Power Quality Troubleshooting

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Introduction

While we've enjoyed enormous benefits from the evolution of solid state technology, the fact is that the microelectronics at the heart of that technology requires clean power. Faster speeds and lower voltages mean that there is less and less tolerance for anything less than quality power.

Power Quality (PQ) covers a wide range of issues, from voltage disturbances like sags, swells, outages and transients, to current harmonics, to performance wiring and grounding. The symptoms of poor PQ include intermittent lock-ups and resets, corrupted data, premature equipment failure, overheating of components for no apparent cause, etc. The ultimate cost is in downtime, decreased productivity and frustrated personnel.

This application note gives you information on how to troubleshoot PQ problems. It also gives you information on how to start fixing those problems. But before grabbing that meter, please read the following cautionary notes:

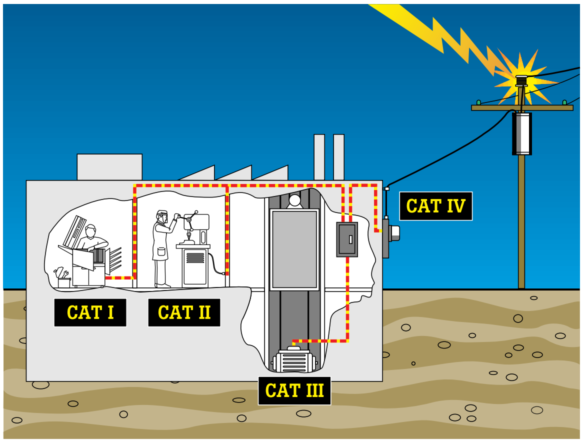
1. Suggested measurements should only be made by qualified personnel who have been trained to make these measurements in a safe manner, using proper procedures and test tools rated for work on electrical power circuits.
2. To the best of our knowledge, recommended solutions are consistent with the National Electric Code (NEC), but in any case, NEC requirements must not be violated.
3. We have tried to make the information accurate and current, but it is not intended to be a substitute for the specialized knowledge and experience of professional power quality practitioners.

What this application note offers is a "starter kit," not the final word on PQ troubleshooting.

International Safety Standards for Test Tools

Overvoltage Category	Summary Description
CAT IV*	Three-phase at utility connection, any outdoors conductors (under 1000V)
CAT III	Three-phase distribution (under 1000V), including single-phase commercial lighting and distribution panels
CAT II	Single-phase receptacle connected loads
CAT I	Electronic

*CAT IV product specifications are not yet defined in the standard.



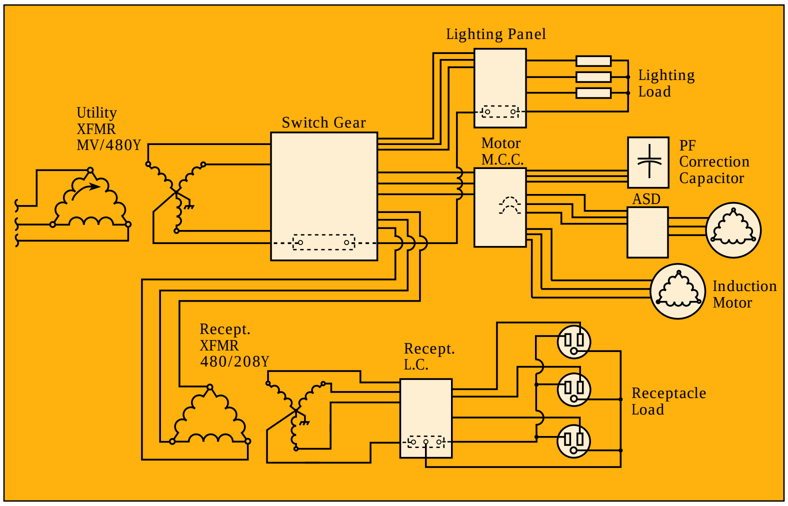
IEC 61010 establishes international safety requirements for low voltage (1000V or less) electrical equipment for measurement, control and laboratory use. The low voltage power distribution system is divided into four categories, based on the proximity to the power source. Within each category are voltage listings—1000V, 600V, 300V, etc.

The key concept to understand is that you should use a meter rated to the highest category, as well as the highest voltage, that you might be working in. For PQ troubleshooters, that means a meter rated to CAT III-600V or CAT III-1000V (the specifications for CAT IV have not yet been defined by IEC). We recommend that you do not use CAT II rated meters, scopes or test leads and probes on CAT III circuits. The CAT ratings should be marked near the voltage inputs of the instrument. Meters designed to IEC 348, the previous standard, will typically not meet the more stringent safety specs of IEC 61010 CAT III-600/1000V.

IEC 61010 requires increased protection against the hazards of transient overvoltages. Transients can cause an arc-over inside an inadequately protected meter. When that arc-over occurs in a high energy environment, such as a three-phase feeder circuit, the result can be a dangerous arc blast. The potential exists for serious harm to personnel as well as damage to the meter. For more information, see the Fluke application note "ABCs of Multimeter Safety" (document number B0317UEN) and the Fluke video "The ABCs of Digital Multimeter Safety" (P/N 609104).

Independent Testing and Certification

Manufacturers can self-certify that they meet IEC 61010 specs, but there are obvious pitfalls for the end-user in self-certification. Certification by an independent testing lab provides assurance that the meter meets IEC requirements. Look for a symbol and listing number of an independent testing lab such as UL, CSA, TÜV, VDE, etc. UL 3111, for example, is based on IEC 61010.



Simplified electrical distribution system typical of commercial and industrial facilities.

Start at the scene of the crime

To troubleshoot PQ problems, one approach is to start as close to the "victim load" as possible. The "victim load" is the sensitive load, typically electronic, that is somehow malfunctioning. Poor PQ is suspected, but part of your job is to *isolate* PQ as a cause from other possible causes (hardware, software?). Like any detective, you should start at the scene of the crime. This bottom-up approach can take you a long way. It relies on making use of a sharp eye and on taking some basic measurements.

An alternative is to start at the service entrance, using a three-phase monitor, and work back to the "victim load." This is most useful if the problems originate with the utility. Yet survey after survey has concluded that *the great majority of PQ problems originate in the facility*. In fact, as a general rule, PQ is best at the service entrance (connection to utility) and deteriorates as you move downstream through the distribution system. That's because the facility's own loads are causing the problems. Another illuminating fact is that *75% of PQ problems are related to wiring and grounding problems!*

For this reason, many PQ authorities recommend that a logical troubleshooting flow is to first diagnose the electrical infrastructure of the building, then monitor if necessary. Our bottom-up troubleshooting procedure is designed to help you do this detective work.

First steps

1. Make a map: Obtain or create a current one-line

It's tough to diagnose PQ problems without having a working knowledge of the site being investigated. You can start by locating or reconstructing a one-line diagram of the site. The one-line will identify the ac power sources and the loads they serve. The "as built" one-line, the one with red-lines, is the one you want.

If you work on-site, the map might already exist in your head, but it will be a big help to everyone, including yourself, if it's on paper. If you're coming to a work site for the first time, getting an up-to-date one-line means identifying new loads or other recent changes in the system. Why go to this effort? Systems are dynamic; they change over time, often in unplanned and haphazard ways. Furthermore, while some problems are local in origin and effect, there are many problems that result from interactions between one part of the system and another. Your job is to understand these system interactions. The more complete your documentation, the better off you'll be.

It's true, however, that the sites that need the most help are the ones least likely to have a good record of what's going on in their system. Many a consultant has earned his fee by upgrading the documentation handed him with what actually exists on-site. So the simple rule is, at this point in the investigation, do the best you can to get good documentation, but don't count on it being available.

2. Do a walk around of the site

Sometimes a visual inspection will offer immediate clues:

- A transformer that's much too hot
- Wiring or connections discolored from heat
- Receptacles with extension strips daisy-chained to extension strips
- Signal wiring running in the same trays as power cables
- Extra neutral-ground bonds in sub-panels.
- Grounding conductors connected to pipes that end in mid-air.

At a minimum, you will get a sense of how the facility is wired and what the typical loads are.

3. Interview affected personnel and keep an incident log

Interview the people operating the affected equipment. You will get a description of the problem and often turn up unexpected clues. It's also good practice to keep a record of when problems happen and what the symptoms are. This is most important for problems that are intermittent. The goal is to find some pattern that helps correlate the occurrence of the problem in the "victim load" to a simultaneous event elsewhere. Logically, this trouble-logging is the responsibility of the operator closest to the affected equipment.

Part I: Facility Distribution System

Section 1
Receptacle Branch Circuit

Many PQ problems show up at the branch circuit level. There's a simple reason for this: that's where most of the sensitive loads (and sensitive employees) are located. It's also the "end of the line" of the electrical system, and the place where shortcomings can't be hidden. Let's assume you've been called in to solve the problem. You've already talked to the people involved, have a rough idea of the symptoms (equipment lock-ups, intermittent resets or crashes, etc.) and as much sense of the timing and history of the problems as you can get. So it's time to gather hard evidence: it's time to take measurements.

Our primary focus with troubleshooting at the receptacle level is to determine if the Line-Neutral (L-N) voltage available is of sufficient stability and amplitude to supply the needs of the load(s).

Measurement

1. Waveform

The waveform gives us quick snapshot information. An ideal waveform would be a sine wave. In this case, (see Fig 1.1) the voltage waveform is flat-topped, which is typical of a building with many non-linear loads such as computers and other office equipment (see "Flat-topped voltage," page 5).

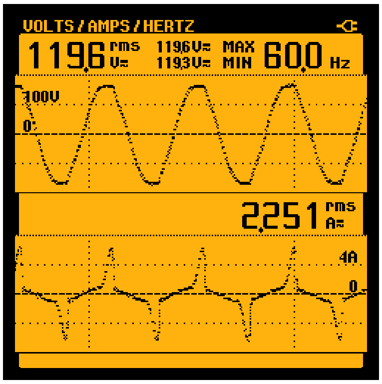


Figure 1.1 Flat-topped voltage at receptacle.

Our other measurements will tell us whether this flat-topping is excessive.

2. Peak voltage

The peak value is critical to electronic loads because the electronic power supply charges its internal capacitors to the peak value of the line voltage. If the peak is too low, it affects the ability of the caps to charge fully and the ability of the power supply to ride through momentary dips in the line voltage. For an RMS voltage of 115V, the peak value would be 1.414 x 115V = 162.6V, if the waveform were a sine wave. However, as we just saw from the flat-topped waveform, what we have is far from a sine wave and will have a lower peak value.

3. RMS voltage

Nominal line voltage is measured in RMS (root-mean-square) which corresponds to the effective heating value. Equipment is rated in RMS, not peak, because their main limitation has to do with heat dissipation.

RMS voltage can be too high or too low, but it is usually the low voltage that causes problems. Low RMS voltage combined with flat-topping (low peak) is a deadly combination for sensitive loads.

Voltage drop is a function of both the loading of the circuit and the source impedance, which in effect means the length and diameter (gauge) of the wire run. The NEC (210-19.a, FPN No. 4) recommends a limit of a 3% voltage drop from the branch circuit breaker to the farthest outlet, and a total voltage drop of less than 5% including the feeder and branch circuit.

4. Recording (short-term)

The limitation of the above measurement is that it is static. Many loads require more current, usually referred to as inrush current, when they are first turned on. This momentary high current may cause a momentary low voltage (sag) because of the additional IR drop through the conductors. Such sags are often caused by loads drawing inrush currents on the same branch circuit, or on the same panelboard.

You can measure a worst-case sag of 100 ms or more (about 6 cycles at 60 Hz) by using the MIN MAX function of the Fluke 87 while energizing the load. What if you want to know if there are recurring sags? The Sags & Swells trending feature of the Fluke 43 Power Quality Analyzer will continuously capture sags of as little as single cycle duration (17 ms). A four-minute to a one-hour recording time (i.e., anywhere from a single cup of coffee to a lunch break) may be enough to tell you if there are recurring sags and swells.

Table 1.1 Measurements on receptacle branch circuits.

Voltage Measurements	Look for	Instrument
1. Waveform	Snapshot of severity of voltage distortion	43 PQ Analyzer 41B Harmonics Analyzer
2. Peak voltage	Excessive flat-topping	43 PQA, 41B 87 DMM (Peak MIN MAX)
3. RMS voltage	Low rms (steady-state low rms or intermittent/cyclical sags)	43 PQA (Sags/Swells) 41B (MIN MAX) 87 DMM (MIN MAX)
4. Recording (short-term)	Sags, swells, interruptions while troubleshooter remains on-site (4 minutes to 1 hour typical recording time)	43 PQA (Sags/Swells or Transients)
5. Recording (long-term)	Up to 4,000 sags, swells, outages, transients	VR101S
6. Neutral-ground	N-G voltage too high (or close to zero)	43 PQA, 87 DMM

Flat-topped voltage

The flat-topped waveform is typical of the voltage in a commercial building with computer loads. What causes flat-topping?

The utility supplies ac power, but electronic equipment runs on dc power. The conversion of ac into dc is done by a power supply. The PS has a diode bridge which turns ac into pulsating dc, which then charges a capacitor. As the load draws the cap down, the cap recharges. However, the cap only takes power from the peak of the wave to replenish itself, since that's the only time the supplied voltage is higher than its own voltage. The cap ends up drawing current in pulses at each half-cycle peak of the supplied voltage. This is happening with virtually all the electronic loads on the circuit. Now that we see what the loads are demanding from the source, let's take a look at what the source can supply.

If the source were perfectly "stiff," meaning that it had an infinite capacity to supply all the current that was required, then there would be no such thing as flat-topping (or sags or any voltage distortion). Think of it this way: if you had all the money in the world, you wouldn't get distorted either when the bills came in. But in the real world there are practical limits to what a source can supply. This limit is usually described by a concept called source impedance, which is the total impedance from the point you're measuring (or the point where the load is located) back to the source. There are two major contributors to this source impedance. One is the wiring; the longer the conductor and the smaller the diameter (higher gauge), the higher the impedance. The other factor is the internal impedance of the transformer (or other source equipment). This internal impedance is simply a way of saying that a transformer of a given size/rating can only supply so much current.

The source impedance is naturally greatest at the end of a branch circuit, the farthest point from the source. That's the same place where all those electronic loads are demanding current at the peak of the wave. The result is that the voltage peak tends to get dragged down—in other words, flat-topped. Maybe you've felt the same way when all the bills come in at the same time of the month. The more loads there are (the more the bills), the greater the flat-topping. Also, the greater the source impedance (the less the cash), the greater the flat-topping.

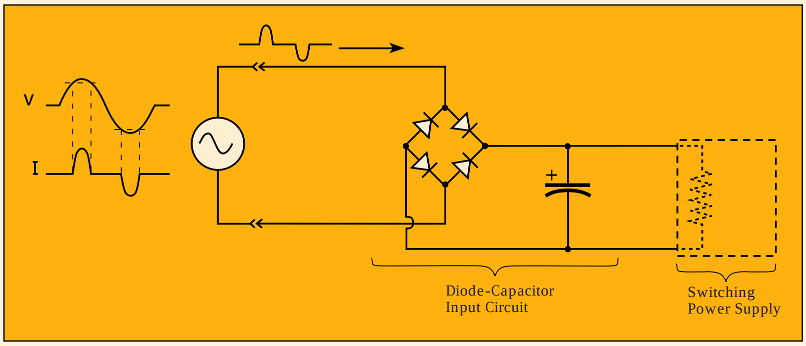


Figure 1.2 Flat-topped voltage.

5. Recording (long-term)

For longer term recording, the VR101S Voltage Event Recorders will record sags, swells, outages, transients and frequency deviations while plugged into the outlet (see "Recording at the Receptacle Outlet," page 7). The device can be left on-site, unattended, for days and weeks, all the time catching intermittent events (4000 event buffer). Now you can see why it's so important to ask the user to keep a troubleshooting log: correlation of equipment malfunction with voltage events is hard evidence of a PQ problem.

6. Neutral-to-ground voltage

Let's say that you make a simple L-N measurement at the outlet and get a low reading. You can't tell if the reading is low because the feeder voltage is low (at the subpanel), or if the branch circuit is overloaded. You could try to measure the voltage at the panel, but it's not always easy to tell which panel feeds the outlet you're measuring and it's also sometimes inconvenient to access a panel.

N-G voltage is often an easier way of measuring the loading on a circuit. As the current travels through the circuit, there is a certain amount of voltage drop in the hot conductor and in the neutral conductor. The drop on the hot and neutral conductors will be the same if they are the same gauge and length. The total voltage drop on both conductors is subtracted from the source voltage and is that much less voltage available to the load. The greater the load, the greater the current, the greater the N-G voltage.

Think of N-G voltage as the mirror of L-N voltage: if L-N voltage is low, that will show up as a higher N-G voltage (see Fig. 1.4).

Receptacle N-G Voltage Measurement Notes

1. A rule-of-thumb used by many in the industry is that N-G voltage of 2V or less at the receptacle is okay, while a few volts or more indicates overloading; 5V is seen as the upper limit. There's obviously some room for judgment in this measurement.
2. A *high reading* could indicate a shared branch neutral, i.e., a neutral shared between more than one branch circuit. This shared neutral simply increases the opportunities for overloading as well as for one circuit to affect another.
3. A certain amount of N-G voltage is normal in a loaded circuit. If the reading is stable at close to 0V, suspect an illegal N-G bond in the receptacle (often due to loose strands of the neutral touching some ground point) or at the subpanel. Any N-G bonds other than those at the transformer source (and/or main panel) should be removed to prevent return currents flowing through the ground conductors.
4. If N-G voltage is low at the receptacle, you're in good shape (see Measurement Note #3 for the exception to the rule). If it's high, then you still have to determine if the problem is mainly at the *branch circuit* level, or mainly at the *panel* level. Remember, assuming there's no illegal N-G bond in intervening panels or receptacles, your ground "test lead" goes all the way back to the source, so you're reading voltage drops all the way to the source.

N-G voltage exists because of the IR drop of the current travelling through the neutral back to the N-G bond. If the system is correctly wired, there should be no N-G bond except at the source transformer (at what the NEC calls the source of the Separately Derived System, or SDS, which is usually a transformer). Under this situation, the ground conductor should have virtually no current and therefore no IR drop on it. In effect, the ground wire is available as a long test lead back to the N-G bond.

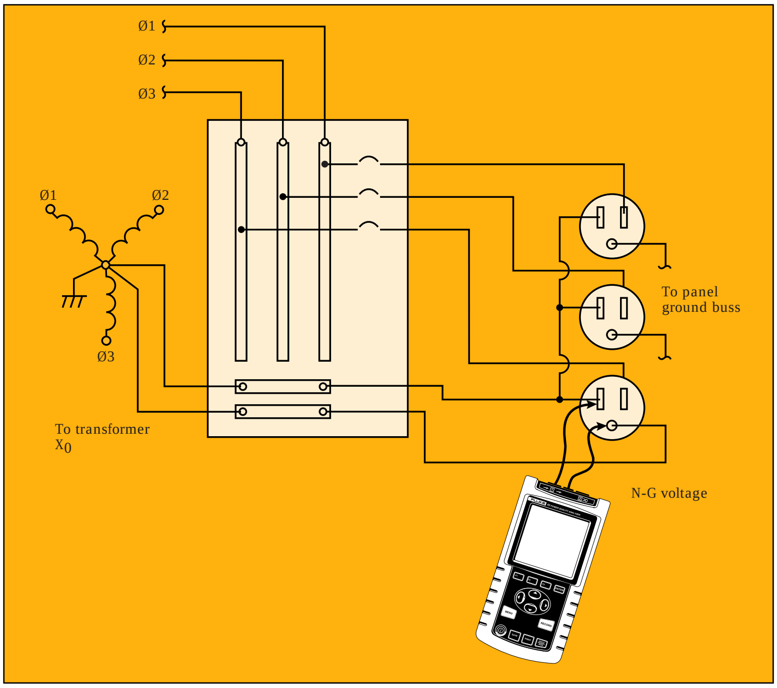


Figure 1.3. Neutral-to-ground voltage increases with shared neutrals.

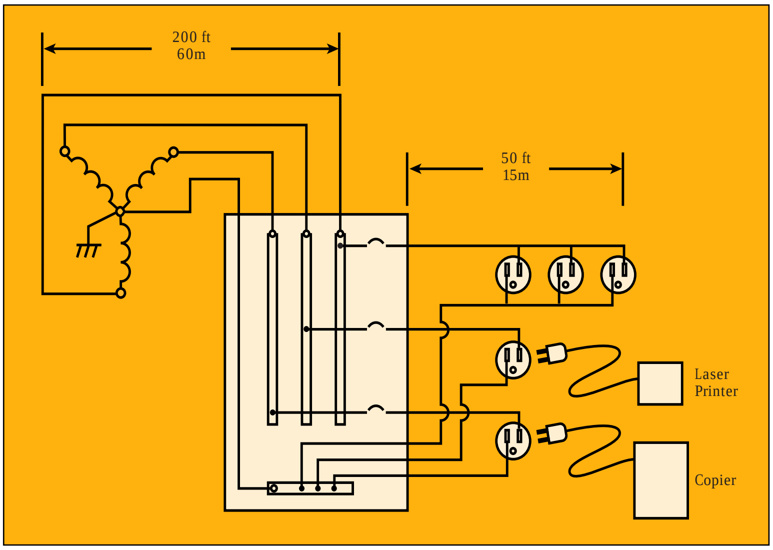


Figure 1.4 Neutral-ground voltage increases as load current goes up.

Shared neutrals

Some buildings are wired so that two or three phases share a single neutral. The original idea was to duplicate on the branch circuit level the four wire (three phases and a neutral) wiring of panelboards. Theoretically, only the unbalanced current will return on the neutral. This allows one neutral to do the work for three phases. This wiring short-cut quickly became a dead-end with the growth of single-phase non-linear loads. The problem is that zero sequence current from nonlinear loads, primarily third harmonic, will add up arithmetically and return on the neutral. In addition to being a potential safety problem because of overheating of an undersized neutral, the extra neutral current creates a higher N-G voltage. Remember that this N-G voltage subtracts from the L-N voltage available to the load. If you're starting to feel that shared neutrals are one of the worst ideas that ever got translated to copper, you're not alone.

Solutions

Performance Wiring vs. Code Minimum

Any experienced PQ troubleshooter will tell you that the first place to look for most problems is in the building wiring system (including its grounding system). Quality power depends on quality wiring; the term the industry uses is performance wiring (See Table 1.2). The basic intent of performance wiring is to maintain or restore L-N voltage to the load. There is a distinction between “performance wiring” and “code minimum” wiring. The NEC sets the absolute minimum requirements for a wiring job and is primarily concerned with fire prevention and personnel safety. The NEC should, of course, never be violated, but it is also important to understand that the Code’s objective is not to establish standards to achieve power quality. However, many facilities are finding that it pays to take the extra step and install or even retrofit a performance wiring job. As one veteran said, “If every building were performance wired, I’d be out of business. . . But there’s no fear of that happening.”

Power conditioning

There are also situations where receptacle-installed power conditioning devices are a good solution, either as a complement to the wiring changes or as an economically viable alternative to some wiring changes.

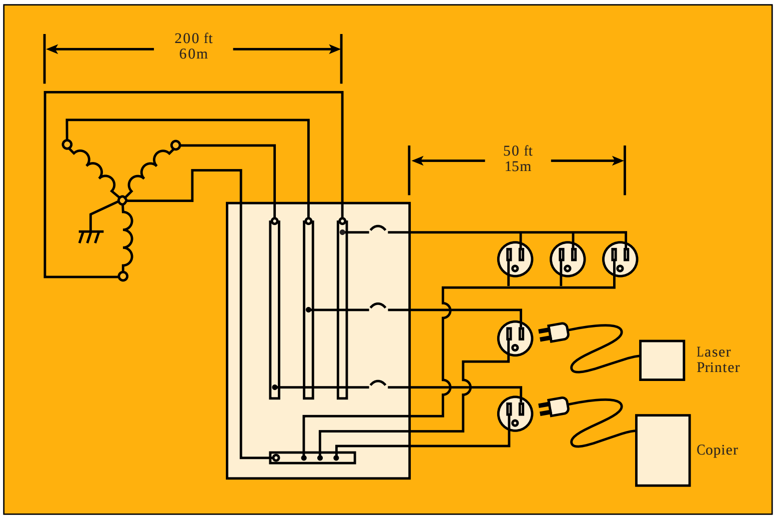


Figure 1.5 Performance wiring.

Table 1.2 Suggestions for performance wiring of branch circuits.

Recommendation	Reason
Check for loose connections.	It’s easy to overlook the obvious.
Eliminate shared neutrals. In new installations, pull individual neutrals for each branch circuit.	Minimize load interaction and source impedance.
Limit the number of receptacles per branch circuit to three.	Minimize loading and load interaction.
Limit length of 120V branch circuits to 50 ft. (15m).	Minimize source impedance.
Install dedicated branch circuits for all laser printers and copy machines. Dedicated circuits should be run in their own conduit.	Keep victim loads and culprit loads separated. Conduit prevents coupling between circuits.
Install a green wire ground (don’t just depend on the conduit connection).	Maintain a continuous, low impedance ground.
Label all panels, circuit breakers and receptacles.	Strictly speaking, this won’t improve power quality, but it will sure make life easier for the troubleshooter and the installer.

Recording at the receptacle outlet

By monitoring voltage events at the receptacle, you can see exactly the same voltage that the sensitive load sees.

The VR101 is plugged into an outlet, and can record up to 4000 events, including:

- Voltage sags and swells (rms)
- Outages
- Transients (L-N and N-G) with peak values
- Frequency deviation

Events are identified by type, real-time stamp, and duration.

VR101S operation

Set up

Use EventView software to configure the device. The unit comes with default thresholds, but users can enter new thresholds. An optical wand, supplied with the software, transfers new configurations to the VR101.

Plug in

The VR101 is left on-site for as long as needed. No computer connection is necessary. It draws power from the line and in the event of outages, a built-in battery saves data.

Download

The VR101 is taken to the computer. The optical wand retrieves its data.

Analyze

Events are displayed in spreadsheet format in EventView software. Charts, graphs and waveform graphics are also provided for report generation.

Section 2
Service Panels

Table 2.1 Service panel measurements.

Measurement	Look for	Instrument
1. Feeder phase current	Overloading and balance.	43, 41B, 87 w/80i-400, True-rms ClampMeter
2. Feeder neutral current	High currents from unbalanced fundamental and 3rd harmonics.	43, 41B for spectrum. 87 to find dominant frequency.
3. Feeder N-G voltage	High voltage indicates excessive current, near-zero indicates possible subpanel N-G bond.	Same
4. Branch L-N voltage	Low voltage.	Same
5. Branch neutral current	Shared neutrals.	Same
6. Voltage drop across breaker contacts. Hot breakers.	Worn contacts. Breakers in need of replacement.	43, 87

Check-out the service panel as follows:

- Visual inspection
- Feeder conductor current test
- Neutral conductor current test (feeder and branch)
- Phase-to-neutral voltage test (feeder and branch)
- Neutral-to-ground voltage test (feeder)
- Circuit breaker voltage drop and current on branch phase conductors

The service panel is where the effects of single-phase harmonic loads are easy to measure. A true-rms meter ensures accurate readings of non-linear voltages and currents (see “Why True-rms, page 27).

Visual inspection

- Look for an illegal Neutral-Ground bond in subpanels. This is a violation of the NEC as well as of PQ wiring. It is also extremely common. If an illegal N-G bond is found in one panel at a site, it is likely to be in any number of them. Who knows why they’re there: perhaps the installer was thinking that all panels are wired like residential service panels; or that the quickest way to reduce N-G voltage was to install a jumper, or that the more grounds the better. In any case, remove all illegal N-G bonds—no exceptions.
- Look for signs of *overheating*, such as discolored connecting lugs. Loose connections and excessive loading show up as heat. High levels of harmonic current that were not accounted for in the original wire sizing can also cause overheating. Infrared sensors are the preferred method for non- contact temperature measurement.
- Of particular concern is the *size of the feeder neutral conductor*. It has long been understood that any fundamental current resulting from the unbalance of single phase loads among the three phases will return on the neutral, but a relatively recent phenomenon is the third harmonic (triplen) currents generated by nonlinear single-phase loads that all return on the neutral.

  The 1996 NEC for the first time stated that “On a 4-wire, 3-phase wye circuit where the major portion of the load consists of nonlinear loads, there are harmonic currents present in the neutral conductor, and the neutral shall be considered to be a current-carrying conductor.” (Article 310, “Notes to Ampacity Tables of 0 to 2000 Volts,” Note 10.c). In effect, this requires that the neutral conductor at least equal the size of the phase conductor. This requirement is based on solid research: a 1990 survey of 146 sites nation-wide found that 22.6% of them had neutral current in excess of 100% of phase current!

  Many experts would recommend that the neutral be double the size of the phase conductor.
- Check for *shared branch neutrals*. Count neutral conductors for branch circuits: if there are fewer than the phase conductors, there are shared neutrals.
- Check tightness of *conduit connections*, especially if the conduit is being used exclusively as the grounding conductor (not recommended).

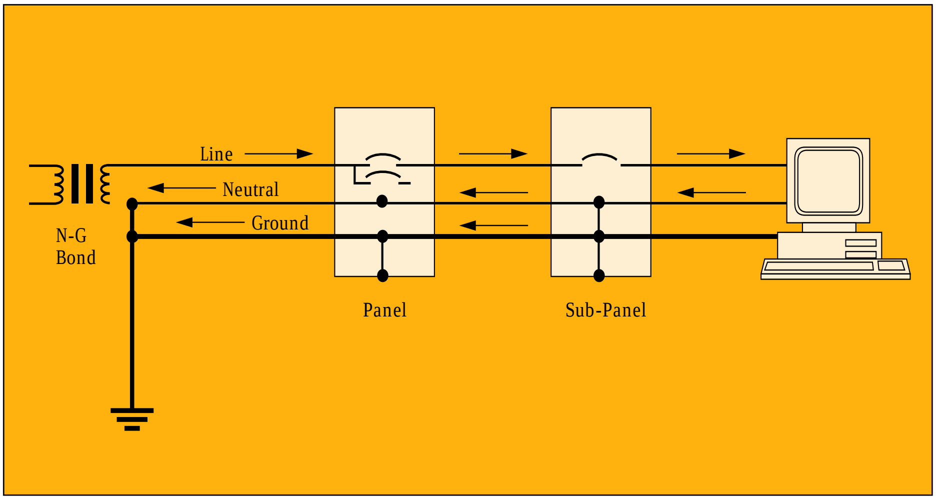


Figure 2.1 Sub-panel N-G bonds cause load return currents to flow on ground conductors. This causes corrosion of pipes in grounding system as well as noisy grounds.

Measurements

1. Feeder phase current

Check each phase to make sure it is not overloaded. Also check for excessive unbalance.

2. Feeder neutral current

Measure the feeder neutral conductor for cumulative neutral current. Third harmonic currents from all three phases will add arithmetically in the neutral.

3. Feeder neutral-to-ground voltage test

As at the receptacle, excessive N-G voltage indicates overloading. A N-G voltage at or very near zero indicates the existence of an illegal N-G bond in a subpanel.

4. Phase-to-neutral voltage test

Phase-to-neutral voltages are measured and recorded. They can be compared with receptacle L-N voltages to measure voltage drop.

5. Branch neutral current

Measure each branch neutral for overloading. The neutrals are measured instead of the phase conductors because they might share the return current of several phase conductors, yet they are not protected by breakers.

6. Circuit breaker voltage drop

The voltage drop across a set of breaker contacts will give you a quick measure of the wear of those contacts. Ideally, the voltage drop should be zero. In practice, there will be some voltage drop in the mV range, with the exact value being dependent on the load current. As a general rule, the voltage drop should not exceed 20-100 mV, depending on load. Replace worn breakers.

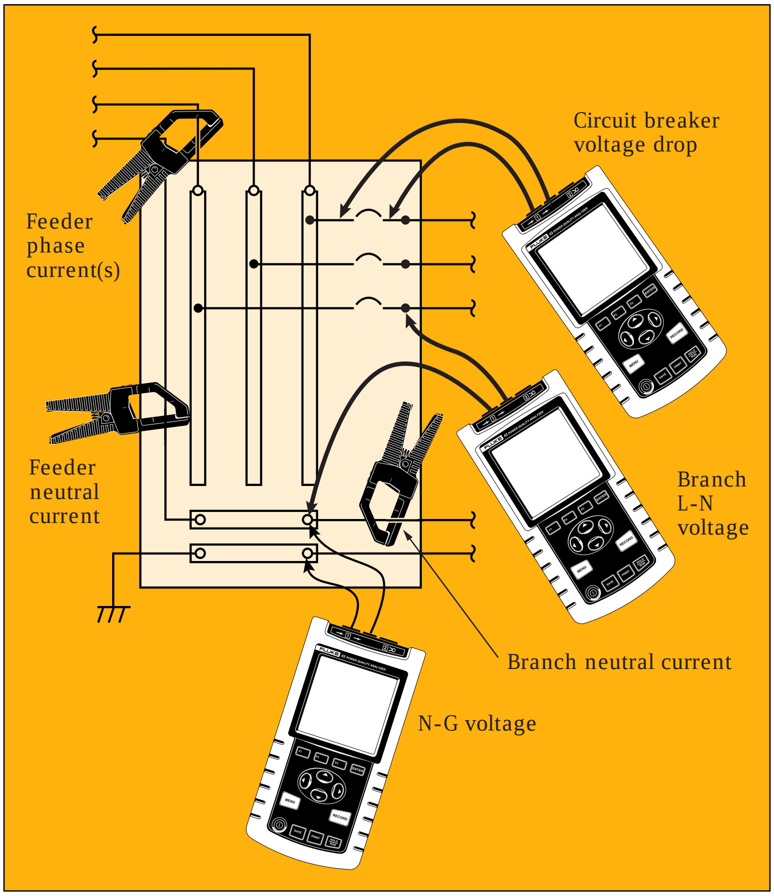


Figure 2.2 Panel with clamps, probes to show measurements.

Solutions

Table 2.2 Service panel recommendations.

Recommendation	Reason
Limit length of 208V feeder runs to 120V subpanels to 200 ft. (65m).	Minimize source impedance and chance of voltage sags.
Don't cascade (daisy chain) subpanels off of other subpanels if possible, and especially if the upstream panel is heavily loaded or has loads with high inrush currents.	Upstream loads can cause voltage sags that will affect all downstream loads.
Install a green wire ground conductor (don't rely on conduit connections).	Maintain a continuous, low impedance ground.
Reduce the load on the panel if necessary.	Minimize heat, voltage sags.
Redistribute branch circuit loads to improve balance of the three phases.	Reduce neutral return current (of the fundamental current).
Upsize the feeder neutral if necessary, to accommodate the third harmonic. This can be done by running another neutral in parallel.	Prevent overloading and heating of feeder neutral. Will reduce N-G voltage.
Install 3rd harmonic filter.	Reduce neutral current.
Nonlinear load panel.	Manufacturer-designed for nonlinear loads.

Section 3
Transformers

Transformers are subject to overheating from harmonic currents. Transformers supplying non-linear loads should be checked periodically to verify operation within acceptable limits. Transformers are also critical to the integrity of the grounding system.

Measurements

1. Transformer loading (kVA)

If the transformer has a four-wire wye secondary, which is the standard configuration for commercial single-phase loads, actual kVA can be easily determined. (See Figure 3.2)

- Connect voltage probes on Phase 1 and Neutral and clamp current probe on same phase. Repeat for Phase 2 and 3.
- Read kVA of each phase and sum all three for total transformer kVA.
- Compare actual load kVA to nameplate kVA rating to determine % loading.

If the load is balanced, a single measurement is sufficient. (see Figure 3.1) Transformers loaded at less than 50% are generally safe from overheating. However, as loads increase, measurements should be made periodically. At some point the transformer may require derating (see page 15).

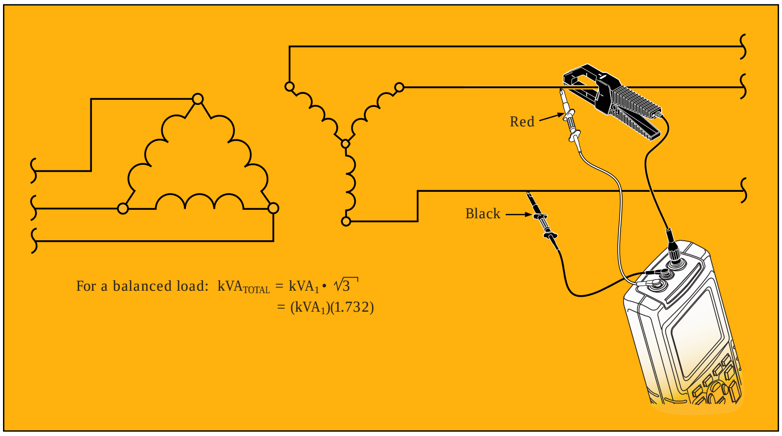


Figure 3.1 Measuring transformer load (balanced).

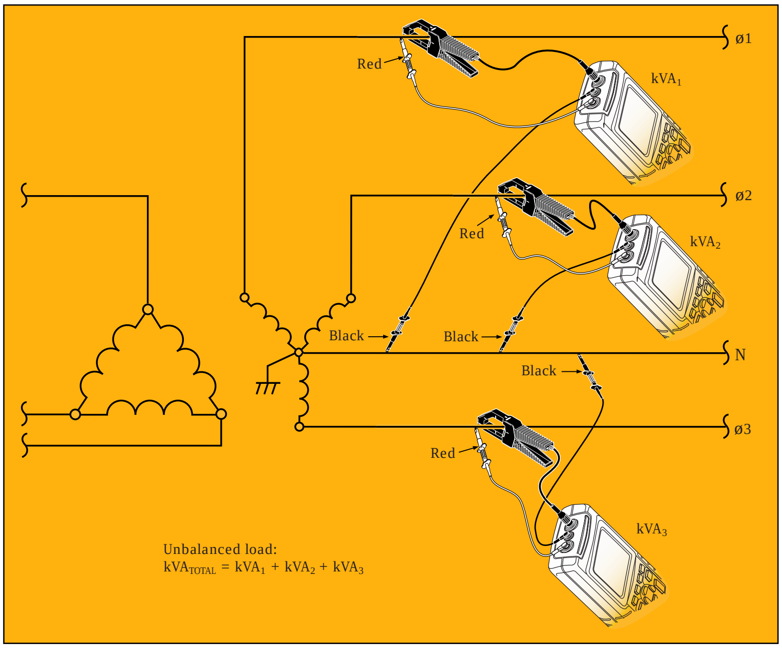


Figure 3.2 Measuring transformer load (unbalanced).

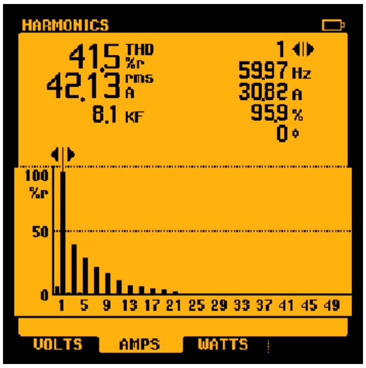


Figure 3.3 Harmonic spectrum.

2. Harmonic spectrum

The harmonic spectrum of the secondary (load) current will give us an idea of the harmonic orders and amplitudes present:

- In a transformer feeding single-phase loads, the principal harmonic of concern is the 3rd. The 3rd will add arithmetically in the neutral and circulate in the delta primary of a delta-wye transformer. The good news is that the delta-wye tends to isolate the rest of the system from the 3rd (though not the 5th, 7th or other non-triplen harmonics). The bad news is that the transformer pays the price with additional heat.
- In a transformer feeding three-phase loads which include drives or UPS systems with 6-pulse converters, the 5th and 7th harmonic will tend to predominate. Excessive 5th is of particular concern because it is negative sequence. It will tend to produce counter-torque and overheating in polyphase motors.

Table 3.1 Measurements at the distribution transformer.

Measurement	Look for	Instrument
1. kVA	Transformer loading. If loading exceeds 50%, check for harmonics and possible need for derating.	43, 41B
2. Harmonic spectrum	• Harmonic orders/amplitudes present: 3rd harmonic (single-phase loads) 5th, 7th (primarily three-phase loads) • Resonance of higher order harmonics • Effectiveness of harmonic trap filters	Same
3. THD	Harmonic loading within limits: Voltage %THD <5% Current %THD <5-20% (Table 3.2)	Same
4. K-factor	Heating effect on transformer from harmonic loads	Same
5. Ground currents	• Objectionable ground currents are not quantified but are prohibited by the NEC. • Neutral-ground bond in place • ESG (Electrical Safety Ground) connector to ground electrode (typically building steel) in place	Same True-rms Clamp

- Harmonic amplitudes normally decrease as the frequency goes up. If one frequency is significantly higher in amplitude than lower frequencies, we can suspect a resonant condition at that frequency. If such a condition is detected, be sure to take readings at capacitor banks to see if the caps are experiencing overcurrent/ overvoltage conditions.
- Before-and-after harmonic spectrum measurement is extremely valuable to determine if harmonic mitigation techniques, like trap filters, which are tuned to specific frequencies, are sized properly and are working as expected.
- Different harmonic frequencies affect equipment in different ways (see below).

Harmonic Sequences

Name	F	2nd	3rd	4th	5th	6th	7th	8th	9th
Frequency	60	120	180	240	300	360	420	480	540
Sequence	+	—	0	+	—	0	+	—	0

Rule: If waveforms are symmetrical, even harmonics disappear.

Effects of Harmonic Sequences

Sequence	Rotation	Effects (from skin effect, eddy currents, etc.)
Positive	Forward	Heating of conductors, circuit breakers, etc.
Negative	Reverse	Heating as above + motor problems
Zero	None	Heating, + add in neutral of 3-phase, 4-wire system

Harmonics are classified as follows:

1. Order or number: Multiple of fundamental, hence, 3rd is three times the fundamental, or 180 Hz.
2. Odd or even order: Odd harmonics are generated during normal operation of nonlinear loads. Even harmonics only appear when there is dc in the system. In power circuits, this only tends to occur when a solid state component(s), such as a diode or SCR, fails in a converter circuit.
3. Sequence:
   - Positive sequence. Main effect is overheating.
   - Negative sequence. Create counter-torque in motors, i.e., will tend to make motors go backwards, thus causing motor overheating. Mainly 5th harmonic.
   - Zero sequence. Add in neutral of 3-phase, 4-wire system. Mainly 3rd harmonic.

3. Total Harmonic Distortion

Check for THD of both voltage and current:

- For voltage, THD should not exceed 5%
- For current, THD should not exceed 5-20% (Table 3.2)

IEEE 519 sets limits for harmonics at the PCC (Point of Common Coupling) between the utility and customer (EN50160 is the European standard). IEEE 519 is based on THD measurements taken at the PCC. Technically, the PCC is the primary of the utility supply transformer (although there are cases where the PCC is at the secondary if the secondary feeds a number of customers). In practice, these measurements are often made at the secondary of the customer's main transformer, since that is the point most easily accessible to all parties (and also since that is generally a Low Voltage measurement).

Some PQ practitioners have broadened the concept of PCC to include points inside the facility, such as on the feeder system, where harmonic currents being generated from one set of loads could affect another set of loads by causing significant voltage distortion. The emphasis is on improving in-plant PQ, rather than on simply not affecting utility PQ.

3a. Voltage THD

THD has a long history in the industry. The underlying con– cept is that harmonic currents generated by loads will cause voltage distortion (E=IZ) as they travel through the system impedance. This voltage distortion then becomes the carrier of harmonics system-wide: if, for example, the distorted voltage serves a linear load like a motor, it will then create harmonic currents in that linear load. By setting maximum limits for voltage distortion, we set limits for the system-wide impact of harmonics.

Table 3.2 IEEE 519 limits for harmonic currents at the point of common coupling. (All percentages are % of $\mathbf{I_L}$, maximum demand load current.)

	Odd Harmonics					
SCR=Isc/I_L	<11	11-17	17-23	23-35	>35	TDD
<20	4.0%	2.0%	1.5%	0.6%	0.3%	5.0%
20-50	7.0%	3.5%	2.5%	1.0%	0.5%	8.0%
50-100	10.0%	4.5%	4.0%	1.5%	0.7%	12.0%
100-1000	12.0%	5.5%	5.0%	2.0%	1.0%	15.0%
>1000	15.0%	7.0%	6.0%	2.5%	1.4%	20.0%

SCR = Short circuit ratio (Isc/I_L)
Isc = Available short circuit current at PCC
$\mathbf{I_L}$ = Maximum demand load current (rms amps)
TDD = Total demand distortion

Note: IEEE allows these limits to be exceeded for up to one hour per day, while IEC allows them to be exceeded for up to 5% of the time.

The concept of $\mathbf{I_L}$, maximum demand load current, is key to using Table 3.2. For existing facilities, $\mathbf{I_L}$ is calculated by *averaging* the maximum demand current for 12 consecutive months (information available in billing records). For new installations, $\mathbf{I_L}$ must be estimated. Transformer rating could be used and would be the most conservative estimate (i.e., it would result in the lowest SCR), since it assumes that the transformer would be used at full capacity.

Voltage distortion, however, depends on source impedance, i.e., on system capacity. It was quite possible for the first (or second or third) customer to inject significant harmonic currents into the system and not cause voltage THD to exceed 5%. The entire responsibility for harmonic mitigation could fall on the last customers unlucky enough to push V—THD over 5%, even if their particular harmonic load was relatively small—literally the straw that broke the camel's back.

3b. Current THD

To restore some fairness to this situation, standards for maximum current harmonics were added, since current harmonics were under the control of the local facility and equipment manufacturer (remember, harmonic "loads" act as "generators" of harmonics). This emphasis on the mitigation of current harmonics at the load, including the not-too-distant requirement that the load generate virtually no harmonics, has become the prevailing regulatory philosophy. It puts the burden of responsibility on the local site and on the equipment manufacturers.

For equipment manufacturers, IEC 1000-3-2, published in 1995, is the applicable standard. It specifies maximum current levels out to the 40th harmonic. Its expected effective date is projected to be early 2001. To certify for CE, a requirement for the European market, manufacturers will have to meet this standard. This edict will have a major effect on power supply design.

For the facility, IEEE 519 is the standard (EN 50160 in Europe). The limits set in IEEE 519 for harmonic currents depend on the size of the customer relative to the system capacity. (See Table 3.2.)

The SCR (Short Circuit Ratio) is a measure of the electrical size of the customer in relation to the utility source. The smaller the customer (higher SCR), the less the potential impact on the utility source and the more generous the harmonic limits. The larger the customer (smaller SCR), the more stringent the limits on harmonic currents.

3c. TDD and THD

TDD (Total Demand Distortion) is the ratio of the current harmonics to the *maximum* load (I_L). It differs from THD in that THD is the ratio of harmonics to the *instantaneous* load. Why TDD instead of THD? Suppose you were running a light load (using a small fraction of system capacity), but those loads were nonlinear. THD would be relatively high, but the harmonic currents actually being generated would be low, and the effect on the supply system would in fact be negligible. So who cares? TDD acknowledges this, and allows harmonic load to be referenced to the maximum load: if harmonic load is high at maximum load, then we have to watch out for the effect on the supply source. So where does that leave current THD as a useful measurement. *The closer the current THD reading(s) is taken to conditions of maximum load, the closer it approximates TDD.*

Table 3.3

Inspection of Transformer Ground	Explanation
Check for *N-G bond*.	A high impedance N-G bond will cause voltage fluctuation.
Check for grounding conductor and integrity of connection to building steel (exothermic weld).	Fault currents will return to the source via these connections, so they should be as low impedance as possible.
Check for tightness of all *conduit* connections.	If the conduit is not itself grounded, it will tend to act as a "choke" for higher frequencies and limit fault current (remember that fault currents are not just at 60 Hz but have high-*f* components).
Measure for *ground currents* on the grounding conductor.	Ideally there should be none, but there will always be some ground current due to normal operation or leakage of protective components (MOVs, etc.) connected from phase or neutral to ground. However, anything above an amp should be cause for suspicion (there is no hard and fast rule, but experienced PQ troubleshooters develop a feel for possible problems).

A final word on measuring THD: the one place not to apply the specs is at the individual harmonic-generating load. This will always be a worst-case distortion and a misleading reading. This is because as harmonics travel upstream, a certain amount of cancellation takes place (due to phase relationships which, for practical purposes, are unpredictable). Measure at a PCC, or at the source transformer.

4. K-factor

K-factor is a specific measure of the heating effect of harmonics in general and on transformers in particular. It differs from the THD calculation in that it emphasizes the frequency as well as the amplitude of the harmonic order. This is because heating effects increase as the square of the frequency.

A K-4 reading would mean that the stray loss heating effects are four times normal. A standard transformer is, in effect, a K-1 transformer. As with THD, it is misleading to make a K-factor reading at the load or receptacle because there will be a certain amount of upstream cancellation; transformer K-factor is what counts. Once the K-factor is determined, choose the next higher trade size. K-factor rated transformers are available in standard trade sizes of K-4, K-13, K-20, K-30, etc. K-13 is a common rating for a transformer supplying office loads. The higher ratings tend to be packaged into PDUs (Power Distribution Units) which are specially designed to supply computer and other PQ-sensitive installations.

5. Ground currents

Two prime suspects for excessive ground current are illegal N-G bonds (in subpanels, receptacles or even in equipment) and so-called isolated ground rods:

- Subpanel N-G bonds create a parallel path for normal return current to return via the grounding conductor. If the neutral ever becomes open, the equipment safety ground becomes the only return path; if this return path is high impedance, dangerous voltages could develop. (Figure 2.1, page 8.)
- Separate isolated ground rods almost always create two ground references at different potentials, which in turn causes a “ground loop” current to circulate in an attempt to equalize those potentials. A safety and equipment hazard is also created: in the case of lightning strikes, surge currents travelling to ground at different earth potentials will create hazardous potential differences. (See page 31.)

Transformer grounding

The proper grounding of the transformer is critical. (Table 3.3.) NEC Article 250 in general and 250-26 in particular address the grounding requirements of the SDS.

- A ground reference is established by a grounding connection, typically to building steel (which, in turn, is required to be bonded to all cold water pipe, as well as any and all earth grounding electrodes). Bonding should be by exothermic weld, not clamps that can loosen over time. The “grounding electrode conductor” itself should have as low a high-frequency impedance as possible (not least because fault current has high frequency components). Wide, flat conductors are preferred to round ones because they have less inductive reactance at higher frequencies. For the same reason, the distance between the “grounding electrode conductor connection to the system” (i.e., N-G bond at the transformer) and the grounding electrode (building steel) should be as short as possible: in the words of the Code, “as near as practicable to and preferably in the same area...”
- The neutral and ground should be connected at a point on the transformer neutral bus. Although permitted, it is not advisable to make the N-G bond at the main panel, in order to maintain the segregation of normal return currents and any ground currents. This point at the transformer is the only point on the system where N-G should be bonded.

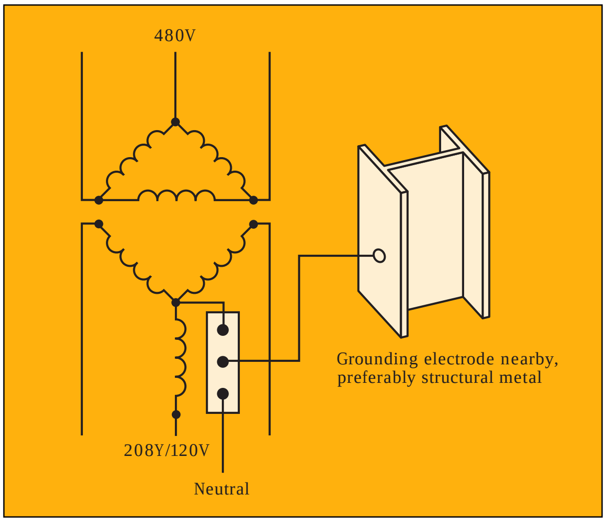


Figure 3.4 Transformer grounding.

Solutions

There are a number of solutions for transformer-related PQ problems:

- Install additional distribution transformers (Separately Derived Systems)
- Derate transformers
- Install K-rated transformers
- Used forced air cooling

1. Separately Derived System (SDS)

The distribution transformer is the supply for a Separately Derived System (SDS), a term which is defined in the NEC (Article 100). The key idea is that the secondary of this transformer is the new source of power for all its downstream loads: this is a powerful concept in developing a PQ distribution system. The SDS accomplishes several important objectives, all beneficial for PQ:

- It establishes a new *voltage reference*. Transformers have taps which allow the secondary voltage to be stepped up or down to compensate for any voltage drop on the feeders.
- It *lowers source impedance* by decreasing, sometimes drastically, the distance between the load and the source. The potential for voltage disturbances, notably sags, is minimized.
- It achieves isolation. Since there is no electrical connection, only magnetic coupling, between the primary and secondary, the SDS isolates its loads from the rest of the electrical system. To extend this isolation to high frequency disturbances, specially constructed "isolation transformers" provide a shield between the primary and secondary to shunt RF (radio frequency) noise to ground. Otherwise, the capacitive coupling between primary and secondary would tend to pass these high-frequency signals right through.
- A new ground reference is established. Part of the definition of the SDS is that it "has no direct electrical connection, including a solidly connected grounded circuit conductor, to supply conductors originating in another system." (NEC 100) The opportunity exists to segregate the subsystem served by the SDS from ground loops and ground noise upstream from the SDS, and vice versa.

2. K-rated transformers

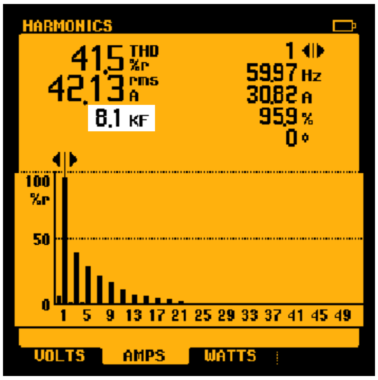


Figure 3.5 Typical K-factor in commercial building.

Harmonics cause heating in transformers, at a greater rate than the equivalent fundamental currents would. This is because of their higher frequency. There are three heating effects in transformers that increase with frequency:

- **Hysteresis.** When steel is magnetized, magnetic dipoles all line up, so that the North poles all point one way, the South poles the other. These poles switch with the polarity of the applied current. The higher the frequency, the more often the switching occurs, and, in a process analogous to the effects of friction, heat losses increase.
- **Eddy currents.** Alternating magnetic fields create localized whirlpools of current that create heat loss. This effect increases as a *square of the frequency*. For example, a 3rd harmonic current will have nine times the heating effect as the same current at the fundamental.
- **Skin effect.** As frequency increases, electrons migrate to the outer surface of the conductor. More electrons are using less space, so the effective impedance of the conductor has increased; at the higher frequency, the conductor behaves as if it were a lower gauge, lower ampacity, higher impedance wire.

The industry has responded with two general solutions to the effects of harmonics on transformers: install a K-factor rated transformer or derate a standard transformer. Let's look at pros and cons of the K-factor approach first. K-factor is a calculation based on the rms value, %HD (harmonic distortion) of the harmonic currents, and the square of the harmonic order (number). It is not necessary to actually perform the calculation because a harmonic analyzer will do that for you. The important thing to understand is that the harmonic order is squared in the equation and that is precisely where the high- frequency heating effects, like eddy current losses, are taken into account.

K-rated transformers are designed to minimize and accommodate the heating effects of harmonics. K-rated transformers do not eliminate harmonics (unless additional elements like filters are added). They accommodate harmonics with techniques such as the use of a number of smaller, parallel windings instead of a single large winding: this gives more skin for the electrons to travel on. The primary delta winding is up-sized to tolerate the circulating third harmonic currents without overheating. The neutral on the secondary is also up-sized for third harmonics (typically sized at twice the phase ampacity).

Application issues with K-factor transformers

K-rated transformers have been widely applied, but there are certain issues with them. Many consultants do not see the need for using transformers with a rating higher than K-13 although K-20 and higher might be supplied as part of an integrated Power Distribution Unit (PDU). Also, early applications sometimes overlooked the fact that K-rated transformers necessarily have a lower internal impedance. Whereas a standard transformer has an impedance typically in the 5-6% range, K-rated transformers can go as low as 2-3% (lower as the K-rating increases). In retrofit situations, where a standard transformer is being replaced by a K-rated transformer of equivalent kVA, this may require new short circuit calculations and re-sizing of the secondary overcurrent protective devices.

3. Derating standard transformers

Some facilities managers use a 50% derating as a rule-of-thumb for their transformers serving single-phase, predominantly nonlinear loads. This means that a 150 kVA transformer would only supply 75 kVA of load. The derating curve, taken from IEEE 1100-1992 (Emerald Book), shows that a transformer with 60% of its loads consisting of SMPS (switched-mode power supplies), which is certainly possible in a commercial office building, should in fact be derated by 50%.

The following is an accepted method for calculating transformer derating for single-phase loads only. It is based on the very reasonable assumption that in single-phase circuits, the third harmonic will predominate and cause the distorted current waveform to look predictably peaked.

Use a *true-rms meter* to make these current measurements:

1. Measure rms and peak current of each secondary phase. (Peak refers to the instantaneous peak, *not* to the inrush or “peak load” rms current).
2. Find the arithmetic average of the three rms readings and the three peak currents and use this average in step 3 (if the load is essentially balanced, this step is not necessary).
3. Calculate Xformer Harmonic Derating Factor:
   $\text{xHDF} = (1.414 * I_{RMS}) / I_{PEAK}$
4. *Or*, since the ratio of Peak/RMS is defined as Crest Factor, this equation can be rewritten as:
   $\text{xHDF} = 1.414 / \text{CF}$
   If your test instrument has the capability, measure the CF of each phase directly. If the load is unbalanced, find the average of the three phases and use the average in the above formula.

Since a sine wave current waveform has a CF=1.414, it will have an xHDF=1; there will be no derating. The more the 3rd harmonic, the higher the peak, the higher the CF. If the CF were 2.0, then the xHDF=1.414 / 2 =.71. A CF=3 gives us an xHDF =.47. A wave with CF=3 is about as badly distorted a current waveform as you can expect to see on a single-phase distribution transformer.

(**Caution:** This method does not apply to transformers feeding three-phase loads, where harmonics other than the third tend to predominate and CF is not useful as a simple predictor of the amount of distortion. A calculation for three-phase loads is available in ANSI/IEEE C57.110. However, there is some controversy about this calculation since it may underestimate the mechanical resonant vibrations that harmonics can cause, and that accelerate transformer wear above and beyond the effects of heat alone.)

4. Forced air cooling

If heat is the problem, cooling is the solution. Break out the fan, turn it on the transformer and use forced air cooling. Some experienced hands figure that’s worth 20-30% on the up side. In any case, it can only help.

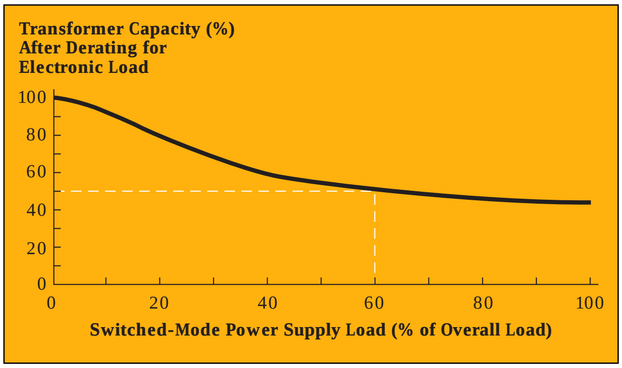


Figure 3-6 Transformer derating curve (IEEE 1100-1992).

Section 4
Electrical Noise and Transients

Electrical noise is the result of more or less random electrical signals getting coupled into circuits where they are unwanted, i.e., where they disrupt information-carrying signals. Noise occurs on both power and signal circuits, but generally speaking, it becomes a problem when it gets on signal circuits. Signal and data circuits are particularly vulnerable to noise because they operate at fast speeds and with low voltage levels. The lower the signal voltage, the less the amplitude of the noise voltage that can be tolerated. The signal-to-noise ratio describes how much noise a circuit can tolerate before the valid information, the signal, becomes corrupted.

Noise is one of the more mysterious subjects in PQ, especially since it must be considered with its equally mysterious twin, grounding. To lessen the mystery, there are two key concepts to understand:

- The first is that electrical effects do not require direct connection (such as through copper conductors) to occur. For an electrician who's been trained to size, install and test wiring, this may not be intuitive. Yet think of lightning, or of the primary and secondary of an isolation transformer, or of the antenna to your radio: there's no direct, hard-wired connection, but somehow complete electrical circuits are still happening. The same electrical rules-of-behavior are in operation for noise coupling, as will be explained below.
- The second concept is that we can no longer stay in the realm of 60 Hz. One of the benefits of 60 Hz is that it's a low enough frequency that power circuits can be treated (almost) like dc circuits; in other words, basic Ohm's Law will get you most places you need to go. But when it comes to noise, we need to keep in mind that signal circuits occur at high frequencies, that noise is typically a broad spectrum of frequencies, and that we need to consider the frequency-dependent behavior of potential sources of noise.

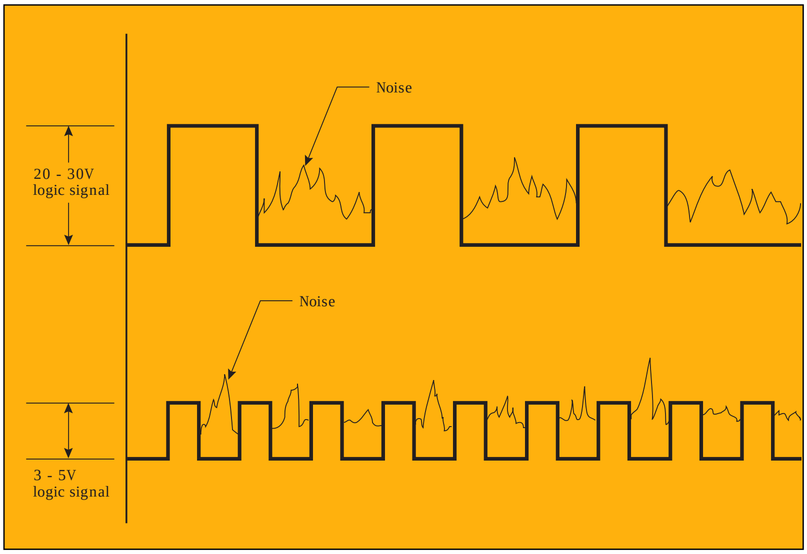


Figure 4.1 Lower voltage, faster signals increase sensitivity to noise.

Coupling mechanisms

There are four basic mechanisms of noise coupling. It pays to understand them and how they differ one from the other because a lot of the troubleshooter's job will be to identify which coupling effect is dominant in a particular situation.

1. Capacitive coupling

This is often referred to as electrostatic noise and is a voltage-based effect. Lightning discharge is just an extreme example. Any conductors separated by an insulating material (including air) constitute a capacitor—in other words, capacitance is an inseparable part of any circuit. The potential for capacitive coupling *increases* as *frequency increases* (capacitive reactance, which can be thought of as the resistance to capacitive coupling, decreases with frequency, as can be seen in the formula: $X_C = 1/2\pi fC$).

2. Inductive coupling

This is magnetic-coupled noise and is a current-based effect. Every conductor with current flowing through it has an associated magnetic field. A changing current can induce current in another circuit, even if that circuit is a single loop; in other words, the source circuit acts as a transformer primary with the victim circuit being the secondary. The inductive coupling effect increases with the following factors: (1) larger current flow, (2) faster rate of change of current, (3) proximity of the two conductors (primary and secondary) and (4) the more the adjacent conductor resembles a coil (round diameter as opposed to flat, or coiled as opposed to straight).

Here are some examples of how inductive coupling can cause noise in power circuits:

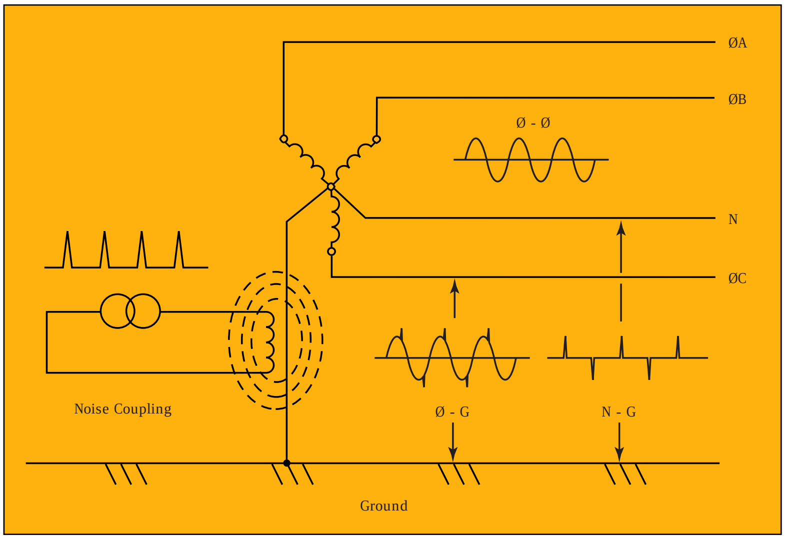


Figure 4.2 Noise coupling. Ground noise measured as Ø-G or N-G noise.

- A transient surge, especially if it occurs on a high-energy circuit, causes a very fast change in current which can couple into an adjacent conductor. Lightning surges are a worst case, but common switching transients or arcing can do the same thing.
- If feeder cables are positioned such that there is a net magnetic field, then currents can be induced into ground cables that share the raceway.
- It is well known that signal wires and power conductors should not be laid parallel to each other in the same raceway, which would maximize their inductive coupling, but instead be separated and crossed at right angles when necessary. Input and output cables should also be isolated from each other in the same manner.

Magnetic fields are isolated by effective shielding. The material used must be capable of conducting magnetic fields (ferrous material as opposed to copper). The reason that a dedicated circuit (hot, neutral, ground) should be run in its own metal conduit when possible is that is in effect magnetically shielded to minimize inductive coupling effects.

Both inductive and capacitive coupling are referred to as near field effects, since they dominate at short distances and distance decreases their coupling effects. This helps explain one of the mysteries of noise—how slight physical repositioning of wiring can have such major effects on coupled noise.

3. Conducted noise

While all coupled noise ends up as conducted noise, this term is generally used to refer to noise that is coupled by a direct, galvanic (metallic) connection. Included in this category are circuits that have shared conductors (such as shared neutrals or grounds). Conducted noise could be high frequency, but may also be 60 Hz.

These are some common examples of connections that put objectionable noise currents directly onto the ground:

- Sub-panels with extra N-G bonds
- Receptacles miswired with N and G switched
- Equipment with internal solid state protective devices that have shorted from line or neutral to ground, or that have not failed but have normal leakage current. This leakage current is limited by UL to 3.5 mA for plug-connected equipment, but there is no limit for permanently wired equipment with potentially much higher leakage currents. (Leakage currents are easy to identify because they will disappear when the device is turned off).
- Another common example is the so-called isolated ground rod. When it is at a different earth potential than the source grounding electrode, a ground loop current occurs. This is still conducted noise, even though the direct connection is through the earth.
- Datacom connections that provide a metallic path from one terminal to another can also conduct noise. In the case of single-ended, unbalanced connections (RS-232), the connection to terminal ground is made at each end of the cable. This offers a path for ground currents if the equipment at each end is referenced to a different power source with a different ground.

4. RFI (Radio Frequency Interference)

RFI ranges from 10 kHz to the 10s of MHz (and higher). At these frequencies, lengths of wire start acting like transmitting and receiving antennas. The culprit circuit acts as a transmitter and the victim circuit is acting as a receiving antenna. RFI, like the other coupling mechanisms, is a fact of life, but it can be controlled (not without some thought and effort, however).

RFI noise reduction employs a number of strategies:

- Fiber optic cable, of course, is immune to electrical noise.
- Shielded cabling (such as coax cables) attempts to break the coupling between the noise and signal.
- Balanced circuits (such as twisted pair) don't break the coupling, but instead take advantage of the fact that the RFI will be coupled into both conductors (signal and return). This noise (called Common Mode noise) is then subtracted, while the signal is retained. In effect, the balanced circuit creates a high impedance for the coupled noise.
- Another example of the high-impedance-to-noise approach is the use of RF chokes. Whether used with data or power cables, RF chokes can offer effective high-frequency impedance (X_L increases with frequency).
- A low-impedance path can be used to shunt away the noise. This is the principle behind filtering and the use of decoupling caps (low impedance to high frequency, but open at power line frequencies). But a sometimes-overlooked, yet critical, aspect is that the ground path and plane must be capable of handling high-frequency currents. High-frequency grounding techniques are used to accomplish this. The SRG (Signal Reference Grid), first developed for raised floor computer room installations, is an effective solution. It is essentially an equipotential ground plane at high-frequency. (For further information on high-frequency grounding, see the references listed on the back page.)

Signal Grounding

To understand the importance of "clean" signal grounds, let's discuss the distinction between Differential Mode (DM) vs. Common Mode (CM) signals. Imagine a basic two-wire circuit: supply and return. Any current that circulates or any voltage read across a load between the two wires is called DM (the terms normal mode, transverse mode and signal mode are also used). The DM signal is typically the desired signal (just like 120V at a receptacle). Imagine a third conductor, typically a grounding conductor. Any current that flows now through the two original conductors and returns on this third conductor is *common* to both of the original conductors. The CM current is the noise that the genuine signal has to overcome. CM is all that extra traffic on the highway. It could have gotten there through any of the coupling mechanisms, such as magnetic field coupling at power line frequency or RFI at higher frequencies. The point is to control or minimize these ground or CM currents, to make life easier for the DM currents.

Measurement

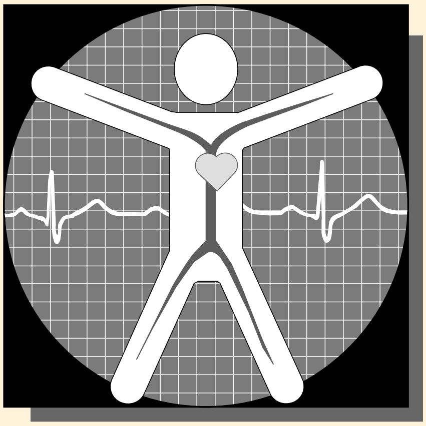
CM currents can be measured with current clamps using the zero-sequence technique. The clamp circles the signal pair (or, in a three-phase circuit, all three-phase conductors and the neutral, if any). If signal and return current are equal, their equal and opposite magnetic fields cancel. Any current read must be common mode; in other words, any current read is current that is not returning on the signal wires, but via a ground path. This technique applies to signal as well as power conductors. For fundamental currents, a ClampMeter or DMM + clamp would suffice, but for higher frequencies, a high bandwidth instrument like the Fluke 43 Power Quality Analyzer or ScopeMeter should be used with a clamp accessory.

A Matter of Life and Death

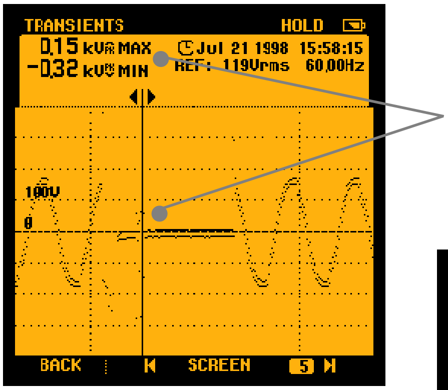
Sometimes PQ troubleshooting is a matter of life and death.

Dave was the on-site field engineer at the hospital. One day he got a call from a very concerned nurse in the ER. One of their patients had died. But as upsetting as that was, it wasn't the main source of concern. What was really unusual was that this particular corpse had a heartbeat.

Dave soon arrived at the scene. A quick glance told him that the dead had *not* come back to life. The problem lay elsewhere. The nurses pointed out what they had seen, a signal on the EKG indicating a heartbeat. But there was something unusual about this signal (above and beyond the fact that it seemed to be coming from a dead body). He noticed that the signal was a 60 Hz sine wave (slightly flat-topped). A further look at the signal wires told him that they had been laid *parallel* to the power cord. The coupling between signal and power wires caused the 60 Hz "Heartbeat" on the EKG machine. The moral of the story is to always isolate the signal and power conductors—before it becomes a matter of life and death.



Transients



Cursor moves to display peak Min/Max values.

Figure 4.3 Fluke 43 can capture and save up to 40 transients.

Transients should be distinguished from surges. Surges are a special case of high-energy transient which result from lightning strikes (see section 5, "PQ Troubleshooting of Lightning Protection Systems"). Voltage transients are lower energy events, typically caused by equipment switching.

They are harmful in a number of ways:

- They deteriorate solid state components. Sometimes a single high energy transient will puncture a solid state junction, sometimes repetitive low energy transients will accomplish the same thing. For example, transients which exceed the PIV (peak inverse voltage) rating of diodes are a common cause of diode failure.
- Their high-frequency component (fast rise times) cause them to be capacitively coupled into adjoining conductors. If those conductors are carrying digital logic, that logic will get trashed. Transients also couple across transformer windings unless special shielding is provided. Fortunately this same high frequency component causes transients to be relatively localized, since they are damped (attenuated) by the impedance of the conductors (inductive reactance increases with frequency).

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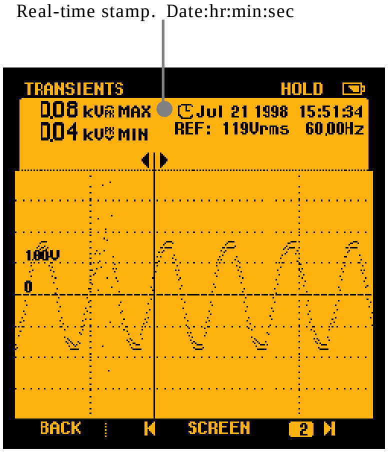


- Utility capacitor switching transients are an example of a commonly-occurring high-energy transient (still by no means in the class of lightning) that can affect loads at all levels of the distribution system. They are a well known cause of nuisance tripping of ASDs: they have enough energy to drive a transient current into the dc link of the drive and cause an overvoltage trip.

Transients can be categorized by waveform. The first category is "impulsive" transients, commonly called "spikes," because a high-frequency spike protrudes from the waveform. The cap switching transient, on the other hand, is an "oscillatory" transient because a ringing waveform rides on and distorts the normal waveform.
It is lower frequency, but higher energy.

Causes

Transients are unavoidable. They are created by the fast switching of relatively high currents. For example, an inductive load like a motor will create a kickback spike when it is turned off. In fact, removing a Wiggy (a solenoid voltage tester) from a high-energy circuit can create a spike of thousands of volts! A capacitor, on the other hand, creates a momentary short circuit when it's turned on. After this sudden *collapse* of the applied voltage, the voltage rebounds and an oscillating wave occurs. Not all transients are the same, but as a general statement, load switching causes transients.

In offices, the laser copier/printer is a well-recognized "bad guy" on the office branch circuit. It requires an internal heater to kick in whenever it is used and every 30 seconds or so when it is not used. This constant switching has two effects: the current surge or inrush can cause repetitive voltage sags; the rapid changes in current also generate transients that can affect other loads on the same branch.

Measurement and recording

Transients can be captured by DSOs (Digital Storage Oscilloscopes). The Fluke 43 PQ Analyzer, which includes DSO functions, has the ability to capture, store and subsequently display up to 40 transient waveforms. Events are tagged with time and date stamps (real time stamps). The VR101S Voltage Event Recorder will also capture transients at the receptacle. Peak voltage and real time stamps are provided.

Transient voltage surge suppressors (TVSS)

Fortunately, transient protection is not expensive. Virtually all electronic equipment has (or should have) some level of protection built in. One commonly-used protective component is the MOV (metal oxide varistor) which clips the excess voltage.

TVSS are applied to provide additional transient protection. TVSS are low voltage (600V) devices and are tested and certified to UL 1449. UL 1449 rates TVSS devices by Grade, Class and Mode. As an example, the highest rating for a TVSS would be Grade A (6000V, 3000A), Class 1 (let-through voltage of 330V max) and Mode 1 (L-N suppression). The proper rating should be chosen based on the load's protection needs:

- A lower Grade might result in a TVSS that lasts one year instead of ten years. The solid state components in a TVSS will themselves deteriorate as they keep on taking hits from transients.
- A lower Class might permit too much let-through voltage that could damage the load. Class 1 is recommended for switch mode power supplies.
- A Mode 2 device would pass transients to ground, where they could disrupt electronic circuit operation.

Voltage susceptibility profile

The new ITIC profile (Information Technology Industry Council) is based on extensive research and updates the CBEMA curve. The CBEMA curve (Computer Business Equipment Manufacturers Association, now ITIC) was the original voltage susceptibility profile for manufacturers of computers and other sensitive equipment. Similar curves are being developed for 230V/50Hz equipment and for adjustable speed drives. Sensitive equipment should be able to survive events inside the curve. Events outside of the curve could require additional power conditioning equipment or other remedial action. A major change in ITIC is that the ride-through times for outages as well as the tolerance for sags have both been increased. The field troubleshooter must keep in mind that the profiles are recommendations and that a particular piece of equipment may or may not match the profile. Having said that, the profiles are still useful because, when recorded events are plotted against them, they give a general idea of the voltage quality at a particular site.

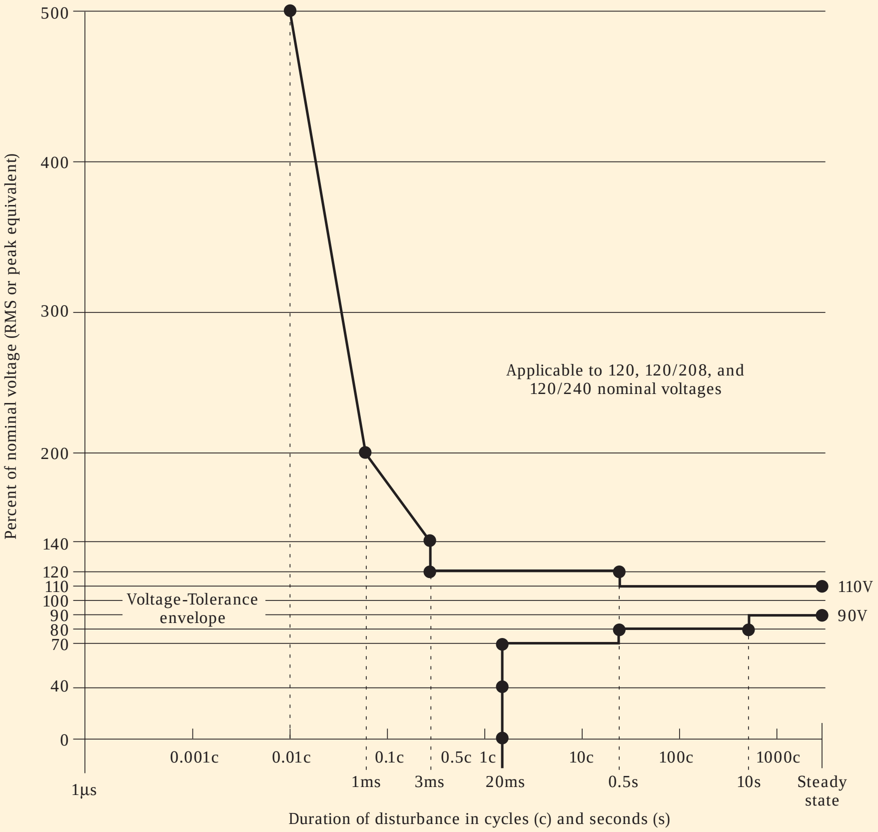


Figure 4.4 ITIC Curve.

Section 5
Lightning Protection

Lightning protection plays a vital part in the overall power quality of an installation. Lightning occurrence varies by geography, with Florida being the lightning capital of the U.S. Lightning does not have to score a direct hit to be disruptive. It has so much energy that it couples surges into conductors, both those exposed to air and those buried in the ground.

Basic lightning protection has two main requirements:

1. Effective grounding

A low impedance of the grounding electrode system to earth is important. But, equally important is that all parts of the grounding system be bonded together: all ground electrodes are bonded (and extraneous ground rods removed), structural steel is tied to service entrance ground, all grounding connections are tight and free of corrosion, etc. This minimizes the phenomenon called "transferred earth potential," where large surge currents create large voltage differences between two ground points with different impedances to earth. This same grounding practice is important for performance reasons, as it tends to minimize ground loop currents that circulate in an attempt to equalize ground potentials.

Table 5.1 Inspection of lightning protection system.

Check	Look for	Reason
Surge arrestors	• Installed at main service panel, subpanels and critical equipment. • To minimize high frequency impedance, leads should be *short, with no bends.*	• Lightning is high energy and needs multilevel protection. • Lightning has high *f* components. Shorter leads have less X_L and less impedance at high *f*.
Grounding electrode conductors at service entrance or at SDS	• Grounding electrode connections are not loose or corroded. • Grounding conductor should not be coiled or have unnecessary bends.	• Ensure low impedance ground to minimize potential to ground with lightning induced surges. • Minimize impedance to high frequency components of lightning.
Grounding electrode bonding	All grounding electrodes should be effectively bonded together (<0.1Ω).	Prevent difference in earth potential between electrodes in event of lightning.
Separately driven ("isolated") electrode	Electrode and equipment ground should both be tied to building steel, and thereby to the service entrance ground.	Same as above—entire grounding system should be an equipotential ground plane for lightning.
Datacom cabling that runs between buildings	Surge arrestors on datacom cabling or use of fiber optic cables.	Datacom cabling run between buildings can be a path for surge currents, due to differences between building earth potentials.

Lightning protection is covered in a number of standards and codes, including:
NEC: Articles 250 and 280
National Fire Protection Association: NFPA 780
Lightning Protection Institute: LPI-175
UL-96 and UL-96A

2. Surge arrestors

A surge arrestor "is a protective device for limiting surge voltages by discharging or bypassing surge current..." (NEC 280). Since the surge current is bypassed to ground, surge arrestors are only as effective as the grounding system.

Surge arrestors are sized for the location where they are installed. Three categories are defined (ANSI/IEEE C62.41-1991). A surge arrestor at an outside installation is closest to the lightning event and must absorb the most energy. This is considered a Category C location (corresponding to CAT IV in IEC 61010). Category B refers to feeders and distribution panels (equivalent to CAT III in IEC 61010), and Category A refers to receptacle connected surge arrestors (equivalent to CAT II).

Surge arrestor or TVSS

A surge arrestor is there to protect the insulation and, ultimately, prevent failures that could lead to fires. It is not necessarily designed to protect sensitive equipment. That's the job of the TVSS (transient voltage surge suppressor).

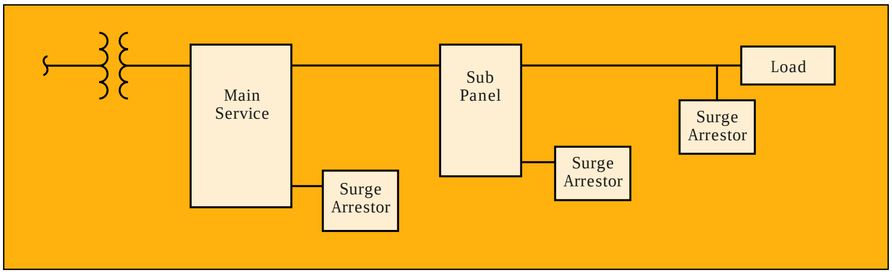


Figure 5.1. Surge arrestors installed at service, panel, load.

Part II: Three-Phase Loads

Section 6
Polyphase Induction Motors

About two-thirds of the electric power in the U.S. is consumed by motors, with industrial three-phase motors above 5 HP (7 kW) being by far the bulk of that load. They are linear loads and therefore don't contribute to harmonics. They are, however, the major contributor to reduced Displacement Power Factor, which is a measurement of the effective use of system capacity.

Measurements

1. Voltage unbalance

Voltage unbalance should not exceed 1-2% (unless the motor is lightly loaded). Why such a small number? Voltage unbalance has a very large effect on current unbalance, in the neighborhood of 8:1. In other words, a voltage unbalance of 1% can cause current unbalance of 8%. Current unbalance will cause the motor to draw more current than it otherwise would. This in turn causes more heat and heat is the enemy of motor life, since it deteriorates the winding insulation.

Voltage unbalance can be caused by severe load unbalance but it could just as easily be caused by loose connections and worn contacts.

Example of voltage unbalance calculation:

$$\%V_{\text{UNBALANCE}} = \frac{\text{Max deviation from average} \times 100\%}{\text{Average (of three phases)}}$$

1. Make three phase-to-phase measurements:
   A-B = 475V A-C = 471V B-C = 470V
2. Find the average: (475+471+470) ÷ 3 = 472V
3. Find the maximum deviation from the average:
   This occurs on the A-B phase: 475V-472V = 3V
4. Divide maximum deviation by average to find
   % unbalance: 3V/472V <1%

2. Voltage %THD and harmonic spectrum

Voltage THD should not exceed 5% on any phase. If the voltage distortion on any phase is excessive, it can cause current unbalance. The usual culprit is the 5th harmonic and therefore the harmonic spectrum should be examined for the 5th in particular. The 5th is a negative sequence harmonic which creates counter-torque in the motor. A motor fed by a voltage with high 5th harmonic content will tend to draw more current than otherwise. This is a major problem when across-the-line or soft-start motors share the same bus with ASDs.

3. Current unbalance

To find current unbalance, measure amps in all three phases. Do the same calculation as for voltage unbalance. In general, current unbalance should not exceed 10%. However, unbalance can usually be tolerated if the high leg reading doesn't exceed the nameplate FLA (Full Load Amps) and SF (Service Factor). The FLA and Service Factor are available on the motor nameplate. If the *voltage* unbalance and the voltage THD are within limits, high *current* unbalance can be an indication of motor problems, such as damaged winding insulation or uneven air gaps.

Current measurement will also find single-phasing. If a three-phase motor loses a phase (perhaps caused by a blown fuse or loose connection), it may still try to run single phase off the remaining two phases. Since the motor acts like a constant power device, it will simply draw additional current in an attempt to provide sufficient torque. A voltage measurement alone will not necessarily find this condition, since voltage is induced by the two powered windings into the non-powered winding.

Table 6.1 Measurements at the motor.

Measurement	Look for	Instrument
1. Voltage unbalance	Unbalance <1%	43, 41B, 87
2. Voltage %THD	%THD <5%	43, 41B
3. Current unbalance **Single phasing** (extreme current unbalance)	Unbalance <10% No current on one phase.	43, 41B 87 w/80i-400
4. Loading	• Nameplate data on FLA[1] and SF[2]: Current < (FLA x SF). • Overloading or extreme underloading. 80% of rated load is optimal.	Same
5. Inrush current	• Inrush causing voltage sag. • Inrush causing nuisance trips.	43
6. Power factor	• Low Displacement PF. • Large difference between DPF and PF (Total Power Factor) indicating harmonics.	43, 41B

[1] FLA = Full Load Amps

[2] SF = Service Factor
(If the FLA = 100A and the SF=1.15, the motor can be run at 115A continuously.)

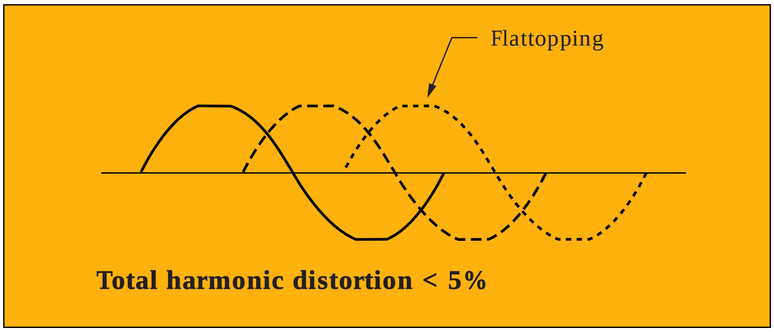


Figure 6.1. Voltage distortion.

4. Loading

Measure current draw of the motor. If the motor is at or near its FLA rating (times the Service Factor multiplier), it will be more sensitive to the additional heating from harmonics, as well as current unbalance. A motor that is only lightly loaded is usually safe from overheating. On the other hand, its efficiency and DPF are both less than optimal. Most motors reach maximum efficiency at 60%-80% of full load rating. Displacement Power Factor is maximum at rated load (including S.F.) and drops off, especially at less than 80% of rated load. This leads to the conclusion that, to the degree a motor load is constant and predictable, 80% of rated load is the most efficient operating range.

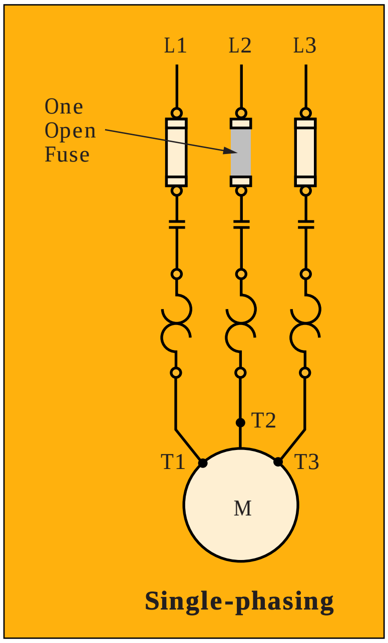


Figure 6.2. Single-phasing.

5. Inrush

Motors which are started across-the-line (as opposed to those using soft-starts or drives) draw a current inrush, also called locked rotor current. This inrush tapers off to normal running current as the motor comes up to speed.

- Older motors draw an inrush of typically 500-600% of the running current. Newer energy efficient designs draw brief inrushes as high as 1200% of running current, a direct result of the lower impedances which help make them more energy efficient in the first place.
- High torque, high HP motor loads require proportionally higher inrush.
- Motor loads started at the same time will have a cumulative inrush.

Another source of inrush is UPS and ASD systems with diode converters. They draw inrush current as their cap banks first charge.

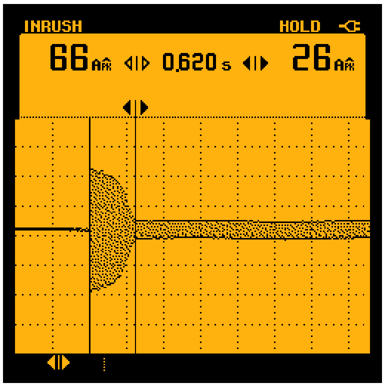


Figure 6.3. Inrush current (Model 43).

Effects of inrush current

1. Inrush causes voltage sags if the source voltage is not stiff enough:
    - Relays and contactor coils might drop out (typically, the sag would have to get as bad as about 70% of normal line voltage); or, if they hold in, their contacts might chatter (especially if the additional load causes a long-term undervoltage).
    - Control circuits might reset or lock up (at 90% and below).
    - Drives might trip off-line (undervoltage trip).
2. High peak demand periods, which may cause higher utility bills.
3. Cycling loads can cause periodic sags, which might show up as flickering lights.
4. If the motor is required to start up a high torque load, the inrush can be relatively prolonged (e.g., 10 to 20 seconds or more) and this can cause nuisance tripping as the overload heaters trip the motor starter.

6. Power Factor

To size PF correction capacitors, it is necessary to measure the DPF (Displacement PF) and Active Power consumption (kW) of the motor load. Measurement of the DPF and kW of a three-phase induction motor is explained in the sidebar on the next page. These measurements assume that the motor voltage and current is balanced. Therefore, before undertaking PF correction, first make sure that voltage and current unbalance are within limits. Either problem can shorten motor life and should take priority over DPF correction.

Measuring Displacement Power Factor on 3-phase Induction Motors

Select which of the two methods to use based on the transformer configuration supplying the motor. Either method will give the same results. Method #1 is for the grounded-Y source. It is simple and can be applied in most situations, since virtually all of the low voltage motors in commercial and light industrial facilities are fed from a grounded-Y source. Method #2 is for floating sources sometimes found in heavy industrial facilities.

Method #1: Grounded-Y source

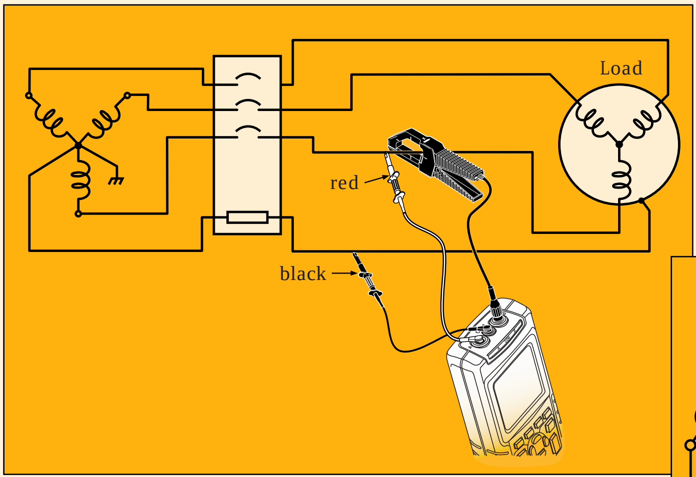
To check if the source is grounded-Y, measure voltage of each phase to ground. If the readings are equal, you can use this measurement method.

Set-up:

1. Clamp the current probe on any phase (with arrow on clamp pointing towards the motor).
2. Attach the red voltage probe to the same phase and the black probe to ground (not to another phase).

Active Power: Read kW and multiply by 3:
$kW_{MOTOR} = 3 * kW$

Displacement PF: Read DPF.
(Not necessary to measure kVA)



Method #2: Three-wire Source

With floating-Y, floating-delta or grounded-delta, the voltage will be different for at least one of the phase-to-ground readings. (For the floating source, the phase-to-ground voltage is unpredictable, since it depends on phase to ground capacitance). Method #2 is known as the Two-Wattmeter method.

Set-up:

1. Connect the black voltage probe to any phase.
2. Connect the red voltage probe and the clamp (arrow towards the load) together on a second phase. Record **kW_1**.
3. Move red probe and clamp to the third phase (do not move the black probe). Record kW_2. Record kVA (kVA of either phase will be more or less equal if the current unbalance is within limits).

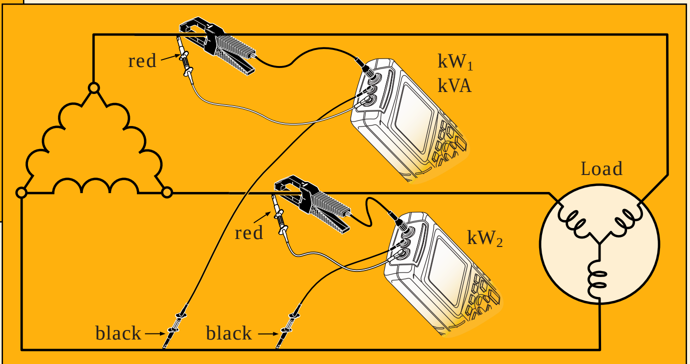
Active Power: $Kw_{MOTOR} = kW_1 + kW_2$ (If either kW reading is negative, as might happen on a very lightly loaded motor, it would be subtracted instead of added)

Apparent Power: $kVA_{MOTOR} = kVA * 1.73$.

$DPF = kW_{MOTOR} / kVA_{MOTOR}$

Example (Two-Wattmeter):
Measurements:
kW_1 = + 1.52
kW_2 = + 1.74
kVA = 2.41

Calculations:
$Kw_{MOTOR} = kW_1 + kW_2$ = (+ 1.52) + (+1.74) = 3.26 kW
kVA_{MOTOR} = kVA * 1.73. = (2.41) (1.73) = 4.17 kVA
$DPF = Kw_{MOTOR} / kVA_{MOTOR}$ = 3.26 / 4.17 = 0.78



Power Factor Using the Two-Wattmeter Method:

$kW_{TOTAL} = kW_1 + kW_2$

$kVA_{TOTAL} = kVA_1 \cdot \sqrt{3}$

$$PF = \frac{kW_{TOTAL}}{kVA_{TOTAL}}$$

Section 7
PQ Troubleshooting of Adjustable Speed Drives

AC ASDs can be both a source and a victim of poor PQ (see “Measurement of Adjustable Speed Drives with Fluke Meters,” document number G0416UEN, for more information on drive troubleshooting).

ASDs as Victim Loads

Although ASDs are usually depicted as the culprit in the PQ scenario, there are ways in which they can be a victim load as well.

Capacitor switching transients
High-energy (relatively low-frequency) transients that are characteristic of utility capacitor switching can pass through the service transformer, feeders, and converter front-end of the drive directly to the dc link bus, where it will often cause a dc link overvoltage trip. Input diodes could also be blown out by these transients.

Table 7.1 Line-side measurements on ASDs.

Measurement	Look for	Instrument
Voltage waveform	• Voltage notching (SCR converters) • Flat-topping	43
Harmonic spectrum	Harmonic orders and amplitudes, before and after filter application	43, 41B
Displacement PF	For PWM drives, DPF should remain high even at low speeds (it will typically decrease slightly)	43, 41B
Voltage unbalance	Less than drive manufacturer specs, or current overload trips can result. The drive may have a higher limit for unbalance than the motor.	43, 41B

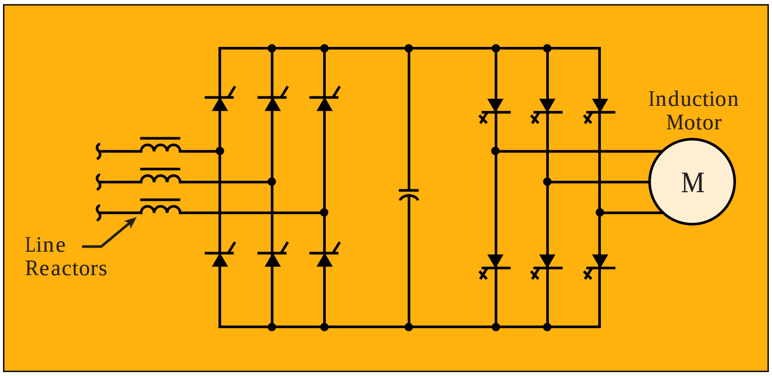


Figure 7.1 Voltage Source Invertor (VSI) ASD

Voltage distortion
If high-voltage distortion shows up as excessive flat-topping, it will prevent dc link capacitors from charging fully and will diminish the ride-through capability of the drive. Thus a voltage sag which would not normally affect a drive will cause the drive to trip on undervoltage.

Improper grounding will affect the internal control circuits of the drive, with unpredictable results.

ASDs as Culprit Loads

A drive can definitely be a “culprit load” and have a major impact on system PQ. But before we talk of problems, let’s put in a good word for the positive effects of drives on PQ. First of all, they offer built-in soft-start capabilities. This means there will be no inrush current and no voltage sag effect on the rest of the system. Secondly, if the drive is of the PWM type, with a diode converter front-end, the Displacement Power Factor is high (commonly >95% at rated load) and more or less constant throughout the range. This means that drives can reduce energy usage and correct for DPF at the same time. It’s a good thing too, because drives and PF correction capacitors don’t mix (see “Power System Resonance,” page 28). Caps are vulnerable to the higher frequency harmonic currents generated by drives, since their impedance decreases as frequency increases.

The type of drive has a major impact on the PQ symptoms, because of the different converter designs (converters or rectifiers turn ac to dc and are the first stage of the drive). There are two major types of converter design.

SCR Convertor with Voltage Source Inverter/Variable Voltage Inverter (VSI/VVI) Drives

Commonly called six-step drives, they use SCRs (Silicon - Controlled Rectifiers) in their converter front-ends (the following discussion applies to CSI, Current Source Inverter drives, which also use SCRs). VSI and CSI drive designs tended to be applied on larger drives (>100HP). SCR converters control the dc link voltage by switching on (or “gating”) current flow for a portion of the applied sine wave and switching off at the zero-crossing points. Unlike diodes, SCRs require control circuits for gate firing.

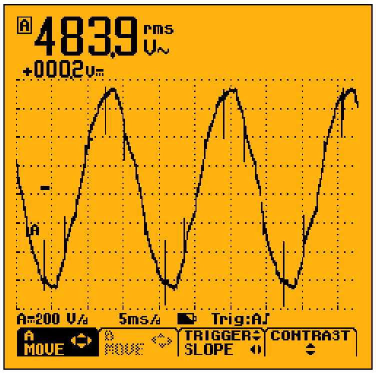


Figure 7.2 Voltage Notching.

For the SCR converter, there are three main issues that affect line-side PQ:

- Commutation notches. SCR switching or commutation is such that there are brief moments when two phases will both be “ON.” This causes what is in effect a momentary short circuit that tends to collapse the line voltage. This shows up as “notches” on the voltage waveform. These notches cause both high V-THD and transients. The solution is to place a reactor coil or isolation transformer in series with the drive’s front end to clean up both problems.
- Displacement Power Factor declines as drive speed decreases. This is not as serious a problem as it sounds, because the power requirement of the drive-motor-load decreases even more.
- Harmonic currents, typically the 5th and 7th, are generated by VSI drives.

Diode Convertor with Pulse Width Modulation (PWM) Drives

The other and more common converter design uses diodes and is used in the PWM drive. The diodes require no switching control circuitry. One of the main trends in the industry has been the proliferation of PWM drives, mainly due to the continued development of fast-switching, efficient IGBTs (Insulated Gate Bipolar Transistors) used in the inverter section of the drive (inverters turn dc to ac). For all practical purposes, PWM drives are the industry standard.

For an in-depth discussion of the efffects of PWM-IGBT drives on motors, see “Measurement of ASDs with Fluke Meters,” document number G0416UEN.

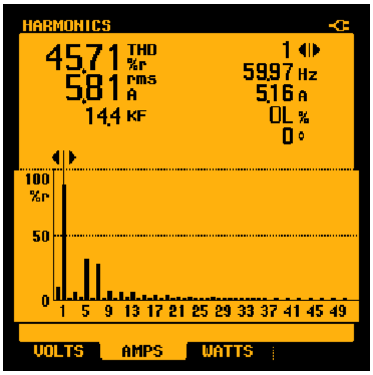


Figure 7.3 Typical ASD Harmonic Spectrum

For the diode converter, the main PQ issue is harmonics. The actual harmonic orders being generated depend on the number of diodes in the front end. For three-phase conversion, a minimum set of six diodes is required. This “six-pulse” converter will generate 5th and 7th harmonics. If a 12-pulse converter were used, the 11th and 13th harmonics will be generated instead of the 5th and 6th—and, very importantly, for the same load, the amplitude of the 11th and 13th would be considerably less than the 5th and 6th. Therefore, the THD would be less. The vast majority of drives, however, are six-pulse PWM style, which is one reason we see so much 5th harmonic on the system.

Harmonics solutions

There are a number of solutions to mitigating drive-generated harmonics:

Harmonic trap filters (Fig. 7.5)
These are typically LC networks connected in parallel at the source of the harmonics (in other words, at the drive input). They are tuned to just below the 5th harmonic (typically 280 Hz) and will tend to sink both 5th and much of the 7th harmonic. Obviously, they must be sized to the harmonic-generating load.

Phase-shift transformers
This can be as simple as a delta-wye transformer feeding one drive(s) and a delta-delta feeding another drive(s). There is a 30 degree phase shift effect between these two configurations, which effectively results in cancellation of harmonics at the closest upstream PCC (Point of Common Coupling). The cancellation effect is optimal when both loads are more or less equal.

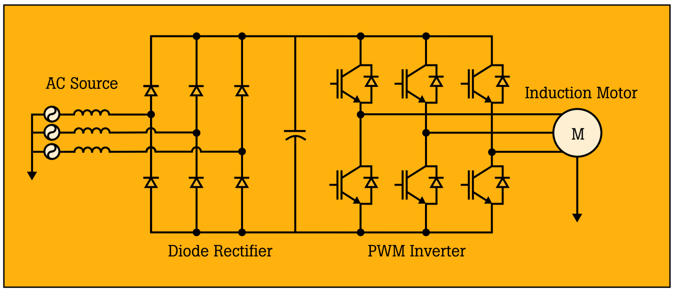


Figure 7.4. Pulse Width Modulated (PWM) ASD.

12-pulse converter

If the delta-wye/delta-delta are packaged together (delta primary, delta and wye secondary) and each secondary feeds one of two paralleled six-pulse converters, a 12-pulse front-end is created with all the benefits mentioned above. 18-pulse designs are also available. Because of the extra cost, this type of solution tends to only get used on high HP loads.

Active filters

This relatively new technology is based on an elegant concept–using power electronics to solve the problems created by power electronics. It senses the instantaneous ac sine wave; it then actively cancels the harmonics it detects by generating equal and opposite polarity harmonics, thus recreating the sine wave. Commercial packages might provide voltage regulation as well.

Active PF Correction

Another recent solution is for manufacturers to offer converter front ends using fast switching technology that generates a minimum amount of harmonics and has near unity power factor (both Total PF and DPF).

There is room for discussion on which approach to harmonic mitigation might prove most effective and economical in a particular situation. However, what is often overlooked by the end-user, and what should be clear from the information in this section, is that the total cost of a drive system should include both the cost of the drive itself and the harmonic mitigation (whether part of the drive or installed separately).

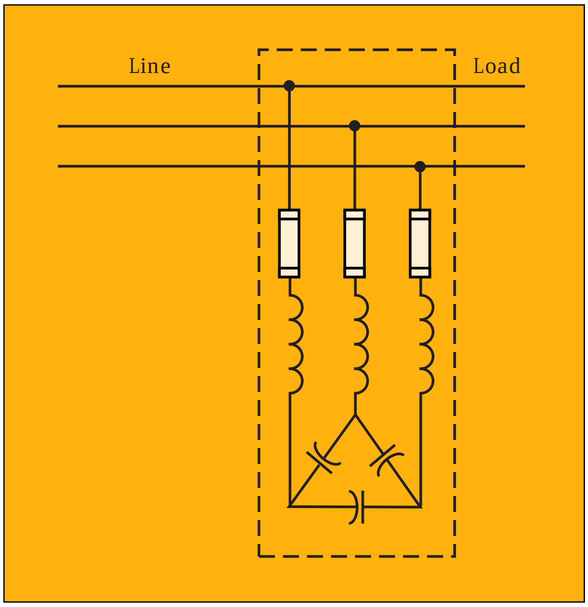
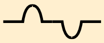
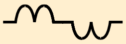


Figure 7.5 Harmonic trap filter.

Why True-rms

True-rms test tools are necessary for accurate measurements of distorted waveforms. For more information, see the Fluke application note *Why True-rms*, document number B0294A.

A comparison of average-responding and true-rms multimeters

Waveform	Description	Multimeter Reading	
		Average-sensing DMM	True-rms DMM
	Sine wave	Correct	Correct
	Square wave (flat-top voltage)	**10% high**	Correct
	Current to single phase diode rectifier	**40% low**	Correct
	Current to 3 phase diode rectifier	**5-30% low**	Correct

Power system resonance

Hot vibes can result when harmonics and capacitors get together

Is it possible to install “Power Factor Correction Capacitors” and have PF get worse? It certainly is, and a starting place to understanding this puzzle lies in the distinction between Displacement PF (DPF) and Total Power Factor (PF). The penalty for not understanding the difference can be blown capacitors and wasted investment.

Total PF and Displacement PF are the same in one basic sense: they are the ratio of Real Power to Apparent Power, or Watts to VA. DPF is the classic concept of power factor. It can be considered as the power factor at the fundamental frequency. Total Power Factor, abbreviated to Power Factor (PF), now includes the effects of fundamental and of harmonic currents (it is also referred to as True PF or Distortion PF, Fig. 7.7). It follows that with the presence of harmonics, PF is always lower than DPF and is also a more accurate description of total system efficiency than DPF alone.

Strictly speaking, the term “Power Factor” refers to Total PF, but in practice can also be used to refer to DPF. Needless to say, this introduces some confusion into discussions of power factor. You have to be clear which one you’re talking about.

Displacement Power Factor

Lower DPF is caused by motor loads which introduce the need for Reactive Power (Volt-Amp Reactive or VARs). The system has to have the capacity, measured in Volt-Amps (VA) to supply both VARs and Watts. The more VARs needed, the larger the VA requirement and the smaller the DPF. The cost of VARs is accounted for in a power factor penalty charge. Utilities often levy additional charges for DPF below a certain level; the actual number varies widely, but typical numbers are 0.90 to 0.95.

To reduce VARs caused by motor loads, power factor correction capacitors are installed. Upstream system capacity, both in the plant and at the utility level, is released and available for other uses. (Fig. 7.6)

Historically, this has been the gist of the PF story: a relatively well-known problem with a relatively straightforward solution.

Harmonics and Capacitors

Harmonics have had a dramatic impact on our approach to Power Factor correction. The motor and capacitor loads described above are all linear and for all practical purposes generate no harmonics. Non-linear loads such as ASDS, on the other hand, do generate harmonic currents.

Take a plant which is step-by-step putting adjustable speed drives on its motor loads. ASDs generate significant harmonic currents (5th and 7th on six-pulse converter drives). Suddenly the fuses on existing PF correction caps start blowing. Since these are three-phase caps, only one of the three fuses might blow. Now you’ve got unbalanced currents, possibly unbalanced voltages. The electrician replaces the fuses. They blow again. He puts in larger fuses. Now the fuses survive, but the capacitor blows. He replaces the capacitor. Same thing happens. What’s going on? Harmonics are higher frequency currents. The higher the frequency, the lower the impedance of a cap ($X_C = 1/\,2\pi f C$). The cap acts like a sink for harmonic currents.

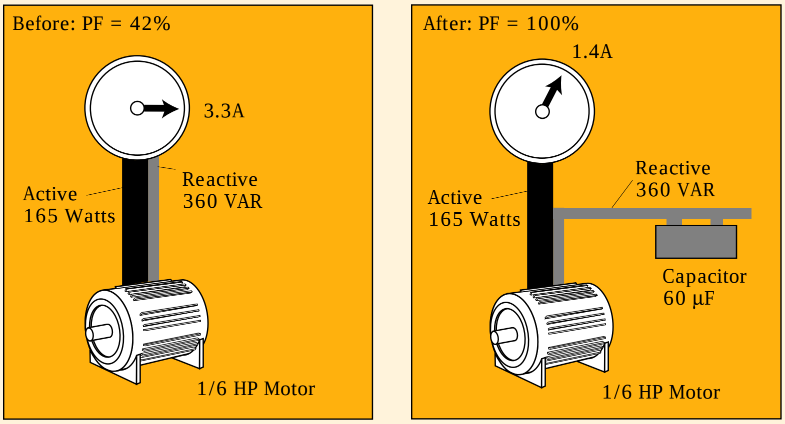


Figure 7.6 Capacitor corrects *Displacement* Power Factor (DPF).

Power System Resonance

In a worst-case scenario, the inductive reactance (X_L) of the transformer and the capacitive reactance (X_C) of the PF correction cap form a parallel resonant circuit: $X_L = X_C$ at a resonant frequency which is the same as or close to a harmonic frequency. The harmonic current generated by the load excites the circuit into oscillation. Currents then circulate within this circuit which are many times greater than the exciting current. This so-called "tank circuit" can severely damage equipment, and it will also cause a drop in power factor. Perversely, this resonant condition often appears only when the system is lightly loaded, because the damping effect of resistive loads is removed. In other words, we have what the audio buffs call a "high Q" circuit. (Fig. 7.8)

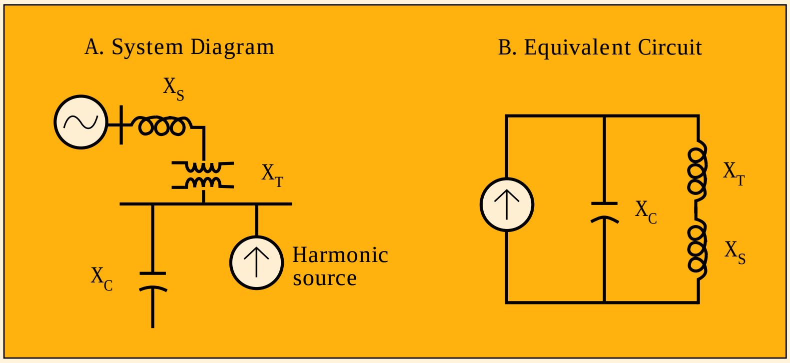


Figure 7.8 Resonant circuit when $X_C = (X_T + X_S)$

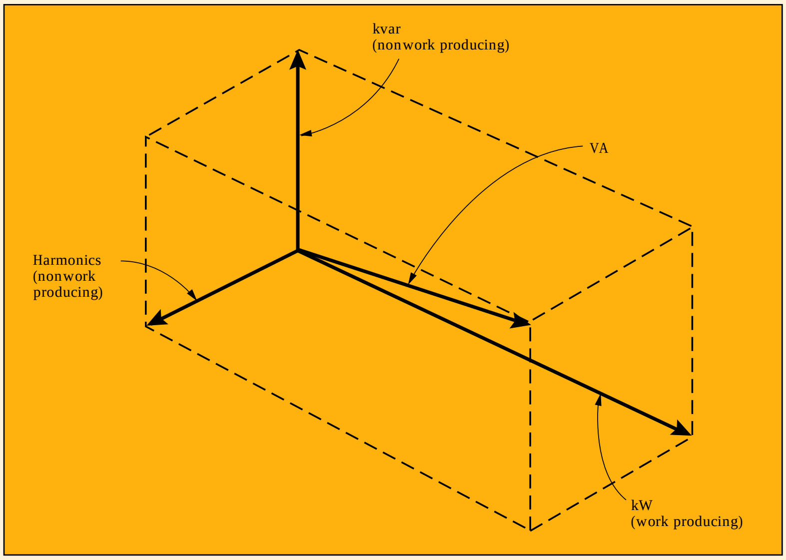


Figure 7.7 *Total* Power Factor increases with harmonics.

Imagine coming to work on a Monday and seeing the insulation on your cables melted off. How can this happen over a weekend when there was hardly any load on the system? Has Ohm's Law been overruled? Not quite. Your power system just spent the weekend tanked out on the Harmonics. It was quite a party, but now comes the clean-up.

Start with Harmonics Mitigation

The correct solution path starts with measuring and mitigating the harmonics generated by the drives. Harmonic trap filters would generally be called for. These trap filters are installed locally on the line side of the drive. Their effect is very much like the traditional PF correction cap, in two senses: they reduce DPF as well as PF, and also they localize the circulation of the problem harmonics (generally the 5th). Harmonics mitigation and traditional DPF correction should be addressed as one systems issue. In other words, manage Total PF, not just DPF.

Section 8
Troubleshooting Commercial Lighting Loads

Lighting loads are a major load for many large facilities. Evaluating these circuits is important for both energy conservation and power quality. Keep in mind that commercial lighting loads are wired single phase, with the loads connected from phase to neutral. Typically, the phase-to-phase voltage is 480V, with the phase-to-neutral voltage at 277V. Measurements must be taken at the lighting panel, one phase at a time, since power consumption and Power Factor could vary on each phase.

1. Power consumption

Excessive phase unbalance can cause voltage unbalance, which in turn can affect three-phase motor loads.

2. Power Factor

Ballast with low PF might have lower cost-of-purchase but higher cost-of-operation.

3. Total Harmonic Distortion

Current THD should be considered when selecting ballast, especially if there is a possibility of transformer overloading.

4. Voltage stability

The sags and swells mode of the Fluke 43 is especially useful for recording repetitive voltage sags which can show up as flickering lights. Both current and voltage are monitored simultaneously. This helps us to tell if sags are downstream of the measuring point (load-related) or upstream (source-related). For example, if voltage *sags* while current *swells*, a downstream current inrush likely caused the sag. If *both* voltage and current *sag*, some event upstream caused the sags.

It could be an upstream load like a motor on a parallel branch circuit which drew down the feeder voltage. Or it could be source voltage-related, for example, a lightning strike or breaker trip/reclosure on the utility distribution system.

Table 8.1 Measurements on commercial lighting loads.

Measurement	Look for	Instrument
1. Power consumption (kW)	Balance among three phases.	43, 41B
2. Power Factor (DPF and PF)	Magnetic ballast will have low DPF. Electronic ballast may have low total PF, although new generations of ballast often have harmonic mitigation built-in.	43, 41B
3. Total Harmonic Distortion (%THD)	Current %THD <20% is desirable.	43, 41B
4. Voltage Stability	Unstable voltage can cause lights to flicker.	43

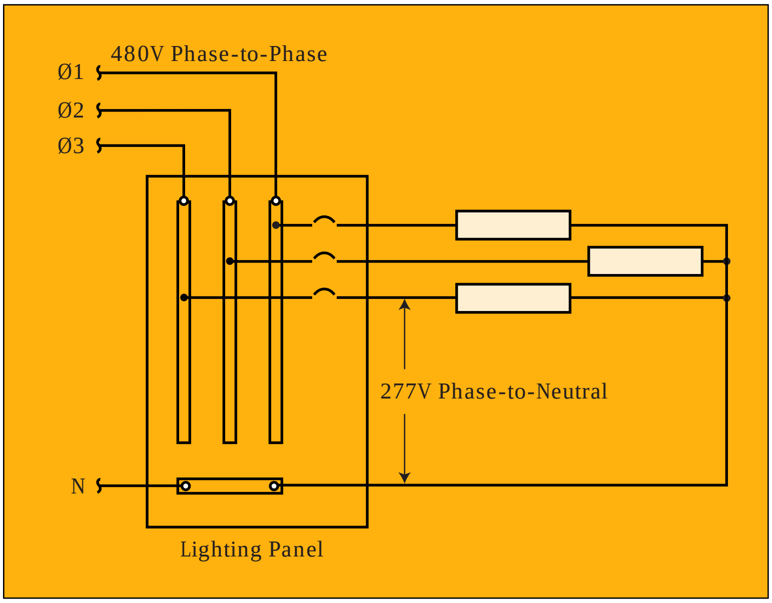


Figure 8.1

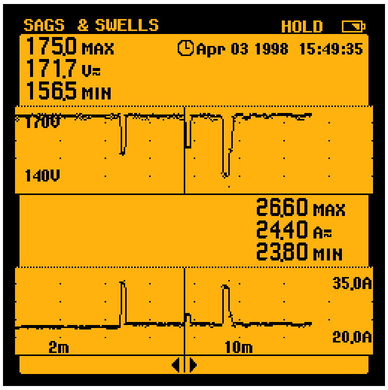


Figure 8.2 Fluke 43 trends voltage (top) and current (bottom) simultaneously. Current swells/inrush caused voltage sags, indicating that a load downstream from the measurement point is the cause of the disturbance.

A Lineup of Power Quality Culprits

From utility source to receptacle

Lightning
Can be extremely destructive if proper surge protection is not installed. It also causes sags and undervoltages on the utility line if far away. If close by, it causes swells and overvoltages. But in the final analysis, lightning is an act of nature and not in the same category as the damage man does to himself.

Utility automatic breaker reclosure
Causes short duration sags/ outages, but better than the alternative, a longer-term outage.

Utility capacitor switching
Causes a high-energy voltage disturbance (looks like an oscillating transient riding on the wave). If the cap bank is near the facility, this transient can propagate all through the building.

Commercial high rises without enough distribution transformers
Trying to cut corners in the wrong places; running 208V feeder up twenty stories is not the road to PQ.

Gen-sets not sized for harmonic loads
Excessive voltage distortion affects electronic control circuits. If SCR converter loads are present, notching can affect frequency control circuits.

Applying PF correction capacitors without considering the effects of harmonics
Harmonics and caps don't mix. Those bulging capacitors are crying for help.

Inrush currents from high torque motor loads started across-the-line
Causes voltage sags if the load is too large or the source impedance too great. Staggered motor starts can help.

Undersized neutrals at panelboard
In the era of the 3rd harmonic, neutrals can easily carry as much current or more current than the phase conductor. Keeping them undersized leads to overheated lugs, potential fire hazards and high N-G voltage.

Running power and signal cables together
Think of the signal cable as a single-wire transformer secondary and the power cable as the primary. The opportunities for coupling are endless.

Loose conduit connections and lack of green wire grounding conductor
Causes open or high impedance ground circuit. Not good for PQ or safety.

Shared neutrals on branch circuits
Causes load interaction and overloaded neutrals.

Laser printers and copiers sharing branch circuits with sensitive loads
Guaranteed periodic voltage sags and switching transients.

Miswired receptacles (N-G swapped)
Hard to believe, but they are out there in quantity. Guaranteed to put return currents on the ground conductor and create a noisy ground.

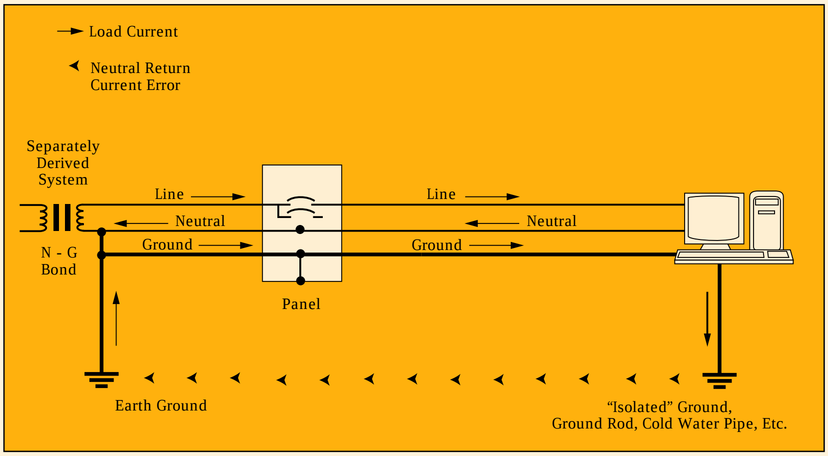
Data cables connected to different ground references at each end
Ouch! Shows up as voltage between equipment case and the data cable connector.

Hi-frequency noise
The most effective high frequency grounding technique is the installation of a Signal Reference Grid (SRG).

And in a class by themselves

Isolated ground rods (below)
They're a safety hazard because the earth is a high impedance path and will prevent enough current from flowing to trip the breaker. They also cause ground loops; after all, every electron still has to go back where it came from. One of the great mysteries of PQ is how some manufacturers get away with insisting that their equipment warranty is void unless an isolated ground rod is installed. My auto mechanic was so inspired by this practice that he now warranties every car he works on unless it's driven.

Illegal N-G bonds (Fig. 2.1, page 8)
Guaranteed to put return currents on ground. A common enough problem that the Union of PQ Consultants wants to charge piecework rates—say, a dollar for every N-G bond found. They'd all get rich. Not only is it a PQ problem, it's a plumbing problem. Circulating ground currents cause corrosion of water pipes. That explains why you can never find the electrician that put in those N-G bonds—it's all being done on the sly by the plumbers. Guaranteed employment, as if they needed it.



Isolated ground rod can cause ground loops. Common problem with CNC machine tool installations.

A word on test tools

The minimum requirement for test tools used in PQ troubleshooting are:

- True-rms for accurate measurement with harmonics and distorted waveforms.
- CAT III-600V or higher (CAT III-1000V) safety rating, which are appropriate for measurements on power circuits

In addition, instruments with recording capability, waveform display and specialized measurements (such as harmonics, sags and swells, transient capture, high frequency noise, etc.) are needed.

The following Fluke test tools are referred to in this application note.

Model	Fluke 43	Fluke 41B	Fluke VR101S	Fluke 87 Series III	Fluke 36
Test Tools	Power Quality Analyzer	Harmonic Analyzer	Voltage Event Recorder	Digital Multimeter	ClampMeter
Power	kVA, kW, kVAR, PF, DPF	kVA, kW, kVAR, PF, DPF			
Recording	TrendPlot™, PC logging	PC logging	4000 voltage events		
Real-Time Clock	●		●		
Harmonics	To 51st harmonic	To 31st harmonic		True-rms volts and current	True-rms volts and current
Voltage Transients	20 nanoseconds with waveform		1 microsecond event recording	250 microsecond Peak MIN/MAX	
Sags & Swells (Voltage only)	Single cycle MIN/MAX with trend		Single cycle event recording	100 millisecond MIN/MAX	
Sags & Swells (Simultaneous Voltage and Current)	Single cycle MIN/MAX				
Outages	Single cycle MIN/MAX with trend	Event recording with duration		100 millisecond MIN/MAX	
Documentation, RS232 Computer	FlukeView® Power Quality Software	FlukeView® 41 Software	EventView™ Software		
Motor In-rush Current	Waveform with cursors			MIN/MAX	MAX Hold
Waveform	20 MHz scope	Fundamental			
Noise	●				
Peak	●	●		●	
True-rms	●	●		●	●

References and acknowledgments

- *EC&M Practical Guide to Quality Power for Sensitive Electronic Equipment*, 2nd Edition.
- *Dranetz Field Handbook for Power Quality Analysis.*
- *Ontario Hydro Power Quality Reference Guide.*
- Association of Energy Engineers: *Fundamentals of Power Quality*.
- IEEE Std 1100-1992: *Recommended Practice for Powering and Grounding Sensitive Electronic Equipment*.
- EPRI, Electrotek Concepts, Inc.: *Power Quality for Utility and Industrial Applications*
- *Power Quality Assurance Magazine*

Power Quality Troubleshooting
Learn to measure, diagnose and solve PQ problems.
Part Number: 800919 - NTSC
800927 - PAL

The ABCs of Digital Multimeter Safety Video Tape
Learn how proper work procedures and equipment can protect you from hazards.
Part Number: 609104
For sale at Fluke distributors, or call the appropriate phone number listed to the right

Understanding and Managing Harmonics
Part Number: 609096

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