Providing insights for today's HVAC system designer

ENGINEERS NEWSLETTER

Volume 54-1 // March 2025

TRANE

Electrical Power Quality for HVAC Equipment

Users, installers, and engineers prefer to connect HVAC system components to the power source and never have to worry about it again. However, issues such as lightning strikes, ground fault events, or even overvoltage trips can occur, resulting in collateral damage to the HVAC equipment.

This EN provides readers with an understanding of how to conduct a power quality analysis and provide options to make equipment more resilient when impacted by electrical transients.

Following are several electrical terms used throughout this *Engineers Newsletter*, to help better understand power quality:

Power quality is the concept of powering and grounding electrical equipment in a manner that results in reliable and consistent operation.

An **electrical transient** is a disturbance to electrical power that may inhibit reliable and consistent operation of electrical equipment.

A **power quality meter (PQM)** is a specialized measurement device used to capture and record electrical transients, as well as other power quality metrics.

A **power quality analysis** is the evaluation of electrical system operation, typically focused on identifying and resolving sources of electrical transients.

Nominal Electrical Ratings

ANSI/AHRI Standard 110, *Air-conditioning, Heating and Refrigerating Equipment Nameplate Voltages*, establishes requirements for nameplate voltage ratings of HVAC equipment. In addition, this standard also specifies voltage utilization ranges. Equipment is expected to operate normally when the input voltage is within this utilization range. The utilization range may differ between various types of equipment. In general, the utilization range is about +/- 10 percent of the nameplate voltage.

Standard 110 also considers a voltage drop from the electrical feeder panel to the equipment. The "nominal system voltage" reflects voltage at the feeder distribution panel and the "nameplate voltage" reflects voltage at the piece of equipment (Table 1).

Frequency is typically controlled in a very tight range. Except for unique installations, the electrical frequency is not a major power quality concern for HVAC equipment.

Table 1. AHRI Standard 110-2024 voltage utilization

Nominal System Voltage (at the Feeder Panel)	Nameplate Voltage (at the Equipment)	Voltage Utilization Range ("Range B")
120	115	104 to 127
208	200	180 to 228
240	230	208 to 254
480	460	416 to 508
600	575	520 to 635

Voltage Operating Envelope

In the 1980s, computer manufacturers recognized that voltage transients occur with different durations and magnitudes. Short duration transients may reach very high magnitude, while longer duration transients tend to be lower in magnitude. The CBEMA[1] and ITIC[2] voltage operating envelope curves were introduced to help manufacturers design equipment that is compatible with expected transient voltages. Standard SEMI F47 further defines test acceptance criteria for undervoltage shutdown of semiconductor processing equipment (Figure 1).

Normal operation refers to when the supply voltage is within the rated voltage utilization range. Equipment should be able to ride through electrical transients that are within this envelope.

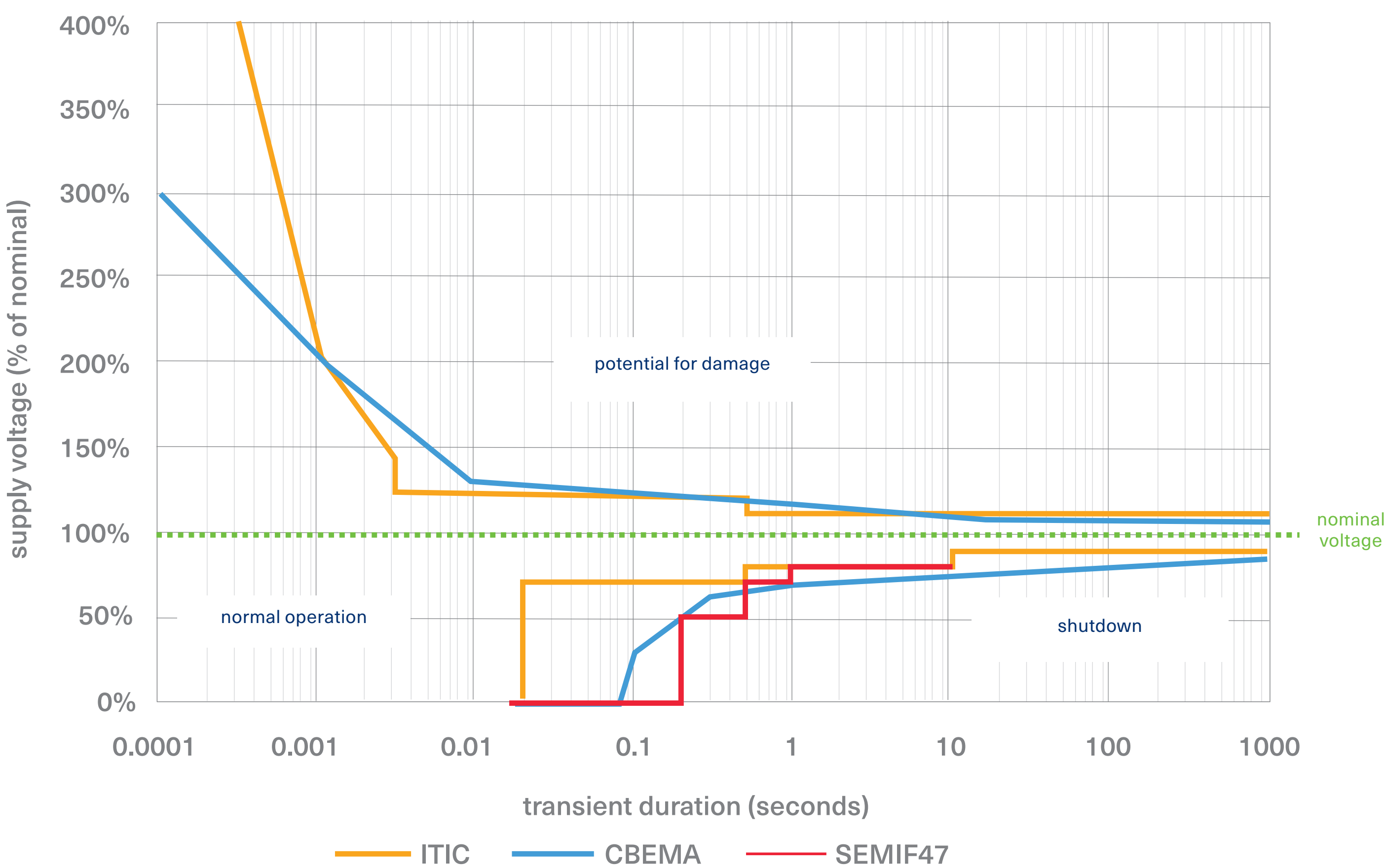
Shutdown occurs when the supply voltage is too low for too long of a duration.

Potential for damage exists when the supply voltage is too high for too long of a duration. Transients of a larger magnitude, or for a longer duration, contain more energy and have more potential for damage.

[1] Computer and Business Equipment Manufacturers Association (CBEMA)

[2] Information Technology Industry Council (ITIC)

Figure 1. Voltage operating envelope



Electrical Transient Types

IEEE Standard 1100 and IEC Standard 61000 define several types of electrical transients.

Table 2 lists electrical transients with commonly used names and descriptions. Note that other names may be used to describe these transients.

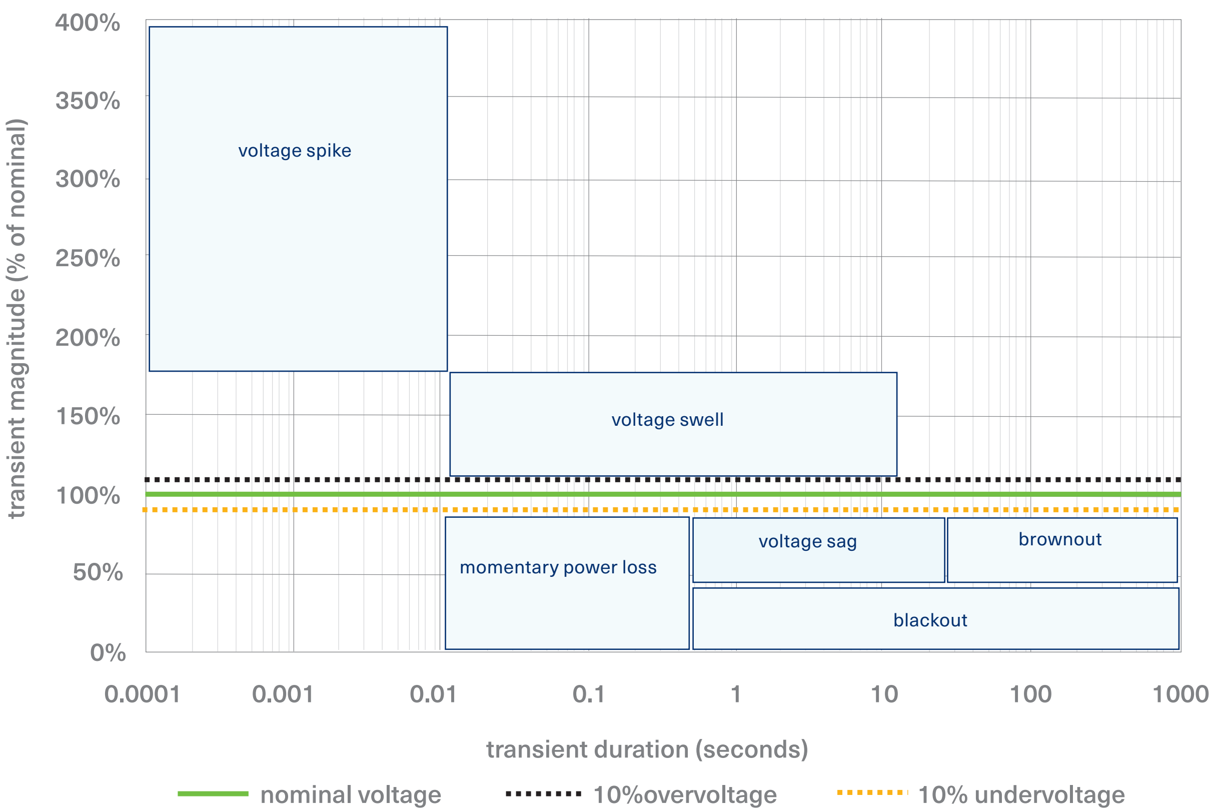
Figure 2 illustrates some of these transient types overlayed onto the voltage operating envelope to provide insight into how they differ.

Note: Electrical power transients are not limited to the magnitude and duration values shown. Table 2 and Figure 2 are not intended to list all possible transients.

Table 2. Electrical transient types

Transient type	Description
Voltage spike	High magnitude, short duration Special measurement equipment is needed to observe. Potential to damage electronic circuits.
Voltage sag	Medium magnitude, medium duration Longer duration sags may show up in RMS (root mean square) trend data, although shorter duration sags will not. Potential for undervoltage trips; overvoltage trips may also occur due to inrush when power returns.
Voltage swell	Medium magnitude, medium duration Longer duration swells may show up in RMS trend data, although shorter duration swells will not. Potential for overvoltage trips.
Momentary power loss	Short duration power outage, often associated with transferring power between sources (e.g., utility to generator). Potential for large transients when the incoming power source is connected.
Voltage “brownout” or “blackout”	Medium-to-long duration loss of electrical power. Expect equipment to shutdown and restart after power returns; restart may be manual or automatic.
Voltage imbalance	Three-phase voltages are not equal A small voltage imbalance may lead to a large current imbalance. Potential to overload phase(s) that carry higher current.
Electrical harmonics	Non-sinusoidal voltage or current, typically associated with variable-speed drives. (refer to *Engineers Newsletter* 47-1 “Harmonic Distortion in Electrical Systems”)
Electromagnetic Interference (EMI)	High-frequency noise interferes with communications and control boards.

Figure 2. Transient types within the voltage operating envelope



Electrical System Grounding

The ground reference of an electrical system can affect the magnitude of voltage transients, especially the voltage from line to ground. This may cause electrical stress on wire insulation, motor windings, or electrical sensor circuits.

The term "grounding" has different meanings in electrical systems:

Equipment grounding ensures that the chassis is properly bonded to earth. This ensures that the voltage potential on the chassis is limited to safe values, even during fault conditions. The term "bonding" is also used to describe equipment grounding.

System grounding sets the line-to-ground voltage value during normal operation. The system ground is made on the secondary side of the feeder transformer.

Ground fault is an unwanted connection from any phase(s) to ground. The most common example is faulty insulation on wires or in a motor. Ground fault protection is often used to quickly remove power from a circuit when current flows to ground.

Note: Equipment chassis must be grounded to earth regardless of system grounding method. Failure to install equipment ground may result in electrical shock hazard.

IEEE Standard 142-2007 provides a detailed description of electrical system grounding methods. The most common methods include:

Center grounded wye limits the line-to-ground voltage to equipment. Ground current may be high during fault conditions, leading to large arc flash potential. Center grounding requires a feeder transformer with wye-connected secondary.

Impedance grounded limits ground current that may flow during fault conditions. This limits the potential for arc flash, as well as transient voltage spikes, during a fault. The voltage across the ground impedance also provides a simple method to measure ground current for ground fault trip capability. This category includes High Resistance Grounded (HRG) systems.

Ungrounded systems may continue to operate with a single line-to-ground fault (acts like a corner grounded system). This results in high transient voltage from line-to-ground during fault conditions.

Corner grounded allows a ground reference to be installed on a transformer with delta secondary.

The system ground reference is made at the feeder transformer. Isolation transformers allow the feeder to be locally ground referenced while the upstream electrical system is ground referenced at the upstream transformer, such as the electrical substation transformer.

These grounding methods differ by how the ground wire is connected to the transformer winding (or left disconnected). Wye connected transformer windings allow for connection at the center point, while delta connected transformer windings do not (Figure 3).

Center grounding is achieved by connecting the center point of a wye connected secondary winding to ground (Figure 4). This provides symmetrical ground reference, meaning that the line-to-ground voltage is the same for all lines.

High-impedance grounded systems include a resistive element between the transformer center point and ground (Figure 5). By measuring the voltage across the ground impedance, a value of ground current can be calculated. The ground current value is used for ground fault interrupt trips, as well as for system monitoring. The ground impedance also limits the peak value of ground current during fault events.

Delta-connected secondary windings do not allow for center grounding. Delta-connected secondary windings are often left ungrounded (Figure 6). The most common method of grounding a delta-connected secondary winding is by connecting one phase to ground, referred to as corner grounding. Some delta-connected windings include a center tap on one winding, which can be connected to ground, referred to as high-leg grounding (not pictured).

Figure 3. Examples of delta-delta and delta-wye transformers

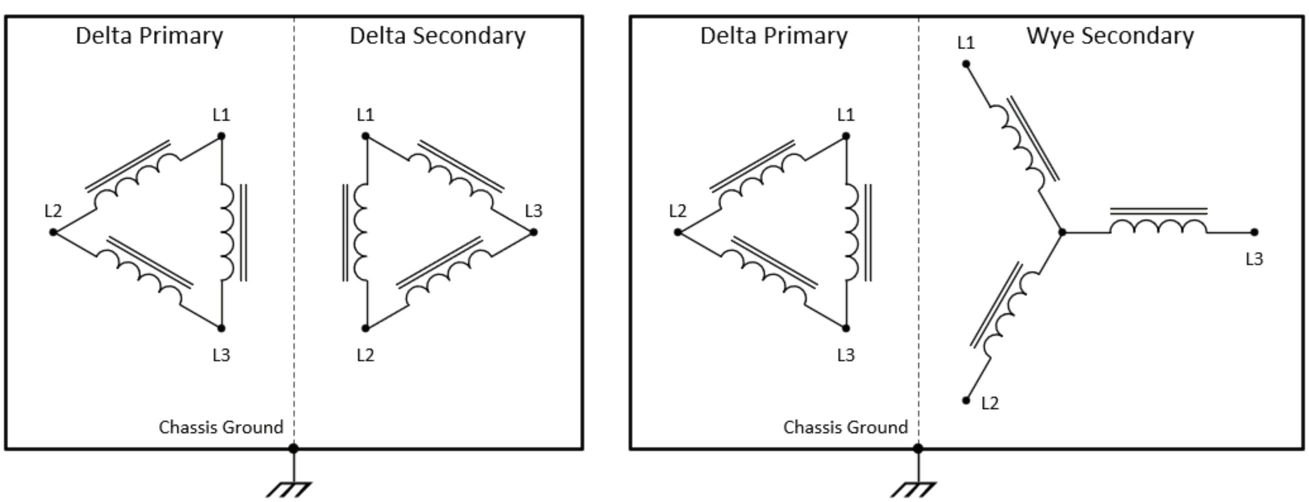


Figure 4. Example of center grounding

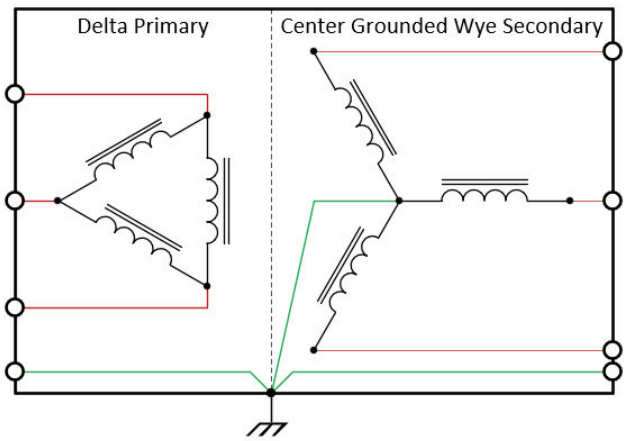


Figure 5. Example of high impedance grounding

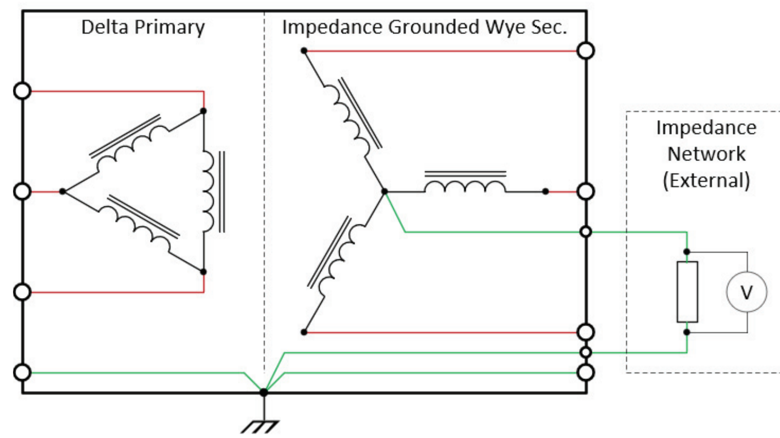
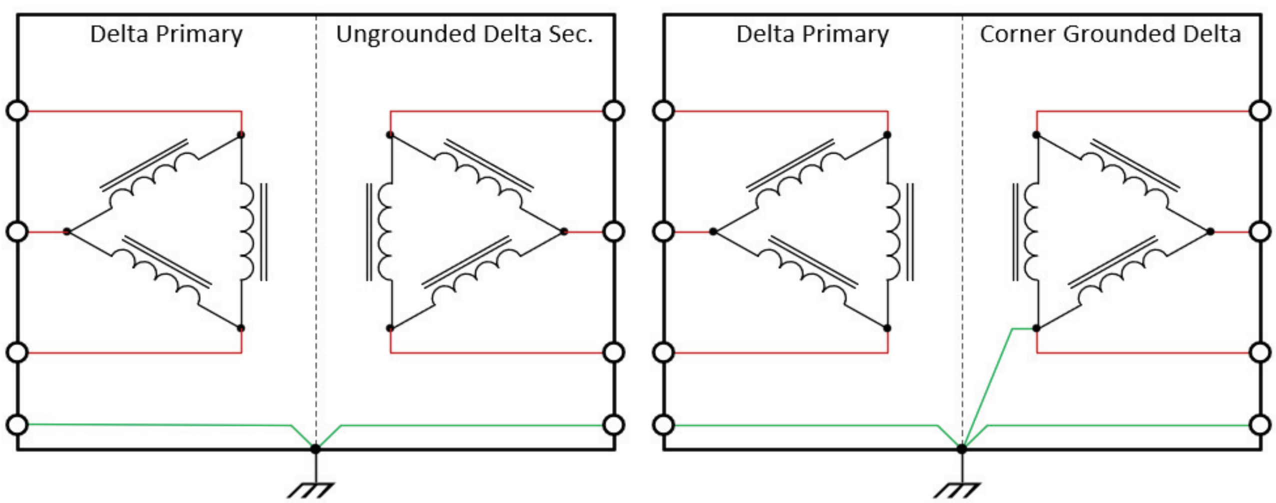


Figure 6. Examples of delta-connected secondary windings



Conducting a Power Quality Analysis

The goal of a power quality analysis is to identify sources of electrical transients to improve the operation and reliability of the electrical system. Specific scenarios that may lead to a power quality analysis include:

- Resolving ongoing equipment issues
- Investigating the root cause of equipment failure
- Trend monitoring of RMS voltages and currents
- Measuring total harmonic distortion (THD) in voltage and current

Capturing electrical power transients is challenging. Severe voltage spikes may occur only a few times per year, and may last only one millisecond. A good power quality meter (PQM) includes event triggering logic and large memory storage to help capture and record these events. The most important part of conducting a power quality analysis is knowing what transient types to look for and where to find them. The following is preparation work that will improve the outcome of this analysis:

1. Gather electrical system diagrams and identify problematic equipment. This will be used to determine where to hook up the power quality meter(s).
2. Collect fault logs and operator manuals for problematic equipment. If possible, involve the equipment manufacturer to better understand which types of electrical events may cause the recorded faults. This will be used in setting the event trigger types and thresholds.
3. Understand that power quality events do not happen every day; it may take weeks or months to gather the appropriate amount of data. Consider a multi-phase approach, such as a one-month initial monitoring period with a six-month follow-up monitoring period. This allows an initial report to be generated while additional data is being collected.

Some owners/operators may not be comfortable conducting a power quality analysis on their own. When hiring third party consultants, be sure to have thorough discussions about the desired outcome. A good power quality report will not only include data, but also conclusions and recommended actions to improve the reliability of the electrical system.

Owners/operators that wish to conduct a power quality analysis "in-house" need a high-quality power quality meter. The Dranetz *Handbook of Power Signatures* is a good reference when interpreting the data.

Installing permanent power quality monitoring equipment is another great option. Long term monitoring of power quality ensures that intermittent faults and one-time events are captured and recorded. This improves the ability to resolve electrical related problems that may happen on-site.

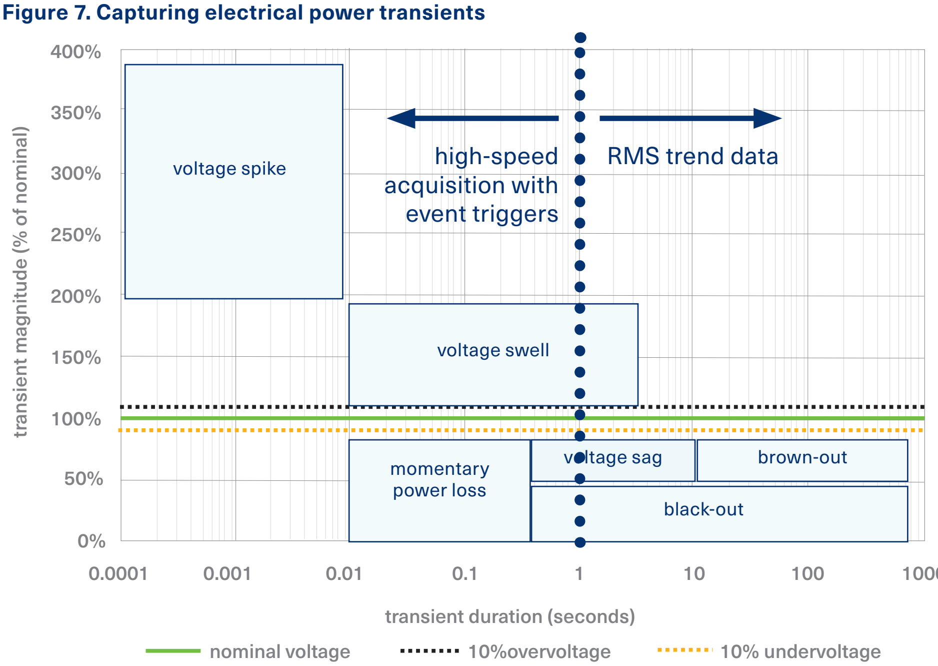
Electrical Safety Warning

High voltages pose significant risk of electrical shock. Only qualified individuals should access or work on high voltage circuits. De-energize equipment, follow lock-out / tag-out (LOTO) procedures, and use appropriate personal protective equipment (PPE).

A common mistake in power quality analysis is using root mean squared (RMS) trend data as "proof" that voltage transients do or do not happen. Keep in mind that RMS values are calculated over a time of approximately one second. This means that any transients faster than 1 second will not show up in the data. For example, a 2000V spike may show up as less than a 1Vrms increase in the RMS trend data. Fast electrical transients require high-speed data acquisition with sophisticated event triggers and thresholds.

Figure 7 illustrates which transient types can be captured with RMS trend data and which require a power quality meter to capture.

Figure 7. Capturing electrical power transients



Interpreting the Results of a Power Quality Analysis

The best possible outcome is a direct timestamp correlation between equipment fault logs and power quality data. This correlation is even stronger if multiple events can be correlated. The stronger the correlation is, the more motivated all stakeholders will be to act.

> *Example: Water-cooled chillers have experienced recurring over-voltage shutdown faults. Power quality analysis showed voltage spike events that matched timestamps from the chiller fault log. Further investigation showed that power factor correction capacitors had been switched on at those times. The building owner worked with the utility provider to adjust timing of the power factor correction capacitors, resolving the shutdown issues.*

In many cases, power quality analysis is conducted in response to equipment failure. Unless power quality meters were connected when the fault happened, it will not be possible to show a direct correlation between electrical power quality and equipment fault logs. The following strategies may be used to help:

- Record fault logs from the failed equipment. Contact the manufacturer to determine if the equipment can be returned for forensic inspection.
- Check replacement equipment for similar faults as the original. This may allow correlation between new power quality data and ongoing fault events with the replacement equipment.
- Instead of focusing on root cause investigation of the original equipment, focus on best practices for the replacement equipment. Use new power quality data to guide improvements to the electrical system. Refer to “potential solutions” for each transient type in the next section of this EN.
- Consult with the equipment manufacturer to determine acceptable power transient levels. If the manufacturer cannot commit to acceptable levels, the CBEMA, ITIC and SEMI curves are a good starting point (see Figure 1).

Making corrective action to the electrical system requires that the source of electrical power transient be known. Capturing the event does not necessarily prove what caused it. The Dranetz *Handbook of Power Signatures* shows dozens of waveform examples that can help identify the root cause based on waveform shape. If the data is still inconclusive, the following strategies may help:

- Measure voltage further upstream. Transients caused by *upstream* events will also show up in the upstream voltage.
- Measure the total current drawn from the feeder. Transients caused *downstream* by other loads on the feeder will show up in the feeder supply current.

Typical Causes and Effects of Electrical Transients, and Potential Solutions

Voltage spike

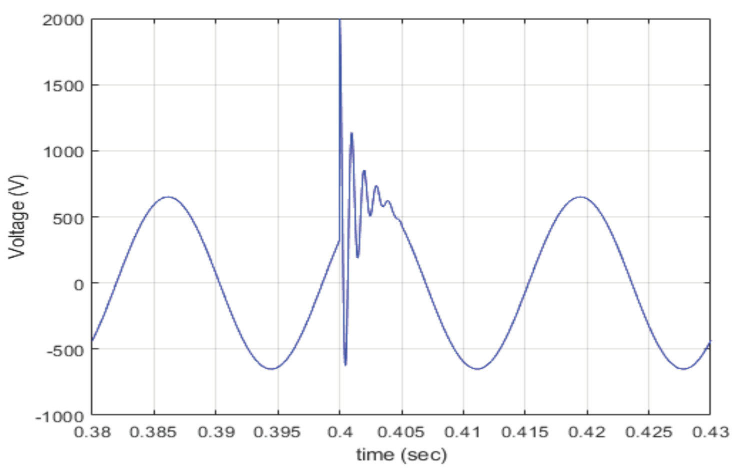
The example waveform shown in Figure 8 is a 2000V voltage spike with duration of ~0.2 milli-seconds. This voltage spike will only show up in high-speed capture using event triggers. RMS trend data for this event will show only a ~0.8V increase because of the 2000V spike.

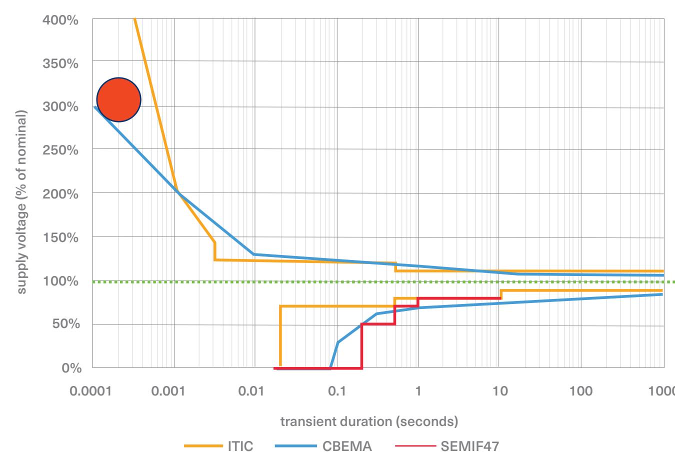
Causes: Lightning strikes, power factor correction (PFC) capacitor switching, fault clearing (the end of a short circuit condition), or inductive kick (turning off a large inductive load). Ungrounded electrical systems are more prone to voltage spikes, especially line-to-ground voltages.

Effects: High voltage magnitude causes stress on insulating materials, such as wire insulation, motor windings, cable harnesses, and circuit boards. Most circuit boards include features to absorb some voltage spikes. If the spike is severe enough, it may exceed the component limits, resulting in failure. Short duration spikes often go undetected by the controls because they occur too quickly. Variable-frequency drives (VFDs) are susceptible to voltage spikes, but they typically protect motors from being affected.

Potential solutions: If possible, identify the source of voltage spikes and suppress the transient at the source. Surge protection devices (SPD) or metal oxide varistors (MOV) can be used to shunt voltage spikes away from sensitive equipment. Isolation transformers can be installed for sensitive equipment. For ungrounded systems, consider converting to center grounded, or create a local grounded network with an isolation transformer.

Figure 8. Example of a voltage spike waveform





Voltage sag

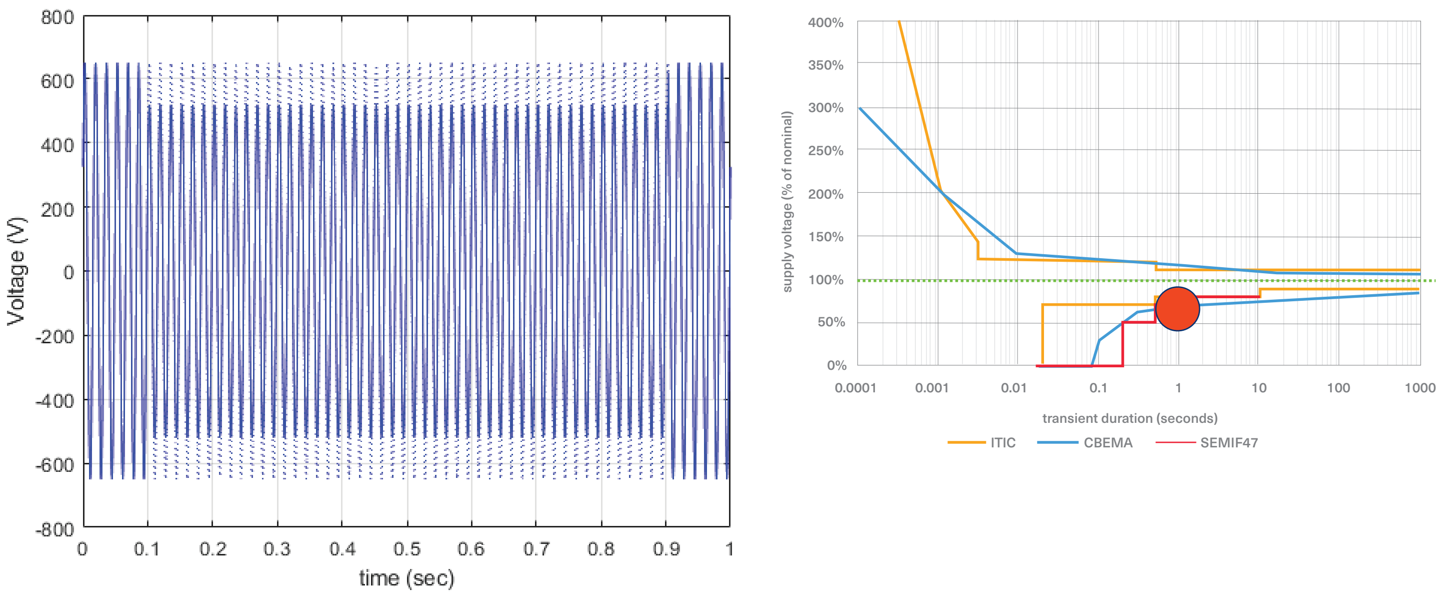
The example waveform in Figure 9 shows a 0.8 second voltage sag, down to 80 percent nominal voltage. RMS trend data can be used to capture longer duration voltage sags, but not shorter duration (< 1 second).

Causes: Line starting a large induction motor, fault conditions, or poor generator voltage regulation

Effects: Very short duration voltage sags may go unnoticed. Longer voltage sags (> 1 second) may cause control voltage to drop out of range, resulting in undervoltage transients. Line connected motors may experience higher current and lower power factor during voltage sag conditions.

Potential solutions: If the voltage sag is due to high inrush current when starting a motor, the inrush current can be reduced with a reduced voltage starter, soft starter, or VFD. If the voltage sag is due to upstream power supply, contact the utility provider or generator manufacturer.

Figure 9. Example of a voltage sag waveform



Voltage swell

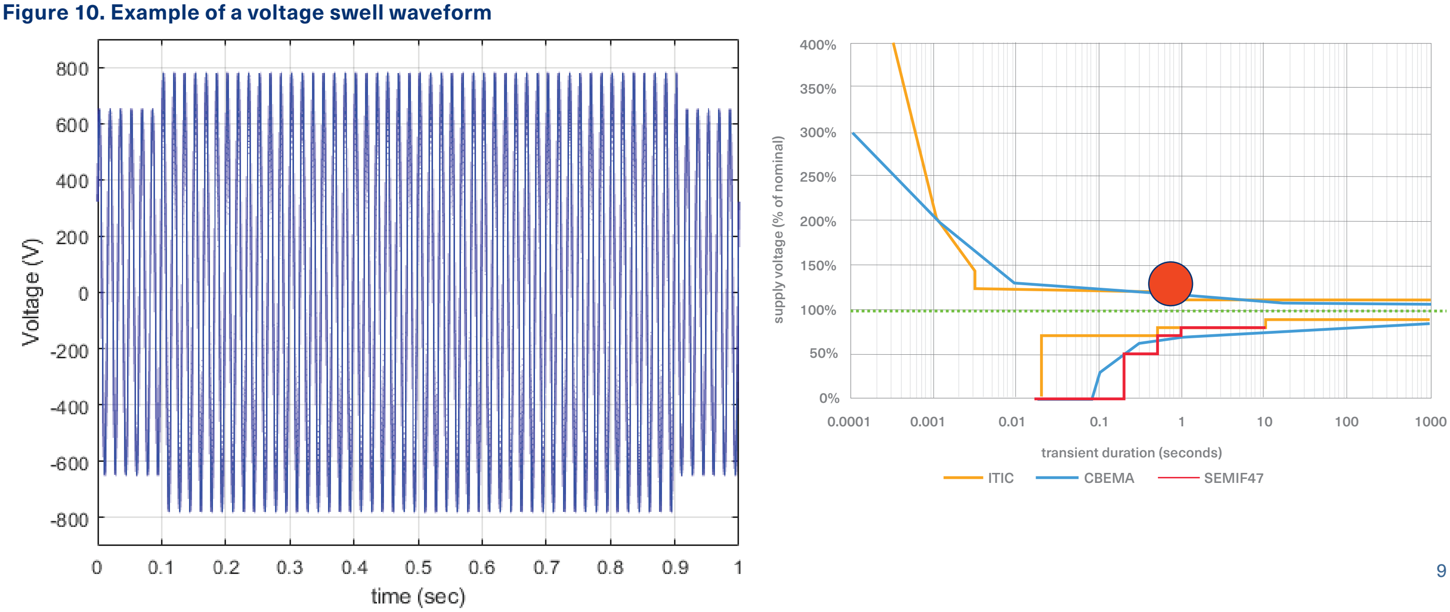
The example waveform in Figure 10 shows a 0.8 second voltage swell, to 120 percent of nominal voltage. RMS trend data can be used to capture longer duration voltage swells, but not shorter duration (< 1 second).

Causes: Utility or generator voltage regulation issues

Effects: While the magnitude of voltage swells is not as high as voltage spikes, the longer duration of voltage swells results in damage potential. Voltage swells are particularly stressful on capacitors inside VFDs and control power supplies.

Potential solutions: Contact the utility provider or generator manufacturer.

Figure 10. Example of a voltage swell waveform



Momentary power loss

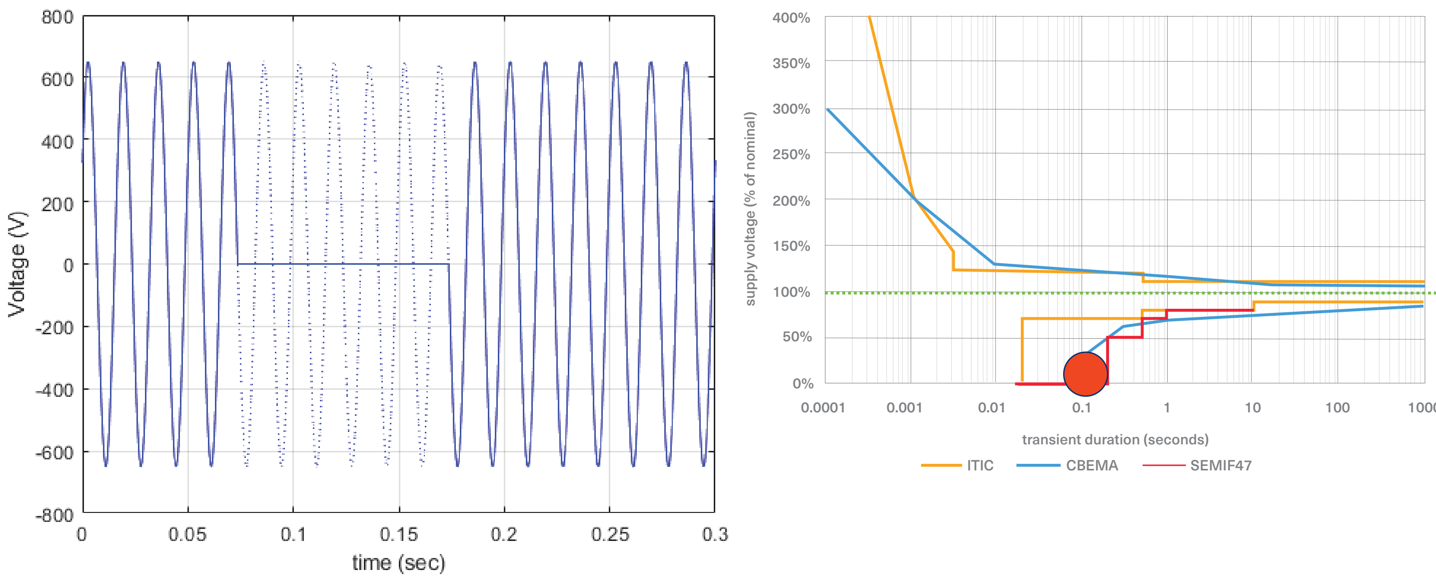
The waveform in Figure 11 shows a momentary power loss for six electrical cycles (0.1 seconds).

Causes: Short duration power outage or switching between power sources (e.g., between utility and generator)

Effects: Equipment should "ride through" or continue operating with momentary power loss of 2 to 3 electrical cycles (0.034 to 0.05 seconds). Longer duration power loss should result in equipment shutdown and subsequent restart when power returns.

Potential solutions: If the momentary power loss is due to electrical transfer switches in the building, check the transfer switch timing. Open transfers should be set for one second or longer.

Figure 11. Example of a momentary power loss waveform



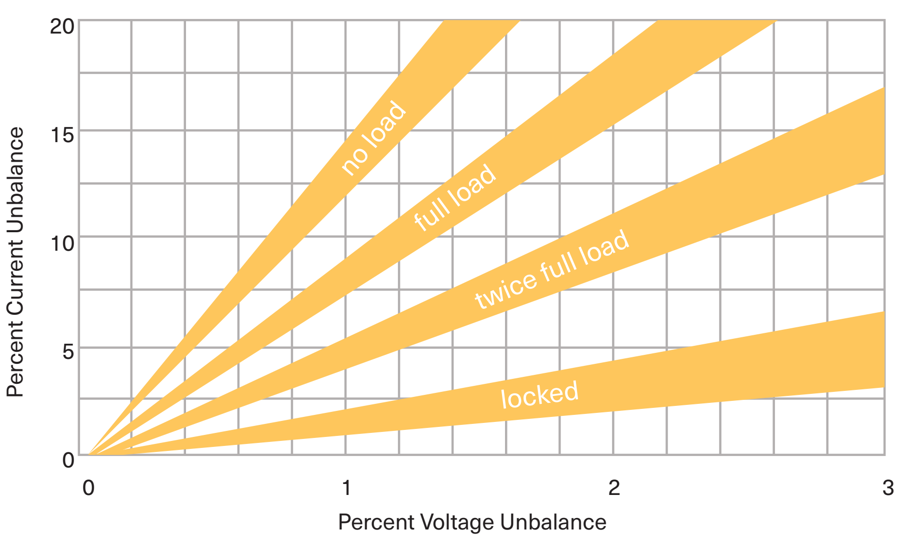
Voltage imbalance

Causes: Feeder transformer issues or unbalanced load distribution

Effects: Small voltage imbalances can cause large current imbalances (e.g., if one phase voltage is 1 percent higher than the others, that phase may draw 10 percent higher current). The phase that draws higher current may become overloaded, triggering a diagnostic or blowing a fuse. VFD harmonic levels go up during voltage imbalance (Figure 12).

Potential solutions: Check for unequal loading between phases, such as distribution of single-phase transformers. Check the upstream supply voltage and feeder transformer output voltage.

Figure 12. Current unbalance caused by applied voltage unbalance



Total harmonic distortion (THD)

Figure 13 illustrates an example waveform for VFD input current harmonics of 42 percent THD. Measurements are typically captured with harmonic spectrum, shown on the right.

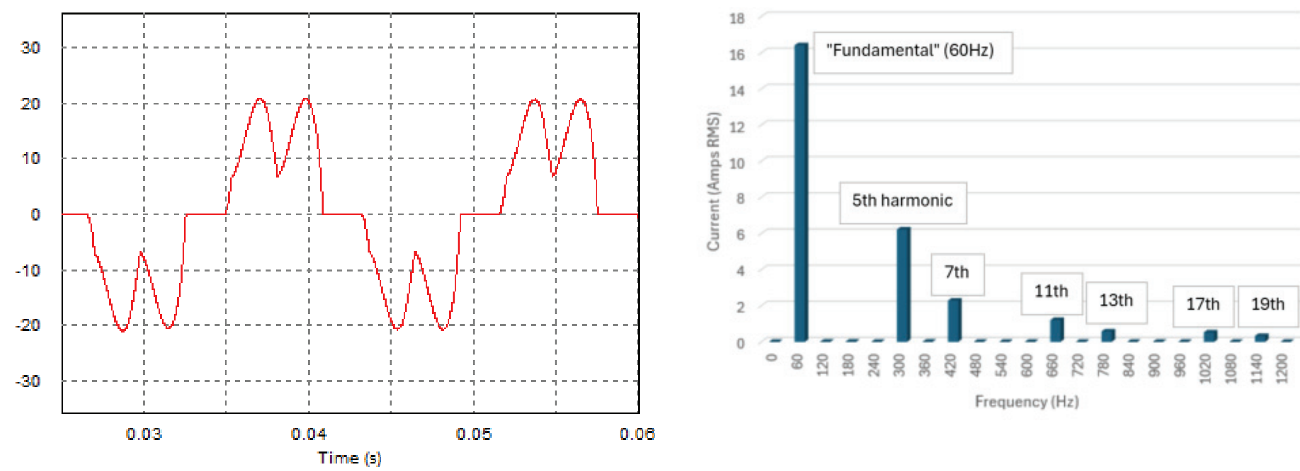
Causes: VFDs without harmonic filtering

Effects: Transformer heating/noise or interference with other equipment (refer to *Engineers Newsletter* 47-1, “Harmonic Distortion in Electrical Systems”).

Potential solutions: Install a harmonic filter. Passive harmonic filters can be installed on individual VFD loads. Active harmonic filters can be installed on individual loads or for multiple loads combined on a feeder. Passive harmonic filters use inductors and capacitors to “trap” the harmonics and dissipate them.

Active harmonic filters measure the distorted current and inject a compensating current, which is the opposite value (think of noise-canceling headphones). Harmonic currents do not have to be completely eliminated. Refer to IEEE-519 to find the acceptable level of harmonics current.

Figure 13. Example of a THD waveform



Voltage brownout or blackout

Causes: Utility provider supply voltage issues (brownout typically refers to a partial loss of voltage, whereas blackout means complete loss of voltage)

Effects: Brownouts and blackouts will typically trigger the undervoltage diagnostic, causing equipment to shut down. Refer to voltage sag and momentary power loss.

Potential solutions: Contact the utility provider or consider adding an uninterruptable power supply (UPS) or backup generator.

Electromagnetic interference (EMI)

Causes: Grounding issues, signal routing (communication wire routed next to power wires), or shielded wires not used

Effects: EMI noise may be conducted through power wires or ground wires, or radiated through air like an antenna. High frequency noise from one device can cause control circuits to malfunction as the communication signals are sensitive. EMI problems are often intermittent and difficult to troubleshoot.

Potential solutions: Check ground connections on the trouble equipment, as well as neighboring equipment (especially VFDs). Route communication wires in shielded cable, away from power wires. Install common mode cores on sensitive communication wires. If the problems are linked to noise from a specific piece of equipment, consider adding an EMI filter on that equipment.

Conclusion

Electrical power quality is important to reliable operation of HVAC equipment. Measuring the quality of electrical power can be challenging. However, specialized equipment is available to make the job much easier.

This *Engineers Newsletter* described several types of power quality events (electrical transients), along with potential causes, effects, and potential solutions to mitigate those effects. Continuous-monitoring equipment can be installed at the feeder to quickly find and resolve power quality issues.

By Ben Sykora, Applications Engineer, Trane. To subscribe or view previous issues of the Engineers Newsletter visit trane.com/EN. Send comments to ENL@trane.com.

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IEEE Standard 1100-2005, “Recommended Practice for Powering and Grounding Electronic Equipment”

IEEE Standard 1159-2019, “Recommended Practice for Monitoring Electrical Power Quality”

SEMI F47, “Specification for Semiconductor Processing Equipment Voltage Sag Immunity”

ADM-APN094-EN
March 2025