AUTOMATED VOLTAGE SAG CHARACTERIZATION AND EQUIPMENT BEHAVIOR ANALYSIS

MLADEN KEZUNOVIC, IEEE Fellow YUAN LIAO, IEEE Student Member

Texas A&M University
Department of Electrical Engineering
College Station, TX 77843-3128

ABSTRACT

Voltage sags are one of the most concerned power quality events in the modern power systems as they often lead to tripping or mis-operation of the customer equipment. The coordination study between the system and the equipment helps alleviate such nuisances. This paper describes new software developments aimed at automated voltage sag characterization and equipment behavior analysis. The proposed methods and software implementation issues are addressed. The advantages of integrating the power system model and data analysis into one unified frame are highlighted. Case studies and the results are reported.

1. INTRODUCTION

In a power system, there are various kinds of power quality disturbances such as voltage sags, voltage swells, switching transients, impulses, notches, flickers, harmonics, etc.[1-2]. Among these disturbances, voltage sags are particularly troublesome since they occur rather randomly and are difficult to predict. More importantly, voltage sags may often cause trips or mis-operations for industrial equipment. Because of the increasing use of electronic devices, modern equipment becomes far more vulnerable to voltage sag events than ever. Hence our paper is focused on the voltage sag analysis that includes voltage sag characterization and equipment behavior analysis under sag events.

One important objective of sag studies is to find efficient approaches to improve the immunity or ride-through ability of the equipment to the sag events and thus enhance the coordination between the system and the equipment [3]. To reach this objective, we need to characterize the voltage sag waveforms to extract various voltage sag descriptors including sag magnitude, duration, phase angle shift, phase angle shift rate, voltage rms unbalance ratio, total harmonic distortion, three-phase phase angle difference, sag initial time, sag end time, and points-on wave. With the advent of electronic devices, the trip or mis-operation can not be just attributed to the sag magnitude and duration any more. Instead, other factors like point-on-wave, unbalance ratio, phase angle shift and angle difference between phases may also play an essential role in the behavior of the modern loads during voltage sag events [4-7]. Therefore, to improve the coordination between the equipment and the system, the operating characteristics of the equipment under various sag events become indispensable and should be specified and evaluated.

This paper deals with sag characterization and equipment behavior analysis and is largely composed of three parts. The first part describes the software developments for characterizing voltage sag waveforms automatically. The sag descriptors and characterization methods are discussed in detail. One typical distribution system has been modeled to illustrate the functions of the developed software. Various sag waveforms can be obtained through simulation. By modifying the system parameters, corresponding changes of the sag descriptors can be observed. In this way, the relationship between the system parameters and sag parameters becomes evident and can be better understood. This may be helpful for the system planning and equipment-system compatibility studies.

The second part of the paper describes our proposed methods for testing equipment behavior under sag events. An asynchronous machine directly fed by a bus is taken as an example to illustrate the proposed methods for equipment sensitivity studies. The effects of the sag magnitude, duration and phase angle jump on the operations of the machine are examined in detail.

The third part of the paper describes the proposed method for automatic equipment behavior analysis using the sag characterization results and the equipment behavior testing results acquired in the first two parts. An example is given to illustrate application of the methods.

2. VOLTAGE SAG CHARACTERIZATION

The methods for characterizing voltage sag waveforms used in our developed software are described first. Then the functions and implementation issues of the software are presented. Finally, a typical distribution system and related waveforms are taken as an example to illustrate some distinctive features of the software.

2.1 Characterization Method

Faults and motor starting are the two leading sources for voltage sags. This paper focuses on the study of sags caused by faults. The parameters used for characterizing sag waveforms caused by faults are listed in Table 1.

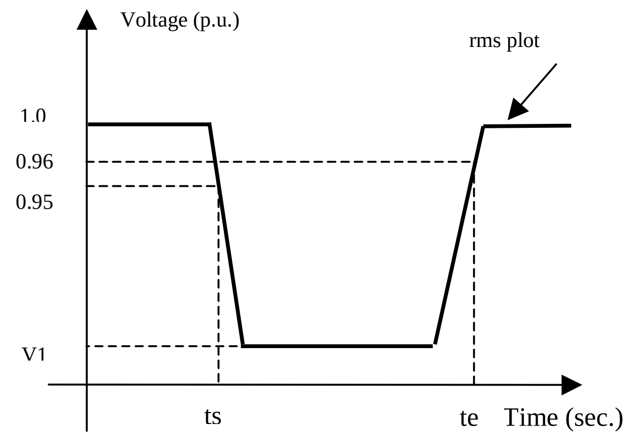
Table 1. Parameters characterizing sag waveforms caused by faults

SAG PARAMETERS
Minimum rms magnitude
Maximum rms magnitude
Sag duration
Sag initial time
Sag end time
Initialization angle
Recovery angle
Initial phase angle shift
End phase angle shift
Maximum THD
Maximum rms unbalance ratio
Maximum three-phase phase angle difference deviation

In the following section, the existing characterization methods proposed in the draft standard [3] are summarized and illustrated first. Then the improved approaches proposed by us are presented.

<u>Characterization Methods Proposed in [3]</u>

Draft standard proposes the following definitions and calculation methods for the sag parameters [3]. Figure 1 plots the rms value of a voltage sag signal and is used for illustrating some of the sag parameters.



ts: sag initial time
te: sag end time
te-ts: sag duration

Figure 1. Illustration of the definition of the sag parameters

- Maximum and Minimum rms Magnitude

The root mean square (rms) value of the sag signal is calculated using the following equation

$$V_{rms} = \sqrt{\frac{1}{N}\sum_{n=1}^{N} v_n^2} \qquad (1)$$

In the above equation, v_n represents the sampled value of the voltage signal. N is the number of samples either in one fundamental cycle or in half cycle. If the samples in one cycle are used, equation (1) represents a full-cycle algorithm. Otherwise, equation (1) is called a half-cycle algorithm.

Based on equation (1), rms values of the voltage signal during the whole event duration can be

computed, from which the following two parameters of interest are obtained.
Maximum rms value: the highest rms value of the waveform during the sample duration.
Minimum rms value: the lowest rms value of the waveform during the sample duration.

- Voltage Sag Initial Time

This refers to the moment when the rms value falls below 0.95 p.u.. This is ts shown in Figure 1.

- Voltage Sag End Time

This refers to the time when the rms value recovers to within 0.96 p.u.. This is te shown in Figure 1.

- Sag Duration

The difference between the sag initial and end times, i.e., te-ts in Figure 1.

- Initialization Angle

The angle at which the sag occurs using the last positive-going zero crossing as the reference angle.

- Recovery Angle

The angle at which the sag ends using the last positive-going zero crossing as the reference point-on wave.

- Initial Phase Angle Shift

The phase angle shift is defined as the difference between the phase angle of the sag waveform and that of the reference waveform. The reference waveform is defined as the 1.0 p.u. nominal waveform in synchronism with the pre-event waveform. It can be calculated by either the zero crossing method or the FFT method.

Zero Crossing Method
The zero crossings of the actual waveform are compared to those of the reference waveform. The phase shift is defined as the difference between the zero crossings of the two waveforms.

FFT method
A one-cycle window FFT is implemented to obtain the fundamental component of the sag waveform, A+jB, and that of the reference waveform, C+jD. Then the phase shift is computed by

$$\text{Phase Shift} = \arctan\left[\frac{BC - AD}{AC + BD}\right] \tag{2}$$

The phase angle shift can be displayed as a continuous plot against time. The angle shift at sag initial time is of particular interest and is defined as the phase shift computed at the first zero crossing after the sag begins using zero crossing method, or the phase shift computed half cycle after the sag begins using FFT method.

- End Phase Angle Shift

The calculation method for the end phase angle shift is similar to the initial phase angle shift except that the angle is calculated at the sag end moment.

- Phase Angle Shift Rate

Phase angle shift rate, called "slew rate" can be obtained after the phase angle shift has been calculated. It is defined as the first derivative of the phase shift. Let the phase shifts be α_1 and α_2 at moments t_1 and t_2 respectively, then the rate of change of phase shift at time t_2 is calculated as

$$\frac{\alpha_2 - \alpha_1}{t_2 - t_1} \tag{3}$$

- THD

This refers to the total harmonic distortion (THD) of the sag waveform scaled to the pre-sag normal fundamental component. If we use the per unit system and make the nominal voltage equal to 1.0 p.u., then the THD is calculated using

$$\text{THD} = \sqrt{V_{rms(total)}^2 - V_{dc}^2 - V_{fund}^2} \tag{4}$$

where, the three terms in the equation are total rms value, dc component and fundamental component, respectively.

- Missing Voltage

The missing voltage is defined as "the instantaneous difference between the reference waveform and the actual sag waveform".

- rms Magnitude Unbalance Ratio

This variable describes the unbalance degree between the three phase voltages during the sag. It is defined by equation

$$\text{Unbalance Ratio} = \frac{V_{high} - V_{low}}{(V_A + V_B + V_C)/3} \tag{5}$$

where V_{high} is the highest rms voltage of the three phases,

V_{low} is the lowest rms voltage of the three phases,

V_A, V_B and V_C are rms voltages of the three phases respectively.

- Three-phase Phase Angle Difference

This refers to the phase angle difference between the three-phase sag voltages. The phase angle can be calculated using the FFT method. The maximum three-phase phase angle difference deviation is defined as the maximum deviation of the phase angle difference from 120 degrees and is abbreviated as MPADD. This definition ensures a zero deviation for normal three-phase signals.

Among these parameters, the unbalance ratio and three-phase phase angle difference describe the relationship between the three phase voltages, while the other parameters characterize each of the three phase signals.

Improved Characterization Methods

The rms value based methods for calculating sag initial and end times described above may cause as much as half cycle errors due to the averaging effects of the moving window. The envelope method is also proposed in [3] to improve accuracy. However, the method is quite involved and difficult to implement. The following wavelet based method for calculating sag initial and end times is proposed and used in our software.

The wavelet transform translates the time-domain function into a representation localized not only in frequency but also in time domain, and hence it has a good time and frequency localization characteristic. Therefore, it provides us a feasible way to accurately pinpoint the moment of the occurrence and termination of the sag disturbance.

Figure 2 shows the scaling function and wavelets of Daubechies-4 family. The actual implementation of the wavelet transform can be realized through the computationally efficient multiresolution analysis, which is graphically represented in Figure 3 [8].

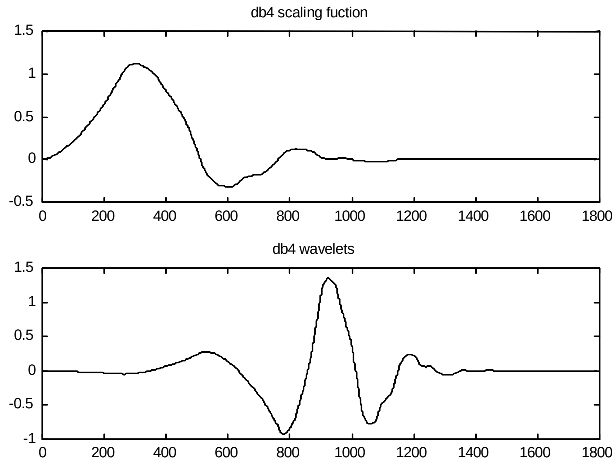


Figure 2. Daub4 scaling function and wavelets

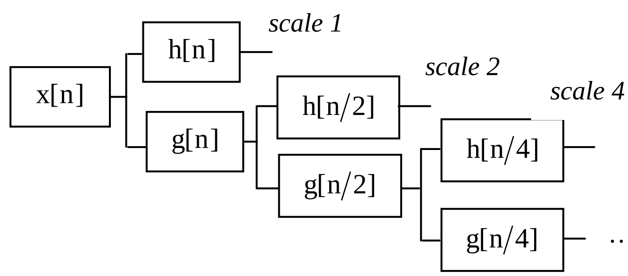


Figure 3. Decomposition method using multiresolution analysis

In Figure 3, x[n] represents the sampled input signal. h[n] and g[n] represents the high-pass and low-pass filters respectively. The outputs labeled as *scale 1*, *scale 2*, etc. represent the details of the input signal at different levels. A higher scale level implies lower frequency contents. Thus, the original signal is decomposed into signals of different frequency levels. This procedure is called the multiresolution analysis. Based on this technique, Figure 4 depicts a sag signal and its wavelet coefficients.

In Figure 4, cD1 and cD2 are the first scale and second scale wavelet coefficients of the sag signal, and abs(cD1) and abs(cD2) are the absolute values of these coefficients. It can be seen that abs(cD1) and abs(cD2) have conspicuous jumps at the sag-begin-moment and sag-end-moment, and hence these jumps can be utilized for accurately determining the sag initial time, sag end time, and sag points-on-wave. In our applications, Daub4 wavelet and a sampling frequency of 5760 Hz are selected.

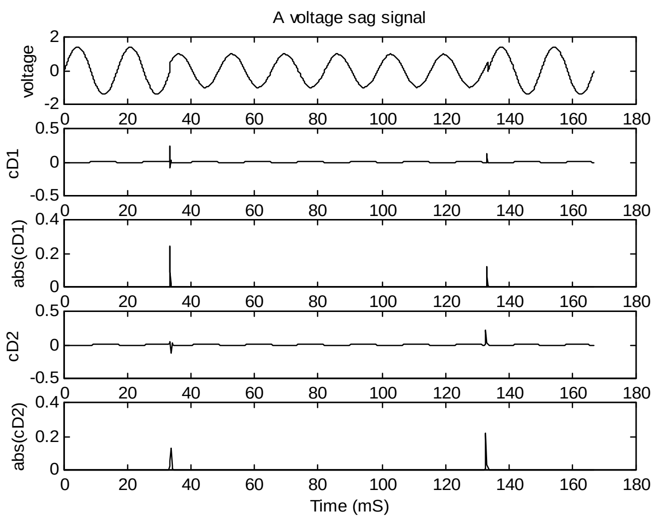


Figure 4. Analysis of a sag signal by wavelet transform

2.2 Software Description for the Characterization Module

MATLAB is a commercial package that provides us with a variety of toolboxes like signal processing toolbox, power blockset toolbox, etc. and is an efficient tool for building up the software prototype [9]. Hence presently, we select MATLAB as the programming language for developing the software. After the prototype is built and thoroughly tested, it can be easily rewritten in C or C++ for commercial purposes. Figure 5 shows the flow chart for the developed characterization module. The inputs for the module are the voltage sag waveforms either recorded by the recording devices such as Digital Fault Recorders (DFRs) and power quality meters, or generated by the simulation packages such as ElectroMagnetic Transients Program (EMTP) and MATLAB Power Blockset. The sub-module "Data Format Conversion" converts the inputs from a specific recording device or simulation package format into a common format comprehensible to other modules of the software. The sub-module "Fourier and Wavelet Based Signal Processing" extracts various sag parameters using both Fourier and wavelet-transform based techniques as discussed before.

The user-interface of the module is displayed in Figure 6. The menus "File", "Edit", "Window", and "Help" are system-provided menus for general purposes like copying and printing. The menus "Load Data", "Display Voltages", "Display Currents", "Voltage and Current Parameters", "Equipment Behavior" and "Sag Help" are the developed application menus. The functions provided by these menus are illustrated as follows. It is noted that the current waveforms, if available, can also be characterized.

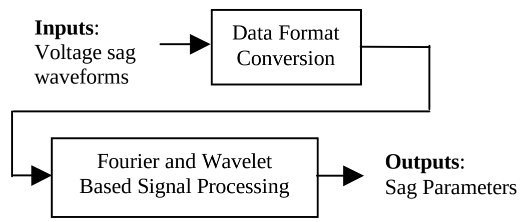


Figure 5. Sag characterization flow chart

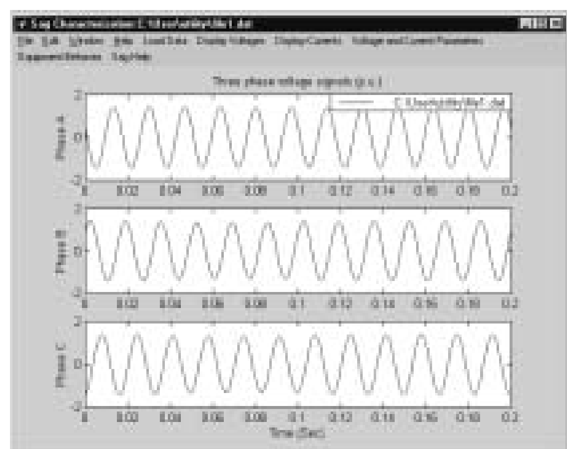


Figure 6. The main menu of the sag waveform characterization module

Load Data

This sub-module is to import the voltage sag waveforms to the data analysis units of the software from the data file or database.

Display Voltages

This sub-module graphically depicts the original voltage signal, rms value, fundamental component, harmonic content, THD value, phase angle shift, phase angle shift rate, three-phase phase angle difference, rms unbalance ratio, and the missing voltage.

Display Currents

This sub-module graphically depicts the original current signal, rms value, fundamental component, harmonic content, THD value, three-phase phase angle difference, and the rms unbalance ratio.

Voltage and Current Parameters

For voltage sag waveforms, parameters such as the maximum and minimum rms magnitude, sag duration, sag initial time, sag end time, initialization angle, recovery angle, initial phase angle shift, end phase angle shift, maximum THD, maximum rms unbalance ratio, and maximum three-phase phase angle difference deviation are computed. For current waveforms, parameters such as the maximum and minimum rms magnitude, maximum THD, maximum rms unbalance ratio, and maximum three-phase phase angle difference deviation are calculated.

Equipment Behavior

This sub-module provides a toolbox for equipment sensitivity study, and will be described in section 3.

Sag Help

Help about the use of the software is provided in this sub-module.

2.3 Features of the Developed Software

One prominent feature of this software is that the simulation and data analysis are unified in one framework. By modifying the network parameters, the corresponding changes in the recorded waveforms and the waveform parameters can be readily observed and studied. This may be important in the system planning. Figure 7 shows a typical 14.2 KV distribution system and is used for illustrating the functions of the software.

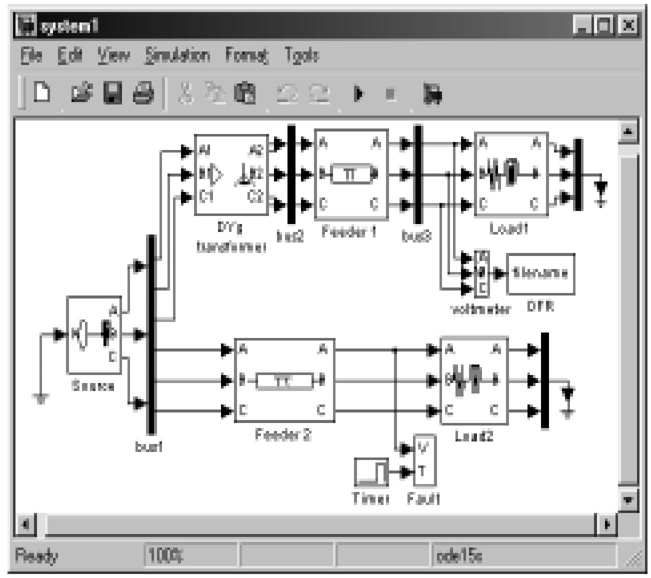


Figure 7. A sample distribution system

This system is modeled in the environment of MATLAB Power Blockset. It consists of one machine and one step-down transformer. The transformer supplies power to one load through a short feeder. In the figure, the block DFR representing the digital fault recorder captures the voltage waveforms at bus 3. The block “Fault” models shunt faults of various types with different inception and end times. Six different cases have been simulated and the corresponding voltage waveforms are saved in different files. Cases 3 and 4 are of the same fault type but have different fault end times. The sag parameters of the sag waveforms are then obtained using the software.

Table 1 shows the comparison of phase-A voltage sag parameters for these sag events. The differences between the parameters of these cases are clearly seen. Thus, unification of the system model and data analysis in one study environment facilitates the sag study.

3. EQUIPMENT SENSITIVITY STUDY DURING VOLTAGE SAG EVENTS

This section describes the proposed methods for the equipment sensitivity study during voltage sag events.

Table 1. Characterization results for phase-A voltage waveforms

Case No. / Parameters	1	2	3	4	5	6
Sag Initial Time (ms)	151.1	153.5	94.99	94.99	151.8	0
Sag Initial Angle (degree)	338.4	34.82	209.0	209.0	175.2	0
Sag End Time (ms)	268.6	266.6	200.0	158.3	300.0	0
Sag Recovery Angle (degree)	11.25	320.6	320.6	140.6	315.0	0
Initial Phase Shift (degree)	11.01	10.14	9.83	9.83	-1.03	0
End Phase Shift (degree)	-11.11	-10.74	-9.74	-10.23	1.03	0
Minimum rms Magnitude (p.u.)	0.59	0.85	0.88	0.89	0.74	1.0
Maximum rms Magnitude (p.u.)	1.0	1.0	1.0	1.0	1.0	1.0
Sag Duration (ms)	117.5	113.1	105.0	63.35	148.1	0
Maximum THD	0.13	0.078	0.11	0.11	0.057	0
Maximum PADD (degrees)	20.1	19.2	5.62	5.62	13.5	19.1
Maximum rms Unbalance Ratio	0.36	0.25	0.20	0.20	0.28	0.2

The equipment operating characteristics during voltage sag events can be evaluated either through physical tests or through digital simulation studies. Simulation methods are usually more cost-effective and flexible than the physical testing methods [10]. This paper aims at determining the equipment operating characteristics during voltage sags using the simulation methods. To do this, the equipment of interest is first mathematically modeled and then is subject to specific voltage sag waveforms. The voltage sag waveforms can be generated either by an artificial sag generator or by replaying previously recorded sag waveforms. The remaining part of the section is organized as follows. The overall structure of the proposed method is described first. Then examples are given to illustrate the methods in some detail.

3.1 Overall Structure for Equipment Behavior Testing

The overall structure for evaluating the equipment behavior under voltage sag events is depicted in Figure 8. In the figure, The inputs are the voltage sag waveforms that can either be recorded from the field or be generated by specific simulation packages. The outputs are the operating characteristics of the equipment during the specified sag events. The block "Voltage Sag Characterization" computes the various sag parameters as described in the previous section. The block "Sag Parameter Tuning" allows the user to tune or edit the sag parameters obtained from the block "Voltage Sag Characterization" to the needed values. The block "Voltage Sag Generator" reconstructs the voltage sag waveforms based on the tuned sag parameters. The constructed voltage waveforms serve as the voltage source for testing the equipment. The voltage sources can be either one phase or three phase depending on the tested equipment. The "Voltage Amplifier" scales the constructed voltages such that the pre-sag rms value of the constructed voltages equals the rated rms value of the equipment under test. The "Equipment Model" mathematically models the tested equipment. The model can either be built by utilizing the elements provided by the Power Library of MATLAB, or be represented by s-functions provided by SIMULINK. Directly using Power Library for building the equipment model is convenient and easy. However, using s-functions for modeling is more versatile and can realize almost any needed non-linear models.

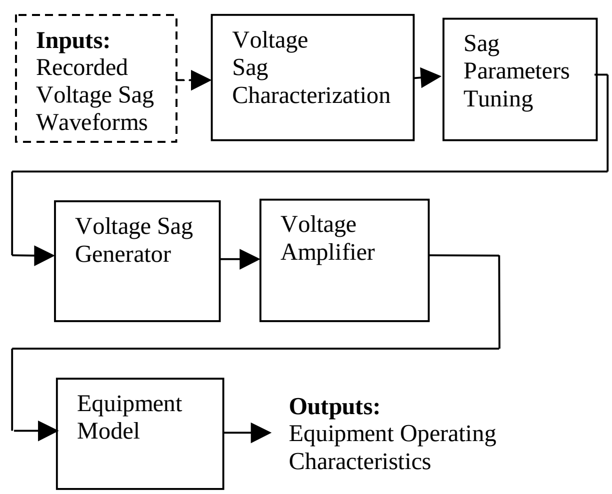


Figure 8. The overall structure for equipment testing

Note that in Figure 8, the inputs "Recorded Voltage Sag Waveforms" are optional. The recorded sag waveforms actually provide us with a set of initial sag parameters based on which further tuning can be made. If the recorded waveforms are available and taken as the inputs to the module, the software can evaluate how the equipment of interest reacts to the recorded sag events or the tuned sag events. If no recorded waveforms are available, the user can input any desired initial sag parameters and then tune them for testing. In either case, by changing the sag parameters such as the sag magnitude, sag duration, phase angle shift, etc., the software allows the user to observe and study how specific sag parameters affect the operating characteristics of the equipment under test. This is what we call the equipment sensitivity study.

3.2 Case Studies for the Equipment Behavior Testing

In this section, an asynchronous machine (ASM) directly connected to the A. C. bus is taken as an example to illustrate the proposed testing methods. Two cases are studied. One is to study the machine behavior under a previously recorded sag event. The other is to study how the machine reacts to specific sag parameters. The system diagrams and some related simulation results are presented as follows.

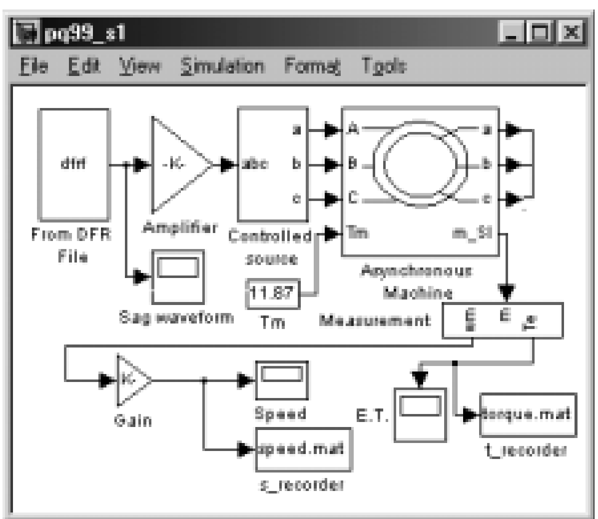


Figure 9. Testing an asynchronous machine using a recorded sag event

<u>Testing the ASM Using Recorded Waveforms</u>

Figure 9 shows the Power Blockset diagram for testing an asynchronous machine directly connected to the A. C. bus. The block “From DFR File” imports the previously recorded sag waveforms from the file specified by the user. The block “Amplifier” scales the recorded sag voltages to the rated voltage of the machine. “Controlled source” interfaces the SIMULINK parts and the Power Blockset parts. The “Asynchronous Machine (ASM)” implements a three-phase induction machine (wound rotor or squirrel cage) modeled in the dq rotor reference frame. It has rated values of 3 hp (horse power), 220 V, 60 Hz and 11.87 N. M. The block “Measurement” interfaces the ASM and the scopes or the recording devices. The scopes display the recorded sag waveforms, speed, and the electromagnetic torque (E. T.). The recorders save the speed and the electromagnetic torque to the disk.

In this example, the sag waveforms shown in figure 10 are used for testing the machine. The voltage waveforms were recorded at bus 3 during a phase-A to ground fault as shown in figure 7. The fault is initiated at 300 ms and cleared at 385 ms. The sag parameters obtained from the module “Voltage Sag Characterization” are listed in Table 2.

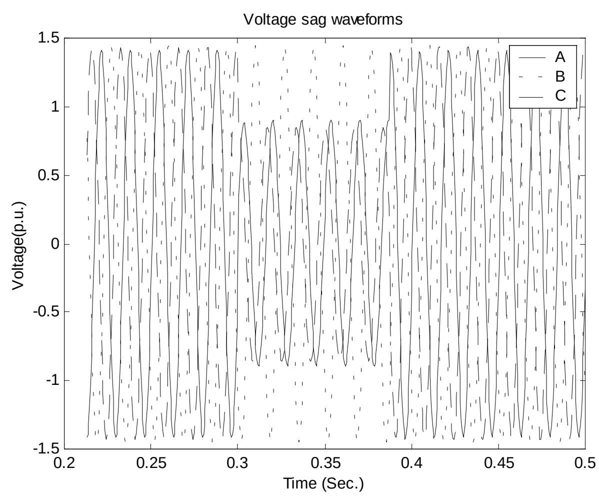


Figure 10. The voltage sag waveforms for testing the asynchronous machine.

It is noted from table 2 that the fault type seen at bus 3 is phase-A-to-C fault rather than phase A-to-ground fault. The phase B does not have significant sags. The sag magnitudes for phase A and for phase C shown in table 2 are not exactly the same due to non-zero resistance fault. This demonstrates that the characteristics of the sags seen at certain locations depend on transformer connection methods as well as the fault types and fault resistance.

Table 2. Sag parameters for the waveforms shown in figure 10.

Phases / Parameters	A	B	C
Sag Initial Time (ms)	301.6	0	301.8
Sag Initial Angle (degree)	328.6	0	121.4
Sag End Time (ms)	384.4	0	384.9
Sag Recovery Angle (degree)	337.5	0	56.25
Initial Phase Shift (degree)	20.34	0	-23.88
End Phase Shift (degree)	-14.67	0	23.76
Minimum rms Magnitude (p.u.)	0.61	1.0	0.59
Maximum rms Magnitude (p.u.)	1.0	1.0	1.0
Sag Duration (ms)	82.81	0	83.1
Maximum THD	0.15	0	0.15
Maximum PADD (degrees)	51.60		
Maximum rms Unbalance Ratio	0.56		

The speed change of the machine during the sag events is shown in figure 11. The normal speed is 1775 rotation per minute (rpm). The speed oscillates around 1710 rpm during the sag events and the lowest point is about 1690 rpm representing a 5% drop. Note that it takes about 90 ms for the machine to recover to its normal speed after the sag recovery.

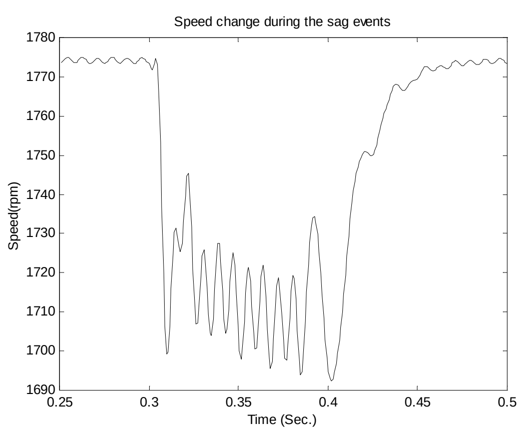


Figure 11. The speed change of the machine during the sag events

The electromagnetic torque of the machine during the sag events is shown in figure 12. It can be seen that the torque of the machine oscillates abruptly between the lowest value –175 N.M. and the highest value 120 N.M. during the sag events.

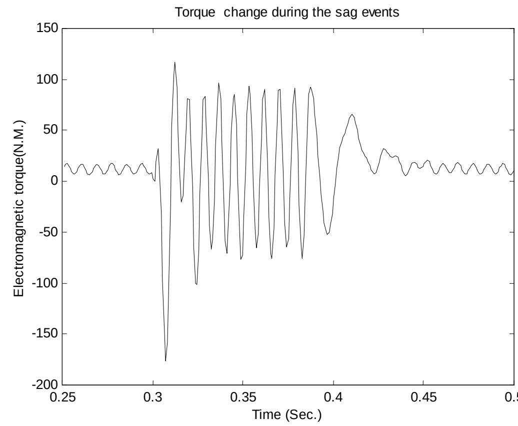


Figure 12. The electromagnetic torque of the machine during the sag events

Studying the Effects of Specific Sag parameters

The previous section evaluates how the machine behaves during a recorded sag event. This section studies how specific sag parameters affect the machine operating characteristics. The system diagram is shown in figure 13.

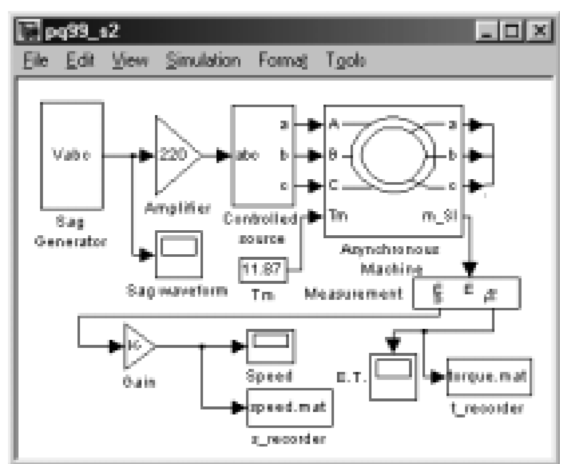


Figure 13. Testing an asynchronous machine using a sag generator

In figure 13, the sag generator constructs the three phase sag waveforms based on the parameters specified by the user for testing the machine. The other elements have the same functions as those shown in figure 12.

Figure 14 shows the testing waveforms used in this example. The sag begins at 20 ms and ends at 40 ms. The sag waveforms have a phase angle shift of 40 degrees while the rms magnitude remains 1.0 p.u.. Hence this example illustrates the effects of the phase angle shift on the machine operation.

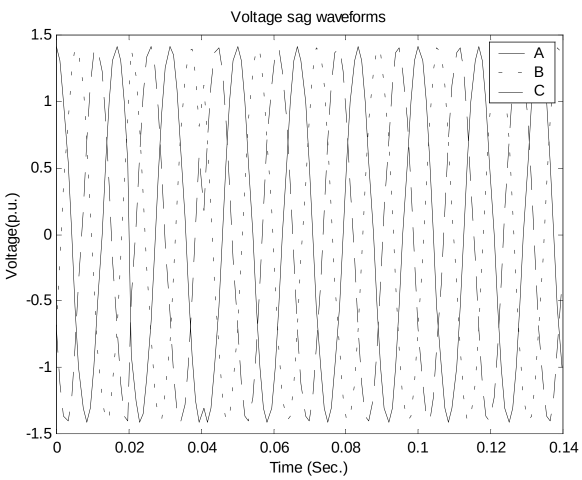


Figure 14. The sag waveforms for studying the effects of the phase angle shift

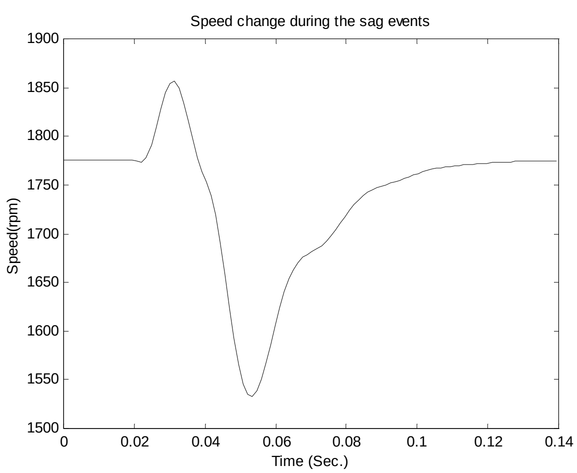


Figure 15. Figure 11. The speed change of the machine due to the phase angle shift

Figure 15 shows the speed change of the machine during the sag events depicted in figure 14. It can be seen that although the rms value of the voltages remains 1.0 p.u., the phase angle shift has caused the speed of the machine to change dramatically and the lowest value is 1525 rpm, representing a 14% drop. This demonstrates the importance of considering the phase angle shift in studying equipment behavior during the sag events.

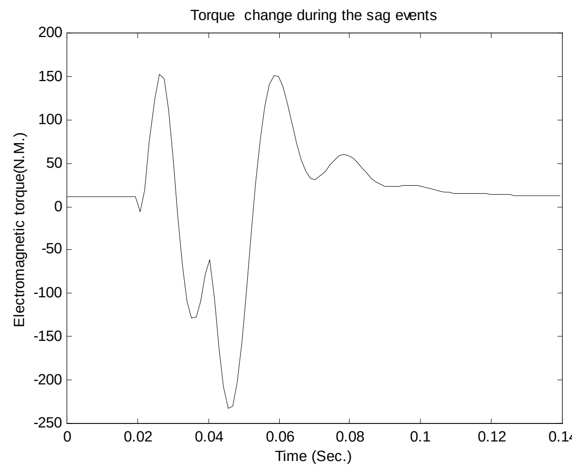


Figure 16. The electromagnetic torque of the machine due to the phase angle shift

The electromagnetic torque of the machine is plotted in figure 16. It clearly shows the phase angle shift has a significant effect on the machine operating characteristics. The effects of other parameters can be studied similarly.

4. AUTOMATIC EQUIPMENT BEHAVIOR ANALYSIS

This section presents the proposed methods for automatic equipment behavior analysis.

To automatically evaluate the equipment behavior during a sag event, the sag parameters of the event are first extracted using the module "Voltage Sag Characterization" and then are compared with the "critical operating values" of the equipment. If the sag parameters exceed the critical operating values, then the equipment is classified as mis-operation during the event.

The "critical operating value" of the equipment is defined as the value beyond which the equipment deviates from the normal operating conditions and the deviation is unacceptable in terms of certain criteria. For example, for the asynchronous machine, the critical value may be defined as the value beyond which the speed of the machine drops below 95 % of the normal speed. Other criteria such as the electromagnetic torque, current, etc. may also be used for evaluating the critical value.

To obtain the critical values of the sag parameters, a lot of tests are entailed. It is impractical to examine exhaustively the effects of all the sag parameters on the equipment behavior by changing all the parameters within a range. In our work, we only examine the critical values of the three most important parameters of the equipment, i.e., sag magnitude, duration and phase angle shift.

To test the equipment, we need first to generate proper voltage sources to simulate the voltage sag events. The voltage sag generator described in figure 8 is utilized for testing the equipment. Both one-phase and three-phase sag voltages need to be generated. In comparison with one phase case, three-phase voltage sags are more difficult to realize because numerous combinations of three phase during-sag voltages can be possible. Fortunately, it has been shown that the three-phase voltages during sag events are following certain regularities rather than taking random values. Under certain assumptions, three-phase sags can be classified into seven types, i.e., types A-G, each of which is completely characterized by an equation [11]. For example, type A sag is characterized by equation (6).

$$\begin{aligned} V_A &= V \\ V_B &= -\tfrac{1}{2}V - \tfrac{1}{2}jV\sqrt{3} \\ V_C &= -\tfrac{1}{2}V + \tfrac{1}{2}jV\sqrt{3} \end{aligned} \qquad (6)$$

In the above equations, all the quantities are during-sag phasor values. The pre-sag phase-A voltage is assumed as the reference voltage. V is called the characteristic voltage whose magnitude and phase angle represent the sag magnitude and phase angle shift, respectively. Once V is specified, phases B and C can be derived using according equations. As discussed in [11], only sags of type A, C and D are normally encountered by the equipment because the other types of sags contain zero-sequence components that will be excluded by the delta or star with neutral connection of either the equipment or the transformer. Consequently, examining only the sags of types A, C and D seems enough for practical applications. Moreover, studies have shown that the angle of the characteristic voltage rarely surpass 60 degrees and is normally greater than zero.

Based on the above analysis, we propose the following procedure for determining the critical values of the sag magnitude, duration and phase angle shift of the equipment. The procedure is for testing three-phase equipment. The procedure for testing single-phase equipment is similar except that one phase voltage rather than three-phase voltages is imposed on the equipment.

<u>Test Steps:</u>

To simplify the tests, the sag magnitude and phase angle shift takes on the following discrete values.
Phase angle shift: (0 20 40 60) degrees.
Sag magnitude: (0 0.2 0.4 0.6 0.8 1.0) p.u.

(a) Set phase angle shift as zero.
(b) Set sag magnitude as zero.
(c) Apply the type-X sag voltages to the equipment, and find the corresponding critical duration.
(d) Change the sag magnitude and repeat (c) until the critical duration for all the sag magnitudes is obtained.
(e) Change the phase angle shift and repeat (d) until the critical duration for all the phase angle shifts are obtained.

In the above procedure, type-X represents types A, C or D.

The testing results can be saved in the format: (sag type, phase angle shift, sag magnitude, critical duration). The units of phase angle jump, sag magnitude and critical duration are degrees, p.u., and millisecond, respectively. For example, (‘A’, 20, 0.2, 100) denotes that the equipment can endure a maximum time of 100 ms under a type-A sag event with 20 degrees of phase angle jump and 0.2 p.u. of sag magnitude.

Based on the proposed procedures, the critical values for the equipment can be obtained and tabulated for later automatic analysis. For instance, Table 3 shows the results for evaluating the behavior of an asynchronous machine during a sag event. It is concluded that the phase angle shift of the sag events will cause the mis-operation of the machine.

Table 3. Equipment behavior analysis results.

Parameters	Critical Values	Actual sag parameters	Difference	Affect
Sag Type	A	A	n/a	n/a
Phase Angle Shift (Degree)	0	20	20	Yes
Sag Magnitude (p.u.)	0.8	0.8	0	No
Sag Duration (ms.)	20	20	0	No

5. CONCLUSION

This paper describes advanced methods for voltage sag characterization and equipment sensitivity studies during the voltage sag events. Software implementation issues and case studies are reported. The implemented method integrates the system model, equipment model, and data analysis into one unified frame, and seems a feasible approach for power quality studies.

6. ACKNOWLEDGEMENT

Software developments reported in this paper are funded by the Texas Higher Education Coordinating Board Advanced Technology Program. The co-funding is provided by TU Electric and Reliant Energy HL&P.

7. REFERENCES

1. Dugan, Roger C., McGranaghan, Mark F., and Beaty, H. Wayne, *Electrical Power Systems Quality*, McGraw-Hill, New York (1996), pp. 1-38.
2. IEEE Std 1159-1995, *IEEE Recommended Practice for Monitoring Electric Power Quality*, IEEE Inc., New York (1995), pp. 1-59.
3. IEEE Project 1346 Working Group, "Electric Power System Compatibility with Industrial Process Equipment, part 1: Voltage Sags", *IEEE Industrial and Commercial Power Systems Technical Conference*, Irvine, CA, USA, May 1-5, 1994, pp. 261-266.
4. IEEE P1159.2, Task Force on Characterization of a Power Quality Event Given an Adequately Sampled Set of Digital Data Points, web site: http://grouper.ieee.org/groups/1159/2/keypts.html.
5. Carl Becker, et. al, "Proposed Chapter 9 for Predicting Voltage Sags in Revision to IEEE Std 493, the Gold Book", *IEEE Transactions on Industry Applications*, Vol. 30, No. 3, May/June 1994, pp.805-821.
6. Ching-Yin Lee, Bin-Kwie Chen, Wei-Jen Lee, Yen-Feng Hsu, "Effects of Various Unbalanced Voltages on the Operation Performance of an Induction Motor under the Same Voltage Unbalance Factor Condition", *IEEE Industrial and Commercial Power Systems Technical Conference*, 1997, pp. 51-59.
7. Elias G. Strangas, Van E. Wagner, Tim D. Unruh, "Variable Speed Drives Evaluation Test", *IEEE Thirty-first Industry Applications Conference Annual Meeting*, Vol. 4, 1996, pp. 2239-2243.
8. David C. Robertson, Octavia I. Camps, Jeffrey S. Mayer and William B. Gish, Sr., "Wavelets and Electromagnetic Power System Transients", *IEEE Transactions on Power Delivery*, Vol. 11, No. 2, April 1996, pp. 1050-1058.
9. MathWorks, Inc., *MATLAB Manuals*, May 1997.
10. E. R. Collins, Jr. and R. L. Morgan, "A Three-phase Sag Generator for Testing Industrial Equipment", *IEEE Transactions Power Delivery*, Vol. 11, No. 1, January 1996, pp. 526-532.
11. G. Yalcinkaya, M. H. J. Bollen, and P.A. Crossley, "Characterization of Voltage Sags in Industrial Distribution Systems", *IEEE Industry Applications Society Annual Meetings*, New Orleans, LA, October 5-9, 1997, pp. 2197-2204.

Mladen Kezunovic (S'77, M'80, SM'85, F'99) received his Dipl. Ing. Degree from the University of Sarajevo, the M.S. and Ph.D. degrees from the University of Kansas, all in electrical engineering, in 1974, 1977 and 1980, respectively. Dr. Kezunovic's industrial experience is with Westinghouse Electric Corporation in the USA, and the Energoinvest Company in Sarajevo. He also worked at the University of Sarajevo. He was a Visiting Associate Professor at Washington State University in 1986-1987. He has been with Texas

A&M University since 1987 where he is a Professor and Director of Electric Power and Power Electronics Institute. His main research interests are digital simulators and simulation methods for relay testing as well as application of intelligent methods to power system monitoring, control and protection. Dr. Kezunovic is a registered professional engineer in Texas, and a Fellow of IEEE.

Yuan Liao (S'99) received his bachelor degree in 1993, and master degree in 1996, both in electrical engineering from Xi'an Jiaotong University, P. R. China. Presently he is pursuing Ph.D. degree at Texas A&M University. His research interests are applications of wavelets, signal processing and artificial intelligence to power system protection and power quality studies.