IEEE Guide for Voltage Sag Indices

IEEE Power and Energy Society

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Transmission and Distribution Committee

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IEEE Std 1564™-2014

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Transmission and Distribution Committee
of the
IEEE Power and Energy Society

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IEEE-SA Standards Board

Abstract: Appropriate voltage sag indices and characteristics of electrical power and supply systems as well as the methods for calculating them are identified. Methods are provided for quantifying the severity of individual voltage sag events, for quantifying the performance at a specific location (single-site indices), and for quantifying the performance of the whole system (system indices). Multiple methods are presented for each. The methods are appropriate for use in transmission, distribution, and utilization electric power systems.

Keywords: IEEE 1564™, power quality, power distribution faults, voltage sags

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Introduction

This introduction is not part of IEEE Std 1564™-2014, IEEE Guide for Voltage Sag Indices.

This guide provides methods for computing voltage sag indices and characteristics. Voltage sag indices are one way of quantifying the performance of electric power and supply systems. Voltage sag is a short-duration root-mean-square (rms) voltage variation associated with a reduction in voltage that may cause disruption of the operation of certain types of equipment. Voltage sags are due to short-duration increases in current, typically due to faults, motor starting, or transformer energizing. Voltage-sag events can occur at any location in the power system, with a frequency of occurrence between several times and hundreds of times per year.

This guide provides equivalent methods for computing indices and characteristics concerning voltage swells. A voltage swell is a short-duration increase in voltage. On multiphase systems, a voltage swell in one phase can be associated with a voltage sag in another phase. Some of the methods discussed will classify such an event as both a voltage sag and a voltage swell.

This guide presents methods for quantifying the severity of individual rms variation events, for quantifying the performance at a specific location (i.e., single-site indices), and for quantifying the performance of the whole system (i.e., system indices). Multiple methods are presented for each of these. This guide does not recommend the use of a specific set of indices because the large variation in customers sensitive to voltage sags and in network companies supplying them makes it impossible to prescribe a specific set of indices for all cases. Instead, this guide recommends the method for calculating specific indices when such an index is used. It aims to assist in the choice of index and to help ensure reproducibility of the results after a certain index has been chosen.

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1. Overview

1.1 Scope

This guide identifies appropriate voltage sag indices and characteristics on electrical power and supply systems as well as the methods for calculating them. Methods are provided for quantifying the severity of individual voltage sag events (single-event characteristics), for quantifying the performance of multiple events at a specific location (single-site indices), and for quantifying the performance of multiple events for the whole system (system indices). The methods are appropriate for use in 50/60 Hz transmission, distribution, and utilization electric power systems, though there may be applications to systems with other fundamental frequencies.

1.2 Purpose

This document identifies and defines different characteristics and indices associated with voltage sags. It does not recommend the use of a specific set of indices but instead recommends the method for calculating specific indices when such an index is used. The large variation in customer equipment's susceptibility to voltage sags and in power providers supply characteristics makes it impossible to prescribe a specific set of indices. Instead, this document aims to assist in the choice of index and to help ensure reproducibility of the results after a certain index has been chosen. The user of this document may decide to calculate the value for just one index or for a number of different indices, depending on the application.

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.

IEC 61000-2-8, Electromagnetic compatibility (EMC)—Part 2-8: Environment—Voltage dips and short interruptions on public electric power supply systems with statistical measurement results.[1]

IEC 61000-4-11, Electromagnetic compatibility (EMC)—Part 4-11: Testing and measurement techniques—Voltage dips, short interruptions and voltage variations immunity tests.

IEC 61000-4-30, Electromagnetic compatibility (EMC) - Part 4-30: Testing and measurement techniques–Power quality measurement methods.

IEEE Std 1159™, IEEE Recommended Practice for Monitoring Electric Power Quality.[2,3]

IEEE Std 1366™, IEEE Guide for Electric Power Distribution Reliability Indices.

3. 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.[4]

characteristic voltage (of a voltage sag): A single-event characteristic that combines the voltages in the three phases providing one single value corresponding to the sliding-window root-mean-square (rms) voltage as defined for single-phase recordings. The characteristic voltage is the lowest of the three per-unit phase-to-phase rms voltages, and the three per-unit phase-to-ground rms voltages after removing the zero-sequence component.

declared voltage: The nominal voltage or a value of a voltage different from the nominal voltage obtained by agreement between the electricity supplier and a consumer.

NOTE—See IEC 61000-4-30.[5, 6]

depth (of a voltage sag): The difference between the reference voltage (either V_{din} or V_{SR}) and the residual voltage. It is generally expressed in percentage of the reference voltage.

NOTE—See IEC 61000-4-30.

duration (of a voltage sag): The length of the interval between the time when the root-mean-square (rms) voltage drops below the sag threshold and the time it subsequently rises above the sag threshold.

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[5] Information on references can be found in Clause 2.
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duration (of a voltage swell): The interval between the time when the root-mean-square (rms) voltage rises above the swell threshold and the time it subsequently drops below the swell threshold.

event characteristic: A time-dependent parameter characterizing a change in voltage or current before, during, and after a voltage or current event. An event characteristic is a function of time. Event characteristics are used to detect the event, to determine the type of event, and to calculate event indices. Examples of event characteristics used for voltage sags are sliding-window root-mean-square (rms) voltage, voltage phase angle, and zero-sequence voltage (for three-phase measurements).

interruption threshold: A root-mean-square (rms) voltage value specified for the purpose of detecting the start and end of an interruption. The choice of the interruption threshold is outside of the scope of this document but should be much lower than the voltage sag threshold. Typical values are between 0% and 10% of the declared voltage or sliding-reference voltage.

NOTE—See IEC 61000-4-30.

magnitude (of a voltage sag): The minimum value of $V_{rms(1/2)}$ recorded during a voltage sag. The magnitude is expressed as a value in volts or as a percentage or per-unit value of the declared voltage or sliding-reference voltage.

magnitude (of a voltage swell): The maximum value of the sliding-window rms voltage $V_{rms(1/2)}$ recorded during a voltage swell. The magnitude is expressed as a value in volts or as a percentage or per-unit value of the declared voltage or the sliding-reference voltage.

retained voltage: *See:* **magnitude (of a voltage sag)**.

root-mean-square (rms) variation: A term often used to express a variation in the rms value of a voltage or current measurement from the nominal.

NOTE—See IEEE Std 1159.

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.

short-duration root-mean-square (rms) variation: A variation of the rms value of the voltage or current from the nominal for a time greater than 0.5 cycles of the power frequency but less than or equal to 1 min. When the rms variation is voltage, it can be further described using a modifier indicating the magnitude of a voltage variation (e.g., sag, swell, interruption) and possibly a modifier indicating the duration of the variation (e.g., instantaneous, momentary, temporary).

NOTE—See IEEE Std 1159.

single-event characteristic: A parameter indicating the severity of a voltage or current event, or otherwise describing the event. Each type of event has specific single-event characteristics. The most commonly used single-event characteristics for voltage sags and swells are magnitude and duration.

single-site index: A parameter indicating the voltage or current quality or a certain aspect of voltage or current quality at a specific site. Single-site indices typically give the monitored or expected count or rate of events within a given period. The term “index” may be used where its meaning is clear from the context.

sliding-reference voltage: A voltage magnitude averaged over a specified time interval, representing the voltage preceding a voltage sag.

NOTE—See IEC 61000-4-30.

sliding-window rms voltage: The value of the rms voltage measured over one cycle and refreshed each half cycle.

system index: A parameter indicating the voltage or current quality or a certain aspect of voltage or current quality for a whole or part of a power system. System indices may be an average or a weighted average of the single-site indices obtained for all or a number of sites within the system. The term “index” may be used where its meaning is clear from the context.

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

voltage sag energy: A single-event characteristic defined from the rms voltage versus time. The voltage sag energy has the unit of time; it may be expressed in cycles, milliseconds, or seconds.

$$E_{VS} = \int_0^T \left[1 - \left\{ \frac{V(t)}{V_{nom}} \right\}^2 \right] dt$$

voltage sag severity: A single-event characteristic defined from the per-unit magnitude and the duration of a voltage sag by comparing them with a reference curve.

$$\mathrm{S}_e = \frac{1 - \mathrm{V}}{1 - \mathrm{V}_{curve}(d)}$$

voltage sag table: A representation of the values of a site or system indices in the form of a table with columns and rows corresponding to ranges in duration (*d*) and magnitude, respectively. The value in each cell in the table indicates the count of voltage sags at a given site, or in a given system, per year with magnitude and duration within the ranges corresponding to the column and row.

voltage sag threshold: An rms voltage value specified for the purpose of detecting the start and end of a voltage sag. Typical values are between 90% and 95% of the declared voltage or sliding-reference voltage.

NOTE—See IEC 61000-4-30.

voltage sag: A temporary reduction of the rms voltage at a point in the electrical system below a threshold. The choice of this threshold depends on the application and is outside of the scope of this guide. The term “sag” may be used instead of “voltage sag” where its meaning is clear from the context.

voltage swell threshold: An rms voltage value specified for the purpose of detecting the start and the end of a voltage swell. Typical values are between 110% and 180% of the declared voltage or sliding-reference voltage.

NOTE—See IEC 61000-4-30.

voltage swell: A short-duration increase of the voltage at a point in the electrical system above a threshold. The term “swell” may be used instead of “voltage swell” where its meaning is clear from the context.

NOTE—See IEC 61000-4-30.

$\mathbf{V_{rms(1/2)}}$: *See:* **sliding-window rms voltage**.

4. Procedure summary

To give a value to the performance of a power system in terms of voltage sags, this guide recommends a five-step procedure:

a) Obtain sampled voltages with a specified sampling rate and resolution.

b) Calculate event characteristics as a function of time from the sampled voltages.

c) Calculate single-event characteristics from the event characteristics.

d) Calculate site indices from the single-event indices of all events measured during a certain period of time.

e) Calculate system indices from the site indices for all sites within a certain power system.

These five steps are discussed in more detail in the remaining clauses of this document. The basic algorithm is shown in Figure 1, where both measurements and calculations are indicated as possible sources of information. Detailed simulations will be able to give voltage waveshape as a function of time, equivalent to sampled voltages obtained from measurements. Any discussion about the accuracy of simulation results is beyond the scope of this document. Simple calculations may be able to provide approximations for the single-event indices. It is important to enable such calculations to help enable a wide use of the indices. An example of an appropriate single-event characteristic is retained voltage and duration for a system fault. The magnitude can be estimated from a power-frequency complex-network theory model; the duration can be obtained from the fault-clearing time.

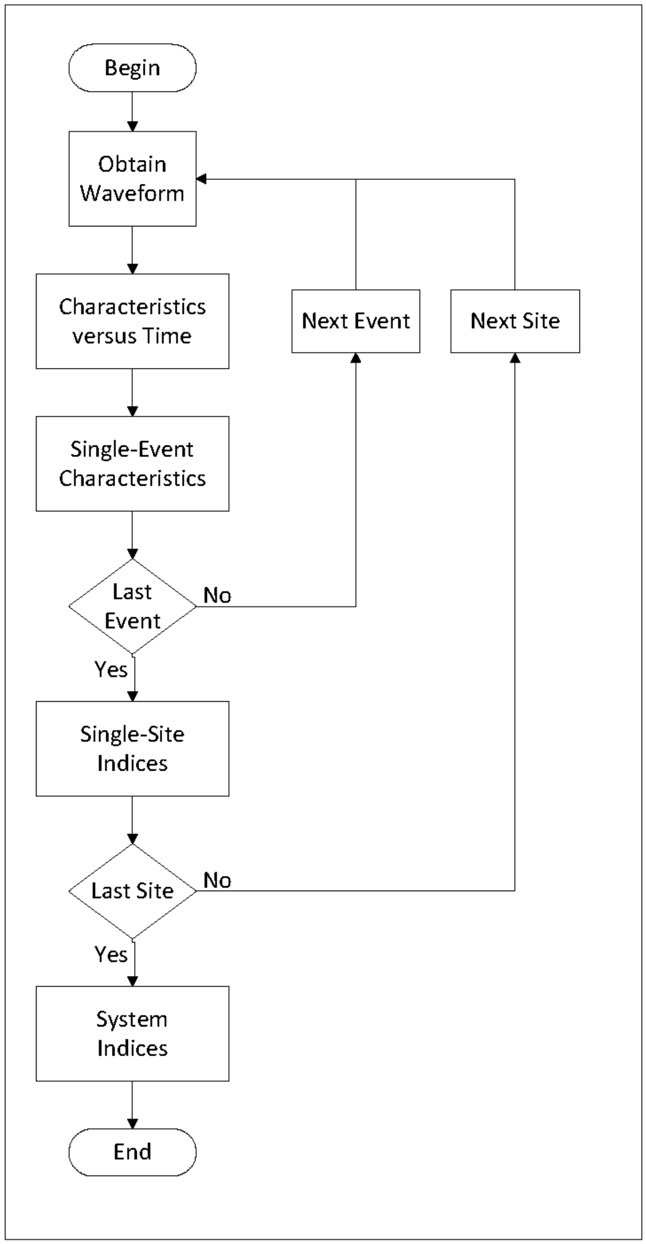

Figure 1—The procedure for obtaining voltage sag-system indices

5. Single-Event characteristics

5.1 General

One or more characteristics as a function of time are calculated from the sampled voltages. Most voltage-sag monitoring configurations include measurements in three-phase systems. In that case, three voltage waveforms are recorded. Some monitors also measure the neutral-to-ground voltage. This neutral-to-ground voltage should not be used for voltage sag indices.

From the sampled waveforms in the three phases, one or three voltage magnitudes as a function of time are obtained. For single-channel measurements and multichannel measurements, the rms voltage is computed over one cycle and is updated every half cycle. This quantity is known as $V_{rms(1/2)}$. For three-phase measurements, either the minimum $V_{rms(1/2)}$ is used to characterize the event, or the characteristic voltage is used. These time functions are used to determine the following single-event indices: retained voltage, depth, and duration.

In addition to the two-index method (retained voltage or depth and duration), two single-index methods will be introduced later in this guide: the voltage sag energy (see 5.4) and the voltage sag severity (see 5.5). In both cases, the severity of each event is quantified by one single value.

5.2 RMS voltage as a function of time

5.2.1 Definition

From the sampled voltages, one or more characteristics as a function of time are calculated for every recording. Most sensors use the rms voltage as a function of time as the only event characteristic. This function is used to determine the retained voltage and the duration of the event. The rms voltage is calculated over a one-cycle interval and is updated every half cycle.

To calculate the rms voltage, the sampled voltages are squared and averaged over a window with a one-cycle duration, as in Equation (1):

$$\mathrm{V}_{\mathrm{rms}(1/2)}(k)=\sqrt{\frac{1}{\mathrm{N}}\sum_{i=1+k-\mathrm{N}}^{k}\mathrm{v}_i^2} \tag{1}$$

where

N is the number of samples per cycle
v_i is the sampled voltage waveform
k is 1,2,3, etc.

The sampling should be synchronized to the power frequency. That is, the sampling frequency is not a fixed number of samples per second but a fixed number of samples per cycle. This synchronization to the power frequency (also referred to as “phase-locked-loop”) is essential for the quantification of harmonic distortion and phase angle change calculations. For rms voltage, the difference between synchronized and nonsynchronized measurements is small.

For multichannel measurements, the rms voltage versus time is calculated for each channel separately.

5.2.2 Example

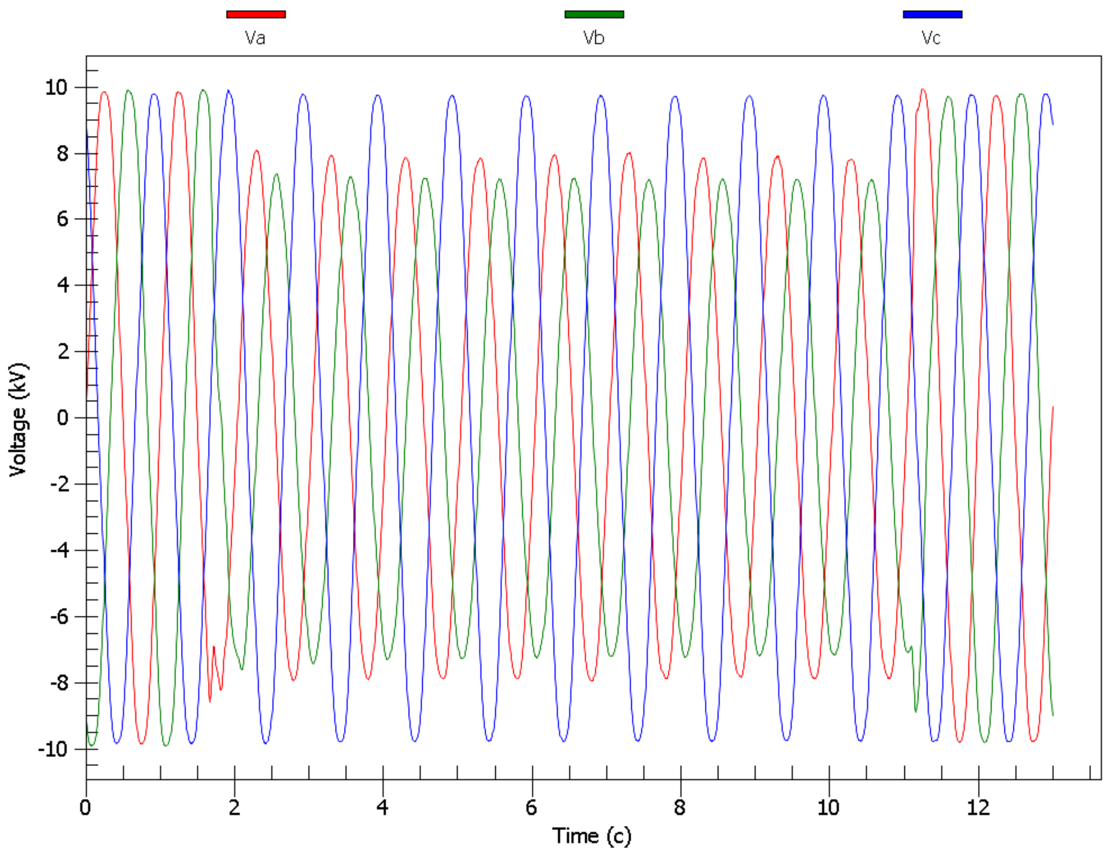

Figure 2—Voltage sag example: Two-phase voltage waveform samples

Figure 2 shows an example of a voltage sag in the three phases. Two of the three phases show a drop in voltage. The voltages were measured at a substation with a line-line declared voltage of 12.47 kV. The cause of the event was a phase-to-phase fault downline on a feeder from the monitored substation.

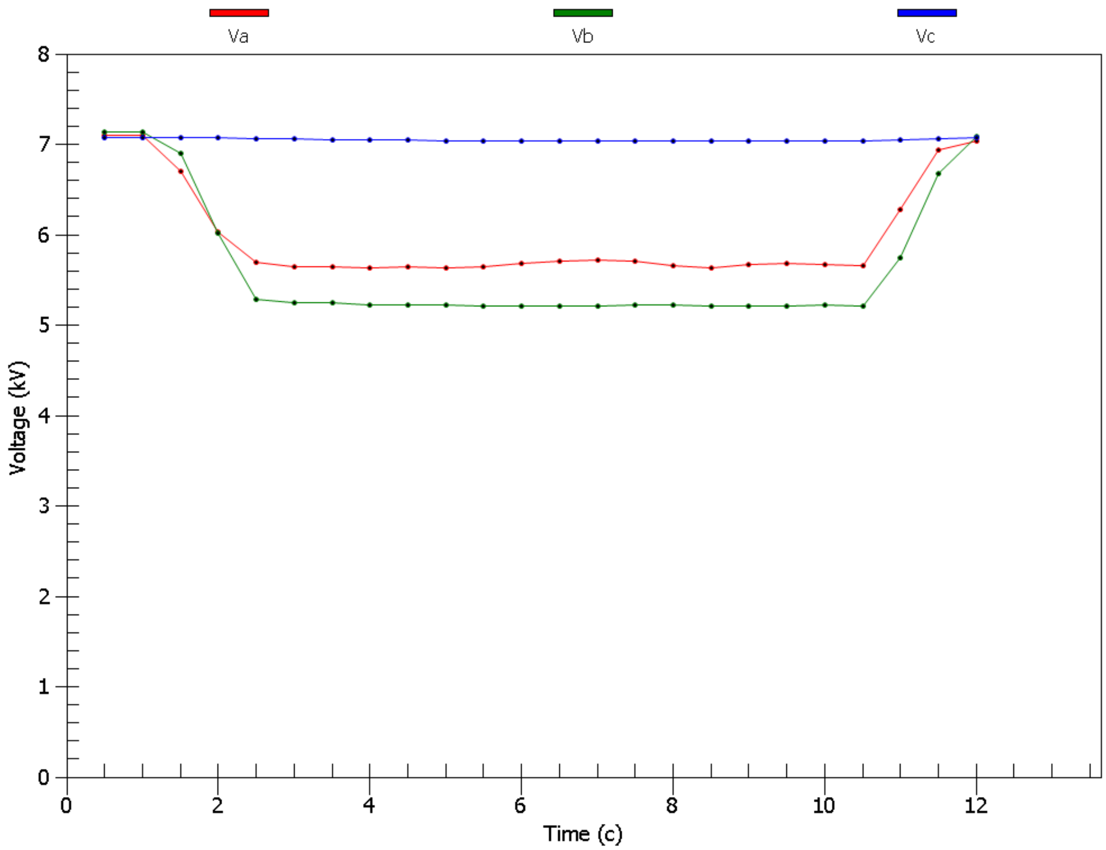

Figure 3—Voltage sag example: Three-phase voltage rms samples

Figure 3 presents the rms samples versus time for the event shown in Figure 2. The markers indicate the values updated every half cycle. The minimum rms voltage was measured on phase B and was 5.21 kV, or 72.4% of the phase-neutral declared voltage of 7.2 kV.

5.3 Retained voltage and duration

5.3.1 Definitions

A voltage sag or voltage swell should be characterized by its duration and its retained voltage. The duration is the time that the rms voltage stays below the threshold. The retained voltage is the lowest rms voltage during the event. Instead of retained voltage, the depth may be used, which is the difference between the retained voltage and a reference or declared voltage.

To determine the duration of the sag, a threshold setting is needed. This threshold can be defined in multiple ways, such as a percentage of the nominal voltage, a percentage of the long-term average voltage at the location, or a percentage of the rms voltage just prior to the beginning of the event.

For measurements in low-voltage and medium-voltage networks, the declared or nominal voltage should be used. This value is the most relevant one for the performance of end-use equipment. In low-voltage networks, the nominal voltage should be used in all cases. In medium voltage networks, a different declared voltage may be used to incorporate the turns ratio of the step-down transformers.

For measurements in transmission systems, it may be more appropriate to use the pre-event voltage. The nominal voltage at the terminals of the end-use equipment is often regulated by automatic tap changers on distribution systems. Therefore, when measurements are obtained on the transmission system, the pre-event voltage is often the best voltage reference to calculate the retained voltage. This issue is discussed in further detail in Annex A.

For pre-fault voltage, the International Electrotechnical Commission (IEC) uses the "sliding-window reference" in IEC 61000-4-30. This is calculated from 10-cycle or 12-cycle rms voltages using a first-order filter with a 1-min time constant. Ten-cycle windows are used in systems with a nominal line frequency of 50 Hz, and 12-cycle windows are used in systems with a nominal line frequency of 60 Hz. This is represented by Equation (2):

$$\mathrm{V}_{\mathrm{SR}}(n) = 0.9967 \cdot \mathrm{V}_{\mathrm{SR}}(n-1) + 0.0033 \cdot \mathrm{V}_{(10/12)\mathrm{rms}} \quad (2)$$

where

V_{SR} is the sliding-reference voltage
$\mathrm{V}_{(10/12)\mathrm{rms}}$ is the most recent 10/12 cycle rms value

Different threshold values may be used for obtaining the starting and ending instants of the sag. The ending threshold could be higher than the starting threshold by an amount that is referred to as the "hysteresis voltage." In that case, the voltage sag would begin when $\mathrm{V}_{\mathrm{rms}(1/2)}$ fell below the sag threshold, and end when $\mathrm{V}_{\mathrm{rms}(1/2)}$ was equal to or above the sag threshold plus the hysteresis voltage.

The recommended value for the starting threshold is 90% of the declared voltage or of the sliding-reference voltage. In case in which a different ending threshold is used, the recommended value is 91% of the declared voltage or of the sliding-reference voltage.

Voltage swells can be characterized in the same way as voltage sags. The rms voltage is again used as a characteristic versus time. The single-event indices are the duration and the retained voltage. The duration equals the amount of time the rms voltage is above the swell threshold. The retained voltage is the highest value of the rms voltage. The recommended value for the swell threshold is 110% of the declared voltage or of the sliding-reference voltage.

Voltage sags with a retained voltage below the interruption threshold can be classified as momentary or temporary interruptions. The duration of the event is the amount of time the rms voltage is below the sag threshold. Alternatively the duration of an interruption can be defined as the amount of time the rms voltage is below the interruption threshold. The difference between these two definitions is normally small compared to the duration of the interruption.

The recommended value of the interruption threshold is 10% of the declared voltage or of the sliding-reference voltage.

5.3.2 Example

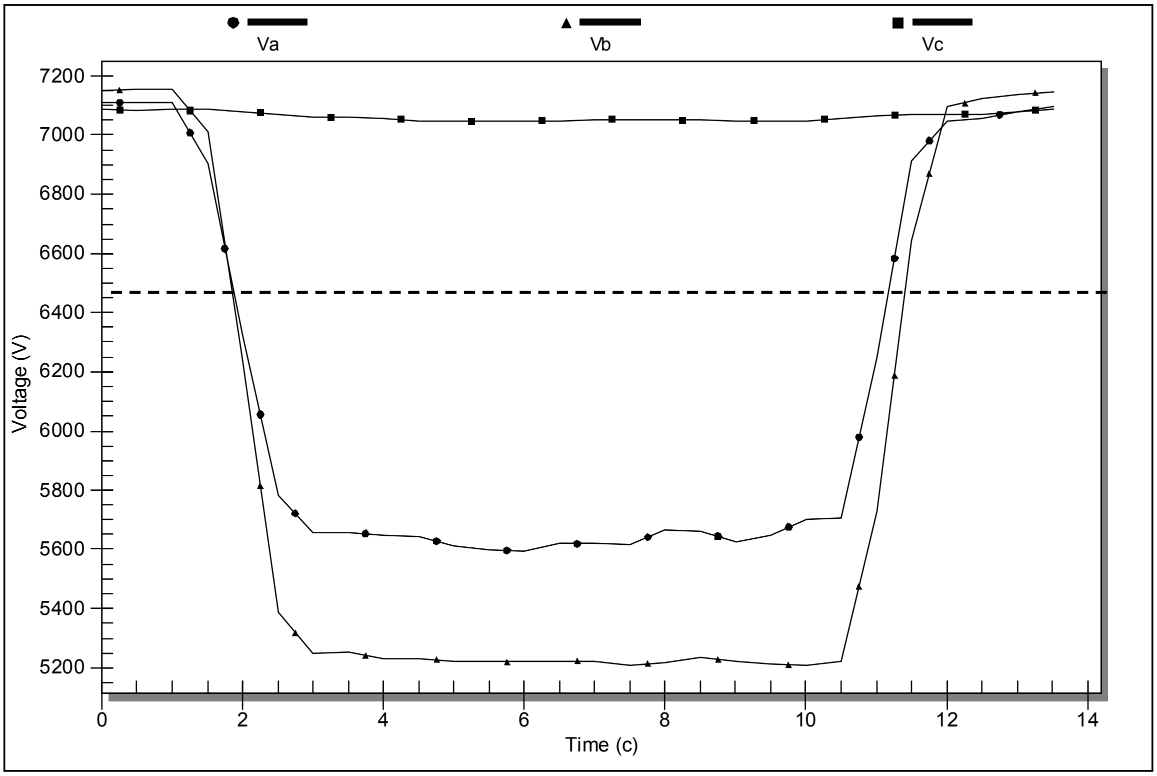

Figure 4—Voltage sag example: Three-phase voltage rms samples with sag threshold

Figure 4 presents the same voltage sag from Figure 3, but with a dashed line that indicates the voltage sag threshold, which is chosen as 90% of the phase-neutral base voltage of 7.2 kV. Considering the three phases individually, two phases show voltage sag of 9.5 cycles duration below the threshold. The retained voltage is 5.21 kV for phase B.

5.4 Voltage sag energy index

The voltage sag energy characteristic, E_{VS}, is defined in Equation (3):

$$\mathrm{E}_{VS} = \int_0^T \left[1 - \left\{ \frac{\mathrm{V}(t)}{\mathrm{V}_{nom}} \right\}^2 \right] dt \tag{3}$$

where

$\mathrm{V}(t)$ is the rms voltage during the event
V_{nom} is the nominal voltage

The integration is taken over the duration of the event; that is, for all values of the rms voltage below the threshold. Note that the rms voltage can be expressed in any unit (e.g., volt, kilovolt, per unit) as long as the nominal voltage is expressed in the same unit. The voltage sag energy has the unit of time; it may be expressed in cycles, milliseconds, or seconds.

When the rms voltage is defined as recommended in 5.2.1, the one-cycle rms voltage updated every half-cycle $V_{rms(1/2)}$, the expression for the voltage sag energy becomes Equation (4):

$$E_{vs} = \frac{1}{2f_0} \sum_{k=1}^{N} \left[1 - \left\{ \frac{V_{rms(1/2)}(k)}{V_{nom}} \right\}^2 \right] \tag{4}$$

where

f_0 is equal to the power frequency

The sum is taken over the duration of the event (that is, for all values of the rms voltage below the threshold).

For cases in which only the retained voltage and duration of an event are available, the rms voltage is assumed to be constant over the duration of the event. This results in the Equation(5) expression for the voltage sag energy:

$$E_{VS} = \left[1 - \left(\frac{V}{V_{nom}} \right)^2 \right] \cdot T \tag{5}$$

where

T is the duration
V is the retained voltage of the event

For example, a voltage sag with a magnitude of 0.75 pu of nominal voltage and four cycles duration (0.0667 s, for a 60-Hz system) will have the following voltage sag energy:

$$E_{VS} = \left[1 - 0.75^2 \right] \cdot 0.0667\,\text{s} = 0.0292\,\text{s or } 29.2\,\text{ms or } 1.75\,\text{cycles}$$

The voltage sag energy is the duration of an interruption that would result in the same loss of energy for an impedance load.

The voltage sag energy, E_{VS}, can be interpreted as the energy (or lack of it) in the voltage sag event. Consider a constant-impedance load with active power consumption P_0 at nominal voltage V_{nom}. As shown in Equation (6), when the voltage drops to V during a sag, the active power consumption by the load drops to the following:

$$P = \left(\frac{V}{V_{nom}} \right)^2 \cdot P_0 \tag{6}$$

As shown in Equation (7), the reduction in delivered power, ΔP, is the following:

$$\Delta \mathrm{P} = \mathrm{P}_0 \left[1 - \left(\frac{\mathrm{V}}{\mathrm{V}_{nom}} \right)^2 \right] \tag{7}$$

Integration over the duration T of the voltage sag gives the expression in Equation (8) for the energy not delivered:

$$\Delta \mathrm{E} = \int_0^{\mathrm{T}} \Delta \mathrm{P} dt = \mathrm{P}_0 \int_0^{\mathrm{T}} \left[1 - \left(\frac{\mathrm{V}(t)}{\mathrm{V}_{nom}} \right)^2 \right] dt \tag{8}$$

Using the definition of voltage sag energy, Equation (9) is obtained:

$$\Delta \mathrm{E} = \mathrm{P}_0 \mathrm{E}_{vs} \tag{9}$$

Thus, the voltage sag energy is proportional to the energy not delivered to an impedance load, expressed in per-unit with the rated power of the load as a base.

For voltage sags involving more than one phase, the voltage sag energy is defined as the sum of the voltage sag energy in the individual channels, as shown in Equation (10).

$$\mathrm{E}_{VS} = \left(\mathrm{E}_{VS,A} + \mathrm{E}_{VS,B} + \mathrm{E}_{VS,A} \right) \tag{10}$$

If it is a three-phase sag, and all phases are 0.1 pu with a 15-cycle duration, E_{VS} will be 74.25 ms.

In cases in which a three-phase approach is used, the voltage sag energy may be calculated from the characteristic voltage as a function of time, with V*(t)* the characteristic voltage as a function of time.

It is not recommended to apply this method to short-duration interruptions, as the resulting value for one short-duration interruption is likely to dominate all voltage sags for the whole measurement period. This will result in rather inflated values for the site and the system indices calculated from the voltage sag energy.

The voltage swell energy can be defined in the same way as the voltage sag energy. Equation (11) defines the voltage swell energy as follows:

$$\mathrm{E}_{VS} = \int_0^{T} \left[\left\{ \frac{\mathrm{V}(t)}{\mathrm{V}_{nom}} \right\}^2 - 1 \right] dt \tag{11}$$

where

$V(t)$ is the voltage magnitude during the event
V_{nom} is the nominal voltage

The integration is taken over the duration of the swell; i.e., as long as the rms voltage exceeds the swell threshold (recommended to be 110%). Using the rms voltage definition in 5.2.1, Equation (12) results as an expression for the voltage swell energy:

$$E_{VS} = \frac{1}{2f_0} \sum_{k=1}^{N} \left[\left\{ \frac{U_{rms(1/2)}(k)}{V_{nom}} \right\}^2 - 1 \right] \tag{12}$$

where

f_0 is the power frequency

The sum is taken over the duration of the event (that is, for all values of the rms voltage above the threshold).

For cases in which only retained voltage and duration of a voltage swell are available, the rms voltage is assumed to be constant over the duration of the event. This results in Equation (13) as an expression for the voltage swell energy:

$$E_{VS} = \left[\left(\frac{V}{V_{nom}} \right)^2 - 1 \right] \cdot T \tag{13}$$

where

T is the duration
V is the retained voltage of the voltage swell

For a voltage swell with retained voltage of 123% and a duration of 230 ms, the voltage swell energy is as follows:

$$E_{VS} = \left[\left(\frac{123\%}{100\%} \right)^2 - 1 \right] \cdot 230\ \text{ms} = 118\ \text{ms}$$

To limit the value of the voltage sag energy, a maximum duration may be chosen. For an event with a duration longer than this maximum duration, the voltage sag energy or voltage swell energy is calculated with T equal to the maximum duration. This should be clearly indicated in the presentation of the results.

5.5 Voltage sag severity

The voltage sag severity is calculated from the retained voltage in per unit and the duration of a voltage sag in combination with a reference curve. This guide recommends using the Information Technology Industry Council (ITI) or Semiconductor Equipment and Materials International Group (SEMI) F47 curve as a reference, but the method works equally well with other reference curves. (See the 2000 ITI curve application note [B11][7] and SEMI F47-0706 [B17].)

The event voltage sag severity is calculated as shown in Equation (14):

$$S_e = \frac{1 - V}{1 - V_{curve}(d)} \tag{14}$$

where

V is the voltage sag magnitude
d is the event duration
$V_{curve}(d)$ is the magnitude value of the reference curve for the same duration

For an event on the reference curve, the voltage sag severity equals one; for an event above the curve, the index is less than one; for an event below the curve, the index is greater than one. For events with a magnitude above the voltage sag threshold (with 90% being the recommended value), the voltage sag severity is equal to zero.

The method is further explained in Figure 5. Events with longer event durations and lower magnitudes will have larger values of voltage sag severity index.

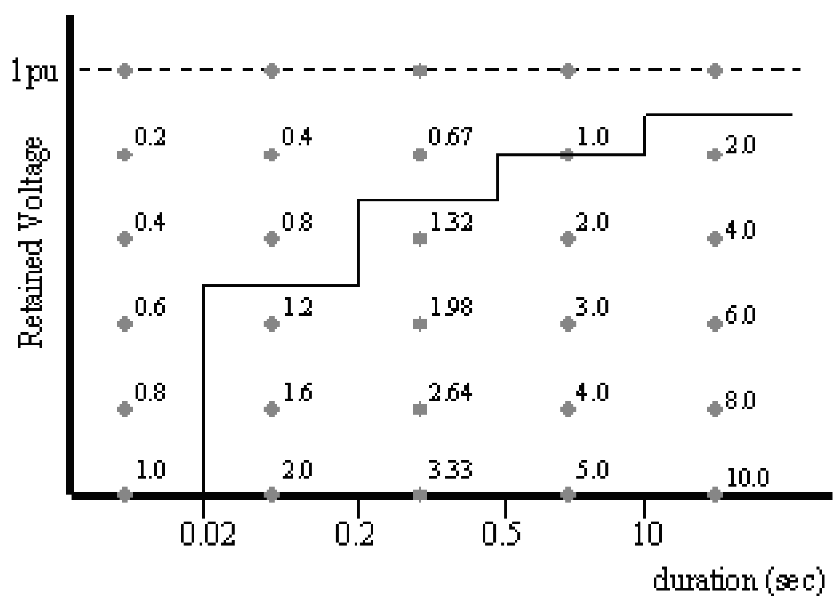

Figure 5—Voltage sag severity with reference to the SEMI F47 curve

Using the SEMI curve as a reference, Table 1 gives the following algorithm for calculating the voltage sag severity from the magnitude V and the duration d:

[7] The numbers in brackets correspond to those of the bibliography in Annex F.

Table 1—Algorithm for calculating voltage sag severity with reference to the SEMI F47 curve

Duration range	Calculation of voltage sag severity
$d \le 20\ \text{ms}$	$\text{S}_e = 1 - \text{V}$
$20\ \text{ms} < d \le 200\ \text{ms}$	$\text{S}_e = 2(1 - \text{V})$
$200\ \text{ms} < d \le 500\ \text{ms}$	$\text{S}_e = 3.3(1 - \text{V})$
$500\ \text{ms} < d \le 10\ \text{s}$	$\text{S}_e = 5(1 - \text{V})$
$d > 10\ \text{s}$	$\text{S}_e = 10(1 - \text{V})$

Table 2 gives some examples of the results of these calculations, where the sag threshold has been set at 90% for calculating the voltage sag severity:

Table 2—Example of calculation of voltage severity

Duration (ms)	Magnitude (pu)	Severity
180	0.73	0.54
1640	0.00	5.00
30	0.65	0.70
85	0.92	0.16
95	0.49	1.02
680	0.67	1.65
190	0.86	0.28
12 000	0.00	10.00

In this example, short-duration interruptions are treated in the same way as voltage sags. It is also possible to use a different index for short-duration interruptions than for voltage sags (for example, as defined in IEEE Std 1366).

The voltage swell severity can be defined for voltage swells in a similar way. However, this guide recommends treating voltage sags and swells as separate events. A voltage sag and a voltage swell with the same severity should not be expected to have the same effect on equipment.

5.6 Multichannel and three-phase measurements

For multichannel measurements, the voltage sag magnitude (retained voltage) is the lowest magnitude for the individual phases. The start time of the sag is the time at which the rms voltage in one of the phases drops below the sag-starting threshold. The ending time of the sag is the time at which all rms voltages have recovered above the sag-ending threshold. The duration is obtained as the time difference between the start time and the stop time. Note that the event may end in a different phase as the one in which it started.

The same result is obtained by defining a multichannel sliding-window rms voltage at any instant as the lowest of the sliding-window rms voltages in the different phases. The duration of the multichannel event is defined as the time during which the multichannel sliding-window rms voltage is below the threshold.

For the event shown in Figure 4, the magnitude of the multichannel measurement would be 5.21 kV and its duration would be 9.5 cycles.

For cases in which only magnitude and duration in the different channels are available, then the lowest magnitude and the longest duration are used to characterize the multichannel event.

5.7 Characteristic voltage

A characteristic voltage as a function of time may be obtained from the three sampled waveforms in the three phases. The characteristic voltage is obtained in the following method:

The three sampled voltage phase-to-ground waveforms, $V_a(t)$, $V_b(t)$, and $V_c(t)$, are used as the starting point.

The zero-sequence voltage is obtained as the average of the three voltages, as shown in Equation (15):

$$V_0(t) = \frac{V_a(t) + V_b(t) + V_c(t)}{3} \tag{15}$$

Three reduced voltages are obtained by subtracting the zero-sequence voltage from the three voltages as shown in Equation (16), Equation (17), and Equation (18):

$$V_{a'}(t) = V_a(t) - V_0(t) \tag{16}$$

$$V_{b'}(t) = V_b(t) - V_0(t) \tag{17}$$

$$V_{c'}(t) = V_c(t) - V_0(t) \tag{18}$$

The difference voltages are obtained as shown in Equation (19), Equation (20), and Equation (21):

$$V_{ab}(t) = \frac{V_a(t) - V_b(t)}{\sqrt{3}} \tag{19}$$

$$V_{bc}(t) = \frac{V_b(t) - V_c(t)}{\sqrt{3}} \tag{20}$$

$$V_{ca}(t) = \frac{V_c(t) - V_a(t)}{\sqrt{3}} \tag{21}$$

Using Equation (1), six sliding-window rms voltages are obtained from the three reduced voltages using Equation (16), Equation (17), and Equation (18) and the three difference voltages using Equation (19), Equation (20), and Equation (21). The lower characteristic voltage is the smallest of the six sliding-window rms voltages. Not shown is the upper characteristic voltage, which is the largest of the six sliding-window rms voltages.

Analyzing the event shown in Figure 2 as a three-phase event results in the characteristic voltage as shown in Figure 6. The lower characteristic voltage has been calculated as the lowest value of the six rms voltages. As before, the calculation has been updated every half cycle. The resulting duration of the three-phase event is again 9.5 cycles, but the remaining (characteristic) voltage is 4.68 kV or 65.0% of the phase-neutral base voltage of 7.2 kV. (See Bollen 2002 [B2] and Bollen and Styvaktakis. [B4].)

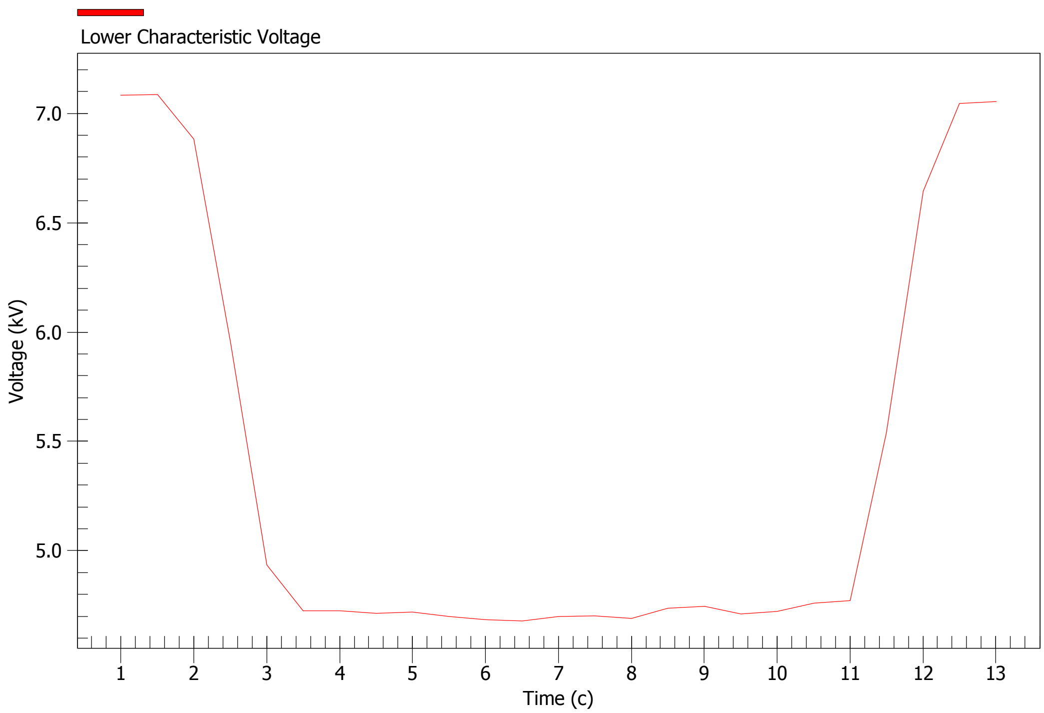

Figure 6—Characteristic voltage as a function of time

6. Site indices

6.1 General

As input to the site indices, the single-event characteristics are used as obtained from all events recorded at a given site over a given period, typically one month or one year. The clauses that follow present a number of alternatives for the two-index method. Each alternative can be summarized as a count of events within a certain range of retained voltage and duration. For single-index methods, the site index is the sum of the single-event indices of all events recorded within the given period.

When publishing site indices, it is important to indicate which method has been used to obtain the single-event characteristics: for example, the lowest of the three phase-to-ground voltages, the lowest of the three phase-to-phase voltages, or the characteristic voltage obtained from three-phase measurements.

6.2 SARFI indices

System Average RMS Variation Frequency Index (SARFI) is a power-quality index that provides a count or rate of voltage sags, swells, and/or interruptions for a system. The size of the system is scalable: it can be defined as a single monitoring location, a single customer service, a feeder, a substation, a group of substations, or an entire power delivery system. There are two types of SARFI indices: SARFI-X and SARFI-Curve. In this clause, SARFI is used as a single-site index (a one-site system). In the next clause, it is used as a system index. The index provides how many (annual) events there are when the magnitude of a voltage sag is below a specified threshold.

is used as a system index. The index provides how many (annual) events there are when the magnitude of a voltage sag is below a specified threshold.

6.2.1 SARFI-X

SARFI-X corresponds to a count or rate of voltage sags, interruptions, and/or swells below or above a specified voltage threshold. For example, SARFI-90 considers voltage sags and interruptions that are below 0.90 per unit, or 90% of the reference voltage. SARFI-70 considers voltage sags and interruptions that are below 0.70 per unit, or 70% of the reference voltage. SARFI-110 considers voltage swells that are above 1.1 per unit, or 110% of the reference voltage. The SARFI-X indices are meant to assess short-duration rms variation events only, meaning that the only events included in its computation are those with durations less than the minimum duration of a sustained interruption as defined by IEEE Std 1159, which is 1 min.

6.2.2 SARFI-Curve

SARFI-Curve corresponds to a rate of voltage sags below an equipment compatibility curve. For example, SARFI-CBEMA considers voltage sags and interruptions that are below the lower Computer Business Equipment Manufacturers Association (CBEMA) curve (CBEMA is now the ITI).[8] SARFI-ITIC considers voltage sags and interruptions that are below the lower ITIC curve. SARFI-SEMI considers voltage sags and interruptions that are below the lower SEMI curve. Again, these curves limit the duration of an rms variation event to the minimum duration of a sustained interruption as defined by IEEE Std 1159, which is 1 min.

6.3 Voltage sag tables

A commonly used method of presenting the performance of a site is by means of a voltage sag table. The columns of the tables represent ranges of voltage sag duration, while the rows represent ranges of retained voltage. Each cell in the table gives the number of events with the corresponding range of retained voltage and duration. Each event (that is, each combination of retained voltage and duration) is tabulated in only one cell of the table. Different values are in use for the boundaries between the cells. Some possible table choices are presented in 6.3.1, 6.3.2, and 6.3.3. In each example, a maximum voltage sag duration of 1 min has been used, which is consistent with the minimum duration of a sustained interruption as defined by IEEE Std 1159. (Note that IEEE Std 1366 uses a minimum of 5 min for a sustained interruption instead, since the recommended practice has a reliability context. The context of IEEE Std 1159 is power quality.)

In the example voltage sag tables below, the retained voltage is expressed in percent, but it may also be expressed in volts. The duration should be expressed in milliseconds, seconds or minutes, with the exception of the first column, for cases in which the maximum duration is one cycle.

A voltage sag table can be used as a system index as well as a site index. Strictly speaking, a voltage sag table is not an index but a way of presenting a set of indices. Each element in the table can be used as an index, just as there are multiple choices for the SARFI indices.

A distinction between short-duration interruptions and other voltage sags is made already when defining the range of retained voltages. In cases in which short-duration interruptions are treated differently from other voltage sags, the lower row of the table should start at 1% or 10%.

Measured voltage sags may have a duration or magnitude value that corresponds exactly with the border between two cells. These events should be placed in a cell according to recommendation in IEEE Std 493™ (IEEE Gold Book™): a voltage sag with characteristics on the border between two cells will be added to

[8] CBEMA was the Computer Based ITIC, Information Technology Industry Council.

6.3.1 UNIPEDE table

A commonly used way of presenting voltage sag frequencies is the “UNIPEDE table” (see Table 3) recommended by the International Union of Producers and Distributors of Electrical Energy in Europe (UNIPEDE). In the original UNIPEDE table, the bottom row is further subdivided into a row for retained voltage 1% –10% and a row for retained voltage less than or equal to 1% (see UNIPEDE 1995 [B20]). This guide does not recommend this subdivision.

Table 3—Recommendation by UNIPEDE for cross-tabulation table of retained voltage and duration

Retained voltage	Duration of the voltage sag						
	<1 cycle	1 cycle–0.1 s	0.1 s–0.5 s	0.5 s–1 s	1 s–3 s	3 s–20 s	20 s–60 s
85%–90%							
70%–85%							
40%–70%							
10%–40%							
≤10%							

6.3.2 IEC 61000-4-11 table

IEC 61000-4-11 Ed. 2.0 recommends the following duration values for the testing of equipment against voltage sags and short interruptions: 0.5 cycle, 1 cycle, 10/12 cycles (200 ms), 25/30 cycles (500 ms), and 250/300 cycles (5 s); and the following magnitude values: 0%, 40%, and 70%. Use of these values as the borders between cells results in the voltage sag table shown in Table 4. Note that 0% has been replaced by the more practical value of 10%.

Table 4—Voltage sag table from IEC 61000-4-11

magnitude	Duration of the voltage sag				
	< 1 cycle	1 cycle–200 ms	200 ms–500 ms	0.5 s–5 s	≥5 s
70%–80%					
40%–70%					
10%–40%					
≤10%					

6.3.3 IEC 61000-2-8 table

The voltage sag table proposed in IEC 61000-2-8 is shown in Table 5. It differs from the UNIPEDE table mainly in the higher resolution in the remaining voltage ranges. There is also an additional duration range with 250 ms as a limit.

Table 5—Voltage sag table from draft IEC61000-2-8

	< 0.1 s	0.1 s–0.25 s	0.25 s–0.5 s	0.5 s–1 s	1 s–3 s	3 s–20 s	20 s–60 s	1 min–5 min
80%–90%								
70%–80%								
60%–70%								
50%–60%								
40%–50%								
30%–40%								
20%–30%								
10%–20%								
≤10%								

6.4 Voltage sag energy

The sag energy method of characterization uses three site indices: number of events per site, total lost energy per site and average lost energy per event.

The sag energy index (SEI) is the sum of the voltage sag energies for all qualified events at a given site during a given period, as shown in Equation (22). The indices are usually calculated monthly and annually.

$$\mathrm{SEI} = \sum_{i\_1}^{n} \mathrm{E}_{VS\_i} \tag{22}$$

where

i is the sag event number
n is the number of qualified events during the given period at a given site

The SEI, when expressed in units of time, can be interpreted as the length of the equivalent interruption with the same lost energy as all sags together that occurred during the observation period.

The average sag energy index (ASEI) is the average of the voltage sag energies for all qualified events measured at a given site during a given period, as shown in Equation (23):

$$\mathrm{ASEI} = \frac{1}{n} \sum_{i=1}^{n} \mathrm{E}_{VS\_i} \tag{23}$$

The ASEI is dependent on the triggering of the monitor. A sensitive setting will result in a large number of shallow events (i.e., with low sag energy values) and a relatively lower value for ASEI. On the other hand, the SEI will increase for sensitive settings of the monitor. To compare results from site to site and from one period to another, a standardized trigger setting needs to be defined. This guide recommends a value of 0.9 pu sag voltage for qualifying the sag events.

The SARFI-90 index is used as a third index to quantify the number of events at the site. Note that only two of the three indices are needed, because they are related according to Equation (24):

$$\mathrm{SEI} = \mathrm{ASEI} \cdot \mathrm{SARFI}_{90} \tag{24}$$

This guide recommends to not include short-duration interruptions when using voltage SEIs, because one short-duration interruption may have a larger contribution to the index than all voltage sags together. The user of the index may decide to add a separate voltage SEI for short-duration interruptions such as SARFI-10, or may decide to use the reliability indices recommended in IEEE Std 1366.

Using the voltage swell energy for all voltage swells over a measurement period, a number of site indices can be calculated along the same lines as for voltage sags. The swell energy index is the sum of the voltage swell energies for all qualified events at a given site during a given period.

The average swell energy index is the average of the voltage swell energies for all qualified events measured at a given site during a given period.

This guide recommends that voltage SEIs and voltage swell energy indices be treated as two independent quantities. They should not be added to reveal one unified index, as the interpretation of such an index remains a point of discussion.

6.5 Voltage sag severity

The calculation of site indices for the voltage sag severity method is very similar to the calculation of site indices based on the voltage sag energy.

Two site indices are introduced to characterize the site performance, total voltage sag severity [Equation (25)] and average voltage sag severity [Equation (26)]:

$$\text{Total Voltage Sag Severity} = \mathrm{S}_{Site} = \sum_{i=1}^{N} \mathrm{S}_{e-1} \tag{25}$$

$$\text{Average Voltage Sag Severity} = \mathrm{S}_{average} = \frac{\mathrm{S}_{site}}{\mathrm{N}} \tag{26}$$

where

N is equal to the number of events for the site

Note that N is equal to SARFI-90 and that the same relation between the indices holds as for the voltage sag energy method, as shown in Equation (27):

$$\mathrm{S}_{Site} = \mathrm{S}_{average} \cdot \mathrm{SARFI}_{90} \tag{27}$$

The user of the index may decide to not include short interruptions in the voltage sag severity indices but instead quantify that aspect of power quality by means of the indices defined in IEEE Std 1366.

Using the voltage swell severity for all voltage swells over a measurement period, a number of site indices can be calculated along the same lines as for voltage sags. The total voltage swell severity is the sum of the voltage swell severity for all qualified events at a given site during a given period.

The average voltage swell severity is the average of the voltage swell severity for all qualified events measured at a given site during a given period.

This guide recommends treating voltage sag severity indices and voltage swell severity indices as two independent quantities. They should not be added to reveal one unified index, as the interpretation of such an index remains a point of discussion.

6.6 Aggregation

The previous subclauses presented methods for calculating site indices from the characteristics of individual sag events. The text assumed implicitly that it is clear what constitutes one individual event. In practice this is not always the case, and different interpretations of what constitutes one individual event could result in significantly different site indices. This subclause discusses a number of cases in which different recordings have to be aggregated into one event before the actual calculation of site indices.

Aggregation refers to the data-reduction technique of collecting many distinct measurement components into a single aggregate event for the purpose of computing site and system indices. How the measurements are combined depends on the specific needs of a particular analysis session. It is not possible to define methods that apply to any measurement case. The various issues presented below form a minimum set that should at least be considered for any survey.

6.6.1 Measurement aggregation

Many monitoring instruments will record one or more phases during an event. For example, a three-phase voltage sag may result in a meter recording one measurement for each phase. In conducting measurement aggregation, this guide chooses to represent the multiple phase measurements as only one measurement. A common practice is to choose the phase measurement that exhibits the greatest deviation from nominal voltage.

6.6.2 Time aggregation

The time aggregation counts a single event if there is a succession of events within a short time, generally caused by a single power system event. An example would be multiple sag events during an automatic reclosing operation. This is generally accepted practice in indexing voltage sag events. If the customer equipment is impacted by a voltage sag event, it is unlikely that the equipment will be up and running and impacted by a succeeding event during the aggregation time period. Another example is the survey results that were published in IEEE journals from the Electric Power Research Institute (EPRI) Distribution System Power Quality Monitoring Project, which used 60-s aggregation time but also explored using 120 s and 300 s. See Sabin 1996 [B14] or Sabin et al. 1999 [B15].

6.6.3 Spatial aggregation

Spatial aggregation refers to finding the worst voltage sags from more than one monitoring point. Spatial aggregation has also been employed when multiple meters are employed to monitor only a single phase of a system. In this case, three meters each monitoring one phase of a feeder can be combined to give the voltage sag performance of the bus supplying the feeder.

When using spatial aggregation to reduce the number of rms variation measurements, the measurements from multiple monitoring instruments are combined into a single measurement. An example of where this has an application is in computing rms variation indices at a single substation that is monitored at multiple buses. Another example is in computing rms variation indices for a single industrial facility that is monitored at each service entrance of its supplying feeders. See Dettloff and Sabin [B8].

6.7 Monitor availability

It is not unusual during the course of a monitoring project to experience periods when an instrument is off-line due to instrument calibration or malfunction. Poor data management practices can also result in missed measurements. When indices taken from different monitoring sites are combined, it is vital that the total time that each monitor was available is taken into account.

The safest method would be to only consider those monitors that have been available during the whole period over which the site indices are calculated (e.g., one year, one month).

Alternatively, the count of events may be corrected for the number of actual days (monitor/days) that the instrument was available. Assuming a constant event frequency during the period of interest makes it possible to use the expression in Equation (28) to correct the count of events:

$$\mathrm{N} = \mathrm{N}_a \times \frac{\mathrm{T}}{\mathrm{T}_a} \tag{28}$$

where

- N is the estimated number of events over the whole period T
- N_a is the number of events recorded over the period during which the monitor was available T_a

Note that such a correction method may only be used when the voltage sag frequency can be assumed constant over the period of interest; for example, when calculating site indices over a short period (such as one month) with rather similar weather, or when the sags are mainly due to switching events or faults in underground cables.

If the voltage sag frequency shows large variations during the period of interest, a correction can be made by correlating sags with the underlying events. The underlying events can be quantified by the number of faults, but if voltage sags are strongly correlated with lightning activity, the latter may be used as well. Equation (29) can be used to estimate the count of events:

$$\mathrm{N} = \mathrm{N}_a \left(1 + \frac{\mathrm{F}_n}{\mathrm{F}_a}\right) \tag{29}$$

where

- F_a is the number of underlying events (faults, lightning strokes, etc) during the period when the monitor was available
- F_n is the number of underlying events when the monitor was not available

7. System indices

7.1 General

System indices are calculated from the site indices obtained for a number of sites. Two principal methods can be distinguished for calculating system indices.

a) The system index is defined as a weighted average of the site indices. To determine weighting factors, system and load information is needed, but often a unity weighting factor is used for all monitored sites.

b) The system index is defined as the value not exceeded for 95% of the sites (the 95th percentile of the site indices). To be able to determine a 95th percentile, a reasonable number of sites has to be monitored, at least 20. When between 10 and 20 sites are available, the 90th percentile may be used instead. For fewer than 10 sites, the weighted average and the maximum value should be reported.

When calculating voltage sag system indices, one ideally has to have access to all sites over a long period of time. The measurement duration for a voltage sag survey should at least be one year, but to get results that have predictive value, a monitoring period of many years is needed. The required number of sites and the required duration of the survey to be statistically significant may not be possible. Typically, a survey is completed in one year over a fraction of the total number of sites. Guidelines are needed for the choice of the number and location of the sites. Voltage sag indices can be obtained much faster and over all nodes by using stochastic prediction methods: from the fault statistics obtained over a long period, the expected number of voltage sags for each site can be calculated. A number of methods for stochastic prediction of voltage sags are described in IEEE Std 493.

The system indices are defined such that they may be applied to systems of varying size. System indices may be calculated for the whole system operated by a network company, for all networks at one voltage level over a whole country or geographical area, for a group of feeders, and so forth. As a result of this scalability of the indices, values can be calculated for various parts of the distribution system and compared to values calculated for the entire system.

7.2 Site selection

When relating the results of the power quality monitoring, weighting is sometime employed to reflect the resulting unequal sampling probabilities. A 1993 paper by Markel et al. [B12] provides an in-depth description of one multistage process used to select the sites for monitoring. It also provides the distribution characteristics of the sites actually selected, including length of feeder, voltage rating, type of customers, type of construction, and size of substation. Examples demonstrating the methods for using selection probabilities to weight measurements are found in Brooks et al. 1998 [B6].

7.3 Weighting and statistics values

The weighting factors for the calculation of the site indices can be obtained in a number of ways. A straightforward way would be to use the number of customers as a weighting factor, similar to the method used in the definition of system average interruption frequency index (SAIFI) in IEEE Std 1366. SAIFI is defined in IEEE Std 1366 as the average number of interruptions longer than 5 min in duration that a customer in a given system would experience. Note that in this guide, the IEEE Std 1159 minimum duration of 1 min is used, but this does not affect the use of the weighting concept. An additional problem with voltage sag statistics is that not each feeder (customer) is monitored; as a result, some assumptions have to be made. Those customers that are not monitored (neither directly nor as part of a feeder) have to be allocated to a certain monitor.

Several important steps are necessary in order to compute the unbiased estimated average made possible by each site's selection probability. The calculation of any unbiased estimated average is given by Equation (30):

$$\text{Unbiased Estimated Average} = \frac{\sum_{i=1}^{n} \mathrm{R}_i \mathrm{W}_i}{\sum_{i=1}^{n} \mathrm{W}_i} \tag{30}$$

where

i is the site
R_i is an arbitrary power quality index
W_i is the sampling weight computed for site i

A sampling weight is the inverse of a site's sampling probability, which describes the monitoring site's probability of having been selected from all possible monitoring locations. The selection probability for each site of this monitoring project differs because of the controlled and systemic site selection approach. In Equation (30), R_i represents an arbitrary power quality index for which it is desired to compute an unbiased estimated average. This average differs from a simple arithmetic average, which ignores the fact that both common and uncommon sites were included in the monitoring project.

7.4 SARFI

The SARFI for a system is obtained as the average of the indices for the different sites. The SARFI values may be interpreted as quantifying the average voltage quality over the whole system or the part of the system being considered. When using SARFI to describe individual sites, it is possible to give a 95th percentile to characterize the quality of the whole system.

7.5 Voltage sag tables

When voltage sag tables are used, both average values over all sites and 95th-percentile values can be used. When average values are used, weighting of the values may be considered. Weighting is also possible when using the 95th percentile but less useful unless a very large number of sites is being monitored.

Each element of the voltage sag table should be considered as one index to which the statistical processing (average, 95th percentile, etc.) has to be applied. The resulting table for the whole system does not correspond to any individual site. Note that the cumulative number of events obtained from the 95th-percentile system index may be more than for the worst site.

The voltage sag table for the whole system may contain a smaller number of cells than for individual sites. For individual sites, a certain level of detail is needed to determine the compatibility of sensitive equipment with the supply. For system indices, a lesser level of detail may be more appropriate because that makes the study of year-to-year variations easier. For cases in which a smaller number of cells are used for characterizing the system performance, then the cells should be merged for each site before the system indices are calculated.

7.6 Voltage sag energy index

When using voltage SEIs, system indices are calculated by taking the average value of the site indices. See Thallam and Heydt in [B19]. The SEI [Equation (31)] and SARFI-90 index [Equation (32)] for the system are obtained by dividing the sum of the site values with the number of sites involved, N.

$$SEI_{system} = \frac{1}{N}\sum_{s=1}^{N} SEI_s \tag{31}$$

$$SARFI_{90,system} = \frac{1}{N}\sum_{s=1}^{N} SARFI_{90,s} \tag{32}$$

The ASEI for the whole system is obtained from the SEI and SARFI-90 values for the system, as shown in Equation (33).

$$ASEI_{system} = \frac{SEI_{system}}{SARFI_{90,\text{ system}}} \tag{33}$$

7.7 Voltage sag severity

The system index for voltage sag severity should be obtained from the site indices in the same way as for the other indices: either as a weighted average or as a 95th percentile.

7.8 Difference between SARFI-10 and MAIFI

IEEE Std 1366 defines the momentary average interruption frequency index (MAIFI) to quantify the number of momentary interruptions experienced in a certain system. The MAIFI is the average number of momentary interruptions that a customer would experience during a given period (typically a year). IEEE Std 1366 defines an interruption event as the operation of an interrupting device. For the calculation of MAIFI, only those momentary interruptions with duration up to 5 min are considered; this clause refers to these as “momentary interruptions.”

In this guide, which follows the recommendations of IEEE Std 1159, an interruption event is defined from the rms voltage. For the calculation of SARFI-10, all rms variations are counted in which the rms voltage remains below 10% of the nominal voltage for duration up to 1 min.

SARFI-10 will not count those momentary interruptions with duration exceeding 1 min. It will also not count momentary interruptions downstream of the monitor location. The presence of on-site generation may further lead to momentary interruptions not being counted by SARFI-10. However, SARFI-10 will count voltage sags due to faults very close to an upstream substation but not leading to an interruption, which are not counted by MAIFI.

Another important difference between MAIFI and SARFI-10 is that MAIFI includes a very well-defined weighting based on the number of customers. For the calculation of the SARFI-10, the customer is allowed to use weighting factors but no recommendations for these are given in this guide.

When using both IEEE Std 1366 and IEEE Std 1564 to quantify the supply performance, the user should be aware that this will result in double counting of some events that are considered an interruption by both indices. The same holds true for several of the other system indices as defined in this guide.

Annex A

(informative)

Choice of sag threshold and reference value

A.1 Reference voltage, choice of threshold

The sag threshold shall be defined by the user as a percentage of the nominal voltage ("declared input voltage" in International Electrotechnical Commission (IEC) 61000-4-30) or as a percentage of the pre-event voltage ("sliding voltage reference" in IEC 61000-4-30).

For measurements at or close to the equipment terminals (i.e., at low voltage) the use of the nominal voltage is recommended. The behavior of the equipment is, in almost all cases, related to the retained voltage. A fixed percentage of the nominal voltage results in a constant value in voltage for the threshold.

For measurements at distribution voltage levels, the main effect is the different average voltage for different locations along a feeder. The average voltage is typically higher close to the substation than further along the feeder. This results in two customers experiencing significantly different retained voltages for the same fault (i.e., for the same system event). Voltage sag indices obtained close to the substation may thus not give a representative value for a customer at the end of a long feeder. Correcting this effect should not be part of the monitoring program, since it is not possible to form indices that are representative for all customers. It is therefore recommended that the nominal voltage is used as a reference. Where deemed appropriate, a correction can be made for an individual customer afterwards.

For measurements at transmission voltages, the pre-event voltage may be used as a reference value. The operational voltage at a certain location in a transmission or distribution system is not always equal to the nominal voltage. Transmission-system voltage is usually regulated for end-users by regulators and/or on-load auto-tap-changing transformers. The effect of on-load tap changers is that the load voltage will be close to the nominal voltage when the transmission-system voltage is constant. The voltage sag as experienced by the end-user equipment is thus similar to the deviation of the transmission-system voltage from the long-term average or pre-event voltage. In IEC 61000-4-30, a 1-min time constant is used to represent the delay of on-load tap changers.

The same reference value as for the sag threshold should be used when expressing the retained voltage as a percentage or per-unit value.

A.2 Effect on indices

The choice of reference value or threshold does not impact the retained voltage in volts. The choice of the reference value does however impact the retained voltage in percent or per unit.

The effect of the choice of reference value or threshold on the duration is normally small, as the rms voltage changes from its normal value to the reduced voltage in about one cycle. The recovery also normally takes about one cycle. The choice of reference value or threshold has the most effect on the measurement of a voltage sag event that has a slow recovery. These events occur due to motor starting, transformer energizing, post-fault motor recovery, and post-fault transformer saturation.

The main effect of the choice of threshold or reference value will be in the number of voltage sags detected, which will impact the single-site and system indices derived from those counts. An event is only counted when the rms voltage drops below the threshold. A change in threshold (either in percentage or in reference value) will cause events that have a voltage close to the threshold to be counted or not counted. For locations with many minor voltage sag events, the difference may be significant.

Annex B

(informative)

Multiple events

B.1 Time aggregation

Collecting voltage sag data often shows that voltage sags have the tendency to occur in clusters. The time between events is not random; instead, shorter times between events are more common than would be expected. The results of five years of monitoring at about 50 locations at medium voltage, high voltage, and extra high voltage levels are summarized in Figure B.1. The horizontal axis gives the time between events (on a logarithmic scale), and the vertical axis gives the probability that the time between events is less than the value on the horizontal axis. The dashed horizontal lines correspond to probabilities plotted in a logarithmic axis. This method is described in more detail in Bollen 2000 [B1].

In Figure B.1, the different curves correspond to different voltage levels. If the occurrence of a voltage sag was independent of the occurrence of the previous sag, the curve would be a straight line with a slope of one. Instead, the curve shows that there is strong clustering on a time scale between about 1 s and several days. The reasons for clustering include periods of adverse weather, reclosing events and recurring faults, and single events detected by the monitoring system as a sequence of events.

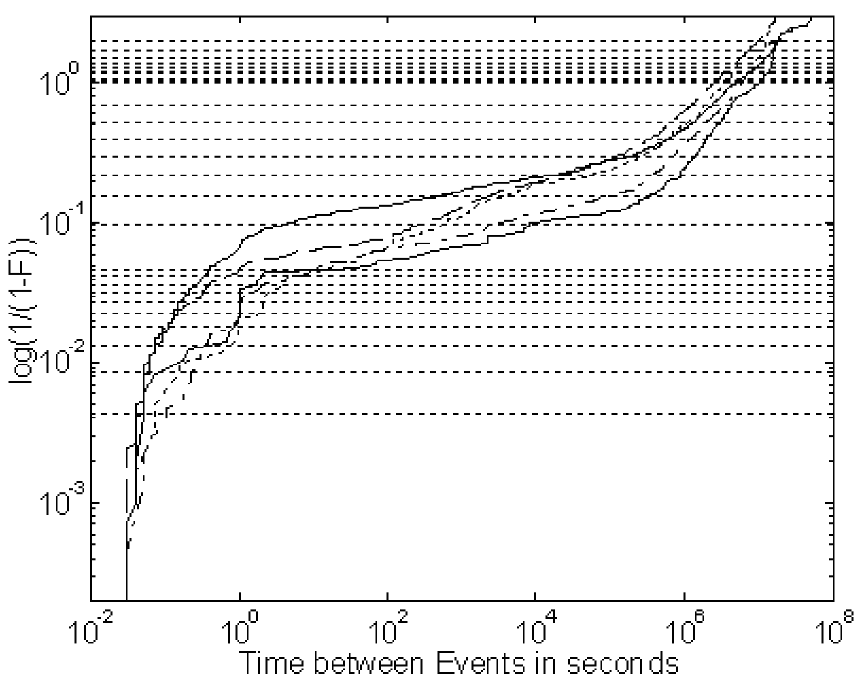

Figure B.1—Distribution of time between voltage sags plotted on Weibull scales

There are several reasons for aggregating voltage sags that are close in time into one single event.

a) When two identical voltage sag events occur with a few minutes of separation, the effect on end-use equipment may be the same as that of one single event. If the first event will cause the equipment to trip the production process, the equipment may still be down when the second event occurs. However, if the equipment manages to ride through the first event, it may equally ride through the second event. Thus, two events that are separated in time less than the production recovery time" may be aggregated into one single event. In cases in which the two events are different, the most severe one will determine the behavior of the equipment.

b) Two voltage sags may be due to essentially the same event in the power system. The standard example is unsuccessful reclosing after a fault. Any customers not on the faulted feeder will experience two voltage sags with the same retained voltage. The duration may be different because of differences in breaker characteristics. Another example is a recurrent fault. Such a power-system event may lead to a number of voltage sags separated seconds through minutes in time.

c) The algorithm used for characterizing voltage sags may detect the end of a sag before the event is actually over. The voltage may recover above the sag-ending threshold for a few cycles and then drop below the threshold again.

Some examples of sequences of recorded voltage sags are shown in Table B.1. The second column gives the time between the end of a voltage sag and the start of the next one. Duration and retained voltage are given for the individual sags as well as for the aggregated events. The right two columns show the results of two aggregation methods, which are discussed below.

Table B.1—Examples of voltage sags close together in time

Sequence	Time elapsed (s)	Duration (s)	Retained voltage (%)	Aggregation method 1 (duration, retained voltage)	Aggregation method 2 (duration, retained voltage)
1		0.12	82.92	0.12 s, 82.92%	N/A
	28.87	0.12	84.02		
	80.04	0.12	83.17		
2		0.33	86.17	0.96 s, 86.11%	N/A
	34.01	0.96	86.11		
3		0.06	73.57	0.06 s, 73.31%	N/A
	85.48	0.06	73.31		
4		0.09	60.15	0.13 s, 55.6%	N/A
	80.22	0.08	55.6		
	52.63	0.13	71.73		
5		0.07	82.4	0.07 s, 82.4%	0.13 s, 82.4%
	0.83	0.06	83.15		
6		0.09	50.15	0.16 s, 50.15%	0.32 s, 50.15%
	0.79	0.16	50.98		
	0.14	0.07	83.13		

Sequence 1 through sequence 4 in Table B.1 illustrate the use of aggregation method 1. Sequence 1 is a standard example of three voltage sags with identical duration and similar retained voltage. The time between events is around 1 min, so these three sags can be aggregated into one event. The retained voltage is slightly different; the lowest of the three is chosen for the aggregated event. For sequence 2, the second voltage sag is of longer duration that the first. This longer duration is chosen for the aggregated event.

In sequence 4, two short, deep events are followed by a longer but more shallow event. This will make it harder to determine which voltage sag is the most severe. In such a case, the duration of the aggregated event is chosen as the longest duration; its retained voltage is chosen as the lowest value for the individual sags.

Sequence 5 and sequence 6 in Table B.1 illustrate the use of aggregation method 2. For very short time between events, it is more appropriate to take the sum of the durations of the individual sags as the duration of the aggregated event. The results of this are shown in the "Aggregation method 2" column in Table B.1. In sequences 5 and 6, the time between events is less than one second. This may mean that the end-use equipment has not yet recovered from the first voltage sag when the second occurs. Thus, even if the equipment will not trip on the first sag, it may be affected such that it trips on the second one. In such a case, it is no longer possible to accurately aggregate the sags by taking the worst of the two.

The discussion is ongoing on which aggregation time to use. At this stage, it is not possible to make recommendations on this issue. Reasonable values for the time aggregation window for aggregation method 1 range between 10 s and half an hour. Reasonable values for aggregation method 2 are between a few cycles and a few seconds.

With some surveys, aggregation is not based on the time elapsed since the end of the previous voltage sag but instead on the time elapsed since the start of the previous voltage sags. This will lead to somewhat higher apparent event frequencies in some cases. An example of a sequence of voltage sags that can be aggregated in two different ways is shown in Figure B.2, where a time-aggregation window of 100 s has been assumed. Using the time since the end of the previous sag, these five sags will be aggregated as one event. Using instead the time since the start of the previous sag will result in two aggregated events, with the first event consisting of three voltage sags and the second event consisting of two voltage sags.

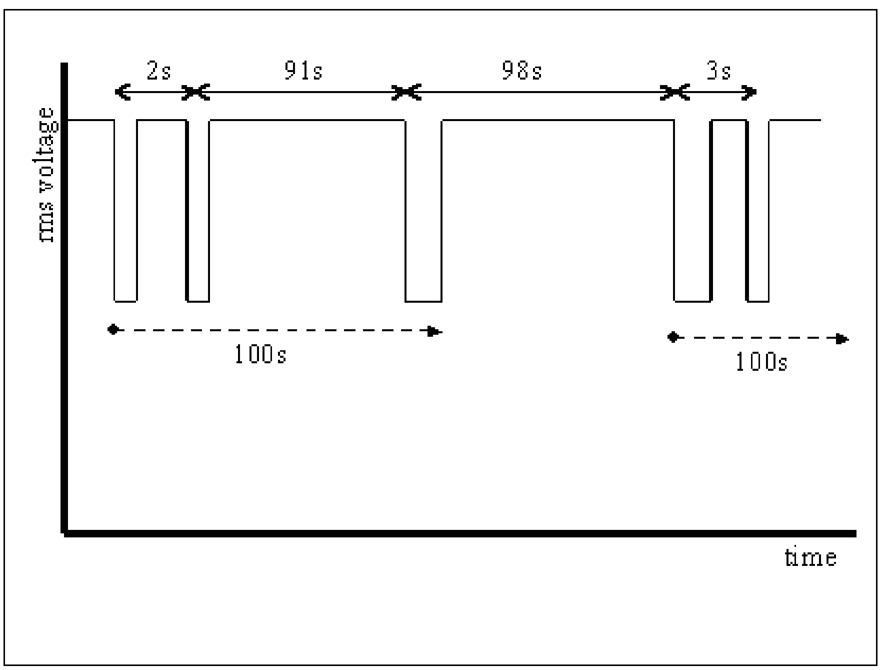

Figure B.2—Sequence of voltage sags that can be aggregated in two different ways

With some sequences of voltage sags there is a range of time-between-event values requiring a combination of aggregation method 1 and aggregation method 2. An example of such a sequence and its aggregation is shown in Table B.2. A time aggregation window of 100 s has been used, and the durations have been added if the time-between-events was 1 s or less.

Table B.2—Example of sequence requiring two-stage time aggregation

Time elapsed (s)	Duration (s)	Retained voltage (%)	First aggregation step (duration, retained voltage)	Second aggregation step (duration, retained voltage)
	0.51	89.26	4.21 s, 89.26%	29.25 s, 0%
0.17	0.48	89.53		
0.10	0.50	89.38		
0.14	0.50	89.41		
0.04	0.59	89.26		
0.11	1.10	89.38		
0.04	0.53	89.38		
46.94	28.23	87.85	29.25 s, 89.28%	
0.22	0.12	89.48		
0.13	0.06	89.46		
0.42	0.03	89.46		
0.75	0.05	89.43		
0.07	0.02	89.58		
0.40	0.32	89.43		
0.05	0.02	89.85		
0.27	0.37	89.28		
0.43	0.03	89.73		
1.81	0.07	89.58	0.07 s, 89.58%	
93.25	22.38	0	22.38 s, 0%	

B.2 Starting and ending thresholds

The start of a voltage sag is defined as the moment at which the rms voltage drops below the sag-starting threshold. The end of a voltage sag is defined as the moment at which the rms voltage recovers above the sag-ending threshold. The sag-ending threshold may be the same as the sag-starting threshold or slightly higher. Some standards, such as International Electrotechnical Commission (IEC) 61000-4-30, require a hysteresis value (1% – 2%) to be used for the ending thresholds. In some cases, the choice of sag-ending threshold will have significant implications for the single-event indices. An example of such a case is shown in Figure B.3; the sag-starting threshold and the sag-ending threshold are indicated by dotted lines. The rms voltage stays around the sag-starting threshold, leading to multiple crossings of the threshold. In cases in which the sag-ending threshold is chosen equal to the sag-starting threshold, this will be recorded as four individual voltage sags. But when the sag-ending threshold is chosen as a higher value, then it will be recorded as only one voltage sag.

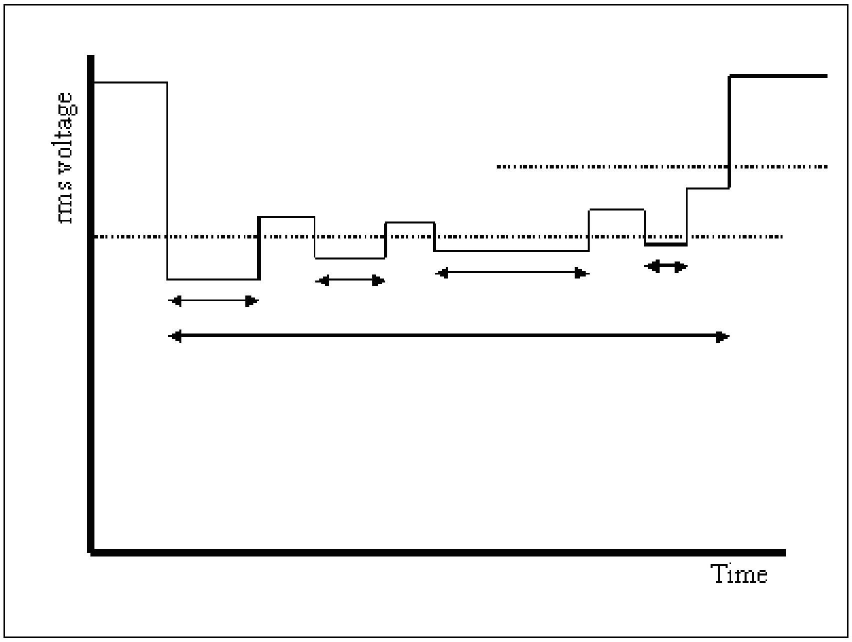

Figure B.3—Example of an event for which the single-event indices are affected by the choice of sag-ending threshold

There are alternative solutions to this problem. One solution is to use a higher voltage sag-starting threshold, e.g., 93% of nominal, and to only consider for further processing those events with a retained voltage below 90%. A second alternative is to merge the individual voltage sags by means of the time aggregation discussed above.

Annex C

(informative)

Examples of calculation of single-site SARFI

C.1 SARFI-X example

Consider the rms variation event summary table in Table C.1, which was hypothetically measured at a single site. The count of voltage sags and interruptions that would be included in SARFI-90 is 8, as there were 8 voltage sags and interruptions measured at this location that had a retained voltage below 0.9 per unit (90%) and between one-half cycle and 5 min in duration. This can be expressed as a rate of 2.61 events per 30 days. This is computed by dividing the 8 events by the 92 days between 2000-07-01 and 2000-10-01, and then multiplying by 30 to normalize the index to events per 30 days. These system average rms variation frequency index (SARFI) counts and rates are summarized in Table C.2.

Table C.1—List of events measured at a single site from July 1 to October 1, 2000

Time stamp	Retained voltage (%)	Duration
2000-07-01 09:48:52	73	9 cycle
2000-07-01 09:50:16	73	9 cycle
2000-07-07 14:20:12	0	82 cycle
2000-07-10 15:55:23	13	100 cycle
2000-07-21 09:48:52	0	2.6 s
2000-08-08 07:35:02	49	34 cycle
2000-09-02 08:30:28	0	41 s
2000-09-08 10:30:40	59	40 cycle

Table C.2—SARFI-X values computed from Table C.1

Index	Count	Events per 30 days
SARFI-90	8	2.61
SARFI-70	6	1.96
SARFI-50	5	1.63
SARFI-10	3	0.98

For voltage swells, SARFI-X is defined as the number of events per year with a retained voltage exceeding *X* percent (for *X* greater than 100).

C.2 SARFI-Curve examples

Figure C.1 provides an example of SARFI-ITIC, where each recorded sag is indicated as one point in the magnitude-duration plot (note that “magnitude” is used here as a synonym for retained voltage). The SARFI-90 count is 152. SARFI-ITIC is 112, meaning that there were 112 events that were outside the lower curve as defined by the Information Technology Industry Council (ITIC).

The power-quality monitor that recorded the data in Figure C.1 provided data for a full 365 days. When expressed in units of events per year, SARFI-90 is 12.49 events per 30 days, and SARFI-ITIC is 9.205 events per 30 days.

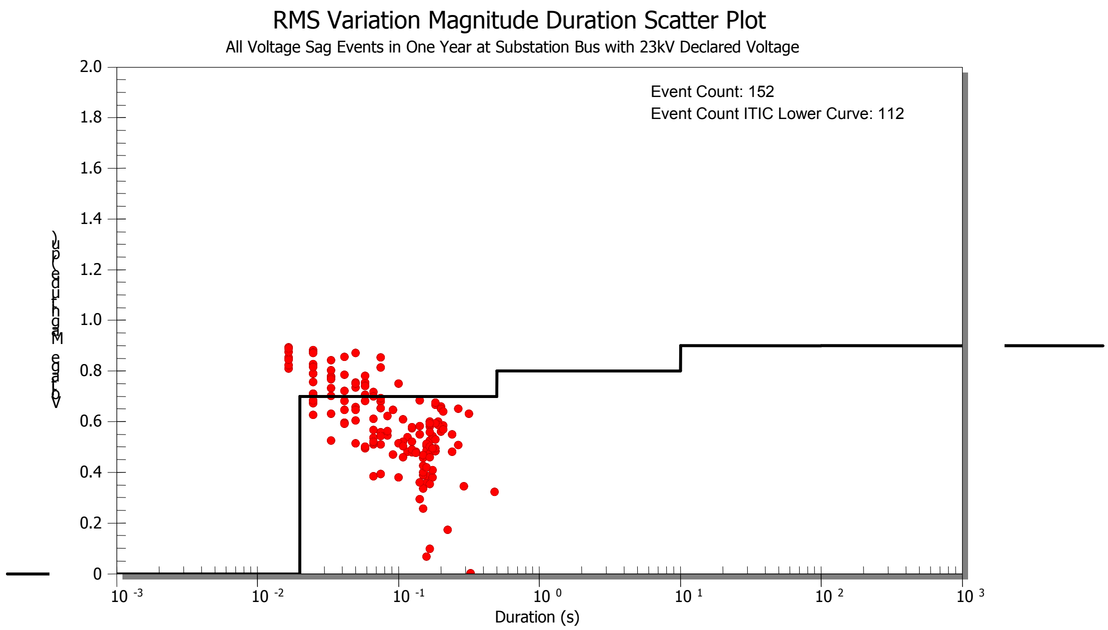

Figure C.1—RMS variation magnitude duration scatter plot showing events with a voltage magnitude and duration outside of the lower ITIC curve

Table C.3 presents a chronological list of the rms voltage variation events recorded at a single site during a single day in which a substation was subjected to a severe thunderstorm with high winds. In this first example, the measurements were not time aggregated. Since only one phase is shown per measurement, the table was built using measurement aggregation. The total number of events obtained by this method is 49.

Table C.4, however, was built from Table C.3 but the measurements were aggregated using 60-s temporal aggregation. The total number of events by this method is 15.

Table C.3—Example table of events using measurement aggregation

Time stamp	Magnitude (pu)	Duration (cycle)
2003-05-15 16:56:30.285	0.822	1.0
2003-05-15 16:58:10.092	0.781	2.5
2003-05-15 16:58:12.191	0.769	5.5
2003-05-15 16:58:27.135	0.795	1.5
2003-05-15 16:59:17.854	0.817	3.5
2003-05-15 17:00:17.938	0.803	1.0
2003-05-15 17:00:50.497	0.598	1.5
2003-05-15 17:01:25.615	0.798	1.0
2003-05-15 17:01:36.095	0.797	3.0
2003-05-15 17:01:56.273	0.584	2.0
2003-05-15 17:01:57.573	0.883	7.5
2003-05-15 17:02:18.263	0.659	2.0
2003-05-15 17:02:31.583	0.849	5.5
2003-05-15 17:02:37.051	0.514	5.0
2003-05-15 17:02:37.418	0.874	5.5
2003-05-15 17:02:52.867	0.845	28.0
2003-05-15 17:02:57.034	0.847	15.5
2003-05-15 17:02:57.334	0.830	10.0
2003-05-15 17:03:00.678	0.837	3.5
2003-05-15 17:03:00.795	0.839	12.0
2003-05-15 17:03:01.894	0.803	1.0
2003-05-15 17:03:18.395	0.822	6.5
2003-05-15 17:03:21.979	0.821	20.0
2003-05-15 17:03:55.491	0.838	1.0
2003-05-15 17:04:09.377	0.619	1.5
2003-05-15 17:04:13.800	0.761	1.0
2003-05-15 17:04:13.983	0.802	1.0
2003-05-15 17:04:25.324	0.523	4.5
2003-05-15 17:04:26.608	0.882	7.5
2003-05-15 17:04:38.864	0.520	7.0
2003-05-15 17:04:44.648	0.535	5.5
2003-05-15 17:05:14.943	0.533	5.0
2003-05-15 17:07:17.198	0.763	35.0
2003-05-15 17:07:22.030	0.764	27.0
2003-05-15 17:07:37.264	0.761	36.5
2003-05-15 17:08:03.732	0.840	3.5
2003-05-15 17:10:11.157	0.823	30.5
2003-05-15 17:10:12.707	0.840	4.5
2003-05-15 17:12:53.998	0.774	38.5
2003-05-15 17:13:11.233	0.845	3.5
2003-05-15 17:13:13.540	0.763	38.0
2003-05-15 17:13:42.654	0.771	36.5
2003-05-15 18:05:31.842	0.512	5.5
2003-05-15 18:05:33.659	0.522	5.0
2003-05-15 18:41:25.903	0.821	1.0
2003-05-15 19:05:01.705	0.870	3.0
2003-05-15 20:07:12.463	0.816	20.0
2003-05-15 20:07:15.930	0.756	17.5
2003-05-15 20:07:17.413	0.815	20.5

Table C.4—Example table of events using 60-second temporal aggregation

Time stamp	Magnitude (pu)	Duration (cycle)
2003-05-15 16:56:30.285	0.822	1.0
2003-05-15 16:58:10.092	0.769	5.5
2003-05-15 16:59:17.854	0.817	3.5
2003-05-15 17:00:17.938	0.598	1.5
2003-05-15 17:01:25.615	0.584	2.0
2003-05-15 17:02:31.583	0.514	5.0
2003-05-15 17:03:55.491	0.520	7.0
2003-05-15 17:05:14.943	0.533	5.0
2003-05-15 17:07:17.198	0.761	36.5
2003-05-15 17:10:11.157	0.823	30.5
2003-05-15 17:12:53.998	0.763	38.0
2003-05-15 18:05:31.842	0.512	5.5
2003-05-15 18:41:25.903	0.821	1.0
2003-05-15 19:05:01.705	0.870	3.0
2003-05-15 20:07:12.463	0.756	17.5

C.3 SARFI-CBEMA example

The Computer Business Equipment Manufacturers Association (CBEMA) chart presents a scatter plot of the voltage magnitude and event duration for each rms variation. The overlaid curves define a tolerance envelope developed by CBEMA, which is described in IEEE Std 446™ (IEEE Orange Book™) [B9]. The CBEMA group created the chart as a means to predict equipment misoperation due to rms variations. An rms variation event with a magnitude and duration that falls above the upper curve or below the lower curve has a high probability to cause misoperation in computer equipment connected to the monitored voltage source. In Figure C.2, the count of events that are below the lower CBEMA curve is 11, giving a SARFI-CBEMA of 11 events. Table C.5 presents the data points that comprise the CBEMA curves.

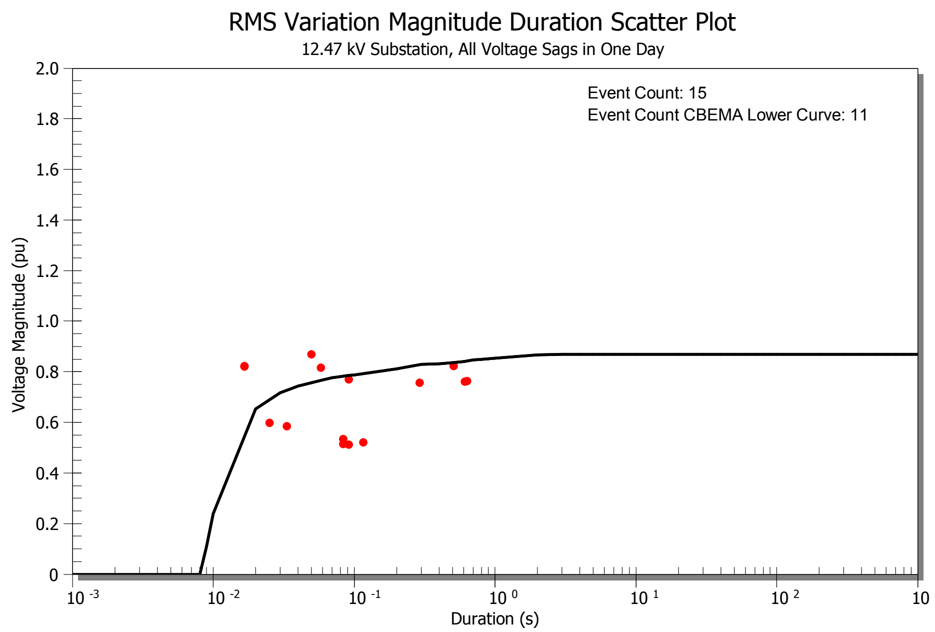

Figure C.2—CBEMA curve scatter plot with 60-second temporal aggregation

Table C.5—Voltage magnitude and duration values for the CBEMA curves

Duration (s)	Voltage magnitude limit for CBEMA lower curve (pu)	Voltage magnitude limit for CBEMA upper curve (pu)
0.0004	0.000	2.050
0.0005	0.000	1.945
0.0006	0.000	1.874
0.0007	0.000	1.814
0.0008	0.000	1.754
0.0009	0.000	1.710
0.001	0.000	1.677
0.002	0.000	1.431
0.003	0.000	1.322
0.004	0.000	1.259
0.005	0.000	1.228
0.006	0.000	1.205
0.007	0.000	1.189
0.008	0.000	1.173
0.009	0.110	1.158
0.01	0.239	1.146
0.02	0.653	1.107
0.03	0.716	1.092
0.04	0.744	1.086
0.05	0.757	1.082
0.06	0.767	1.078
0.07	0.776	1.075
0.08	0.782	1.072
0.09	0.785	1.070
0.1	0.788	1.068
0.2	0.813	1.060
0.3	0.829	1.060
0.4	0.831	1.060
0.5	0.835	1.060
0.6	0.841	1.060
0.7	0.846	1.060
0.8	0.850	1.060
0.9	0.852	1.060
1	0.854	1.060
2	0.867	1.060
≥3	0.870	1.060

C.4 SARFI-ITIC example

The ITIC curve describes an alternating current (ac) input voltage boundary that typically can be tolerated (i.e., without an interruption in function) by most information technology equipment. (See the Information Technology Industry Council's (ITI's) application node in [B10]). Like its predecessor, which was the Computer Business Equipment Manufacturers Association (CBEMA) curve, the ITIC curve consists of a scatter plot of rms voltage variations in terms of voltage magnitude and event duration. The scatter plot also includes two overlay curves that represent upper and lower limits. Events above the upper curve or below the lower curve are presumed to cause the misoperation of information technology equipment (e.g., computers, computer network components, communications networks). The curve describes both steady-state and transitory conditions and is applicable to 120 V nominal voltages obtained from 120 V, 208 /120 V, and 120/240 V 60-Hz systems. The curve is not intended to serve as a design specification for products or ac distribution systems. However, the normal functional state of information technology equipment is not typically expected when rms variations occur that are outside the upper and lower magnitude-duration limits described by curve. In Figure C.3, the count of events that are below the lower ITIC curve is 8, giving a SARFI-ITIC of 8. Table C.6 presents the data points that comprise the ITIC curves.

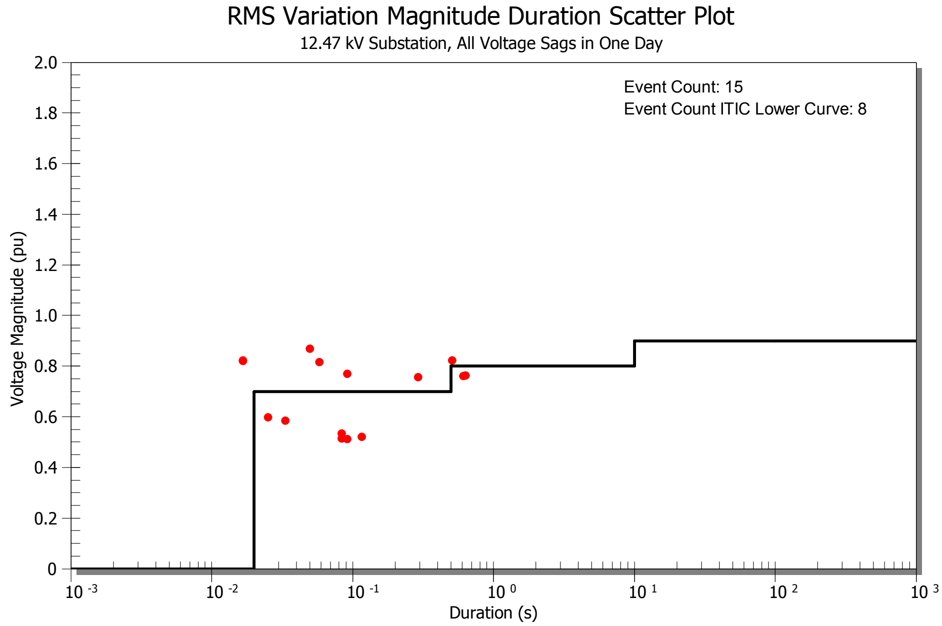

Figure C.3—ITIC curve scatter plot with 60-second temporal aggregation

Table C.6—Voltage magnitude and duration values for the ITIC curves

Duration (ms)	Voltage magnitude limit for ITIC lower curve (pu)	Voltage magnitude limit for ITIC upper curve (pu)
0.001	0	5
0.0166667	0	5
0.166667	0	5
1	0	2
3	0	1.4
3.001	0	1.2
20	0	1.2
20.001	0.7	1.2
500	0.7	1.2
>500	0.8	1.1

C.5 SARFI-SEMI example

In 1998, the Semiconductor Equipment and Materials International Group (SEMI) Power Quality and Equipment Ride-Through Task Force recommended the SEMI F47 curve to predict voltage sag problems for semiconductor manufacturing equipment. In Figure C.4, the count of events that are below the SEMI curve is 2, giving a SARFI-SEMI of 2. Table C.7 presents the data points that comprise the SEMI F47 curve. See SEMI F47-0706 [B17].

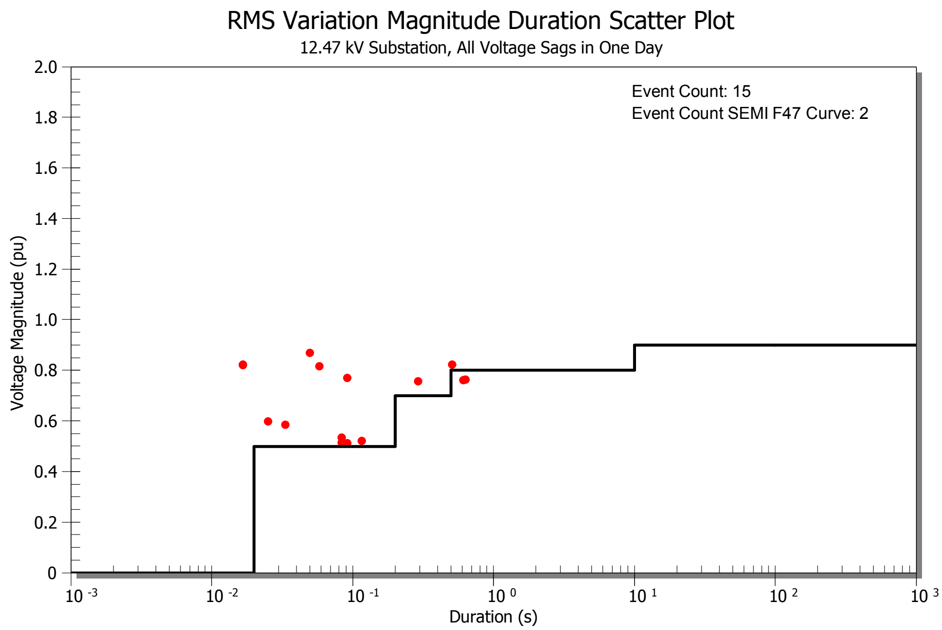

Figure C.4—SEMI curve scatter plot with 60-second temporal aggregation

Table C.7—Voltage magnitude and duration values for the SEMI F47 curve

Duration (ms)	Voltage magnitude limit for SEMI F47 (pu)
<0.02	0
0.02	0.5
0.1	0.5
0.1999999	0.5
0.2	0.7
0.4999999	0.7
0.5	0.8
1	0.8
9.999999	0.8
≥10	0.9

In Table C.8, the SARFI indices were recomputed to be represented in events per 30 days. The monitoring instrument was available for 31 days during May 2000, but the event rates were normalized to events per 30 days.

Table C.8—SARFI summary using 60-second aggregation during May 2003 (events per 30 days, exact monitor•day normalization

	SARFI-CBEMA	SARFI-ITIC	SARFI-SEMI	SARFI-90	SARFI-80	SARFI-50	SARFI-10
Count of events	18	13	4	29	19	1	0
Events per 30 days	17.419	12.581	3.871	28.065	18.387	0.968	0.000

Annex D

(informative)

Examples of measurement aggregation

D.1 High-Voltage survey D-6

This survey covered 22 sites at 70 kV with monitoring period up to 6 years and a total of 110 monitor-years. See Bollen 2000 [B1]. The results are shown in Table D.1, Table D.2, and Table D.3 for the average, 50th-percentile and 95th-percentile tables with and without time aggregation. Time-aggregation windows of 10 s and 10 min in length have been applied.

The effect of a 10-s time aggregation is significant for the 95th-percentile table, especially for short and shallow events (that is, above about 70%). The additional effect of a 10-min time-aggregation window is small. The 50th-percentile and average tables are not much affected by time aggregation. The clustered events are concentrated at a small number of sites. All values in the tables are number of events per year.

Table D.1—High-voltage survey D-6, 95th-percentile table, no time aggregation

	0–20 ms	**20–100 ms**	**0.1–0.5 s**	**0.5–1 s**	**1–3 s**	**3–20 s**	**20–60 s**	**1–3 min**
85–90%	3.2	12.2	7.6	2.8	1.0			
70–85%	0.7	13.0	11.0	2.5	0.7			
40–70%	1.5	6.7	8.7	2.0				
10–40%	0.2	1.8	4.0	0.2				
0–10%		0.3	0.7	1.0	1.2	1.0	0.3	2.0

Table D.2—High-voltage survey D-6, 95th-percentile table, 10-second time aggregation

	0–20 ms	**20–100 ms**	**0.1–0.5 s**	**0.5–1 s**	**1–3 s**	**3–20 s**	**20–60 s**	**1–3 min**
85–90%	1.0	8.6	5.8	2.6	1.0			
70–85%	0.3	11.5	10.5	2.5	0.7			
40–70%	1.3	6.0	8.8	2.0	0.2			
10–40%	0.2	1.8	4.0	0.2				
0–10%		0.3	0.7	1.0	1.3	1.0	0.3	2.0

Table D.3—High-voltage survey D-6, 95th-percentile table, 10-minute time aggregation

	0–20 ms	**20–100 ms**	**0.1–0.5 s**	**0.5–1 s**	**1–3 s**	**3–20 s**	**20–60 s**	**1–3 min**
85–90%	1.0	8.2	5.3	2.4	0.7			
70–85%	0.3	10.3	9.7	2.7	0.5			
40–70%	1.3	5.5	7.8	1.8	0.3			
10–40%	0.2	1.8	3.3	0.2	0.2			
0–10%		0.3	0.7	1.0	1.2	1.0	0.3	1.7

Annex E

(informative)

Example of computations of sag energy

The sag energy indices data presented in this informative annex are based on monitoring for four years at an electric utility distribution system. See Thallam and Heydt [B19]. The number of monitors installed and the number of events recorded during the four years is shown in Table E.1. The number of events is given for a triggering level of 90% of the nominal voltage. The counts of measurements were reduced by using temporal aggregation. The annual indices were obtained as the maximum of the monthly values.

Table E.1—Sag indices for 1999–2002

	1999	2000	2001	2002
Number of monitors	25	36	43	57
Number of recorded events	609	926	747	1831
Maximum of monthly SEI (ms)	128	158	87	130
Maximum of monthly SARFI-90	1.9	1.9	1.3	2.0

The monthly sag energy indices for the four years are shown in Figure E.1, and the monthly sag count indices are shown in Figure E.2. Overall, power quality was worst in 2000, with a highest monthly sag energy index of 158 ms compared to 87 ms in 2001, which was the best year. Indices also indicate the worsening of power quality in 2002 compared to 2001. The monthly sag energy index was up nearly 50% in 2002.

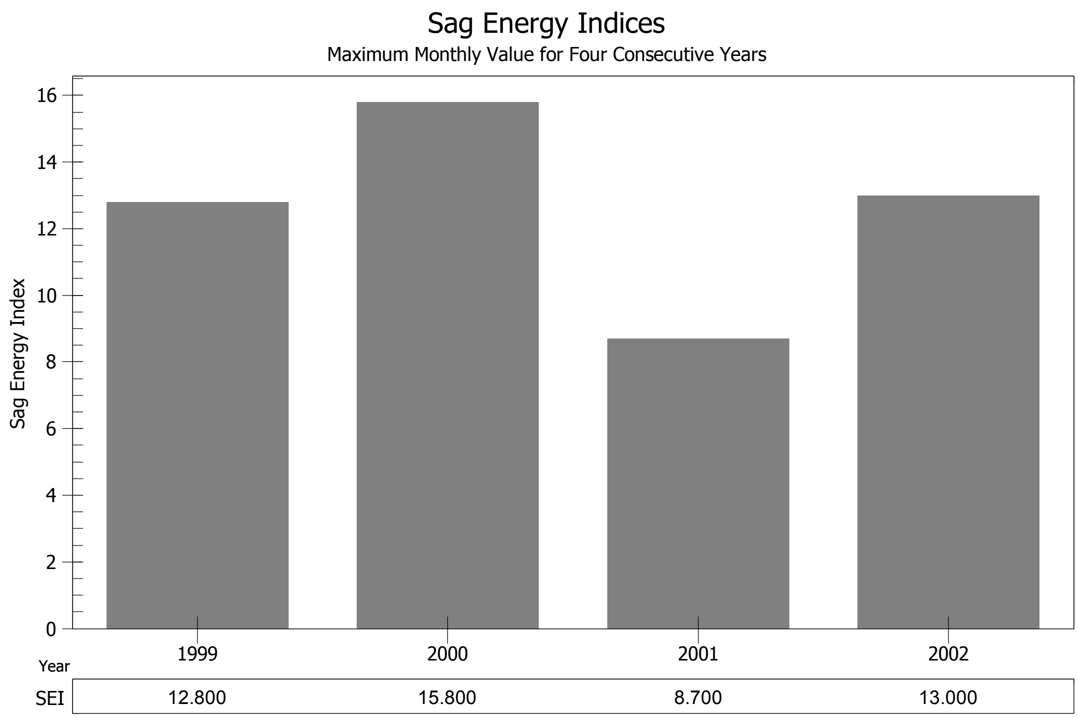

Figure E.1—Sag energy indices obtained as the maximum monthly value for four consecutive years

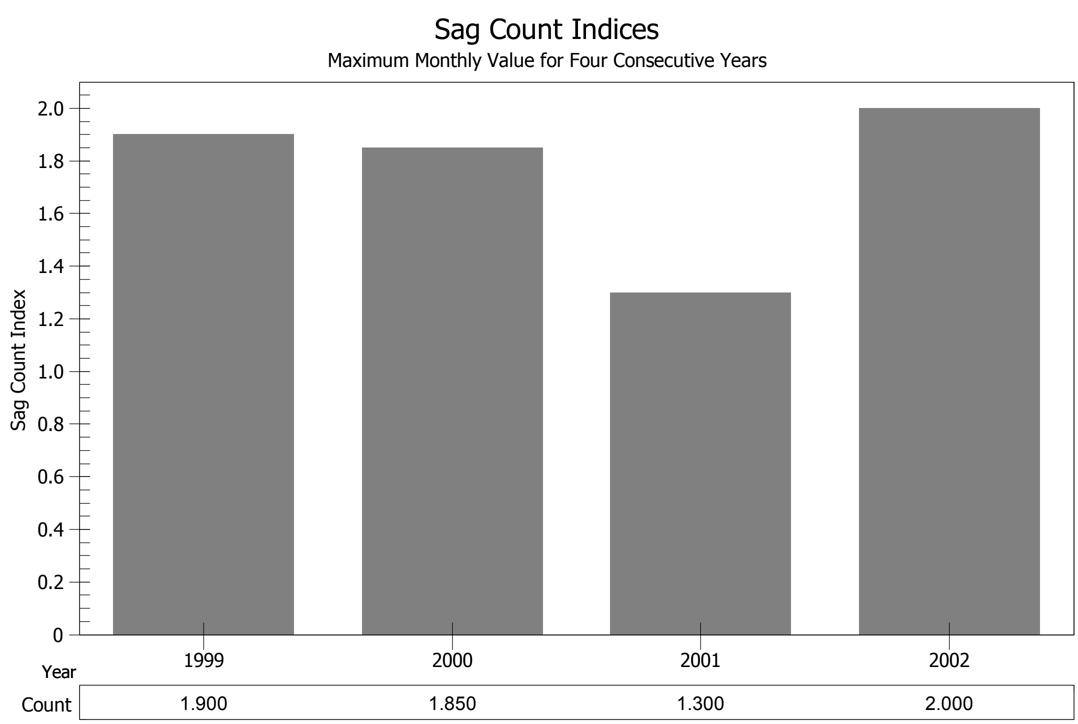

Figure E.2—Sag count indices obtained as the maximum monthly value for four consecutive years

The monthly sag energies of dedicated industrial customer substations are compared with indices for substations serving residential customers. In 2002, monitors were located at 25 industrial substations and 29 residential substations. As shown in Table E.2, the indices for industrial substations were significantly better than for residential substations.

Table E.2—Sag energy indices for industrial and residential locations

	Industrial	**Residential**
Sag energy index	89 ms	168 ms
SARFI-90	1.7	2.2

Annex F

(informative)

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