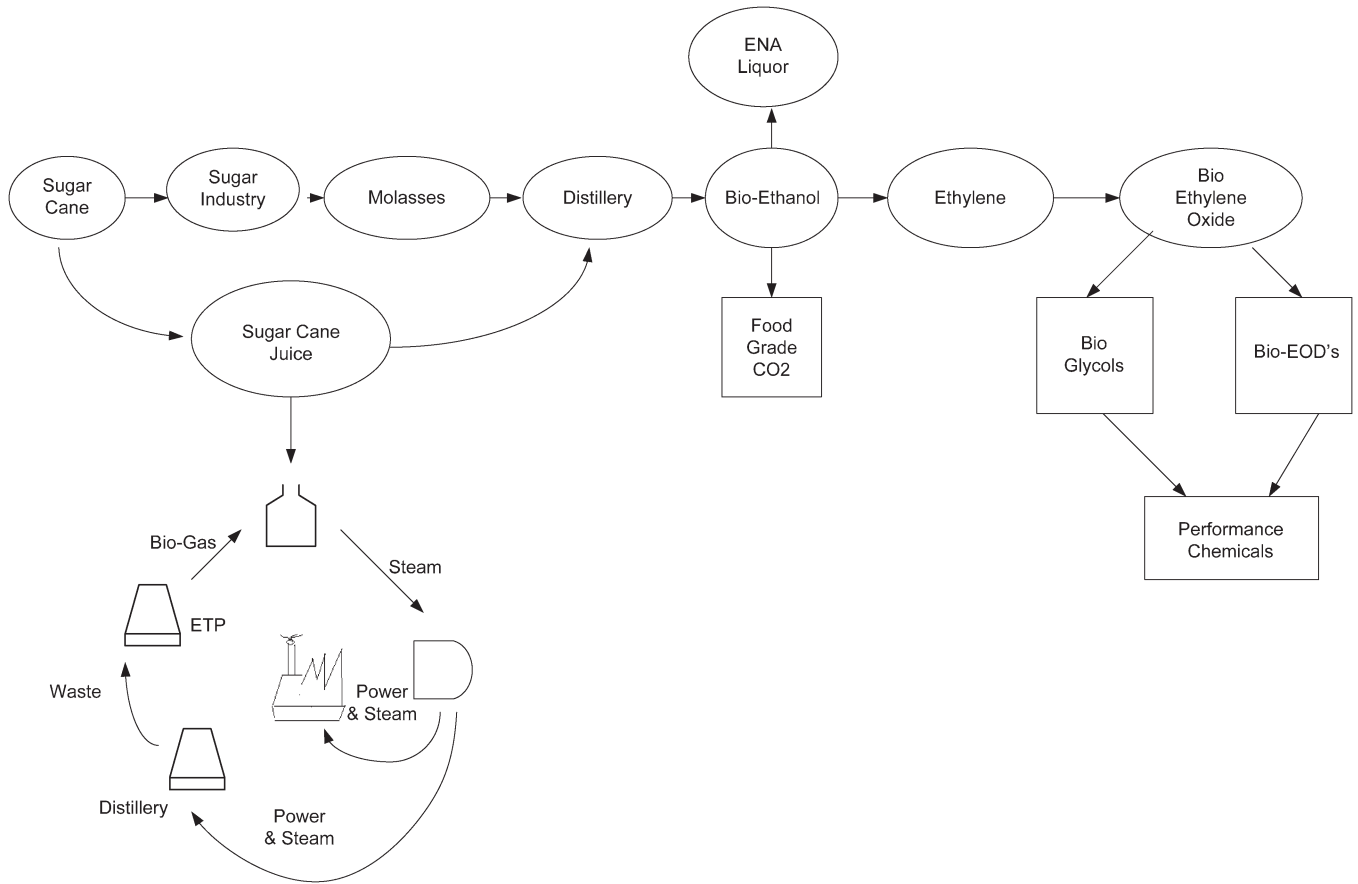
Fig. 1.   Process methodology and captive power generation for chemical industry [20].

from 160 kW to 4.1 MW. HT motors which are basically centrifugal process compressors trip 3–4 times in a week and cause the whole plant to trip. It takes approximately 1 to 3 h, depending upon the nature of the problem, to restart the plant. At present, the production capacity is approximately 50 MT per hour, and the cost of the 50 MT output would be approximately 3.5 million rupees (0.07 million US $). Therefore, if the production is stopped for an average of 4 h in a week, it costs around 14 million rupees (0.28 million US $) to the industry in a week [20]. Everything led to the conclusion that the assessment of voltage sag (i.e., magnitude and number of voltage sag) at the equipment terminal is necessary. Therefore, in this paper, a voltage sag assessment study has been done for the large chemical industry. The influence of local generation on voltage sag is discussed.

II. PROCESS METHODOLOGY

Today, potable alcohol, glycol [mono ethylene glycol (MEG), die ethylene glycol (DEG), tri ethylene glycol (TEG)], a range of ethylene oxide derivatives, and specialty performance chemicals find application in various industries. For example, potable alcohols are used as a solvent by the paint and printing industry and liquor industry after being denatured. Glycol (MEG, DEG, and TEG) are used in manufacturing polyester yarn/staple fiber which is ultimately used by the textile industry. Ethylene oxide derivatives and specialty performance chemicals find application in textile, paint, oil field, jute,

emulsion polymerization, lubricant, explosives, pharmaceuticals, cosmetics industry, etc. The production process consists mainly of four steps as shown in Fig. 1. Molasses, which is the by-product of sugar mill, is converted into ethyl alcohol by fermentation with the help of yeast. Then, ethyl alcohol is converted into ethylene by dehydration process with the help of a catalyst. Finally, ethylene oxide is produced by oxidation process with the help of oxygen from ethylene. From ethylene oxide glycols, guar gum, glycol ether acetates, potable alcohol, ethoxylate poly ethylene glycol, and performance chemical are produced. The industry has collaboration with Scientific Design, Inc., USA, and is operating through fully automated distributed control system (DCS) controlled system. Voltage sags play a very damaging role in the production because the DCS control system is very sensitive to voltage sags and causes the whole plant to trip, resulting in production loss [20].

III. METHOD OF CRITICAL DISTANCES

Often, there is a need for a simple/fast method to estimate the number of sags causing the equipment to trip. A way forward would be to calculate the sag magnitude and duration for many fault positions and add the fault rates for those that cause a sag that is too long and/or too deep which would trip the customer equipment. The method used for this purpose is the method of critical distances [24]. However, the method of critical distances is applicable for a radial system only. To quantify the sag
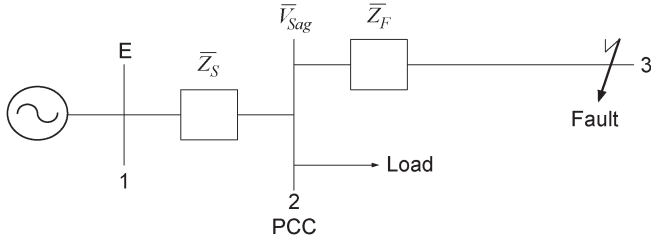
Fig. 2. Voltage divider model.

Fig. 3. Impedance angle.

magnitude in a radial system, the voltage divider model as shown in Fig. 2 is used.

The expression for voltage sag at the PCC can be expressed as [21]–[23]

$$\overline{V}_{\text{sag}} = E \times \frac{\overline{Z}_F}{\overline{Z}_F + \overline{Z}_S} \qquad (1)$$

where $\overline{Z}_F = \overline{z} \times L$ and $\overline{z}$ is the feeder impedance per unit length. $\overline{z} = R_F + jX_F$, and $\overline{Z}_S = R_S + jX_S$. L is the distance of the fault position (on the radial feeder) from the PCC.

We will assume that the prefault voltage is exactly 1 p.u.; thus, $E = 1$. This results in the following for the voltage sag magnitude (in p.u.):

$$\overline{V}_{\text{sag}} = \frac{\overline{Z}_F}{\overline{Z}_F + \overline{Z}_S}. \qquad (2)$$

The PCC is the point from which both the fault and the load are fed. In other words, it is the place where the load current branches off the short-circuit current. The load current is neglected in the method of critical distances; therefore, the voltage at the PCC equals the voltage at the equipment terminals. Assume that a piece of equipment trips if the voltage at a certain PCC drops below a critical voltage V_{Crit} over a particular duration. In that case, the equipment will trip for all the faults within a critical distance L_{crit} from the PCC. The voltage magnitude as a function of the distance is given in (2). From this equation, we obtain the distance at which a fault will lead to voltage sag of a certain magnitude.

The expression can be derived for the magnitude V. The equation for the magnitude of the voltage reads as follows [24]:

$$V = \frac{\lambda}{1 + \lambda} \times \frac{1}{\sqrt{1 - \frac{2\lambda(1-\cos\alpha)}{(1+\lambda^2)}}} \qquad (3)$$

where

$$\lambda = \frac{\overline{Z}_F}{\overline{Z}_S} = \frac{\overline{z} \times L}{\overline{Z}_S}. \qquad (4)$$

To obtain an expression for the critical distance, λ needs to be solved from (3) for known V. Therefore, this equation is rewritten into the second-order polynomial equation

$$\lambda^2(V^2 - 1) + 2\lambda V^2 Cos\alpha + V^2 = 0. \qquad (5)$$

The positive solution of (5) can be written as

$$\lambda = \frac{V}{1-V}\left[\frac{V\cos\alpha + \sqrt{1 - V^2\sin^2\alpha}}{V+1}\right]. \qquad (6)$$

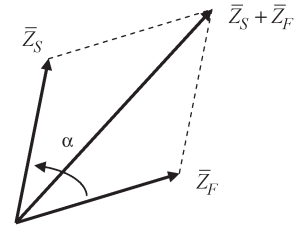Together with (4), the desired expression for the critical distance L_{crit} is given by

$$L_{\text{Crit}} = \frac{Z_s}{z} \times \frac{V_{\text{crit}}}{1 - V_{\text{crit}}} \times \left[\frac{V_{\text{Crit}}\cos\alpha + \sqrt{1 - V_{\text{crit}}^2\sin^2\alpha}}{V_{\text{Crit}} + 1}\right] \qquad (7)$$

where $\alpha = \tan^{-1}(X_F/R_F) - \tan^{-1}(X_S/R_S)$ is the impedance angle between the source impedance $\overline{Z}_S$ and the feeder impedance $\overline{Z}_F$ as shown in Fig. 3.

Assuming that the X/R ratios of the source and feeder are equal, a simplified expression can be obtained

$$L_{\text{crit}} = \frac{Z_S}{z} \times \frac{V_{\text{Crit}}}{1 - V_{\text{Crit}}}. \qquad (8)$$

If we assume further that the number of faults is proportional to the line length within the critical distance, we would expect that the number of voltage sags below a level V is proportional to $V/(1 - V)$. Another assumption is needed to arrive at this conclusion. Every feeder connected to every PCC needs to be infinitely long without any branching off. The error made by using (8) is acceptable in most cases; therefore, (8) is a useful approximation [23].

The above equation applies to three-phase fault only. For the three-phase fault, the positive-sequence impedances have to be used in (2) and (7), whereas for unbalanced faults, the equations have to be modified, i.e., for single-phase-to-ground faults, the sum of positive-, negative-, and zero-sequence impedances has to be used, and for phase-to-phase faults, the sum of the positive- and negative-sequence impedances has to be used [21]. The method of critical distances now can apply as follows [22] as shown in Fig. 4.

The exposed area contains all fault positions that lead to voltage sag causing spurious trip of the equipment. The expected number of spurious trips is found by simply adding the failure rates of all power system equipment within the exposed area. The assessment of the number of voltage sags at a given PCC is being made in which the frequency of voltage sags of interest is determined by the method of critical distance [21]. For equipment with a given critical voltage, the exposed area can also be determined. Every short circuit within this exposed area will lead to the voltage sag below the critical voltage. Adding the failure rates of all power system components within the exposed area gives the number of spurious trips of the equipment [22], [23].
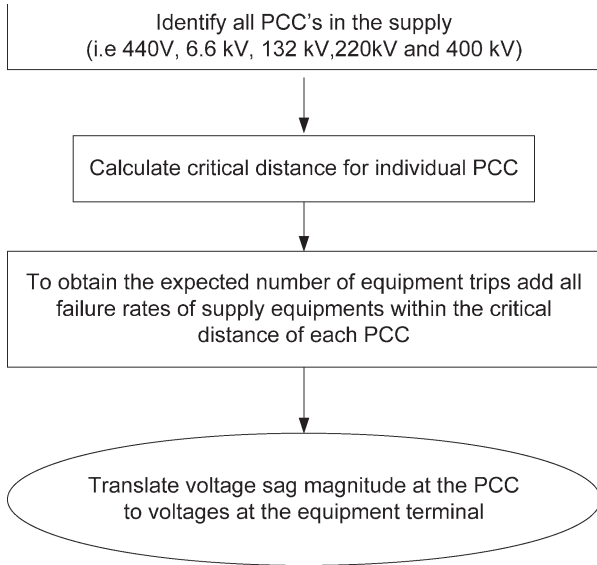
Fig. 4.   Flowchart for application of critical distance in the chemical industry.
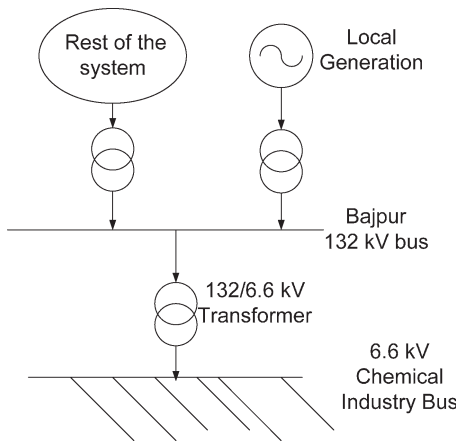

Fig. 5.   Connection of a local generator to a distribution bus.

IV. Influence of Local Generation

A local generator is connected to the chemical plant bus, mitigating voltage sag due to fault occurring on the distribution system by increasing the fault level at the distribution bus. It also mitigates voltage sags due to fault in the rest of the system. The connection of the local generator is shown in Fig. 5 [24].

An equivalent circuit to quantify this effect has been shown in Fig. 6. The impedance of the local generator is Z_1, the source impedance at the PCC is Z_4, and Z_3 is the impedance between the generator bus and the PCC. Z_2 is the impedance between the fault and the PCC. The PCC as indicated in the figure is the PCC without considering the influence of the local generator. The voltage at the equipment terminal would be equal to the voltage at the PCC when local generators are not present in the system. Therefore, the voltage at the equipment terminals during fault is equal to the voltage on the local generator bus. The voltage is related to the voltage at the PCC according to the following equation:

$$(1 - V_{\text{Sag}}) = \frac{Z_1}{Z_3 + Z_1}(1 - V_{PCC}). \qquad (9)$$

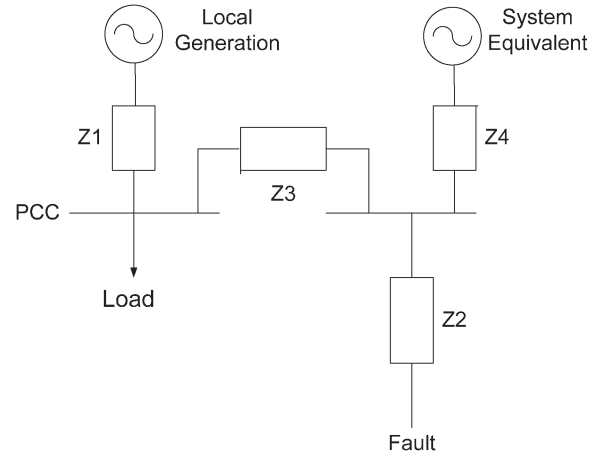Fig. 6.   Equivalent circuit for the system with local generation.

Thus, the voltage drop at the generator bus is $Z_1/(Z_3 + Z_1)$ times the voltage drop at the PCC. The voltage drop becomes smaller for larger impedance to the PCC (weaker connection) and also for smaller generation impedance (larger generator) [24]

$$V_{\min} = \frac{Z_1}{Z_3 + Z_1} \qquad \text{(in p.u).} \qquad (10)$$

V. Supply Arrangement

The supply arrangement is as shown in Fig. 7. The chemical plant is supplied from the BAJPUR-132 kV substation. This substation is fed through four 220/132-kV transformers and a 132-kV overhead line, and another three feeders are connected to this substation. The KASHIPUR-220 substation is supplied in a similar way. The KASHIPUR-400 substation is supplied through two overhead lines from MUZAFFARNAGAR-400 kV and MORADABAD-400 kV. The industry contains three HT PCCs at 6.6 kV, each having 36, 32, and 15 distribution feeders, respectively. Within the plant, 6.6 kV is being step-down to a 440-V level to supply the low-voltage equipment connected at LT PCCs.

To estimate the number of voltage sags due to faults at various voltage levels, the method of critical distances has been used [21]. This method requires the source impedance as input parameters at the various voltage levels. These are given in Table I [25].

The method of critical distances provides the number of voltage sags at the PCC. The voltage sag at PCC is equal to the voltage sag at the load bus for the three-phase fault. However, for single-phase-to-ground and phase-to-phase faults, the winding connections of the transformers between the PCC and the load need to be taken into account. The transformer winding connections and the neutral earthing of the various systems are given in Table II.

VI. Result and Discussions

First of all, various critical distances and exposed lengths for LT PCC, HT PCC, 6.6-kV chemical plant bus, and
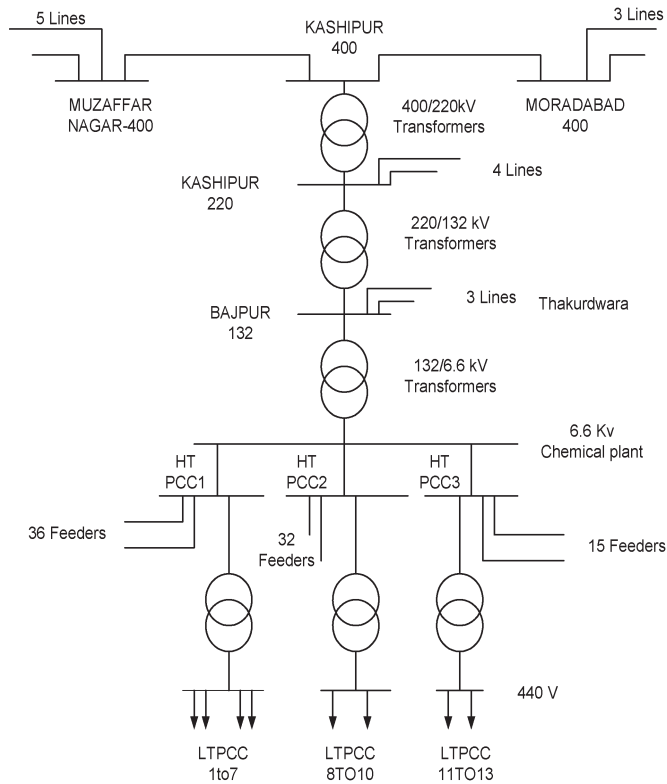
Fig. 7. Supply arrangement of the chemical plant.

TABLE I
SOURCE IMPEDANCE

Substation	Zero Sequence (%)	Positive and Negative sequence (%)
440 V	993.07+j588.91	125.49+j 674.13
6.6 kV	311.8+j366.6	8.23+j109.8
132 kV	0.047+j2.75	0.09+j2.86
220 kV	0.028+j1.65	0.054+j1.716
MUZAFFARNAGAR 400 kV	0.329+j2.273	0.084+j1.061
MORADABAD 400 kV	0.653+j5.124	0.132+j1.94

TABLE II
TRANSFORMER CONNECTION AND NEUTRAL EARTHING

Voltage level	Transformer winding connection	Neutral earthing at LV side
400/220 kV	YY Auto Transformer	Solidly earthed
220/132 kV	YY	Solidly earthed
132/6.6 kV	Yd	Resistance earthed
6.6 kV/440 V	Dy	Solidly earthed

BAJPUR-132 kV, KASHIPUR-220 kV, and KASHIPUR-400 kV substations are calculated using the method of critical distances. The critical distances for the network are shown in Table III for three-phase faults.

It is observed from Table III that the critical distances for a voltage sag of given severity are increasing with the increase in voltage level. For example, for a 90% voltage sag, the critical length is only 3.4 km for 440 V, whereas the same voltage sag is being experienced for the fault occurring at a faraway distance of 260.6 km (on a 400-kV level). However, for a specific voltage

TABLE III
CRITICAL DISTANCES FOR THREE-PHASE FAULTS

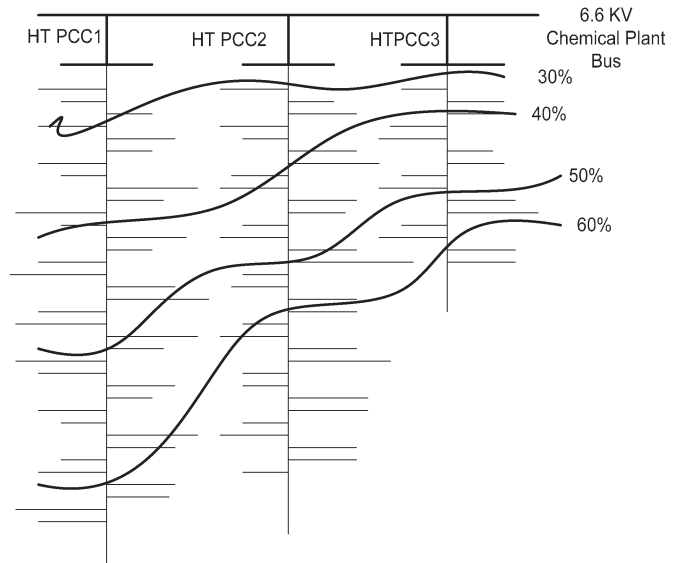| Voltage sag magnitude at PCC	Critical distances for different voltage levels. (in Km)			
	440 V level	6.6 kV level	132 kV level	400 kV level
90%	3.4	11.4	56.6	260.6
80%	1.9	8.3	38.9	198.5
70%	1.1	4.6	26.4	132.6
60%	0.9	2.4	13.8	48.5
50%	0.6	1.8	11.6	16.5
40%	0.4	1.1	9.8	11.4
30%	0.3	0.6	4.6	2.4

Fig. 8. 6.6-kV network with exposed area contour.

level, the severe voltage sags are experienced for closure faults. In other words, the critical distance decreases with the increase in the severity of the voltage sag experienced at the PCC.

A. Faults at 6.6 kV

The 6.6-kV network is purely radial. The method of critical distances can thus be applied without modification. The 6.6-kV bus is having three HT PCCs with a total feeder length of 34.5 km.
1) HT PCC1 is having 36 feeders with a total length of 14.5 km.
2) HT PCC2 is having 32 feeders with a total length of 12.5 km.
3) HT PCC3 is having 15 feeders with a total feeder length of 7.5 km.

However, the maximum feeder length among all the feeders connected at the 6.6-kV bus is 1.7 km. It is observed that three-phase faults at the farthest point of all the feeders will cause voltage sag down to less than 60%. The exposed length is thus equal to 34.5 km for critical voltages of 60% and higher.

The critical distances for different severity levels of voltage sags experienced are as shown in Fig. 8. It is observed from Fig. 8 that the deep voltage sag occurs at the equipment terminal due to faults near the 6.6-kV chemical bus and the shallow voltage sag occurs at the equipment terminal due to fault

TABLE IV
VOLTAGE SAG MAGNITUDE DUE TO PHASE-TO-PHASE FAULTS

Sag Magnitude At 6.6 kV PCC	Voltage magnitude in the three phases at equipment terminal connected at 440 V bus		
	Phase A	Phase B	Phase C
0%	48%	48%	100%
30%	58%	58%	100%
40%	62%	62%	100%
50%	67%	67%	100%
60%	73%	73%	100%
70%	80%	80%	100%
80%	86%	86%	100%
90%	94%	94%	100%

occurring farthest from the chemical plant bus. Once we have the sensitivity information of all the equipment connected at the 6.6-kV bus, it is easy to assess from such a graph which fault will lead to the tripping of the equipment. Knowing the failure rates of various power system equipment with the exposed area, it is possible to estimate the expected number of spurious trips.

However, the influence of a phase-to-phase fault on the load depends on its connection; a delta-connected load will see a different voltage sag than a star-connected load. The voltage sags seen by a delta-connected load at 440 V due to phase-to-phase faults at 6.6-kV level are shown in Table IV. In Table IV, the first column gives the magnitude of the voltage difference between the two faulted phases at the 6.6-kV PCC. The other columns give the voltage magnitude for individual phases at the equipment terminals. From the table, it follows that the sags due to phase-to-phase faults are not as severe as those due to three-phase faults.

For example, the phase-C voltage is completely unaffected for any voltage sags experienced at 6.6 kV. Even the deeper sags experienced at 6.6 kV get converted into shallow voltage sags in all the three phases at the 440-V bus. However, the duration of the sag can be up to 1 s which can still disturb the operation of the controlled rectifiers in dc drives [5].

B. Faults at 132 kV

The three other feeders connected to the 132-kV Bajpur substation are long feeders connected between Thakurdwara and Bajpur. Their contribution to the exposed length is thus large. The parallel feeders between Bajpur-132 kV and 6.6-kV chemical industry bus cause some complications as well. The transformers connected directly to the lines make the calculation more complex. The exposed area contours for the 132-kV network supplying the chemical industry are shown in Fig. 9.

It is observed from Fig. 9 that the deep voltage sags occur at the equipment terminal due to faults near the 6.6-kV chemical bus, whereas shallow voltage sags are experienced at the equipment terminal due to remote faults.

C. Faults at 400 kV

While calculating critical distances, the two lines feeding the Kashipur-400 bus must be treated differently. For a fault on the feeder to MuzaffarNagar-400, the source impedance at Moradabad-400 is not the same as for a fault on the feeder to MuzaffarNagar-400. The failure rate is given in Table V,
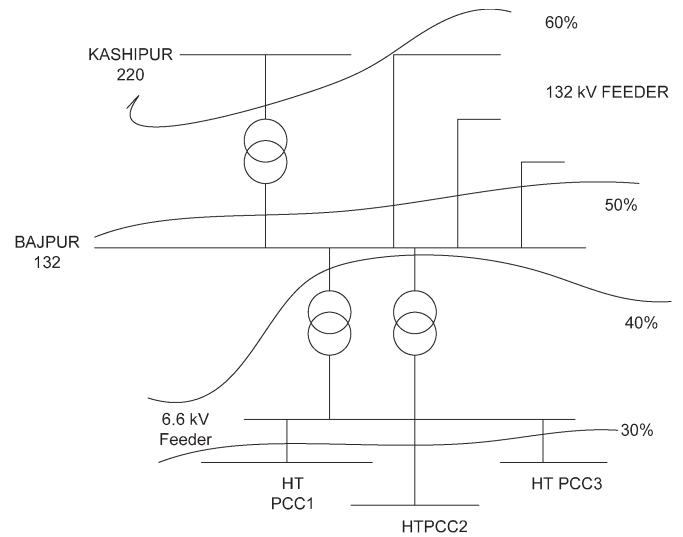

Fig. 9. 132-kV network with exposed area contour.

TABLE V
FAILURE RATE/100 km/YEAR [11]

Voltage Level (kV)	Three-phase faults	Phase-to-phase faults	Single–phase faults
6.6	1.9	2.3	12.9
132	1.2	1.7	5.4
220	0.7	0.9	1.9
400	0.6	0.8	1.7

TABLE VI
TYPICAL FAULT CLEARING TIME

Voltage Level (kV)	Typical Fault Clearing Time (ms)
220	60
132	80
33	150
11	300

TABLE VII
CRITICAL DISTANCE AND EXPOSED LENGTH FOR
THREE-PHASE FAULTS IN THE 400-kV GRID

Voltage sag magnitude	Critical distances for PCC				Exposed length (Km)
	To Moradabad (Km)	Behind Moradabad (Km)	To Muzaffar Nagar (Km)	Behind Muzaffar Nagar (Km)	
90%	610	80	1015	268	532
80%	320	26	760	112	405
70%	211	8	340	78	318
60%	136.6	-	210	66	210
50%	98	-	148	32	160
40%	58	-	98	18	105
30%	39	-	78	9	70

and the fault clearing times are given in Table VI. The critical distances for the two directions are summarized in Table VII, in the columns labeled "to Muzaffar Nagar" and "to Moradabad." It is observed from Table VII that the critical distance for 60% or deeper voltage sags is up to 136.6 km. Since the length of the feeder to Moradabad-400 is 148 km, it shows that the fault occurrences on this feeder would cause deeper voltage sags at
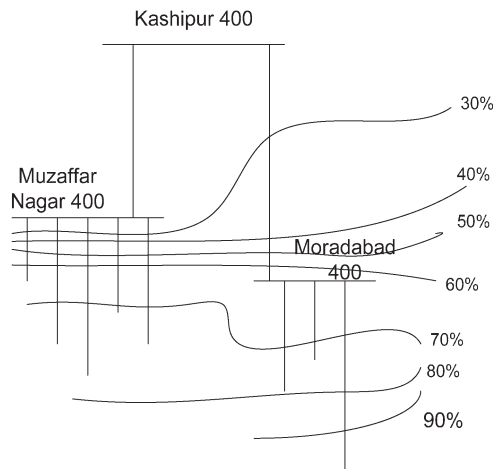
Fig. 10. 400-kV network with exposed area contours.

TABLE VIII
NUMBER OF VOLTAGE SAGS AT THE EQUIPMENT TERMINALS

Sag magnitude (%)	Expected number of voltage sags per year at equipment terminal		
	Faults at 6.6 kV	Faults at 132 kV	Faults at 400 kV
30	2.5	1.32	0.87
40	3.23	2.64	1.32
50	4.68	3.86	3.56
60	7.8	8.3	9.4
70	12.5	13.5	14.3
80	23.6	28.9	29.7
90	33.6	39.6	40.7

the PCC, whereas the faults behind Moradabad-400 contribute to shallow voltage sags above 70%. Fig. 10 shows the exposed area contours for the 400-kV system as seen from Kashipur-400 which depicts contour lines for three-phase faults only. The contours for single-phase faults would be slightly different. Three-phase faults always cause severe sags, no matter at which voltage level they occur.

The expected number of voltage sags has been calculated as the exposed length times the failure rates, given in Table VIII, for various voltage levels.

The assumption that the network is radial is certainly not true for the 400-kV grid. A more accurate assessment would be required for the calculation of sag magnitudes for individual faults in a large part of the 400-kV grid.

D. Influence of Local Generation

The industry is having its own generator which is connected to the 6.6-kV bus, and the industry also contributes its power to the grid. The fault level at the 6.6-kV bus is 432 MVA which includes the contribution of two 20-MVA on-site generators with a transient reactance of 17% each. The actual industrial load is fed from the 6.6-kV bus, for which we will calculate the voltage sag magnitude. With reference to (10) and Fig. 6, we set the following impedance value for this system:

$$Z_4 = 0.64\ \Omega,\ Z_2 = 0.075\ \Omega/\text{km},\ Z_3 = 1.605\ \Omega,\ Z_1 = 4.625\ \Omega.$$

The calculation results are as shown in Fig. 11. The bottom curve gives the voltage sag magnitude at the 6.6-kV bus for
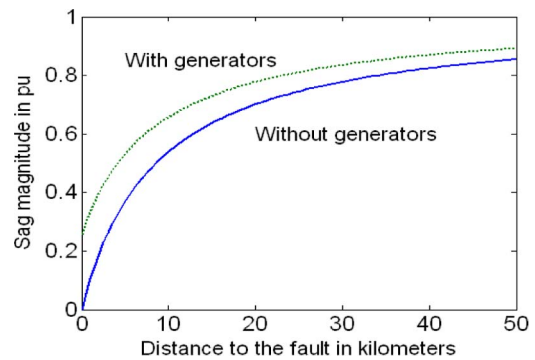

Fig. 11. Voltage sag magnitude versus distance.

faults at a 132-kV feeder, when the 6.6-kV generators are not in operation. In that case, the voltage sag magnitude at the 6.6-kV bus equals the voltage sag magnitude at the 132-kV bus as all load currents are neglected. The top curve of Fig. 11 gives the voltage sag magnitude at the 6.6-kV bus with the on-site generator connected. Due to the generator keeping up the voltage at the 6.6-kV bus, the voltage sag magnitude never drops below 26%. It shows that the local generation contributes in mitigating the effect of voltage sags.

VII. CONCLUSION

The assessment of voltage sags in a large chemical industry was done by using the method of critical distances, and the influence of local generation is discussed. The various exposed area contours were described for different voltage levels. The deep voltage sags occur due to faults occurring near the location of the sensitive load bus, and shallow sags occur due to faults occurring away from the sensitive load bus. In general, the local generation contributes to mitigating voltage sags.

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C. P. Gupta (M'03) received the B.E. degree from Malaviya Regional Engineering College, Jaipur, India, in 1987, the M.E. degree from the University of Roorkee, Roorkee, India, in 1990, and the Ph.D. degree from the Indian Institute of Technology Kanpur, Kanpur, India, in 2001.

He is currently an Assistant Professor in the Department of Electrical Engineering, Indian Institute of Technology Roorkee, Roorkee, India. From 2001 to 2004, he was a Research Associate, and in 2005, he was an Academic Visitor in the School of Electrical and Electronics Engineering, University of Manchester (formerly the University of Manchester Institute of Science and Technology), Manchester, U.K. His research interests include power quality, voltage instability, and power system dynamics.

G. K. Singh received the B.Tech. degree in electrical engineering from the G. B. Pant University of Agriculture and Technology, Pantnagar, India, in 1981, and the Ph.D. degree in electrical engineering from Banaras Hindu University, Varanasi, India, in 1991.

He worked in industry for nearly five and a half years. In 1991, he joined M. N. R. Engineering College, Allahabad, India, as a Lecturer. In 1996, he moved to the University of Roorkee, Roorkee, India. He is currently a Professor in the Department of Electrical Engineering, Indian Institute of Technology Roorkee, Roorkee. He has been involved in the design and analysis of electrical machines, in general, and high-phase-order ac machines, in particular, and power system harmonics and power quality. He has coordinated a number of research projects sponsored by the Council of Scientific and Industrial Research (CSIR) and University Grants Commission (UGC), Government of India. He has served as a Visiting Associate Professor in the Department of Electrical Engineering, Pohang University of Science and Technology, Pohang, Korea, and as a Visiting Professor in the Department of Electrical and Electronics Engineering, Middle East Technical University, Ankara, Turkey.

Dr. Singh received the Pt. Madan Mohan Malaviya Memorial Medal and the Certificate of Merit Award 2001–2002 of The Institution of Engineers (India).

A. K. Goswami (S'08–M'10) received the B.Tech. degree in electrical engineering from the National Institute of Technology, Kurukshetra, India, in 1997, the M.E. degree in electrical engineering from the Birla Institute of Technology, Mesra, India, in 2005, and the Ph.D. degree in electrical engineering from the Indian Institute of Technology Roorkee, Roorkee, India, in 2010.

He worked with the Hydro Electric Power Project. In 2005, he joined the Department of Electrical and Electronics Engineering, National Institute of Science and Technology, Berhampur, India, as a Senior Lecturer. He is currently an Assistant Professor in the Department of Electrical Engineering, National Institute of Technology Silchar, Silchar, India. His research interests include power system reliability, digital signal processing, and voltage sag analysis.