# An Overview of Transients in Power Systems

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## Executive summary

This paper discusses the problem of transient voltages and their effects in electrical power systems. It examines some typical sources of transients and shows how to use advanced metering techniques to identify potential transient issues. Finally, general solutions to transient problems are considered.

# Introduction

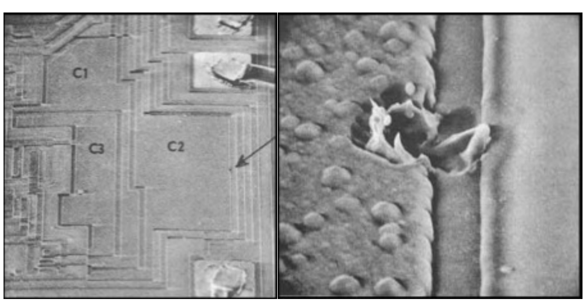
Electrical transient voltages can originate inside an energy consumer's facility or out on the utility's grid and can propagate through various levels of electrical and data systems. Sources of destructive transient voltages can range from the obvious—such as a lightning stroke during a thunderstorm (**Figure 1**)—to the subtle—such as static discharge from a human finger.

**Figure 1**

*From lightning strokes to static electricity, voltage transients are destructive to equipment and components.*

Transient overvoltages that exceed insulation ratings can stress electrical insulation, leading to gradual breakdown or abrupt failure of the dielectric. It is not uncommon for an industrial facility to experience many transients every hour, with voltage impulses exceeding 5 to 10 times the nominal system voltage. Reducing the magnitude and duration of voltage transients can extend the life of equipment insulation.

Because the damage due to transient voltages may not be obvious, identifying the cause of a component's damage is difficult, and often diagnosed as "unknown." Many integrated circuit and component failures result from voltage transients such as shown in **Figure 2**[1]. Large equipment such as the induction motor shown in **Figure 3**[2] are also susceptible to costly voltage transient damage. It has been estimated that billions of dollars in electronic equipment losses occur globally each year due to voltage transients, with these numbers increasing each year as technology evolves.



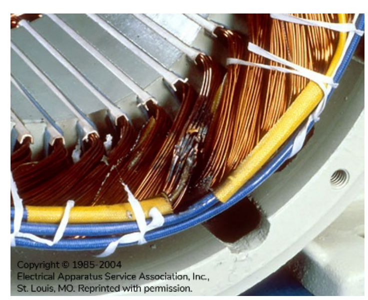




**Figure 2 (left)**

*Electrostatic discharge (ESD) damage to C2 MOS capacitor.*

**Figure 3 (right)**

*Transient impact on motor stator winding. Image reprinted with permission.*

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[1] Image taken from https://nepp.nasa.gov/index.cfm/6095

[2] Image used courtesy of *Electrical Apparatus Service Association (EDSA), Inc.*

# Transients: causes and effects

## Types of transients

IEEE 1159-2019 defines two types of transients: impulsive and oscillatory. Impulsive transients are described as a sudden, non-power frequency changes in the voltage, current, or both that is unidirectional in polarity.[3] An example of an impulsive transient would be a lightning transient or electrostatic discharge. Conversely, an oscillatory transient is described as a sudden non-power frequency change in the voltage, current, or both that is bidirectional in polarity. An example cause may be a capacitor bank energizing or a cable switching.

Several factors are used to characterize voltage transients including crest (or peak) value of the transient, area of the transient, maximum rate of rise of the transient, duration on the transient, periodicity, and associated frequencies related to the transient. The impact of a transient on a specific load will depend on the level of susceptibility of components or the system to one or more of these factors; however, the energy contained in a transient is usually critical in determining its effect on components or systems.

## The Nature of Transients

Transient voltages typically last from less than a microsecond to several milliseconds. Transient voltages are generally classified into two different types depending on where they occur on a power system: normal mode or common mode. Normal-mode transient voltage appears between any two power or signal conductors. Common-mode transient voltage generally appears equally and in phase from each power or signal conductor to ground.

Transients may damage equipment through several means, including dielectric breakdown, electrical flashover, fracture, thermal and instantaneous peak power overloads, and surpassing *dV/dt* and *dI/dt* limits. Dielectric (insulative) properties of equipment may be compromised when transient voltage magnitudes and rates of change cause insulators to become electrically conductive. When the dielectric is air such as the physical separation of two conductive mediums at two different voltage potentials, the dielectric breakdown of the air is generally referred to as electrical flashover (or arc flash). Electrical stresses associated with voltage transients may be converted into mechanical energy, resulting in fracturing of component materials. Energy from voltage transients may also be converted into thermal energy, adversely altering the insulative material at a molecular level. The rate of voltage and current changes associated with transients also plays an important role in the impact these stresses can produce in exposed materials and components.

[3] IEEE Standard 1159-2019 – Recommended Practice for Monitoring Electric Power Quality.

## The Effects of Transients

The influence of voltage transients on electronic equipment generally falls into one of four categories:

1. intermittent interruption
2. chronic degradation
3. latent failure
4. catastrophic failure

*Intermittent interruptions* may occur when a transient event is injected into a data or control network, resulting in lost or corrupted data. This may result in a load or device locking up, tripping off, or operating improperly. Factors that influence a transient's ability to disturb a load include design and operating speed of semiconductors, system filters, grounding configuration, susceptibility to electromagnetic interference (EMI) and radio frequency interference (RFI), and the configuration of the data or control cable.

*Chronic degradation* may occur when repetitive transient events diminish the integrity of an exposed component (or components). Over time–generally days, weeks, or even months–the cumulative effect of transient voltages results in the eventual inoperability of the vulnerable component. Because the transient voltages are frequent and relatively consistent in this case, locating their source is possible.

*Latent failures* are similar to chronic degradation, except that they are precipitated by a significant transient event that damages components, but not to the point that the component cannot perform its intended function. Over a period of time–again, days, weeks, or even months–the ordinary stresses due to normal operation will ultimately result in the component's inoperability. This type of mode is more difficult to troubleshoot because the root cause of the failure may have occurred at an indeterminate time in the past.

*Catastrophic failures* due to transient voltages are somewhat obvious, as the affected component will immediately cease to operate, and damage may be visible. In this case, the transient's voltage peak magnitude or rate of rise exceeds the rated threshold of the component in such a manner as to create a permanent open circuit or short circuit within the component. The odds of correlating the component failure with a power system disturbance are usually better with this type of event.

Solid-state products, microprocessor-based devices, and programmable logic controllers (PLCs) are especially susceptible to damage from voltage transients. Accordingly, exposure to voltage transients can reduce the reliability and shorten the operational life of these types of equipment. As technology evolves and the scale of these devices shrinks, the device components are becoming smaller and their susceptibility to damage from voltage transients increases.

It has been shown that transient voltages can interfere with the normal operation of equipment resulting in erratic behavior and the diminished quality of the end-product. Furthermore, interruptions in continuous manufacturing processes can result in revenue losses due to production downtime.

Table 3-1 in IEEE 1100-2005[4], Recommended Practice for Powering and Grounding Electronic Equipment, describes the effects of transients on equipment failure modes (recreated in **Table 1** in this paper):

[4] IEEE Standard 1100-2005 – Recommended Practice for Power and Grounding Electronic Equipment.

**Table 1**

*Surge Parameters Affecting Equipment Failure Modes*

| Type of Equipment | Surge Parameters | | | | | |
|---|---|---|---|---|---|---|
| | Source Impedance | Peak Magnitude | Maximum Rate of Rise | Tail Duration | Repetition Rate | $I^2t$ in Device* |
| Insulation | | | | | | |
| • Bulk | | • | | • | | |
| • Windings | | • | • | | | |
| • Edges | | • | • | | | |
| Clamping SPDs | | | | | | |
| • Bulk | • | • | | | • | • |
| • Boundary Layer | | • | | | | |
| Crowbar SPDs | • | | | • | • | • |
| Semiconductors | | | | | | |
| • Thyristors | | • | • | | | • |
| • Triacs | • | • | • | | | • |
| • IGBTs | | • | • | | | • |
| Power Conversion | | | | | | |
| • DC Level | • | • | | • | • | |
| • Other | | | • | • | | |
| Data Processing Malfunction | | • | • | | • | |

*The $I^2t$ in the device is the combined result of surge parameters and the device response to the surge. Like other power and energy-related equipment stress, $I^2t$ is not an independent parameter of the surge.

## Sources of transients

Many components and apparatuses make up the total electrical system, both inside the facility and outside on the utility grid. Within the facility, components that are inductive by nature, such as transformers and motors, can generate transient voltages in electrical systems. Any disruption in the flow of current to these devices concurrently with the collapse of the device's magnetic field results in voltage impulses or transients. The effect of these transient voltages is determined by several factors, such as location on the electrical system, size of the source and its resulting transient, periodicity of events, susceptibility of adjacent equipment, and configuration of the electrical system. Several sources of transient voltages within a facility are presented in the following list:

- Capacitor Switching
- Current interruption (motors, etc.)
- Power electronics operation (SCRs, etc.)
- Electrostatic discharge
- (Arc) welding
- Copy machines
- Faulty wiring or circuit breaker operation
- Contact and relay closure
- Load startup or disconnect

When a transient voltage event occurs on the utility's electrical system, the magnitude of the transient event within the facility will depend on multiple criteria, such as location of the transient source, magnitude of the transient voltage, configuration of the electrical system, and mitigation devices present. While lightning is the usual suspect for transient voltages from the utility (due to the magnitude of damage generally associated with it), voltage transients resulting from capacitor switching events are more common, especially in the summer. When a capacitor bank is energized, a large inrush current charges the capacitors, resulting in an initial notch into the voltage waveform. The system voltage recovers quickly and overshoots its original point, continuing to oscillate or ring. The ringing of the system voltage is due to the addition of capacitance to a system that is inductive by nature, and typically ends within one-half to one full cycle. Some loads–such as variable speed drives (VSDs)–are sensitive to this ringing and may trip offline as a result.

Several sources of transient voltages external to a facility are presented in the following list.

- Lightning
- Capacitor switching
- Line/cable switching
- Transformer switching
- Current limiting fuse operation

Although voltage transients originating on the utility's electrical system can impact a facility's operation, transient voltage sources within the facility are more common. The normal daily operation of loads within the facility—such as electric furnaces, ovens, induction heaters, welders, or motors—can produce voltage transients that affect adjacent equipment.

## Identifying transient sources

Most facilities are exposed to external transient voltages; additionally, many facilities use equipment that produces transient voltages. Because transient voltages have an extremely short duration, the limitations of many metering devices may not allow them to detect high-speed transients on their electrical systems. It is necessary to evaluate the voltage waveforms at a higher sample rate (or resolution) to identify these occurrences; however, standard available metering equipment may not be "fast enough" to capture many transient voltage events.

The appropriate metering equipment make it easier to determine the sources and effects of transient voltages. A voltage transient metering instrument should have sufficient resolution to detect and record the transient's amplitude, duration, and time of the event. Recording the time of day is also important because it helps a troubleshooter correlate transient issues with events occurring internal or external to the facility. The leading edge of a voltage transient will have a polarity either into the waveform or out of the waveform. With a high-resolution transient waveform capture, the troubleshooter can use the initial polarity of the transient's leading edge to narrow down the type of equipment or event producing the transient voltage. Employing multiple high-speed metering instruments across an electrical system may also facilitate determining a transient source's location, which is typically nearer to the metering instrument recording the highest voltage transient magnitude.

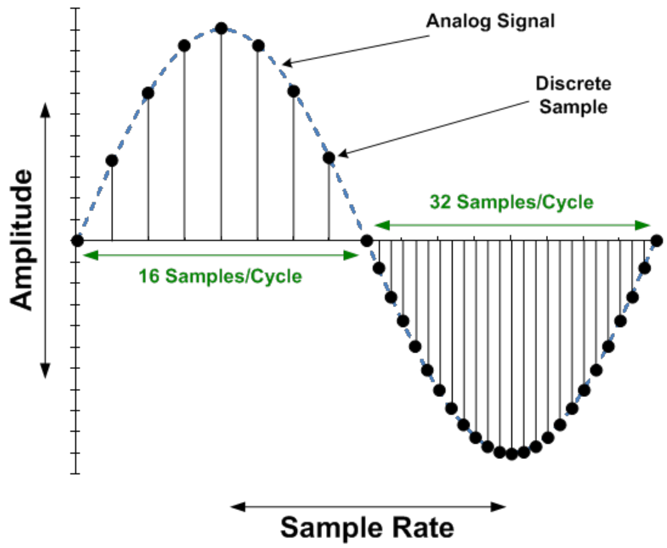
## Characterizing transient voltages in metering instruments – why is it important?

Two important aspects should be considered when attempting to accurately characterize and digitally represent analog signals such as voltage and current: the signal's amplitude (or peak) and its associated frequency components. The amplitude of a transient voltage signal is arguably the most important factor in determining the impact of transient events on equipment or loads within an electrical system. The electrical stresses and energies associated with transient voltages are generally dependent on the amplitude of the transient voltage signal, so the ability to accurately measure a transient voltage event's amplitude is crucial to quantify the issue and take the appropriate corrective actions.

Identifying frequency components associated with transient events is more complicated, and therefore, requires a more thorough explanation. To accurately represent the analog signal, a metering instrument takes discrete snapshots of the analog signal and converts them to their approximate digital equivalent. Sample rate is the number of samples taken per cycle of the analog signal to digitally represent the analog signal. The more samples taken per cycle, the more accurate the digital representation of the signal will be (Figure 4).

**Figure 4**

*Signal amplitude at two different sample rates*




Many transient events are missed or not accurately approximated because metering instruments use fewer samples than are necessary to accurately depict the analog signal. In general, most metering instruments will sample between 32 and 1024 samples per cycle with 128 points per cycle being typical. While standard metering instruments may be fast enough to detect voltage sag events over multiple cycles, subcycle events such as transients may either be missed completely or not accurately represented in the digital recording.

By definition[5], the duration of a transient event is less than one cycle. Because of their short duration and often unpredictable pattern of occurrence, capturing and analyzing voltage transient events requires the use of more sophisticated metering instruments. High-speed metering instruments sample the analog signal at a much higher rate than standard metering instruments. For example, the Schneider Electric® ION9000T samples the analog voltage signal at 10 MHz or 166,666 samples per cycle (based on a 60-Hz system) during a high-speed event, compared to 128 samples per cycle (or less) in a typical meter. This produces data with approximately 1,300 times better resolution than the standard available data. While longer duration events such as a voltage sags may be properly diagnosed using lower sample rates, transient events often cannot.

[5] IEEE Standard 1159-2019 – Recommended Practice for Monitoring Electric Power Quality.

# Examples

To illustrate the benefit of using higher data sampling rates when troubleshooting power events, this section illustrates waveform captures of transient events at different sampling rates. An impulsive transient was "injected" onto the source voltage with a capacitive load. The resulting waveforms were captured using a range of different data sample rates: 64 samples per cycle, 512 samples per cycle, and 83,333 samples per cycle.

## Example 1: Voltage transient events captured at 64 samples per cycle

The result of a lower data sample rate (64 points per cycle) is illustrated in Figures 5 and 6. While the occurrence of a ¼-cycle event is apparent; accuracy of the information becomes questionable when the two waveform captures are compared. Notably, both events were caused by the **same** source on the same load at roughly the same point in the waveform, and therefore, should have the **same** initial voltage polarity. However, **Figure 5** shows the initial polarity of the event to be out of the voltage signal, while **Figure 6** shows the initial polarity to be into the voltage signal. This information can be misleading and costly, should the wrong solution be employed to correct the issue.

**Figure 5**

*Transient captured at 64 samples/cycle*

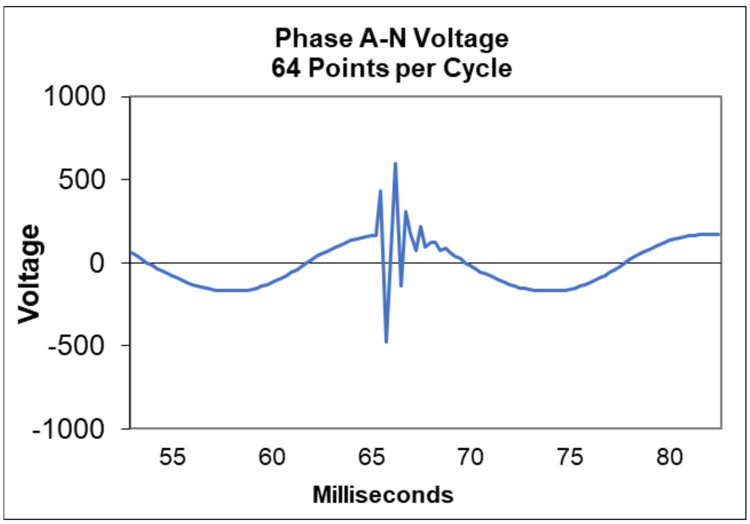
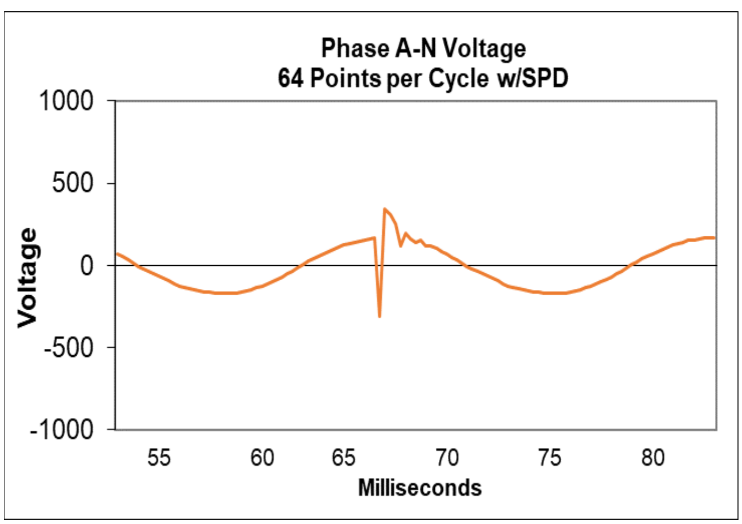



**Figure 6**

*Transient captured at 64 samples/cycle using a surge protective device (SPD)*



Because the event occurred at slightly different phase angles on the waveform, the longer intersample intervals (i.e. duration between samples) associated with slower sample rate may miss the initial polarity of the event. The initial polarity of an event is an important clue to determine the source of a transient (and its respective mitigative solution), therefore, it is important to obtain a high enough resolution to correctly establish the initial polarity of the event. In this case, a positive polarity event was produced by a transient generator on the positive half of the sine wave and should have an additive impact on the original signal.

When the initial polarity of an event is **into** the voltage signal, the source or effect of the event is taking energy **out** of the system. An example of this effect is an upstream capacitor switching event. A large inrush current is created when the capacitor charges and an initial notch into the voltage signal (with subsequent oscillation or "ringing" due to the system impedance) is produced. Conversely, the polarity of an event **out** of the voltage signal indicates energy is being **introduced** to the system. An example cause of this effect may be some lightning strikes, switching of inductive loads, or as illustrated in this example, a transient generator.

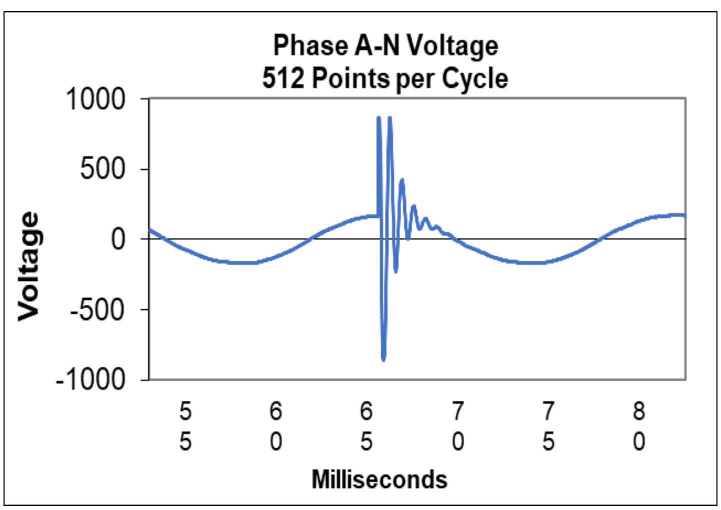
The two waveform captures also provide information about the surge protective device (SPD) operation. The 64 samples per cycle waveform shown in Figure 6 confirms the SPD attenuated the transient event, reducing the amplitude of the transient event and shortening the ringing period. However, it is a mistake to assume the true magnitude of attenuated transient peak voltage is reflected in Figures 5 and 6 because of the lower sample rate used to produce the waveform. This is illustrated in the following examples.

## Example 2: Voltage transient events captured at 512 samples per cycle

**Figures 7 and 8** illustrate the same type of event described in Example 1; however, a sample rate of 512 samples per cycle is used. The initial polarity of the transient event in Figure 7 is out of the waveform as expected, but the lack of data points in the waveform shown in Figure 8 barely indicate the correct initial polarity. Even at 512 samples per cycle, a troubleshooter should not erroneously assume the polarity of the event has been accurately recorded.

**Figure 7**

*Transient captured at 512 samples/cycle*



Although 512 samples per cycle is one sample every 32.5 microseconds, a meter sampling at this rate may not provide enough information to determine the cause of a short duration event, which may disrupt equipment and processes. Bouncing mechanical contacts, removal of inductive loads from the electrical system, and electrostatic discharge (ESD) impulses may all exhibit short duration occurrences with potentially damaging effects to adjacent equipment. In some cases, these rapid events go undetected even at high sample rates such as 512 samples/cycle.

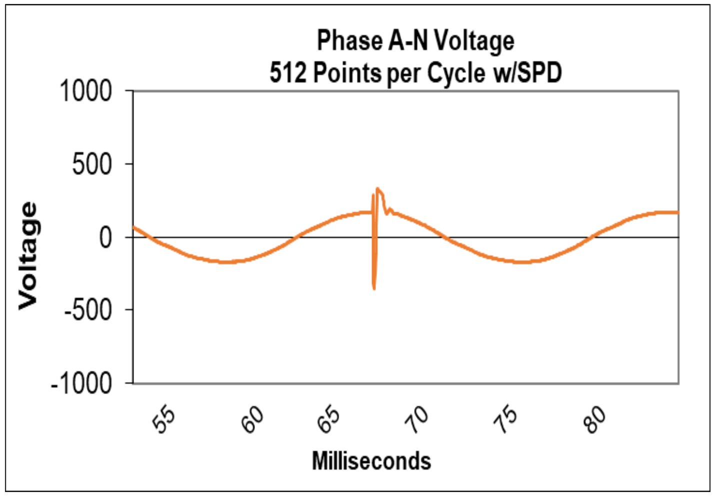



**Figure 8**

*Transient captured at 512 samples/cycle using an SPD*

The waveforms in **Figures 7 and 8** illustrate the SPD did attenuate the transient event's peak voltage. However, once again the sampling rate does not necessarily allow reliable conclusions to be made regarding the actual magnitude of attenuation.

## Example 3: Voltage transient events captured at 83,333 samples per cycle

**Figure 9** shows that much more information can be gathered at a much higher sampling rate such as 83,333 samples per cycle. This figure illustrates a voltage transient event with and without an SPD applied. In this case, the polarity of the transient event is clearly shown to be out of the waveform; that is, something appears to be introducing energy into the system. Zooming into both the slow-speed and high-speed waveforms shows the impulse contains two ringing signals superimposed on each other at approximately 25 kHz and 250 kHz. This type of ringing is typical of an RLC (resistive, inductive, capacitive) circuit that has been injected with energy from another source. The load was later revealed to be a capacitor (with the leads being resistive and inductive).

**Figure 9** shows the same event shown in **Figures 5, 6, 7, and 8**; however, much more energy is present in the voltage transient event than is indicated by the slower sampling rates. **Table 2** below illustrates the measured magnitudes of this transient voltage event are significantly disparate at different sampling rates, with and without SPDs installed. Therefore, it should be concluded that higher sample rates provide a better characterization of voltage transient events, and subsequently, the potential impact to equipment.

**Figure 9**

*Transient captured at 83,333 samples/cycle with and without an SPD*

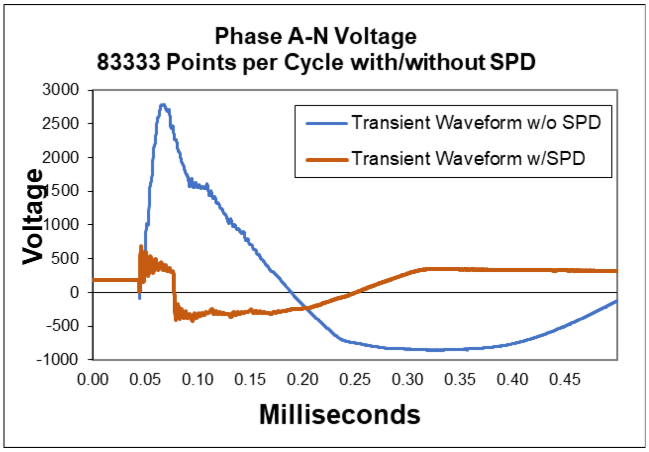



**Table 2**

*Transient magnitude vs. data sampling rate*

| | 64 samples / cycle | 512 samples / cycle | 83,333 samples / cycle |
|---|---|---|---|
| **Without TVSS** | ≈ 865 volts | ≈ 866 volts | ≈ 2,800 volts |
| **With TVSS** | ≈ 341 volts | ≈ 349 volts | ≈ 680 volts |

## Summary

Due to the short duration and indiscriminate occurrence of voltage transients, and metering instrument limitations, facility personnel may be oblivious to the existence of voltage transients on their electrical system. Over time, voltage transients may be responsible for unexplained machinery mis-operation, component damage, and/or equipment failure. A myriad of voltage transient sources can impact equipment operation, and voltage transients may originate either inside a facility or on a utility's electrical system. When attempting to troubleshoot and resolve voltage transient problems, it is important to have metering instruments that can adequately measure and represent the true likeness of the original transient waveform.

Sampling the waveform at higher rates allows troubleshooters to more conclusively determine the magnitude, duration, and initial polarity of extremely fast voltage events. Higher sampling rates in metering instruments also provide troubleshooters with better information associated with events—a higher and more accurate level of detail that may not be available at standard sampling rates. This allows a quicker diagnosis and resolution to transient voltage events. More damaging energy may be associated with voltage transient events than would be assumed from a waveform captured using standard sampling rates. In the examples provided above, characteristics of voltage transient events were accurately determined using higher sample rates. Additionally, it was possible to conclusively demonstrate the chosen solution, an SPD, was effective in mitigating voltage transient events.

## About the author

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