Voltage Sag Analysis and Load Loss Detection

by Jon Bickel, P.E.,
Power Applications, Schneider Electric

Executive summary

This paper discusses the impacts of voltage events such as sags/dips and short interruptions related to power quality issues. Whether originating at the utility or inside an end user's facility, it is important to understand operational impacts, and to differentiate nuisance events from disruptive events. Ascertaining the level of impact from voltage events allows easier prioritizing of alarms, creating and trending historical effects from disruptive perturbations, and determining locations and sizes of mitigation equipment.

Introduction

It is well-documented that power quality issues are one of the most significant and costly impacts on electrical systems. Studies have shown poor power quality costs the European economy up to €150 billion annually and the U.S. economy up to $188 billion annually, according to two independent studies by the Leonardo Power Quality Initiative and the Electric Power Research Institute (EPRI), respectively. One economic model summarizes the total cost associated with power quality events as follows:

Total losses = production losses + restart losses
+ product/material losses + equipment losses
+ third-party costs + other miscellaneous costs

Other miscellaneous costs may include intangible losses such as a damaged reputation with customers and suppliers or more direct losses such as the devaluation of credit ratings and stock prices.

Of the seven power quality categories defined by IEEE 1159-2019, short-duration rms variations are the most disruptive and have the largest universal economic impact on energy consumers. Short-duration rms variations include voltage sags/dips, swells, instantaneous interruptions, momentary interruptions and temporary interruptions. One study by EPRI estimates an average of 66 voltage sags are experienced by industrial customers each year. As the trend of industries becoming more dependent on sag-sensitive equipment has increased, so has the impact of these events.

Definitions

Aperiodic Event – An electrical event that occurs non-cyclically, arbitrarily or without specific temporal regularity. For the sake of this paper, both short-duration rms variations and transients are considered to be aperiodic events (i.e., notching is considered as a harmonic phenomenon).

Instantaneous Interruption – A deviation to 0-10% of the nominal value for a duration of ½ cycle to 30 cycles.

Momentary Interruption – A deviation to 0-10% of the nominal value for a duration of 30 cycles to 3 seconds.

Sag – A deviation to 10-90% of the nominal value for a duration of ½ cycle to 1 minute.

Short-duration RMS Variations – A deviation from the nominal value with a duration of ½ cycle to 1 minute. Sub-categories of short-duration rms variations include instantaneous interruptions, momentary interruptions, temporary interruptions, sags and swells.

Swell – A deviation greater than 110% of the nominal value for a duration of ½ cycle to 1 minute.

Temporary Interruption – A deviation to 0-10% of the nominal value for a duration of 3 seconds to 1 minute.

Transient – A deviation from the nominal value with a duration less than 1 cycle. Sub-categories of transients include impulsive (unidirectional polarity) and oscillatory (bidirectional polarity) transients.

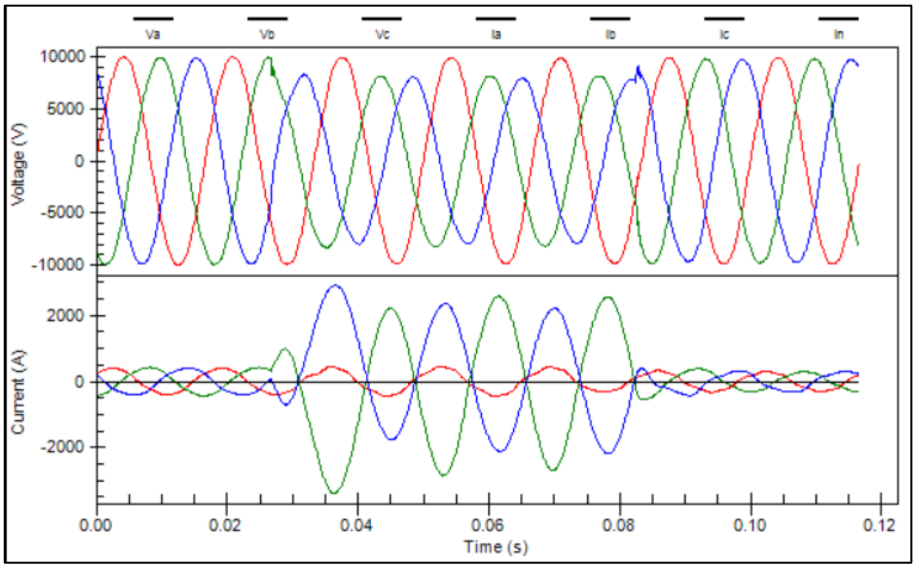
Background

Prescribed voltage range

All equipment is designed to operate within a prescribed voltage range. For example, a residential microwave oven may have a nominal voltage rating of 120 volts while an electric oven adjacent to the microwave may have a nominal rating of 240 volts. Similarly, industrial equipment may use equipment designed for hundreds of volts (e.g., 120 volts) to thousands of volts (e.g., 4160 volts). As the voltage to a particular piece of equipment deviates from its expected nominal value, the equipment may exhibit a range of issues such as de-energization, erratic operation, or even damage.

Figure 1

Phase-to-phase downstream fault.



By definition, a voltage sag (dip) is an unexpected excursion of the normal operating voltage to 10-90% of the nominal rated voltage lasting less than one minute. Figure 1 illustrates an example of a downstream fault on a utility distribution feeder. As shown in this figure, the downstream fault causes large current flow and a voltage sag/dip on the two phases. The degree of impact this type of event has on an energy consumer's facility is primarily dependent on the four factors:

1. The nature and source of the event,
2. The susceptibility of the load(s) to the event,
3. The event's influence on the process or activity, and
4. The cost sensitivity to this effect.

Consequently, each customer system and operation will respond differently to an electrical perturbation. For example, it is possible for a voltage sag event to significantly impact one customer's operation while the same voltage sag may have little or no noticeable impact on another customer's operation. It is also possible for a voltage sag to impact one part of a customer's electrical system differently than it does another part of the same electrical system.

Managing voltage events

In order to accurately describe aperiodic events such as voltage sags, it is important to measure the voltage signals associated with the event. Two attributes often used to characterize voltage sags and transients are magnitude (deviation from the norm) and duration (length in time) of the event.[1] Both parameters are instrumental in characterizing, and thus, mitigating these types of power quality issues. Scatter plots of the magnitude (y-axis) and corresponding duration (x-axis) of an event are shown in a single graph called a "Magnitude-Duration" plot or a Tolerance Curve. The RED area in Figure 2 highlights the event magnitude and duration for short-duration rms variations, including voltage sags/dips, swells, and brief interruptions (<1 minute). The nominal operating voltage in this figure ranges between ±10% of the nominal rated voltage.

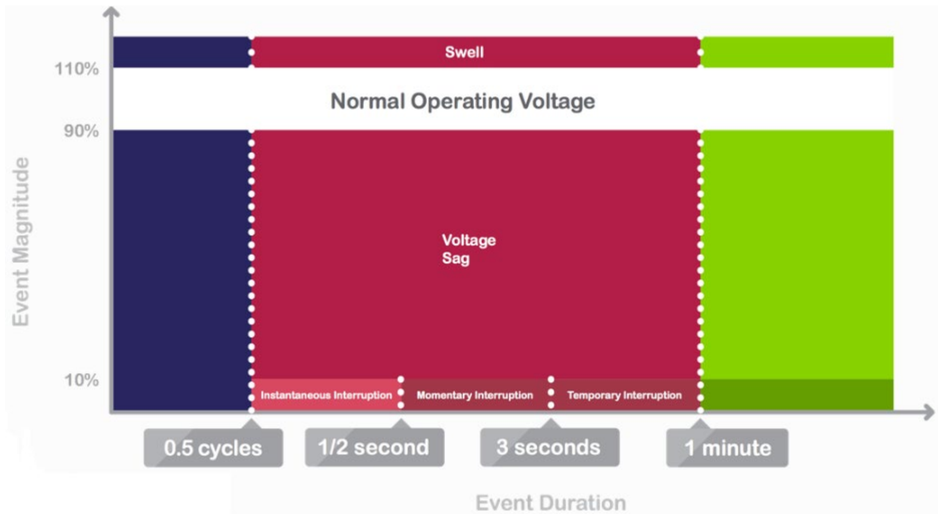


Figure 2

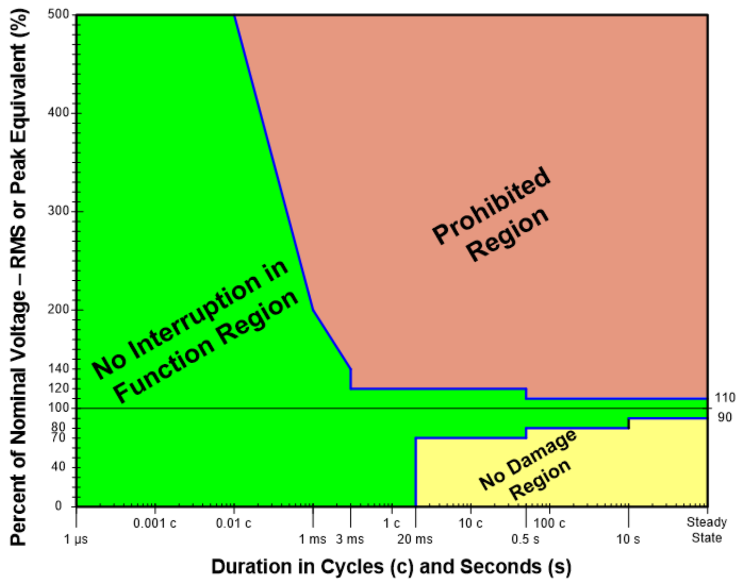
General graphical view of short-duration RMS variations.

Figure 3 (next page) illustrates a well-known Magnitude-Duration plot: the ITI Curve (often referred to as the ITIC curve or CBEMA Curve). The ITI Curve (blue line) describes "an AC input voltage envelope which typically can be tolerated (no interruption in function) by most Information Technology Equipment (ITE)," and is "applicable to 120V nominal voltages obtained from 120V, 208Y/120V, and 120/240V 60 Hertz systems." The "Prohibited Region" (RED shaded area) in the graph "includes any surge or swell which exceeds the upper limit of the envelope. Events occurring in this region may result in damage to ITE. The "No Damage Region" (YELLOW shaded area) includes sags or interruptions (i.e., below the lower limit of the envelope) that are not expected to damage ITE. Finally, the "No Interruption in Function Region" (GREEN shaded area) describes the area between the blue lines where sags, swells, interruptions and transients can normally be tolerated by most ITE.

[1] Note: Phase angle is sometimes considered but is not discussed in this document.

Figure 3

ITI (CBEMA) curve.



Tolerance curves such as the ITIC are useful for comparing voltage event characteristics from multiple events, specifying ride-through characteristics of ITE, and identifying persistent issues; however, they have several important limitations to note:

1. It is a static/fixed envelope curve,
2. It is proposed for specific applications (e.g., ITE, etc.),
3. It is intended for 120V 60Hz electrical systems,
4. It is a standardized/generic graph describing what "normally" should be expected,
5. It inherently provides no information regarding the consequences of an event, and
6. It is solely a voltage-based graph and does not consider any other electrical parameter(s).

In short, tolerance curves have their uses, but they are ***generalized recommendations*** for ***specific*** applications at explicit voltage levels. They do not indicate how a specific system or piece of equipment will actually respond to a sag/swell event, what the event's impact will be to the electrical system, or how and where to economically mitigate the issues. Furthermore, various zones (subsets) within the electrical system are treated the same, even though each metering device typically monitors a unique load or combination of loads. An effective analogy is a road atlas: while the atlas illustrates the location of the road, it does not indicate the location of road hazards, expected gas mileage, condition of the vehicle, speed traps, and so forth.

A New Approach to Evaluating Voltage Events

Mid/high-end metering devices have had the ability to capture short-duration rms variations such as voltage sags/dips for decades. These devices typically provide a time-series image of voltage perturbations (e.g., sags/dips) that include all metered voltage and current phases. Unfortunately, analyzing waveform captures without experience and training is complicated, akin to a radiologist analyzing an MRI or CT-scan. In fact, many power systems engineers are unable to diagnose waveform captures without years of experience.

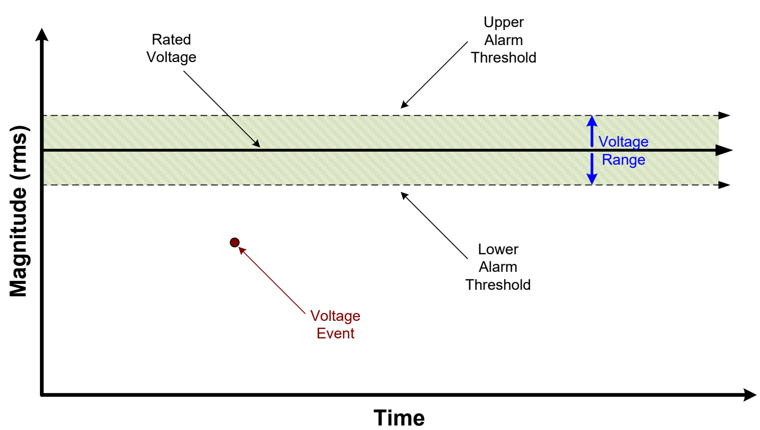
When analyzing voltage events, there are several questions to be answered including:

- What type of voltage event was it?
- How long did the voltage event last?
- Was the source of the voltage event internal or external (e.g., inside the facility/outside on the utility)?
- Where was the location of the voltage event's source?
- How much of my system was affected by the voltage event?
- What caused the voltage event?
- Is this voltage event a reoccurring issue?
- and most importantly…WAS MY OPERATION IMPACTED?

If configured properly, a capable metering device will provide an "alarm" (i.e., indication) when the voltage measurement on at least one phase deviates outside of a predefined magnitude range for a predefined duration. Figure 4 illustrates the normal voltage range (shaded area) that is bounded by an upper and lower alarm threshold. The rated or nominal voltage is also shown. For example, when the measured voltage level goes below the lower alarm threshold (e.g., see the voltage event shown in Figure 4), an alarm will be initiated by the metering device.

Figure 4

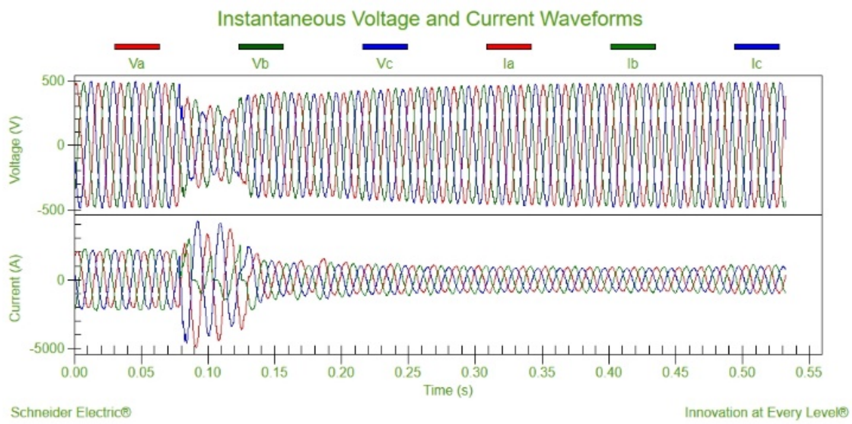
Illustration of RMS alarm thresholds.



The event alarm data typically includes information such as worst magnitude of the event, duration of the event, start time and date of the event, alarm type, and (depending on the device) a waveform capture of the three-phase voltages and currents during the event. Each of these event parameters provide important clues to troubleshoot the voltage event and answer the questions listed above. However, one very important question is not directly addressed: Did the voltage event impact the load? To determine whether the voltage event resulted in a load impact, a more thorough analysis of the waveform capture must be performed.

Figure 5

Instantaneous waveform capture of voltage event (Example 1).



Example 1: Load loss

Figures 5-7 illustrate a voltage sag event on a three-phase, 60 Hertz, 347/600-volt wye-configured system. The event shown in this example appears to have been caused by an upstream fault. **Figures 6 and 7** are derived from the event waveform data captured in **Figure 5**. The voltage event lasted approximately 11 cycles (or about 180 milliseconds) in duration, and the worst-case voltage deviation during the event was approximately 53% of the nominal voltage (or 184 volts) on Phase C as shown in **Figure 6** (rms voltage).

Figure 6

RMS voltage from voltage event (Example 1).

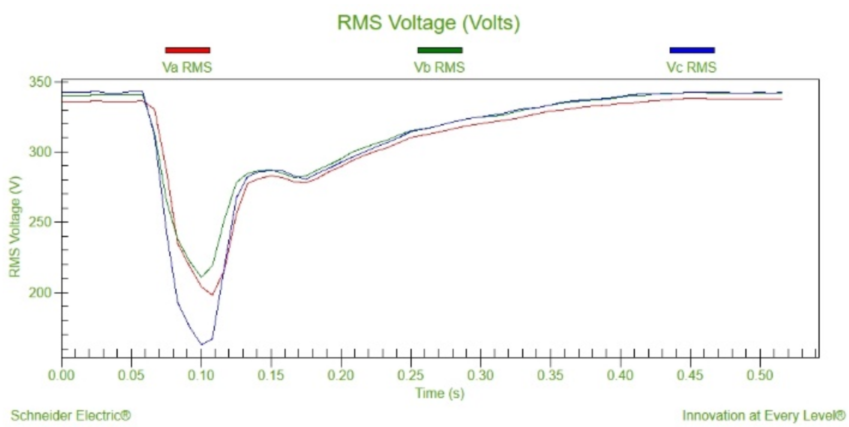


Figure 7

RMS Real Power from voltage event (Example 1).

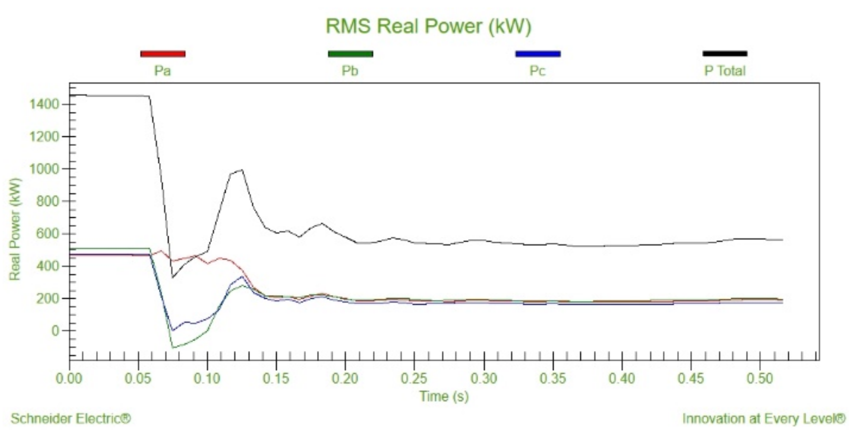


Figure 7 illustrates the rms real power data throughout the voltage event, and is the data with the most relevance for troubleshooting the event's impact. Before the event began (pre-event), the total real power consumed by the downstream load(s) was approximately 1,458kW. The voltage event began when t ≈ 0.07 seconds, and is assumed to have concluded once the voltage recovered to its normal operating range (t ≈ 0.26 seconds). Upon the conclusion of the event (i.e., post-event), the total real power consumed by the downstream load(s) was approximately 544kW. Therefore, the pre-event versus post-event total power flow to the load(s) decreased by about 914kW (or 63%) as a result of the voltage sag event. The conclusion is the voltage event caused 914kW (or 63%) of load to de-energize (drop offline), likely resulting in a significant impact to the facility's operation. A negative load change between 0 and -100% that is coincident with a voltage event generally indicates the voltage event was responsible for the load loss. An investigation should be performed to identify the root cause of this event and take the appropriate steps to mitigate future occurrences (if possible).

Example 2: Load Gain

Figures 8-10 illustrate a voltage sag event on the same electrical system described in Example 1. The event shown in these figures was caused by the energization of a downstream three-phase load. **Figures 9 and 10** are derived from the event waveform data captured in **Figure 8**. The voltage event lasted approximately 1 cycle (or about 16 milliseconds) in duration, and the worst-case voltage deviation during the event was approximately 87% of the nominal voltage (or 301 volts) on Phase A as shown in **Figure 9** (rms voltage).

Figure 8

Instantaneous waveform capture of voltage event (Example 2).

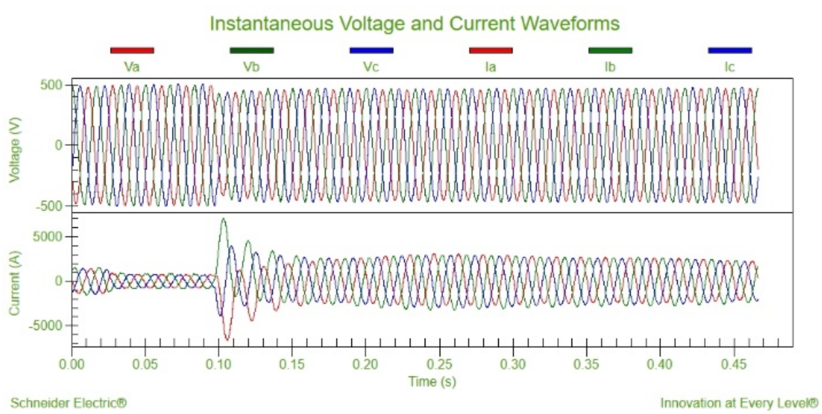


Figure 9

RMS voltage from voltage event (Example 2).

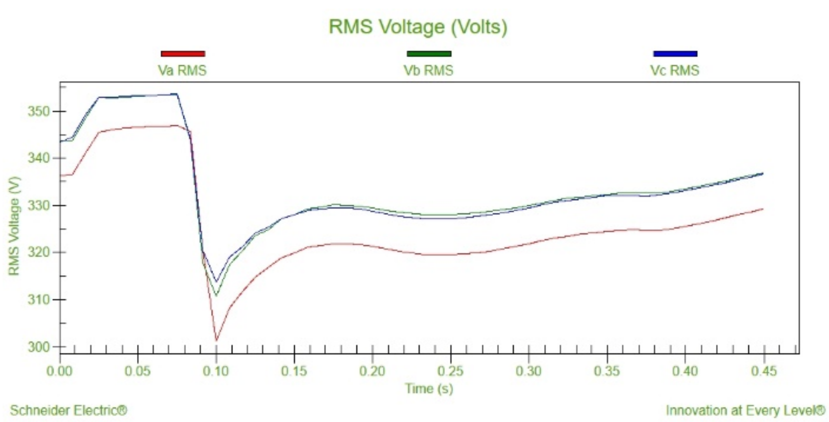


Figure 10

RMS Real Power from voltage event (Example 2).

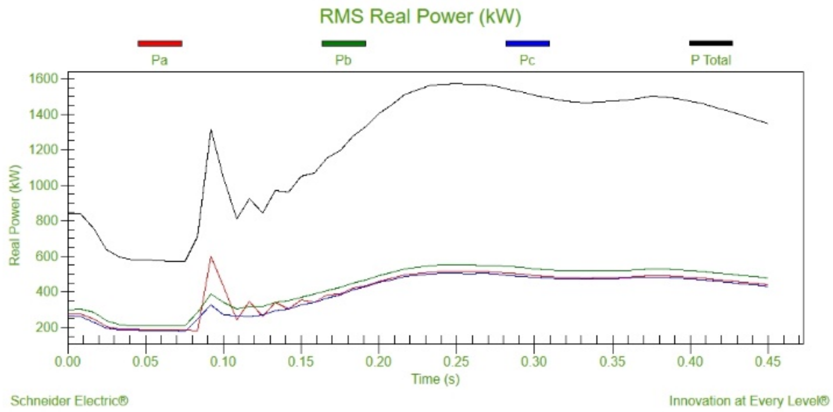


Figure 10 illustrates the rms real power data throughout the voltage event, and again is the data with the most relevance for troubleshooting the event's impact. Before the event began (pre-event), the total real power consumed by the downstream load(s) was approximately 837kW. The voltage event began when t ≈ 0.10 seconds, and is assumed to have concluded once the voltage recovered to its normal operating range (t ≈ 0.12 seconds). Upon the conclusion of the event (i.e., post-event), the total real power consumed by the downstream load(s) was approximately 1,345kW. Therefore, the pre-event versus post-event total power flow to the load(s) increased by roughly 508kW (or 61%) as a result of the voltage sag event. For this example, the voltage sag event was coincident with an increase of 508kW (or 61%) in the total load, and should not have impacted the facility's operation. A positive load change that is coincident with a voltage event generally indicates the voltage event was produced by energizing a significant load(s). While voltage sags/dips often correlate with the energization of a load(s), an investigation should still be performed to ensure: 1) the voltage deviation isn't excessive, 2) there are no overlooked load impacts due to the voltage sag/dip, and 3) the metering device's alarm thresholds are set appropriately.

Example 3: Load Reversal

Figures 11-13 illustrate a unique voltage sag event captured from a different system than those shown in the previous two examples. The cause of this voltage event is unknown; however, the results are certainly interesting. In this example, the voltage event occurs on a three-phase, 60 Hertz, 277/480-volt wye-configured system. **Figures 12 and 13** are derived from the event waveform data captured in **Figure 11**. The voltage event lasted approximately 25 cycles (or about 417 milliseconds) in duration, and the worst-case voltage deviation during the event was approximately 81% of the nominal voltage (or 224 volts) on Phase B as shown in **Figure 12** (rms voltage).

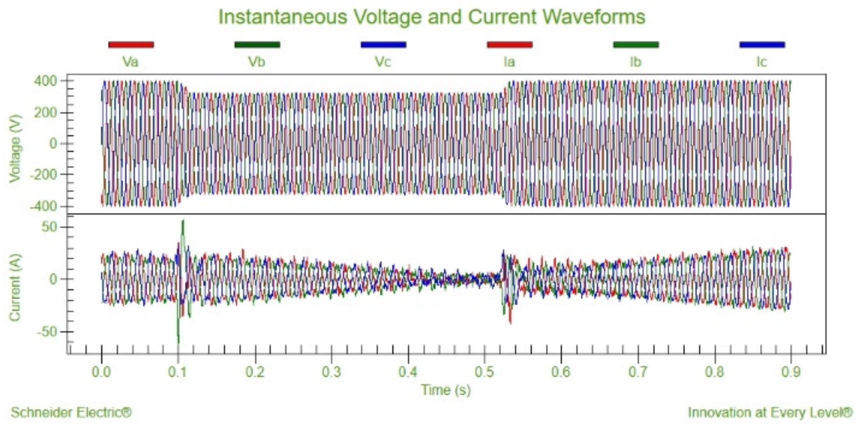


Figure 11

Instantaneous waveform capture of voltage event (Example 3).

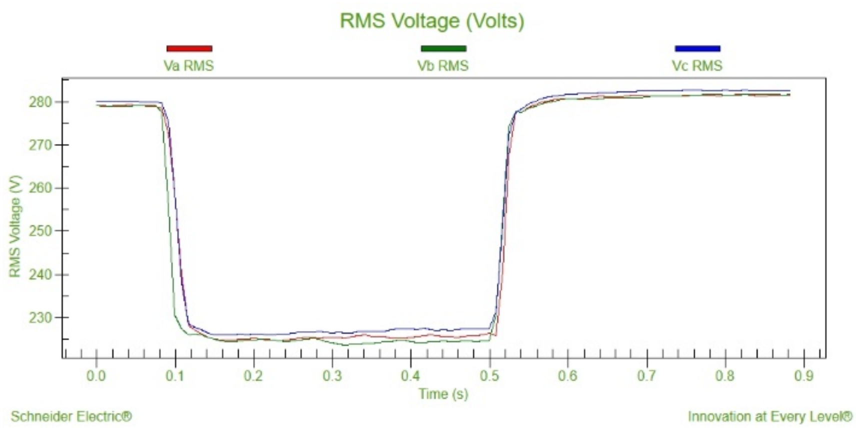


Figure 12

RMS voltage for voltage event (Example 3).

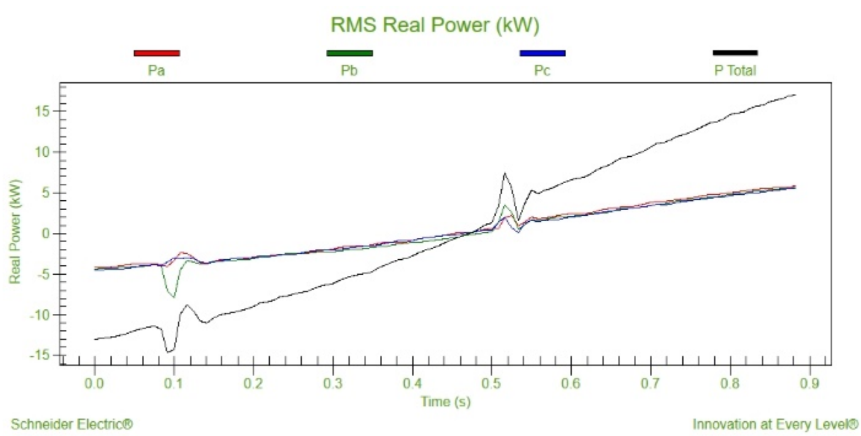


Figure 13

RMS Real Power from voltage event (Example 3).

Figure 13 illustrates the rms real power data throughout the voltage event, and provides valuable insight for a troubleshooter when trying to determine the cause of the event. Before the event began (pre-event), the total real power consumed as measured by the metering devices was approximately -13kW. The negative power indicates the directional flow of the energy with respect to the meter's polarity. If the meter is configured to indicate positive energy flow when the energy is flowing from the source to the load, a negative power flow would be shown when energy is flowing from the load to the source.[2]

The voltage event began when t ≈ 0.10 seconds, and is assumed to have concluded once the voltage recovered to its normal operating range (t ≈ 0.52 seconds). Upon the conclusion of the event (i.e., post-event), the total real power consumed by the was approximately +5kW. Moreover, the load continued to increase for the duration of the waveform capture to a value of approximately +17kW. As a result, the pre-event versus post-event total power flow experienced a reversal of -231% (i.e., about 131% of the original power flow in the opposite direction). While the power flow reversal is likely intentional, it should still be investigated to ensure this behavior is normal and acceptable. Additionally, one or more loads may have been impacted during this voltage event and subsequent power flow reversal, so mitigation opportunities may need to be considered

[2] Note: As used herein, "source" and "load" are simply nomenclature to indicate direction; not necessarily to indicate where the energy is actually generated and consumed. The source-side and load-side polarity are determined during commissioning and are at the discretion of the person installing and configuring the meter.

Conclusion

Globally, voltage events such as sags/dips and short interruptions are the biggest contributor to losses related to power quality issues. Voltage events can be external (e.g., originate on the utility) or internal (e.g., originate inside the end-user's facility), anticipated (e.g., starting a large load) or unpredictable (e.g., a system fault), impactful (e.g., loads de-energize) or inconsequential (e.g., system continues to operate with no issues). Recognizing the existence of voltage perturbations and characterizing their properties (e.g, worst magnitude, duration, etc.) is not sufficient; it is important to understand the operational impact to differentiate nuisance events from disruptive events. Ascertaining the level of impact from voltage events (regardless of their origin) facilitates easier prioritizing and filtering metering system alarms, creating and trending historical effects from disruptive perturbations, and determining locations and sizes of mitigation equipment.

About the author

Jon BICKEL (PE, BEP, CEM, CMVP, CPQ) is a Distinguished Technical Expert and Senior Level Edison Expert in Power Applications at Schneider Electric's R&D Center in Franklin, Tennessee, USA. He holds a BS in Electrical Engineering and MS Electrical Engineering from Kansas State University, and specializes in power systems, power quality and metering systems applications.