Stochastic Voltage Sag Prediction in Distribution System by Monte Carlo Simulation and PSCAD/EMTDC

T. Meananeatra and S. Sirisumrannukul

Abstract— *Voltage sag is defined as a temporary rms reduction in voltage typically lasting from a half cycle to several seconds. Voltage sag may produce unfavorable consequence in production processes if the process-control equipment trips. Therefore, analysis of voltage sags at a location of interest provides useful information for assessing the compatibility between equipment and the electrical supply. As the primary cause of voltage sag is due to faults that may occur anywhere in distribution systems, a Monte Carlo simulation method is proposed as the main tool for voltage sag prediction in this paper. The Monte Carlo simulation method is employed to capture stochastic behavior of fault consisting of fault location, initial time of fault, fault duration and fault type. PSCAD/EMTDC, which is a software package developed to simulate electric-magnetic transient phenomena, calculates voltage sag magnitude and duration. Power flow solution is obtained from the software PSS/E and used by the E-TRAN program to directly initialize the circuit in PSCAD/EMTDC. A distribution system of Metropolitan Electricity Authority (MEA) is tested in a case study. With the proposed methodology, the expected value of voltage sag magnitude and their probability distribution can be obtained. This information is useful for the utility and customers for voltage sag prevention.*

Keywords— **Monte Carlo simulation, PSCAD/EMTDC, sag duration, sag magnitude, voltage sag.**

1. INTRODUCTION

A variety of power quality problems exists in distribution systems but voltage sag is probably the most prominent one due to the fact that temporary faults are most often seen. Voltage sag is a temporary root mean square (rms) drop in voltage magnitude ranging from 0.1 per unit and 0.9 per unit of the nominal voltage and sag duration is one half cycle to one minute [1].

The problem of voltage sags is gaining importance because they affect industrial and large commercial customers whose production processes can be disrupted as a result of tripping of their sensitivity equipment such as adjustable speed drive, computers and computer-controlled equipment. The consequence of voltage sags may produce high economic loss of productivity.

The primary cause of voltage sag is due to faults that may occur anywhere in a system and cannot be eliminated completely. There are a number of factors associated with voltage sag such as location, the characteristics of utility's distribution system (underground, overhead, lengths of the distribution feeder circuits, and number of feeders), number of trees adjacent to the power lines, and several other factors [2].

This paper presents a methodology for predicting voltage sags characteristics caused by faults in a distribution system. Predicting voltage sag requires a tool that can provide information for the utility to identify the weak points or locations and to assist the utility' customers to select appropriate equipment specifications to assure the optimum operation of their production facilities [3].

A Monte Carlo simulation is proposed for voltage sag prediction in which time domain analysis is carried out using the PSCAD/EMTDC software package interfaced with PSS/E and MATLAB programs. The advantage of the proposed method is that the stochastic nature of faults can be statically captured with minor mathematical calculation involved. With our method, prefault voltage, a variety of fault types, sag magnitude, and sag duration can be taken into account. The developed tool is tested with a distribution system of Metropolitan Electricity Authority (MEA).

2. STOCHASTIC VOLTAGE SAG PREDICTION

There are basically two major methods for voltages sag assessment: analytical and simulation methods. Analytical methods, such as fault position [4], represent the system by analytical model and evaluate system indices using mathematical solutions. The Monte Carlo simulation method, on the other hand, estimates the system indices by simulating the actual process and random behavior of the system [5]. The analytical method is superior to the Monte Carlo simulation method in computation time because the Monte Carlo simulation method is normally computationally expensive to arrive at results with sufficient confidence. However, for systems with complex operating conditions or those in which parameters cannot be explicitly modeled, Monte Carlo methods are preferable.

Monte Carlo simulation mimics system behaviors and estimates system parameters by simulating the actual process. It does not solve the equations describing the model; instead the stochastic behavior of the model is

T. Meananeatra (corresponding author) is with Better Care and Power Quality Department, Metropolitan Electricity Authority 132/18, Soi Charansanitwong 20, Charansanitwong Rd., Banchanlor, Bangkoknoi, Bangkok, 10700, Thailand. Phone: +66-2878-5297; E-mail: tanit.m@mea.or.th.

S. Sirisumrannukul is with the Department of Electrical Engineering, Faculty of Engineering, King Mongkut's University of Technology North Bangkok, 1518, Pibulsongkram Rd., Bangsue, Bangkok, 10800, Thailand. Email: spss@kmutnb.ac.th.

simulated and observed for several iterations [6]. The simulation process is repeated until the solutions converge. The convergence can be confirmed when no significant variation in the solution is observed or the prespecified number of iterations has been reached. Monte Carlo simulation generally requires considerable computation time in order to obtain sufficient confidence in the results [7]. Alternatively, for the sake of computation time reduction without losing confidence in the accuracy of the results, a number of techniques based on variance reduction were developed and often employed, such as importance sampling, stratification, control variates and antithetic variates.

Every time the system is run, several quantities are randomly generated to represent fault characteristics whose probability distributions are normally predefined based on statistical behavior of fault. Two factors that describe voltage sag characteristic are sag magnitude and sag duration. Figure 1 shows a sag produced by a single line to ground fault at phase C in the test system detailed in Section 5. With this waveform, the sag occurs at phase C, while the voltages at phases A and B remain unchanged. The sag magnitude is 0.193 pu. with a duration of 71.2 milliseconds.

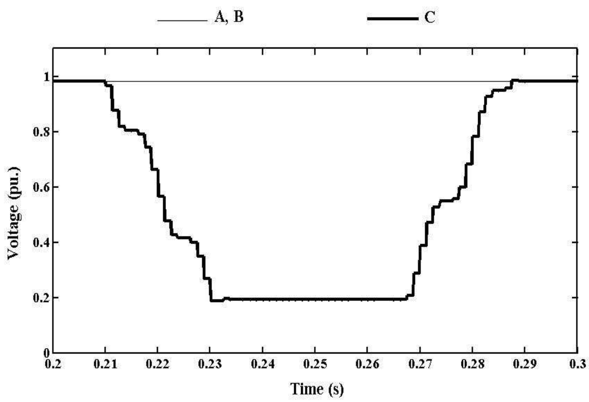

Fig.1. Voltage Sag Waveform.

In the process of Monte Carlo simulation, four parameters need to be randomly generated as follows.

a) Fault locations can be modeled by the method of fault position [8]. The main concept behind this method is that a fault can be originated from every single position on a distribution line (sending and receiving end buses are considered as points on the line). However, taking into consideration of all the points on the line, although possible, is time-consuming. Thus, a distribution line with equally divided intervals, say four segments as shown in Fig. 2, would be reasonably approximated. This approximation introduces three dummy buses between bus 1 and bus 2. Therefore, there are five possible locations exposed to faults.

The parameters associated with a probability distribution of fault position can be determined from past experience. However, without historical data, a density function for fault location can be based on the uniform density function. A fault location is mathematically expressed by (1).

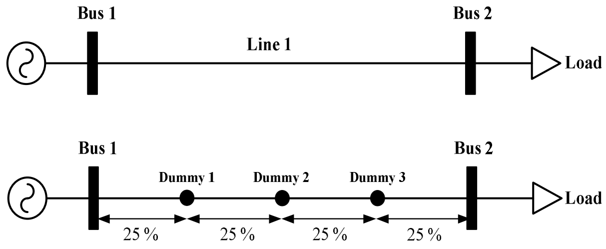

Fig.2. Method of Fault Position.

$$FL_i = \begin{cases} i = 1, & \text{if } 0 < U_1 \le 1 \\ i = 2, & \text{if } \frac{1}{n} < U_1 \le \frac{2}{n} \\ \bullet & \\ \bullet & \\ \bullet & \\ i = n-1, & \text{if } \frac{n-2}{n} < U_1 \le \frac{n-1}{n} \\ i = n, & \text{if } \frac{n-1}{n} < U_1 \le 1 \end{cases} \quad (1)$$

where i = bus index
n = total bus number
U_1 = uniform random number under [0,1]

b) The initial time of a fault is represented by a random number that is uniformly distributed within 1 cycle (50 Hz or 20 milliseconds).

$$FI = U_2, \quad \text{if } 0 < U_2 \le 0.02 \quad (2)$$

where FI = initial time of the fault
U_2 = uniform random number under [0,0.02]

c) The fault duration of voltage sag is assumed to be normally distributed with a mean and a standard deviation. For a given uniform random number under [0, 1], it can be converted to a normally distributed random number by an approximate inverse transform method [7].

$$X = \begin{cases} z, & \text{if } 0.5 < U_3 \le 1.0 \\ 0, & \text{if } U_3 = 0.5 \\ -z, & \text{if } 0 < U_3 < 0.5 \end{cases} \quad (3)$$

$$FD = (X \times \sigma) + \mu \quad (4)$$

where z = random variable calculated using the equations given in the appendix
U_3 = uniform random number under [0,1]
X = normally distributed random variants
μ = mean of fault duration
σ = standard deviation of fault duration
FD = fault duration

d) Fault types are classified as three-phase fault, double line-to-ground fault, line-to-line fault and single-line-ground fault. A probability distribution of fault type can be modeled by a discrete distribution derived in (5).

$$FT_j = \begin{cases} j=1, & \text{if } U_4 \le P_{LLL} \\ j=2, & \text{if } P_{LLL} < U_4 \le (P_{LLL}+P_{LLG}) \\ j=3, & \text{if } (P_{LLL}+P_{LLG}) < U_4 \le (P_{LLL}+P_{LLG}+P_{LL}) \\ j=4, & \text{if } (P_{LLL}+P_{LLG}+P_{LL}) < U_4 \le 1 \end{cases} \quad (5)$$

where j = fault index
FT_j = fault type
U_4 = uniform random number under [0, 1]
P_{LLL} = probability of occurrence of a three-phase fault
P_{LLG} = probability of occurrence of a double line-to-ground fault
P_{LL} = probability of occurrence of a line-to-line fault
P_{LG} = probability of occurrence of a line-to-ground fault

In practice, the values of the four probabilities can be determined from statistical collected data.

After bus voltages have been calculated, the expected bus voltage magnitude is given by the following equation:

$$\overline{V}_j = \frac{1}{N}\sum_{k=1}^{N} V_k \quad (5)$$

where $\overline{V}_j$ = expected value of sag magnitude at bus j
V_k = sag magnitude of iteration k
N = number of samples

The unbiased sample standard deviation for bus voltage magnitude is calculated from:

$$\sigma_j = \sqrt{\frac{1}{N-1}\sum_{k=1}^{N}\left(V_k - \overline{V}_j\right)} \quad (7)$$

where σ_j = sample standard deviation

Note that according to IEEE Std 493-1997 [9], V_k in (6) is considered from the lowest of three phase voltages for each sag event.

3. DEVELOPED SIMULATION TOOL

Power System Computer Aided Design (PSCAD)/ Electromagnetic Transients including DC (EMTDC) [9] is a fast, accurate, and user-friendly power system simulation software. The software is suitable for time domain simulation, particularly in transient periods. It contains extensive libraries of power and control system models organized in forms of circuit schematic. A user can construct a circuit, run a simulation, analyze the results, and manage data in graphical environment.

Although PSCAD/EMTDC offers a convenient way for voltage sag simulation, it still needs an interface with external subroutines that is able to perform special tasks. The proposed simulation tool links the multiple run option in PSCAD/EMTDC with PSS/E for calculating power flow solutions and with a module developed on MATLAB for data recording and post processing of output results. Figure 3 shows a flowchart of proposed stochastic simulation tool for voltage sag prediction. The duration of each run performed by PSCAD/EMTDC is 0.5 second with a time step of 0.1 milliseconds.

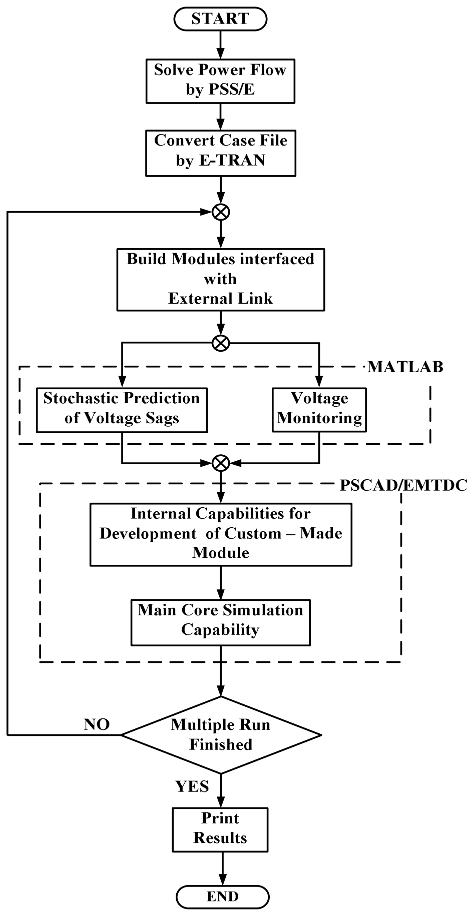

Fig.3. Developed Simulation Tool for Voltage Sag Prediction.

4. METHODOLOGY FOR VOLTAGE SAG ASSESSMENT

The proposed methodology consists of following steps.

Step 1: Input data of loads, branches, buses, network equivalent of supply point and maximum number of iterations.

Step 2: Perform power flow by a subroutine in the PSS/E program to obtain pre-fault bus voltages (including those at dummy buses). The PSS/E program gives a case file that contains all the input data and the power flow solution.

Step 3: Convert the case file by the E-TRAN program, which directly initializes the circuit in PSCAD/EMTDC.

Step 4: Interface PSCAD/EMTDC with MATLAB by a custom-made module for a Monte Carlo simulation and for data recording.

Step 5: Generate random numbers by a subrountine in MATLAB to represent fault characteristics (fault location, initial time of fault, fault duration, fault type). These random number will be used in PSCAD.

Step 6: Perform an electromagnetic transient simulation by PSCAD/EMTDC to obtain sag magnitude and sag duration of all the buses until the maximum iteration has been reached. These two parameters as well as the fault characteristics will be passed to MATLAB for recording.

Step 7: Manipulate the recorded data to obtain the expected voltage sag magnitude and its density function of each bus.

5. CASE STUDY: BANG–PU INDUSTRIAL ESTATE

Description of test system

The 115/24kV Praekasa (PR) distribution substation of MEA is selected for demonstrating a practical case study. The substation is located in the Bang–Pu Industrial Estate of Samutprakan province and supplies 3 power transformers, serving 33 load points with a total demand of 28.5 MW. There are 4 outgoing 24 kV feeders from power transformer No.3, namely PR432 with 2.46 circuit-km, PR434 with 39.4 circuit-km, PR435 with 8.90 circuit-km, and PR433 with 1.45 circuit-km. This system is of interest because it has experienced a number of sags that caused interruption to customers' production processes. The single line diagram of the system is shown in Figure 4. As described in Section 2 for the modeling for fault position, this system has 129 dummy buses in total for the Monte Carlo simulation. The mean and standard deviation for fault duration are 0.06 second and 0.01second [11], [12]. The values used in fault type simulation are $P_{LG} = 0.80$, $P_{LLG} = 0.17$, $P_{LL} = 0.02$, $P_{LLL} = 0.01$ and [11]. It is assumed that fault resistance is neglected.

Simulation Results

The test system is simulated by a multiple run of 500 iterations. The frequency distribution with 10 bins of fault location and initial time of fault is shown in Figures 5 and 6. It is seen that both figures follow the prespecified uniform distribution. As shown in Figure 7, the distribution of fault duration has a mean value of 0.0610 second and a standard deviation of 0.0108 second. These values follow the predefined statistical property of fault duration. As expected from Figure 8, the probability of simulated fault type has a good agreement with the given assumption of fault type; that is $P_{LG} = 0.744$, $P_{LLG} = 0.20$, $P_{LL} = 0.038$, $P_{LLL} = 0.018$.

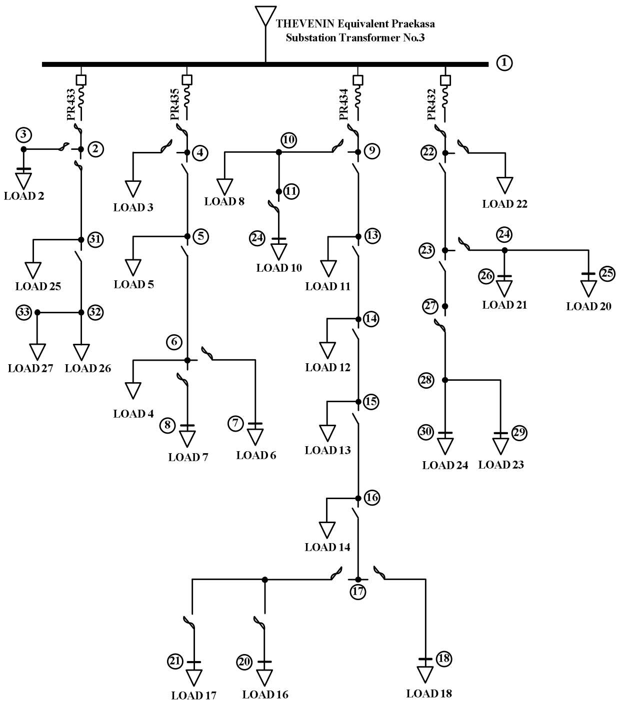

Fig.4. 115/24kV Praekasa Distribution System.

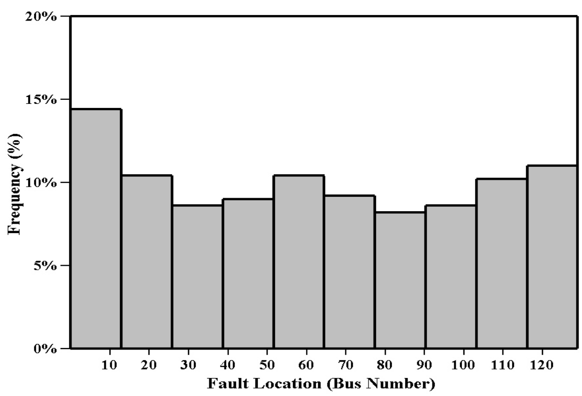

Fig. 5. Density Functions of Fault Location.

Figure 9 shows the density functions of 4 selected buses of interest: bus 9, bus 8, bus 21 and bus 30. It is obviously seen from the figure that bus 9 has the highest average bus voltage while that of bus 21 is lowest. This is not surprising because bus 9 is close to the substation, while bus 21 is at the end of feeder PR434, which is the longest feeder. Downstream customers, of course, tend to suffer more from voltage sags than those upstream. The reason is that a downstream fault may not create a sag seen by upstream customers but downstream customers will certainly be affected by an upstream fault.

Figure 10 illustrates a convergence report of the bus voltages. It is observed that the simulation converges after 300 iterations. The cumulative voltage sag density function of bus 9 is depicted in Figure 11, indicating for example that if a device can ride-through short duration sag, say above 70% of the nominal voltage within 0.1 second, there is a 80% chance that the device will be tripped.

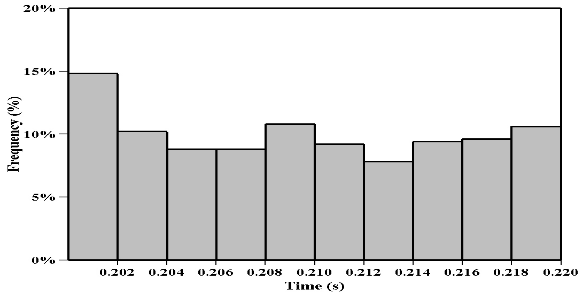

Fig.6. Density Function of Initial Time of Fault

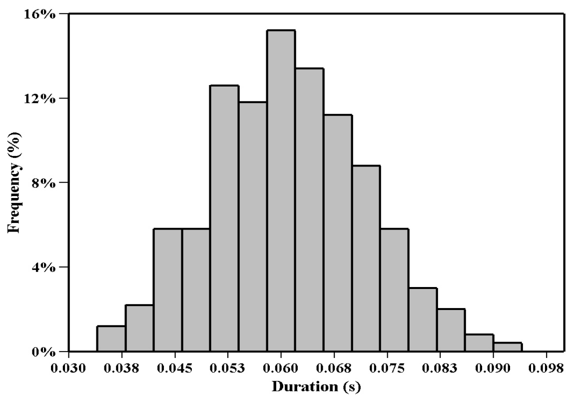

Fig.7. Density Function of Fault Duration.

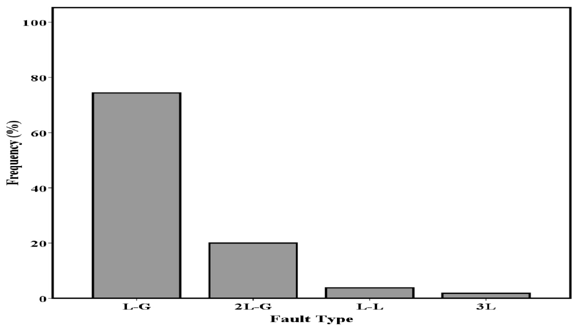

Fig.8. Density Functions of Fault Type.

The developed program takes 36 hours on PC Pentium M 1.6 GHz with 1GB of RAM. The major contribution to the computation time is the number of nodes (or buses) and sampling period (solution time step) being considered. To be specific, the more nodes (buses) or smaller sampling periods, the more computation time. Our problem has in total 129 nodes with a sampling period of 0.0001 sec. It was recommended in [13] that a time step size be equal to or greater than 100 μs (0.0001 sec). The computation time is greatly reduced if we do an analysis only at a bus of interest. As an illustration, it takes only 1.5 hours if only bus 21 is selected in our calculation. Alternatively, if a sampling period is changed from 0.0001 sec to 0.0004 sec with the same 129 nodes, the computation time is only about 9.5 hours, scarifying very small amount of accuracy. Figure 12 emphasizes our confirmation. Nonetheless, computation time does not matter as voltage sag assessment is not for real-time application but rather for planning objective.

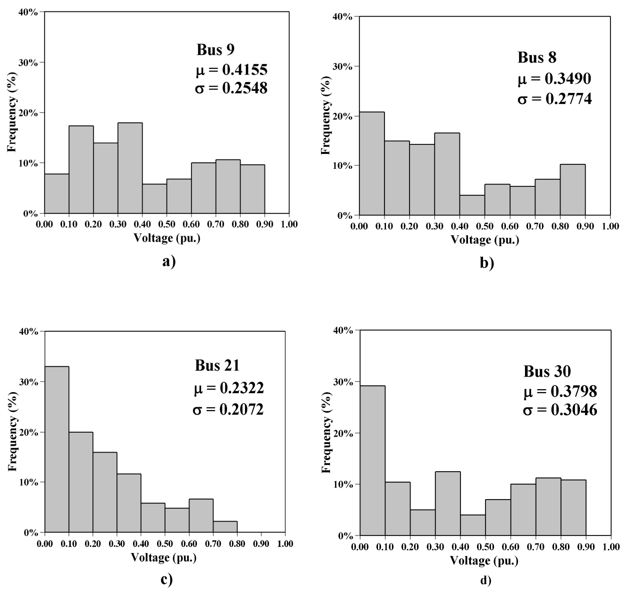

Fig.9. Density Functions of Voltage Sag Magnitudes at 4 Buses.

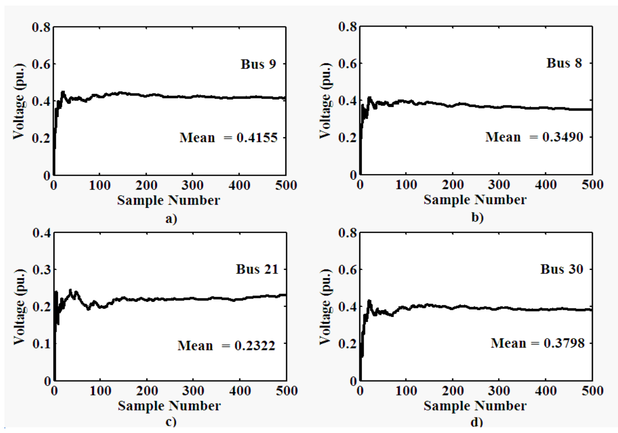

Fig.10. Convergence of Expected Voltage Sag Magnitudes at 4 Buses with sampling period of 0.0001 sec.

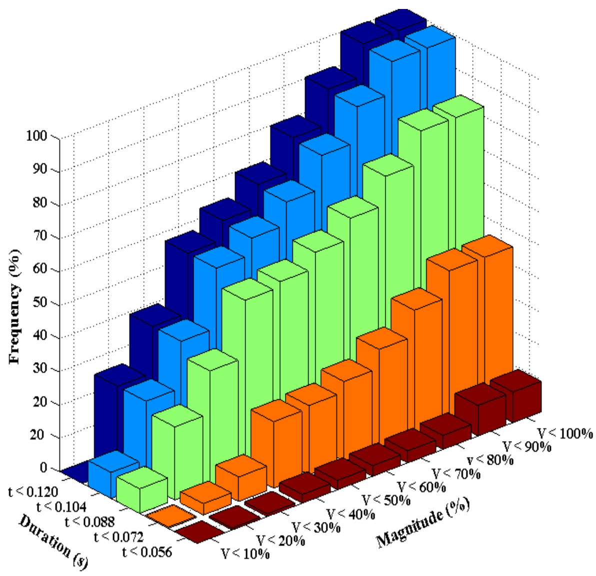

Fig.11. Voltage Sag Distribution Function at Bus 9.

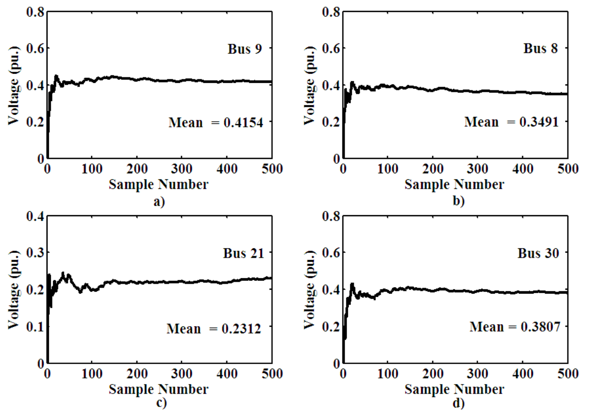

Fig.12. Convergence of Expected Voltage Sag Magnitudes at 4 Buses with sampling period of 0.0004 sec.

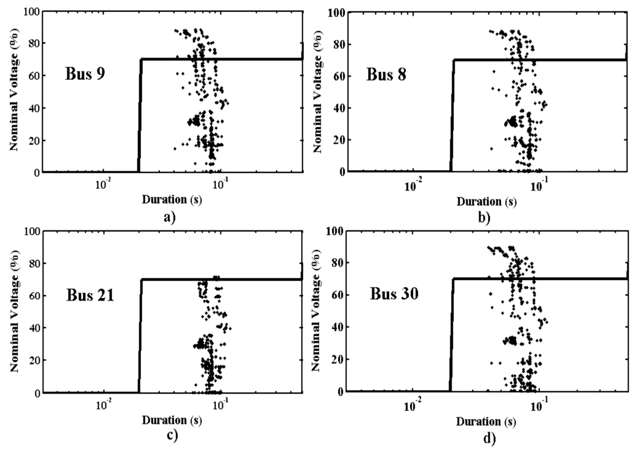

Fig.13. Scatter Diagram of 4 Buses with ITIC Curve.

Figure 13 shows a scatter diagram of sag magnitude versus semi-logarithmic duration for the 4 buses, plotted on a part of the so called ITIC (Information Technology Institute Council) curve [14]. This curve is a loci drawn that establishes a criterion of the tolerance voltages of variations. Any point above the line has a ride-through capability for voltage sags. It is very interesting to note that although the expected voltage at buses 8, 9, 21 and 30 is below 70%, some sag events do not cause problems on the equipment connected to these buses.

6. CONCLUSION

A Monte Carlo based simulation of voltage sags has been presented in this paper. A time-domain simulation tool that integrates the PSCAD/EMTDC software package with PSS/E and MATLAB was developed to estimate voltage sag characteristics quantified by their magnitude and duration. The proposed methodology is demonstrated by a distribution system of MEA. The obtained results are statistically analyzed to give average bus voltages and their density functions. The case study reveals that voltage sag problems are location-specific. Downstream customers are more subject to voltage sag than those upstream because the distribution system under study is radially operated. Scatter diagrams on the ITIC curve is also presented which provides a useful indicator for voltage sag problems. From the utility point of view, voltage sags can be mitigated by fault prevention activities and modification of fault clearing practices, while from the customers' point of view, installing mitigating equipment such as uninterruptible power supply and voltage source converter could be a good option for improving the immunity of sensitive equipment.

ACKNOWLEDGMENT

The first author would like to express his sincere thanks to Research and Development Department, Power System Control Department, and Better Care and Power Quality Department, Metropolitan Electricity Authority (MEA), Bangkok, Thailand.

REFERENCES

[1] IEEE Standard 1159-1995. 1995. IEEE Recommended Practice for Monitoring Electrical Power Quality.

[2] http://www.ecmweb.com.

[3] Barry, W. Kennedy. 2000. *Power Quality Primer*, McGraw-Hill.

[4] Ford G. L. and Sengupta S. S. 1982. Analytical methods for probabilistic shot circuit studies. *Electric Power Systems Research*, vol 5, pp. 13-20.

[5] Billinton, R., and Allan, R. 1996. *Reliability Evaluation of Power Systems.* Plenum Press: New York.

[6] Math H.J. Bollen. 2000. *Understanding Power Quality Problems : Voltage Sags and Interruptions.* IEEE Press: New York.

[7] Faried, S.O., Billinton,R. and Aboreshaid, S. 2005. Stochastic evaluation of voltage sag and unbalance in transmission system. *IEEE Tran. Power Delivery*, vol. 20, no. 4, pp. 2631-2637.

[8] Bakar, N.A., Mohamed, A., and Ismail, M. 2003. A case study of voltage sag analysis in a utility distribution system. In *Proceedings of Power Engineering Conference*, pp. 333-336.

[9] IEEE Standard 493 – 1997. 1998. IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems, (Gold Book).

[10] http://www.pscad.com.

[11] Martinez, J.A., and Martin-Arnedo, J. 2004. Voltage sag stochastic prediction using an electromagnetic transients program. *IEEE Trans. Power Delivery*, vol. 19, no. 4, pp. 1975-1982.

[12] Martinez-Velasco, J.A., and Martin-Arnedo, J. 2006. Voltage sag studies in Distribution networks – part II : voltage sag assessment. *IEEE Trans. Power Delivery*, vol. 21, no. 3, pp. 1679-1687.

[13] Martinez-Velasco, J.A., and Martin-Arnedo, J. 2006. Voltage sag studies in Distribution networks – part I : System Modelling. *IEEE Trans. Power Delivery*, vol. 21, no. 3, pp. 1670-1678.

[14] http://www.itic.org.

APPENDIX

Generating Normally Distributed Random Variates

A normally distributed random variate can be generated the normal culmulatime probability distribution function

$F(x)$. The inverse function of $F(x)$ has the following approximate expression [7]:

$$z = t - \frac{\sum_{i=0}^{2} c_i t^i}{1+\sum_{i=1}^{3} d_i t^i} \quad \text{(A1)}$$

where

$$t = \sqrt{-2\ln Q} \quad \text{(A2)}$$

$c_0 = 2.515517$ $\quad d_1 = 1.432788$

$c_1 = 0.802853$ $\quad d_2 = 0.189269$

$c_2 = 0.010328$ $\quad d_3 = 0.001308$

The implications of z and Q are shown in Figure A1, where $f(z)$ is the standard normal probability density function.

$$f(z) = \frac{1}{\sqrt{2\pi}} e^{\left[-\frac{z^2}{2}\right]} \quad \text{(A2)}$$

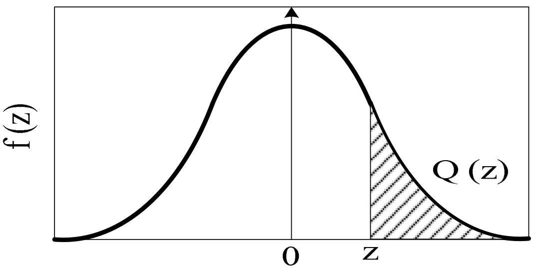

Fig.A1. Area Under Normal Density Function $Q(z)$

Table A1. Load Data of 33-Bus Distribution System

Bus No.	P_L (MW)	Q_L (MVAR)	Bus No.	P_L (MW)	Q_L (MVAR)
3	1.785	0.988	15	1.478	0.818
4	2.783	1.540	16	1.740	0.963
5	2.168	1.200	18	0.420	0.232
6	1.050	0.581	20	0.533	0.295
7	1.628	0.901	21	1.050	0.581
8	1.313	0.726	22	0.656	0.363
10	0.656	0.363	25	1.050	0.581
12	0.822	0.455	26	1.575	0.871
13	0.559	0.309	29	1.313	0.726
14	1.890	1.046	30	2.562	1.418
31	0.525	0.291	33	0.525	0.291
32	0.473	0.261			

Table A2. Equivalent Source Impedance

Source	Impedance (pu.)			
	$R_{1,2}$	$X_{1,2}$	R_0	X_0
PR. Substation Transformer No.3	0.13114	0.42173	0.09547	0.37962

Table A3. Branch Data of 33-Bus Distribution System

From Bus	To Bus	$R_{1,2}$ (pu.)	$X_{1,2}$ (pu.)	R_0 (pu.)	X_0 (pu.)	Length (km)
1	2	0.0233	0.0349	0.1727	0.1754	1.00
1	4	0.0116	0.0174	0.0860	0.0873	0.50
1	9	0.0105	0.0157	0.0778	0.0873	0.45
1	22	0.0022	0.0033	0.0165	0.0873	0.10
2	3	0.0042	0.0062	0.0251	0.0342	0.12
2	31	0.0017	0.0025	0.0101	0.0137	0.05
4	5	0.0069	0.0102	0.0419	0.0570	0.20
5	6	0.1042	0.1537	0.6281	0.8547	3.00
6	7	0.0556	0.0819	0.3350	0.4558	1.60
6	8	0.1250	0.0369	0.0445	0.0730	3.60
9	10	0.0764	0.0225	0.0272	0.0446	2.20
9	13	0.1181	0.0348	0.0420	0.0689	3.40
10	11	0.0972	0.0287	0.0346	0.0568	2.80
11	12	0.1677	0.0492	0.0593	0.0973	4.80
13	14	0.0694	0.0205	0.0247	0.0405	2.00
14	15	0.0972	0.0287	0.0346	0.0568	2.80
15	16	0.1250	0.0369	0.0445	0.0730	3.60
16	17	0.1250	0.0369	0.0445	0.0730	3.60
17	18	0.1250	0.0369	0.0445	0.0730	3.60
17	19	0.1736	0.0512	0.0618	0.1014	5.00
19	20	0.0972	0.0287	0.0346	0.0568	2.80
19	21	0.0972	0.0287	0.0346	0.0568	2.80
22	23	0.0049	0.0014	0.0017	0.0028	0.14
23	24	0.0035	0.0010	0.0012	0.0020	0.10
23	27	0.0174	0.0051	0.0062	0.0101	0.50
24	25	0.0097	0.0029	0.0035	0.0057	0.28
24	26	0.0090	0.0027	0.0032	0.0053	0.26
27	28	0.0028	0.0008	0.0010	0.0016	0.08
28	29	0.0174	0.0051	0.0062	0.0101	0.50
28	30	0.0174	0.0051	0.0062	0.0101	0.50
31	32	0.0035	0.0010	0.0012	0.0020	0.10
32	33	0.0035	0.0010	0.0012	0.0020	0.10