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IEEE Recommended Practice for Voltage Sag and Short Interruption Ride-Through Testing for End-Use Electrical Equipment Rated Less than 1000 V

IEEE Industry Applications Society

Sponsored by the
Power Systems Engineering Committee

IEEE
3 Park Avenue
New York, NY 10016-5997
USA

IEEE Std 1668™-2017
(Revision of IEEE Std 1668-2014)

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IEEE-SA Standards Board

Abstract: A non-industry-specific recommended practice for voltage sag and short interruption ride-through performance and compliance testing for all electrical and electronic equipment connected to low-voltage power systems that can experience malfunction or shutdown as a result of reductions in supply voltage lasting less than one minute is detailed in this document. Testing procedures and requirements for test equipment are clearly defined within this document to reflect this electrical environment, including single-phase, two-phase, and three-phase balanced and unbalanced voltage sags. Requirements for certification and test reporting, including characterization of voltage-sag ride-through equipment are also defined.

Keywords: equipment testing, IEEE 1668™, immunity, power quality, ride-through, voltage dip, voltage sag, voltage-sag characteristics

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Introduction

This introduction is not part of IEEE Std 1668-2017, IEEE Recommended Practice for Voltage Sag and Short Interruption Ride-Through Testing for End-Use Electrical Equipment Rated Less than 1000 V.

IEEE Std 1668-2017 is a non-industry-specific recommended practice for voltage-sag ride-through performance and compliance testing for all electrical and electronic equipment connected to low-voltage power systems that can experience malfunction or shutdown as a result of reductions in supply voltage lasting less than one minute. The recommended practice includes defining minimum voltage-sag immunity requirements based on actual voltage-sag data. A clause dedicated to the detailed analysis of voltage sags experienced by end users provides insight into real-world voltage sags. Testing procedures and test equipment requirements are clearly defined within this document to reflect this electrical environment, including single-phase, two-phase, and three-phase balanced and unbalanced voltage sags. This recommended practice also defines certification and test reporting requirements, including voltage-sag ride-through equipment characterization.

Grateful acknowledgment

The following material from CIGRE Working Group C4.1 10 Final Report, Voltage Dip Immunity of Equipment and Installations, April 2010 is reprinted with permission:

— Table 7 adapted from Table 6-5 page on 185 of CIGRE report

— Figure 19 adapted from 6-6 page 145 and Figure 6-35 on page 160 of CIGRE report

— Table 8 adapted from Figure 2-17 page 40, and from Table 4.1 on page 101 of CIGRE report

— Table 9 from un-numbered table on page 35 of CIGRE report

— Figure 20 adapted from Table 4.2 on page 102 of CIGRE report

— Figure 21 adapted from Table 4.1 on page 101 of CIGRE report and Table 4.2 and Table 4.3 on page 104 of CIGRE report

— Table A.1 adapted from Table 4.1 on page 101 of CIGRE report and Table 4.2 and Table 4.3 on page 104 of CIGRE report

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IEEE Recommended Practice for Voltage Sag and Short Interruption Ride-Through Testing for End-Use Electrical Equipment Rated Less than 1000 V

1. Overview

1.1 Scope

This document is a non-industry-specific recommended practice for voltage-sag ride-through performance and compliance testing for all electrical and electronic equipment connected to low-voltage power systems (with nominal/rated voltage less than 1000 V) that can experience malfunction or shutdown as a result of reductions in supply voltage lasting less than one minute. The recommended practice includes defining minimum voltage-sag immunity requirements based on actual voltage-sag data. A clause dedicated to the detailed analysis of voltage sags experienced by end users provides insight into real-world voltage sags. Testing procedures and requirements for test equipment are clearly defined within this document to reflect the electrical environment, including single-phase, two-phase, and three-phase, balanced and unbalanced voltage sags. The recommended practice also defines requirements for certification and test reporting, including characterization of voltage-sag ride-through equipment.

1.2 Purpose

The purpose of this recommended practice is to clearly define test methods and ride-through performance for determining the sensitivity of electrical and electronic equipment to voltage sags. Analysis of real-world sags provides the foundation for both test methods and performance criteria, aligning themselves as closely as possible to the end user's electrical environment. The recommended practice will define the characteristics in terms of the depths/magnitudes, durations, phase angles, and vectors of voltage sags required to relate to real-world voltage sags. The recommended practice will show how different voltage-sag testing methods can be used to simulate real-world sags. End users will be able to use the recommended practice in their purchase specifications to help ensure the required level of equipment performance. In addition, end users can use the voltage-sag criteria as a performance benchmark for existing equipment. This recommended practice can be used to provide a benchmark that can be used to identify equipment that has enhanced ride-through characteristics.

1.3 Limitations

This recommended practice is limited to the testing of equipment to voltage sags. Other power disturbances—including swells and harmonic and high-frequency impulsive transient events—are not within the scope of this document.

This recommended practice assumes a baseline electrical environment in compliance with ANSI C84.1-2011 Range A for steady-state utilization voltage and IEEE Std 519™-2014 for harmonics.[1]

Proper application of this recommended practice does not require any filtering of the harmonics during the testing or analysis to achieve accurate quantification of ride-through performance.

This recommended practice is a performance specification and does not address safety issues. It should not supersede any safety requirements.

This recommended practice does not override applicable international, national, and local codes.

This recommended practice does not address product quality that may or may not result in the application of the required immunity test levels.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ANSI C84.1-2011, American National Standard for Electric Power Systems and Equipment—Voltage Ratings (60 Hertz).[2]

IEC 61000-4-34, Electromagnetic compatibility (EMC)—Part 4-34: Testing and measurement techniques—Voltage dips, short interruptions and voltage variations immunity tests for equipment with mains current more than 16 A per phase.[3]

IEEE Std 519™-2014, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.[4,5]

SEMI F47-0706, Specification for Semiconductor Processing Equipment Voltage-Sag Immunity.[6]

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.[7]

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[1] Information on references can be found in Clause 2

[2] ANSI publications are available from the American National Standards Institute (http://www.ansi.org/).

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[6] This standard may be obtained from the Semiconductor Equipment and Materials International (SEMI) organization at www.semi.org.

[7] *IEEE Standards Dictionary Online* is available at: http://dictionary.ieee.org/.

calibration: The checking of a measuring instrument against an accurate standard to determine any variation of measured from actual values.

equipment under test (EUT): The electrical or electronics equipment being tested for voltage-sag ride-through performance.

galloping conductor: A transmission or distribution line that is moving unpredictably, typically due to heavy loading of ice and high winds.

immunity: The ability of equipment under test (EUT) to continuously operate (as intended) in the presence of an electromagnetic disturbance, such as voltage sags.

impulsive transient: A sudden non-power frequency change in the steady-state condition of voltage or current that is unidirectional in polarity (primarily either positive or negative) disturbance in the ac waveform typically evidenced by a sharp, brief waveform discontinuity.

interruption: *See:* **voltage interruption**.

malfunction: The failure of the equipment under test (EUT) to maintain continuous operation (as intended) in the presence of a voltage sag or momentary interruption.

momentary interruption: A type of short duration variation. The complete loss of voltage (< 0.1 pu) on one or more phase conductors for a time period between 0.5 cycles and 3 s.

nominal voltage: The voltage by which a portion of the system is designated and to which certain operating characteristics of the system are related. Each system voltage pertains to a portion of the system bounded by transformers or utilization equipment. Nominal voltage as referenced throughout the text of this document refers to nominal system voltage. All voltage values are given as root-mean-square (rms) values unless stated otherwise.

original equipment manufacturer (OEM): A company that supplies equipment to other companies for use in their manufacturing process or to incorporate into another product.

per unit (pu): A per-unit quantity is the ratio of the actual value of a quantity to the base value of the same quantity.

phase under test (PUT): The selected phase or combination of phases during a voltage-sag test of equipment under test (EUT).

residual/remaining voltage: Minimum voltage during a voltage sag expressed in volts, as a percentage of nominal voltage, or in per unit. All residual voltage values are root-mean-square (rms) unless stated otherwise.

ride-through capability: The ability of the equipment under test (EUT) to withstand voltage sags and momentary interruptions to specified durations and magnitudes without malfunctioning.

sag: *See:* **voltage sag**.

sag generator: A test apparatus capable of reducing the voltage supplied to equipment under test (EUT) with specified magnitudes and phase angles for a specific duration in order to accurately reproduce different types of voltage sags and momentary interruptions.

sustained interruption: A type of long-duration root-mean-square (rms) voltage variation where the complete loss of voltage (< 0.1 pu) on one of more phase conductors is for a time greater than 1 min.

System Average Interruption Frequency Index (SAIFI): Indicates how often the average customer experiences a sustained interruption over a predefined period of time.

System Average rms Variation Frequency Index (SARFI-X): For X less than 100, the system average rms variation frequency index (SARFI) is the count of voltage sags at a given site, or in a given system, per year with a magnitude less than X percent. For X more than 100: the count of voltage swells at a given site, or in a given system, per year with a magnitude greater than X percent. For X a predefined curve: the count of voltage sags at a given site, or in a given system, per year more severe than the curve limits

NOTE—See Sabin [B20].[8]

system integrator: A company that integrates equipment, components, and subsystems into a whole and verifies that they all function together.

temporary interruption: A type of short duration variation. The complete loss of voltage (< 0.1 pu) on one or more phase conductors for a time period between 3 s and 1 min.

uninterruptible power supply (UPS): An electrical apparatus that provides reliable power to a load when the input power source, typically from the utility, fails.

voltage dip: *See:* **voltage sag**.

voltage interruption: The disappearance of the supply voltage on one or more phases. An additional qualifying term (i.e., momentary, sustained, or temporary) indicates the relative duration of the interruption.

voltage sag: A reduction in any or all phases of supply voltage to between 0.1 pu and 0.9 pu in rms voltage or current at the power frequency for durations of 0.5 cycle to 1 min.

voltage swell: An increase in any or all phases of supply voltage or current at the power frequency for durations from 0.5 cycles to 1 min. Typical values are 1.1 pu to 1.8 pu.

3.2 Acronyms and abbreviations

CNC	computerized numerical controller
DAS	data acquisition system
DEV	device
DPQ	distribution power quality
EUT	equipment under test
IGBT	insulated gate bipolar transistor
ITE	information technology equipment
OEM	original equipment manufacturer
PLC	programmable logic controller
POC	point of connection
PPE	personal protective equipment
pu	per unit

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[8] The numbers in brackets correspond to those of the bibliography in Annex D.

PUT	phase under test
rms	root-mean-square
SAIFI	System Average Interruption Frequency Index
SARFI-X	System Average rms Variation Frequency Index
SCR	silicon controlled rectifier
SEMI	Semiconductor Equipment Materials International
UPS	uninterruptible power supply

4. Primer on voltage sags

4.1 Background on voltage sags

While the electricity delivered today generally meets the demands of the average consumer, the power quality and reliability of delivered electrical energy can vary significantly over time and from one region to another. Interruptions in electrical service and voltage anomalies can be common and accepted in some areas of the world. However, in today's more highly developed industrial and digital economies, the manufacturing processes have more stringent power quality requirements. These requirements have resulted in customers expecting higher-quality and continuity of electrical power supply with significant reductions in interruptions, as well as other power quality disturbances. However, even in the most highly developed power systems, variations in voltage do occur from time to time, and these variations affect some customers more than others. Interruptions, voltage sags, swells, overvoltages, harmonics, switching transients, flicker, and many other power quality events and disturbances are realities of all electric power systems.

One of the more predominant power quality events is the voltage sag, which is a reduction in the rms voltage magnitude below a given threshold lasting typically from several cycles to several seconds.[9], [10] It is widely known that voltage sags can have a strong impact on high-tech industries. One source [B4] has reported that a single voltage sag can cost manufacturers from tens of thousands to as much as $2M US. Electrical and electronics equipment connected to electrical networks have varying degrees of sensitivity to voltage sags. This sensitivity is determined by two major factors: the design of the equipment and the physical characteristics of the voltage sag.

The goal of this recommended practice is to present and recommend voltage-sag test levels and test methods that best represent actual voltage sags. The audiences for this recommended practice include the following:

- The equipment owners who want to better understand the phenomena of voltage sags and specify voltage-sag immunity testing aimed at obtaining less sensitive electrical equipment resulting in improved ride-through for critical processes.
- System integrators or original equipment manufacturers (OEMs) who are designing and building electrical equipment and should understand the electrical environment and the test methods that will be used to determine the immunity of their equipment.
- The test engineers who want to properly evaluate individual electrical equipment, or processes involving a number of different equipment, against voltage sags to determine the immunity or robustness of the equipment under test (EUT).

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[9] The most common value for a sag-magnitude threshold (including monitoring applications) is 90% of the nominal or declared voltage.

[10] The minimum duration for which voltage-sag magnitude based on rms voltage value could be calculated is one half of a cycle. The upper limit for voltage-sag duration is usually set to distinguish voltage sags from steady state undervoltages which may be as long as a few minutes.

To help the reader understand the recommended requirements for voltage-sag immunity presented in this document, it is important to provide a brief background on voltage-sag characteristics and to explain how voltage sags occur and then propagate through the electrical system. This clause also aims to help the reader understand the background statistics related to the types of voltage sags as they occur on the electrical network.

4.2 The basics of voltage sags

The two basic characteristics of a voltage sag are the reduction in rms voltage magnitude (depth) and the duration of the voltage reduction. These are the most common voltage-sag parameters used.

The terminology used to describe the magnitude of voltage sags varies and is often confusing. Most commonly, voltage-sag magnitudes are expressed in percentage of the remaining nominal voltage, also stated as residual or remaining voltage during the disturbance. For example, if a 48-V reduction in voltage magnitude occurs as a result of a voltage sag on a system with 480-V nominal voltage, resulting in a remaining/residual voltage of 432 V, this would be referred to as a "sag to 90% of nominal voltage." Expressing the magnitude of a voltage sag as a percentage of nominal voltage allows for easy comparison between different voltage levels. This is especially helpful when analyzing the effect of faults resulting in voltage sags across wide areas and at different voltage levels.

Per IEEE Std 1159™-2009 [B13], duration of the voltage sag is defined as the time from when the rms voltage decreased below 90% of the nominal steady-state voltage to when it returned above 90% of the nominal steady-state voltage, measured in milliseconds, seconds, or cycles. An example of a voltage sag as an rms plot to 46% of nominal for 5.4 cycles (60 Hz) is shown in Figure 1.

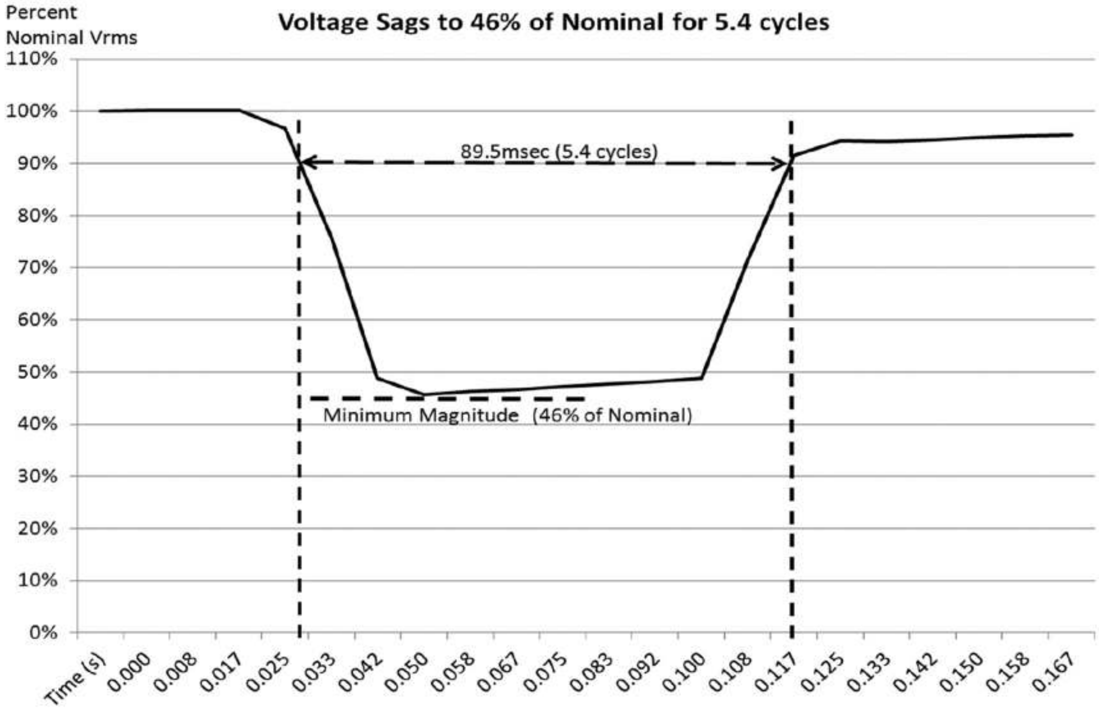

Figure 1—Single-phase voltage sag (instantaneous voltage rms plot)

Consideration should also be given when doing voltage-sag analysis to other voltage-sag characteristics and waveform data that may be lost if the sag characterization is kept as only an rms voltage magnitude and duration. Characteristics such as phase-shift, point-on-wave of initiation, and recovery of the instantaneous voltage waveform during the sag may have an effect on equipment performance as well.

When considering three-phase systems, the magnitude and duration of three voltages should be measured to obtain complete information about the voltage sag. This can be a set of three phase-to-neutral voltages or a set of three phase-to-phase voltages, or a set of three phase-to-ground voltages. Furthermore, in a three-phase system, voltage sags can be single-phase, two-phase, or three-phase in nature.

In order to simplify understanding of voltage sags, it is customary to represent a voltage sag by visualizing the worst-case voltage-sag magnitude and duration (i.e., the minimum voltage of all sagged phases and the total duration for which at least one phase is experiencing rms voltage reduction below 90% of the nominal voltage) to represent a voltage reduction event that has occurred on an electrical supply. These representations can omit the magnitude and duration of the readings that occurred on the other monitoring channels when polyphase voltage-sag events occur. The event summary shown in Table 1 is an example of the simplification that is often used to represent voltage sags. The data in the table includes the time and date of the event and the magnitude and duration information for the worst-case channel measurement from the power quality monitor.

Table 1—Example of simplification of voltage-sag events in data analysis, rms voltage variation events (7.56-kV base voltage)

Time stamp	Phase	Magnitude (kV)	Magnitude (pu)	Duration (s)	Duration (cycles)
05/25/2008 14:41:13.0000	A	3.175	0.420	0.067	4.0
07/31/2009 07:58:49:3367	C	0.056	0.007	8.417	505.0
10/30/2009 11:16:47.0767	A	5.901	0.781	0.050	3.0
05/02/2010 13:03:12.2967	B	6.244	0.826	0.050	3.0
05/14/2010 14:47:09.5467	C	5.999	0.794	0.150	9.0
12/14/2010 07:05:20.5167	B	1.092	0.144	0.800	48.0
04/24/2011 06:57:56.8867	B	6.237	0.825	0.217	13.0
05/01/2011 06:14:52.4367	A	5.383	0.712	0.150	9.0
07/06/2011 08:13:52.5567	A	0.084	0.011	4.100	246.0
07/21/2011 16:11:18.0567	C	4.921	0.651	0.133	8.0
11/16/2011 02:15:05.4367	B	5.908	0.781	0.150	9.0
01/20/2012 22:24:57.1567	B	5.257	0.695	0.133	8.0
05/31/2012 17:14:26.9067	A	5.866	0.776	0.050	3.0
06/20/2012 22:26:02.3167	C	3.661	0.484	0.050	3.0
07/02/2012 17:58:48.7467	C	6.384	0.844	0.117	7.0
07/10/2012 16:09:16.7567	A	4.053	0.536	0.683	41.0
07/20/2012 05:07:58.7267	C	5.740	0.759	0.067	4.0
08/05/2012 12:06:24.4667	C	6.153	0.814	0.133	8.0
09/08/2012 00:00:43.3967	A	5.964	0.789	0.100	6.0
10/30/2012 14:05:18.0367	C	5.747	0.760	0.117	7.0

A "one-point" representation of the voltage-sag data shown in Table 1 is typically graphed as depicted in Figure 2. The per unit voltage-sag minimum data in the chart (dots) are plotted against voltage-sag duration time. The solid line shows the sensitivity limit for an example 24-V dc power supply.

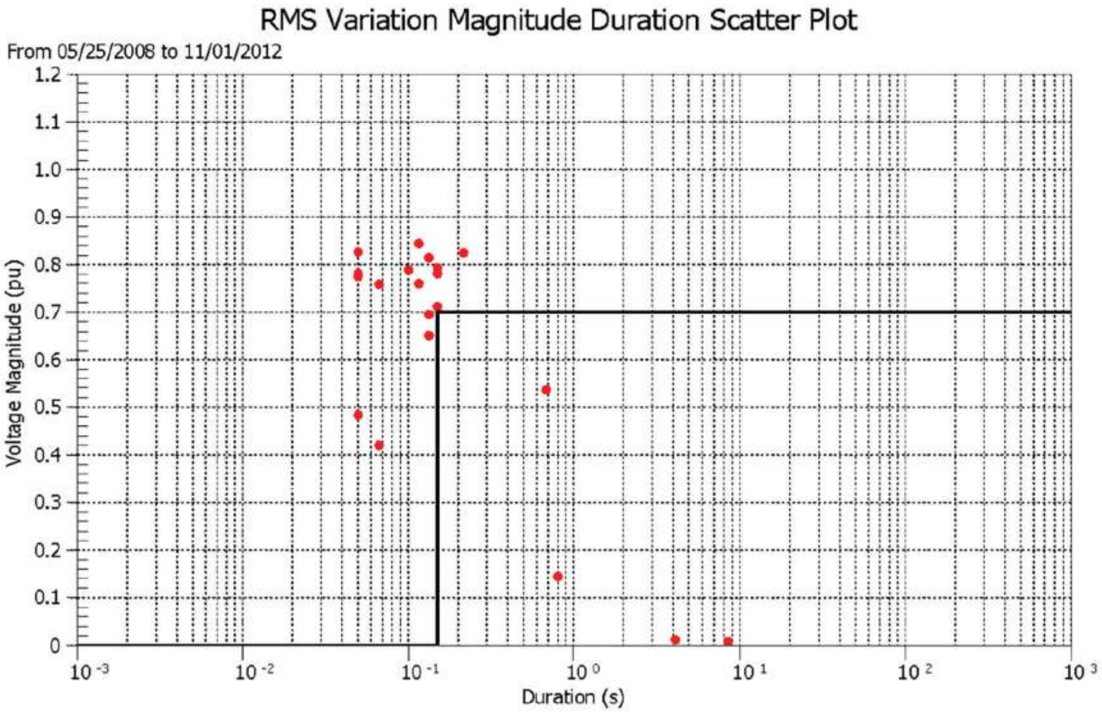

Figure 2—Simplified voltage-sag magnitude duration scatter plot with an example of a 24-V dc power-supply sensitivity overlay

These data-visualization methods and representations are useful to quickly review the information. They are especially useful in looking at events occurring at a site over an extended time period. This approach is widely adopted, and often equipment sensitivity curves are also displayed with the voltage-sag data as shown in Figure 2. The solid line represents an example voltage-sag level where a control component may shut down. As the legend states, of the 20 events seen over the study period, there were four events that were below the voltage-sag sensitivity limit for this device.

The simplified approach (worse phase only, max duration) does not help the end user to understand the true mechanics of the event. Such a simplified view can lead to misunderstanding regarding why one event of a certain magnitude and duration can cause an industrial process to shut down, where another of a similar magnitude and duration does not. Therefore, a more detailed understanding of voltage-sag characteristics, as well as how these events occur, is required.

4.3 Other key voltage-sag characteristics

In order to characterize voltage sags representative of the real-world electrical environment, it is important to understand some additional characteristics: the point on the sine wave of the instantaneous voltage where the voltage sag occurs, how the voltage phase angle can change during the voltage sag, and the difference between balanced and unbalanced voltage sags. In 4.4, the relation between fault clearing time and duration of a fault-caused voltage sag will be discussed, as well as how voltage recovers after the fault is cleared.

Although it can seem logical that voltage sags usually occur at or near the peak of the sine wave because there is more energy at that instant, research shows that the sag initiation is not partial to voltage peaks; in fact, it is generally random according to one source [B8]. In the event where a voltage sag occurs at the zero crossing, the sine wave will maintain its symmetry during the voltage reduction. When a voltage sag occurs elsewhere on the sine wave, there is an abrupt change in voltage leaving a portion of the sine wave present.

Figure 3 shows how point-on-wave can influence the shape of the sine wave. Here, we see two voltage sags to 60% of nominal lasting three cycles (60 Hz). The waveform shown in Figure 3 part a) shows the voltage sag occurring at the zero crossing. Note how there is little change in shape of the sine wave. Figure 3 part b) shows the resulting change in the waveform when the voltage sag occurs at the peak of the sine wave, or 90°. The actual values of points on wave of sag initiation or ending can influence performance of equipment during or after a voltage sag. For example, in the case of a switch-mode power supply, the point-on-wave of initiation of the voltage sag will determine the energy available for ride-through in the dc link capacitor. Subsequently, the point-on-wave at the end of the voltage sag will determine inrush current at the end of the event.

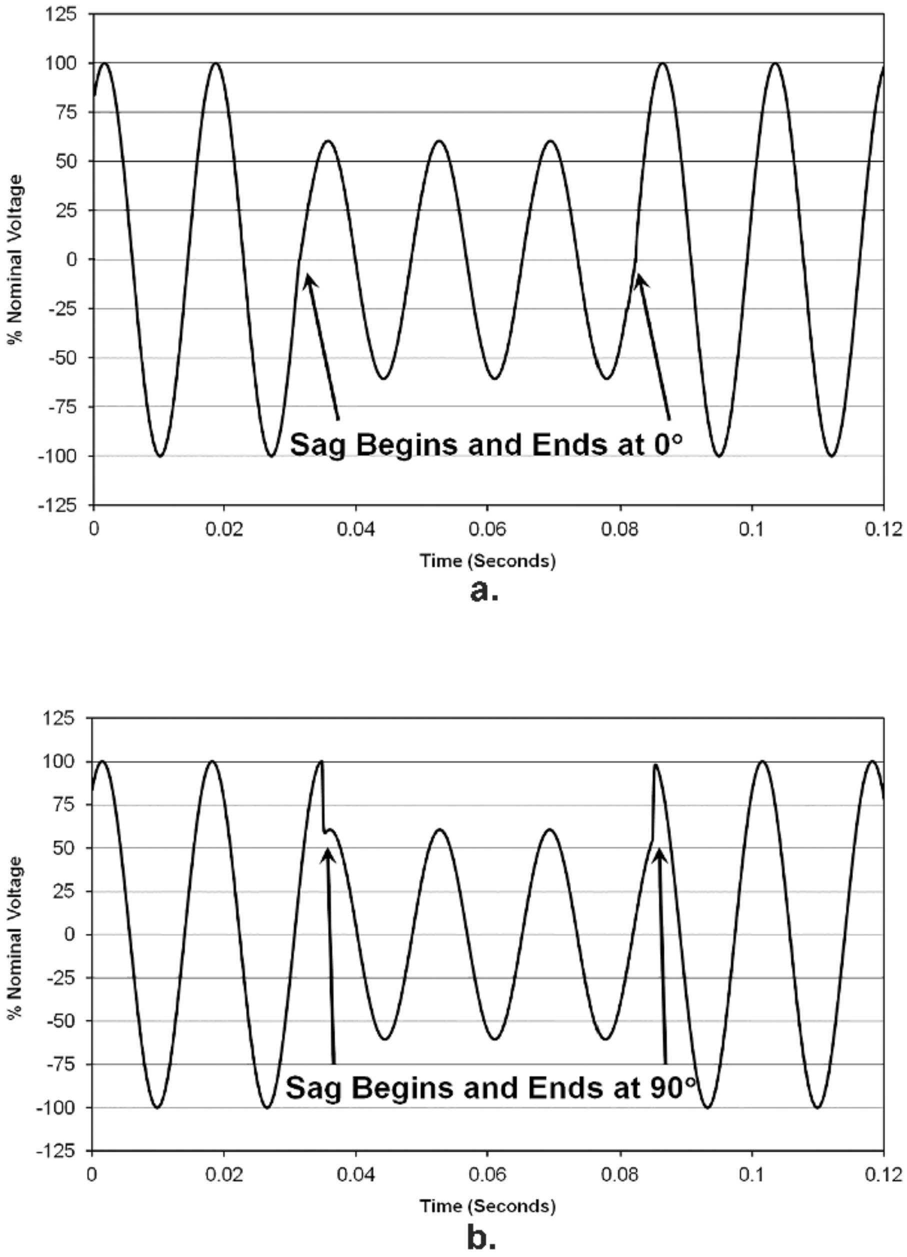

Figure 3—Waveforms of two voltage sags illustrating point-on-wave

Equipment and devices in many industrial processes sometimes malfunction when subjected to shallow sags and yet do not malfunction during deeper sags. Even though this can seem counterintuitive, devices such as contactors—electromechanical devices used for on/off switching and control/protection of electrical equipment—are extremely sensitive to the point-on-wave at which the sag is initiated. Figure 4 shows the voltage required to keep the contactor operational in reference to the point-on-wave of where the voltage sag is initiated. If the voltage falls below the curve during the sag event, the contactor will malfunction. Note that higher voltage is required after approximately 3.5 cycles to keep the contactor operational at the 0° and 180° points-on-wave of initiation (e.g., 60 Hz contactor). Conversely, the contactor will hold in down to lower voltages after 3.5 cycles if the voltage sag event begins at 90° point-on-wave as well as 270°. Figure 4 shows the rms voltage magnitude of the sag versus the point-on-wave of initiation of the event. Voltage sags below the curve will cause the contactor to malfunction magnetically in the form of contactor chatter and electrically by opening the contacts and disconnecting the associated electrical circuit [B22]. For this contactor, the average percent difference at five cycles between 0° tolerance and 90° tolerance was 5.9% for the contactors (Djokic, et al. [B7]).

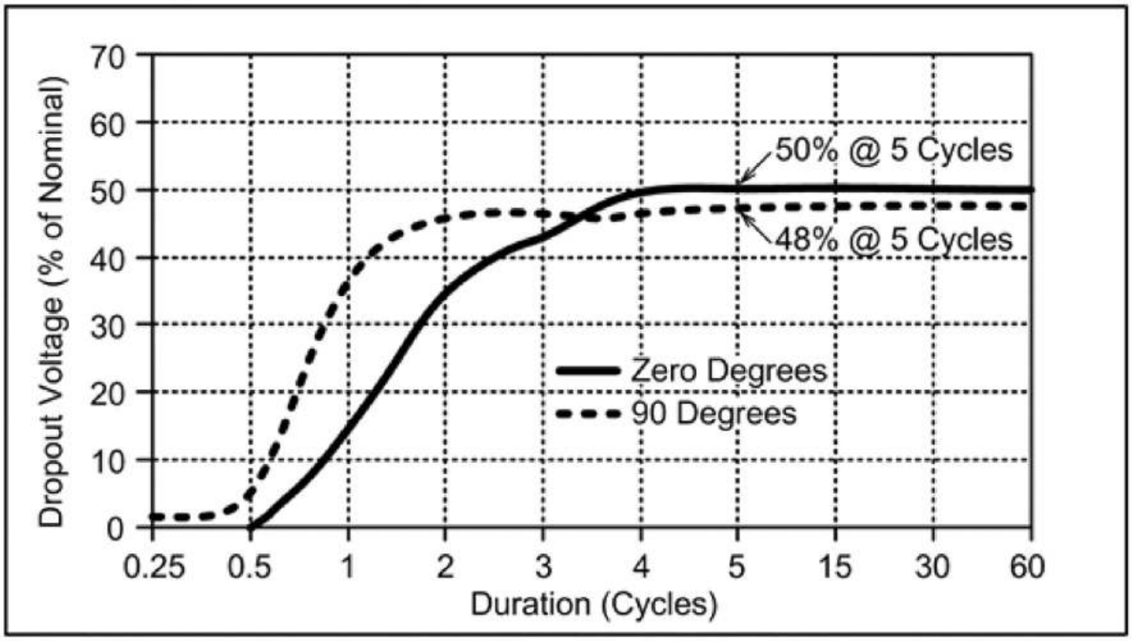

Figure 4—Example of point-on-wave of voltage-sag initiationinfluencing the trip level of an ac contactor [B11]

As a result of a voltage sag, the sine-wave voltage during the sag can also experience a phase-angle change or phase shift. The phase shift typically results from a complex interaction between the fault current and impedance in the electrical system. In the real-world electrical environment, phase shifts in voltage can occur and can result in a brief deviation from the line frequency, possibly resulting in equipment malfunction or interruption. An ac voltage waveform that crosses the zero point after the voltage normally would indicate a positive phase shift. An ac voltage waveform that crosses the zero point before the voltage normally would indicate a negative phase shift. Figure 5 shows an example of a voltage sag with a negative and positive phase shift. The waveforms show a typical three-phase supply system. The Vbn and Vcn waveforms indicate a deviation from the nominal voltage as a result of a voltage sag to 58% of nominal. In the case of the Vcn waveform, note that the voltage sag crosses the zero crossing before it normally would have, resulting in a negative phase shift. The Vbn waveform crosses the zero crossing later than it normally would have, resulting in a positive phase shift. Voltage-sag susceptibility testing conducted by one source [B21] shows that relays can be more sensitive to voltage sags that include phase shifts

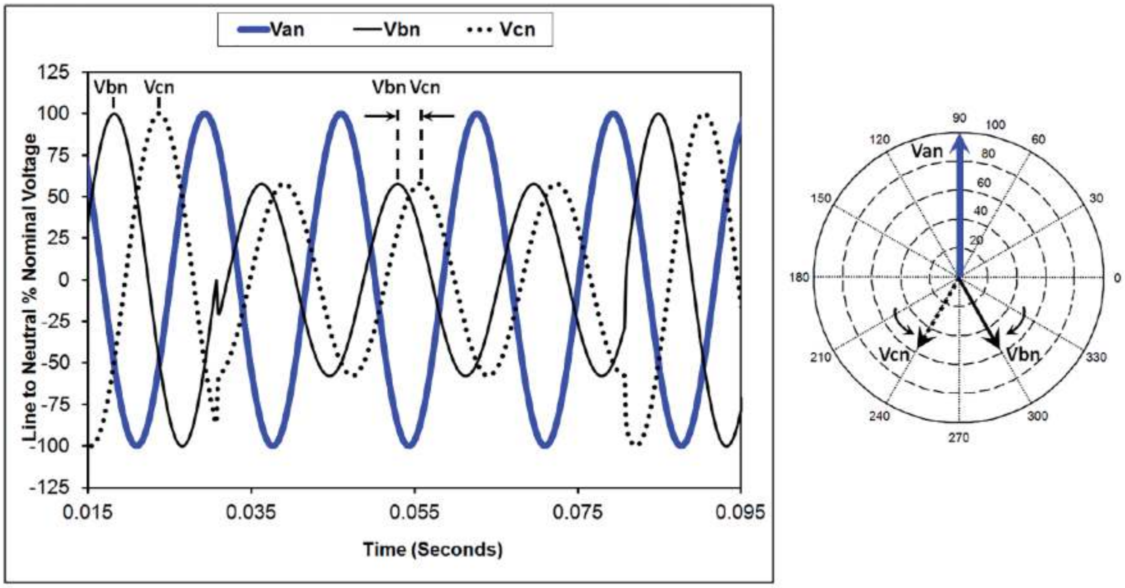

Figure 5—Two-phase voltage sag with positive and negative phase shift

Up to this point, all the reviewed characteristics apply to all voltage sags. When dealing with three-phase systems, it is important to understand that based on their origins, some voltage sags are balanced and others are unbalanced, based on their origin (e.g., type of fault). Balanced voltage sags affect all three phases equally, and the normal phase angle relationship between the voltages remains at 120°. In unbalanced voltage sags, the voltage magnitudes differ, as does the relationship between the phase angles. Unbalanced voltage sags occur much more frequently in the real-world electrical environment than balanced sags. For example, when the load(s) is (are) all three-phase, a balanced phase-to-phase sag is more likely than when the loads are all phase-to-neutral or a mixture of phase-to-phase and phase-to-neutral. A fault on one phase-to-neutral would not affect all three phases. This phenomenon is described in greater detail later in Figure 14. An example of a three-phase balanced voltage sag is shown in Figure 6, whereas an unbalanced voltage sag impacting two phases is shown in Figure 7. Note how the phasor magnitudes and phase angle relationship between the phasors are the same for the balanced voltage sag and different for the unbalanced voltage sag.

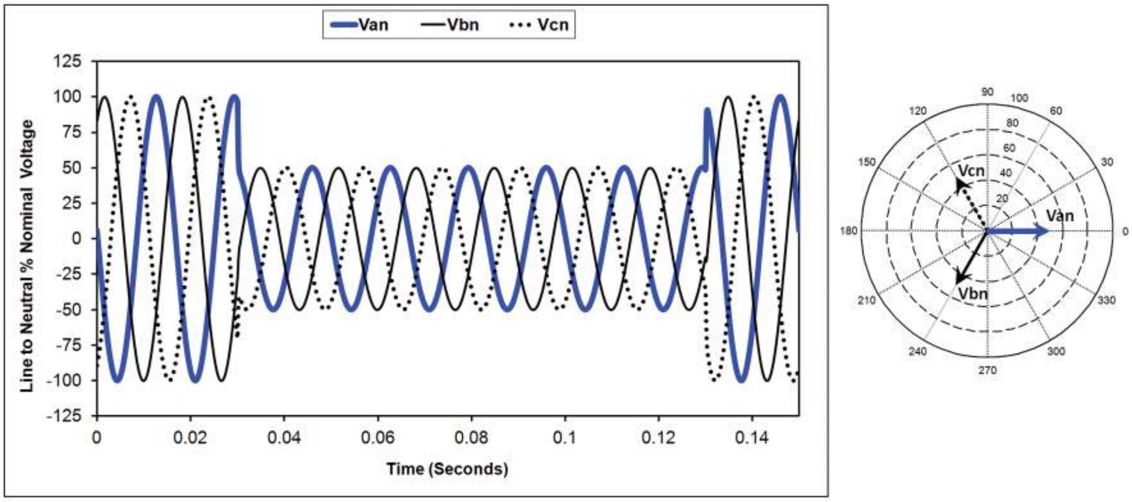

Figure 6—Balanced voltage-sag simulation

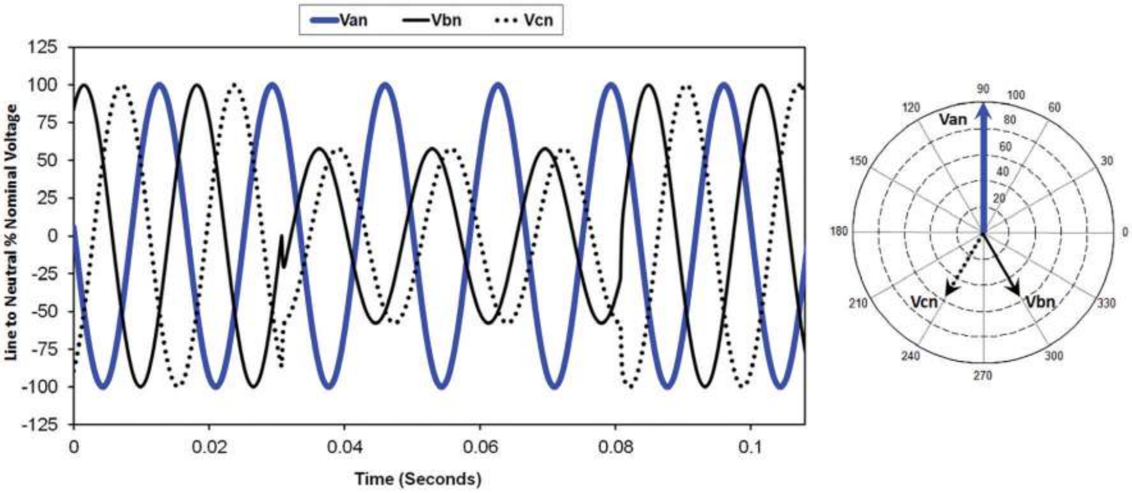

Figure 7—Unbalanced voltage-sag simulation

4.4 Faults and voltage sags

While minor voltage sags can occur as a result of starting large motors and energizing transformers, most severe voltage sags are the result of electrical faults on power systems. When faults occur, protective relaying plays a critical role in detecting the fault current and then isolating the fault (i.e., disconnecting the faulted part of the system) in a timely manner and restoring the nominal supply conditions elsewhere. During the time it takes to clear the fault, a voltage sag occurs, the magnitude of which is based on the type and location of the fault and strength of the system (system impedance). Clearing times vary considerably based on the location of the fault within the power system. However, a general rule of thumb is that protective relaying systems should be designed to operate more quickly for greater magnitudes of fault current. Based on this methodology, it should come as no surprise that faults on transmission systems are more quickly isolated than faults on distribution systems. Faults in transmission systems are typically cleared within two to three cycles, while on sub-transmission systems, faults are cleared within three to six cycles. However, some protective relaying schemes can take as long as 20 cycles to clear the fault (60 Hz). Fault clearing times on distribution systems and at the utilization level vary widely. Figure 8 shows two different voltage sags: one on the transmission system (solid waveform), which clears in three cycles; and the other on the sub-transmission system (dotted-line waveform—also smallest magnitude), which clears in six cycles (60 Hz).

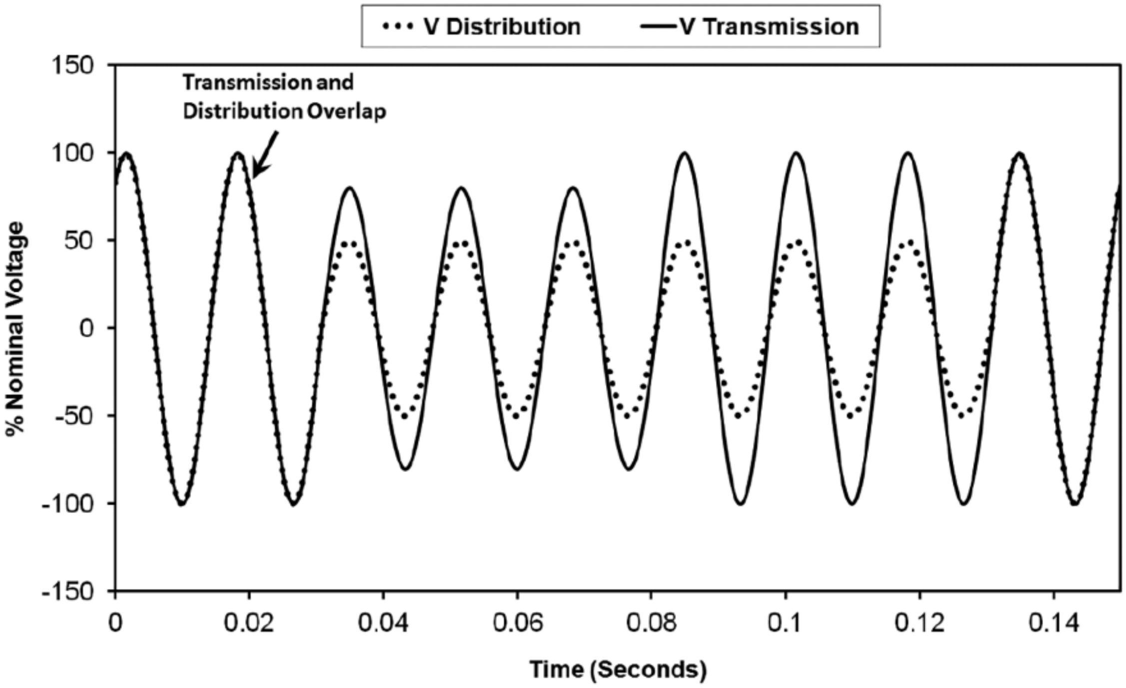

Figure 8—Example of voltage sags and fault clearing timesfor distribution and transmission lines

Once protective relaying clears the fault, the voltage can recover to pre-faulted conditions, given that there is an adequate supply of reactive power. This usually occurs quickly, as seen in Figure 9 where the voltage returns to nominal in 15 ms (60 Hz). In some cases, customer loads can stay online, causing significant post-sag inrush current and requiring reactive power flow from generation to return the system to pre-faulted conditions. Should enough generation be interrupted or critical transmission lines lost due to a fault, voltage collapse or slow voltage recovery can ensue, preventing or delaying the return to nominal voltage. Utilities try to minimize these conditions, but slow voltage recovery will occur on occasion. An example of slow voltage recovery is shown in Figure 10.

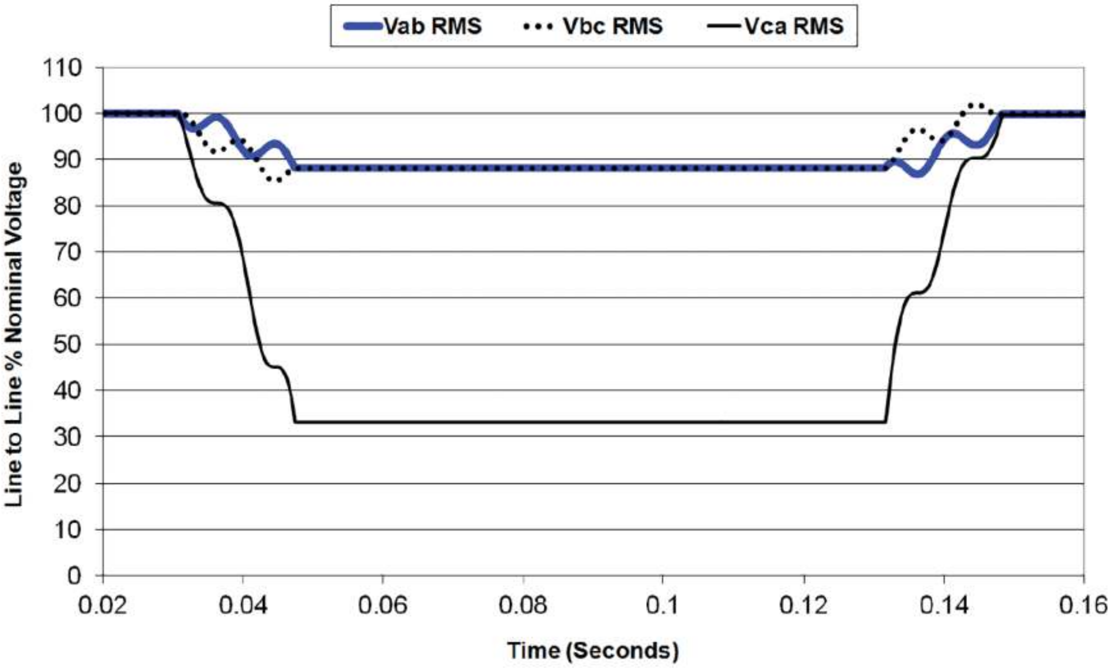

Figure 9—Voltage recovery after fault is cleared (simulation)

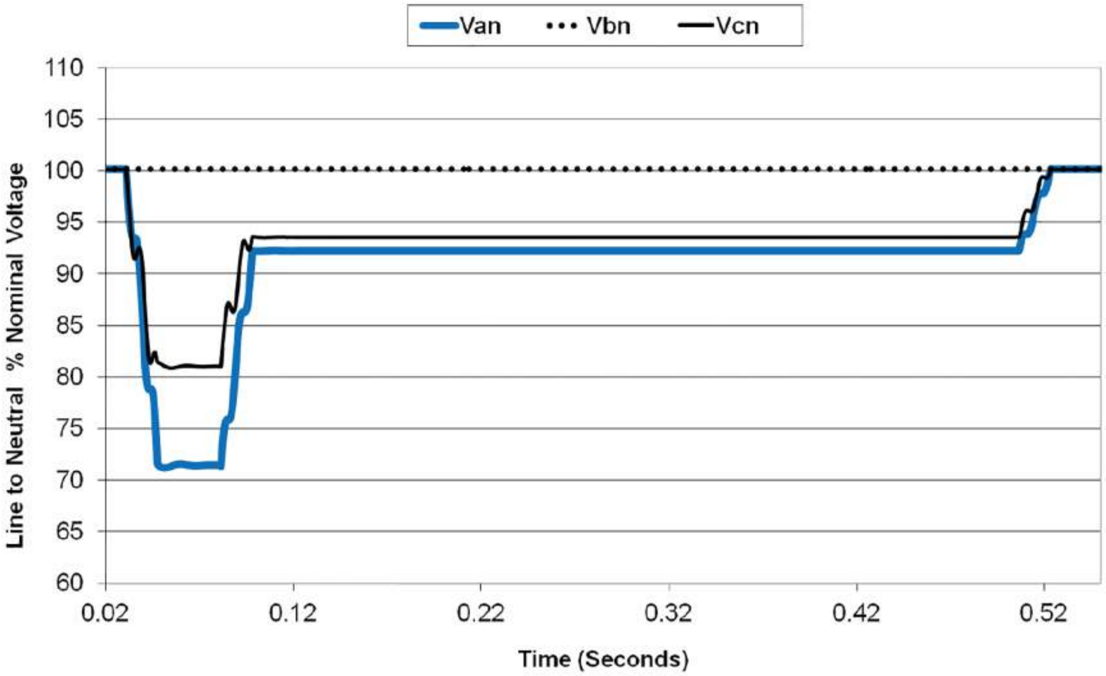

Figure 10—Slow voltage recovery after fault is cleared (simulation)

It is important to understand how faults throughout the power-delivery system impact customers at the utilization level. Many factors influence what the voltage sag looks like (characteristics of a voltage sag) to these customers—factors such as the number of step-down voltage transformations to the fault. This includes wye-delta, delta-wye, delta-delta, and wye-wye transformer winding configurations. The system impedance to the fault, impedance of the transformations, pre-fault voltage, protective relaying equipment in place, and the type of fault also help shape the magnitude and duration of the voltage sag as seen at the utilization voltage.

Some voltage sags at a facility may result from starting large, line-connected motor loads located within the facility or at one nearby. Faults to ground may also occur within the facility. While faults and voltage sags are known to occur within customers' facilities, the following material deals with effects from voltage sags originating on the utility system.

Faults on transmission systems result in all adjacent and downstream circuits experiencing a voltage sag. Indeed, some transmission-level faults can result in voltage sags hundreds of miles away. Interruptions are rare because transmission systems are almost always networked with multiple sources feeding into the network. Figure 11 shows a single-phase fault on Phase A to ground on a 161-kV transmission line and the resultant voltage sag at a customer's 480-V bus. The utilization voltage (locations where end-use equipment is interconnected), 480 V in this case, is transformed via two delta-wye transformers; the first with a secondary voltage of 13.8 kV and the second with a secondary voltage of 480 V. The transformer connections have a significant impact on how the voltage sag propagates to the utilization level. At the location of the fault, the voltage from Phase A to ground will be 0 V. Note how the phase-to-phase voltages (BC and CA) and phase-to-neutral voltages (AN, BN, and CN) are affected from the single-phase fault due to the two delta-wye transformers.

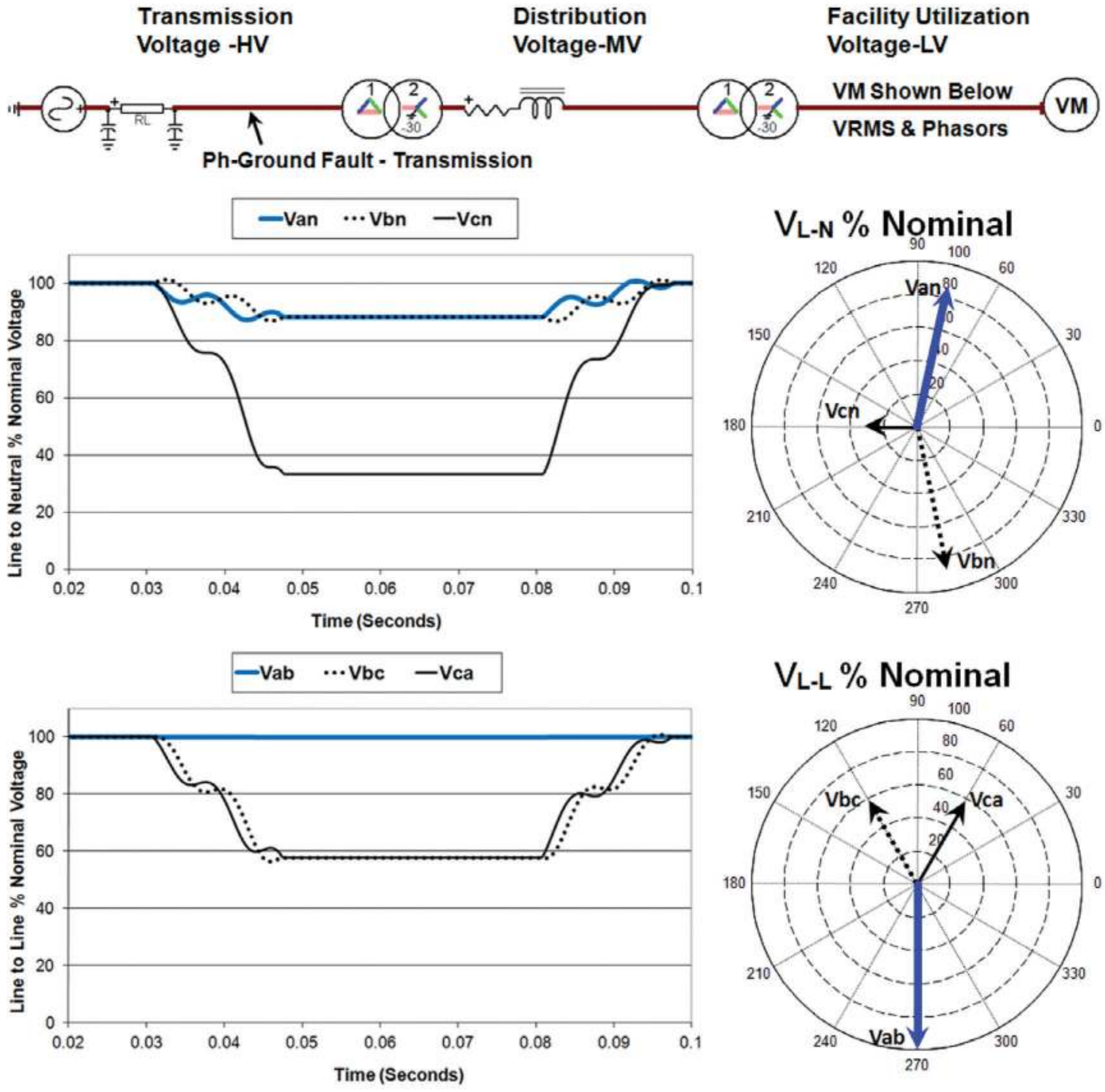

Figure 11—Voltage sag at 480 Vrms utilization voltagefrom a transmission-system fault (A-G) simulation

In the previous example, the transmission voltage was transformed to utilization voltage by two delta-wye transformers. Although this is a common system configuration, there are numerous other arrangements used today. Table 2 shows how a voltage sag due to a single-phase-to-ground fault on Phase A in the transmission system will propagate through the different types of transformers. Some transformer combinations produce a higher secondary voltage after the second transformation than others. It should be noted that values represented in this table represent an idealized approximation because it does not model system impedances and assumes ideal transformations.

Table 2—Secondary transformer voltages (pu) and phase angles from a transmission-system fault (A-G)

Transformation #1	VLL (AB, BC, CA)	VLN (AN, BN, CN)	Transformation #2	VLL (AB, BC, CA)	VLN (AN, BN, CN)
Delta-wye (g)	33% ∠ 180, 88% ∠ 79.1, 88% ∠ 280.9	58% ∠ 300, 58% ∠ 240, 100% ∠ 90	Delta-wye (g)	58% ∠ 120, 58% ∠ 60, 100% ∠ 270	88% ∠ 280.9, 33% ∠ 180, 88% ∠ 79.1
Wye (g)-wye (g)	58% ∠ 240, 100% ∠ 90, 58% ∠ 300	0%, 100% ∠ 240, 100% ∠ 20	Delta-wye (g)	33% ∠ 180, 88% ∠ 79.1, 88% ∠ 280.9	58% ∠ 300, 58% ∠ 240, 100% ∠ 90
Wye (g)-wye (g)	58% ∠ 240, 100% ∠ 90, 58% ∠ 300	0%, 100% ∠ 240, 100% ∠ 120	Wye (g)-wye (g)	58% ∠ 240, 100% ∠ 90, 58% ∠ 300	0%, 100% ∠ 240, 100% ∠ 120
Wye-wye (g)	58% ∠ 240, 100% ∠ 90, 58% ∠ 300	33% ∠ 0, 88% ∠ 259.1, 88% ∠ 100.9	Delta-wye (g)	33% ∠ 180, 88% ∠ 79.1, 88% ∠ 280.9	58% ∠ 300, 58% ∠ 240, 100% ∠ 90
Wye (g)-delta	33% ∠ 180, 88% ∠ 79.1, 88% ∠ 280.9	58% ∠ 300, 58% ∠ 240, 100% ∠ 90	Wye (g)-delta	58% ∠ 120, 58% ∠ 60, 100% ∠ 270	88% ∠ 280.9, 33% ∠ 80, 88% ∠ 79.1

Voltage sags occur more often on distribution systems for a variety of reasons. More equipment and conductors on the distribution system offer more opportunities for faults. Furthermore, the distribution system may not be built to the same high standards as the transmission system, which by itself can lead to the greater possibility of faults occurring. Unlike transmission systems, distribution systems are seldom networked with multiple simultaneous sources (except in special circumstances or high-density downtown areas). Also, it is common for overhead distribution conductors to be supported on wood poles, whereas most conductors on transmission systems are carried via steel poles or towers. During severe storms, steel poles are much more likely to withstand high winds. Distribution lines are more directly exposed to vegetation, vehicles, debris, and animals due to height and placement of poles.

In addition to a higher frequency of faults on distribution systems, the clearing times of protective relaying are much slower; therefore, voltage sags tend to be longer in duration. It is also very common on distribution systems to reclose in an attempt to clear the faulted condition. Should the faulted condition remain during subsequent reclose attempts, then additional voltage sags will occur (repetitive sags or sag sequences).

Automatic reclosers are installed on distribution circuits to help restore power after a transient fault has occurred downstream on the circuit. In some cases, they act to test the circuit and clear the fault. Consider the fault scenario and timing diagram shown in Figure 12. Should a fault on Feeder "A" cause the circuit protection to open, a recloser will attempt to reapply power. In some cases, a fault will clear itself (temporary fault) and power can be restored with the reclosing action. If not, the recloser will typically make three attempts before "locking out" and requiring manual intervention. These repeated operations are experienced by customers on the adjacent Feeder "B" as a succession of voltage sags. The rapid sequence of open/close operations can result at the equipment utilization end as a single event characterized by a combination of over voltage and sag components as equipment draws and then loses current.

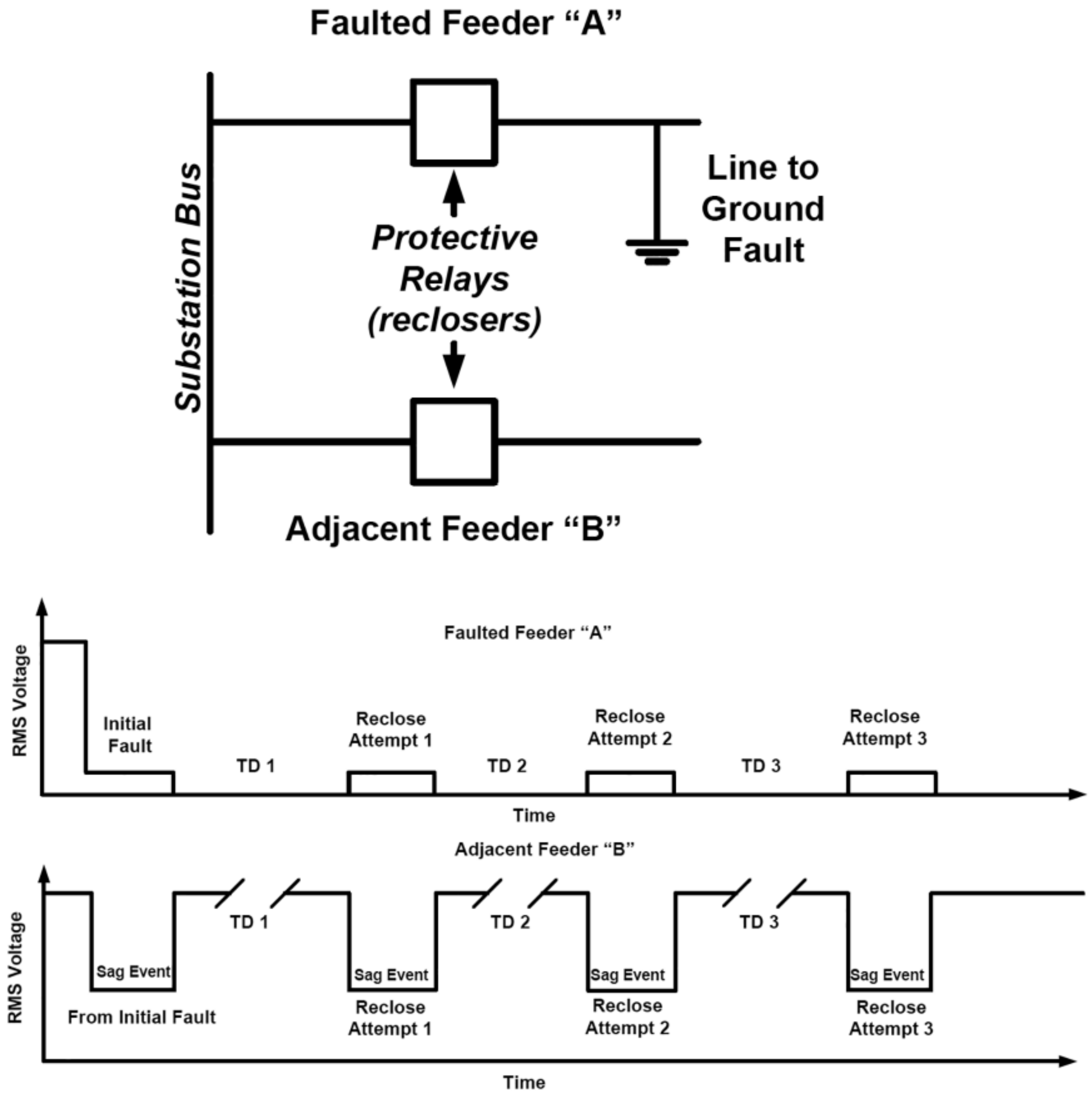

Figure 12—Example fault scenario and timing diagram

Utilities use different recloser setting schemes based on the network characteristics, coordination requirements, and the customer loads. Four different recloser schemes are presented in Table 3. The minimum recloser time is based on the time delay required for allowing the arc and ionizing gases to dissipate at the point of the fault. These representative schemes are based on the review of an IEEE Distribution Protection Practices Industry Survey [B5], and a survey of various utility recloser schemes by the Voltage Sag Ride-through Working Group.

Table 3—Four representative recloser schemes

Recloser scenario	Types of recloser schemes	Time delay 1 (TD1)	Time delay 2 (TD2)	Time delay 3 (TD3)
1	Instantaneous	30 cycles	15 s	30 s
2	Fast	2 s	15 s	30 s
3	Delayed	5 s	30 s	60 s
4	Hydraulic	2 s	2 s	2 s

Typically, there are several distribution feeders on the low side of a substation transformer (example, 69 kV to 13.8 kV). When faults occur downstream of this transformer on the utility feeder or at an individual customer's point of common coupling, the protective equipment will operate to isolate the faulted feeder, resulting in a voltage sag on all of the adjacent circuits. Due to the large impedance of substation transformers, most voltage sags will be significantly dampened and will not impact the transmission system (the upstream circuits).

Figure 13 shows a single-phase fault (Phase A to ground) on a 13.8-kV distribution line and the resultant voltage sag at a 480-V customer bus. Once again, in this example the utilization voltage is 480 V. In this instance, however, only one delta-wye transformation exists between the location of the fault and the customer. Note how the phase-to-phase voltages (AB, BC, and CA) and phase-to-neutral voltages (AN and CN) are affected due to one delta-wye transformation.

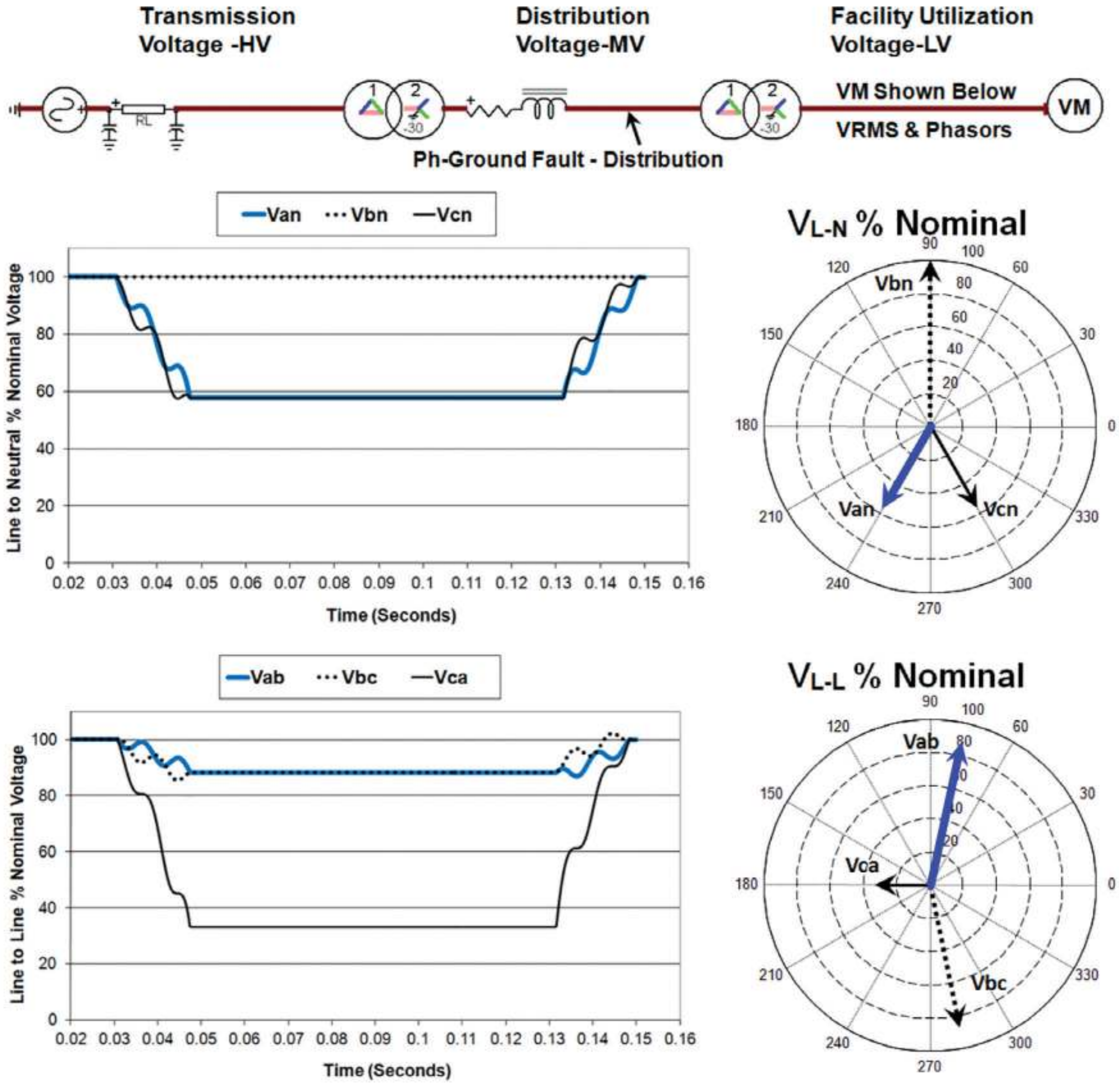

Figure 13—Voltage sag at 480-Vrms utilization voltage from a single-phase faulton the distribution system (Phase A to ground, simulation)

As discussed previously, it is important to show how different transformer connections affect the utilization voltage. Table 4 shows how a voltage sag will propagate through the system due to a single A-phase-to-ground fault on the distribution system. Once again, note how some transformer combinations produce a higher secondary voltage than others. It should be noted that values presented in this table represent an idealized approximation because it does not model system impedances and assumes ideal transformations.

Table 4—Secondary transformer voltages (pu) and phase anglefrom distribution system fault (A-G)

Transformation	VLL (AB, BC, CA)	VLN (AN, BN, CN)
Delta-wye (g)	33% ∠ 180, 88% ∠ 79.1, 88% ∠ 280.9	58% ∠ 300, 58% ∠ 240, 100% ∠ 90
Wye-wye (g)	58% ∠ 240, 100% ∠ 90, 58% ∠ 300	33% ∠ 0, 88% ∠ 259.1, 88% ∠ 100.9
Wye (g)-wye (g)	58% ∠ 240, 100% ∠ 90, 58% ∠ 300	0%, 100% ∠ 240, 100% ∠ 120
Wye-Delta	33% ∠ 180, 88% ∠ 79.1, 88% ∠ 280.9	58% ∠ 300, 58% ∠ 240, 100% ∠ 90

Faults can also occur within a facility. Corresponding voltage sags on upstream systems—including the utility's distribution and transmission system—are severely dampened by the impedance of the service transformer. In large facilities, power is often dispersed via distribution-level voltage to various substations throughout the facility for transformation to a lower voltage required by connected equipment. Most utilization voltages are below 600 V; however, in some large industrial plants, some central plant equipment can require higher voltages (such as 4160 V). A typical industrial plant consists of a mixture of three-phase and single-phase loads. Most of the motors are three-phase loads while support-control systems are usually single-phase loads. In addition, computers in office areas and process-related loads are also usually single-phase. How the equipment is connected plays a major role in how the equipment is impacted because most voltage sags do not affect all three phases. This explains why not all single-phase loads on a particular three-phase circuit are affected by a fault. Figure 14 shows a single-phase fault (Phase A to ground) at the 480-V utilization voltage and the corresponding voltage sag. At the location of the fault, the voltage from Phase A to ground is zero. The fault affects the phase-to-phase voltage from AB and CA and the phase-to-neutral voltage as the figure shows. The voltage sag at the higher voltage level is significantly dampened and shallow.

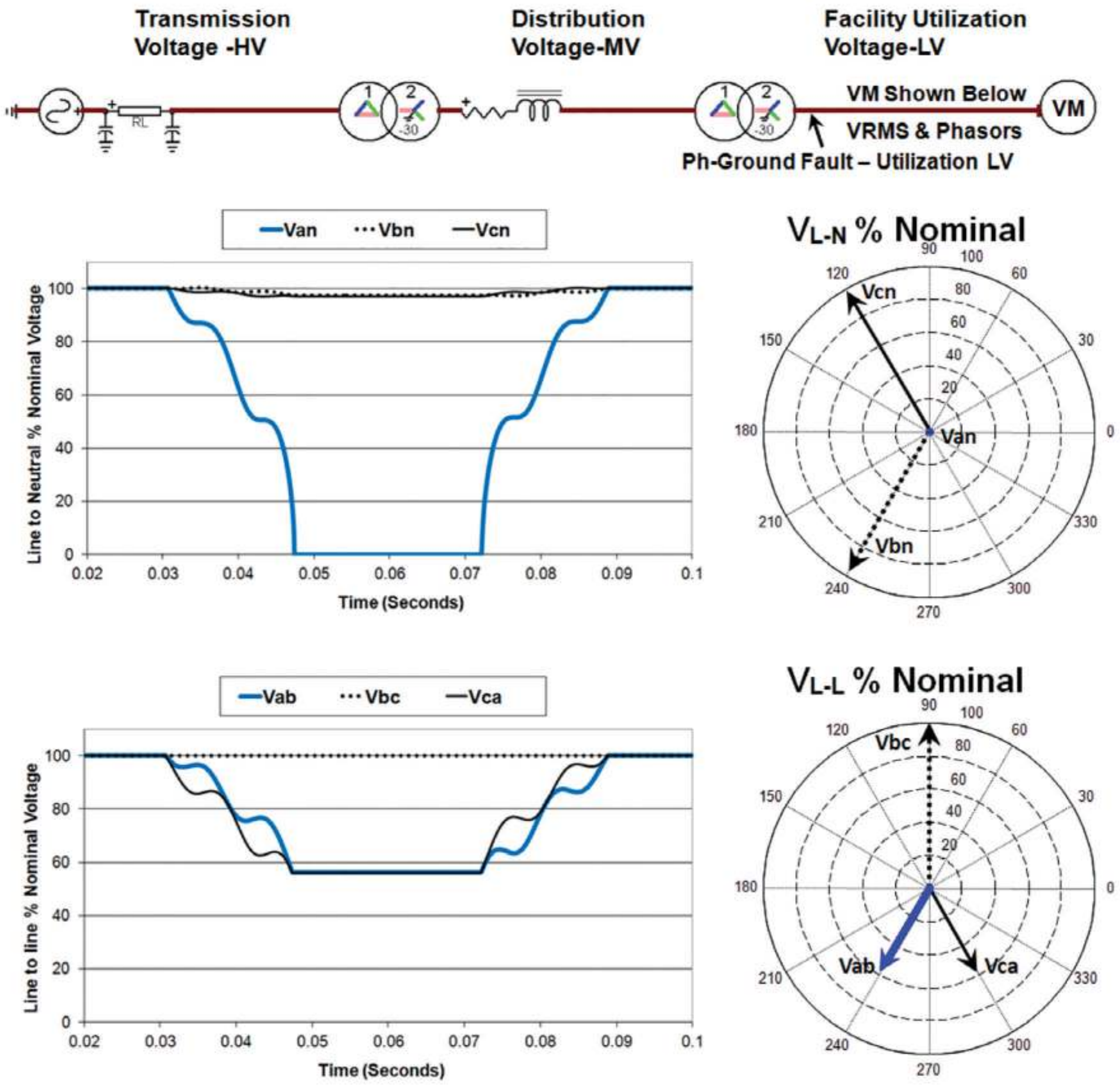

Figure 14—Voltage sag at 480-Vrms utilization voltage from a fault within a facility (simulation)

All preceding examples have shown the impact of a phase-to-ground fault at the transmission, distribution, and end-use levels. There are other possible types of faults including phase-to-phase, phase-to-phase-to-ground, three-phase, and three-phase-with-ground. Each will result in different sag magnitude and phase angle relationships during the fault.

Phase-to-phase (or line-to-line) faults are commonly caused by forestry contacts, snow unloading, and galloping conductors. These are highlighted here because of some of their unique characteristics. In a phase-to-phase fault, the phase angles of the two faulted phases approach each other and are close to 180° out of phase with the unfaulted phase. In a bolted-fault condition, the two faulted phases would be 180° out of phase with the unfaulted phase and would have 50% of the magnitude of the nominal line-to-neutral voltage. Phase-to-phase faults often have relatively high impedance, and the degree to which the faulted phases come into alignment is related to the impedance of the fault. Note that distance of the measuring point from the fault also contributes to how the faulted phases appear at the measurement point. It is important to note that this type of fault can approach becoming a single-phase condition.

In general, three-phase faults are balanced—they have the same relative phase magnitudes and little or no phase shift. These faults result in three-phase voltage sags on the adjacent feeders. For the other fault types, without involving all three phases, there will be unbalanced voltages and phase shifts. The preceding line-to-ground examples show the impact of phase shifts and magnitude shifts for multiple delta-wye transformations. It is not the intention of this document to show all possible combinations of fault types and transformations. Nevertheless, unbalanced voltages and phase shifts will be part of the real-world conditions expected for voltage sags.

4.5 Voltage sags and current relationships

The discussion thus far has focused on various characteristics of voltage sags. One relationship that has not been discussed is how the current responds (i.e., current waveforms and rms values) during the voltage sag. However, it is important to understand some of the most rudimentary current relationships. Since the current relationship during a voltage sag is load-dependent, it is beyond the scope of this document to address all the possible current responses of different equipment, particularly nonlinear equipment.

Resistive components and loads typically respond linearly with current decreasing proportionally to voltage, while induction motors, which are generally constant power devices, will experience a current increase in response to the voltage drop. Synchronous motors tend to inject reactive power toward the fault and will provide some voltage support during sags. Nonlinear loads such as power electronics devices exhibit special current relationships, thus they will be discussed here in greater detail.

Examples of nonlinear loads include dc power supplies, adjustable-speed drives, double-conversion uninterruptible power supply (UPS) systems, battery chargers, and voltage-support systems. The common topology shared between these devices is a front-end rectifier. During a voltage sag, adjustable-speed drives draw additional current to support the constant-power characteristics of the motor load. Voltage-support equipment will draw elevated current from unfaulted phases in attempting to reinforce the voltage drop of the faulted phases. Stepped power supplies have large capacitor banks in the front-end rectifier circuits. Upon abrupt restoration of nominal system voltage, the capacitors in the front-end circuitry will draw high inrush current to recharge (briefly—one to two cycles).

4.6 How common are voltage sags?

A fault at a particular location on an electrical system will cause a voltage sag at a wide variety of locations. The propagation of voltage sags is generally correlated to the topology or characteristics of the electrical system and the type of fault. Available capacity, configuration of transformer connections, and line impedance are some of the characteristics that can vary significantly over the electrical system. Due to the varying nature of these characteristics, particular locations for connecting equipment to the electrical system can provide some immunity to voltage sags.

Figure 15 is a single-line diagram of a utility electrical system and depicts transmission (left side of figure) and distribution networks (right side of figure). Power quality monitoring of voltage events—including voltage sags—is shown at the locations labeled A through H. The transmission system in Figure 15 comprises a bulk-transmission portion along with Transmission Loop 1 and Transmission Loop 2. The higher-voltage bulk-transmission system is coupled through step-down transformers at two points to Transmission Loop 1 and Transmission Loop 2.

The inherent interconnected nature of the transmission system generally provides improved reliability. On the other hand, voltage sags caused by a fault on the interconnected transmission system are generally more pervasive. In a first example, a fault on the bulk transmission loop can result in the recording of voltage sags on all of the monitors (Monitor A through Monitor H). Customers receiving power directly from the transmission system are dependent mainly upon the fault characteristics of the transmission system. Furthermore, customers supplied by the distribution system are dependent upon the characteristics of both the transmission and distributions systems. As previously illustrated in Figure 13 and Figure 14, the propagation of voltage sags can be further affected by the connection configuration of the transformer coupling between portions of the electrical system. For example, asymmetrical faults can propagate at changed magnitudes across different transformers. In contrast, the magnitudes of voltage sags from symmetrical three-phase faults are usually not dependent upon transformer connections.

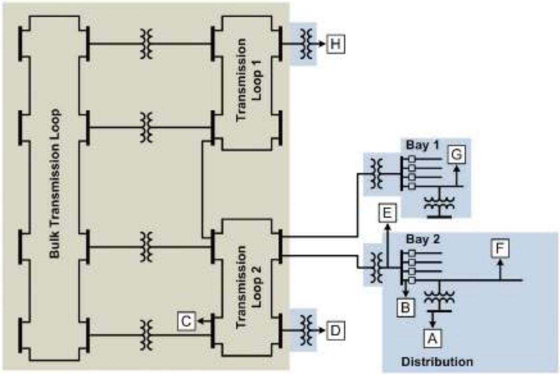

Figure 15—Single-line diagram of a typical electrical system

As a second example, a fault occurs on Transmission Loop 1. Depending upon the severity of the fault, voltage sags can be expected to be recorded only at Monitor H, but not likely at Monitor A through Monitor G. In contrast, a fault on Transmission Loop 2 will likely result in recording voltage sags at Monitor A through Monitor G, although normally not at Monitor H. Should a voltage sag be recorded on Monitor H from a fault on Transmission Loop 2, the voltage sag typically would be at a substantially reduced magnitude. Voltage sags generally tend not to propagate across a higher voltage transmission system to another portion of the transmission system. As a result, the location on the electrical system can play a role in detecting voltage sags. For this reason, a customer having a sensitive manufacturing process might want to consider service directly from the transmission system, thereby reducing exposure from faults on the distribution system. Hence, a customer having sensitive equipment and attempting to reduce exposure to voltage sags might consider connecting to the electrical system at Monitor D and Monitor H.

Among other things, Figure 15 shows two distribution systems referred to as Bay 1 and Bay 2, each coupled to Transmission Loop 2 through step-down transformers. For a third example, a fault occurring on Bay 1 might normally be expected to cause voltage sags at Monitor G but not at Monitor A, Monitor B, Monitor E, and Monitor F. In contrast, a fault on Bay 2 will typically cause voltage sags at Monitor A, Monitor B, Monitor E, and Monitor F, but generally not on Monitor G. Hence, voltage sags from a fault on a portion of the distribution system tend not to propagate across a higher-voltage transmission system to another part of the distribution system.

The magnitude of a voltage sag is generally a function of the impedance between the monitoring point and the fault. This impedance is typically related to the length of the conductor or distance from the fault. Voltage division calculations based on conductor impedance are commonly used to assess voltage sags on radial systems. In a fourth example, Monitor F as shown in Figure 15 is on a conductor many miles from Bay 2. A fault occurring in the vicinity of Monitor F fed from the bus of Bay 2 can be expected to provide a substantial voltage sag at Monitor F. In contrast, due to the impedance between the fault and the monitoring point, the same respective fault near Monitor F can be expected to result in minor voltage sags at Monitors A, Monitor B, and Monitor E. In addition to the impedance, the capacity of the electrical system can affect the propagation of voltage sags. The available system capacity is known as the short circuit megavolt-amperes and is commonly referred to as “stiffness.” This system capacity is expressed as a ratio of the upstream transformer’s megavolt-amperes to reactance.

In addition to the point of connection (POC) to the electrical system relative to the fault, the number of voltage sags experienced by a customer can be affected by many factors. Two detailed studies referred to as "The Distribution Power Quality" [B5] (DPQ, also known as DPQ I) and the more recent "The Distribution Power Quality II" (DPQII) [B6] indicated the relative order of importance of the causes of voltage sags. These causes can include equipment failures, lightning-flash density, tree branches near power lines, animals, vehicles contacting power poles, and inadequate ground resistance. The causes of voltage sags, though predominately weather-related, can be affected by maintenance of equipment by the utility, tree trimming, and reducing access to animals and vehicles. Furthermore, the extent to which a power system is located underground can influence the rate of voltage sags.

The DPQII study was conducted in 2001 and 2002 and comprises monitoring data from nearly 500 sites representing 13 utilities. The monitoring locations of DPQII, though primarily on the distribution system (424 locations), represent all of the major portions of the electrical system, including the transmission system (56 locations). As mentioned earlier and detailed in DPQII, voltage sags are generally more common on the distribution system as compared to the transmission portion of the electrical system. However, some distribution systems with limited exposure can have a frequency of voltage sags comparable to transmission systems, although the frequency of voltage sags in distribution systems can vary significantly. This variation in frequency of sags in distribution systems is typically impacted by fault clearance practices of different utilities, a wide diversity of radial network distances, various maintenance schedules of different utilities, a variety of design practices in the utility industry, and climate.

In attempting to assess the relative frequency of voltage sags, statistics on voltage sag are discussed here to allow the reader to make comparisons based on available data. A major objective in collecting statistics on events such as voltage sags is that only one occurrence should normally be recorded per event. In other words, collecting a plurality of events from a single occurrence can confound the collected data and inaccurately represent the true nature of the event on the system. Multiple counting from the same event is typically precluded by collecting only the most significant event over a particular window or time interval, referred to as a "time aggregation period."

A frequently used index called the System Average rms Frequency Variation Index (SARFI) can be used to count voltage events, including sags, swells, and interruptions. In particular, to account for voltage sags, the SARFI index typically is written in the form of SARFI-X, and SARFI-CURVE. For example, SARFI-70 indicates interruptions and voltage sags having at least one remaining voltage equal to or less than 70% of the nominal voltage. Table 5 includes data from all of the DPQII sites and shows the average annual rate of voltage sags and interruptions at various SARFI levels. The far right column of the table shows the SARFI-10 index representing momentary interruptions with remaining voltage of less than 10% on at least one phase of voltage. The table also indicates that 26.83 voltage sags per year per monitor site are shown under SARFI-85 at an aggregation period of 5 min; this, and the generalized tables and figures that follow serve to illustrate the concept that more voltage-sag events—as opposed to interruptions—tend to occur, and that such events tend to be shallow in magnitude rather than deep. Furthermore, the tables and figures suggest that riding through such voltage-sag events would be advantageous.

Table 5—Annual average SARFI rate of voltage sags (DPQ II—all sites) [B6]

Aggregation period	SARFI-85	SARFI-70	SARFI-50	SARFI-10
60 s	28.49	13.69	5.74	0.91
5 min	26.83	13.02	5.49	0.83
1 d	17.85	9.84	4.49	0.62

The DPQ II study [B6] included transmission locations, distribution-system bus locations, and, finally, locations near the end of the distribution-system feeders and/or inside the customer's internal network at the low-voltage level. This final group was referred to as "Group 1" in the DPQ II study and was comprised of site locations designated A, F, and G, with locations similar to those illustrated in Figure 15. A comparison of the DPQ I and DPQ II, and DPQ II Group 1 data are shown in Table 6.

Table 6—Yearly SARFI rates(60-s aggregate period, DPQ I, DPQ II, and DPQ II Group 1 sites) [B6]

SARFI level	DPQ Phase I	DPQ Phase II	DPQ Phase II Group 1 (A, F, and G sites)
SARFI-70	23.4	13.7	22.4
SARFI-50	12.2	5.7	13.2
SARFI-10	5.8	0.9	3.4
SARFI-ITIC[a]	23.5	13.9	23.9
SARFI-SEMI[b]	17.0	8.3	19.9

[a] SARFI-ITIC refers to the number of times per site per year that the voltage drops below the ITIC curve.
[b] SARFI-SEMI refers to the number of times per site per year that the voltage drops below the SEMI F47 curve.

Figure 16 displays a histogram of data collected over a 1 min aggregation period from the DPQII [B6] study. The graph shows the percentage cumulative frequency on the right-side vertical axis, while the horizontal axis illustrates the percentage of the rms residual voltage. Further, a left-side vertical axis indicates a 30-d voltage sag and interruption rate per site.

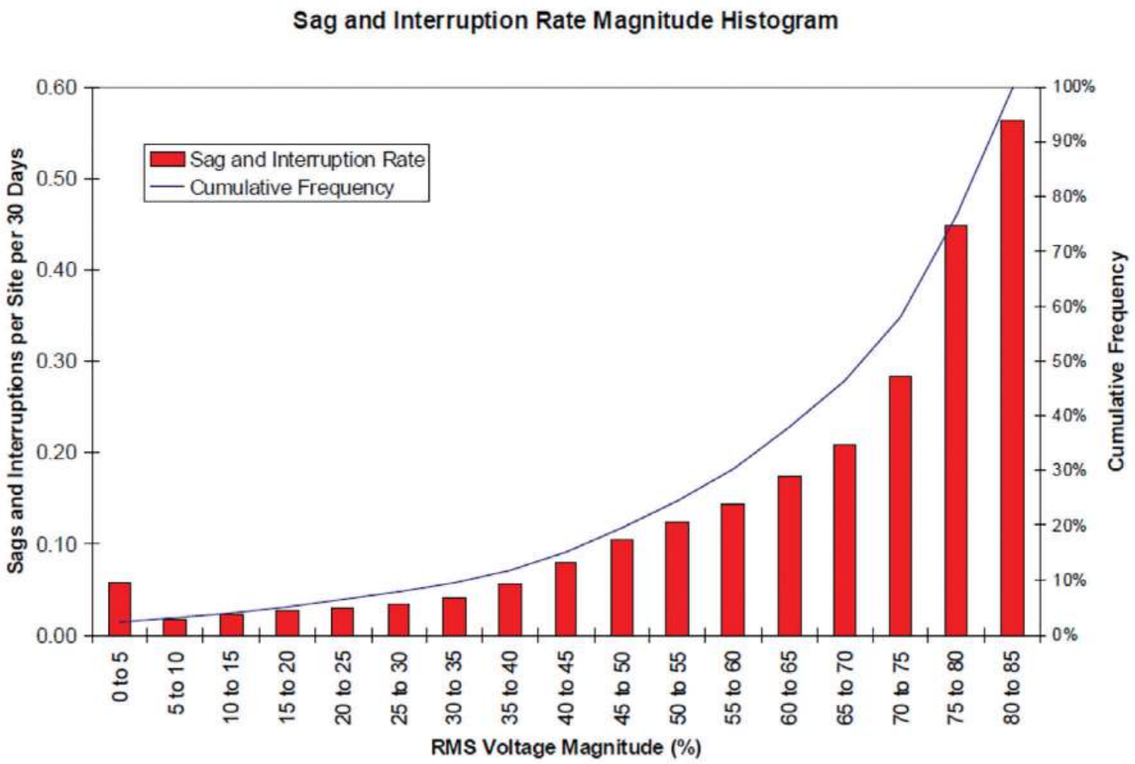

Figure 16—Sag and interruption rate magnitude histogram [B6]

Figure 17 illustrates the number of affected phases for recorded voltage sags over a 1 min aggregation period from the EPRI DPQ II study. Typically, voltage sags are classified by the number of phases that have dropped below a certain threshold (such as 85% of nominal voltage) during the voltage sag. A root-cause analysis of voltage sags can determine, for example, that a three-phase voltage sag/fault began as a single-phase voltage-sag/fault. The development of the voltage sag across phases and their impact are not discussed here. Instead, a voltage sag is classified by the final state of the number of affected phases.

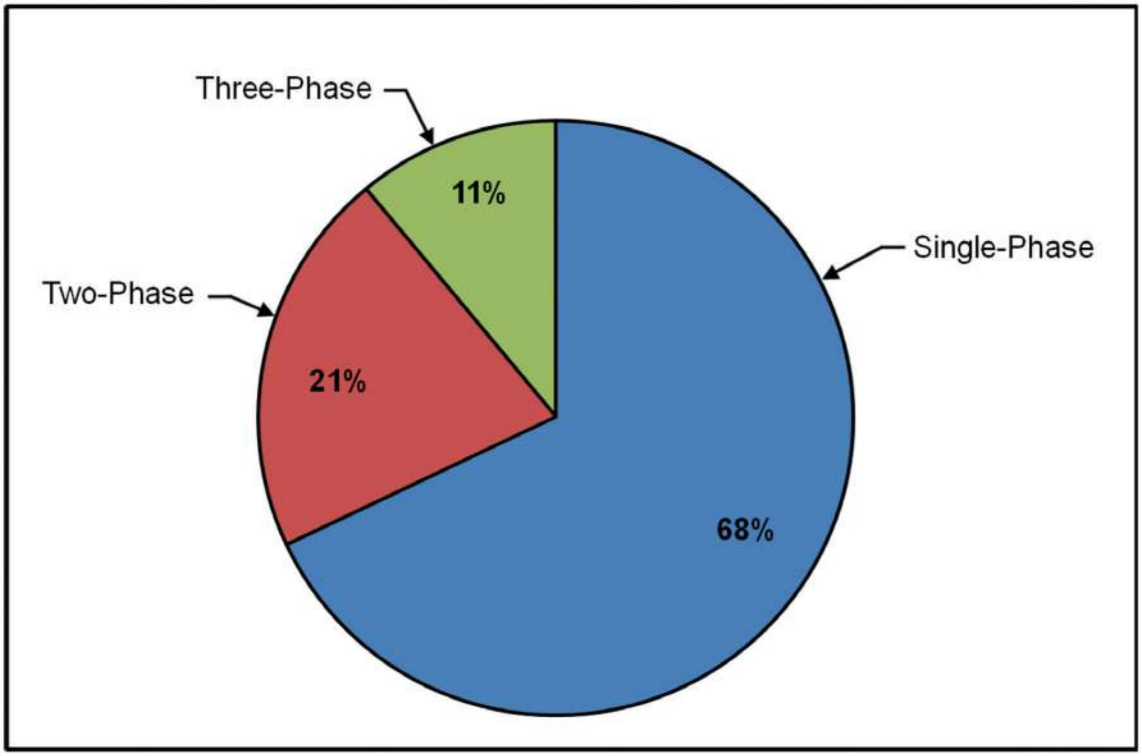

Figure 17—Number of affected phases (i.e., voltage-sag types) for voltage sagswith at least one remaining voltage below 85% of nominal [B6]

Figure 18, also taken from the DPQII study [B6], shows three plots with the number of affected phases for voltage sags with different magnitudes aggregated over a 1 min period. To use the graph, locate a particular percentage voltage or residual voltage on the horizontal axis. Next, a vertical line is extended to intersect all the plots (one, two, or three phases). Finally, horizontal lines are extended from the above intersections to the vertical axis. On the vertical axis, the yearly voltage-sag rate can be read for each plot. For example, of all recorded sags with 50% residual voltage (horizontal axis), annual numbers/percentages of single-, two-, and three-phase sags are 63%, 11%, and 25%, respectively. The occurrence of single-phase voltage sags dominates over a range of residual voltage from about 85% to about 19%. Therefore, single-phase voltage sags are more frequent and are generally not deep. The impact of voltage sags originating from a single-phase fault upon a customer's equipment can depend on the particular phase or line exposed to the fault and which line or lines are connected to the equipment. This can explain why only a portion of the customer's equipment is affected while other equipment is not impacted by voltage sags of the same magnitude and duration. In contrast to single-phase sags, three-phase voltage sags appear to be less common but are deeper in magnitude and dominate over a range of residual voltage of about 19% down to about 5%. Two-phase voltage sags are generally the least common and do not dominate over any particular range of residual voltage.

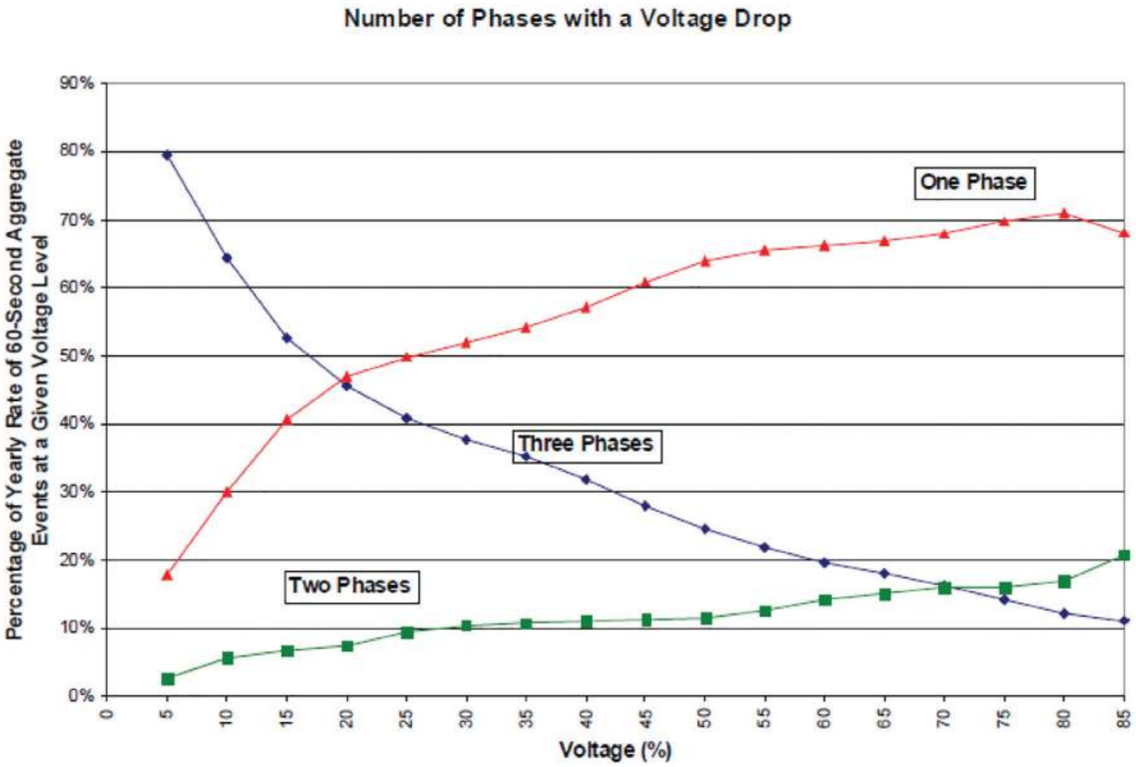

Figure 18—Percent residual voltage by type of sag [B6]

The method in which the DPQ II study [B6] determined single-, two-, and three-phase voltage sags was based on the number of phase voltages that fell below a given threshold. Another benchmark study [B1], defining Type I (single-phase), Type II (two-phase), and Type III (three-phase) events was more complex than counting the number of phases below a threshold, such as 85% of nominal. Instead, the group examined an international database and matched against the sag vectors to fit the Type I, Type II, or Type III criteria. Table 7 shows the breakout at both the medium- and high-voltage sites as well as separate data for low-voltage sites. The study examined 969 medium- and high-voltage sites with voltages ranging from 6 kV to 230 kV. Furthermore, the study included over 206 low-voltage sites where the monitored voltage was below 1 kV. Single-phase, two-phase, and three-phase voltage sags were classified as Type I, Type II, and Type III, respectively. A major finding was that 11% to 20% of the voltage sags examined were three-phase in nature [B1].

Table 7—Breakout of voltage-sag types [B1]

Sites	Voltage range	Number of sites	Single-phase (Type I)	Two-phase (Type II)	Three-phase (Type III)
MV and HV sites	6 kV–230 kV	969	27%	53%	20%
LV sites	< 1KV	206	64%	25%	11%

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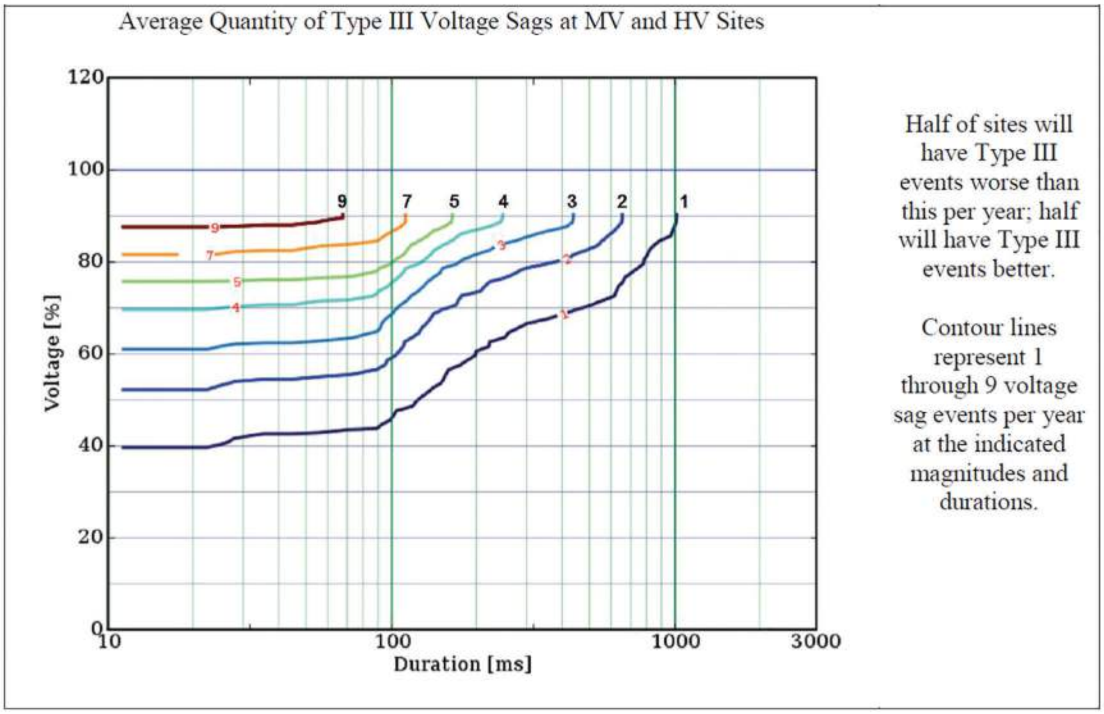
The C4.110 Working Group has produced significant findings with regard to three-phase voltage sags. The contour chart shown in Figure 19 [B1] represents the 50% best sites where data was gathered from the medium- and high-voltage sites included in the study. From the chart, one can deduce that half of the sites studied would have at least one three-phase voltage sag per year at the level of 40% of nominal or better. Furthermore, half of the sites would see three-phase events lasting one second or less in duration.

The study further indicates that any site is guaranteed to experience at least one three-phase event per site per year with remaining voltage less than 10% of nominal, which would be classified as a momentary interruption per IEEE Std 1159™-2009 [B13].



Half of sites will have Type III events worse than this per year; half will have Type III events better.

Contour lines represent 1 through 9 voltage sag events per year at the indicated magnitudes and durations.

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Figure 19—Three-phase (Type III) voltage-sag contour charts [B1]

4.7 Other causes and effects of voltage sags

Up to this point, discussion has focused mostly on voltage sags originating in the electrical utility supply. This is partly because they are often the least understood by end-use customers and have more wide-spread impact on multiple customers. It now becomes necessary to consider voltage sags that originate from within the end-user's facility. Generally stated, some degree of voltage sag commonly occurs either due to a fault on the system or to a large load abruptly appearing on the system. The severity of the sag is related to the size of the fault or load increase compared to the capacity and stiffness of the energy supply and impedance of the distribution system. The offending fault could be as small as an incandescent light bulb burning out in a single family residence or a neighbor’s table saw being started. In an industrial facility, the voltage sag could result from a large horsepower motor starting across the line, a welding process, or a fault on the in-plant distribution system. In the industrial environment, localized sag occurrences can be very common related to the starting and stopping of a cyclic process load.

The frequency of occurrence of voltage sags on the electrical utility supply varies with the level of the system as discussed in the previous clauses and varies across regions of the world. Distribution level circuits experience four to six times as many sags as similar transmission level circuits. For the end-use customer, this can translate to a transmission-fed service experiencing voltage-sag events deep enough to disrupt operations two times per year while distribution fed customers in the same area could experience eight to 12 occurrences at their particular locations. These occurrence rates consider sags that commonly cause disruption to end-use equipment. They do not include sags that would not be expected to disrupt the most common office and manufacturing equipment (above 75% or 80% retained voltage). They are cited as an example to communicate the relative rates of occurrence and are not hard numbers that can be applied across wide regions. Locations experiencing frequent lightning or winter ice storms with high winds could experience voltage sags causing process disruption three or four times per year on the transmission level of service while another region can very rarely experience sags originating on the electric utility supply.

Also important is understanding how often the voltage-sag event is single-phase versus multi-phase. A single-phase event can selectively impact some customer loads while not affecting other customer loads based upon the phase connection(s) serving the particular load(s) of concern—two different sag events of the same magnitude and duration can impact different customer equipment. It is also important to understand that single-phase events often migrate into multi-phase events before the system protection equipment acts to clear the fault. Events are typically recorded as the worst condition occurring over the duration of the event. Therefore, many events that originate as single-phase events can be documented as multi-phase events. With this understanding as background, some utilities in the United States have recorded approximately 50% of faults as single-phase, approximately 20% as phase-to-phase and as many as 30% as three-phase.

IEEE SAIFI (IEEE Std 1366™-2012 [B16]) is a commonly-used reliability indicator used by electric power utilities. It is the rate of total customer interruptions per total number of customers served. SAIFI data can be obtained for selected region(s) and used to compare the relative probability of disruption between areas within a particular country or between countries. In this context, recognize that a voltage sag at one location can often result from a fault that causes an outage somewhere else on the system. Comparing SARFI outage data between the locations will yield relative occurrence rates.

The physical and economic impact of any particular voltage-sag event varies significantly by industry depending on the type of process and sensitivity of equipment at the customer's operation. In industrial operations such as assembly or machining that include variable frequency drives, test equipment, or equipment that can be rapidly reset and restarted, the impact on operations can be limited to reset time. Additionally, many businesses rely on information technology equipment (ITE) that often includes data centers, many of which run processes in which a power interruption could have significant consequences. For a large facility this reset time could have significant economic impact. Should the industrial process involve heavy machining where tools incur physical damage due to the voltage sag and require replacement, or where combustion processes require purge time before restoration, a far greater economic impact can result. For other types of processes, such as in microelectronics, the disruption of the process equipment can damage the product being made resulting in irreparable scrap. In chemical processes, interruption can expose the product to extended heating or cooling or reaction stages that result in unpredictable interim products that not only cannot be used, but also are difficult to dispose of due to toxicity, flammability, corrosive properties, etc. In processes such as metal casting or plastics—especially injection molding—interruption can allow the product to solidify inside the process equipment or piping, thus requiring significant process replacement. In summary, both the frequency and severity of economic impacts on the customer due to voltage-sag events depend on the customer's processes within the facility and the time required to restore the processes after the disruption.

5. Recommended voltage-sag test requirements

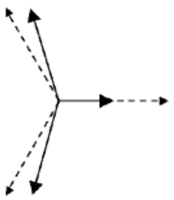
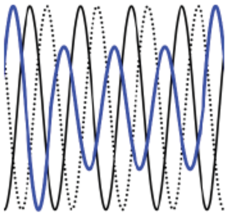
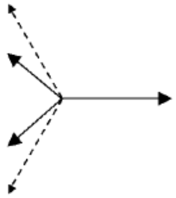
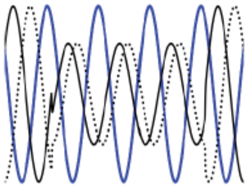
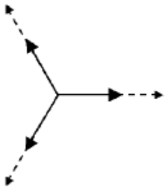
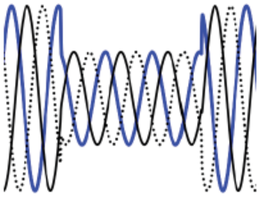
5.1 Background on test requirements

This clause details the voltage-sag test requirements of this recommended practice. The recommended voltage-sag types and voltage-sag immunity levels are detailed herein. All voltage-sag tests should be initiated at 0° point-on-wave with respect to the phase in which the voltage sag is being created during the evaluation of the EUT. If multiple phases are being subjected to the sag, the test should be initiated at 0° point-on-wave of the leading phasor.

5.2 Classification of voltage-sag types in three-phase systems

In its basic form, voltage sags can be classified as three general types that can occur at the terminals of sensitive equipment. Classified as Type I, Type II, and Type III, a representation of these three basic types is shown in Table 8 (taken from [B1]) along with their description, vector diagram, and waveform.

Table 8—Recommended Type I, Type II, and Type III voltage-sag classifications [B1]

Voltage-sag type	Description[a]	Vector diagram	Waveform
Type I	This is a voltage sag in which a drop in voltage takes place mainly in one of the phase-to-ground voltages. $\bar{U}_a = \bar{V}$ $\bar{U}_b = -\frac{1}{2}\bar{V} - \frac{1}{2}j\bar{E}\sqrt{3}$ $\bar{U}_c = -\frac{1}{2}\bar{V} + \frac{1}{2}j\bar{E}\sqrt{3}$		
Type II	This is a voltage sag in which a drop in voltage magnitude takes place mainly in one of the phase-to-phase voltages. $\bar{U}_a = \bar{E}$ $\bar{U}_b = -\frac{1}{2}\bar{E} - \frac{1}{2}j\bar{V}\sqrt{3}$ $\bar{U}_c = -\frac{1}{2}\bar{E} + \frac{1}{2}j\bar{V}\sqrt{3}$		
Type III	This is a voltage sag in which there is a drop in voltage magnitude that is equal for the three voltages. $\bar{U}_a = \bar{V}$ $\bar{U}_b = -\frac{1}{2}\bar{V} - \frac{1}{2}j\bar{V}\sqrt{3}$ $\bar{U}_c = -\frac{1}{2}\bar{V} + \frac{1}{2}j\bar{V}\sqrt{3}$		

[a] Where: V = characteristic voltage of the sag event, E = pre-sag voltage, and Ua, Ub, Uc = phase-to-neutral voltages.
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The three basic voltage-sag types can aid in understanding how faults and voltage sags propagate through the electrical system. Table 9 shows an example of propagation of voltage sags and their resultant type based on various transformation levels.

Table 9—Fault propagation as described by Type I, Type II, and Type III voltage-sag type classifications [B1]

Type of fault	Voltage sag at faulted voltage level	Voltage sag after one delta-wye transformer	Voltage sag after two delta-wye transformers
Three-phase	Type III	Type III	Type III
Single-phase in a solidly grounded network	Type I with a zero-sequence voltage	Type II	Type I
Single-phase in a non-solidly grounded network	Zero-sequence voltage only	No voltage sag	No voltage sag

Table continues

Table 9—Fault propagation as described by Type I, Type II, and Type III voltage-sag type classifications [B1] *(continued)*

Type of fault	Voltage sag at faulted voltage level	Voltage sag after one delta-wye transformer	Voltage sag after two delta-wye transformers
Two-phase	Type II	Type I	Type II
Two-phase-to-ground in a solidly grounded network	Type II with a zero-sequence voltage	Type I, but with a bigger drop in magnitude in all phases than the common Type I	Type II, but with a bigger drop in magnitude in all phases than the common Type II
Two-phase-to-ground in a non-solidly grounded network	Type II with a zero-sequence voltage	Type I	Type II

When performing voltage-sag testing, alternative voltage-sag vector forms are allowed. When testing three-phase equipment, single-phase sags (i.e., Type I voltage sags) are created on one phase at a time. Although the allowed Type I voltage sag has no phase shift with respect to the neutral, this sag is relatively easy to create with standard test equipment and has been used in existing standards such as IEC 61000-4-11, IEC 61000-4-34, and SEMI F47–0706 to represent Type I events. Figure 20 shows the recommended Type I test vector for voltage-sag testing. One point of confusion may arise due to the intentional use of X, E, and V within the mathematical relationships found in Table 8 and Figure 20. The study [B6] providing this information intentionally referenced the "characteristic voltage" or "residual voltage" of the Type I voltage sag in this manner (*V* in Table 8 and *X* in Figure 20) because the two may not be compared directly due to the differences in phase shift. The reader is directed to the study [B1] for a more detailed explanation.

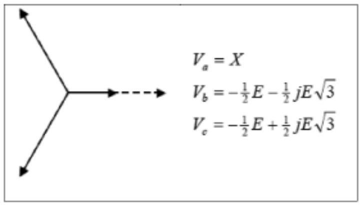


Figure 20—Recommended Type I test vectorwhere *E* represents the nominal phase-to-neutral voltage, *V* represents the residual voltage or "Dip magnitude", and *X* represents the residual phase-to-neutral voltage [B1]

Type II sags normally occur on the secondary side of a delta-wye transformer when there is a single-phase fault on the primary side of the transformer. A Type II event can also occur when two conductors are faulted together. There are three common methods for creating Type II voltage sags. Figure 21 shows the recommended two-phase test vector (Type II) and two allowable alternatives designated as Type II.A1 and Type II.A2. A Type II.A1 event does not occur often and induces the most phase shift. The Type II.A2 event can occur when there is a simultaneous phase-phase-to-ground fault. Because the choice of test vector for Type II sags has been known to change the outcome of the voltage-sag test result, consult Annex A for guidance.

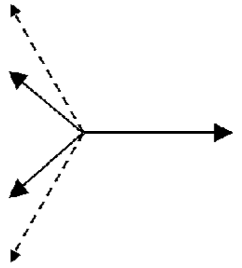
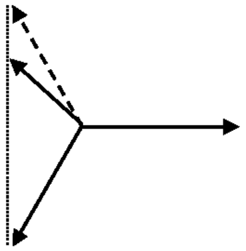
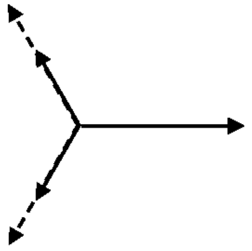
Type II (Recommended)	Type II.A1 (Alternate 1)	Type II.A2 (Alternate 2)
		
$V_a = E$ $V_b = -\frac{1}{2}E - \frac{1}{2}jV\sqrt{3}$ $V_c = -\frac{1}{2}E + \frac{1}{2}jV\sqrt{3}$	$V_a = E$ $V_b = -\frac{1}{2}E - \frac{1}{2}jV\sqrt{3}$ $V_c = -\frac{1}{2}E + \frac{1}{2}j(2X - E)\sqrt{3}$	$V_a = E$ $V_b = -\frac{1}{2}X - \frac{1}{2}jX\sqrt{3}$ $V_c = -\frac{1}{2}X + \frac{1}{2}jX\sqrt{3}$

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Figure 21—Recommended and alternative Type II test vectors where *E* represents the nominal voltage and *V* represents the residual voltage [B1]

For Type III voltage sags, the recommended test vectors are as shown previously in Table 8.

5.3 Recommended voltage-sag immunity levels

5.3.1 Recommended Type I and Type II voltage-sag test immunity levels

The recommended Type I and Type II voltage-sag immunity test levels are similar to those presented in SEMI F47–0706. However, the test point with the longest duration has been increased to reflect the longer clearing times of utility breakers that are known to occur for shallow voltage sags at the distribution level. Table 10 and Figure 22 detail the recommended test points for Type I and Type II voltage sags.

Table 10—Recommended test points for Type I and Type II voltage sags

Minimum test point no.	Residual voltage in percent nominal	Duration in seconds	Duration at 50 Hz	Duration at 60 Hz
1	50%	0.2	10 cycles	12 cycles
2	70%	0.5	25 cycles	30 cycles
3	80%	2.0	100 cycles	120 cycles

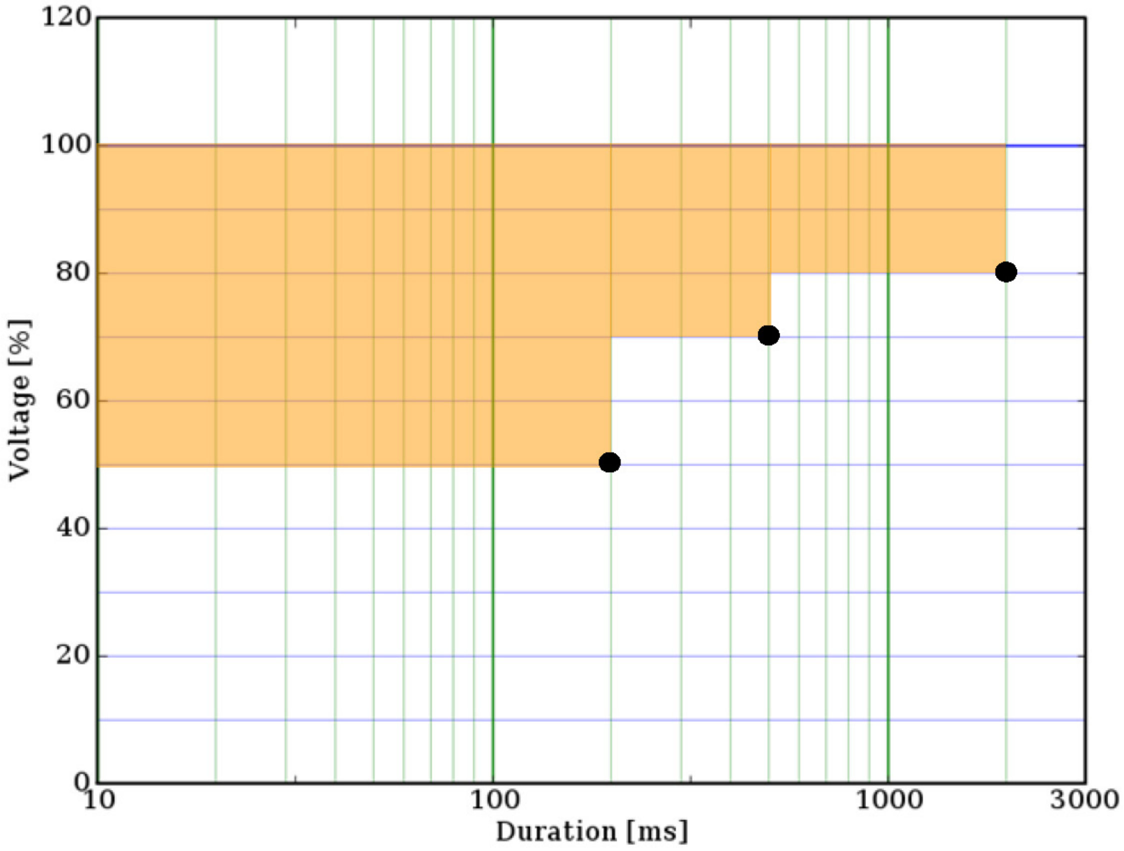


Figure 22—Recommended Type I and Type II test levels

5.3.2 Recommended Type III voltage-sag test immunity levels

Voltage-sag events on the three-phase electric systems can involve one, two, or three phases and are accordingly classified as single-, two-, and three-phase (Type I, Type II, and Type III) voltage sags. Neither the SEMI F47–0706 nor the IEC 61000-4-34 standards require testing of equipment against three-phase voltage sags. However, one study cited previously [B1] has shown that three-phase Type III voltage-sag events are common on the electrical systems, accounting for 11% to 20% of all recorded voltage sags from these studies. Based on these statistics, this document recommends limited Type III sag testing of equipment in order to better understand the response of the equipment to all possible types of voltage-reduction events. Because Type III events happen less frequently than Type I and Type II events, the test levels presented here are considered reasonable for equipment ride-through and not onerous for the equipment manufacturer to achieve. The working group considered voltage-sag test data from typical industrial equipment and the C4.110 study [B1] when considering what levels would be reasonable for three-phase systems. For variable-frequency ac drives, many units have built-in ride-through capability and thus have the ability to ride through and continue operation even for three-phase voltage sags to 80% of nominal, albeit with some drop in speed. However, dc drives are known to be one of the most sensitive load types to voltage sags. Therefore, three-phase test results [B19] from these units were examined to understand their capabilities as representative of one of the worst-case types of three-phase loads. Furthermore, specific industries whose requirements are more stringent than the recommended levels can refer to test levels as defined in other documents such as IEC 61000-4-34, Class 3. Table 11 and Figure 23 detail the recommended test points for Type III voltage sags.

Table 11—Recommended test points for Type III voltage sags

Minimum test point no.	Residual voltage in percent nominal	Duration in seconds	Duration at 50 Hz	Duration at 60 Hz
1	50%	0.05	2.5 cycles	3 cycles
2	70%	0.1	5 cycles	6 cycles
3	80%	2.0	100 cycles	120 cycles

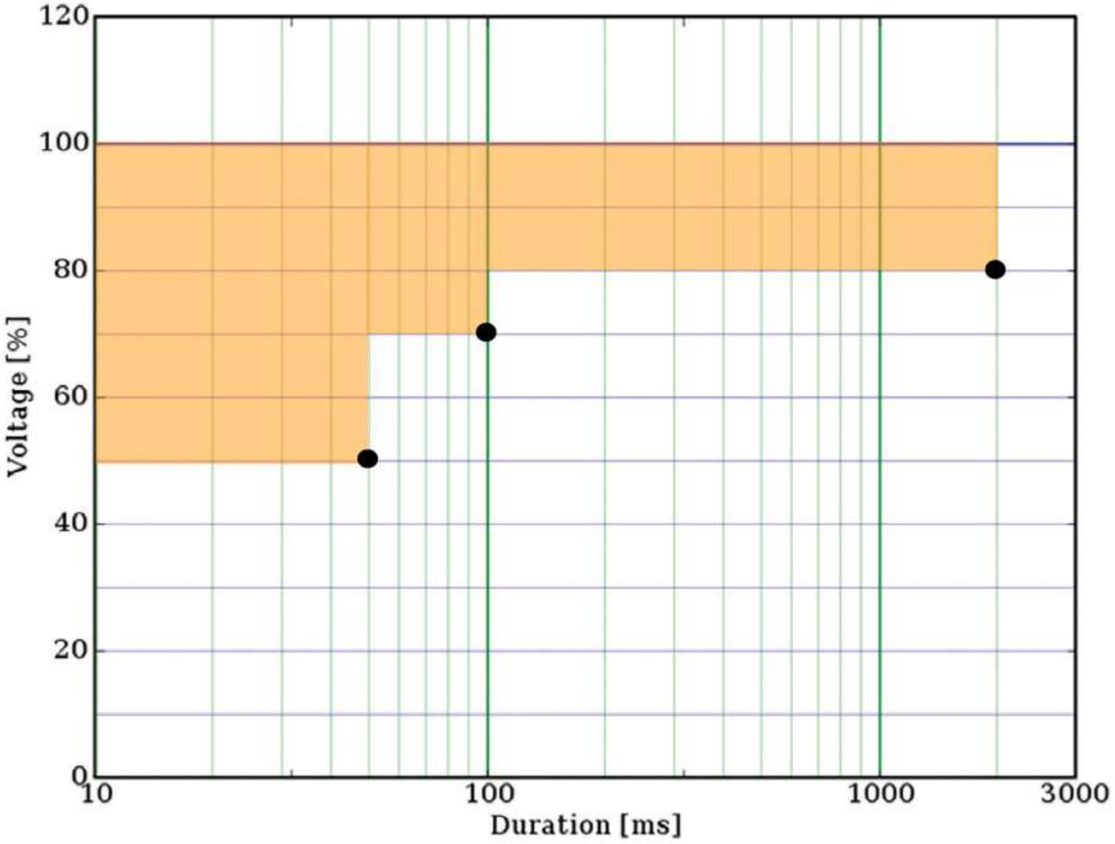


Figure 23—Recommended Type III test levels

5.3.3 Test conditions

The intent of this specification is to make reasonable efforts to determine whether process equipment, ITE, subsystems, and components are immune to typical voltage sags. The EUT should be tested for immunity to voltage sags under conditions that will, according to the reasonable engineering judgment of the equipment manufacturer, approximate expected factory operating conditions. Engineering judgment should take into account the following considerations:

- The EUT should be tested in its most sensitive process states as determined by the EUT manufacturer. For example, these process states can include robot movement, maximum power processing, and most sensitive measurement.
- Components and subsystems, when tested independently, should be tested under load (for example, dc power supplies and ac drives).

5.3.4 Pass/fail criteria

5.3.4.1 Background

Clear identification of equipment behavior during and after voltage sags is crucial for the assessment of equipment immunity. Accordingly, equipment immunity to various types/severities of voltage sags can be quantified only if clear distinction is made between the two following equipment performance criteria: “normal equipment operation” and “equipment tripping/malfunction.” Generally, a process or equipment (including all components and subsystems) will respond to a voltage sag in one of the following ways:

a) *Full (normal) operation:* Equipment performs as expected or intended and all of its relevant parameters are within technical specifications or within allowable tolerance limits. Equipment performance should be expressed and measured against the set of relevant/critical “equipment outputs” (for example, speed, torque, and voltage level), which have to be defined as per the process requirements.

b) *Self-recovery:* Equipment does not perform its intended functions or its outputs vary outside the technical specification/limits, but equipment is able to automatically recover after the end of a voltage sag without any intervention from the user.

c) *Assisted-recovery:* Equipment does not perform intended functions or its outputs vary outside the technical specification/limits, and equipment is not able to automatically recover after the end of a voltage sag. Assisted-recovery criteria should be applied only when there are dedicated and/or trained personnel/staff, who either operate the equipment or are responsible for supervising the equipment at all times when equipment is in use. If some external control circuit is applied for automatic restarting of equipment, this should be treated as a self-recovery criterion.

5.3.4.2 Choosing pass/fail criteria for process machines/equipment

In the absence of other instructions or requirements, the default pass/fail criteria for the testing of equipment to determine its immunity to voltage sags should be full (normal) operation. Table 12 allows for the buyer to specify the required response of the equipment for Type I and Type II sags as well as Type III sags. Table 13 is provided for specifying the requirement for single-phase equipment.

Table 12—Voltage-sag equipment-immunity specification sheet (for use with three-phase equipment)

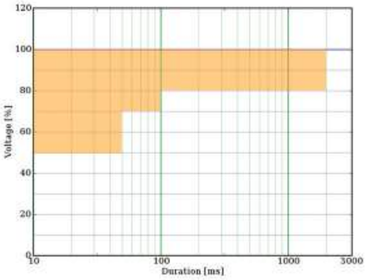
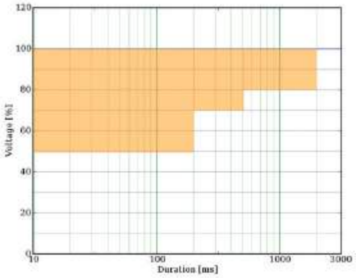
<table>
<tr>
<td colspan="3">Immunity curve for Type I and Type II sags
 </td>
<td>Immunity curve for Type III sags
 </td>
</tr>
<tr>
<td colspan="3">Type I and Type II voltage-sag test points:
80% for 2 s
70% for 500 ms
50% for 200 ms
Repeat for test points for each phase-neutral and phase-to-phase combination.</td>
<td rowspan="4">Testing for Type III voltage sag required:
80% for 2 s
70% for 100 ms
50% for 50 ms</td>
</tr>
<tr>
<td colspan="3">Desired Type II test vector</td>
</tr>
<tr>
<td>Type II</td>
<td>Type II.A1</td>
<td>Type II.A2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</table>

Table continues

Table 12—Voltage-sag equipment-immunity specification sheet (for use with three-phase equipment) *(continued)*

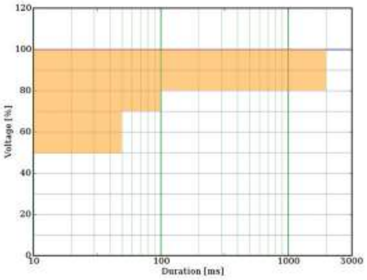
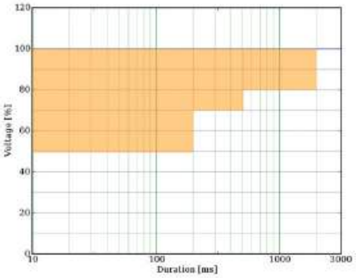
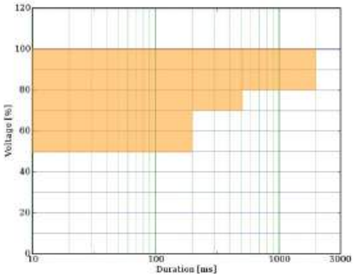
<table>
<tr><th colspan="3">Immunity curve for Type I and Type II sags</th><th colspan="3">Immunity curve for Type III sags</th></tr>
<tr><td colspan="3">
</td><td colspan="3">
</td></tr>
<tr><td colspan="3">Pass/fail criteria</td><td colspan="3">Pass/fail criteria</td></tr>
<tr><td>Full operation</td><td>Self-recovery</td><td>Assisted-recovery</td><td>Full operation</td><td>Self-recovery</td><td>Assisted-recovery</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="6">Testing procedure requirements: IEEE Std 1668</td></tr>
</table>

Table 13—Voltage-sag equipment-immunity single-specification sheet (for use with single-phase equipment)

<table>
<tr><th colspan="3">Immunity curve for Type I sags</th></tr>
<tr><td colspan="3">
</td></tr>
<tr><td colspan="3">Type I voltage-sag test points:
80% for 2 s
70% for 500 ms
50% for 200 ms</td></tr>
<tr><td colspan="3">Pass/fail criteria</td></tr>
<tr><td>Full operation</td><td>Self-recovery</td><td>Assisted-recovery</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td colspan="3">Testing procedure requirements: IEEE Std 1668</td></tr>
</table>

5.3.4.3 Choosing pass/fail criteria for subsystems and components

For component testing performed by the equipment buyer/user or system integrator/OEM, the required response of the subsystem or component for Type I, Type II, and Type III sags can be specified as in Table 13 of 5.3.4.2.

When constructing equipment that will comply with this specification, each system integrator/OEM should select components and subsystems that respond appropriately to voltage sags.

The simplest yet most costly approach is to require that all components and subsystems provide full (normal) operation during all required voltage sags, or pass/fail criteria in item a) of 5.3.4.1.

Malfunction criteria in item a) of 5.3.4.1 should be chosen by the system integrator/OEM for components whose full specified operation is required for normal operation of finally-constructed equipment during voltage sags. For example, contactors with ac coils, relays with ac coils, dc power supplies, and computers often fall into this category.

If reasonable engineering judgment determines that equipment is unlikely to shut down due to a brief change in the effectiveness of operation (i.e., malfunction) of a component or subsystem (for example, blowers and HEPA filters), then the system integrator/OEM might select pass/fail criteria in item b) of 5.3.4.1 to allow self-recovery for these components or subsystems.

The system integrator/OEM can recognize that the system software will respond appropriately to signals from certain subsystems and components during voltage sags (and will not cause a system shutdown), and therefore might select assisted-recovery pass/fail criteria in item c) of 5.3.4.1.

If the system integrator/OEM knows that the component or subsystem will never be used at its full-rated output, the system integrator might consider accepting test conditions under 5.3.4.1 that more closely match the intended application (for example, if an ac drive is rated at 15 kW, but the equipment design only calls for it to be used at a maximum of 10 kW, the system integrator can choose to accept voltage-sag testing at 10 kW load instead of testing at full-load).

5.3.5 Use of this specification for procurement

With the establishment of the recommended voltage-sag test vectors, immunity levels, and desired equipment performance, it is possible for the equipment buyer/user to specify the desired equipment immunity in a purchase requisition. A specification sheet for equipment immunity is provided in Table 12 and Table 13 for use by equipment buyers when purchasing three-phase or single-phase equipment.

The equipment buyer can use this document to specify requirements for voltage-sag immunity to a system integrator/OEM. In turn, the system integrator/OEM can use this document to specify voltage-sag immunity requirements to their subsystem and component suppliers. Specific industries whose requirements are more stringent than the recommended levels can refer to test levels as defined in other documents such as IEC 61000-4-34, Class 3.

Orders for equipment, subsystems, and components should specify the following:

a) This recommended practice document number and date of publication.
b) The requirement for a certificate per Annex C of this document (optional).
c) The requirement for a test report per Annex C of this document (optional).
d) Whether a third-party certificate is required, or whether self-certification is acceptable (optional).

Annex A

(informative)

Test procedures and guidelines

A.1 Considerations and guidance on test vector

Because it is not always practical to reproduce the voltage sags exactly as shown in Table 8 of this recommended practice, approximations might need to be made to allow the use of available test equipment. For this reason, Table A.1 presents both recommended and allowed test vectors and important considerations.

In many initial system compatibility tests, most Type II tests were completed using what is referred to as Type II.A2 because the first models of voltage-sag generators were based on referencing the voltage sag to a neutral conductor. This method has provided the most severe scenario for phase-vector magnitudes during tests and has been proven to lead to improvements in voltage-sag immunity of end-use equipment. However, Type II.A2 induces little phase shift for the phase-to-phase vectors and no phase shift for the phase-to-neutral vectors. For equipment with active front ends and phase-locked-loop type controls, testing by Type II.A2 could lead to a false sense of robustness for certain types of loads because no phase shifting occurs.

Likewise, testing with the Type II.A1 method can lead to a false sense of robustness for certain three-phase loads in that these loads do not trip during test but could trip during actual voltage sags. Again, this is most critical for loads such as the diode-bridge ac drive. If tests are conducted for all Type II combinations (i.e., Type II, Type II.A1, and Type II.A2), the weakness of any one test can be offset. The most thorough approach would be to evaluate the EUT against all five test-vector scenarios.

Table A.1—Recommended and allowed voltage-sag test vectors and considerations [B1] (where *E* represents the nominal voltage, *V* represents the residual voltage, *X* represents the residual phase to neutral voltage)

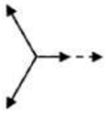
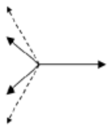
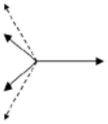
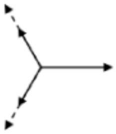
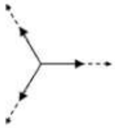
Type description	Example test-vector method	Vector descriptions	Comments
Recommended Type I		$V_a = X$ $V_b = -\frac{1}{2}E - \frac{1}{2}jE\sqrt{3}$ $V_c = -\frac{1}{2}E + \frac{1}{2}jE\sqrt{3}$	This testing is most relevant to single-phase equipment or three-phase equipment with a neutral.
Recommended Type II (IEC Type 3c)		$V_a = E$ $V_b = -\frac{1}{2}E - \frac{1}{2}jV\sqrt{3}$ $V_c = -\frac{1}{2}E + \frac{1}{2}jV\sqrt{3}$	One study [B1] indicated that this type of voltage sag makes up 82% to 91% of Type II events on HV and MV networks.

Table continues

Table A.1—Recommended and allowed voltage-sag test vectors and considerations [B1] (where *E* represents the nominal voltage, *V* represents the residual voltage, *X* represents the residual phase to neutral voltage) *(continued)*

Type description	Example test-vector method	Vector descriptions	Comments
Allowed Type II.A1 (IEC Type 3b)		$V_a = E$ $V_b = -\frac{1}{2}E - \frac{1}{2}jE\sqrt{3}$ $V_c = -\frac{1}{2}E + \frac{1}{2}j(2X - E)\sqrt{3}$	The previous study [B1] indicated that this type of voltage sag makes up 9% to 18% of Type II events on HV and MV networks.
Allowed Type II.A2 (IEC Type 3d)		$V_a = E$ $V_b = -\frac{1}{2}X - \frac{1}{2}jX\sqrt{3}$ $V_c = -\frac{1}{2}X + \frac{1}{2}jX\sqrt{3}$	This type of voltage sag can occur when two phases are shorted to ground at the same time.
Recommended Type III		$V_a = V$ $V_b = -\frac{1}{2}V - \frac{1}{2}jV\sqrt{3}$ $V_c = -\frac{1}{2}V + \frac{1}{2}jV\sqrt{3}$	Two studies [B1] and xdc [B6] indicated that this is a common type of voltage sag that occurs in 11% to 20% of the events recorded.

It is recognized that users of this recommended practice can require guidance to determine which vector test schemes are relevant for various equipment and devices. For this reason, Table A.2 provides a matrix for guiding the user in selecting the relevant test methods that will best uncover voltage-sag susceptibilities. It should be noted that the recommended vector test types for three-phase equipment are shown in the shaded columns. If the user conducts phase-to-phase tests with either of the alternate Type II forms, the table provides guidance for the form that is most effective for various equipment and devices.

Table A.2—Test method guidance matrix for various equipment and devices

Equipment/ device type	Example devices	Type I	Type II	Type II.A1	Type II.A2	Type III
Three-phase machine with neutral	Semiconductor tools, computerized numerical controller (CNC) machines, plastic extrusion equipment, conveyor	√	√	√	√	√
Three-phase machine without neutral	Semiconductor tools, CNC machines, plastic extrusion equipment, conveyor	See NOTE 1	√	√	√	See NOTE 2
Three-phase, passive front-end devices	Electronic motor drives or power supplies with diode-based rectifier front-end sections	√	√	See NOTE 3	√	√
Three-phase, active front-end devices	Electronic motor drives or power supplies with IGBT or SCR based rectifier front-end sections	√	√	√	See NOTE 4	√
Single-phase, passive front-end devices (See NOTE 5)	Electronic motor drives or power supplies with diode-based rectifier front-end sections	√				

Table continues

Table A.2—Test method guidance matrix for various equipment and devices *(continued)*

Equipment/ device type	Example devices	Type I	Type II	Type II.A1	Type II.A2	Type III
Single-phase, active front-end devices (See NOTE 5)	Electronic motor drives or power supplies with IGBT- or SCR-based rectifier front-end sections	√				
Electromechanical switching devices (See NOTE 5)	Relays, contactors, motor starters, and solenoids with ac coils	√				
NOTE 1—If the EUT does not have a neutral, Type I voltage-sag testing might not be relevant unless the neutral is again derived internally by the equipment by a local voltage-matching transformer. In this case, if single-phase testing is desired, tests should be done on the secondary of the transformer, or an additional delta-wye transformer can be installed to obtain the neutral reference. NOTE 2—Type III testing normally requires a neutral reference. If derived internally by the equipment through a local voltage-matching transformer, testing should be done on the secondary of the transformer in order to reference the neutral. Otherwise, an additional delta-wye transformer can be installed to obtain the neutral reference. NOTE 3—Type II.A1 voltage sags result in one of the phase-to-phase vectors remaining at 1.0 pu. Therefore, the secondary side of a passive front end (rectifier-based) three-phase load will charge to the peak every cycle. This testing might lead to results that are overly optimistic due to the magnitudes of the phase vectors. NOTE 4—Type II.A2 voltage sags create the minimum phase vectors but do not induce any phase shifting with respect to neutral. If the load contains items sensitive to phase shifts—such as active front-end, three-phase loads—application of this test might lead to overly optimistic results due to lack of phase shift in the voltage sag. NOTE 5—These specific single-phase loads may be connected line-to-neutral or line-to-line, which would require testing in either Type I or Type II configurations as necessary.						

A.2 Safety precautions for voltage-sag testing

This recommended practice does not purport to specifically address safety issues, if any, associated with its use. It is the responsibility of the users of this standard to establish appropriate health and safety practices and determine the applicability of regulatory or other limitations prior to use. However, basic safety precautions are discussed in this clause to help the reader understand common safety measures when performing voltage-sag testing.

Whether the EUT is a simple device, such as a single-phase power supply, or a complex device, such as a three-phase integrated machine or process-control cabinet, voltage-sag testing requires the connection of monitoring points for both power and data acquisition. For this reason, the system should be first powered down and locked out, the connections made, and power re-applied. The following precautions must be taken when conducting this work:

- Pre-planning is essential. Tests require a written test plan that discusses how the equipment will be tested, main power requirements, and so on. The test plan must be reviewed and approved by all who participate in the testing process.
- Work should be done in an orderly fashion as described in the written test plan.
- No monitoring points or power wires should be connected or wired when electricity is present unless proper personal protective equipment (PPE) is utilized.

- Appropriate arc-flash-rated clothing should be worn as required by National Electrical Code® (NEC®) NFPA 70E [B18]. Required PPE shall be as determined by the level of energy source present and level of exposure.[11]
- Safety glasses with integral side-shields or side-shields for those with safety-rated prescription glasses should be worn at all times.
- Lock, tag, and try procedures shall be followed when test leads are applied and the testing is conducted.
- Circuits must be visually inspected before power is restored.
- The immediate area surrounding the EUT must be cordoned off and monitored for intrusion.
- To reduce the chance of accidents, only essential personnel should be allowed within the cordoned test area.

A.3 Test setup

Before the test setup can begin, a study of the power-distribution diagrams and control schematics should be undertaken. During this planning phase, the test engineer should locate the EUT components and their interconnections. It is often quite helpful to create a process flow/block diagram that illustrates the interconnections and interdependences of devices such as the following:

- Servo motor drives
- Variable-frequency drives
- Motor drive start, stop, and enable signals
- Pilot relays that can provide those signals
- Programmable logic controllers (PLCs) that can provide those signals or that can control other devices
- Contactors that control the flow of power to the entire process or section such as start or stop circuits
- Contactors that are part of an emergency-stop or master-control relay circuit
- Servo or other controllers
- Power supplies

All of these devices are potential weak links that should be addressed. Should the susceptibility of the device or component not be of concern, testing of that device can be eliminated. Otherwise, the answer to the problem might lie in testing that component alone. For monitoring purposes, each of the suspect components should be observed during sag testing. In this way, it can be precisely determined what impact each device could have on the overall process. A representative power-flow diagram is shown in Figure A.1.

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[11] National Electrical Code, NEC, and NFPA 70E are registered trademarks of the National Fire Protection Association.

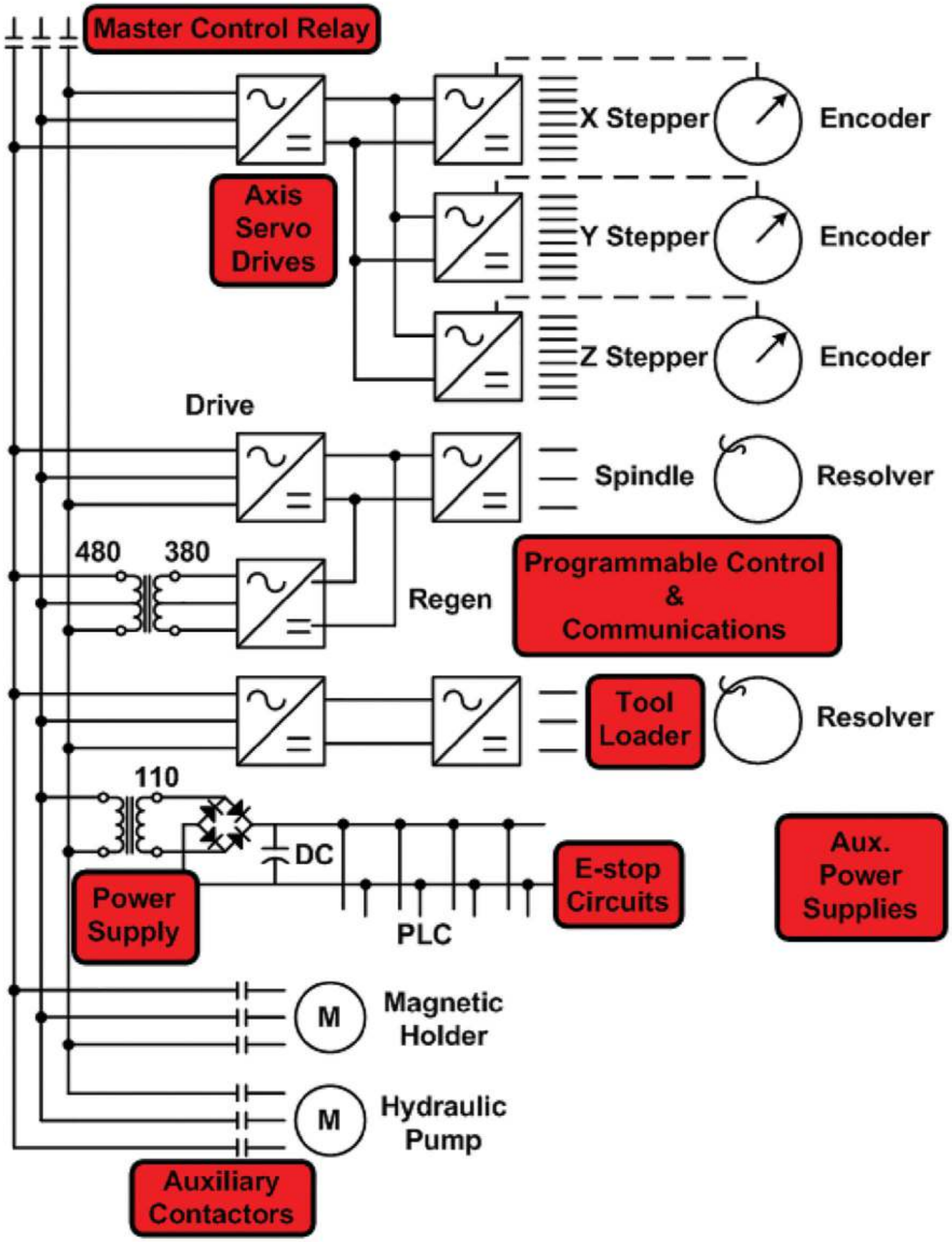


Figure A.1—Example EUT power distribution [computerized numerical controller (CNC) machine]

Possible monitoring points include contacts on critical relays (a low-voltage signal applied across these contacts or the normal operating voltage across them can provide an indication of the relay status through the monitoring system), dc output voltage on power supplies, PLC inputs/outputs, PLC processor enable signal, drive inputs/outputs, and drive dc bus values. All of these can be critical components to a process, and therefore provide pertinent information as to the status of the process. An example of data-acquisition system (DAS) monitoring points is shown in Table A.3 for a three-phase voltage-sag test. In this example, the first nine DAS channels are used for monitoring the current, phase-to-neutral voltages, and phase-to-phase voltages. When conducting Type I, Type II, and Type III tests, both phase-to-neutral and phase-to-phase voltages should be monitored. Channel 10 through Channel 16 in the example are used for monitoring the response of the EUT. The monitoring points shown in Table A.3 are provided for example only and are not meant to imply any specific requirement. The test engineer should determine what points should be monitored based on the review of the equipment design and power distribution. The DAS points should be included in the voltage-sag test plan.

Table A.3—Example DAS monitoring points (three-phase test)

No.	DAS monitoring points
1	Ia, phase A current
2	Ib, phase B current
3	Ic, phase C current
4	V a-n, phase a-n voltage
5	V b-n, phase b-n voltage
6	V c-n, phase c-n voltage
7	V a-b, line a-b voltage
8	V b-c, line b-c voltage
9	V c-a, line c-a voltage
10	Emergency-off circuit/master control relay
11	Equipment power contactor
12	DC power supply output
13	AC drive dc bus voltage
14	Multi-axis drive dc bus voltage
15	PLC run relay status
16	Motor starter status

A representative test setup is shown in Figure A.2. The setup includes the power source, which can originate from a branch circuit breaker in the test facility or from a source generator. Should an amplifier-based generator be used for the source voltage, the unit should be sized such that it will not limit the requirements of the EUT for inrush current. When using a utility source voltage, it is desirable that the voltage be at or near the rated voltage at which the equipment is to be operated. If the EUT has a voltage range for operation, testing at the lower range can be desirable in order to represent the worst-case performance of the equipment.

As shown in Figure A.2, the voltage-sag generator and DAS can be separate components or can be part of an integrated voltage-sag test and monitoring system. In order to determine where to connect the sag generator, the current rating of the test equipment should be matched to that of the load. When the current required by the EUT is within the sag generator's rating, the sag generator should be connected between the incoming power source and the point of connection (POC) for the EUT. If the current required by the EUT is greater than the rating of the sag generator, then individual subsystems of the EUT can be tested separately as long as the subsystem current requirements are less than that of the voltage sag generator. Should testing of the EUT subsystems be required due to the limitation of the sag generator, then each subsystem should be tested independently while the other parts of the EUT are operating. When the EUT is tested in this manner, any interlocks or alarms that might activate during the test will be apparent.

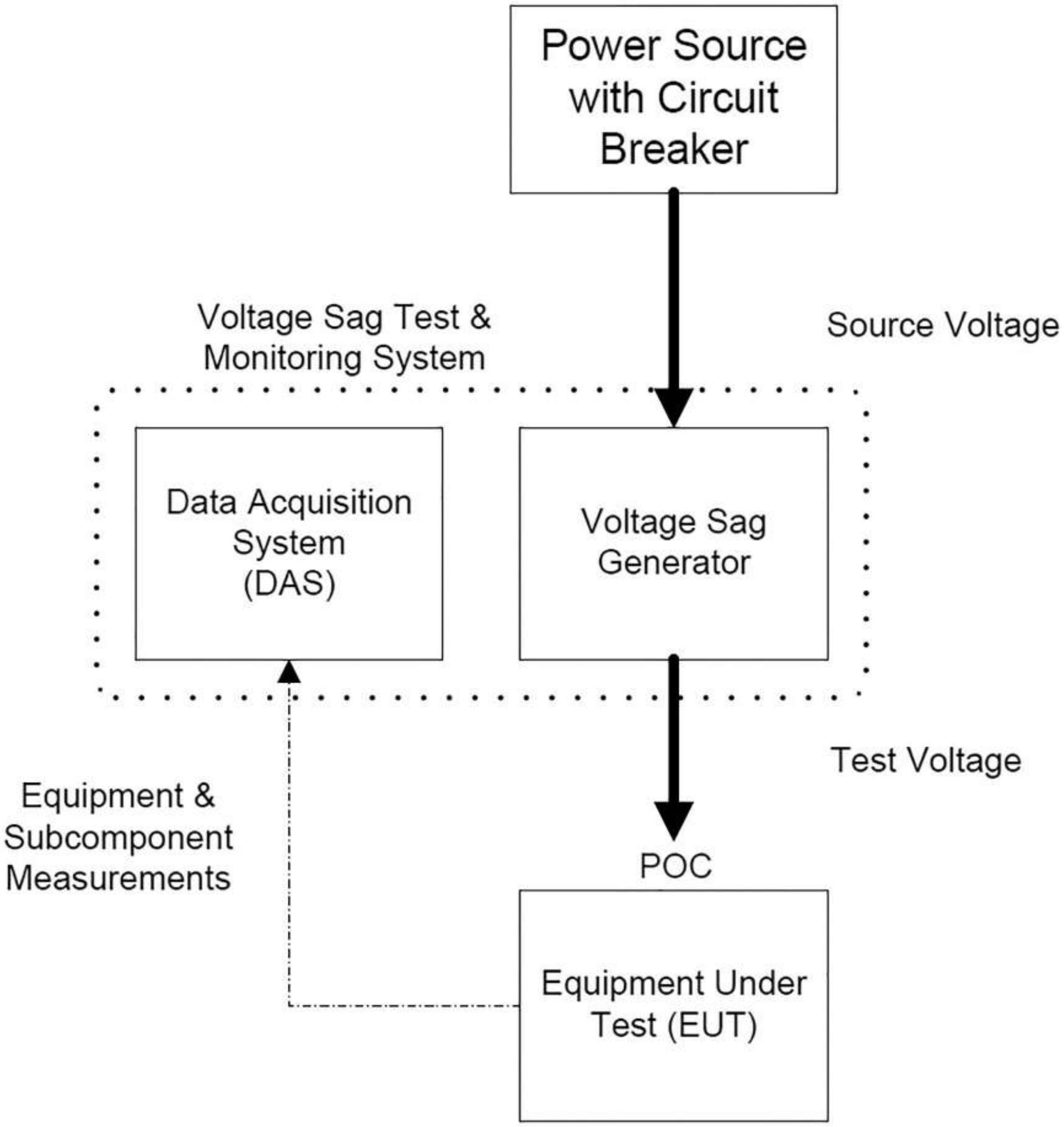


Figure A.2—Test setup (single-phase test setup shown for clarity)

A.4 Compliance test procedures

A.4.1 Background on compliance test procedures

Compliance testing should be performed by a qualified test laboratory. Such tests are by nature expensive because the test results must be trustworthy and reproducible. The number of tests and the complexity of the tests should not be more than absolutely necessary; however, the results of the tests should give a reasonable prediction of the general performance of the equipment in practical applications and real operating conditions. The tables presented in this clause are based on the recommended test levels shown in 5.3 of this recommended practice. The equipment performance should be documented using the designators referred to in 5.3.4 of this recommended practice. The reader should also refer to Table A.2 to determine the appropriate voltage-sag types that should be administered based on the equipment that is being tested.

The advocated voltage-sag tests should be initiated at 0° point-on-wave with respect to the phase in which the voltage sag is being created during the evaluation of the EUT.

A.4.2 Type I compliance testing

Type I compliance testing is relevant for single-phase equipment or single-phase devices that can be bench tested. Type I testing is also useful when evaluating three-phase equipment for loads wired between phase and neutral. For example, on 208-V ac systems, 120-V ac control voltage is easily derived phase-to-neutral. Table A.4 shows the required test matrix for single-phase equipment while Table A.5 shows the Type I test matrix for three-phase equipment with a neutral.

Table A.4—Type I single-phase equipment compliance test matrix

Test no.	Duration of voltage sag			$\%V_{nominal}$	Pass/fail response[a]		
	Seconds	60 Hz cycles	50 Hz cycles		Full operation	Self-recovery	Assisted-recovery
1	2.0	120	100	80%			
2	0.5	30	25	70%			
3	0.2	12	10	50%			

[a] The "pass/fail response" results should be documented using the terminology designated in this recommended practice. These designations are: full operation, self-recovered, or assisted-recovery. See 5.3.4 for definitions of the pass/fail criteria.

Table A.5—Type I three-phase system with neutral compliance test matrix

Test no.	Duration of voltage sag			$\% V_{A\text{-}N}$	$\% V_{B\text{-}N}$	$\% V_{C\text{-}N}$	Pass/fail response		
	Seconds	60 Hz cycles	50 Hz cycles				Full operation	Self-recovery	Assisted-recovery
1	2.0	120	100	80%	100%	100%			
2	0.5	30	25	70%	100%	100%			
3	0.2	12	10	50%	100%	100%			
4	2.0	120	100	100%	80%	100%			
5	0.5	30	25	100%	70%	100%			
6	0.2	12	10	100%	50%	100%			
7	2.0	120	100	100%	100%	80%			
8	0.5	30	25	100%	100%	70%			
9	0.2	12	10	100%	100%	50%			

A.4.3 Type II compliance testing

Type II compliance testing is relevant for three-phase and single-phase, line-to-line connected equipment to determine its susceptibility to phase-to-phase voltage sags. As discussed in this recommended practice, there are three different ways in which Type II sags can be generated. Refer to Clause A.1 for the implications of the chosen Type II test vector. The ideal vector magnitudes for Type II, Type II.A1, and Type II.A2 are illustrated in Figure A.3 for the three Type II test scenarios.

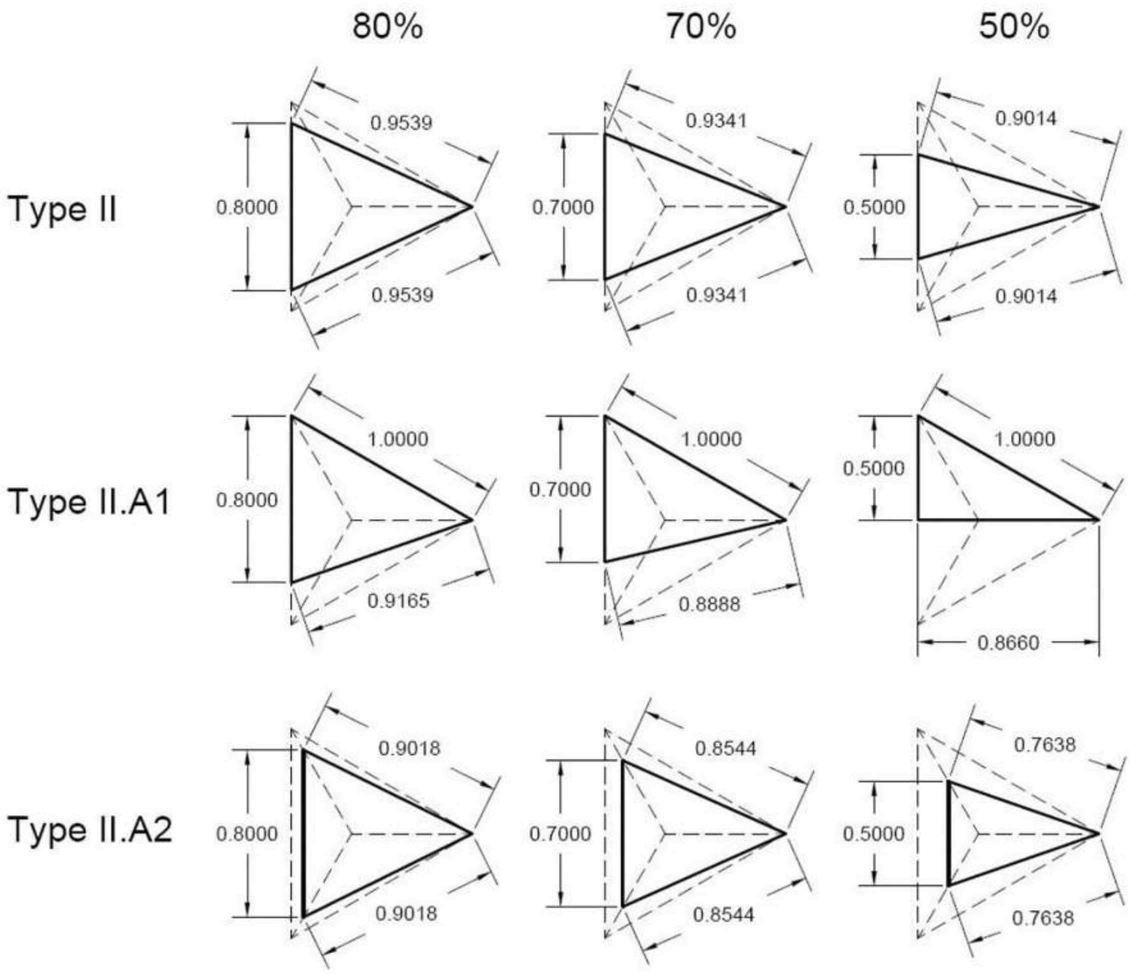


Figure A.3—Ideal vector magnitudes for Type II, Type II.A1, and Type II.A2 voltage-sag compliance test points

Table A.6, Table A.7, and Table A.8 show the test matrix for recommended Type II voltage-sag vectors and the two alternative forms. The three required test points are to be done separately on each of the phase-to-phase combinations ($V_{A\text{-}B}$, $V_{B\text{-}C}$, or $V_{C\text{-}A}$). The settings for the test point for the voltage-sag generator are shown in bold and shaded. Also shown are the expected magnitudes of the other phase-to-phase vectors.

Table A.6—Type II compliance testing test matrix

Test no.	Duration of voltage sag			$V_{A\text{-}B}$	$V_{B\text{-}C}$	$V_{C\text{-}A}$	Pass/fail response		
	Seconds	60 Hz cycles	50 Hz cycles				Full operation	Self-recovery	Assisted-recovery
1	2.0	120	100	**80%**	95.39%	95.39%			
2	0.5	30	25	**70%**	93.41%	93.41%			
3	0.2	12	10	**50%**	90.14%	90.14%			
4	2.0	120	100	95.39%	**80%**	95.39%			
5	0.5	30	25	93.41%	**70%**	93.41%			
6	0.2	12	10	90.14%	**50%**	90.14%			

Table continues

Table A.6—Type II compliance testing test matrix *(continued)*

Test no.	Duration of voltage sag			V_{A-B}	V_{B-C}	V_{C-A}	Pass/fail response		
	Seconds	60 Hz cycles	50 Hz cycles				Full operation	Self-recovery	Assisted-recovery
7	2.0	120	100	95.39%	95.39%	**80%**			
8	0.5	30	25	93.41%	93.41%	**70%**			
9	0.2	12	10	90.14%	90.14%	**50%**			

Table A.7—Type II.A1 (Alternative 1) compliance testing matrix

Test no.	Duration of voltage sag			V_{A-B}	V_{B-C}	V_{C-A}	Pass/fail response		
	Seconds	60 Hz cycles	50 Hz cycles				Full operation	Self-recovery	Assisted-recovery
1	2.0	120	100	**80%**	100%	91.65%			
2	0.5	30	25	**70%**	100%	88.88%			
3	0.2	12	10	**50%**	100%	86.6%			
4	2.0	120	100	91.65%	**80%**	100%			
5	0.5	30	25	88.88%	**70%**	100%			
6	0.2	12	10	86.6%	**50%**	100%			
7	2.0	120	100	100%	91.65%	**80%**			
8	0.5	30	25	100%	88.88%	**70%**			
9	0.2	12	10	100%	86.6%	**50%**			

Table A.8—Type II.A2 (Alternative 2) compliance testing matrix

Test no.	Duration of voltage sag			V_{A-B}	V_{B-C}	V_{C-A}	Pass/fail response		
	Seconds	60 Hz cycles	50 Hz cycles				Full operation	Self-recovery	Assisted-recovery
1	2.0	120	100	**80%**	90.18%	90.18%			
2	0.5	30	25	**70%**	85.44%	85.44%			
3	0.2	12	10	**50%**	76.38%	76.38%			
4	2.0	120	100	90.18%	**80%**	90.18%			
5	0.5	30	25	85.44%	**70%**	85.44%			
6	0.2	12	10	76.38%	**50%**	76.38%			
7	2.0	120	100	90.18%	90.18%	**80%**			
8	0.5	30	25	85.44%	85.44%	**70%**			
9	0.2	12	10	76.38%	76.38%	**50%**			

A.4.4 Type III compliance testing

The test matrix for Type III compliance testing is shown in Table A.9. Type III testing normally requires the equipment to have a neutral conductor or that a neutral conductor be derived. See A.1 of this document for additional guidance.

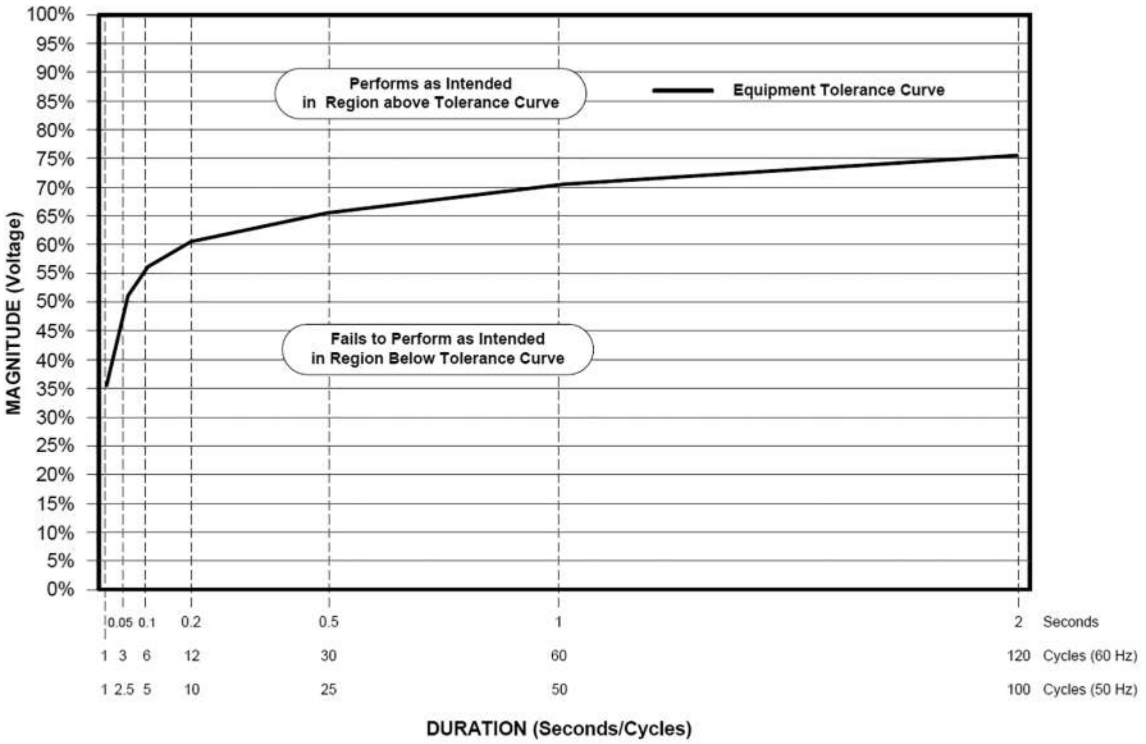
Table A.9—Type III compliance testing test matrix

Test no.	Duration of voltage sag			V_{ABC}	Pass/fail response		
	Seconds	60 Hz cycles	50 Hz cycles		Full operation	Self-recovery	Assisted-recovery
1	2.0	120	100	**80%**			
2	0.1	6	5	**70%**			
3	0.05	3	2.5	**50%**			

A.5 Voltage-sag immunity characterization test procedures

A.5.1 Background on voltage-sag immunity characterization test procedures

Voltage-sag immunity characterization testing should reveal the ability of the equipment to ride through voltage sags at the power terminals of the EUT. The "voltage-sag tolerance curve" is an important tool to understand the compatibility between the equipment and the electric power supply at a given location. Unlike compliance testing against a small set of specific test points, characterization testing is typically done at numerous test points and voltage levels in order to fully characterize the compatibility of the EUT. For single-phase equipment, one curve is sufficient. For three-phase equipment, it is recommended that three voltage-tolerance curves be presented—one for each type of sag. The three types of voltage sags, referred to as Type I, Type II, and Type III, correspond to voltage drops in one, two, and three phases, respectively. Determining the voltage-tolerance curve is a valuable effort that can yield far more information about equipment immunity than the pass/fail results found in compliance testing. An example equipment voltage-sag tolerance curve is shown in Figure A.4.



NOTE—This example is conceptual and is relevant for phase-to-neutral voltage sags.

Figure A.4—Example voltage-sag tolerance curve of an EUT

Specific methods for quantifying compatibility are proposed in IEEE Std 493™-2007 [B11] and IEEE Std 1346™-1998 [B15].[12] The method combines the voltage-tolerance curve of a device with the (annual) voltage-sag frequency contour chart of the local supply, resulting in an expected number of per-year equipment trips. Other common methods are to plot the individual voltage sags seen at the site against the voltage-sag tolerance curve of the equipment. This method can help one see how many events occur above and below the tolerance curve during the monitoring period.

By overlaying the actual voltage sags (magnitude and duration) on top of the tolerance curve, one can obtain an idea of the susceptibility of the equipment to voltage sags. The correlation between the equipment performance and actual voltage-sag data is most closely related when the monitoring data is obtained at the utilization voltage at which the equipment is installed. An example of such an overlay is shown in Figure A.5. In the example, the equipment is expected to ride through the seven events above the tolerance curve and shutdown for the seven events that are on or below the tolerance curve.

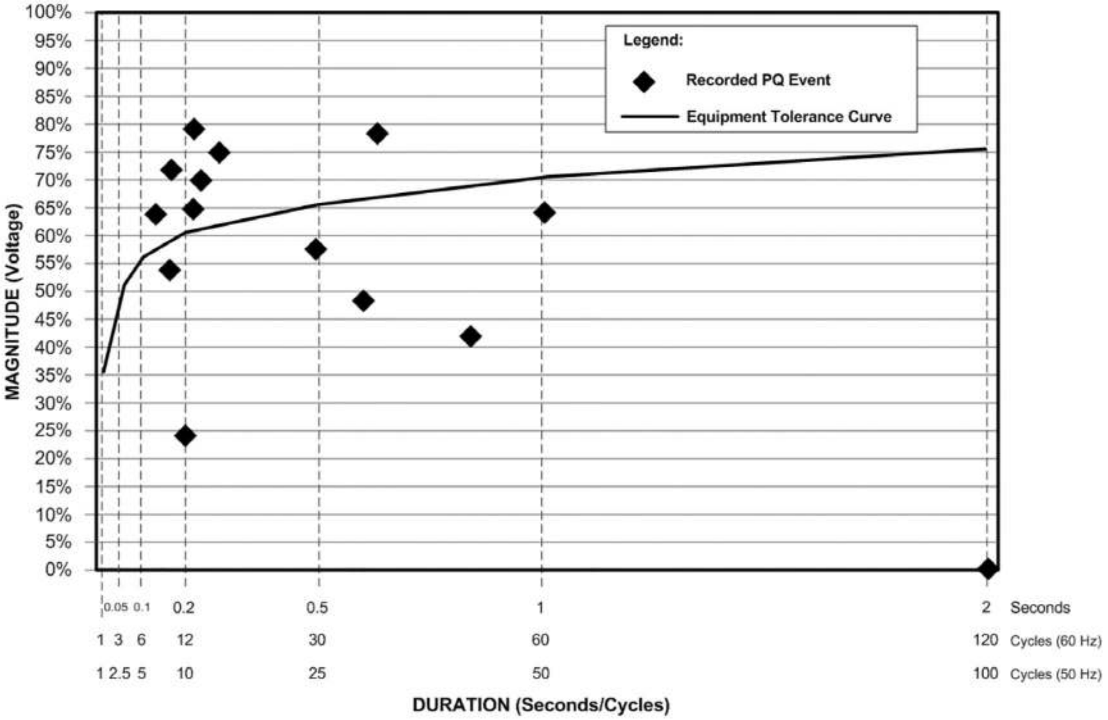


Figure A.5—Example EUT voltage-sag tolerance curve with PQ data overlay

A.5.2 Test plan

Based on the knowledge gained in the study of the EUT and the site, a specific test plan referencing this procedure and outlining the important test measurement points should be developed. At a minimum, the test plan should reference the following:

- The most sensitive process states of the EUT
- EUT loading information (such as 50% loaded)

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[12] IEEE Std 1346-1998 has been withdrawn; however, copies can be obtained from the Institute of Electrical and Electronics Engineers (http://standards.ieee.org/).

- The required test durations (such as 0.05 s, 0.1 s, 0.2 s, 0.5 s, 1.0 s, and 2.0 s)
- The minimum voltage to be applied (such as 0% or 50%) during tests
- Voltage-sag voltage incremental change (such as 5%)
- Phase modes required (such as phase-to-neutral or phase-to-phase)
- Data-acquisition measurement points (such as in Table A.3)

A.5.3 Initial procedures

This procedure provides an example checklist of steps to be done prior to starting the actual voltage-sag testing. The purpose of this procedure is to accomplish the following:

a) Connect the EUT into the test setup as shown in Figure A.2. Refer to A.2 for safety precautions.
b) Connect DAS monitoring channels per the test plan using Table A.3 as a general reference.
c) Visually inspect all connections prior to energizing the test setup.
d) Energize the power source and verify source voltage using a digital voltmeter.
e) Energize the voltage-sag generator, measure and record the phase voltages, and confirm the output of the sag generator.
f) Power up the EUT.
g) Perform any final configuration and setup of the DAS channels and confirm their readings.
h) Verify that the EUT is in a desired process state for voltage-sag testing. Tests should be done in the most sensitive process state as determined by the equipment user or OEM. Tests can be repeated in various states to fully characterize the equipment. These states should be outlined in the test plan.

A.5.4 Equipment voltage-sag characterization methods

A.5.4.1 Background on voltage-sage characterization methods

Several methods can be used to characterize equipment performance against voltage sags. The chosen characterization method can depend on the test location and time available to conduct the test. The procedure for each test method is described in terms of “test loops” consisting of a series of tests that can be repeated until the EUT malfunctions, at which time the next successive test loop is conducted. The three basic characterization methods used to determine the ride-through performance of an EUT are the top-down, left-right, and box-in methods.

Each of the test methods described in this clause can be used to evaluate a single-phase or three-phase EUT. For single-phase equipment, the phase voltage designated as the phase under test (PUT) is essentially the single phase that powers the EUT. For three-phase equipment, the phase voltages designated as the PUT refers to the selected voltage for evaluation for a given test run ($V_{A\text{-}N}$, $V_{B\text{-}N}$, $V_{C\text{-}N}$, $V_{A\text{-}B}$, $V_{B\text{-}C}$, $V_{C\text{-}A}$, and $V_{A\text{-}B\text{-}C}$). The test voltage designated PUT is expressed in a percent of nominal voltage.

A.5.4.2 Top-down characterization method

This method of voltage-sag testing involves holding the sag duration constant while the magnitude of the sag voltage is stepped down in intervals from the maximum magnitude (defined by the test plan) until the minimum magnitude (also defined by the test plan) is reached or the EUT trips. At that point, the sag duration is decreased to its next scheduled value, and the magnitude steps are repeated at that duration. This magnitude down-stepping within a duration loop continues until all scheduled durations are exhausted. Figure A.6 shows the flow chart for this top-down method of sag testing. Figure A.7 shows how the trip points that are determined by this method result in a voltage-tolerance curve for the EUT. Table A.10 (50 Hz) and Table A.11 (60 Hz) are test worksheets, wherein the example parameters of the test plan are as follows:

- Maximum magnitude: 85% of nominal
- Minimum magnitude: 0% of nominal
- Maximum duration: 2 s
- Minimum duration: 0.02 s
- Magnitude interval: 5% of nominal (18 steps)
- Duration schedule: 2 s, 1 s, 0.5 s, 0.2 s, 0.1 s, 0.05 s, and 0.02 s (seven loops)

For illustration purposes, Step 1 through Step18 within Loop 1 are explicitly shown.

This method enables the investigator to find a trip point (should it exist) at all given test durations outlined in the plan. In the example, single-phase test matrices shown in Table A.10 and Table A.11, as many as seven trip points for the EUT can be identified during the test. Of course, it is possible to include more or fewer duration values in the schedule, depending upon the test plan.

A variation of this test method can be used in an industrial setting—when EUT downtime should be held to a minimum—where the duration of most voltage sags are known from power quality data and substation recloser settings. In this case, a single, or only a few test loops can be necessary to get the idea of the EUT's immunity to voltage sags. For example, a common voltage-sag duration at the site (such as 6 cycles) could be selected with voltage successively decreased in magnitude from the highest planned test level (such as 85%) to the trip level of the EUT. Then, that test point could be extrapolated to create a line at the trip level (magnitude) across all durations (from 0 s to 2 s). Should time remain, additional test loops can be executed at longer or shorter test durations to determine a more precise voltage-sag ride-through curve.

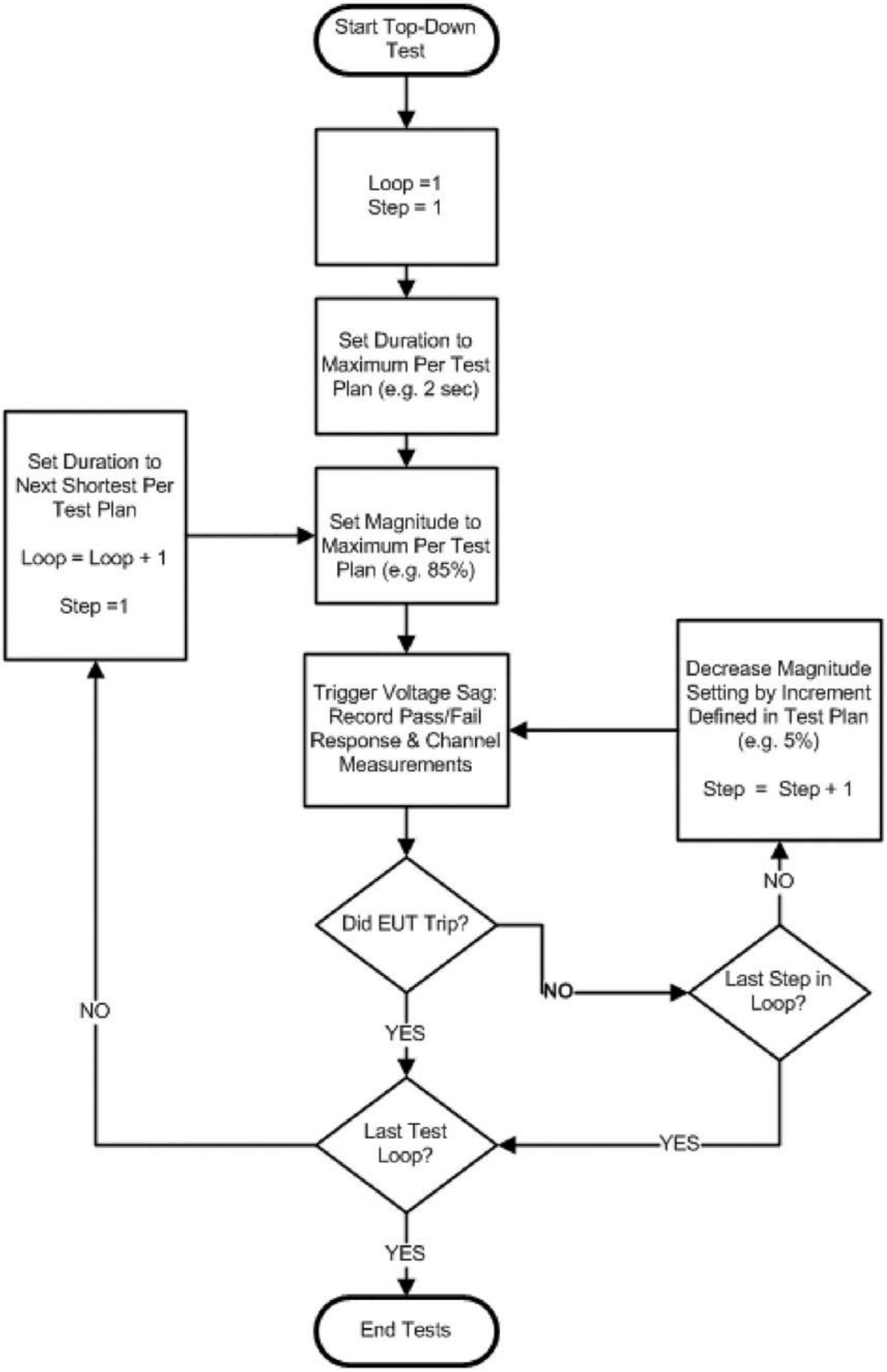

Figure A.6—Top-down voltage-sag characterization test flow chart

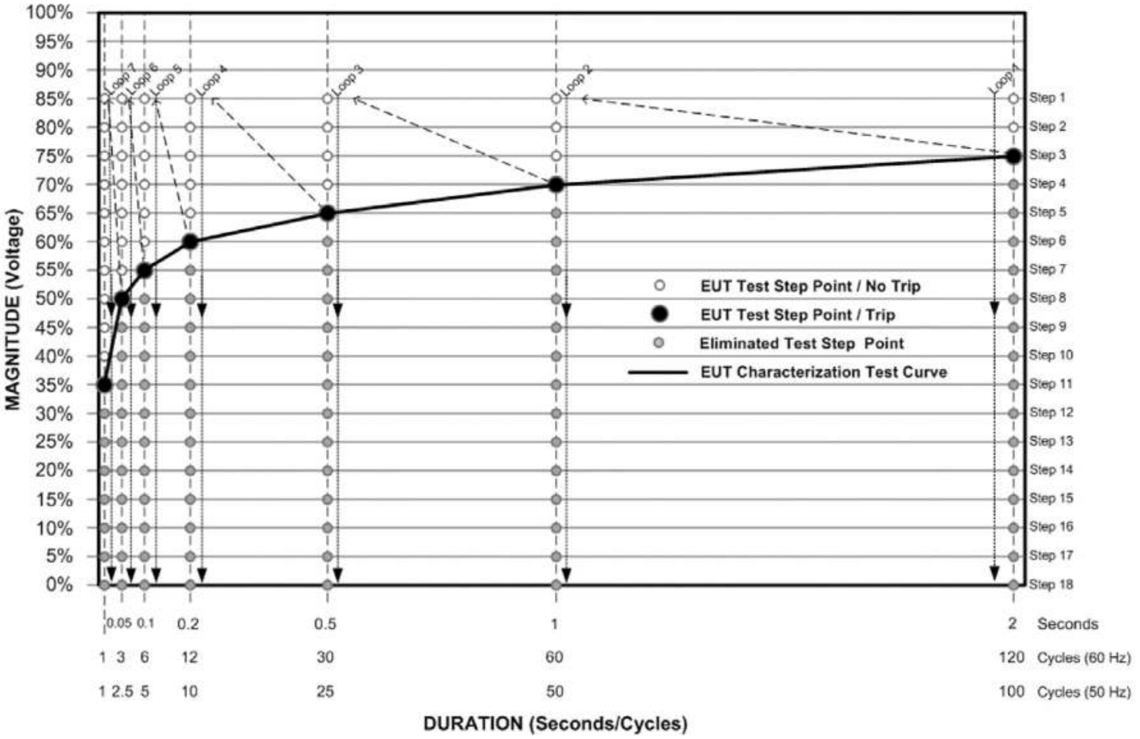

Figure A.7—Top-down voltage-sag characterization method

Table A.10—Top-down method equipment characterization test matrix, 50 Hz example

Test loop	Step no.	Voltage-sag duration		$\%V_{\text{nominal}}$ of PUT	Pass/fail response			Notes
		Seconds	50 Hz cycles		Full operation	Self-recovery	Assisted-recovery	
Loop 1	1	2	100	85%				
	2	2	100	80%				
	3	2	100	75%				
	4	2	100	70%				
	5	2	100	65%				
	6	2	100	60%				
	7	2	100	55%				
	8	2	100	50%				
	9	2	100	45%				
	10	2	100	40%				
	11	2	100	35%				
	12	2	100	30%				
	13	2	100	25%				
	14	2	100	20%				
	15	2	100	15%				
	16	2	100	10%				
	17	2	100	5%				
	18	2	100	0%				

Table continues

Table A.10—Top-down method equipment characterization test matrix, 50 Hz example *(continued)*

Test loop	Step no.	Voltage-sag duration		$\%V_{nominal}$ of PUT	Pass/fail response			Notes
		Seconds	50 Hz cycles		Full operation	Self-recovery	Assisted-recovery	
Loop 2	1→ 18	1	50	85% → 0%				
Loop 3	1→ 18	0.5	25	85% → 0%				
Loop 4	1→ 18	0.2	10	85% → 0%				
Loop 5	1→ 18	0.1	5	85% → 0%				
Loop 6	1→ 18	0.05	2.5	85% → 0%				
Loop 7	1→ 18	0.02	1	85% → 0%				

Table A.11—Top-down method equipment characterization test matrix, 60 Hz example

Test loop	Step no.	Voltage-sag duration		$\%V_{nominal}$ of PUT	Pass/fail response			Notes
		Seconds	60 Hz cycles		Full operation	Self-recovery	Assisted-recovery	
Loop 1	1	2	120	85%				
	2	2	120	80%				
	3	2	120	75%				
	4	2	120	70%				
	5	2	120	65%				
	6	2	120	60%				
	7	2	120	55%				
	8	2	120	50%				
	9	2	120	45%				
	10	2	120	40%				
	11	2	120	35%				
	12	2	120	30%				
	13	2	120	25%				
	14	2	120	20%				
	15	2	120	15%				
	16	2	120	10%				
	17	2	120	5%				
	18	2	120	0%				
Loop 2	1→ 18	1	60	85% → 0%				
Loop 3	1→ 18	0.5	30	85% → 0%				
Loop 4	1→ 18	0.2	12	85% → 0%				
Loop 5	1→ 18	0.1	6	85% → 0%				
Loop 6	1→ 18	0.05	3	85% → 0%				
Loop 7	1→ 18	0.02	1	85% → 0%				

A.5.4.3 Left-right characterization method

This method of voltage-sag testing involves holding the sag magnitude constant while the duration of the sag voltage is increased according to a schedule from the minimum duration (defined by the test plan) until the maximum duration (also defined by the test plan) is reached or the EUT trips. At that point, the sag magnitude is decreased to the next lower value determined by a prescribed interval, and the duration steps are repeated at that magnitude. This duration up-stepping within a magnitude loop continues until the prescribed maximum sag duration is reached. Figure A.8 shows the flow chart for this left-right method of sag testing. Figure A.9 shows how the trip points that are determined by this method result in a voltage-tolerance curve for the EUT. Table A.12 (50 Hz) and Table A.13 (60 Hz) are test worksheets, wherein the example parameters of the test plan are as follows:

- Maximum magnitude: 85% of nominal
- Minimum magnitude: 0% of nominal
- Maximum duration: 2 s
- Minimum duration: 0.02 s
- Magnitude interval: 5% of nominal (18 loops)
- Duration schedule: 2 s, 1 s, 0.5 s, 0.2 s, 0.1 s, 0.05 s, and 0.02 s (seven steps)

This method will result in finding a trip point at all given test durations outlined in the plan (unless a certain duration yields no trip, which might be the case for extremely short durations, such as 0.001 s). With this test method, many initial tests can be accomplished quickly if the EUT does not trip for the higher-magnitude test points. Because some trip levels on a ride-through curve reach a plateau after a certain duration, this method can result in fewer EUT trips once the magnitude trip level is determined.

Should the goal be to characterize the response against a desired immunity level, the minimum test magnitudes can be something other than 0% at the subject durations (such as 50%, 70%, and 80%). In this case, the EUT might not trip at all if it is robust down to the minimum test magnitude.

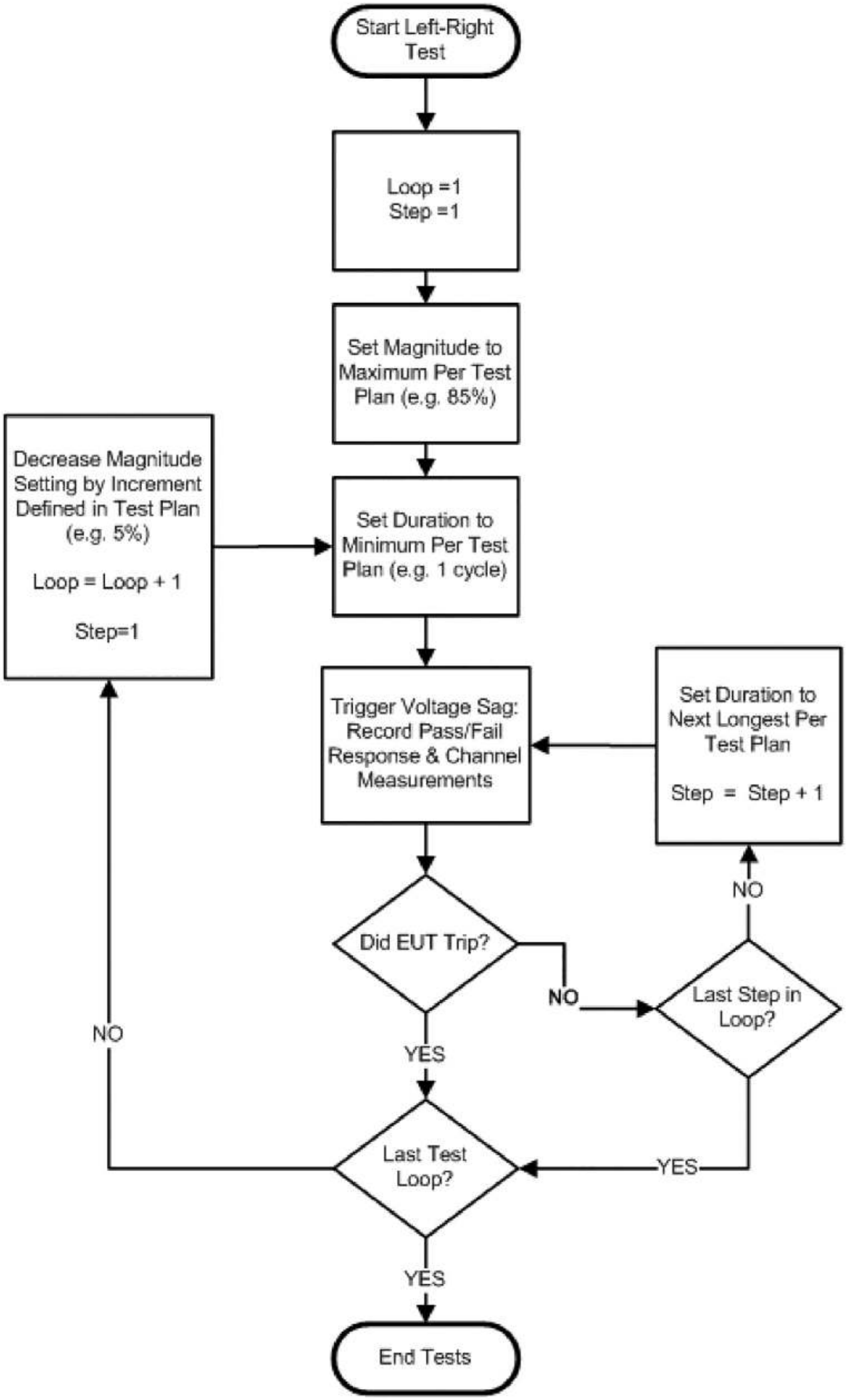

Figure A.8—Left-right voltage-sag characterization test method flow chart

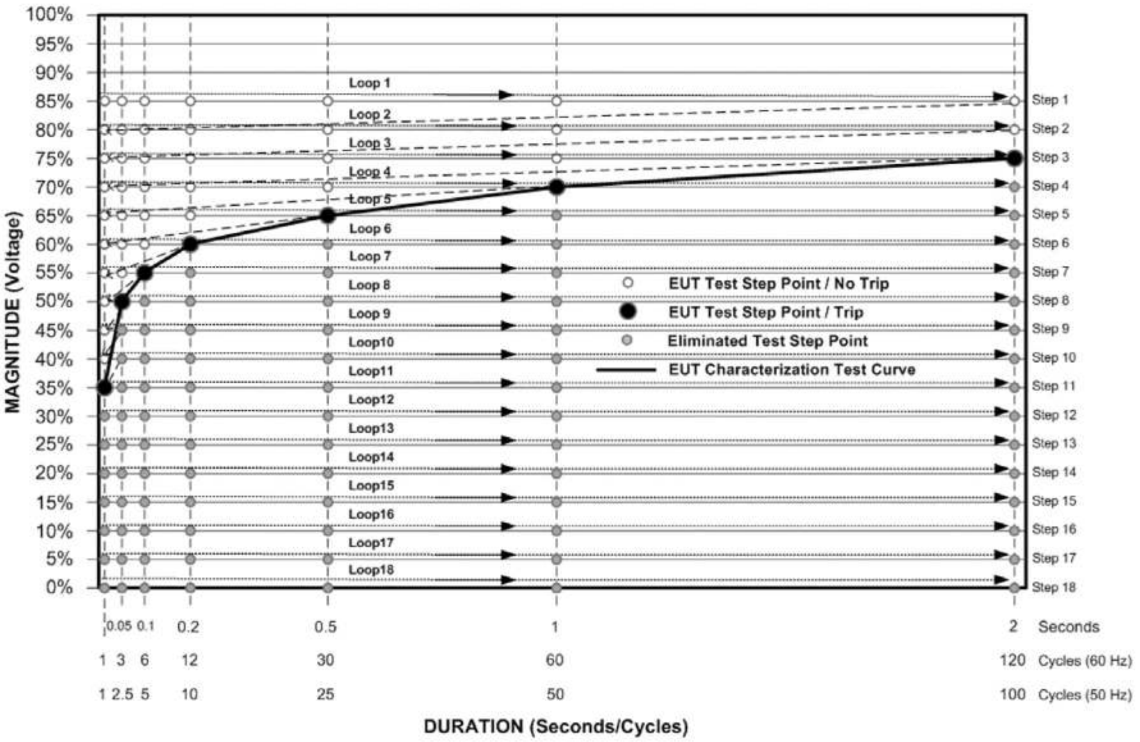

Figure A.9—Illustration of left-right voltage-sag characterization test method

Table A.12—Left-right method equipment characterization test matrix, 50 Hz example

Testloop	Step no.	Voltage-sag duration		$\%V_{\text{nominal}}$ of PUT	Pass/fail response			Notes
		Seconds	50 Hz cycles		Full operation	Self-recovery	Assisted-recovery	
Loop 1	1	0.02	1	85%				
	2	0.05	2.5	85%				
	3	0.1	5	85%				
	4	0.2	10	85%				
	5	0.5	25	85%				
	6	1	50	85%				
	7	2	100	85%				
Loop 2	1 → 7	0.02 → 2	1 → 100	80%				
Loop 3	1 → 7	0.02 → 2	1 → 100	75%				
Loop 4	1 → 7	0.02 → 2	1 → 100	70%				
Loop 5	1 → 7	0.02 → 2	1 → 100	65%				
Loop 6	1 → 7	0.02 → 2	1 → 100	60%				
Loop 7	1 → 7	0.02 → 2	1 → 100	55%				
Loop 8	1 → 7	0.02 → 2	1 → 100	50%				
Loop 9	1 → 7	0.02 → 2	1 → 100	45%				
Loop 10	1 → 7	0.02 → 2	1 → 100	40%				
Loop 11	1 → 7	0.02 → 2	1 → 100	35%				
Loop 12	1 → 7	0.02 → 2	1 → 100	30%				

Table continues

Table A.12—Left-right method equipment characterization test matrix, 50 Hz example *(continued)*

Testloop	Step no.	Voltage-sag duration		$\%V_{nominal}$ of PUT	Pass/fail response			Notes
		Seconds	50 Hz cycles		Full operation	Self-recovery	Assisted-recovery	
Loop 13	1 → 7	0.02 → 2	1 → 100	25%				
Loop 14	1 → 7	0.02 → 2	1 → 100	20%				
Loop 15	1 → 7	0.02 → 2	1 → 100	15%				
Loop 16	1 → 7	0.02 → 2	1 → 100	10%				
Loop 17	1 → 7	0.02 → 2	1 → 100	5%				
Loop 18	1 → 7	0.02 → 2	1 → 100	0%				

Table A.13—Left-right method equipment characterization test matrix, 60 Hz example

Test loop	Step no.	Voltage-sag duration		$\%V_{nominal}$ of PUT	Pass/fail response			Notes
		Seconds	60 Hz cycles		Full operation	Self-recovery	Assisted-recovery	
Loop 1	1	0.0167	1	85%				
	2	0.05	3	85%				
	3	0.1	6	85%				
	4	0.2	12	85%				
	5	0.5	30	85%				
	6	1	60	85%				
	7	2	120	85%				
Loop 2	1 → 7	0.0167 → 2	1 → 120	80%				
Loop 3	1 → 7	0.0167 → 2	1 → 120	75%				
Loop 4	1 → 7	0.0167 → 2	1 → 120	70%				
Loop 5	1 → 7	0.0167 → 2	1 → 120	65%				
Loop 6	1 → 7	0.0167 → 2	1 → 120	60%				
Loop 7	1 → 7	0.0167 → 2	1 → 120	55%				
Loop 8	1 → 7	0.0167 → 2	1 → 120	50%				
Loop 9	1 → 7	0.0167 → 2	1 → 120	45%				
Loop 10	1 → 7	0.0167 → 2	1 → 120	40%				
Loop 11	1 → 7	0.0167 → 2	1 → 120	35%				
Loop 12	1 → 7	0.0167 → 2	1 → 120	30%				
Loop 13	1 → 7	0.0167 → 2	1 → 120	25%				
Loop 14	1 → 7	0.0167 → 2	1 → 120	20%				
Loop 15	1 → 7	0.0167 → 2	1 → 120	15%				
Loop 16	1 → 7	0.0167 → 2	1 → 120	10%				
Loop 17	1 → 7	0.0167 → 2	1 → 120	5%				
Loop 18	1 → 7	0.0167 → 2	1 → 120	0%				

A.5.4.4 Box-in characterization method

This method enables the investigator to quickly “box in” a ride-through curve. In the top-down and left-right methods, the EUT is meticulously subjected to as many as 126 tests. The box-in method resembles the top-down method in most respects. When the EUT trips during the top-down method, that trip point does not influence the magnitude of the next test point. However, during a box-in test and after the zero-magnitude trip point is found, each trip point influences the magnitude of the next test point, reducing the number of test points required to characterize the ride-through performance of the EUT. For example, if the EUT trips at a duration of 0.5 cycles and a magnitude of 70%, then for the next duration loop, the magnitude does not have to be reset to the maximum magnitude (such as 85%) but can start at 75% (assuming that the magnitude interval is 10%).

After the initial trip point is found, a new loop/test strategy is employed, with the first test point at the maximum planned magnitude and the maximum planned duration. As with the top-down method, the sag duration is held steady while the magnitude is incrementally decreased. Once a trip point is determined during a loop, the duration is decreased to the next value and the magnitude is increased by the magnitude interval from the value of the trip point. This process continues until all steps in the final duration loop are completed. A flow chart and illustration of this test method are shown in Figure A.10 and Figure A.11. The method is further detailed in Table A.14 and Table A.15 for 50 Hz and 60 Hz electric supply sources. For illustration purposes, Test 1 through Test 7 from Loop 1 are explicitly shown.

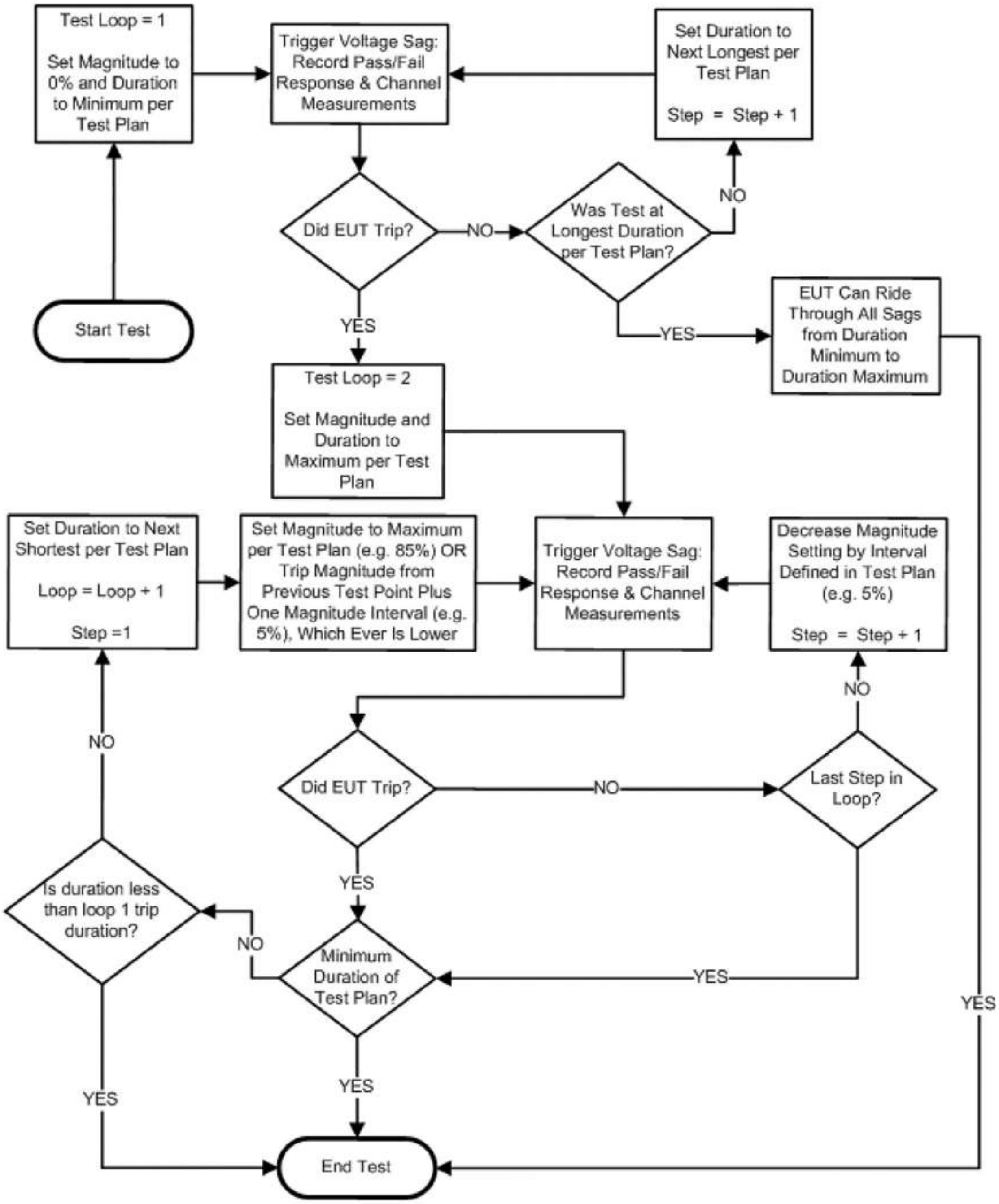

Figure A.10—Box-in voltage-sag characterization test method flow chart

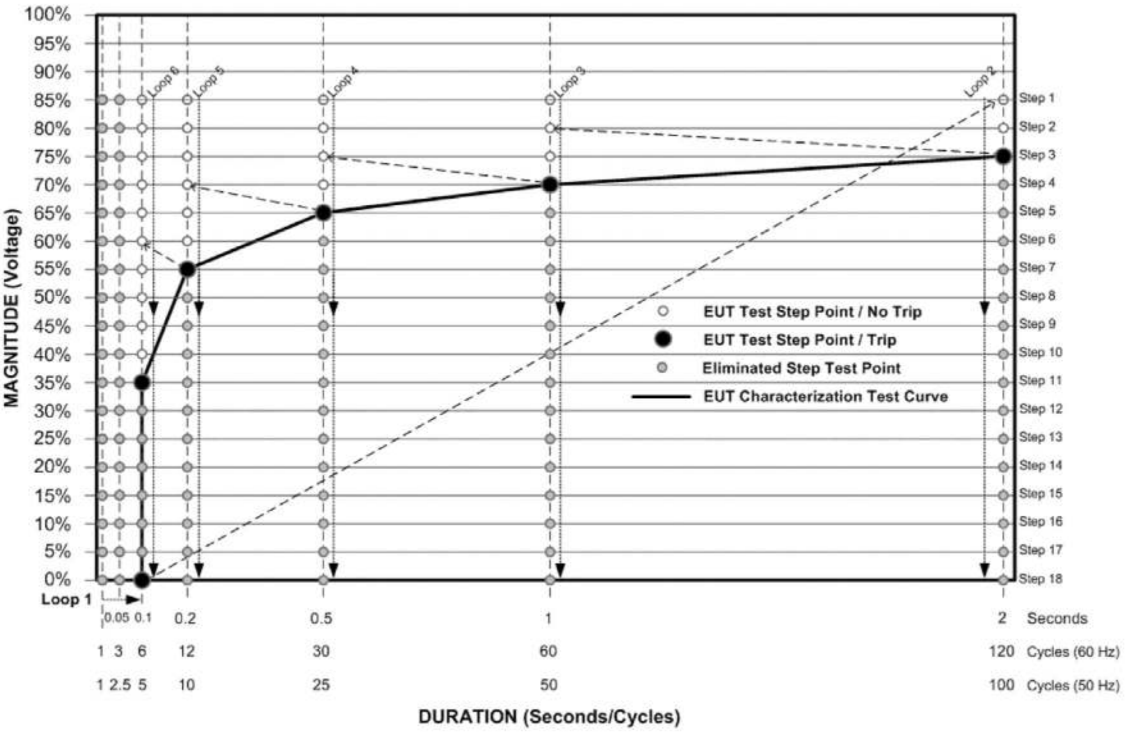

Figure A.11—Illustration of box-in voltage-sag characterization test method

Table A.14—Box-in method equipment characterization test matrix, 50 Hz example

Test loop	Step no.	Voltage-sag duration		$\%V_{\text{nominal}}$ of PUT	Pass/fail response			Notes
		Seconds	50 Hz cycles		Full operation	Self-recovery	Assisted-recovery	
Loop 1	1	0.02	1	0%				
	2	0.05	2.5	0%				
	3	0.1	5	0%				
	4	0.2	10	0%				
	5	0.5	25	0%				
	6	1	50	0%				
	7	2	100	0%				If EUT has not tripped at the maximum duration test point, testing can stop.

Table continues

Table A.14—Box-in method equipment characterization test matrix, 50 Hz example *(continued)*

Test loop	Step no.	Voltage-sag duration		%$V_{nominal}$ of PUT	Pass/fail response			Notes
		Seconds	50 Hz cycles		Full operation	Self-recovery	Assisted-recovery	
Loop 2	1	2	100	85%				
	2	2	100	80%				
	3	2	100	75%				
	4	2	100	70%				
	5	2	100	65%				
	6	2	100	60%				
	7	2	100	55%				
	8	2	100	50%				
	9	2	100	45%				
	10	2	100	40%				
	11	2	100	35%				
	12	2	100	30%				
	13	2	100	25%				
	14	2	100	20%				
	15	2	100	15%				
	16	2	100	10%				
	17	2	100	5%				
Loop 3	1→17	1	50	85%→5%				
Loop 4	1→17	0.5	25	85%→5%				
Loop 5	1→17	0.2	10	85%→5%				
Loop 6	1→17	0.1	5	85%→5%				
Loop 7	1→17	0.05	2.5	85%→5%				
Loop 8	1→17	0.02	1	85%→5%				

Table A.15—Box-in method equipment characterization test matrix, 60 Hz example

Test loop	Step no.	Voltage-sag duration		%$V_{nominal}$ of PUT	Pass/fail response			Notes
		Seconds	50 Hz cycles		Full operation	Self-recovery	Assisted-recovery	
Loop 1	1	0.0167	1	0%				
	2	0.05	2	0%				
	3	0.1	6	0%				
	4	0.2	12	0%				
	5	0.5	30	0%				
	6	1	60	0%				
	7	2	120	0%				If EUT has not tripped at the maximum duration test point, testing can stop.

Table continues

Table A.15—Box-in method equipment characterization test matrix, 60 Hz example *(continued)*

Test loop	Step no.	Voltage-sag duration		$\%V_{\text{nominal}}$ of PUT	Pass/fail response			Notes
		Seconds	50 Hz cycles		Full operation	Self-recovery	Assisted-recovery	
Loop 2	1	2	120	85%				
	2	2	120	80%				
	3	2	120	75%				
	4	2	120	70%				
	5	2	120	65%				
	6	2	120	60%				
	7	2	120	55%				
	8	2	120	50%				
	9	2	120	45%				
	10	2	120	40%				
	11	2	120	35%				
	12	2	120	30%				
	13	2	120	25%				
	14	2	120	20%				
	15	2	120	15%				
	16	2	120	10%				
	17	2	120	5%				
Loop 3	1→17	1	60	85%→5%				
Loop 4	1→17	0.5	30	85%→5%				
Loop 5	1→17	0.2	12	85%→5%				
Loop 6	1→17	0.1	6	85%→5%				
Loop 7	1→17	0.05	3	85%→5%				
Loop 8	1→17	0.0167	1	85%→5%				

A.5.5 Three-phase equipment characterization test procedures

Either of the test characterization methods presented in A.5.4.2, A.5.4.3, and A.5.4.4 can be used to guide single-phase, two-phase, and three-phase voltage-sag testing. For three-phase equipment, single-phase (Type I), two-phase (Type II), and three-phase (Type III) testing is required for full characterization. Three-phase equipment requires a neutral to create single-phase (Type I) and three-phase (Type III) events. If the EUT does not have a neutral, Type I voltage-sag testing might not be relevant unless the neutral is again derived internally by the equipment through a local voltage-matching transformer. In this case, if single-phase testing is desired, tests should be done on the secondary of the transformer, or an additional delta-wye transformer can be installed to obtain the neutral reference. Type III testing requires a neutral reference. If derived internally by the equipment through a local voltage-matching transformer, testing should be done on the secondary of the transformer in order to reference the neutral. Otherwise, an additional delta-wye transformer can be installed to obtain the neutral reference.[13]

Voltage-sag testing of three-phase equipment generally begins by first performing single-phase Type I characterization of each of the three phases independently ($V_{A\text{-}N}$, $V_{B\text{-}N}$, $V_{C\text{-}N}$). Afterward, Type II characterization

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[13] It is not advised to substitute the ground conductor for the return conductor if a neutral is not present. Ground currents may back-feed, causing elevated voltage on the grounding system and tripping of upstream ground fault current interrupters.

is performed independently for each of the three phase-to-phase combinations ($V_{A\text{-}B}$, $V_{B\text{-}C}$, $V_{C\text{-}A}$). Finally, three-phase Type III voltage sags are performed until the EUT is fully characterized ($V_{A\text{-}B\text{-}C}$). The voltage-sag test types, PUT combinations, and the source-voltage requirements for characterization are shown in Table A.16. The flow chart provided in Figure A.12 illustrates a general example of the three-phase voltage-sag testing methodology.

Table A.16—Source requirements for full characterization

Voltage-sag test type	PUT combinations	Source requirements for characterization
Type I	$V_{A\text{-}N}$, $V_{B\text{-}N}$, $V_{C\text{-}N}$	3 phases, neutral, ground
Type II/ Type II.A1/ Type II.A2	$V_{A\text{-}B}$, $V_{B\text{-}C}$, $V_{C\text{-}A}$	3 phases, ground
Type III	$V_{A\text{-}B\text{-}C}$	3 phases, neutral, ground

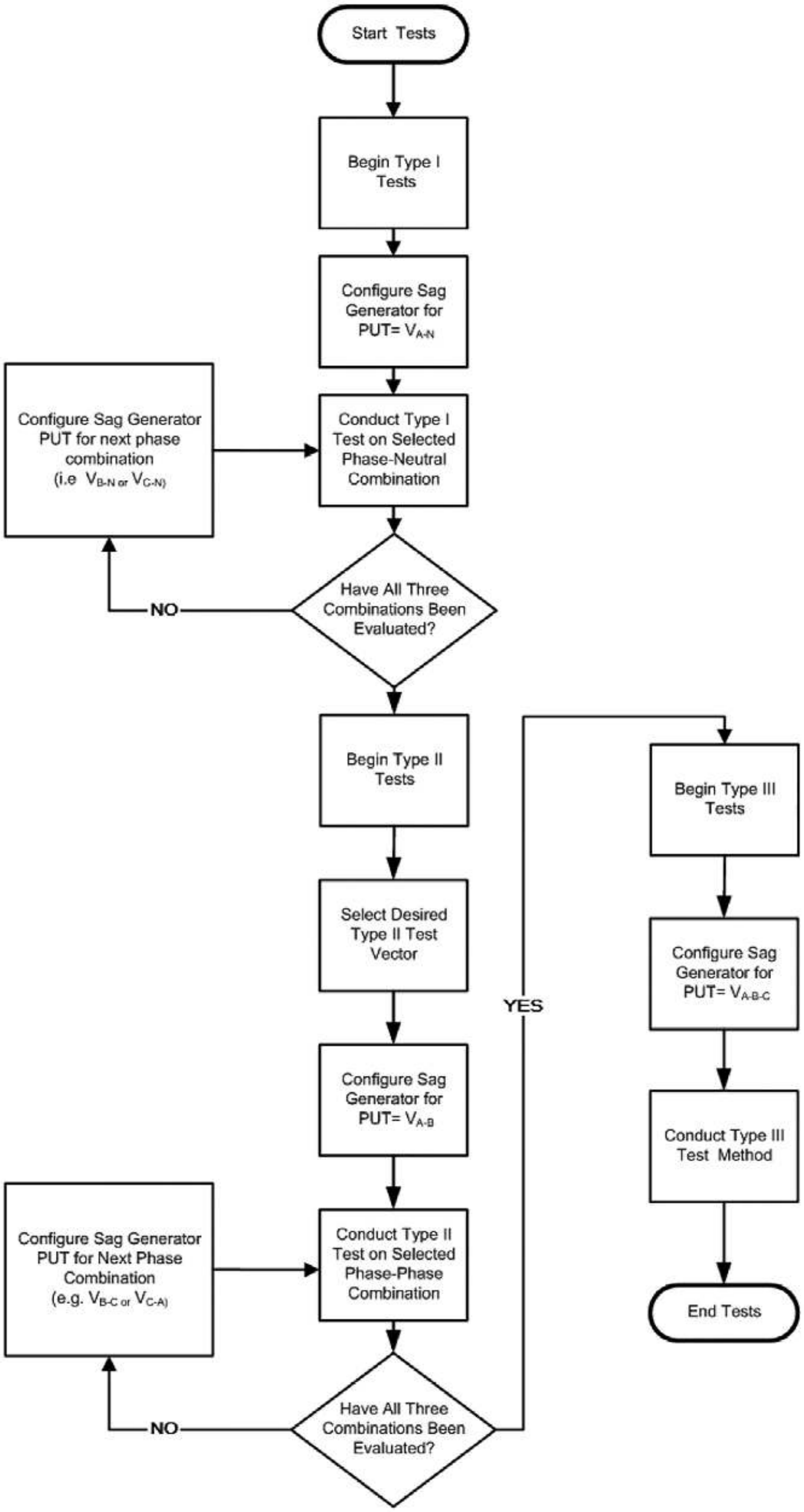

Figure A.12—Example of a three-phase voltage sag characterization procedure

Annex B

(normative)

Test equipment requirements

Generally, there are three designs of portable voltage-sag generators. A first design is frequently referred to as an amplifier type and includes a controller, a waveform generator, a data-acquisition system, and a power-amplification section. This waveform generator can simulate any point-on-wave and provide varying magnitude, duration, frequency, and harmonics, thereby allowing a user more precise control of the voltage-sag characteristics. The amplifier sag generator typically employs multiple power conversions—requiring transformer isolation—and is generally limited to low-power applications. A second form of sag generator for most high-power applications is the transformer type, which uses some form of switching. Contactors can be used, but typically cannot provide precise switching nor can they allow phase-angle control of sags. Hence, most such voltage-sag generators use electronic switches employing either an insulated gate bipolar transistor (IGBT), or a silicon controlled rectifier (SCR). A switching delay of up to a half-cycle can occur because the generator must switch at a zero crossover point to preclude switching transients. Various methods can be used to mitigate or eliminate switching delays. Perhaps the biggest disadvantage of the transformer type of portable sag generator is the substantial weight. A third form of sag generator is commonly referred to as the "impedance divider type", which uses a thyristor-controlled reactor to switch impedances for creating voltage sags. Generally, the impedance-divider sag generator weighs less than the other types of sag generators and provides maximum power.

Parameters of a sag generator include the following:

- A sag generator should be able to perform Type I, Type II, and Type III sags per this specification.
- Voltage output at no load is per 5.3 and should be ± 5% of the desired residual voltage.
- Voltage output during test is per 5.3 and should be ± 10% of desired residual voltage as measured per 1/2 cycle.
- The peak output current drive capability of the voltage-sag generator is a function of the load type. The generator should not inhibit the inrush current of the EUT.
- Instantaneous peak voltage overshoot/undershoot of the actual voltage for the generator loaded with a resistive load should be less than 5% of the test voltage.
- Voltage rise (and fall) times tr (and tf) in response to abrupt changes should be between 100 ms and 200 ms for resistive loads.
- The phase angle at which the voltage sag begins and ends should include a range of 0° to 360° and have a maximum resolution of 5°.
- The phase relationship of voltage sags with the power frequency should be less than ± 5%.
- Zero-crossing control of the generators should be less than ± 10°.
- The sampling rate shall be at least 10 kHz, and the data resolution should be at least 12 bits.
- The output configuration should be either wye or delta, as required by the test.
- The operating frequency of voltage should be 50 Hz or 60 Hz.

Annex C

(normative)

Certification and test reports

C.1 Certificates

A certificate indicating compliance to the requirements in this document should include, at a minimum, the following information:

a) The organization issuing the certificate
b) The EUT manufacturer, manufacturer address, and manufacturer primary phone contact information
c) The EUT model number and serial number
d) The test date
e) The test location
f) Any conditions of use for the certificate, such as voltage-range limitations, required modifications, process limitations, equipment configuration(s), and special/unusual installation requirements
g) The range of model numbers and/or serial numbers to which the certificate applies
h) The nominal voltage(s) and frequency(s) tested
i) The test equipment used, including a statement that test equipment fully complies with all requirements of this recommended practice
j) A reference to this specification, including publication date
k) The test conditions, including loading and process recipe information if applicable
l) The pass/fail decision with details related to the test levels, test procedures, or equipment specifications

C.2 Test reports

A test report indicating compliance to the requirements in this document should include, at a minimum, the following information:

a) All information required in C.1 for a certificate
b) The test plan
c) The identity of the engineers who performed or participated in the testing
d) The voltage and current waveforms for all phases, including pre-sag and post-sag data, for at least a single worst-case voltage sag (worst-case being defined by the largest current drawn by the EUT, either during or after a voltage sag)
e) The following is a complete list of all sags applied during the testing, including for each sag:
    1) the phase(s) to which the sag was applied
    2) the depth and duration of the sag
    3) the process state of the EUT
    4) the results of the sag

    5) any useful comments or observations during and after the sag

f) Photographs of the test setup, EUT, and environment

g) The rationale for the pass/fail decision, including detailed performance criteria

h) Any recommendations and/or conclusions that resulted from the testing

Annex D

(informative)

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