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Cost Analysis of Trips in Chemical Industry due to Line Faults with flexible controller

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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**.** Predication of number of voltage sags seen by a sensitive load requires a sag calculation for every possible fault on the distribution system. The overall estimated number of voltage sags then is the sum of the individual instances. Calculation demonstrates how the author estimated the number of trips seen by a sensitive load in a distribution system.

Keywords— Critical distance, industrial power supply, power quality, voltage sag, distribution system, short-circuit faults, industry, sensitive load

1. 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]. Voltage sags are the most frequent among various types of power-quality disturbances (e.g., voltage sag, voltage swells, over voltages, interruptions, transients, voltage unbalance, volt age flickers, and harmonics) [1]. 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 [2]-[16], [18] 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

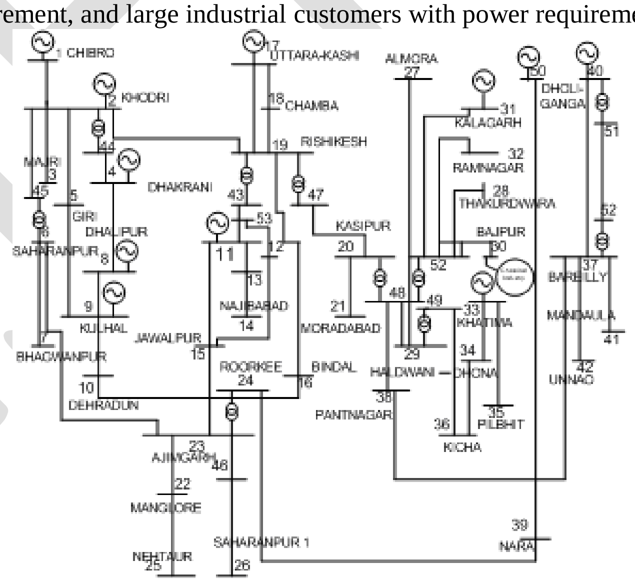

Figure 1.1 Uttarakhand State Transmission Systems

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. as in Fig.1.1 (UPCL) [17]. 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 (O_2, N_2)], 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 25000 MT of CO2 emission reductions per annum. Also, the utilization of effluent/waste (spent wash) in the boiler as fuel after evaporation produces 100 000 MT of CO2 emission reduction per annum. The industry has its own captive power plant consisting of two diesel generators of 4MWeach, which are using the by-product of the industry as fuel as shown in Fig. 1.2. The total power requirement of the plant is 19 MW, so the rest of the 11 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 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 [13]. 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.

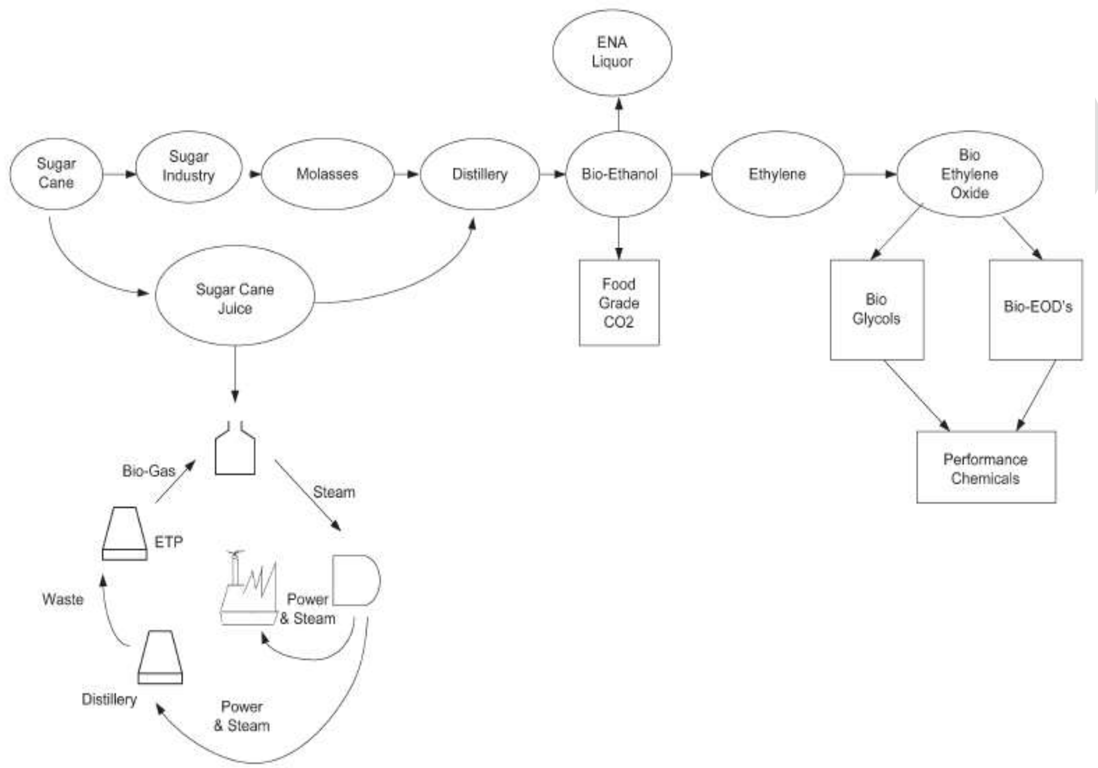

Fig. 1.2 Process Methodology and Captive Power Generation for Chemical Industry [13].

2. 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. 1.2 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 [13].

3. 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 [1]. However, the method of critical distances is applicable for a radial system only. To quantify the sag magnitude in a radial system, the voltage divider model as shown in Fig.3.1 is used.

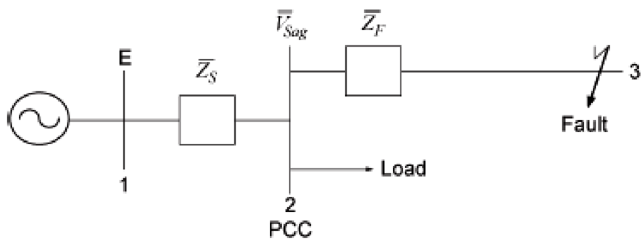

Fig.3.1 Voltage Divider Model

The expression for voltage sag at the PCC can be expressed as

$$\boldsymbol{V}_{\mathbf{sag}} = \mathbf{E} * \frac{\mathbf{Z_F}}{\mathbf{Z_F+Z_S}} \qquad (3.1)$$

where

Z_s is the source impedance

Z_F=z*l

z is the feeder impedance per unit length

l is the distance of fault position from the point of common coupling (PCC).

Assuming the pre-fault voltage (E) is assumed to be 1.0 per unit.

The voltage sag magnitude in (p.u) as per Eqn. (3.1) is

$$\boldsymbol{V}_{\mathbf{sag}} = \frac{\mathbf{Z_F}}{\mathbf{Z_F+Z_S}} \qquad (3.2)$$

The above equation is the voltage magnitude as a function of the distance. From this equation we obtained the distance at which a fault will lead to voltage sag of certain magnitude. The PCC is the point from which both fault and the load are fed. In case the voltage at PCC drops below the critical voltage V_{crit} over a particular duration, the equipment will trip for all faults within a critical distance L_{crit} from the PCC.

The expression for the magnitude voltage at PCC (V)

$$\mathbf{V} = \frac{\lambda}{1+\lambda} * \frac{1}{\sqrt{1-\frac{2\lambda(1-\cos\alpha)}{(1+\lambda^2)}}} \qquad (3.3)$$

where

$$\lambda = \frac{\mathbf{Z_F}}{\mathbf{Z_S}} = \frac{\mathbf{z*l}}{\mathbf{Z_S}} \qquad (3.4)$$

To obtain an expression for the critical distance, λ needs to be solved from Eqn.3.4 for known V. therefore, Eqn.3.3 is rewritten into the second order polynomial equation

$$\lambda^2(\mathbf{V}^2-\mathbf{1}) + \mathbf{2}\lambda\mathbf{V}^2\cos\alpha + \mathbf{V}^2 = \mathbf{0} \qquad (3.5)$$

The positive solution of Eqn.3.5 can be written as

$$\lambda = \frac{V}{1-V}\left[\frac{V\cos\alpha+\sqrt{1-v^2\sin^2\alpha}}{v-1}\right] \tag{3.6}$$

on putting the value of λ from Eqn.3.4 in Eqn.3.6, the desired expression for the critical distance L_{crit} is given by

$$L_{crit} = \frac{Z_s}{z} * \frac{V_{crit}}{1-v_{crit}} * \left[\frac{V_{crit}\cos\alpha+\sqrt{1-v_{crit}^2}\sin^2\alpha}{V_{crit}+1}\right] \tag{3.7}$$

where

$\alpha = tan^{-1}\left(\frac{X_F}{R_F}\right) - tan^{-1}\left(\frac{X_S}{R_S}\right)$ is the impedance angle between the source impedance Z_s and the feeder impedance Z_f as shown in Fig.3.2

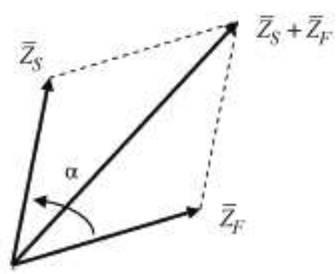

Fig. 3.2 Impedance Angle.

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

$$L_{crit} = \frac{Z_s}{z} * \frac{V_{crit}}{1-v_{crit}} \tag{3.8}$$

4. CALCULATION OF NUMBER OF TRIPS FOR DIFFERENT LINE FAULTS

4.1 Calculation of Number of Trips for Single Line to Ground Faults

For single phase fault, source impedance is the sum of positive, negative and zero sequence impedances. The feeder impedance is the combination of feeder length of F_2 which is 12km long with impedance (z, i.e. feeder) of per unit per km. The average number of faults event per year is considered as the fault rate(r) and this is given from the industry.

For a voltage sag level (V_{sag}) at the feeder bus, the feeder length of exposure L (critical distance) can be determined by Eqn. (3.1).

The data collected from the chemical industry are given below.

Source impedance Z_{s1} (p.u) = (4.94 + j65.9) + (787 + j220)

$|Z_{s1}|$ = (841.966)

Feeder impedance Z_{f1} (p.u) = z*L = (9.7 + j26) + (18.4 + j112)

$|Z_{f1}|$ = (140.831)

Fault rate(r) = 0.645 faults/km/year

$$L_{crit} = \frac{V_{sag} * Z_s}{(1-V_{sag}) * Z_f} \tag{3.9}$$

where

L_{crit} is critical distance

V_{sag} is given sag voltage

Z_s is per unit source impedance to the feeder

Z_f = feeder impedance=z*L

z is feeder impedance per unit per km.

L is feeder length in km

The number of trips per year for given fault rate (r) is given by Eqn. 3.2

$$\mathbf{Trips} = \mathbf{L_{crit}} * r \tag{3.10}$$

Now using Eqn.3.9 and Eqn.3.10 the length of exposure (L_{crit}) and total number of trips for single line to ground fault(SLG) for given sag voltage (V_{sag}) has been calculated as shown in Table 4.2

Table 4.1 Data Collected from the Chemical Industry

IMPEDANCE	SLG FAULT	DLG FAULT	TPG FAULT
SOURCE(Z_S)	(4.94 + j65.9) + (787 + j220)	(4.94 + j65.9)	(787 + j220)
FEEDER(Z_F)	(9.7 + j26) + (18.4+ j112)	(9.7 + j26)	(18.4 + j112)

Table 4.2 Values of the Length of Line Exposure and Number of Trips for SLG Fault

FAULT POINT	SAG VOLTAGE (V_{SAG}) %	LENGTH OF LINE EXPOSURE L_{CRIT}(KM)	TRIPS FOR SLG FAULTS PER YEAR
f_1	0.1	0.6948	0.4481
f_2	0.2	1.5633	1.0083
f_3	0.3	2.6799	1.7285
f_4	0.4	4.1687	2.6888
f_5	0.5	6.2531	4.0332
f_6	0.6	9.3796	6.0499
f_7	0.7	14.5906	9.4109
f_8	0.8	25.0124	16.1330
f_9	0.9	56.2779	36.2992
TOTAL TRIPS PER YEAR (T1)			77.7999

4.2 CALCULATION OF NUMBER OF TRIPS FOR PHASE TO PHASE FAULT

For phase to phase faults, source and feeder impedance is the sum of positive and negative sequence impedances

The data collected from the industry are given below.

Source impedance Z_{s2} (p.u) = (4.94 + j65.9)

$|Z_{s2}|$ (p.u) = (65.1873)

Feeder impedance Z_{f2} (p.u) = (9.7 + j26)

$|Z_{f2}|$ (p.u) = (27.75)

Failure rate = 0.645faults/km/year

Now using Eqn. 5.1and Eqn. 5.2 the length of exposure (L_{crit}) and total number of trips per year for phase to phase fault for given sag voltage (V_{sag}) has been calculated as shown in Table 4.3

Table 4.3 Values of the length of Line Exposure and Number of Trips for Phase to Phase Fault

FAULT POINT	SAG VOLTAGE (V_{SAG}) %	LENGTH OF LINE EXPOSURE L_{CRIT}(KM)	TRIPS FOR PHASE TO PHASE FAULTS PER YEAR
f_1	0.10	0.2646	0.1707
f_2	0.20	0.5953	0.3840
f_3	0.30	1.0205	0.6582
f_4	0.40	1.5875	1.0239
f_5	0.50	2.3813	1.5359
f_6	0.60	3.5719	2.3039
f_7	0.70	5.5563	3.5838
f_8	0.80	9.5250	6.1437
f_9	0.90	21.4314	13.828
TOTAL TRIPS PER YEAR (T2)			29.6273

4.3 CALCULATION OF NUMBER OF TRIPS FOR THREE PHASE FAULT

For three phase fault, source and feeder impedances are positive sequence impedances since this fault is symmetrical and the values are given below.

Z_{s3} (p.u) = (787 + j220)

$|Z_{s3}|$ (p.u) = (817.17)

Z_{f3} (p.u) = (18.4 + j112)

$|Z_{f3}|$ (p.u) = (113.50)

Failure rate = 0.645faults/km/year

The length of line exposure (L_{crit}) and total number of trips for three phase fault for a given sag voltage (V_{sag}) has been calculated by using Eqn.5.1and Eqn.5.2 and is shown in Table 4.4.

Table 4.4 Values of the length of Line Exposure and Number of Trips for Three Phase Fault

FAULT POINT	SAG VOLTAGE (V_{SAG}) %	LENGTH OF LINE EXPOSURE L_{CRIT}(KM)	TRIPS FOR THREE PHASE FAULTS PER YEAR
f_1	0.10	0.800	0.5160
f_2	0.20	1.7999	1.1610
f_3	0.30	3.0856	1.9902
f_4	0.40	4.7998	3.0959
f_5	0.50	7.1997	4.6438
f_6	0.60	10.7996	4.9657
f_7	0.70	16.7994	10.8356
f_8	0.80	28.7989	18.5753
f_9	0.90	64.7976	41.7945
TOTAL TRIPS PER YEAR (T3)			89.5780

Table 4.2, Table 4.3, Table 4.4 shows the expected number of trips per year caused by single line to ground fault, phase to phase fault, and three-phase faults on different fault locations for the above system. The overall number of voltage sags that may be experienced

by the sensitive loads can then be calculated by summing up the number of voltage sags caused by each individual fault. Therefore the total number of trips for all three types of faults are T1+T2+T3=197.0052 per year.

5. CALCULATION OF FINANCIAL LOSSES

As the number of trips with all three type of faults per year are very high which affect the productivity and also financial loss associated with trips of the industry. Therefore it is very necessary to calculate and find the solution to reduce it.

5.1 COST ANALYSIS WITHOUT INCORPORATING ANY MITIGATION DEVICES

The financial loss for one process trip is approximately 0.02 million rupees/year as per the record of industry and the total number of process trips is calculated as 197.0052 for all the three types of faults in previous section by the author.
Therefore the approximate financial loss for that much number of trips = 197.0052*0.02 = 3.9401 million rupees/ year.
This is a huge financial loss due to process trip and also it affects the production and cost the industry. Therefore it is very necessary to reduce this loss.
The two FACTS devices named D-STATCOM and SVC are proposed to reduce the electrical and economic losses and also improve the power quality.

5.2 COST ANALYSIS OF MITIGATION STRATEGIES

The expected annual financial losses due to voltage sags are too high. Therefore for the minimization of financial losses, managements have a choice to install one of two types of mitigation devices D-STATCOM or SVC with respect to cost.
The approximate load at industry bus is 11MW, power factor of 0.95. So the reactive power requirement is 3.6 MVAR.
As per the data[19], after installation of a mitigation device DSTATCOM or SVC, the expected number of process trips is reduced to 26.55% with D-STATCOM i.e. 46.85 trips/year then the calculated value of 197.0062 trips per year similarly with SVC, the expected number of process trips is reduce to 36.45% i.e. 64.32 trips/year.
Therefore the associated financial losses due to voltage sags are also reduced with the reduction of the process trips.

Therefore the associated financial loss with the use of D-STATCOM and SVC is calculated below.
The approximate loss for one process trip is = 0.02 million rupees/year (collected from industry).
The financial losses with D-STATCOM = 46.85 trips/year*0.02 million rupees/year
= 0.937 million rupees/year
Similarly financial losses with SV = 64.32*0.02million rupees/year
=1.2864million rupees/year
Saving in losses on using D-STATCOM = 3.9401-0.937
=3.0031million rupees/year
Similarly
Saving in losses for SVC = 3.9401-1.2864
= 2.6537 million rupees/year
The maintenance cost of D-STATCOM = 1.032 million rupees/year (collected from industry) and the maintenance cost of SVC = 0.83 million rupees/year (collected from industry)
Therefore,
Net saving for DSTATCOM = 3.0031-1.032 = 1.9711 million rupees/year
Net saving for SVC = 2.6537 - 0.83 = 1.8237 million rupees/year
Hence it is observed that DSTATCOM is more beneficial then SVC.

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CONCLUSION

This paper presents a method for the assessment of voltage sags caused by short-circuits line faults in a large chemical industry. The expected annual financial losses due to voltage sags are too high when no compensation is used, and the no of trips and the financial losses associated with trips is also very much reduced when compensation is used . Therefore for the minimization of financial losses, industry has a choice to install one of two types of mitigation devices D-STATCOM or SVC with respect to cost. The DSTATCOM is found a better option to reduce the losses due to sag.

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