Voltage Sag Assessment by Considering Financial Losses and Equipment Sensitivity

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Abstract

This paper presents a method for determining the network lines and buses where the occurrence of faults will lead to voltage sags causing severe financial losses in the power system. The proposed method is based on a typical stochastic assessment of voltage sags. The network regions where fault occurrences will simultaneously lead to voltage sags at different sensitive load points can be determined by an area of severity (AOS) analysis. The damage infliction ranking of network lines is also addressed. The ranking of damage infliction is determined from the results of estimation of financial losses due to voltage sags caused by faults on each line. The financial losses are calculated by using the annual expected number of trips of sensitive equipment and the tripping costs per sag event of the equipment. The damage infliction ranking is useful for establishing efficient planning for the mitigation of financial damage due to voltage sags and evaluating the relationship between sensitive equipment and system voltage sag performance.

Keywords
Area of Severity, Equipment Sensitivity, Power Quality, Power System, Voltage Sag

1. Introduction
Voltage sags usually cause severe damage to many industrial processes using sensitive equipment. A single voltage sag can cause the trip of sensitive equipment in a process and such damage can stop the entire process. With the rising use of sensitive electronic equipment, voltage sag is considered to be the most important power quality problem in modern industrial processes. As there are far more voltage sags than interruptions, the total production and financial losses due to voltage sags are still large (Bollen 2000). In order to improve voltage sag performance and devise efficient solutions to mitigate damage due to voltage sags, an assessment of system performance is basically needed. In this paper, an effective method for assessing system voltage sag performance by considering equipment sensitivity and financial losses due to voltage sags is presented. In the remaining sections of this paper, an overview of the stochastic assessment of voltage sags is presented. The damage infliction ranking of network lines are also addressed. The network regions where fault occurrences will simultaneously lead to voltage sags at different sensitive load points can be determined by an area of severity (AOS) analysis. The network lines where the occurrence of faults will cause severe financial losses can be identified from the damage infliction ranking.

2. Stochastic Assessment of Voltage Sags

2.1 Area of Vulnerability (AOV)
The stochastic assessment of voltage sags calculates the annual expected sag frequency (ESF) at an individual sensitive load point or system bus by using the concept of the AOV and system fault statistics. The AOV and the fault rates of system components are important factors in voltage sag assessment. Therefore, accurate network model and the reliability data of fault statistics should be provided. Many methods for stochastic assessment of voltage sags have been addressed (Qader et al. 1999, Lim and Strbac 2000, Aung et al. 2004, Park and Jang 2007). The accurate

determination of AOV for sensitive loads is a key point in the stochastic assessment of voltage sags. The AOV is the region of the power system where the occurrence of faults will lead to voltage sags at a given load point (Park and Jang 2007). Figure 1 shows an example of the AOV of specific sensitive equipment. When faults occur anywhere within the dark area, the sensitive equipment will be damaged due to voltage sags. Because the characteristics of voltage sags vary according to the types of faults and the unbalanced faults affect the three phases differently, the AOV should be separately determined for each fault type (i.e., Single line-to-ground fault (SLGF), Line-to-line fault (LLF), Double line-to-ground fault (DLGF), and Three phase fault (3PF)) and for phase (Aung et al. 2004)

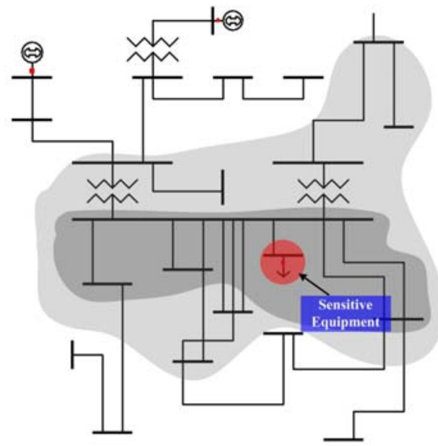


Figure 1: Example of AOV

2.2 Equipment Sensitivity to Voltage Sags

Different types of equipment have different sensitivity to voltage sags. In order to estimate the ESF at a specific equipment terminal, it is necessary to understand the equipment sensitivity to voltage sags (Park and Jang 2007). The magnitude and duration are essential characteristics of voltage sags. Therefore, the equipment sensitivity to voltage sags is usually expressed in terms of the magnitude and duration of voltage sag (Milanovic, and Gupta 2006) The sensitivity of individual equipment to voltage sags can be obtained from the equipment manufacture, standards available, or through laboratory tests (Milanovic, and Gupta 2006). Generally, the Information Technology Industry Council (ITIC) and Computer Business Equipment Manufacturers Association (CBEMA) curves can be used as a reference for voltage-tolerance characteristics of equipment (Heydt et al. 2001). The lower curves of the ITIC and CBEMA curves can be considered as the equipment sensitivity to voltage sags. In this paper, the rectangular type curve of voltage-tolerance like the ITIC curve is used to define the sensitivity of equipment.

3. Area of Severity (AOS)

3.1 The AOS for Sensitive Equipment

Park et al. (2010) addressed the concept of AOS. The AOS is defined as the region of the network where the occurrence of faults will simultaneously lead to voltage sags at different sensitive load points. The AOS can be determined by overlapping the AOVs of sensitive loads. Diagrammatically, the AOS is the intersection region of different AOVs. The AOS has levels of severity. If the number of sensitive loads is N, the AOS has different N levels. The AOS_N (i.e., the AOS of level N) is the area where the occurrence of faults will lead to voltage sags at all the sensitive load points. On the other hand, the fault occurrences in the AOS_1 will lead to voltage sags at only one of the N sensitive load points. Figure2 shows an example of the AOS for three different types of sensitive equipment. The AOS is determined by overlapping the three AOVs of the sensitive equipment (A, B, and C). The fault occurrences in the AOS_3 will lead to voltage sags causing damage to all the equipment. Therefore, the AOS_3 is the most vulnerable area for the equipment. It is expected that fault occurrences in the AOS_3 will cause more severe financial damage than fault occurrences in the AOS of other levels. In our study, the AOV and the AOS were determined by using a method based on quadratic interpolation and the secant method (Park and Jang 2007). The critical points and the AOV on each network line are determined by using the quadratic formula and the secant method. The critical points are the fault positions where fault occurrences lead to sag voltages equal to the sensitivity threshold of equipment. The sensitivity threshold (voltage threshold) is defined as the minimum rms voltage for a certain duration that a piece of equipment can withstand without misoperation or failure (Dugan et al. 2002). After determining the critical points and the AOVs for the sensitive equipment of interest, the AOS can be obtained by overlapping the AOVs.

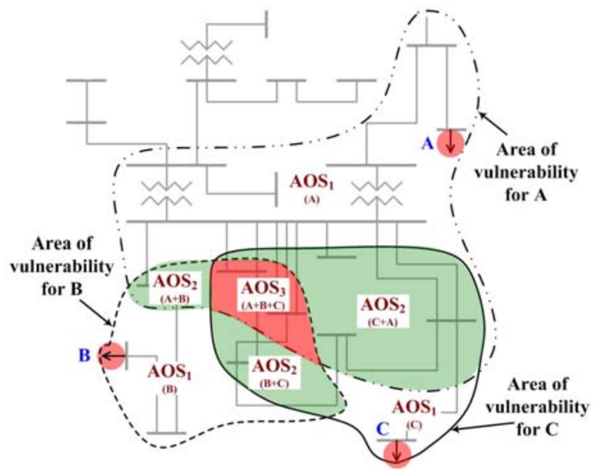


Figure 2: AOS for three different sensitive load points (A, B and C) (Park et al. 2010)

3.2 Equipment Types and Connections

Equipment types (single-phase or three-phase equipment) and connections (line-to-natural or line-to-line connection) should be considered for the determination of the AOS due to unbalanced faults. The AOS varies with the equipment types and connections to the supply. A SLGF can occur at any phase of a three-phase system (i.e., Phase a, b, or c), and a LLF or DLGF occurs between different two phases of a three-phase system (i.e., a-b, b-c, or c-a) (Aung and Milanovic 2006). Generally, the voltages in the faulted phases mainly dropped whereas in the non-faulted phases remain more or less unchanged or rise (Park and Jang 2007). Considering the effect of transformer winding connections (e.g., delta-wye or wye-delta), the voltages in non-faulted phases can be dropped below the voltage threshold of equipment (Park and Jang 2007). Assuming that two pieces of single-phase equipment are connected to different phases and the effect of transformer winding connections are ignored, the AOS_2 due to SLGFs would not exist. That is, any SLGF occurrence in the network will not lead to simultaneous voltage sags at the two equipment points. Therefore, in the case of SLGFs, the AOS_1 for each of the two pieces of equipment only exists. Therefore, the AOS due to unbalanced faults should be determined after suitable consideration for the relation between equipment connected to phases and the faulted phases. In this paper, we assume that all sensitive equipment is single-phase type and the equipment is connected to the same phase.

4. Damage Infliction Ranking

4.1 Financial Losses due to Voltage Sags

Modern process controls are very sensitive to voltage sags. Some pieces of equipment trip when the rms voltage drops below 90% for longer than one or two cycles (Bollen 2000). The trip of the sensitive equipment can lead to severe production and financial losses in industrial processes. The financial losses may rise as the occurrences of voltage sags increase. Therefore, the accurate estimation of ESF at a specific load point is very important to the assessment of expected financial losses due to voltage sags. Several studies of the assessment of financial damage due to voltage sags have been addressed (Gupta et al. 2004, Milanovic and Gupta 2006). The prediction of financial losses due to voltage sags incurred in a specific customer site is not easy. This is because many different types of equipment are participating in the customer process and the equipment is interconnected mutually (Milanovic and Gupta 2006). In order to assess the financial losses to a specific customer process, the some information (i.e., the process type, the customer type, the sensitivity of equipment participating in the process, and the associated damage cost per sag event) should be available (Milanovic and Gupta 2006). Milanovic and Gupta (2006) addressed a method for probabilistic assessment of the individual customer and total network financial losses due to interruptions and voltage sags. In this paper, we assume that the financial damage per sag event corresponding to a single tripping of specific equipment is available.

4.2 Determination of Damage Infliction Ranking

The damage infliction ranking is defined as the order of network lines and buses according to the severity of financial losses due to voltage sags caused by faults on each line and each bus. From the damage infliction ranking, we can find the lines and buses where the occurrence of faults will cause more severe financial damage than others. In order to determine the damage infliction ranking, the expected financial losses caused by faults on each line and each bus should be calculated.

The damage infliction ranking can be determined as follows:

1) The AOVs for the sensitive equipment of interest are determined.

2) The expected numbers of voltage sags (the expected number of trips of the equipment) caused by faults on each line and each bus are calculated.

3) The expected financial losses are calculated by multiplying the financial damage per sag event by the expected numbers of voltage sags caused by faults on each line and each bus.

4) The damage infliction rankings of the lines and buses are determined according to the severity of the expected financial losses caused by faults on each line and each bus.

The financial losses due to each of the line faults and each of the bus faults are also separately calculated for each fault type and for each phase. The financial losses caused by the three unbalanced faults on line L and bus B can be calculated:

$$FLB(B)_{UF} = \sum_{i=1}^{3}\sum_{j=1}^{3}\sum_{S=1}^{N} I_{Sij} \times BFR_i \times FL_S \tag{1}$$

$$FLL(L)_{UF} = \sum_{i=1}^{3}\sum_{j=1}^{3}\sum_{S=1}^{N} I_{Sij} \times LL_{Sij} \times LFR_i \times FL_S \tag{2}$$

The financial losses caused by the balanced faults on line *L* and bus *B* can be calculated:

$$FLB(B)_{BF} = \sum_{S=1}^{N} I_{S41} \times BFR_4 \times FL_S \tag{3}$$

$$FLL(L)_{BF} = \sum_{S=1}^{N} I_{S41} \times LL_{S41} \times LFR_4 \times FL_S \tag{4}$$

Assuming that all equipment is single-phase type, the expected financial losses due to faults on line *L* and bus *B* can be calculated as

$$FLB(B) = FLB(B)_{UF} \,/\, 3 + FLB(B)_{BF} \tag{5}$$

$$FLL(L) = FLL(L)_{UF} \,/\, 3 + FLL(L)_{BF} \tag{6}$$

where

FLB(B) financial loss caused by faults on bus *B*

FLL(L) financial loss caused by faults on line *L*

S sensitive equipment

N total number of sensitive equipment

I_{Sij} conditional number (1 for the bus *B* or line *L* inside AOV for the equipment *S* (for fault type *i* and for phase *j*), and 0 for the bus *B* or line *L* outside the AOV)

FL_S financial loss per sag event at the point of equipment S

LL_{Sij} length of the line *L* inside AOV for the equipment *S* (for fault type *i* and for phase *j*)

For example, assuming that three sensitive pieces of equipment (A, B and C) are in a network; the AOS due to 3PFs of the general line *F-T* is as shown in Figure 3.; the fault rate of the line is 5.0 (event/100km/year); and the tripping costs per sag event of the equipment are 3,000 ($/event), 4,000 ($/event) and 5,000($/event), respectively, the annual expected financial loss can be calculated:

$$FLL\,(L_{F-T})_{BF} = (1\times 20\times 0.05\times 3{,}000) + (1\times 10\times 0.05\times 4{,}000) + (1\times 5\times 0.05\times 5{,}000) = 6{,}250$$

The expected financial loss due to 3PF on the line *F-T* is calculated at 6,250 ($/year).

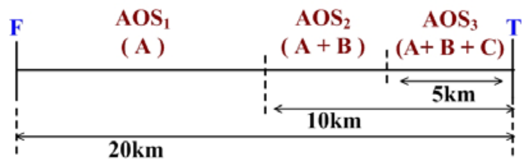


Figure 3: The AOS and the exposed lengths on line *F-T*

5. Case Study

5.1 The System and Case under Study

The case study in this paper was carried out using the IEEE 30-bus test system as shown in Figure 4. This system has four transformers, 37 lines, six generators and 21 loads. The detailed system data are available from Park and Jang (2007). The assumed sag durations considering the fault clearing time are given in Table 1. Because the fault rate of system bus was remarkably lower than the line fault rate, the expected financial losses due to bus faults and damage infliction ranking of the buses were ignored. The fault rates for lines were 4.2 (event/100km/year), respectively. The fault type distribution was assumed: 80% (SLGF), 5% (LLF), 11% (DLGF) and 4% (3PF). The detailed system fault statistics used in the case study are listed in Table 2. Three different types of sensitive equipment A, B, and C were assumed to be connected to buses 14, 20, and 29, respectively. The voltage-tolerance curves of the equipment are as shown in Figure 5 (a), (b), and (c). The voltage thresholds for the assumed sag durations were determined from the voltage-tolerance curves. The tripping costs per sag event of the equipment (A, B, and C) were assumed to be 5,000 ($/event), 10,000 ($/event) and 15,000 ($/event), respectively.

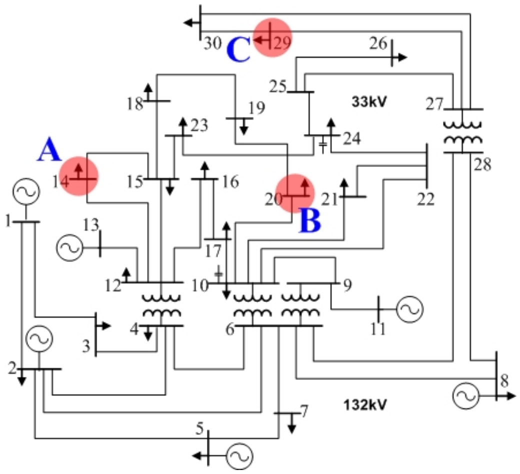


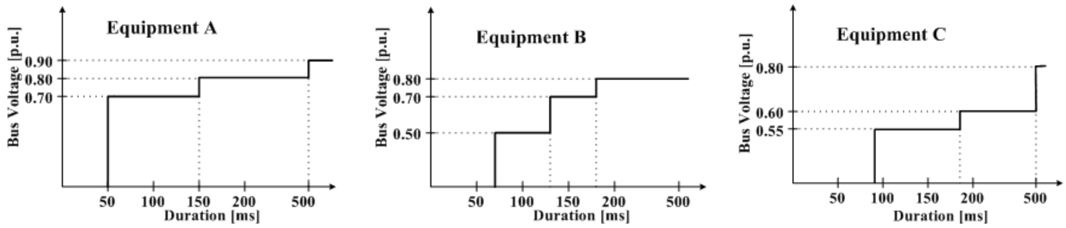
Figure 4: Single-line diagram of IEEE-30 bus system

Table 1: Assumed sag durations at different voltage levels

Voltage Level (kV)	Duration (ms)
132	100
33	200

Table 2: Line fault rate

Type of Fault	Line Fault Rate (Event/100km/year)
SLGF	3.360
LLF	0.210
DLGF	0.462
3PF	0.168



(a) (b) (c)

Figure 5: Voltage-tolerance curves (a) Equipment A (b) Equipment B (c) Equipment C

5.2 Results

The AOS for the three pieces of equipment was determined from the AOV for the equipment. Also, the expected numbers of voltage sags and the expected financial losses, according to severity levels of the AOS, were calculated. The three pieces of equipment will simultaneously be damaged by about 4 voltage sags per year. The number of voltage sags expected to damage only equipment C was calculated at about 3 times per year. The damage infliction ranking of the lines was determined. We calculated the annual expected financial losses due to faults on each line. The ESFs for the AOS and the expected financial losses are reported in Table 3. The damage infliction ranking of the lines is illustrated in Figure 6. From the results, we can expect that the financial loss due to the faults on line 4-6 will be the most severe. On the other hand, the faults on line 5-7 are expected to cause the least financial loss.

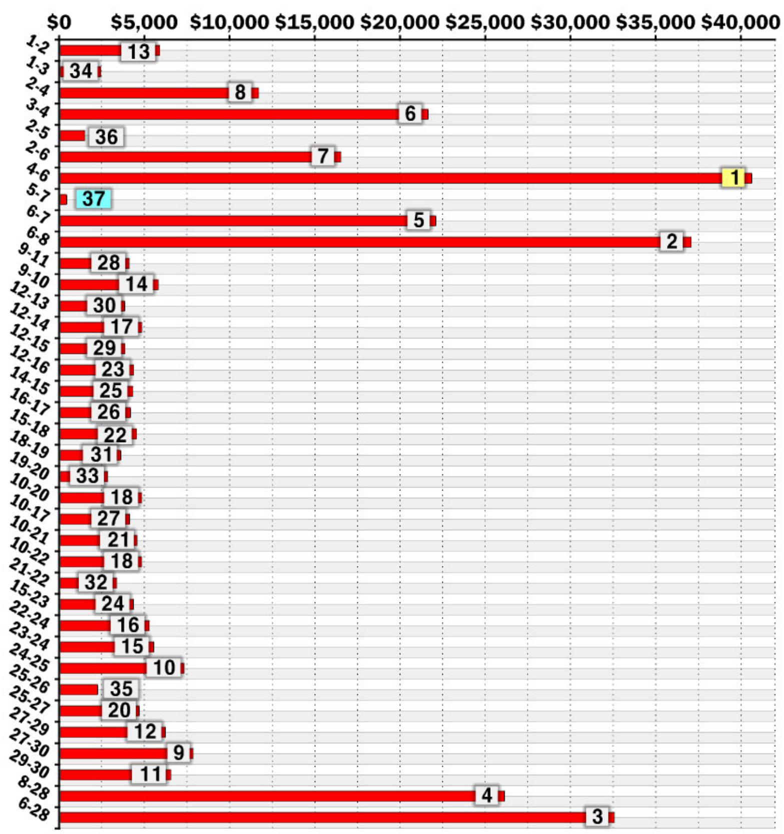


Figure 6: The damage infliction ranking of lines

Table 3: ESFs and expected financial losses caused by faults on lines

Line	ESF (event/year)							Financial Loss ($/year)
	AOS_3	AOS_2			AOS_1			
	A+B+C	A+B	B+C	C+A	A	B	C	
1-2				0.215	0.313			5,865
1-3				0.032	0.354			2,410
2-4	0.068			0.340	0.564			11,660
3-4	0.243			0.580	0.543			21,605
2-5				0.056	0.068			1,460
2-6	0.189			0.475	0.127		0.045	16,480
4-6	1.283			0.103	0.010			40,600
5-7				0.019	0.002			390
6-7	0.333			0.521	0.008		0.107	22,055
6-8	0.914			0.472			0.012	37,040
9-11	0.020	0.155				0.114		4,065
9-10	0.162	0.061						5,775
12-13	0.005	0.243						3,795
12-14	0.002	0.315			0.004			4,805
12-15	0.007	0.241						3,825
12-16	0.004	0.281						4,335
14-15		0.284			0.005			4,285
16-17		0.276						4,140
15-18		0.300						4,500
18-19		0.238						3,570
19-20		0.187						2,805
10-20	0.027	0.266						4,800
10-17	0.056	0.161						4,095
10-21	0.089	0.124						4,530
10-22	0.067	0.186						4,800
21-22	0.048	0.126						3,330
15-23		0.288						4,320
22-24	0.091	0.163				0.007		5,245
23-24	0.040	0.282				0.008		5,510
24-25	0.106	0.082	0.045			0.003	0.115	7,290
25-26			0.003				0.143	2,220
25-27			0.028				0.264	4,660
27-29			0.000				0.413	6,195
27-30			0.000				0.521	7,815
29-30							0.434	6,510
8-28	0.002			0.339	0.001		1.283	26,090
6-28	0.490			0.730			0.215	32,525
Total	4.246	4.259	0.076	3.882	1.999	0.132	3.552	335,400

In order to reduce the financial damage due to voltage sags, the number of fault occurrences on the network lines which are expected to cause severe voltage sag costs should be reduced. If the voltage sags caused by faults on five high-ranking lines (lines 4-6, 6-8, 6-28, 8-28 and 6-7) can be prevented, the total financial losses would be reduced by about 47%. Fault mitigation measures such as implementation a strict policy of tree trimming, insulator washing, installation additional shielding wires and increase the insulation level should be especially considered for the high ranked lines (Bollen 2000). Most faults on the line 4-6 will lead to voltage sags at all the equipment points. Therefore, voltage sag mitigation solutions for the line should be considered the sensitivity of all the equipment

6. Conclusion

This paper described a stochastic method for assessing system voltage sag performance by considering financial losses due to voltage sags. The damage infliction ranking of network line was also addressed. The line sections where the occurrence of faults will cause severe financial damage can be determined by the AOS analysis and the damage infliction ranking. The AOS and damage infliction ranking would be useful for assessing the voltage sag performance of a power system and establishing optimal plans to mitigate financial costs due to voltage sags.

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Biography

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