FLUKE®

PQ measurements at receptacle branch circuits

Application Note

Many power quality 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 Figure 1) the voltage waveform is flat-topped, which is typical of a building

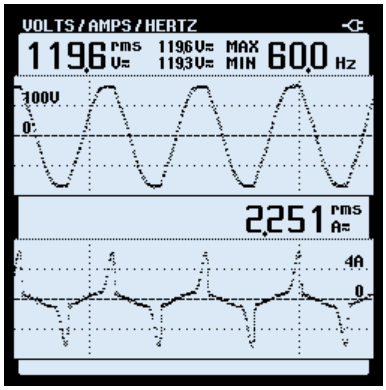

Figure 1. Flat-topped voltage at receptacle.

with many non-linear loads such as computers and other office equipment (see Figure 2). 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 115 V, the peak value would be 1.414 x 115 V = 162.6 V, 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.

Table 1: Measurements on receptacle branch circuits

Voltage Measurements	Look for	Instrument
1. Waveform	Snapshot of severity of voltage distortion	43, 41B
2. Peak voltage	Excessive flat-topping	43, 41B, 87 DMM (Peak MIN MAX)
3. RMS voltage	Low rms (steady-state low rms or intermittent/cyclical sags)	43 (Sags/Swells) 41B, 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 (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, 87 DMM

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 a Fluke 87 DMM while energizing the load. What if you want to know if there are recurring sags? Use the Sags & Swells trending feature on a Fluke Power Quality Analyzer to continuously capture sags. 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.

5. Recording (long-term)
For longer term recording, the Fluke VR101S Voltage Event Recorders will record sags, swells, outages, transients and frequency deviations while plugged into the outlet. 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 Figure 4).

Flat-topped voltage

The flat-topped waveform is typical of the voltage in a commercial building with computerloads. 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.

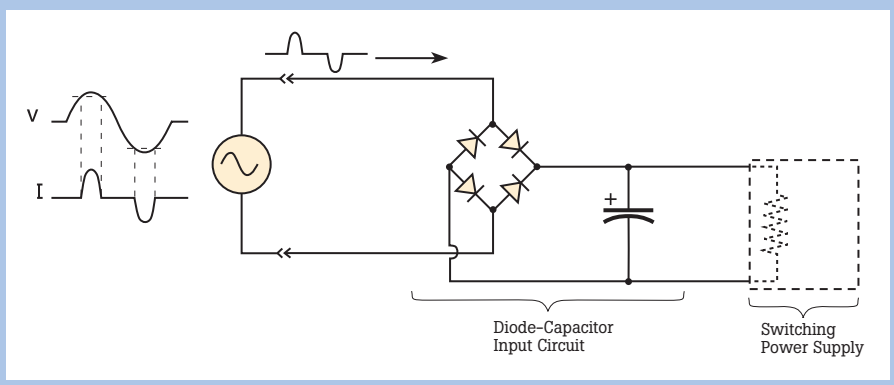

Figure 2. Flat-topped voltage.

Receptacle N-G voltage measurement notes

1. A rule-of-thumb used by many in the industry is that N-G voltage of 2 V or less at the receptacle is okay, while a few volts or more indicates overloading; 5 V 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 0 V, 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. 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.

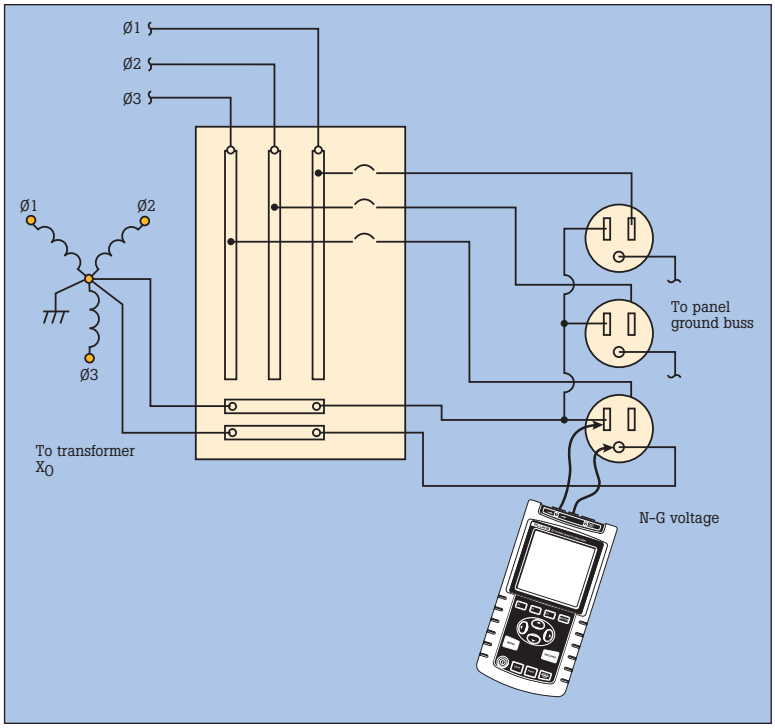

Figure 3. Neutral-to-ground voltage increases with shared neutrals.

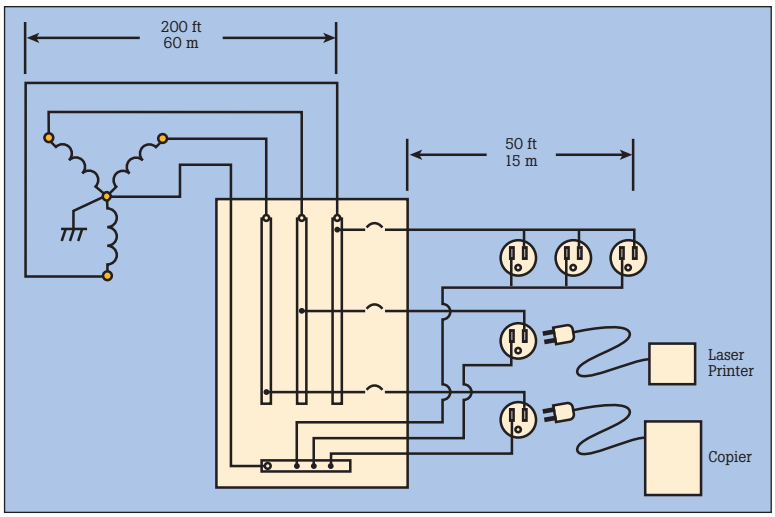

Figure 4. Neutral-ground voltage increases as load current goes up.

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.

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 shortcut quickly became a dead-end with the growth of single-phase nonlinear 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 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.

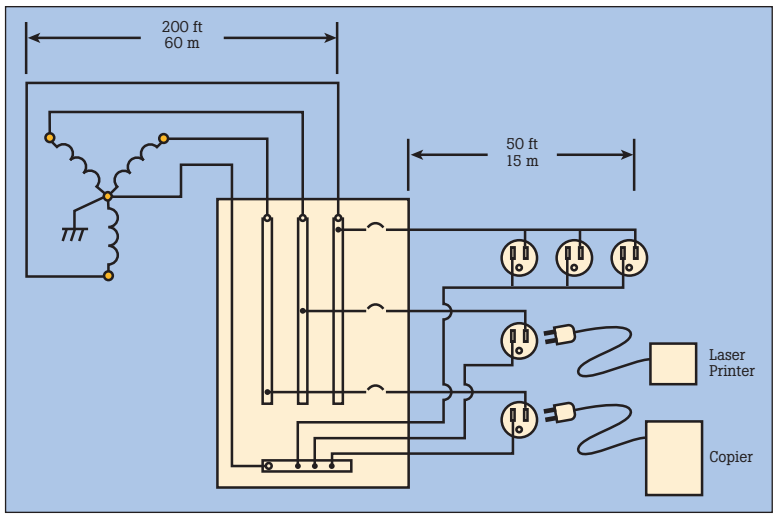

Figure 5. Performance wiring.

Table 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 120 V branch circuits to 50 ft. (15 m).	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.

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