PQ Encyclopedia
A product of the EPRI Power Quality Knowledge program

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Power Quality Monitoring: Concepts, Equipment, and Applications

Chapter 10

Contents

Phil Barker, Nova Energy Specialists
Bill Howe, EPRI

Today, many different types of power quality (PQ) studies can be performed, and when a PQ project is being considered, understanding the types of measurements needed, how to make them, over what time frame, and at what locations is indispensable in keeping costs reasonable. Power quality monitoring is a broad subject, but some basic principles and concepts can be applied to make any project go more smoothly. This chapter covers the definitions, equipment types, measurement strategies, and analytical approaches needed to achieve good results.

To begin with, an analysis must be made about whether a PQ-related problem exists. Therefore, a working understanding of waveforms and what shape the power needs to be in for a particular application is important. While the power does not need to be perfect, it must be close enough to perfection to meet the operational requirements of end-use loads and various regulatory standards and guidelines.

Once a problem has been identified, the next step would be to choose monitoring equipment. Specific questions are offered here to help in matching instruments to needs. The discussion covers both stand-alone and embedded PQ monitoring technologies, communication links, and various ways of correlating load disruptions with PQ events.

Power quality monitoring doesn't just end with instrument selection, procurement, and installation, however. Once the instruments are up and running, time and effort should be put into setting proper trigger thresholds and insuring that a procedure exists for data download to periodically collect data before the instrument memory fills. Procedures also need to be in place for archiving and analysis of the data.

About the EPRI Power Quality Knowledge program

The EPRI Power Quality Knowledge program provides a wealth of resources in well-designed, readable, and accessible formats. Paramount among these are documents covering a wide range of PQ topics, written not only for use by busy PQ professionals, but also to be shared with important end-use customers and internal utility management. The program's website, www.mypq.net, is the most comprehensive electronic PQ resource available, providing 24-7 access to proven expertise via the PQ Hotline, hundreds of PQ case studies, over 200 PQ technical documents, PQ standards references, indexes, conference presentations, and a wealth of other resources.

For more information, please visit www.mypq.net.

1018668

Understanding which types of measurements are needed, how to make them, over what time frame, and at what locations is crucial to any study and to keeping the costs of the project in line.

OVERVIEW OF POWER QUALITY MONITORING

Maintaining adequate power quality (PQ) is increasingly important when serving modern loads such as sensitive microprocessor-based devices, critical manufacturing processes, and data centers. It is estimated that power quality disturbances of all types cost the U.S. economy at least $10 billion per year in lost productivity and damaged equipment. To insure that adequate power quality is being maintained or to diagnose and/or benchmark specific problems resulting from power quality phenomenon, often electric power conditions must be monitored. Understanding how to monitor PQ conditions is crucial to solving specific PQ-related problems. This chapter of the *PQ Encyclopedia* focuses on general methodologies for monitoring, covering the definitions, equipment types, measurement strategies, and analytical approaches needed to achieve good results.

Power quality monitoring has advanced greatly in recent decades, not just because of more interest and need for it, but also because of the arrival of much-improved instrument technology. Fifty years ago, monitoring was usually done only with recording pen-charts (circle charts) and/or analog metering systems that had limited ability to record the full spectrum of power quality conditions that may be present—especially voltage sags/swells, rapid transient disturbances, and waveform distortion issues. Analog oscilloscopes were available at that time and could be used to observe waveforms and certain transients, but these early oscilloscopes were cumbersome to use as field instruments, not easily capable of unattended operation, and lacked the sophistication of modern digital recording and data storage devices that make it so easy today to capture and evaluate various transient waveform events.

In today's world, the engineer is well equipped to study power quality due to the availability of advanced microprocessor-based digital recording devices that can measure the full range of power conditions. In addition, the analytical tools and computer resources available today greatly assist with archiving and analysis of data. Today, many different types of power quality studies are performed, ranging from "full spectrum" studies to studies focused just on a specific type of condition. Understanding which types of measurements are needed as well as how to make them and over what time frame and at what locations is a crucial first step to any study and to keeping the costs of the project in line with reasonable expectations.

Power quality is a measure of the condition of the electric power supply waveform and magnitude considering both the allowable industry guidelines and the conditions needed for satisfactory operation of equipment and load-devices connected to the system. Power quality measurements are based upon numerous metrics, including voltage regulation limits, voltage balance limits, harmonic distortion levels, voltage sag/swell rates, interruption rates, voltage flicker limits, switching and lightning transients, electrical noise, and unwanted stray voltage potentials. In many power quality studies, the issue of electric power reliability (that is, the presence of momentary and/or sustained interruptions) is a key factor in the study of power quality. Some people treat reliability as a separate area of study that is distinguishable from classical "waveform-related" power quality, but in more cases than not, reliability plays a major role in the operation of sensitive loads and devices and is difficult to break apart as a separate entity from overall power quality. In this chapter, we'll include reliability as part of power quality.

A working knowledge of the expected interruption and sag rates for various types of power systems in typical operating environments is helpful to plan and interpret power quality studies.

The user must thoroughly understand the capabilities, limitations, and features of each type of instrument relative to the needs of the proposed project.

To know whether power quality is acceptable, we need to define the requirement of an acceptable waveform. Therefore, as part of the discussion in this chapter, we'll discuss the various standards and guidelines that apply to monitoring. The target range for acceptable power quality is specifically defined by industry technical standards for some aspects of the waveform. For example, there are Institute of Electrical and Electronics Engineers (IEEE) and American National Standards Institute (ANSI) standards that specify the allowable range of conditions for total harmonic distortion and the specific levels of harmonics that can be present (e.g., IEEE 519-1992). There are also specifications for voltage regulation and voltage balance (e.g., ANSI C84.1-1995). For factors like voltage sags and interruptions, the industry standards do not firmly define the specific rates or severity of these disturbances because the performance needs in these areas are more subjective and are interpreted based on load criticality, the susceptibility of the load to such disturbances, and power system design and/or exposure factors. The reliability performance and voltage sag rates measured in a power quality study may be contrasted against benchmarked rates observed in other parts of the power system or based upon national averages or system design expectations such as described in IEEE 1366. Obtaining a working knowledge of the expected interruption and sag rates for various types of power systems in typical operating environments is helpful to plan and interpret power quality studies.

A key factor in achieving successful measurements is selecting a compatible instrument that meets the measurement objectives. When it comes to selecting specific equipment for monitoring of power quality, the engineer or technician is faced with a wide range of available devices. Literally hundreds of models of data loggers, digital oscilloscopes, and PQ monitors are available. To add to the array of choices, engineers and technicians also have a choice between "stand-alone" PQ instruments, which are intended solely for measuring power quality, and the many new emerging PQ monitoring devices that are "embedded" into revenue meters, protective relays, power conditioning equipment, voltage regulator controls, reclosers, and other equipment. Selecting the most suitable instrument(s) from the maze of available devices requires that the user thoroughly understand the capabilities, limitations, and features of each type of instrument relative to the needs of the proposed project. The measurement capabilities of the instruments aren't the only thing involved in the selection criteria. Compatible instruments must be able to deal with the environmental conditions at the locations where they will be installed, so they must have a reliable instrument power supply with backup power (if needed), a communication link for remote data transfer (when needed), and sensing input ports and/or transducers with sufficient bandwidth and sensitivity for the required measurement. Also, voltage and current levels at the desired measurement locations may need to be converted to a reduced level that is suitable to safely feed into the instrument inputs. Given these factors, some serious thinking about instrument needs is required before simply plunging headfirst into a power quality project. Failure to adequately address some of these issues can result in project delays, excessive project cost, instrument failures, safety issues, and inaccurate or improperly recorded data. In this chapter, we'll review all of these issues and provide general practices and guidelines that will be helpful.

The final aspect of power quality monitoring we will address in this chapter is the actual

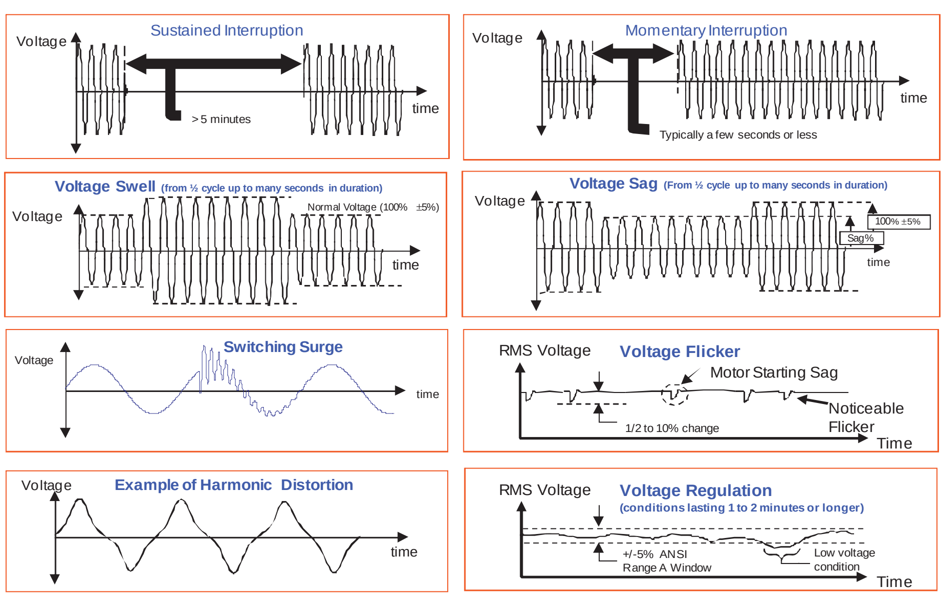
The effort required for power quality monitoring doesn't just end with instrument selection, procurement, and installation.

monitoring effort that follows procurement and installation of the instruments. The effort required for power quality monitoring doesn't just end with instrument selection, procurement, and installation. Once the instruments are up and running, then the fun really begins. But for this stage of the project to be productive, much effort is required to make sure the instruments are set to the proper trigger thresholds and to insure that a procedure for data download is in place to periodically collect data before the instrument memory fills. Procedures are needed for archiving and analysis of the data too. The more instrument points involved in the study, the more complex and critical this process is.

REVIEW OF POWER QUALITY DISTURBANCES, DEFINITIONS, IEEE STANDARDS, AND GENERAL REQUIREMENTS

As a prerequisite to identifying the specific types of measurements needed for a given power quality project, PQ engineers must have an understanding of the range of disturbances that can be present on the power system, the standards by which these disturbances are judged, and the expected impacts on loads and system equipment. As a starting point, let's consider the ideal power quality condition. The ideal power condition is a 60-Hz waveform that has a voltage exactly at nominal rating with no variations, has 0% harmonic distortion, and is totally free of lightning surges, switching surges, sags/swells, and power interruptions. Furthermore, for this waveform to be absolutely perfect, it should be free of electrical noise and the power system grounding must be such that no stray voltages are present. This "perfect" condition just described is *entirely theoretical* since no electrical supply in the world no matter how robust or well designed can be entirely free of small quantities of all these mentioned defects. In the real world, we don't need perfect power; we just need power that is close enough to perfection that it meets the operational requirements of end-use loads and various regulatory guidelines. In some cases, far from perfect can be good enough! The figure below illustrates some of the most common types of real-world power quality conditions that are measured.

Examples of Common Power Quality Conditions



Understanding which area to focus on for a particular study requires having awareness about the nature of the site to be studied and the power system feeding the site.

Different sites have different PQ requirements. Critical loads, like data centers, require a high level of PQ that is only satisfied with specialized power distribution and conditioning equipment such as dual feeders, backup generators, and uninterruptible power supply (UPS) banks. Residential loads, on the other hand, are considered low priority from a PQ perspective and are allowed to be exposed to more disturbances, such as high rates of voltage sags, voltage swells, interruptions, and other anomalous conditions. Regardless of the grade of power needed for a particular site, the types of conditions that exist are always going to fall into one of the five areas or a combination of the five areas listed below:

- **Steady-state voltage levels and demand conditions.** These conditions include voltage regulation (high or low sustained voltage), voltage unbalance, real and reactive power demand, and harmonic distortion.
- **Reliability conditions.** These are momentary and sustained interruptions.
- **Multicycle transients**. These conditions include voltage sags, voltage swells, voltage flicker, motor-starting transients, inrush and fault currents, and transient harmonic-distortion bursts.
- **Subcycle switching and lightning transients.** These conditions include surges caused by equipment switching operations and lightning strikes.
- **Other conditions.** These include electrical noise, electromagnetic interference, voltage flicker, and stray voltage.

Understanding which area to focus on for a particular study requires having awareness about the nature of the site to be studied and the power system feeding the site. Electrical anomalies on power systems originate on both the utility side of the system and at customer loads. In general, studies that focus on voltage sags, voltage swells, and interruptions are likely to focus on the utility side, because in many but not all cases theses anomalies are due to utility-side faults (short circuits) caused by factors such as lightning strikes, wind damage, tree contact, animals, and so on. On the other hand, issues like voltage flicker, harmonic distortion, stray voltage, or electrical noise are often caused by the influence of customer loads on the power system. The loads present can greatly determine the study needs. For example, a factory with computer-controlled milling machines might be impacted mainly by voltage sags or interruptions that could disrupt the milling process. On the other hand, a facility with arc furnaces could be generating harmonics and voltage flicker due to the nonlinear effects of an arc load.

PQ Monitoring Study Objectives

The types of waveform conditions monitored are not the only thing that define a power quality study, but also the broader context of how the data will be used. From the perspective of data utilization, most studies fall into one of three categories:

- Benchmarking studies
- Specific problem-solving studies
- Proactive “just-in-case” monitoring

Knowing which of the study types the investigative team will be performing is a critical part of defining the types of measurements needed, instrument needs, locations, settings, and data gathering and analysis processes.

PQ focused benchmarking study targets specific power conditions and locations that are considered to be the most vulnerable areas.

The goal of a problem-solving study is to identify as quickly as possible the offending power condition so that corrective action can be taken.

Benchmarking Studies

The usual objective of a benchmarking study is to compare power quality conditions at a particular site to industry standards or to national averages or some comparative index to determine if it is up to par with expectations and needs. This type of study often requires equipment capable of analyzing both steady-state and transient events and usually involves measurements at several locations over a sufficient period of time to obtain meaningful statistics. The results may be used for design upgrades at an existing facility or the planning of new equipment or processes in a new facility or to verify that power conditions are within proper limits for contractual reasons.

Benchmarking studies may be of a generic nature (that is very broad and involving many or all types of power quality conditions) or may be focused on a particular type of condition, such as voltage sags or interruptions. The period of time involved for a typical benchmarking study could be anywhere from several months to up to a year or so depending on needs. For many studies, the data collection interval must be sufficient to observe conditions that are representative of the environment throughout all seasons of the year. Thunderstorm and tree contact faults tend to occur primarily in the summer season. Whereas snow- and ice-related issues tend to come up in winter.

Generic benchmarking studies, because they involve measuring all types of conditions, are the most comprehensive and expensive. They produce valuable information, but they also produce huge quantities of data that may require a large effort to manage and analyze. Even though such a study can be costly, if conducted as a diagnostic tool ahead of making the final investment in plant designs and equipment purchases, it can still be worthwhile in helping to identify power quality conditions that may affect the optimal design configuration of the final facility power system, the type of power conditioning employed, and selection of load equipment.

A way to reduce the cost of benchmarking is to focus just on the disturbance types and seasons that are likely to be important for the type of loads or processes involved. Therefore, a focused benchmarking study targets specific power conditions and locations that are considered to be the most vulnerable areas. An example of a focused benchmarking study would be to monitor a site for a proposed process plant with voltage-sag-sensitive loads only for such sags and interruptions at the proposed facility's electric power service entrance and only during the summer months when such sags are most prevalent. This focused approach is more cost efficient and can help investigators more quickly define power-conditioning needs for a new or existing facility.

Specific Problem-Solving Studies

A specific problem-solving study is conducted in response to an identified problem, such as periodic crashes of data-processing equipment or upsets of facility loads. The goal of this type of study is to identify as quickly as possible the offending power condition so that corrective action can be taken. This is a cause-and-effect type troubleshooting analysis that involves correlating observed facility problems with measurements of power conditions that occur at the times those problems arise. These studies can lead to a solution with just a few hours of measurements, but they may require much longer monitoring depending on the specific case.

Problem-solving studies involve two approaches: either wait for the problem to occur naturally so that it can be measured,

For just-in-case monitoring, the power quality instrumentation must always be running in the background and ready to record disturbances at a moment's notice.

or trigger it so the effect can be measured at the discretion of the analyst. For fault conditions, deep voltage sags, lighnting, and so on, usually we must wait for these events to occur to study the system impact. But other types of events can be triggered. For example, if a motor-starting event is causing voltage flicker, the motor can be intentionally started while voltage conditions are measured. Or, as another example, if harmonics are created by a certain type of load device that impacts the power system, the device can be operated and harmonic conditions observed.

Proactive "Just-in-Case" Monitoring

Power quality monitoring is sometimes done as a "just-in-case" insurance policy to have a record of conditions available if a problem occurs. In this way, data will be readily accessible to more quickly identify anomalous conditions and resolve problems when they arise. For this type of monitoring, the power quality instrumentation must always be running in the background and ready to record disturbances at a moment's notice. Data from the recording equipment will rarely be needed during normal system operation, but at the time it is needed, its availability will be critical. This type of monitoring requires instruments to operate unattended and reliably for long periods of time.

Voltage, Current, or Both?

A key question addressed with all PQ studies is if the measurement of both the voltage and current are needed to meet the project objectives or if just measuring the voltage alone will suffice. For many types of studies, only voltage measurements are necessary for adequate results—for example, quantifying incoming power interruptions at a facility, or quantifying depth, duration, and rates of incoming voltage sags of utility system origin at a facility service entrance. But there can also be good reasons to measure current in addition to voltage. Situations in which current monitoring is critical are those where the load current impacts and dynamically interacts with the system voltage conditions so that it is not possible to fully understand one parameter without knowing the other. For example, by measuring motor starting and transformer energization inrush current along with the simultaneous voltage conditions, a power quality analyst can better assess the voltage flicker conditions and the motor starting settings needed to alleviate the issue. Another example where current measurements are valuable is the case of harmonic distortion assessments. Knowing the harmonic current associated with the loads as well as the voltage distortion levels can allow the analyst to better determine relative contributions of the facility loads and the power system source to the harmonic distortion conditions. In addition, IEEE 519 guidelines specify maximum levels of allowed current distortion, which must be measured to determine if the loads are in compliance with that standard. Finally, current measurements along with voltage are necessary anytime a power demand and power factor analysis is performed.

In some situations voltage measurements alone will suffice, and in other situations both current and voltage are required.

Overall, in some situations voltage measurements alone will suffice and in other situations both current and voltage are required. Knowing when to apply these measurements is helpful in specifying the type of equipment that will be needed and setting up an overall plan for the project. The table on the following page illustrates some situations where measuring both voltage and current is generally appropriate.

Deciding Whether to Measure Voltage or Current

Type of Study	Type of Measurement Usually Needed to Accomplish	Comments
Voltage sag and interruption studies	Typically voltage only	Current is only needed if it is desired to understand how voltage sags dynamically interact with facility load currents (such as motors).
Voltage flicker studies	Voltage only or voltage and current (depending on study objectives)	Current might not be needed if the only objective is to determine presence of flicker and not resolve the origin and/or determine solutions.
Harmonic distortion studies per IEEE 519 guidelines	Voltage only or voltage and current (depending on study objectives)	Current might not be needed if only utility voltage-distortion compliance is to be assessed and the causes and solutions are not to be addressed.
Fault current studies	Current	Voltage would usually be part of this, however, because most fault recorders have that capability and available channels.
Switching and lightning surges	Typically voltage only	Current might be desired if surge duty is to be calculated.
Power factor and demand	Always voltage and current	Both voltage and current are always needed to calculate power and power factor.

A key part of many power quality studies is determining if measured conditions are within industry expectations and guidelines.

IEEE Standards Associated with PQ Monitoring

A key part of many power quality studies is determining if measured conditions are within industry expectations and guidelines. Some IEEE and ANSI guidelines and technical standards that are used to make this assessment are shown in the table on the following page.

The first standard discussed in the table is ANSI C84.1-1995. This standard deals with *steady-state voltage regulation* limits on power systems. The steady-state voltage (that is, the voltage condition over several minutes or longer) is supposed to be maintained at the point of delivery (what's known as the *point of common coupling*) to within ±5% of the nominal rated voltage. This is known as the ANSI C84.1 Range-A voltage. On a 120-V base, this is between 114 and 126 V. Occasionally, steady-state voltage may be allowed to go outside this range into what is known as the ANSI C84.1 Range-B limits—a slightly broader window of about +6% and –8% deviation from nominal. A power quality study of steady-state voltage would monitor conditions over several days or weeks or even months to make sure the voltage regulation is within these appropriate ranges. The ANSI C84.1 standard also recommends the relative balance of voltage between phases, which should be within 3%. Significant voltage unbalance or out-of-range voltage can cause heating of motor loads and other problems.

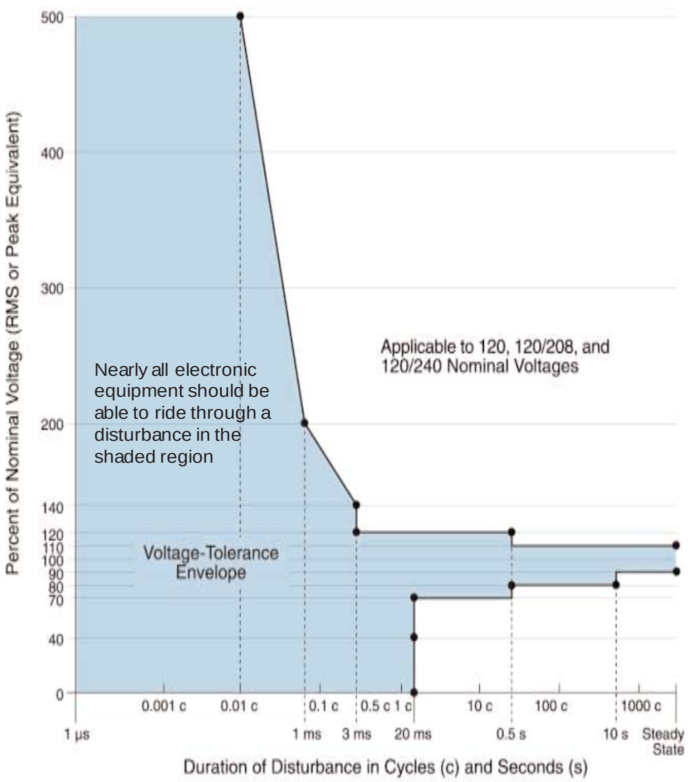
Voltage sags are another area of power quality focus. No specific requirements exist for voltage sags with regard to the rates, magnitudes, or durations of these disturbances, but there are standards that define their general characteristics and expected impacts on loads. These include IEEE Standard 1250-1995, Standard 1346-1998, and Standard 1159-1995, as well as susceptibility curves for loads, like the Information Technology Industry Council (ITIC) curve or the older Computer and Business Equipment Manufacturers

Some Common Power Quality Standards

Standard or Guideline	What It Covers
ANSI Std. C84.1-1995, *American National Standard Electric Power Systems and Equipment—Voltage Ratings*	Steady-state voltage limits on AC power systems (also includes voltage balance limits). Also covers voltage balance limits between phases.
IEEE Std. 1250-1995, *IEEE Guide for Service to Equipment Sensitive to Momentary Voltage Disturbances*	Focuses on various transient disturbances and their impacts on equipment.
IEEE Std. 1346-1998, *IEEE Recommended Practice for Evaluating Electric Power System Compatibility with Electronic Process Equipment*	Focuses on the power quality, EMI, and general process compatibility issues between power systems in industrial/commercial process facilities.
IEEE Std. 1159-1995, *IEEE Recommended Practice for Monitoring Electric Power Quality*	A comprehensive guide discussing all of the various power quality disturbance types and how to measure and diagnose them. (Note: there are several subparts under development, including 1159.1, .2, and .3.)
IEEE Std. 1366-2000, *IEEE Guide for Electric Power Distribution Reliability Indices*	Deals with the definitions and calculation methods for sustained and momentary interruptions.
IEEE Std. 519-1992, *IEEE Recommended Practices for Harmonic Control in Electrical Power Systems* (also see International Electrotechnical Commission standard IEC-61000-3-7 for European flicker standard)	Limits for steady-state power system harmonics and voltage flicker. Methods of control and evaluation are discussed.
IEEE Std. C62.41, *IEEE Recommended Practice for Surge Voltages in Low Voltage AC Circuits* (also see C62.42 and C62.64)	Lightning transients in low-voltage power system environments (residential, commercial, industrial buildings).

Association (CBEMA) curve (see figure on top of the following page). The ITIC curve as shown is fairly conservative and intended for sensitive information technology and data process devices. It does not necessarily give good guidance on less-sensitive devices. As a general guide, studies show that disruptive voltage sags outside of ITIC bounds occur roughly 3–5 times per year at typical higher-level subtransmission-voltage-fed loads, whereas average suburban distribution feeder-fed sites (such as 13.2-kV feeders) typically see 10–25 disruptive sags per year depending on location. Very rural distribution-feeder-fed sites may see as many as 30–75 disruptive sags each year. The differences between different types of systems demonstrate that each circuit needs to be considered based upon many factors, such as its length, design, voltage level, and exposure to the environment. Most disruptive sags are caused by faults—due to animals, wind, lightning, accidents, etc.—the rate of which are greatly influenced by these factors.

Information Technology Industry Council (ITIC) Curve



Most utilities are under pressure from their respective public service commission to operate near or above average levels of reliability.

Reliability disturbances such as sustained and momentary interruptions are another area of concern. They are addressed in IEEE Standard 1366-2000. The industry uses several indices, including CAIDI, SAIDI, and MAIFI, to track interruptions. Standard 1366-2000 provides guidance on average levels of reliability per these indices and other indices for the U.S. for both sustained interruptions and momentary interruptions. There is no particular requirement for reliability, but most utilities are under pressure from their respective public service commission to operate near or above average levels of reliability. Power system design and exposure greatly impact reliability. Networked underground-fed systems in urban areas tend to be very reliable, whereas, overhead radial power systems in rural areas are the least reliable.

The average distribution customer in the country (all system types combined) experiences 1–2 sustained interruptions each year and about 4–8 momentary interruptions each year. Networked underground urban customers may go for more than 10 years without seeing a single interruption of any kind (although they still see voltage sags) and rural, radial overhead system could see more than 3 sustained interruptions and well over 10 momentary interruptions each year.

Harmonic measurements are another key area of power quality. Steady-state harmonic distortion limits in the U.S. are based on IEEE standard 519-1992, which sets limits for the maximum voltage distortion and current distortion levels. Voltage distortion limits of 5% total harmonic distortion (THD) apply to the utility-company delivery of power at the point of common coupling (PCC) at voltage levels of 69 kV or less. Current distortion limits apply to load current demand of facilities as measured at PCC. The limits imposed become increasingly strict as the power system to which the loads are connected becomes weaker. For example, if the ratio of available short-circuit (fault) current to total demand current is less than 20:1 at the PCC, then the THD of the total demand current is limited to no more than 5%. On the other hand, if the ratio is 1000:1, then up to 20% THD of the total demand current is allowed. Harmonic measurements are needed to insure compliance with the IEEE standard as well as troubleshoot typical harmonic-related issues such as distortion magnification caused by resonances, overheating equipment due to harmonics, and interference with waveform sensitive circuitry.

The typical lightning and switching surge exposure at the low-voltage system level is documented in IEEE Standards C62.41-1991,

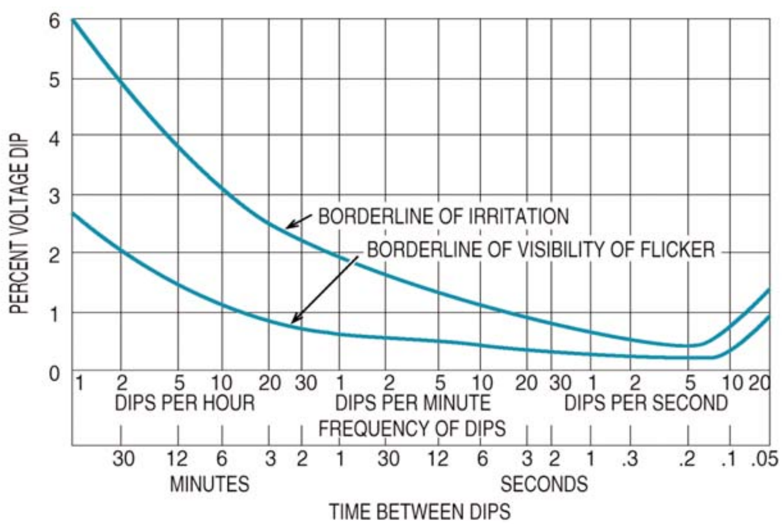
Industry experience suggests that surges become a threat when their peak voltage is greater than about four times the normal peak AC voltage operating level of the device.

Power quality assessments also involve the need to measure voltage flicker.

C62.41.1-2002, and C62.41.2-2002. Surges at this level of the system have been shown to be short-duration spike-shaped or impulsive ringing waveforms with voltage levels ranging from under 100 V up to a maximum of about 6 kV. They originate from a number of causes, including lightning strikes to or near the facility and to the power system near the facility. They also can originate from switching operations such as utility capacitors and internal load switching within the building. Faults can also create a ringing switching surge-like transient at the leading edge of the event. The reason why surges in the low-voltage environment aren't usually greater than 6 kV is because wiring systems begin to flashover at that level. For power quality studies, the key question is at what threshold surge level should the power quality analyst become concerned and recommend mitigation? There is no perfect answer to that question since so many factors influence the surge susceptibility threshold of unprotected loads. These factors include surge waveshape and magnitude, the type of electronics in the load, the age of the load, and prior exposures that may have degraded it. Also, the AC operating voltage level of the load plays a role (120, 208, 240, 277, or 480 V). As a rough guide, industry experience suggests that surges become a threat when their peak voltage is greater than about four times the normal peak AC voltage operating level of the device. For example, an AC appliance that operates at 120 V_{rms} has a peak AC supply voltage of about 170 V_{pk}. So the danger of damage to an unprotected device may start at a surge threshold level of about 4 × 170 = 680 V. For a 277/480V device, the threshold would be about 1567 V (line-to-neutral) or 2700 V (line-to-line). However, these numbers should be taken as rough approximations; certainly many devices have been known to survive larger surges than these without damage, and occasionally damage may be due to a lesser surge.

Power quality assessments will also involve the need to measure voltage flicker. Voltage flicker is a subtle power quality condition where small voltage variations in the root mean squared (RMS) voltage level (usually a few percent or less) are sufficiently rapid and repetitive that visible fluctuations in the output of lighting systems occur. There are several standards that deal with voltage flicker. The key ones are IEEE 519-1992, IEEE Standard 141-1993, and International Electrotechnical Commission (IEC) Standards 868 and 61000-3-7. The IEEE standards use the old GE Flicker Curve (developed back in the 1930s), and that particular methodology is very much entrenched in the U.S. In fact, most flicker standards at utilities today are still based on the GE Flicker Curve or some variation of it. The GE Flicker Curve is really two curves: the borderline of visibility and the borderline of irritation (see figure on the following page). The objective when measuring voltage variations is to make sure that they fall below the threshold of the visibility curve. Power quality events that result in voltage envelope fluctuations of about 8 Hz are at the most sensitive part of the flicker curve where even just a 0.25% fluctuation in voltage is noticeable. Many U.S. electric utilities have flicker requirements based on this curve, but some use the newer IEC approach or a flicker curve of their own that is slightly modified from the GE curve. The GE curve was based on the human eye's sensitivity to light fluctuations of incandescent light sources subjected to sharp (sudden) voltage envelope variations. Because up to recently the incandescent light was the dominant light source and the most sensitive type of light source to be impacted by flicker (compared to fluorescents), it made sense that this curve would still be used. However, in the past 5–10 years, compact fluorescent technology and light-emitting diode (LED) lighting has started to significantly displace incandescent bulbs. In the near future, incandescent bulbs may be almost fully replaced by these newer light sources and the GE curve would no longer be viable. EPRI studies have shown that fluorescent bulbs are on average one-half to one-third as sensitive to flicker as incandescent bulbs. The IEC 61000-3-7 methodology has mathematical representations of light-source response and voltage-envelope shape and so is better suited for studies involving these newer light sources and varying voltage envelope shapes.

GE Flicker Curve from IEEE 519-1992

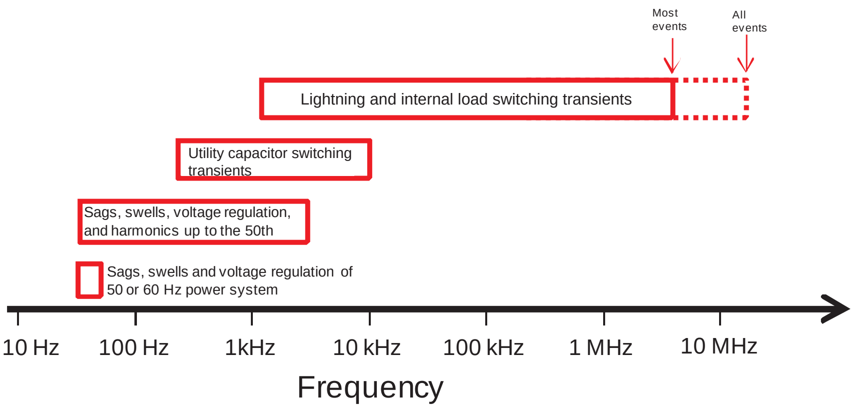


Analog and Digital Waveform Capture

Having discussed some key standards that apply to power quality measurement, this section is a good location to discuss waveform sampling and capture techniques of power quality recorders. There are two basic types of instruments: analog and digital. Today, almost all instruments employ digital sampling as a key part of waveform acquisition and storage. However, even with a digital instrument, analog components and stages in the measurement process still need to be considered. These include the analog transducers (such as current and potential transformers) as well as analog input amplifiers or input attenuator circuits that feed signal to the instrument's analog-to-digital (A/D) converter units. So any full accounting of an instrument's ability to measure a waveform must include all stages of the process and not just the final A/D converter sampling rate.

A power quality monitor must have an adequate A/D converter sampling rate and an adequate bandwidth of its analog input circuitry to study the desired highest frequency content of the waveform that is of interest. The figure on the next page shows the bandwidth requirements for various types of measurements. Many PQ monitors are designed to be suitable only for measuring conditions with frequency content from the 50th harmonic (3 kHz) on down. This limitation is often not a major handicap for power quality projects, because many studies can be adequately performed by focusing only on the “slower” transients related to power quality (that is sags, swells, interruptions, flicker, and harmonics to the 50th) that require only 3-kHz bandwidth . In fact, the majority of big issues related to power quality are not surge related, and so in many cases we can ignore the faster transients such as lightning and internal load switching surges that may require up to several megahertz of bandwidth to resolve. Nonetheless, occasionally measurement of some of the faster phenomenon like lightning transients is required. Instrument users must understand the bandwidth needs so that they don't misapply a low bandwidth device to a high bandwidth surge measurement task.

The Frequency Range of Various PQ Conditions That Are Often Monitored



Instrument bandwidth should equal or exceed the indicated amount.

Steady-state 60 Hz conditions can be evaluated by saving the value of the measured parameter (such as RMS voltage or current) every few minutes, whereas transient conditions such as voltage sags or swells require saving data at shorter intervals (every ½ cycle to resolve voltage sags or swells). If harmonics are not to be part of the study and are sufficiently small to not impact the RMS value accuracy, then the bandwidth required for measuring sags and swell magnitudes is only about 60 Hz. To represent the voltage as an RMS plot, a PQ monitor simply evaluates the RMS value of the voltage at intervals of ½ cycle, saves the value of the voltage at each interval (if a change occurs), and plots this on its display. (Note: a sample rate of 120 Hz translates into 60 Hz equivalent bandwidth.)

To reproduce the actual waveform with harmonics, our samples must be measured at a rate dictated by the Nyquist theorem. The Nyquist theorem states that the minimum sampling rate needed for accurate waveform reproduction is *twice the maximum* frequency component of the waveform being measured. The table below summarizes the requirements for sampling for various types of conditions. For certain studies, we may want to see the actual waveform with its various harmonic components. In other words, to accurately reproduce a 60-Hz waveform containing all harmonics up to the 50th harmonic (3 kHz) requires a sampling rate of 6 kHz or higher.

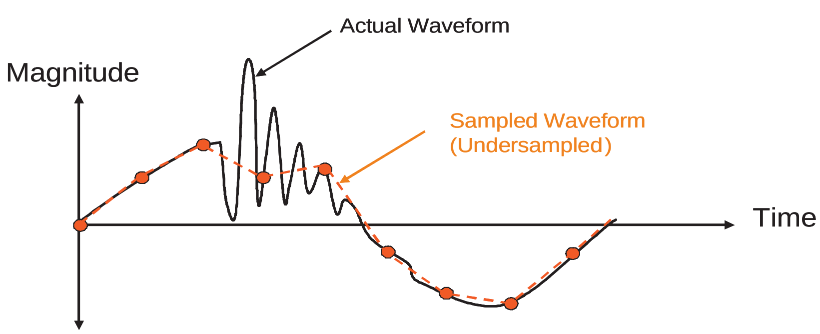
Minimum Sampling Requirements to Capture Power Waveform Data

Condition to Be Monitored	Minimum Digital Sampling Rate Needed (per Nyquist)
60-Hz waveform(no harmonics included)	120 Hz
Full 60-Hz waveform with harmonics (fundamental frequency plus the harmonics up to the *n*th harmonic)	Minimum sampling rate needed = $2nf$, where f = fundamental frequency, and n = highest harmonic to be studied. For a waveshape with up to the 50th harmonic, the minimum sampling rate needed is 6 kHz.
Switching surges	Many utility power factor switching surges can be resolved with just a 6-kHz sampling rate. Internal load-switching transients may require high sampling rates up to many megahertz.
Lightning surges	Up to 20 MHz sample rate is required for the fastest events. Many events can be adequately resolved with a 1 to 2 MHz sample rate. (The presence of lightning surges can be detected with only 6 kHz sampling rates, albeit with significantly reduced accuracy of magnitude and shape.)
Electrical or radio frequency (RF) noise	RF and electrical noise may need to be sampled at many tens or hundreds of megahertz depending on the spectrum of interest. An RF noise transducer can be used to alleviate the need for a high sampling rate of the instrument itself.

The latest power quality instrument devices use much higher sample rates than the still widely used legacy instruments of 10–25 years design age.

Measuring up to the 50th harmonic is sufficient for most common types of power quality studies that don't involve lightning or fast switching surges since the harmonics above the 50th are usually so tiny as to not influence the waveshape in a significant manner. This is why some of the mainstream commercial instruments have a maximum sample rate that is in the range of 6 kHz to 10 kHz, since this meets the 50th harmonic requirement. Many instruments simply don't bother to sample for lightning surges because the high sampling rates required for lightning surges, which are at least several megahertz, are more complex to implement and, for older instrument designs, raise the cost of the instruments too much. Some monitors have unique methods to capture lightning transients. For example, some use a peak-detect circuit and save only the peak value of the surge in memory while recording all the other types of events at lower sample rates. Another approach is to use a separate "fast" surge sampling converter for surges and combine that data with lower bandwidth data collected by the main A/D converter that samples in the 6 to 10 kHz range. The Dranetz 658 is an example of that approach. Recent improvements in the speed, resolution, and data compression of digital sampling systems allow the latest power quality instrument devices to use much higher sample rates than the still widely used legacy instruments of 10–25 years design age.

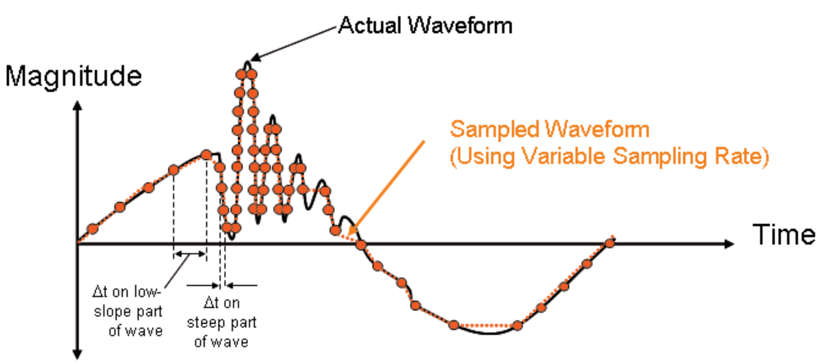
Misrepresentation of Waveform Features and Magnitude as a Result of Undersampling



Waveforms must be sampled at least per the minimum Nyquist criteria to accurately represent the true waveform. For example, a 60-Hz waveform with embedded switching surge is shown in the figure below. In that example, it is sampled with an *insufficient* sampling rate to adequately capture the ringing switching surge on the wave. We can see that the undersampling misrepresents the true nature of the event and the switching surge is almost entirely missed, although the 60-Hz portion of the wave is adequately sampled. To capture the switching surge adequately in this example requires a much higher sampling rate. A phenomenon of undersampling for periodic waveforms is something called *aliasing*—this can make undersampled waveforms in certain cases appear as a lower frequency than the actual waveform.

While a higher sampling rate solves the problem of waveform distortion and aliasing, a disadvantage of using a high fixed sampling rate is the large amount of data that must be stored in the monitor's physical memory for each recorded power quality event. This issue is becoming less important now with modern high-capacity memory chips. Nonetheless, even with modern memory a tradeoff is still made between the large memory requirements of high fixed sampling rates that enable faithful reproduction of the pertinent high-frequency transient data versus lower sample rates that require less memory but may not faithfully capture all aspects of the waveform. A creative data compression method used in some instruments to get around this issue is a variable sample rate algorithm based on the rate-of-change of the waveform (as illustrated in the figure on the following page). It works on the principle that most of the time a lower sample rate will suffice and a higher rate is only needed during each short burst of transient activity. This technique offers an effective means to capture high-frequency data while also limiting memory needs at times when high-frequency content is not present on the waveform. Not only does this allow the instrument with finite memory capabilities to store many more waveforms before it fills (allowing longer intervals between downloads), but also the smaller data files are less cumbersome to work with and analyze. Variable sampling rate algorithms can reduce memory requirements by typically a factor of up to 100 depending on the nature of the data.

Example of a Variable Sampling Rate Algorithm



This algorithm speeds up the sample rate during portions of the waveshape needing faster sampling.

Analog-to-Digital Quantization

In addition to having adequate sampling rates to capture all of the pertinent frequency components of power quality waveforms in the time domain (time axis), we also need sufficient resolution in the vertical (amplitude) axis to resolve the amplitude changes of the waveform. The vertical-axis resolution of a digital measuring device is determined by the number of bits in its A/D converter and associated input circuitry. An A/D converter has a specific number of steps (measured levels) as determined by 2 raised to the *n*th power, where *n* is the number of bits in the converter. For example, an 8-bit converter has 2^8 possible steps (256 steps). The “magnitude resolution” of the A/D conversion system must be adequate to accurately resolve the waveform features that are of interest. The range of available quantization steps must cover the expected magnitude range (negative full-scale to positive full-scale) of the waveform. Many measurements require considerable headroom above the ordinary peak steady-state load currents and voltage levels (in order to capture higher transients such as lightning surges, fault currents, inrush, and transient DC offsets). Any value outside that range will saturate the A/D converter, and the recorded signal will be chopped off (flat-topped).

When an A/D converter measures an AC waveform, 1 bit must be used as a sign bit (to determine positive or negative value of wave), so in practice the available number of steps for quantization is actually only 2^{n-1}. These steps must fit between 0% and 100% full-scale reading. In the case of an 8-bit converter, this is 2^7, which is 128 steps or 0.78% change per step. Considering the headroom needs for faults and other transients, an 8-bit device may not have enough steps for applications where it is desired to look at both steady-state waveform characteristics and the higher transients that rise well above the magnitude of steady-state wave. Fault levels can be 20 times greater than full-load currents at a facility. To measure the peak fault currents accurately (without flat-topping) while still also accurately measuring load currents is a demanding task. For this reason, A/D converters with 12 bits or greater (that is 4096 steps from –100% to +100% full scale) are more suitable for situations where accurate measurements are needed over a wide range of signal levels. If the range is limited and/or accuracy is not critical, then perhaps 8 or 10 bits is acceptable, but not usually. Most instruments today have better than 10 bits of resolution. The table below shows the available quantization steps for various A/D converters.

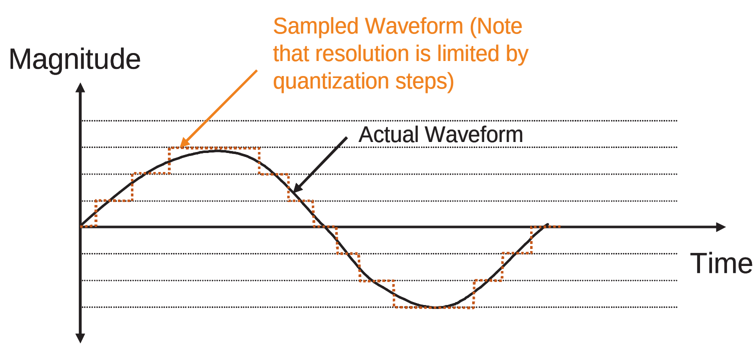
The figure below shows how quantization artifacts are created when the individual quantization steps become too large relative to the waveform details being studied.

Quantization Levels Achieved with Various A/D Converters

A/D Converter Bits	Number of Quantization Steps Available[a]	Percent Change of Each Step Relative to Full Scale[b]
8	256	0.78
10	1,024	0.20
12	4,096	0.05
16	65,536	0.0031
20	1,048,576	0.00019
24	16,777,216	0.000012
32	4,294,967,296	0.000000047

[a] Minus full scale to plus full scale.
[b] Assumes steps are distributed linearly between ±100% full scale.

Quantization Artifacts in Waveform Record



Quantization artifacts can look like the steps of a "staircase."

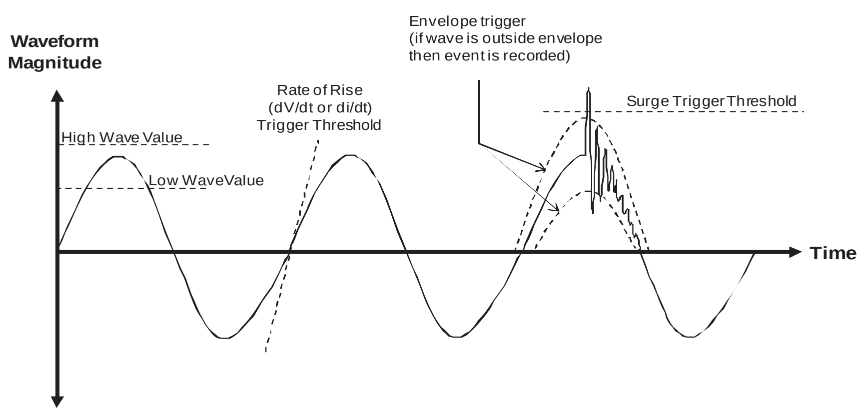
Instrument Triggering Approaches

Triggering of power quality instruments to capture anomalous power quality event waveforms is a critical part of any PQ study. The objective is to be just sensitive enough to capture all of the significant PQ events that are pertinent to the study, but not so sensitive that the instrument constantly triggers on the thousands of insignificant events down near the noise level that occurs every day. This keeps the data build-up manageable and keeps the instrument memory from prematurely filling up (which could lead to loss of pertinent data).

In event windowing,when a power quality anomaly occurs, the instrument trigger detectors initiate the waveform capture process, and then the recorder stores in its memory the waveform for a certain "window" of time that contains the power quality event.

A number of different approaches are used for event capture trigger settings depending on the type of machine, its capabilities, and its data collection algorithm. The figure below shows some commonly employed techniques. These include low or high trigger thresholds for the 60-Hz AC waveform (usually based on an RMS value calculated each ½ cycle). These settings can be used to trigger the recorder when a voltage sag or swell occurs or if a sustained high or low voltage outside set limits occurs. Some recorders also have a rate of rise trigger (based on change of voltage over time [dV/dt] or change of current over time [di/dt]) that will activate if a steeper than usual waveform occurs (which can be used in various ways to detect many types of disturbances). Another method is a waveform envelope trigger (where deviation outside of the envelope triggers the recorder), which can detect high distortion, high- or low-voltage RMS magnitude conditions, and certain types of surges. A few recorders also use the above-mentioned methods for the slower transients (such as sags and swells) and then use a special high-pass filter trigger for the higher frequency content such as lightning surges. Use of any one triggering technique above does not prohibit a recording device from also using another technique at the same time. In fact, many PQ recorders use a combination of these triggers, and some of the full-featured units have the ability to program many different types of trigger thresholds into the recorder that can all act simultaneously if needed. This improves the flexibility in tailoring event capture to specific types of events.

Examples of Some Trigger Techniques That Many Power Quality Recorders Use to Capture Events

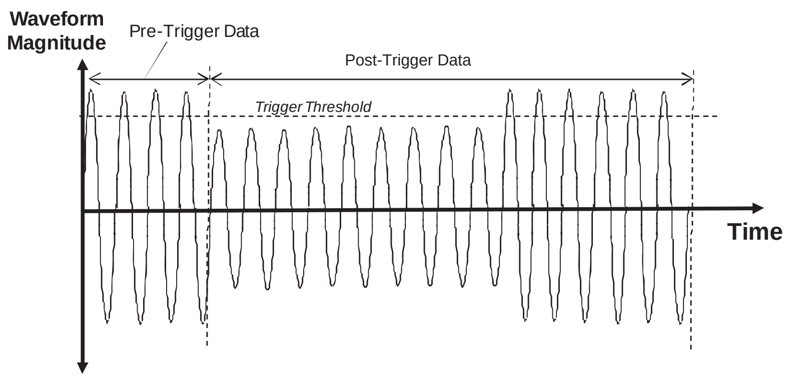


Another important idea related to data acquisition is the concept of "event windowing." What that term means is that when a power quality anomaly occurs, the instrument trigger detectors initiate the waveform capture process, and then the recorder stores in its memory the waveform for a certain "window" of time that contains the power quality event. To do this efficiently, only the event data near or during the time window of the event needs to be stored. For some recorders, the event capture window is automatically determined by software algorithms within the recorder—so the user has no control over the window. For others, the event capture window can be programmed to provide a certain amount of pre-trigger and post-trigger data by the instrument user.

In addition to event windowing, many PQ recorders and fault recorders have what is called a pre-trigger data buffer. This is a fancy term that means that 24/7 the recorder is always digitally sampling the waveform and the moment it is triggered it can store not only the waveform information just after that trigger (what we call the post-trigger period), but also information just prior to the trigger (what we call the pre-trigger period). The total event window that includes pre-trigger and post-trigger data constitutes the total event recorded to memory (see figure on the following page).

The pre-trigger information can be just as important as post-trigger date, because it provides the context of what the power system condition was just before the event started. This is especially important for gauging the depths of voltage sags, measuring the severity of voltage swells, evaluating motor-starting flicker, and looking for subtle precursor events leading up to insulation faults or other problems on the power system.

Event Windowing Concept



Pre-trigger and post-trigger data are captured during a voltage sag, providing an "event window" for this PQ occurrence.

As mentioned before, many power quality recorders use automatic event windowing and don't give the user much or any flexibility in programming the event windowing settings. This can be a disadvantage for analysts who need the flexibility to set the windowing parameters to specific values for certain types of studies. On the other hand, automatic windowing can be valuable to optimize memory usage and avoid window-length errors that can occur when operated by less-experienced users who might not employ the proper settings if given the option.

Another point on event windowing and overall PQ recorder data acquisition is that most recorders actually have several forms of data acquisition going on simultaneously. For example, they can be continuously collecting and storing information on steady-state current and voltage conditions, while also simultaneously being triggered when transient events occur to store the transient power quality waveform events in memory. When both of these types of data are combined, the recorder is able to provide a complete representation of both the steady-state operating conditions (showing voltage regulation, demand, power factors, etc.) as well as transients such as sags, swells, and momentary interruptions that are occurring.

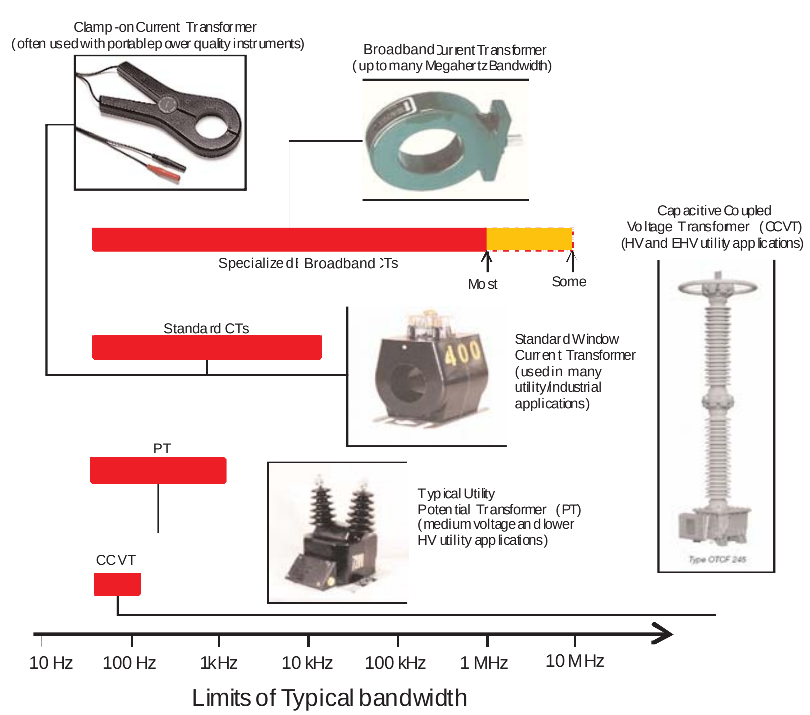
Instrument Transformers

Before a waveform can be sampled, it must arrive at the instrument in analog form at a magnitude level that is safe for the instrument input terminals. In cases where a voltage or current level conversion is needed, we use instrument transformers. These devices also provide isolation from the main circuits being measured. There are several types of instrument transformers used for these purposes, including current transformers (CTs), potential transformers (PTs), and capacitively coupled voltage transformers (CCVTs). At levels of 600 V_{rms} or less, most PQ monitors handle direct voltage input from the system without any PT. In the case of current measurements, CTs or Hall Effect probes are almost always used regardless of the voltage level of the power system being measured. CTs are either clamp-on types (that usually come with portable instruments) or fixed window types, like those used in many utility and industrial applications.

Standard and clamp-on current transformers are excellent devices to measure the current associated with most types of power quality disturbances.

The frequency and phase response of instrument transformers can impact the accuracy of the measured signal into the recorder. The bandwidths of typical voltage and current instrument transformer devices are shown in the figure below. Standard CTs and clamp-on CTs are usually accurate up to about 10 to 30 kHz (depending on the burden and type). This means they are excellent devices to measure the current associated with most types of power quality disturbances such as sags, swells, inrush, faults, harmonics, and most utility switching surges. The only types of measurements where standard CT bandwidth limits come into play are with faster internal facility switching surges and lightning surge currents. If those are to be measured, then some sort of broadband CT or noninductive current shunt can be used. Specialized broadband CTs are available with up to 1 MHz bandwidth and some have greater than 10 MHz bandwidth. The bandwidth of PT and CCVT devices is not as good as CTs. Normally, standard PTs used on utility power systems are accurate up to about 1 kHz in most situations. Above this frequency, the user may encounter resonances that exaggerate or greatly attenuate the measured signal at certain frequencies. Studies where waveforms have content above 1 kHz that is of interest may not be able to be performed accurately with a conventional PT. The situation with the CCVTs is even worse. These are accurate to only within a few hundred hertz at best and sometimes, depending on their design, only to 60 Hz. This means a CCVT can be used only to measure the fundamental frequency (50 or 60 Hz) and perhaps the 2nd harmonic. Special compensated wideband capacitive voltage dividers are available with bandwidths over 1 MHz, but these are very costly and not typically employed for power quality projects unless lightning surges need to be measured. For voltage measurement studies on commercial, industrial, and residential power systems, the voltage at the monitoring site is between 120 V and 480 V, and PT and CCVT devices are not needed for the voltage inputs since the instrument can be directly connected at that level. With direct connections, the only bandwidth limitations are essentially the instrument electronics and sampling rates employed.

Event Windowing Concept



Bandwidths of transformers such as PTs, CCVTs, and CTs must be considered when setting up PQ monitoring equipment. The bandwidth shown is for general illustration; consult PT/CT manufacturer data for specific details.

Use of Transducers

There are a wide variety of "function-based" transducers available that can be used to feed signals to various types of fault recorders, oscilloscopes, chart recorders, and PQ-type recorders. A function-based transducer performs a mathematical transformation on the signal and feeds this transformed signal into the monitor. For example, an RMS voltage transducer converts an AC waveform into a varying DC output level that represents the RMS value of the waveform fed into it. Many transducer

Some transducers can respond very quickly (in one cycle), and others may take many cycles or longer to respond to a change in conditions.

functions are available, including RMS voltage, RMS current, real power, total power, VARs, power factor, total harmonic distortion, temperature, frequency, noise, magnetic field intensity, vibration, stress, torque, rotational speed, and other types. The figure below shows an example of a three-phase volt-ampere transducer. An important distinction between transducers and instrument transformers is that most transducers are designed to only handle up to about 600 V. For higher voltage levels, a PT or CCVT may be required to lower the voltage to within the transducer's input limits. Vendors do provide transducers that can provide some electrical isolation when specified by the user.

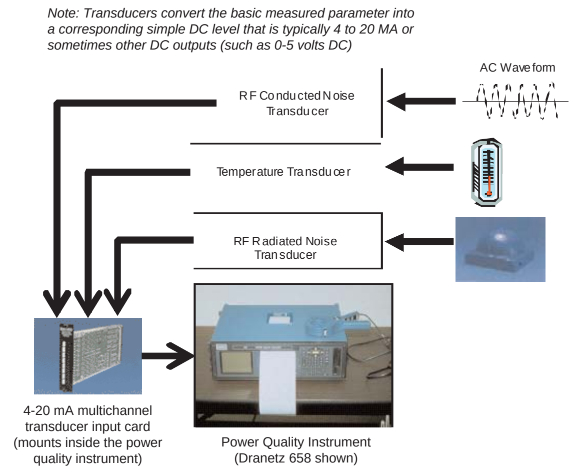
To use a transducer, a power quality instrument needs properly calibrated transducer inputs suitable for the output signal of the transducer. Only some instruments have these. Typical output signals from transducers include a representative current signal (such as 4–20 mA DC) or a representative voltage signal (such as 0–5 V or 0–24 V DC). As an example, a temperature transducer designed to measure from 0 to 100 degrees Celsius would have an output of 4 mA at 0 degrees Celsius and 20 mA at 100 degrees Celsius, and the values between represent all temperatures in between. The figure below shows some transducers being used with a power quality instrument. Typical transducers can cost from $50 to over $1,000 each depending on the type. Transducers have a response time that must be considered when evaluating results. Some units can respond very quickly (in one cycle), and others may take many cycles or longer to respond to a change in conditions.

A Function-Based Transducer

This transducer provides a DC-level signal that represents the three-phase volt-ampere product for the inputs.

Source: Scientific Columbus

Power Quality Recorder with Transducer Inputs



REVIEW OF POWER QUALITY INSTRUMENTS AND APPLICATIONS

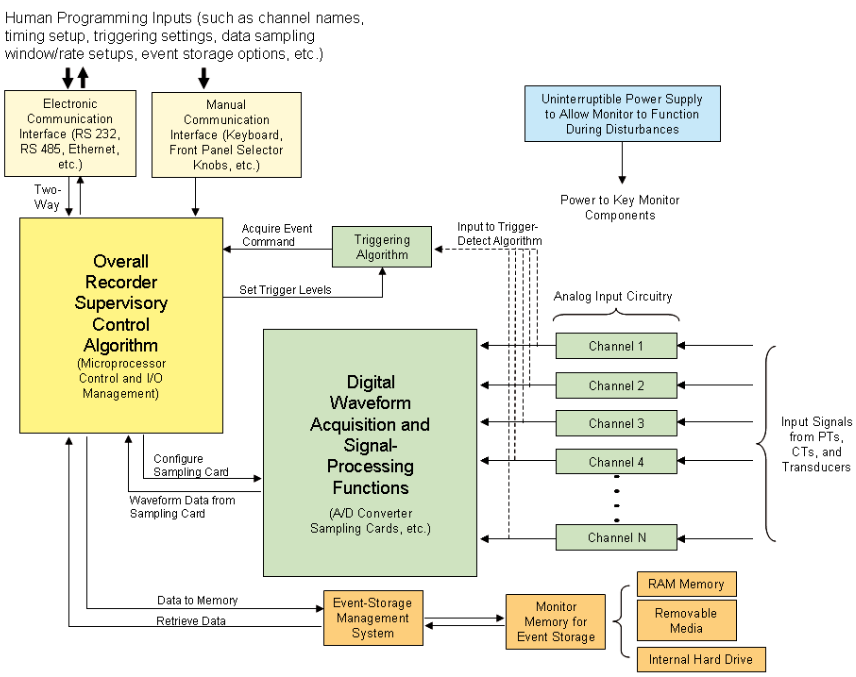
PQ Instrument Functional Architecture

The architecture shown in the figure on the following page is representative of many power quality recording instruments. PQ monitors are basically a digital waveform-sampling card supervised by a microprocessor controller and surrounded by input electronics, signal conditioners, memory devices, keyboard/front panel controls (user inputs), and communication ports. The microprocessor controller has various algorithms that control event triggering, input/output (I/O), and

Most PQ monitors are constantly sampling data and the moment they are triggered by a disturbance are able to save the waveform information just before the event as well as the event itself.

processing of sampled data into suitably formatted data. Events are stored in memory such as an internal hard drive, internal flash memory, random access memory, or removable external media. Most PQ monitors work on the principle that they are constantly sampling data in a circular data buffer and the moment they are triggered by a disturbance they are able to save to the permanent event record the waveform information just before the event (pre-trigger data) as well as the event itself (post-trigger data).

Generic Architecture of a PQ Recording Instrument



PQ Instrument Application Considerations

Some specific details must be addressed to determine the needs for a project. Since PQ monitoring equipment comes in a wide variety of configurations and capabilities, instrument procurers must understand which instruments best match their needs.

Some critical questions to consider in the selection of instruments are:

- **Measurement capabilities.** What specific types of power quality conditions does the monitor need to record? How much time is desired between data downloads?
- **Data format, acquisition, and memory.** What data format is desired (text summaries, waveform, or combination) and what data-acquisition settings are suitable for the project (trigger thresholds, sampling rates, pre-trigger and post-trigger buffers, etc.)?
- **Channel and signal input level needs.** How many channels (voltage, current, and transducer) are needed and at what input levels? Is the measurement to be three-phase or single-phase? Do the inputs need to be double-ended (differential)? Will CTs, PTs, or transducers be needed?
- **Site communication needs.** What communication capabilities are desired (Ethernet, wireless, phone modem, etc.)? What baud rate is needed? Do communication links need substation-grade isolation?
- **Multi-instrument coordination.** Is the power quality program a single instrument project or are there to be multiple instruments at many sites that must be coordinated from a timing and triggering perspective?
- **Operating environment.** What is the environment at the proposed instrument site(s)—outdoors or indoors? What type of enclosure is needed? Are there any moisture issues, temperature extremes, and/or dust issues? Is a conditioned instrument power supply needed? What site ancillary services are needed?

Whether a fully featured PQ monitor with waveform analysis and multichannel capability is better than a simple single-channel device is a function of available budget and the specific project requirements.

- **Postcapture data analysis.** Will postprocessing of data be needed? If so, what software capabilities are desired (such as adding or subtracting waveforms, multiplying waveforms, Fourier analysis, RMS plots, susceptibility curve plots, export of recorded data into spreadsheets, etc.)?

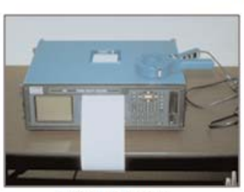
While there are hundreds of available instrument types sold, the process of considering the preceding questions will usually help sort out the options so that only a few instruments actually remain that meet the desired project objectives. From that point, the main choices may involve whether to go with *embedded* instruments or the more typical *stand-alone* power quality instruments.

Some Commonly Used Power Quality, Fault Recorder, and Data-Acquisition Monitors


Fluke 434/435 Power Quality Analyzer


Fluke Voltage Event Recording System (VR101S)


AEMC Model L215 Voltage Event Logger


Dranetz 658 Power Quality Analyzer


BMI 7100 PQ Node


Reliable Power Meters Insite Power Recorder (PQ, Flicker)


IDM.Hathaway Data Acquisition System


Ametek DL-8000 and DL-9000 Series Power Quality Monitors


Rochester Instruments TR-2000 Multi Function Recorder

Source: Photographs courtesy of various instrument manufacturers as indicated

Stand-Alone Power Quality Instruments

A stand-alone power quality instrument is a separate device solely intended for power quality or power system monitoring that is installed at some point on the system. Some present and legacy manufacturers of stand-alone power quality devices include AEMC, BMI, Dranetz, Fluke, IDM/Hathaway, RIS, and Ametek. The examples shown in the figure to the left represent a sampling of some of the better-known products, but there are many other devices on the market today. The available products range from single-channel voltage monitors that cost a few hundred dollars, up to multichannel PQ monitors and fault recorders that can measure voltage and current, come with digital status inputs, have transducer inputs, and offer extensive waveform recording and analysis features. These full-featured units can cost over $10,000 when fully equipped. Monitors differ not only in their measurement capabilities and number of channels, but also in how they can sort and analyze data. Some offer text reports of the measured disturbance—showing the date, time, duration, type, and magnitude of the disturbance. Others offer the ability to record the waveform, display it, and analyze its characteristics in detail. Some can plot the data in relation to industry metrics like load-susceptibility curves, such as the ITIC curve.

Full-feature instruments are those like the Dranetz 658 or BMI 7100 PQ Node. Whether a fully featured PQ monitor with waveform analysis and multichannel capability is better than a simple single-channel device is a function of available budget and the specific project requirements. The more sophisticated monitors may be overkill for certain simple PQ projects where only a basic indication of a voltage disturbance is necessary. On the other hand, in cases where in-depth analysis is required (as well as three-phase measurements), a multichannel capability with full-featured waveform recording is a must.

Modern fault recorders include demand metering, harmonic trending, and the ability to record various transient disturbances in addition to faults—so they make excellent fixed-location PQ monitors.

The portability of the PQ monitor is sometimes very important. A device such as the Fluke 434/435 is fully portable and has a built in display screen that allows easy in-field waveform assessment and live "scope-like" viewing of the waveform. Another portable, albeit larger, device is the Dranetz 658. Many portable instruments come complete with probes and clamp-on CTs so that a field technician can quickly set them up for on-the-spot measurements. Portable instruments, while often used for short-duration human-tended measurements, can also be used for longer-term measurements with unattended operation when set up properly.

At the other end of the spectrum from handheld portable instruments are fault recorders. Fault recorders are usually meant to be part of a hardwired integrated rack-mounted package installed at a fixed location—often a substation control house, generator plant, or industrial power service room. The early fault recorders (of 25 years ago) were strictly for voltage and current transients associated with faults; however, today's modern fault recorders include demand metering, harmonic trending, and, of course, the ability to record various transient disturbances in addition to faults—so they have adopted many PQ features and in fact make excellent fixed-location PQ monitors if equipped with the correct features. A nice feature of fault recorders is that they allow the user to customize data acquisition parameters. With most fault recorders, the user can specify the sampling rates, pre-trigger buffer, post-trigger buffer, and various trigger types and levels to a high level of detail, whereas with many PQ monitors, the sampling rates, pre-trigger buffer, and post-trigger buffer are usually automatically controlled and cannot be changed by the user (although some of the more-advanced products allow change). For those technicians who like and/or need the flexibility of adjusting these parameters and a fixed installation capable of being expanded to a large number of input channels, a fault recorder with PQ features is an excellent choice, or one of the higher-featured PQ monitors with adjustable data acquisition is an excellent choice.

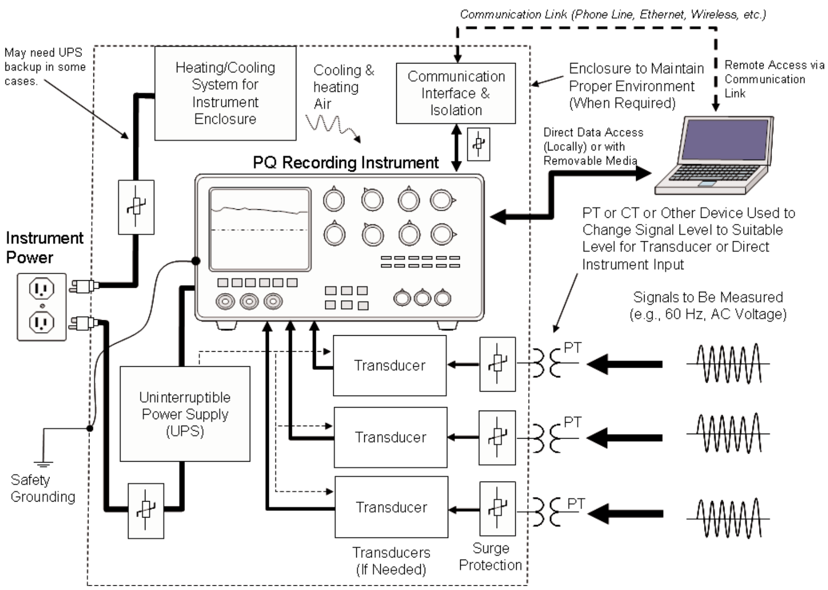
Applying Stand-Alone Power Quality Instruments at Field Sites

Installation of a power quality instrument at a specific field site is not simply a matter of dropping it in place at a desired location and then being done with it! Each site has a number of critical installation considerations that must be addressed. Factors to consider include:

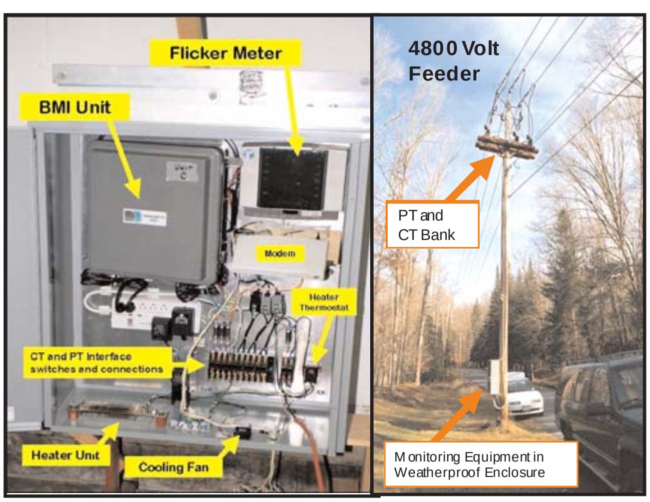
- Protecting the instrument from the environment
- Powering the instrument
- Connecting the instrument signal leads and transducers
- Instrument grounding and safety
- Instrument surge protection/isolation
- Communication and data connections

The first figure on the following page shows the configuration of an instrument with the above factors addressed. The extra hardware needed includes a weatherproof enclosure, temperature conditioning equipment, an uninterruptible power supply, surge protection, communication link interface, provisions for optional transducer interfaces and wiring devices, and safety grounding. The degree to which all these items will be needed depends on the power quality instrument as well as the characteristics of the monitoring site itself. Some power quality instruments are rated for an outdoor environment and have many features that can alleviate the need for some of these peripherals. Two examples of PQ monitors that come with weather-tight enclosures and other helpful features are the BMI PQ Node and PMI Eagle 440 (see the figure on the right). Even instruments that are weatherproof to begin with and have their own UPS sometimes need to be placed in a larger weatherproof enclosure to facilitate space for peripheral equipment that may not be weatherproof or may need to be enclosed for safety reasons.

PQ Instrument with Support Peripherals Needed to Create a Functional Site



Field Packaging for a Feeder Monitoring Site at an Outdoor Location



Close-up of enclosure interior is on the left. The overall installation showing CT and PT bank is on the right.

Examples of PQ Monitors Designed for Indoor/Outdoor Service

PMI Eagle 440

BMI 7100 PQ Node

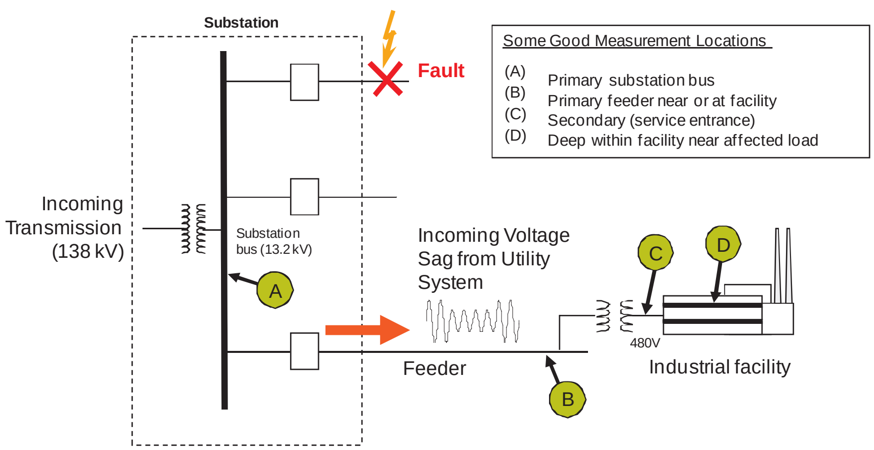
These monitors come with weatherproof enclosures and battery UPS features.

An integrated PQ package at a real site is illustrated in the figure to the bottom left. The site includes the PQ instruments and the needed CT and PT banks to convert the signal down to a safe instrument level. The enclosure is weatherproof and has a heater, instrument power strip, modem, surge protection, and special wiring terminations for CT and PT units. This type of installation is costly because so much utility line work is required to get it operational. The instruments cost roughly $10,000 to $20,000, but once installed with all the ancillaries the cost ends up being $50,000 to $100,000 per site. By siting instruments where they don't need site preparation, the costs can be controlled.

Instrument Locations

Having discussed instrument packaging for various outdoor/indoor locations, it is appropriate here to digress to the topic of the impact of instrument location. Instruments may be located at a wide variety of points on the power system ranging from the transmission level all the way down to the customer facility. The figure below shows some possible locations on the distribution system (see locations A through D). While all sites have commonalities with regard to what the instrument sees (electrically speaking), the instrument user/analyst should be aware of some big differences between sites that will have an impact on the electrical conditions observed.

Instrument Locations Can Be Many and Varied



In this example, a voltage sag is due to an adjacent feeder fault.

An instrument at the substation (location A) can measure the voltage quality entering from the subtransmission system and will be able to measure the impacts of distribution feeder faults and other disturbances on the substation bus. So location A is an excellent spot to measure power conditions at the substation, but it won't necessarily be a good site to measure voltage quality conditions farther out on the feeders themselves. The impedance of the feeders and intervening protection devices (circuit breakers and reclosers) mean that feeders typically have deeper voltage sags, more interruptions, greater flicker, and increased harmonic distortion present compared to the substation bus.

To determine feeder power quality as it impacts a customer, it may be necessary to measure at locations B or C. Location C is often the point of common coupling, so it can be ideal to measure for regulatory reasons too—but understand that there will be a difference between conditions at B and C due to the impedance of the distribution transformer. Also, the winding arrangement of the transformer can change the conditions. Certain arrangements (such as delta-wye transformers) change the phasing, ground currents, and nature of the voltage/current readings. These changes may need to be considered in some studies (depending on the context of the study). A measurement at location C is particularly practical when there is only a single instrument site planned and the power quality at the point of common coupling is the main objective. Also, measurement at location C often means that a lower-cost indoor installation using low-voltage class connections to the instrument is feasible. Whereas, measurement at location B may require installation of CT/PT units, an outdoor pole-mounted enclosure, and other peripherals that add greatly to the site cost.

A monitor at location D (a site deep down within the customer facility near the impacted load) may also be considered because this site can give a good indication of what is happening right near a specific affected load in a building. This site is ideal if you just want to know what's happening right at that load and don't care much about other areas in the facility. However, a drawback of this location is that because it does not always adequately indicate

The best of all worlds, if you have the resources, is to use instruments at multiple sites.

As digital electronics have become more ubiquitous, there has been an emergence of monitoring features in a broader range of consumer and utility equipment.

electrical conditions at the point of common coupling or other parts of the facility, the larger picture of where they originate and how they propagate throughout the facility may be more difficult to understand.

Of course, the best of all worlds, if you have the resources, is to use instruments at multiple sites. With this approach there is the advantage that the user can simultaneously see the relative intensity of disturbances at various system levels. This added information can help identify the origin of the disturbance. For example, if a voltage sag of essentially equal magnitude is measured at sites A through D, then this would indicate an adjacent feeder fault as shown in the earlier illustration. On the other hand, if a sag is measured that has increasing intensity as one moves farther down the feeder, then this sag condition probably originated on the feeder or perhaps even at the facility if C and D are much worse than B. An experienced power quality analyst does not necessarily need multiple instruments to gauge the origin of an event (they can use waveshape and phasing cues instead), but having multiple sites certainly can be helpful in that regard.

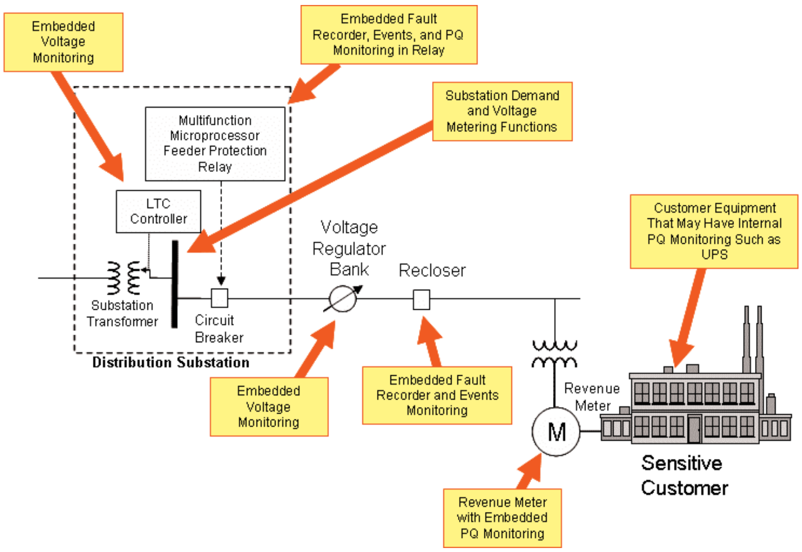
Embedded PQ Monitoring Technologies

So far we have talked about stand-alone instruments and their applications on the power system. However, another type of PQ monitoring technology is the embedded monitoring device. An embedded PQ monitor is a device that is part of, and internal to, a piece of equipment that has some other primary function besides power quality monitoring. Since it resides inside a larger device of a different primary function, the cost of the added PQ functionality is the marginal cost of the added software and electronics needed to record and store power quality waveform data. The marginal cost can be quite small compared to stand-alone monitors. The idea of an embedded monitor is not new; in fact, some of the premium UPS systems have had embedded monitoring for almost 20 years. What is new is that as digital electronics have become more ubiquitous in devices, there has been an emergence of monitoring features in a broader range of consumer and utility equipment that formerly would not have had such capabilities. Examples of devices available today include:

1. Revenue metering systems
2. Protective relays (some of the more advanced products such as multifunction three-phase relays)
3. Switchgear devices like reclosers and sectionalizing switches
4. Voltage regulator equipment
5. Power conditioning equipment (UPS, static switch, etc.)

On power systems and at customer facilities the range of possible sites where embedded monitors can be located can allow for many different sites to have recording instruments (see the figure on the following page). In fact, a large amount of existing embedded monitors may already be in use on many distribution systems without customers or utility power quality staff being fully aware of these instrument resources. For power quality analysts, as the first part of any study where monitoring is being planned, an effort ought to be made to verify what is already in place before considering additional stand-alone or embedded instruments.

Embedded Power Quality Capabilities



The most modern distribution systems may already have many devices that can perform some limited power quality measurements—always check to see what's available before forging ahead with new equipment.

Examples of Revenue Meters with Embedded Power Quality Monitoring Capabilities


Schweitzer Sel-734 Revenue Meter with PQ Functions


Siemens 9300 Series Power Meter with PQ Recording/Analysis


Nexus 1272 Revenue Meter with PQ Functions


Satec Combination PQ Analyzer and Revenue Metering (Model PM 172EH)


PMI VS-3S Meter Socket Power Quality Meter


EDMI MK10 Revenue Meter with PQ Monitoring Functions

Source: Photographs courtesy of various instrument manufacturers as indicated.

Revenue Meters with Embedded PQ Monitoring

The revenue meter with embedded monitoring is a naturally synergistic product. By adding PQ functionality to an electronic revenue meter, measurement of PQ is achieved in a device that is easily installed and has ready access to the necessary voltage and current signals. Many product styles are available (socket type, rack, and draw-out case style), which allow these meters to be placed at a variety of utility, industrial, residential, and commercial facilities. Many of the meters also have communication capabilities that enable linkage by radio, phone line, or Ethernet connection, as well as precise time referencing to enable measurements from large groups of meters to be cross-analyzed. Some examples of commercially available revenue metering devices with PQ monitoring features are shown in the figure on bottom left.

Revenue meters with embedded PQ monitoring have a broad range of demand metering capabilities and, depending on the specific product, have various capabilities to measure voltage sags, interruptions, out-of-range voltage, and harmonics. Many can provide detailed waveform measurement and come close to matching full-featured stand-alone PQ recorder capabilities. While the cost of a revenue meter with PQ features is not necessarily any less than a stand-alone PQ monitoring device with about the same monitoring capability, only a small portion of the cost of the meter should be attributed to its power quality function because a meter must be installed anyway to collect revenue data. Furthermore, the installation costs are very low because the wiring connections, protection, and weather issues are all essentially already accounted for—simply slide the meter in the socket and start monitoring! Consequently, this type of

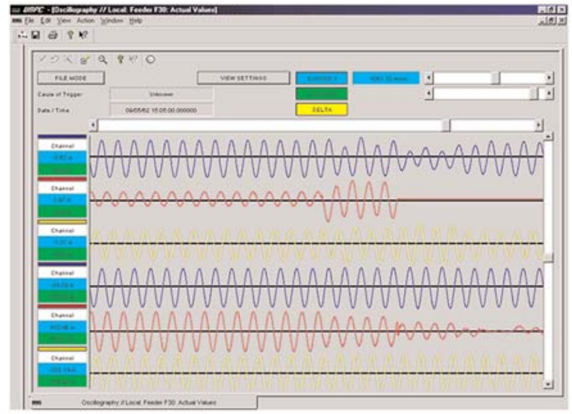
Embedded monitors can be found in some protective relays, switchgear, voltage regulators, and other power system control devices.

metering on an "installed cost basis" can be very cost-effective compared to a stand-alone PQ monitor.

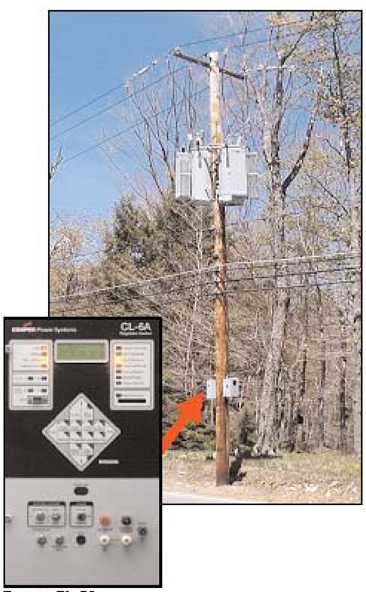
Protective Relays and Other Controls

Revenue meters are not the only possibilities for embedded monitors. Embedded monitors can be found in some protective relays, switchgear, voltage regulators, and other power system control devices. Several leading products with built-in monitoring are shown in the figure below; these include two relays and a voltage regulator control. The figure on the right shows a screen capture of a current waveform obtained with GE F60 relay.

Software Screen Sample Showing Measured Current Waveform Obtained by GE F60 Relay



Voltage Regulator and Protective Relays with PQ Monitoring



Cooper CL-6A Regulator Control

GE Multilin®
F60 Feeder Protection System

Schweitzer SEL-451 Protection, Automation, and Control System

At left is a voltage regulator control with power quality monitoring, and two leading protective relays that provide power quality monitoring are at top right and bottom right.

Just as is the case with revenue meters, relays with embedded PQ monitoring can have the ability to monitor sags, swells, interruptions, and steady-state system trends such as harmonics, demand, voltage regulation, and so on. Capabilities vary quite a bit from device to device, so the potential device purchaser/user needs to check carefully with the manufacturer for specific product specifications. Besides being used as a means of measuring system power quality, embedded PQ monitoring in relays and control equipment can also help diagnose problems with the settings or operation of the equipment itself. As an example, a protective relay with built-in monitoring can record fault current, load currents, and other transient current levels, and this data can be used to verify that the pickup and tripping functions are operating effectively. Another example of the value of embedded PQ capability can be seen in the case of a voltage regulator. Voltage and current monitoring help in the adjustment of the control settings such as the voltage set point, line-drop compensation, and time

Microprocessor-type protective relays are ideal devices to serve as embedded power quality monitors.

Users needs to weight all factors and determine whether a stand-alone or relay-based PQ monitor makes sense for their projects.

delay. The data can even be used to optimize the voltage regulator's ability to perform energy conservation through voltage reduction.

Microprocessor-type protective relays are ideal devices to serve as embedded power quality monitors. This is because their basic functionality requires that they have onboard an advanced digital signal processing and sampling capability to evaluate the waveform for overcurrent protection purposes—so adding PQ monitoring is really just a marginal increase in the complexity of the device. In addition, the relay usually is located where it is directly wired to a suitable three-phase current and/or voltage signal, so the issue of getting the proper signals at safe useable levels is not a problem in most cases and installation is very simple, usually involving just some basic connections at the back of the relay. Lastly, relays are often located at substations or industrial service entrance points where the monitored voltage and current conditions are particularly useful for power quality studies. Furthermore, these locations are usually protected from weather elements and often have readily available communications. For facilities where new or upgraded relays are being specified for protection and control and when PQ monitoring is needed, selecting a relay that has internal PQ monitoring functions can be an ideal choice and much less of a hassle than a stand-alone PQ meter. Many relays of this nature cost only $3,000 to $10,000, and the cost of installation and ongoing operation is often minimal for the reasons discussed earlier.

Given all of the discussed attributes for relays that have embedded PQ monitoring, it seems plausible that this should always be the preferred approach compared with use of stand-alone PQ monitors. However, the use of a relay as a PQ monitor does have some disadvantages that for some studies might rule them out. First, the locations where they are suitable is generally limited to the substation, major service rooms, and locations where there are existing provisions for sliding in relays. If the desired monitoring location is different from these spots, then a stand-alone PQ device would likely be a better choice. Second, while some of the more advanced PQ relays perform a moderately broad spectrum of power quality measurements, the sample rates and measurement capabilities can still be limited in many products compared to full-featured stand-alone PQ monitors. They also may not record the data in a format that is as effective to analyze from a power quality perspective as some of the pure stand-alone PQ monitors. And flexibility in the configurations for input channels and accessories is limited. Ultimately, users need to weight all these factors and determine whether a stand-alone or relay-based PQ monitor makes sense for their projects.

Power Conditioners with Embedded Monitors

Some power-conditioning devices at electric customer facilities have embedded PQ monitoring features. Power-conditioning devices include UPSs, high-speed solid-state tap-changing autotransformers, dual-source-fed static switches, and various other power quality enhancement devices. With these devices, and in particular with UPS equipment, these units may monitor their status (position of static switch, bypass breakers, inverter temperature, remaining battery time, and so on) and provide a record of the disturbances that caused the machine to transition to a particular mode. Some UPS devices have software that allow many UPS units to report status and power quality conditions back to a central location so that an entire facility with many scattered UPS devices can be assessed in real time and managed. UPS monitoring is helpful in

Using the Internet as well as automated data collection procedures can allow the collection, analysis, and dissemination of results to data-users in a very cost-effective manner.

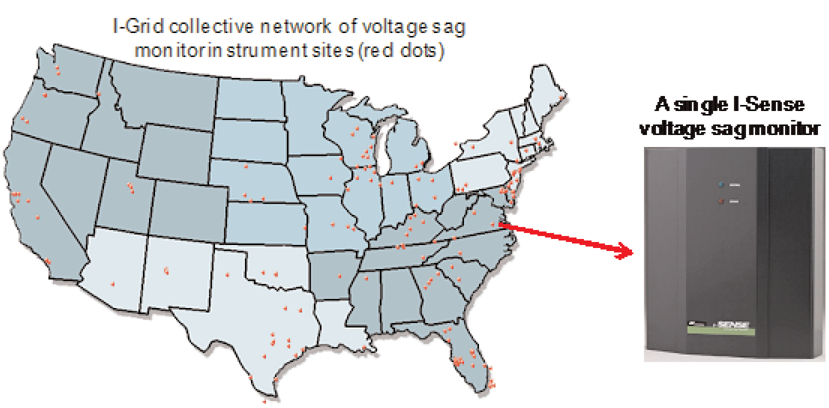
diagnosing problems and preventing failures of power-conditioning devices because the status of the power-conditioning equipment itself can be monitored and corrective steps taken sooner. Depending on the type of power-conditioning device, the power quality data collected by the machine's embedded monitor could be rudimentary (only a basic time tag of the event and its severity) or it could be more detailed allowing for waveform analysis. The larger UPS systems, such as those pictured in the figure below, have fairly advanced capabilities, many even allowing detailed waveform processing of incoming interruptions, voltage sags, swells, harmonics, and so on.

UPS Power Conditioning Devices with Embedded Monitors

Powerware 9315 UPS

Liebert Series 610 UPS - 60Hz

Map of I-Grid Instrument Network and Photo of I-Sense Voltage Sag Monitor



Collective Instrument Groups and Web-Based Instruments

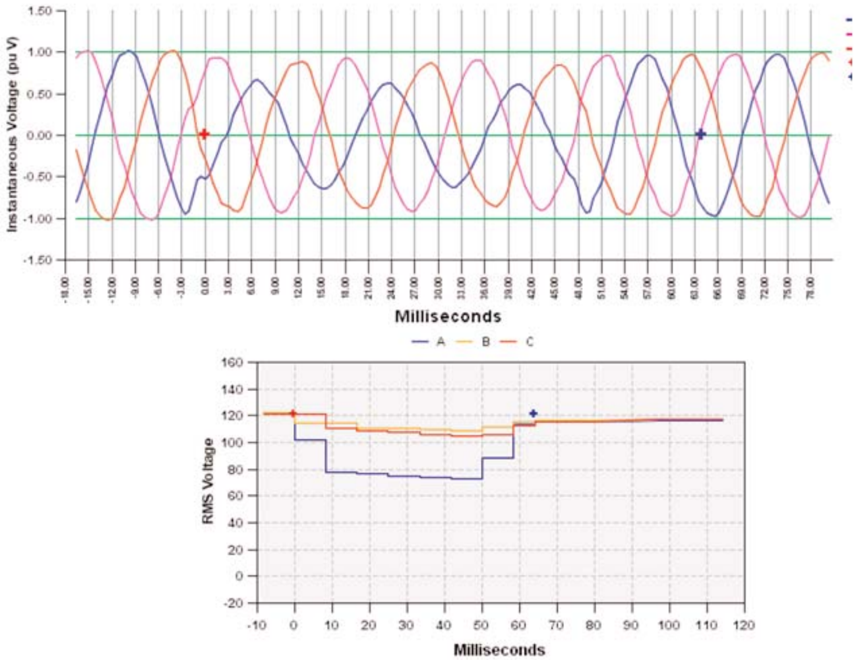
A relatively new approach to power quality monitoring is the use of collective instrument networks that report data back to a central location over the Internet. Using the Internet as well as automated data collection procedures with a web-based approach can allow the collection, analysis, and dissemination of results to data-users in a very cost-effective manner.

This concept of a coordinated network of instruments reporting back to a central location can involve just a few units or possibly up to thousands of units. Perhaps the most impressive instrument collective from the perspective of scale is the I-Grid project. It is a web-based distributed power quality and reliability monitoring and notification system that covers much of the U.S. It uses thousands of monitors called I-Sense units (see the figure on below left) scattered at various client sites around the nation to capture power quality events. Individual I-Sense users and data subscribers can focus on their own sites for specific analysis, but the data can also be used in a larger context to assess regional and national power quality conditions. An example of a voltage sag event recorded with an I-Sense unit is shown in the figure on the following page.

Communication Links

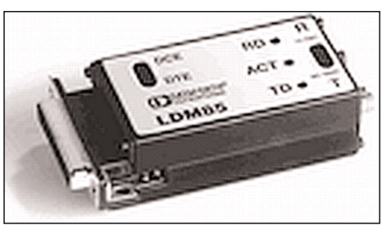
Communication link access is an important part of power quality monitoring. By having communication link access at each instrument site, the instruments can be periodically accessed from a central location to check for problems, adjust data acquisition settings, have their timing aligned to improve interinstrument coordination, and most importantly, download the event data.

Example of a Voltage Sag Recorded Using an I-Sense Unit



Top trace is three-phase waveform, and bottom trace is RMS value of sag associated with above waveform.

Wireless and Fiber-Optic Technologies That Can Provide Dielectrically Isolated Communication with PQ Instruments



Fiber Optic Modem
Dataforth LDM85

The DataRemote, Inc.
CDS 9022 CDMA Modem (800 MHz Cell Phone)

Local Wireless Modem (2.4 GHz)
XBee-PRO™ Zigbee/802.15.4 RS-232 RF Modem

The costs and difficulty of establishing a link have historically been prohibitive at some sites. For example, substation communication was one of the toughest problems facing instrument installers in the past. If the substation did not already have an existing data line connection with isolation, then adding a metallic phone or data line was particularly costly because special high-voltage isolation equipment was required by the phone company. The isolation equipment, which in the past could cost up to $50,000, eliminates the risk of high-voltage transients getting into the phone system due to ground potential rise (GPR) during fault conditions. However, over the past decade new technologies have emerged that have dramatically lowered the cost of communication. Today there are low-cost alternatives to hard-wired metallic communication links at substations that can provide the needed isolation at relatively low cost and can offer fairly high data rates. These include wireless local area network (LAN)–interfaced Ethernet (via Bluetooth or 802.11), satellite, and cell-phone modem technologies. Fiber-optic data service is also available that can provide isolation, but with a higher installation cost than typical wireless technologies. All of these methods have been successfully used for many fault recorder and power quality monitoring applications that require isolation. The figure on left shows examples of some wireless and fiber-optic interface technologies.

Utility substations are not the only ones that may need instrument communication link. Commercial and industrial power quality monitoring sites also often need communication links. Fortunately, at these locations it is likely that Ethernet LAN and wide area network (WAN) connections and phone lines are readily available to serve as

Precise timing can facilitate greater automation of the data analysis process, allowing the instrument measurements to be better correlated with load-disruption events.

a link. These sites usually don't need the type of dielectric isolation that substations require because most sites operate at less than 600 V. If the facility has medium- or high-voltage internal systems, then additional isolation similar to that used at a utility substation might be needed in some instances—depending on the specifics of the installation. In some larger facilities where communication leads cross between buildings, use of optically isolated systems (fiber optics) and wireless data transfer devices can help solve the problem of potential differences between structures and along the earth. This issue of ground potential rise is particularly important if the user intends to tie many recorders together into a large collective network of instruments over a large factory with various separate buildings.

A final point on communication is that many modern PQ instruments have Ethernet capability and are equipped with an RJ45 connector port. However, some power quality instruments do not have Ethernet ports (RJ45-type connector) and only have RS232, IEEE-485, M-bus, or Mod-Bus interfaces. These can in some cases use a conversion module to convert the communication signals to Ethernet-compatible data. Two examples of these types of devices are shown in the figure below. Keep these converter options in mind if you need to connect to an Ethernet port but have one of the other communication interfaces.

Data Transfer Converters That Enable RS-232, IEEE-485, and M-bus Devices to Interface with an RJ45 Ethernet System

Lantronics UDS-10-IAP
Converts Serial Data Port (RS-232 or IEEE-485) to Ethernet (RJ45)

PiiGAB M-Bus 800
Converts M-Bus to Ethernet (RJ45)

Instrument Timing

Twenty-five years ago, most power quality studies at the power distribution level were done without precise timing of the instruments. Back then, most instruments used free-running clocks (not linked to any other centralized time reference) that were often set manually. The instrument timing could be maintained within about ±20 s of actual time over the course of a long study (that is if extra care was taken). If less care was taken, then experience showed the error could approach several minutes between instruments. While some fairly good analysis can still come out of instrument data sets that are inaccurate by up to several minutes, the ability to have more precise timing has many benefits.

More precise event timing to within 1 s or better is helpful to reduce the effort to analyze the data—especially if there are a large number of instrument sites involved. Precise timing can facilitate greater automation of the data analysis process, allowing the instrument measurements to be better correlated with fast-paced load-disruption events within a facility. Instruments can be connected by wired or wireless Ethernet networks or by means of dial-up modems to central timing devices. Network-connected instruments can have their timing updated daily or in some cases almost continuously to maintain precise instrument alignment. With Ethernet interfaced instruments, 1-s accuracy is easily obtained by making sure that the reference polling computer is properly time-synched. In fact, in many cases if instruments have time-synchronization

Sometimes manual logging of equipment disruptions is not enough by itself and automated logging is needed to track how a power quality disturbance impacts a facility.

capabilities and are connected to a WAN full-time, they can be synched to an accuracy within 10 to 100 ms. On LANs, this can be to within about 1 ms. For even tighter accuracy, a Global Positioning System (GPS) timing receiver for each instrument may be needed. The use of GPS timing signals at each device enables accuracy down to better than 1 µs and in some cases down to within 50 to 100 ns. Many instruments sold today can be purchased with a GPS antenna and an internal (card type) or externally connected GPS time synchronizer unit. An example of one such unit is shown in the figure below. That level of timing accuracy is not really needed for most power quality studies.

GPS-Synchronized Clock

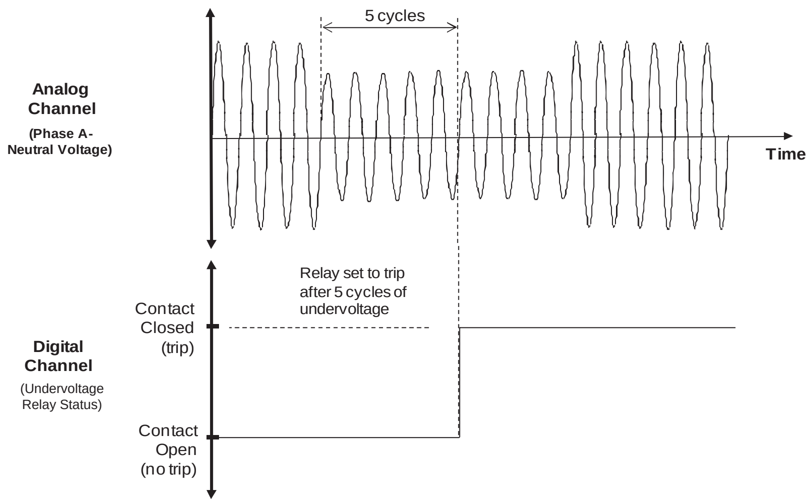
Source: Photo courtesy Arbiter Systems

Correlating Load Disruptions with PQ Events

For many monitoring studies, a key objective is to identify which disturbances cause disruption of sensitive load processes. So the task at hand is to measure the electrical disturbances as they occur and log the corresponding impacts of these disturbances on the facility loads and on power-system equipment. This correlation between equipment disruptions and PQ disturbances can be done in a number of ways. The least sophisticated method is simply by manual gathering of such data. With this approach a log book or a standardized form is filled out each time a problem is noticed within the facility. The problems to be logged include anything that is out of the ordinary that is considered a significant issue, such as noticeable flicker in the facility lights, unexpected equipment or process shutdowns, circuit breakers tripping, devices overheating or failing, and so on. For this type of logging to be the most effective, the person doing the logging must provide accurate descriptions and times of the associated disruptions and they should be reasonably knowledgeable regarding the type of information that is pertinent to the analysis process. A standardized log entry form can go a long way toward insuring that the proper data with sufficient detail are provided.

Sometimes manual logging of equipment disruptions is not enough by itself and automated logging is needed to track how a power quality disturbance impacts a facility. In complex process situations where many devices can be impacted quickly (within fractions of a second), knowing the exact sequence in which devices were disrupted may be critical in order to understand which stages of the process were impacted by the power quality event and which stages were simply cascading effects of the initially disrupted device. Automated logging can time tag the operation of key circuit breakers, switches, and operating states of equipment down to the millisecond level. A power quality monitor or fault recorder with digital inputs is one way to do this. A digital input is a binary input channel with two states that can be used to monitor the status of a device (e.g., 0 = off, 1 = on). This is done usually with a DC voltage signal on the two wires to the digital input. With digital inputs, power quality recorders can determine exactly when a breaker tripped, a switch changed state, or a load device changed its operating status. When states of switches and devices are plotted alongside the actual power quality event waveform, they can show how the equipment responded to the event. For example, the figure below shows how an undervoltage relay responded to a voltage sag event.

Response of Undervoltage Relay to PQ Event



The digital channel shows that a relay tripped about 5 cycles into an undervoltage event, just as it was set to do.

Utility and Weather Data

In addition to the facility load disruption data records, utility power system operating and outage records can be useful for certain projects—especially if the project objective is to focus on the utility system causes of power quality events. Utility companies usually have SCADA records of key system circuit breaker operations, switching events, fault and outage reports, and other information that are helpful to the power quality analyst. Obtaining this data from the utility can be critical to troubleshooting the origins of a particular disturbance. The data in these utility logs are usually time-tagged with a fair amount of precision using the company SCADA system clocks. Even when time-tagging is not so accurate, the data can still be helpful to compare against power quality records and load disruptions.

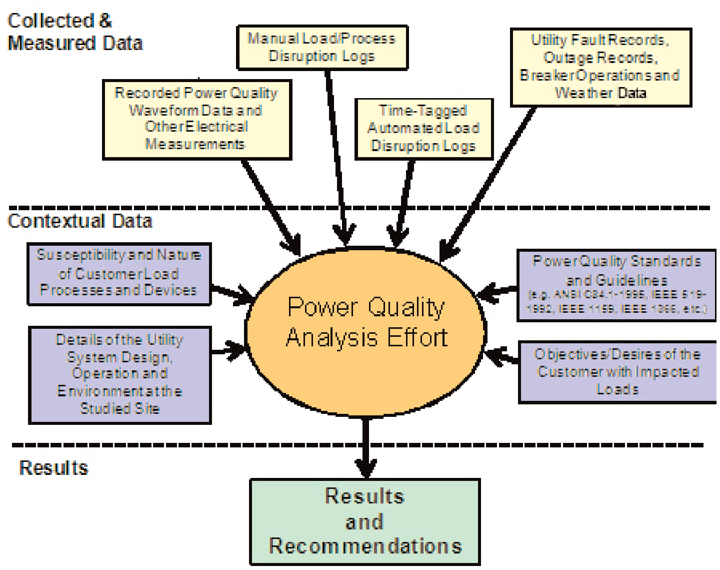
Weather records such as the presence of lightning storms, high winds, rains, and so on, can also be helpful. These can be obtained from a variety of sources, some government based and others commercial. The National Lightning Detection Network operates a network of sensors that together can detect and locate within 500 meters ground truth accuracy about 90% of lightning strikes occurring throughout the continental U.S. For power quality studies involving lightning surges and voltage sags or outages caused by lightning, this data can be purchased and can provide valuable information on the time, stroke multiplicity, and stroke magnitudes of lightning strikes near a facility or power system asset.

MANAGEMENT AND ANALYSIS OF PQ DATA

Power quality studies involve collating a variety of data such as electrical measurements, load disturbance records, and utility outage/switching reports. This data must be analyzed within the context of facility load characteristics, utility system design/exposure, and the various applicable power quality guidelines and customer objectives that apply. This overall effort is illustrated in the figure on the following page.

As shown in this figure, the study consists of both measured/collected data as well as contextual data. The contextual data of the study is as important as the actual measurement data. For example, if a site located on a rural radial distribution circuit is experiencing one sustained interruption each year, this can be considered good, because in this case national reliability statistics show that one interruption per year is better than average for most rural

Overall Effort of a Power Quality Study



All of the contextual and measured information pertinent to the power quality project must be analyzed as a whole to arrive at the appropriate results and recommendations.

The type of power system feeding a site affects how we interpret the measured PQ data.

radial distribution circuits. On the other hand, if a site is located on an urban low-voltage network circuit, then one interruption per year is much worse than average for that type of system. So we can see that the type of power system feeding a site affects how we interpret the measured PQ data. In the first case, performance was better than average for that type of design, so it would not necessarily warrant the utility company improving that side of the system; a customer-side solution would probably be the best approach. However, the urban network system in our example is performing much worse than average, and a strong case could be made to the utility company that the system is operationally deficient in some way—the utility could investigate, find the flaw, and make the needed upgrades. Overall, from this example we can see how the contextual design data associated with the site is important.

Data Collection and Archiving

The plan for data collection and archiving must be well organized and properly documented if the project is to be a success. Proper archiving of data is not just about storing the instrument measurement files. It's also about documenting the instrument installation setup, the trigger settings, scaling factors, and other elements that impact the study. Some general tips that are helpful to the process include:

- **Select the proper balance for the instrument trigger settings.** Use settings and data download intervals sufficiently sensitive to capture all the necessary data while avoiding the superfluous data. This will help contain the size of the archived database. Be consistent with settings at all instruments if possible. Upon completion of the first 10% of the planned monitoring period, as well as at other stages, the data should be assessed to make sure the records are meeting expectations and determine if any adjustments to settings are needed.
- **Use understandable data file nomenclature.** Make sure data files are saved with easy-to-understand file nomenclature. File names need a unique site identifier as well as start-date and end-date representing the monitoring period for each file.
- **Document the instrument trigger and calibration settings.** Document the instrument trigger settings at all stages of the project. Make sure all scaling factors needed to convert data to engineering units are documented too.

Having a power quality data specialist can be helpful to insure that all pertinent information is properly archived.

- **Document site conditions and instrument configuration.** Make sure to document the details of each PQ instrument installation—these include the wiring details into each instrument, the transducer and instrument transformer ratios, burdens, and grounding. Note any special issues at each site that could impact the measurements (photographs of equipment are helpful).
- **Check load disruption event logs periodically.** Archive these in a fashion that works best with the type of measurements being performed and processes studied. Check the quality of the gathered load disruption data early in the project to make sure it is collected accurately and with proper detail. For event logs that are manually filled out, make sure these are done in a timely fashion so that events are fresh and details not forgotten.
- **Back up all files and data.** This point is obvious, but make sure the electronic and paper data materials are safely stored and backed up.

Power quality analysts will typically use a combination of vendor software, spreadsheets, and manual analysis/ calculations for the various projects in which they are involved.

One way of managing a large power quality measurement database is through the use of the PQView™ software and its associated options. This software, originally developed by EPRI and Electrotek, performs instrument management, data sorting, archiving, plotting, and analysis. PQView can read data files from many instrument brands, allowing data from different instruments to be compiled into a single database. Data can be from stand-alone PQ monitors, fault recorders, voltage recorders, embedded revenue meter monitors, and embedded monitors in protective relays. Another tool called PQWeb™ allows a PQ archived database to be accessed by many users over a LAN or the Internet. This approach is a good method for disseminating data if a project involves many data users. Having a power quality data specialist who is charged with maintaining and backing up the database at the central server can be helpful to insure that all pertinent information is properly archived.

The industry has also developed standardized data output formats such as IEEE 1159.3-2003 (PQDIF) and IEEE C37.111-1991 COMTRADE format which can be read by PQView and other software to allow exchange of recorded information between different types of instruments and various software packages.

Analysis of Data

The types of analytical methods needed for a particular project will depend on the conditions studied and if it's a benchmarking, problem-solving, or just-in-case type of monitoring study. Power quality analysts will typically use, to varying degrees, a combination of vendor software (such as PQView/PQWeb), spreadsheets, and manual analysis/calculations for the various projects in which they are involved. They may also use power system modeling software such as ElectroMagnetic Transients Program (EMTP) to verify measurements. These tools along with experience and common sense can tackle most issues. The list below shows many of the analysis tools and activities that will be required of the power quality analyst at one time or another during the course of a project:

- Basic waveform plotting: RMS magnitude and raw waveform plots
- Advanced waveform manipulations: sums, differences, multiplication, division, high or low pass filtering, and waveform derivatives/integrals

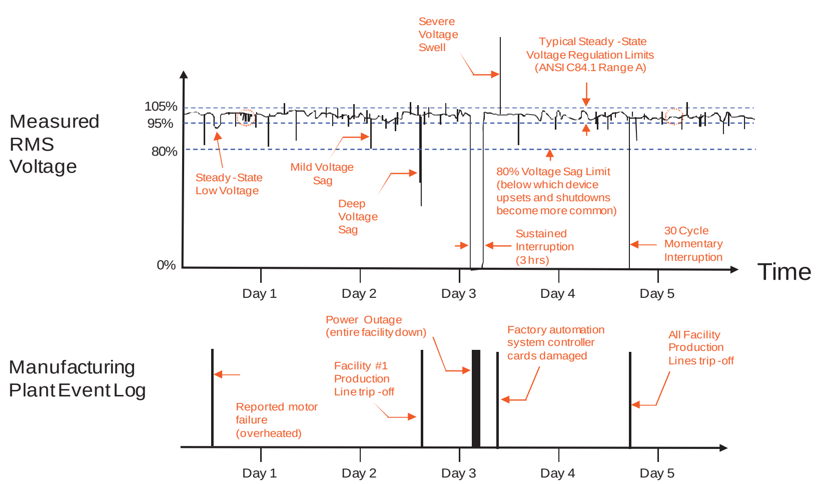
Besides simple plotting of waveforms or RMS traces, mathematical manipulation of measurements or waveforms may also be required for an effective analysis.

- Electrical calculations from waveforms/data: apparent power, power factor, real and reactive power, unbalance, sequence components, harmonic analysis (fast Fourier transform), noise level, impulse levels, notching, voltage flicker, etc.
- Creation of "comb diagrams" that correlate PQ events and load disturbances.
- Plotting of PQ events on susceptibility curves (for example ITIC or SEMI-47)
- Sorting of events by severity
- Automatic event categorization
- Statistical analysis of events (event rates, probabilities, industry indices, etc.)
- Wide area power quality event correlation (over multiple sites)

For basic studies only some of the fundamental plotting functions listed above may be needed. On the other hand, comprehensive studies may require most or all of these forms of evaluation. The figure below (see top trace) is an illustration of a five-day plot of phase-to-neutral RMS voltage down to ½ cycle resolution—many of the PQ recorders with viewing software can make traces of this nature. This type of RMS trace is great for quickly evaluating voltage regulation conditions as well as picking out transient sags, swells, and interruption events. When a trace of this nature is plotted alongside a facility load disruption plot (bottom trace of the figure), it becomes an effective tool for correlating power quality conditions with load disruptions.

Besides simple plotting of waveforms or RMS traces, mathematical manipulation of measurements or waveforms may also be required for an effective analysis. They may need to be added, subtracted, multiplied, or divided. Furthermore, a derivative or integration may need to be applied to certain cases. These operations may be needed to assess certain types of conditions such as power, energy, unbalance, and so on. For example, the voltage multiplied by the current is equal to the apparent power, or the summation of three-phase currents entering a node is equivalent to the current leaving the node (zero sequence ground and neutral current), or the integral of the power multiplied by the current over a defined time window equals the apparent energy during that window. A fast Fourier transform (FFT) may need to be applied to assess harmonic content of the waveform. Programs such as PQView allow many of these sorts of manipulations to be made, and in cases where the programs themselves can't do a certain type of specialized calculation, then the ability to export instrument data samples from the software into spreadsheet data files (e.g., comma-delimited data files) is a valuable feature. Once in a spreadsheet format, essentially any type of customized mathematical analysis can be performed by

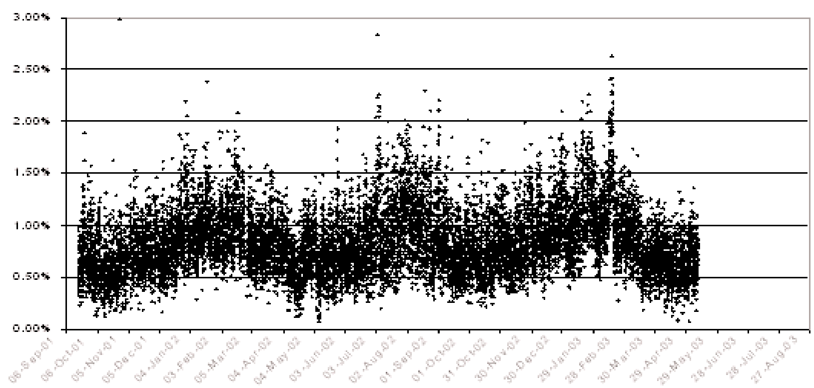
Plot of the RMS Voltage and Corresponding Plant Log



A five-day RMS voltage measurement is compared with the corresponding facility event log to show which events were associated with facility disruptions.

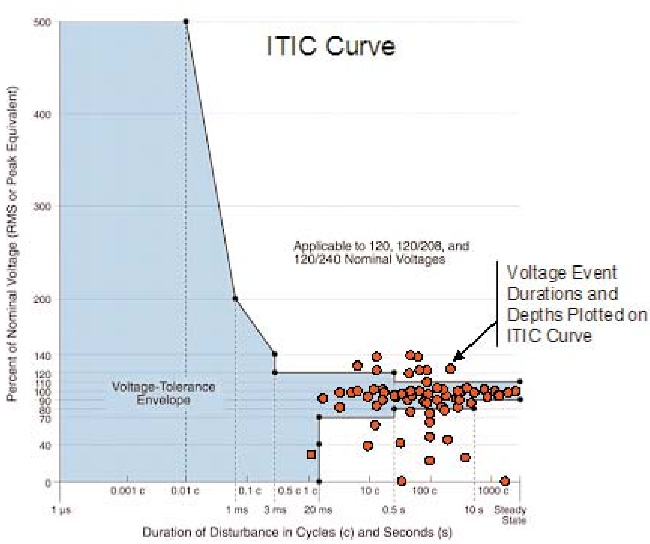
writing specific equations to apply to the data. For example, the figure below shows a voltage unbalance plot that was created by exporting nearly two years of three-phase voltage data from a PQView data file into a spreadsheet file. Once in spreadsheet format, the ANSI C84.1-1995 voltage unbalance equation plus some additional adjustments were applied to the data and the result was plotted as shown here. This graph nicely summarizes that the voltage balance at this site was well within the 3% limit over the nearly two-year duration of the data file.

Nearly Two Years of Voltage Unbalance Data Plotted with Microsoft Excel



Data was exported from PQView into a comma-delimited data file, then an equation was applied and the result was plotted.

Example of Voltage Disturbance Durations and Depths Plotted on the ITIC Curve



Another type of analysis often used for visualization of power quality conditions is the plotting of transient event points overlaid on top of load-sensitivity curves (such as ITIC; see figure on lower left). In this case, each event point is shown as a small circle on the graph. The coordinates of each circle are based on the duration and severity of the event. In our example, the plot shows the coordinates of several dozen events plotted on the ITIC curve. In theory, the events inside the curve should not be disruptive to loads, and those outside the boundary may be disruptive depending on the load type. By keeping track of how many points are outside the ITIC limits over a given time period, it is possible to statistically calculate the rates of occurrence of disturbances outside ITIC. The method of analysis can be used for both benchmarking as well as for specific problem-solving by identifying which specific events are outside of the curve limits. Obviously, the method is not limited to ITIC and can be applied to other curve types such as SEMI-47, relay and contactor drop-out curves, and so on. By collating sag and swell data and site load disruptions over time, it is even possible to generate a customized susceptibility curve for a specific facility. That type of curve could be helpful in determining mitigation options.

Overall, the analysis and visualization methods we have described here are just the tip of the iceberg. There are many other types of calculations for quantifying PQ conditions such as sag indices (known as SARFIx) and reliability indices (SAIFI, CAIDI, MAIFI, etc.). The space we have here does not allow for more detail in these other areas, but the main point the reader should take home regarding PQ analysis is that the instruments and software tools used should be flexible enough to contain within the software itself the frequently used analytical methods of the PQ industry while also giving the user the ability to customize the analysis

The instruments and software tools used should be flexible enough to contain the frequently used analytical methods of the PQ industry while also giving the ability to customize the analysis.

Power quality engineers and analysts must have a thorough understanding of the instrumentation requirements and capabilities as well as a good working knowledge of the origins and effects of power disturbances.

or export to spreadsheet files and other software where customized data-processing routines can be applied. The software also needs the ability to generate graphics that can easily be pasted into word processing and presentation software for reports.

SUMMARY AND RECOMMENDATIONS

As shown here, power quality monitoring is a broad subject. While this chapter was only able to cover the basic principles and concepts, hopefully, at a minimum, it conveyed the important point that, to perform monitoring in the most effective manner, power quality engineers and analysts must have a thorough understanding of the instrumentation requirements and capabilities as well as a good working knowledge of the origins and effects of power disturbances. Below are some general strategy points to follow for monitoring that should be helpful for any project.

General Monitoring Recommendations and Strategies

Guidelines for effective power quality monitoring include:

- **Premonitoring planning.** Have a clear idea of the objectives and the likely suite of measurements needed to accomplish a project. This means knowing whether or not a project is for problem-solving, benchmarking, or long-term just-in-case monitoring. It also means having a plan for collecting specific types of measurements over a specific period of time.
- **Instrument selection.** Understand which types of instruments are appropriate to meet the plan spelled out in the premonitoring planning. Make sure to select the instruments that provide the best balance of performance and cost (consider cost-saving measures discussed later) from a total project cycle perspective (instrument installation, operation, data analysis, and presentation efforts). Understand the limitations of measurements from the perspective of instrument bandwidth, needed resolutions, triggering capabilities, and so on.
- **Instrument locations.** When selecting instruments, know which locations are suitable for certain measurements and which ones are not (based on measurement needs, cost, and instrument performance capabilities).
- **Data archiving, analysis, and presentation.** Recognize that power quality monitoring is not simply about collecting electrical disturbance data. To fully assess conditions, the characteristics of the loads, the power system, load disruptions, and other data pertinent to the site need to be well documented. Use of suitable software tools that provide automated data management, a full range of analysis functions, and flexible data export and graphic presentation capabilities is helpful.

Check for embedded instruments before starting a possibly redundant measurement program, and don't forget that sometimes issues related to equipment disruptions can be identified at little cost by simple review of the symptoms of problems without any monitoring.

The cost of PQ monitoring is greatly impacted by the labor intensity associated with retrieval and analysis of the data.

Recommendations for Limiting Costs of Power Quality Studies

We would be remiss if we did not mention as a final subject the important role that cost plays in determining the structure of a power quality study. PQ studies can be very expensive and maintaining a low cost can be an overriding concern that limits what can be done. However, experience shows that some general guidelines can help keep costs under control. These include:

- **Make use of existing resources and observations.** Existing embedded instruments operated by the electric utility, within the facility loads/devices, and at other customer sites on the feeder may already have the needed data—check for these before starting a possibly redundant measurement program. Also, don't forget that sometimes issues related to equipment disruptions can be identified at little cost by simple review of the symptoms of problems without any monitoring.
- **Avoid monitoring overkill.** Stick only to the types of measurements that are needed. Use the minimum number of devices needed.
- **Chose the most cost effective instruments and locations.** Make sure to identify the total costs of an instrument, including installation labor and site needs such as instrument power, communication, instrument transformers, enclosures, archiving and analysis software, and so on. Consider instrument locations and types that have a low total cost of installation and operation including these factors.
- **Lease equipment versus buying equipment.** As a rule of thumb, the typical cost of leasing an instrument is roughly 10% of the instrument's retail cost each month of usage. Also, add an extra month at each end for time and costs associated with shipping, setup, and familiarization. Considering these factors, if an instrument is to be required for monitoring on a one-time basis for seven months or less, it would normally be better to lease the instrument rather than buy it. If it is to be used for longer than this or more than one time, then purchase may be the best option.
- **Use efficient archiving and analysis techniques.** Consider the use of software that allows the most automated data retrieval, data archiving, and data analysis approaches that help to limit the costs associated with retrieving data and analyzing results. Careful usage of instrument trigger settings to reduce superfluous data can also help control the analysis effort required. The cost of PQ monitoring is greatly impacted by the labor intensity associated with retrieval and analysis of the data. In fact, because the cost of engineering and technician time can typically be anywhere from about $600/day up to over $1,800/day, over 50% of the total project cost can easily be associated with the retrieval and analysis phases of the effort.

If the above points are considered, the power quality engineer can limit the project cost. However, for some situations, following the recommendations may not be practical due to the types of measurements that are needed or the particular site conditions that exist. For example, sometimes an instrument simply must be located at an outdoor point on a feeder where considerable effort is needed to install instrument transformers, instrument power, and so on. As a general guide to budgeting power quality projects, consider the table below. This table shows the typical worst-case and typical best-case project cost for a single-site, six-month study including instrument procurement, installation data analysis, and reporting. With multiple sites and/or longer monitoring periods, the costs do not go up linearly by the number of instruments due to the efficiencies achieved when operating and analyzing data from multiple sites and/or over longer periods of time.

Project Life Cycle Breakdown of Costs for a Single-Point, Six-Month PQ Study on a Medium-Voltage Distribution Line

Cost Element Description	Typical Cost Range (Equipment and/or Labor)	Comments
PQ instrument	$200–30,000	Cost range starts at the most basic instrument and goes up to higher-end, full-featured instruments with options
Ancillary hardware and installation efforts (excluding instrument communication equipment and services)	$1,000–30,000	Low end of range represents the simplest installation. High end of range requires special PT/CT units, instrument power, enclosure, etc.
Communication equipment and services	$0–50,000	Low end of range, no communication needed. High end of range is a fully isolated wire line installation at a substation per IEEE-487 standards (less costly substitutes are available).
Software and PC costs	$0–12,000	Some instruments come with basic software, and others require a major software purchase to realize needed analytical features.
Project management, data archiving, analysis, and reporting	$15,000–40,000	The engineering labor and project management are often the largest components.
Total project cost	$16,200 to $162,000	