By Dan Strassberg, Senior Technical Editor

Get a (power) line on mysterious malfunctions

SOPHISTICATED TECHNOLOGY HELPS EEs BULLETPROOF NEW DESIGNS AGAINST THE VICISSITUDES OF THE AC LINE AND DISCOVER WHY PRODUCTS SOMETIMES DEVELOP ALLERGIES TO LESS-THAN-PERFECT SINE-WAVE POWER.

A handheld LCD digital scope can be handy for troubleshooting ac-line-related problems, but few such scopes display captured waveforms' harmonic content. Tektronix's THS720P can do so. Besides displaying waveforms and numerically indicating a variety of measurements, the instrument provides a bar-graph display of harmonic content.

In the United States and Canada, most people take for granted the reliability and quality of the ac power that runs so many things in their lives. Of course, not all parts of the world are so fortunate. Even in the United States, summer lightning storms cause fairly frequent power outages in certain areas. Nevertheless, most engineers who design ac-powered electronic products for consumer, office, and medical applications spend little time worrying about the primary ac power supply. Usually, field reports of mysterious product-performance problems serve as these designers' first reminder that ac lines don't always deliver pure sine waves of constant amplitude. Indeed, when you hear about unexplained glitches in the operation of a product you designed, you probably examine many possible causes before you begin to suspect the power line. If you rarely think about how ac-power imperfections affect your product, or how your product affects the ac line, you may find the following material enlightening.

One group of EEs for whom power quality is important is designers of industrial-electronic products used near heavy machinery. Large machines are notorious for contaminating the ac lines that feed them. The anomalies include sags (low voltage), swells (high voltage), flicker (rms-voltage fluctuations), transients, noise, and waveform distortion (or its frequency-domain equivalent, the presence of harmonics).

Another group that is quickly learning to concentrate on ac-power quality is designers of products that are exported to Europe. Where EMI is concerned, many modern electronic products "get as good as they give." That is, they not only generate EMI, they also suffer from its effects. To ensure that products sold in Europe suit their intended purpose, the European Union has promulgated standards called European norms (ENs). Some of these documents specify how much interference products may create; several others specify EMI levels that products must tolerate without misbehaving. For conducted EMI, ENs mainly apply to power-line tolerance—how much EMI products may cause and how much they must tolerate. The US situation differs slightly. The nearest equivalent regulations from the Federal Communications Commission (FCC) govern EMI generation but mostly ignore susceptibility.

GLOBAL MARKETPLACE

As the marketplace globalizes, versions of electronic products sold in different parts of the world become more similar every day (though ac-power-line characteristics still vary regionally). In the hope of selling nearly identical products everywhere, growing numbers of companies now design to meet regulations that cover EMI susceptibility as well as EMI generation.

Many design practices that reduce radiated and conducted EMI also reduce EMI susceptibility (**Reference 1**). Following these practices is a good start. Eventually, however, besides characterizing your product's generation of radiated and conducted EMI, you will likely have to measure—or have someone measure—the product's EMI susceptibility. Although necessary, determining that EMI emissions meet EN or FCC limits isn't always sufficient. Sometimes, emissions that meet specified limits still interfere with nearby sensitive equipment. As for susceptibility, even if your product passes standardized tests, the application—for example, a location near severe EMI sources—can necessitate verifying the product's performance under more rigorous conditions.

Generally speaking, resistive loads are the most benign in their treatment of ac lines. Except when you first switch them on, loads such as incandescent lights, toasters, and electric heaters, draw sinusoidal currents that are in phase with the line voltage. In other words, in the steady state, resistive loads are linear and operate at a power factor (PF) of 1. Because their cold resistance is a small fraction of their steady-state resistance, most resistive loads—especially light bulbs—draw sizeable current transients at turn-on. The transient current diminishes as the load approaches its steady-state operating temperature.

Electronic equipment presents loads that, quite often, are less well behaved. The majority of such equipment uses power supplies in which capacitor-input filters follow rectifiers. This statement is true whether the supplies use linear or switching regulators. In linear supplies, the rectifiers and filters normally appear in the power transformer's secondary circuit. Most ac-input switching supplies are so-called offline switchers in which a set of rectifiers and filters acts directly on the line

AT A GLANCE

- ▷ Not only does modern electronic equipment often malfunction in the presence of less-than-perfect ac power, the equipment can also cause power-line disturbances.
- ▷ Many measuring instruments can help you to correlate mysterious product malfunctions with power disturbances and determine whether your product causes power-line problems.
- ▷ There is no such thing as a one-size-fits-all ac-power-quality-measuring-and-monitoring instrument. The audience for such products is diverse, and the range of products that address the audience's needs is equally diverse.

Monitoring of ac-line events is about as simple as it can be with Fluke's VR101 event recorder. First, use the optically isolating cable (right) to connect the compact data logger (top left) to your PC. Next, use the supplied software to define the types of events to capture. Then disconnect the PC and plug the logger directly into the line (a standard ac plug is on the back). A seven-year-life lithium battery inside the logger supplies power to continue logging even if the ac power fails. Finally, reconnect the logger to the PC to obtain a report describing as many as 4000 time-stamped events.

voltage. The power transformer, which appears later in the circuit, operates on the switching regulator's high-frequency output. Additional rectifiers and filters in the transformer's secondary circuit convert the transformer output to dc. During the past few years, primarily in response to European regulations, increasing numbers of offline switchers have begun using active power-factor correction (PFC) to reduce the line-current waveform's harmonic content.

SINUSOIDAL VOLTAGE, SPIKY CURRENT

Without PFC, the capacitor-input filter of a power supply that uses full-wave rectifiers draws current only near the voltage-magnitude peak in each half ac-line cycle. In other words, the supply's input current consists of a series of alternating-polarity pulses, a half-cycle apart (every 8.33 msec at 60 Hz). Each pulse is roughly triangular in shape, and, in offline switchers, is typically about one-eighth-cycle wide. The pulse width increases as the supply's load increases, and tends to be somewhat wider in linear supplies than in offline switchers. Although you might not suspect it, the line's series impedance is often high enough that the current pulses cause voltage drops that noticeably flatten the voltage waveform's peaks. In the frequency domain, then, the voltage waveform contains, in addition to the fundamental frequency, odd-harmonic components (odd multiples of the line frequency).

PF is the ratio of real power to apparent power (where apparent power is the product of the rms voltage and rms current). PF originally described the effect of rotating ac machines in systems in which the line voltage is purely sinusoidal. In the steady state, these machines draw (theoretically) sinusoidal currents that can be out of phase with the line voltage. In such systems, PF=cos θ, where θ is the phase angle between the voltage and current. The real power, P, delivered to the machine is then E×I×PF, where E and I are the rms values of the line voltage and current respectively. The apparent power is simply E×I.

In systems that supply power to electronic equipment that draws nonsinusoidal currents, the equation P=E×I×PF still applies. However, because the current is nonsinusoidal, it contains appreciable harmonic components, which do not transmit power that the load can use. To determine the load's real power consumption, you must use a wideband wattmeter. To measure apparent power, you need an rms voltmeter and an rms ammeter. Because the waveforms are nonsinusoidal, both meters require wide bandwidth, although the typically greater current distortion usually makes the ammeter's bandwidth more important.

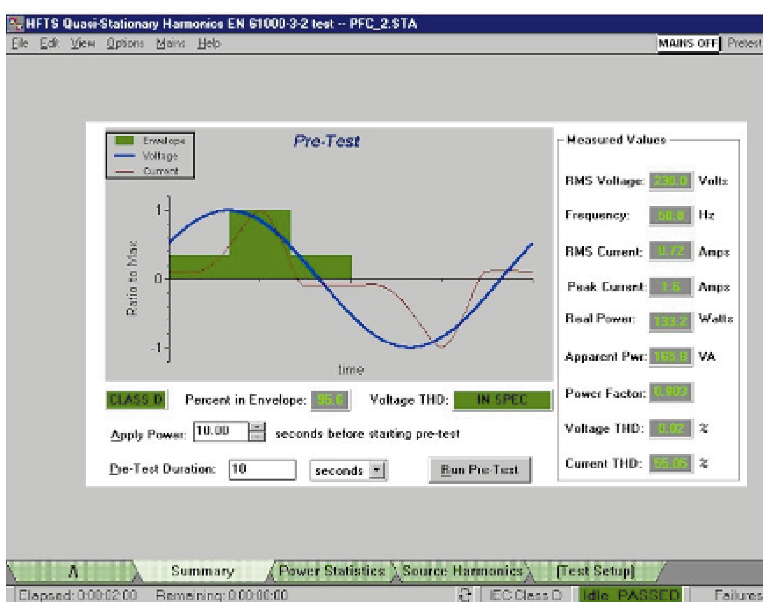
DIGITAL TECHNIQUES MOVE IN

Today, many power-measurement instruments digitize the voltage and current waveforms and mathematically process the numeric values to compute instantaneous and average power. Many modern ac voltmeters and ammeters use similar approaches to compute rms voltages and currents. In addition, many instruments use DSP techniques, especially FFTs, to extract the harmonic content of voltage and current waveforms.

If you think of ac-power measurements in terms of the line frequency alone, the necessary A/D conversion rates may surprise you. Because some ENs require determining the harmonic content to the 40th harmonic or beyond (2000 Hz on a 50-Hz European power line), the ADCs must convert at surprisingly high rates. Although, in theory, you need take only incrementally more than 4000 samples/sec to perfectly reconstruct a 2000-Hz-bandwidth waveform, sampling five or more times as fast considerably simplifies the instrument design. Fortunately, making 20,000 conversions/sec for a 50-Hz line or 24,000 for a 60-Hz line hardly taxes modern ADCs—even units that have 16-bit resolution.

Besides pressure from Europe to reduce the harmonic content of the current that electronic equipment draws, there are excellent reasons for concern about harmonics. The 120V single-phase power in most US commercial and industrial buildings originates as one phase of a three-phase, four-wire (wye-connected) supply. Even in relatively new buildings, the ac-power system's neutral conductor (fourth wire) is often no larger than any of the phase (ac-hot) wires. If every load consisted only of resistors connected between a phase wire and neutral, and if the total loads on all phases were identical, the net neutral current would be zero. In this ideal situation, a neutral conductor of the same size as each phase wire would be more than adequate.

Unfortunately, in modern power systems, such ideal situations rarely exist, so the neutral conductor is dangerously undersized. For one thing, it is usually impossible to guarantee the equality of the loads on the



Growing numbers of engineers must design and test products for compliance to European norms that govern the products' generation of and susceptibility to EMI. Agilent's 14769A software package includes modules for testing harmonic and flicker emissions, immunity to voltage and frequency disturbances, and immunity to the effects of multiple line-voltage harmonics.

three phases. Moreover, in commercial buildings, increasing numbers of loads contain offline switching supplies that lack power-factor correction and that, therefore, return harmonic-rich currents to the neutral conductor.

NEUTRAL CURRENTS

The neutral current is zero in the ideal case because three equal sinusoidal currents separated in phase by 120° sum to zero. However, if you replace each of these fundamental-frequency currents with a third-harmonic current having the same zero-crossing time and dv/dt polarity at the zero crossing as the fundamental, all of the neutral currents are in phase. Now, instead of summing to zero, the neutral currents add, making the total neutral current equal to the sum of the phase currents. If the phase currents consist only of third-harmonic components whose rms values equal those of their fundamental-frequency counterparts in the initial example, the total neutral current is three times any one phase current. To avoid overheating the neutral conductor, you must triple its cross-sectional area (decrease its wire gauge by approximately 5 AWG units).

A power system whose neutral current exceeds the neutral conductor's capacity is a fire hazard and can cause both additional safety problems and equipment malfunctions. The chassis of all pieces of ac-line-powered equipment should connect to a safety-neutral conductor, which, except under fault conditions, carries only leakage current (normally measured in microamps or milliamps). This conductor (often called a ground conductor) should connect to the current-carrying neutral at only one point. Ideally, this point is where the distribution transformer's three wye-connected phase windings join. Many power systems violate this rule, however. The result can be chassis whose potentials differ substantially from one another and from true ground. Although a water pipe might constitute such a ground, don't depend on water pipes for grounding; many of them are, in fact, electrically floating. Not only can chassis that aren't at ground potential pose shock hazards, a system will probably malfunction if it interconnects two or more pieces of equipment whose chassis potentials differ. The malfunction can take the form of continuous or intermittent errors, or equipment damage.

Instruments that measure ac current, voltage, and power may not help much in pointing out a neutral conductor that is

FOR MORE INFORMATION...

For more information about power-quality-measuring-and-monitoring instruments and systems, circle the appropriate number on the Information Retrieval Service card or use *EDN*'s InfoAccess service. If you contact any of these companies directly, please tell them that you read about them in *EDN*.

Agilent Technologies
1-800-452-4844
www.agilent.com
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California Instruments
1-858-677-9040
www.calinsts.com
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www.dranetz-bmi.com
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Electrotek Concepts
1-800-554-4767, 1-865-470-9222
www.electrotek.com
Circle No. 313

Elgar Corp
1-800-733-5427, 1-858-450-0085
www.elgar.com
Circle No. 314

Extech Instruments Corp
1-781-890-7440
www.extech.com
Circle No. 315

Fluke Corp
1-425-347-6100
www.fluke.com
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Gould Instrument Systems
1-216-328-7000
www.gouldis.com
Circle No. 317

Hioki USA Corp
1-609-409-9109
www.hioki.co.jp
Circle No. 318

IOtech Inc
1-440-439-4091
www.iotech.com
Circle No. 319

LeCroy Corp
1-800-553-2769, 1-914-425-2000
www.lecroy.com
Circle No. 320

Magtrol Inc
1-800-828-7844, 1-716-668-5555
www.magtrol.com
Circle No. 321

Northwest EMC Test Lab
1-503-537-0728
www.nwemc.com
Circle No. 322

Pacific Power Source
1-800-854-2433, 1-714-898-2691
www.pacificpower.com
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PowerTronics
1-800-746-9586, 1-603-483-5876
www.powertronics.com
Circle No. 324

Reliable Power Meters
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www.reliablemeters.com
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www.schaffner.com
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Select Energy
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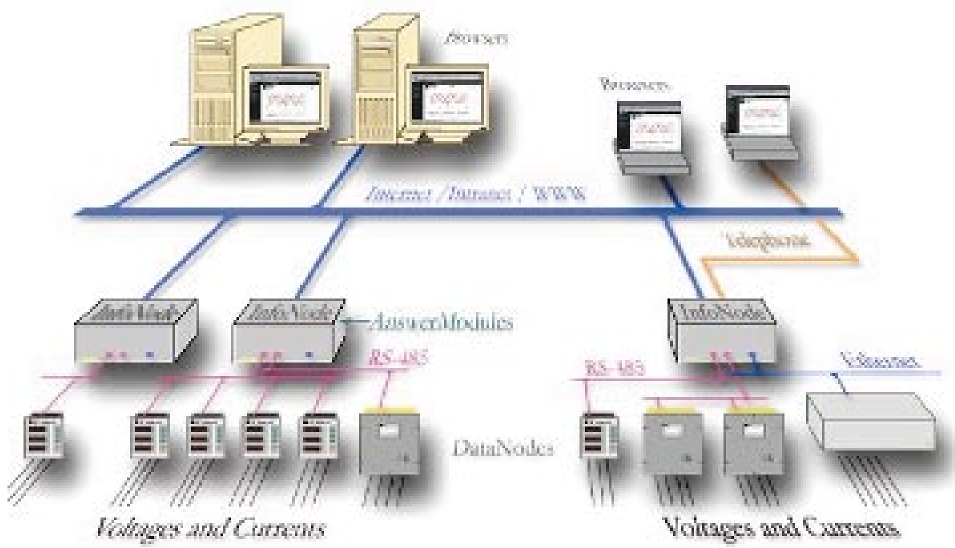
carrying too great a current for its size. Still, once you suspect an overloaded neutral and can identify the conductor you suspect, an ammeter (preferably a true-rms-responding ammeter) can quickly confirm or invalidate your suspicions. With a clamp-on instrument or a current probe, making the measurement doesn't require even momentarily breaking the circuit. For intermittent problems, a data logger or a meter that stores or records readings over extended periods can enable you to determine whether or not your suspicions are accurate. However, to correct the problem at its source, you need to understand why the neutral is overloaded. For that, you should have an instrument that performs harmonic analysis.



The quality of ac power in large manufacturing facilities often concerns many people. Dranetz's Signature system monitors voltages and currents at several points and publishes the information on Web pages that users of the corporate intranet can view. A standard browser displays the information; specialized viewing software is unnecessary.

INFORMATION NEEDS AND INSTRUMENTS

Nobody should be surprised that the kind of ac-power-quality data you need to gather depends on why you're gathering the data. Because information needs cover such a wide range, there is no such thing as a one-size-fits-all ac-power-quality-measuring-and-monitoring instrument. Power-quality instrumentation comes in many sizes, shapes, capabilities, and costs, from handheld units that cost a few hundred dollars to rack-mounted systems that cost many thousands. The target audiences, which include electricians, maintenance personnel, transmission-and-distribution engineers, equipment-design engineers, and EMI and compliance engineers, are nearly as diverse as the instruments' physical characteristics.

One trait is common to almost all of the newer products, however. Although these instruments emphasize ease of use, impressive technology lies behind the panels. Once you discover how much computing power resides within these devices, you are likely to ask, "who woulda' thunk it?" Some units even publish power-quality data directly to Web pages on company intranets. Instruments that have this capability appeal mainly to facilities engineers who must keep track of power quality at many locations.

Instruments such as more expensive general-purpose digital storage oscilloscopes (DSOs) often contain specialized power-analysis packages. These packages make such power-related calculations as determining a waveform's harmonic content. Although general-purpose scopes offer bandwidth many orders of magnitude higher than power-system analysis demands, for many design engineers, the instruments' myriad other functions make the cost quite reasonable. On the other hand, general-purpose scopes' input amplifiers are unsuitable for direct ac-line measurements, so safe measurement of ac phenomena can require purchasing current transformers and isolation amplifiers.

At 24k samples/sec, a DSO with a memory depth of 8M samples takes more than 5½ minutes of data. Though not a huge amount of time, 5½ minutes allows you enough time to capture some intermittent phenomena after only a few tries. In addition, if you sample more slowly, you can extend the captured interval's duration. When you're attempting to correlate a malfunction with an ac-line phenomenon, you usually don't have to reconstruct the line frequency's 40th harmonic. You may be able to sample more slowly until you determine when the problem arises. Then, sampling at a higher rate can help you to explain why the problem occurs. Don't forget, though, that sampling folds (aliases) any frequency components higher than half the sampling rate into the region between dc and half the sampling rate. Still, because most DSOs' ADCs resolve only 8 bits, harmonics above the ninth or 11th shouldn't seriously affect the scope display.

Many high-end DSOs also let you capture records that are much longer than the acquisition memory. The scopes accomplish this feat by periodically writing the memory's contents to an internal hard disk, or to a high-capacity removable disk, such as a SuperDisk (www.superdisk.com). Although writing to the disk usually causes gaps during which the scope acquires no data, such gaps rarely hinder searches for phenomena that occur more or less randomly.□

You can reach Senior Technical Editor Dan Strassberg at 1-617-558-4205, fax 1-617-558-4470, e-mail ednstrassberg@cahners.com.

REFERENCE

1. Gerke, D, and B Kimmel, *EDN designer's guide to electromagnetic compatibility*, EDN supplement, Jan 20, 1994.