A Systems Approach to Power Quality Monitoring for Performance Assessment

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Why Monitor Electric Power?

In the dawn of deregulation, power providers and consumers are changing their view of system performance. This evolution is being driven due to the increasing awareness of power quality's role in customer systems. Already many providers are laying the groundwork worldwide for a new type of service contract in which a provider may promise one or more of its large industrial or commercial customers a certain level of "quality" in delivered power. In return, the customer agrees that for the duration of the contract it will not turn to another source – an important new option with the advent of retail wheeling in the electric power industry. Some states are revolutionizing the electric industry by permitting even residential customers to select their provider. Anyone who has watched U.S. television in the last few months is quite aware of the increasingly common commercial advertisements enticing the viewing public of a better future for power with promises of cheaper and more reliable energy.

The EPRI Distribution Power Quality Monitoring Project

In response to the concerns expressed by utility companies and their customers over the power quality issue, the Electric Power Research Institute conducted a study to determine the state of power quality on distribution feeders across the United States. Monitoring for the project began in June 1993 and ended in September 1995. There were 24 different utilities involved in the data collection effort with 277 measurement sites. EPRI selected the measurement locations to yield a database which was statistically important at a national level. We have used experiences and results from this project to develop the guidelines presented in this article.

Objectives for a Power Quality Monitoring Project

The objectives for a monitoring program determine the choice of measurement equipment and triggering thresholds, the methods for collecting data, the data storage and analysis requirements, and the overall level of effort required. We have identified several general classifications for monitoring objectives:

- **Monitoring to characterize system performance.** This is the most general requirement. A power producer may find this objective important if it has the need to understand its system performance and then be able to match that system performance with the needs of customers. System characterization is a *proactive* approach to power quality monitoring. By understanding the normal power quality performance of a system, a provider can quickly identify problems and can offer information to its customers to help them match their sensitive equipment's characteristics with realistic power quality characteristics.

- **Monitoring to characterize specific problems.** Many power quality service departments or plant managers solve problems by performing short-term monitoring at specific customers or at difficult loads. This is a *reactive* mode of power quality monitoring, but it frequently identifies the cause of equipment incompatibility which is the first step to a solution.
- **Monitoring as part of an enhanced power quality service.** Many power producers are currently considering additional services to offer customers. One of these services would be to offer differentiated levels of power quality to match the needs of specific customers. A provider and customer can together achieve this goal by modifying the power system or by installing equipment within the customer's premises. In either case, monitoring becomes essential to establish the benchmarks for the differentiated service and to verify that the utility achieves contracted levels of power quality.

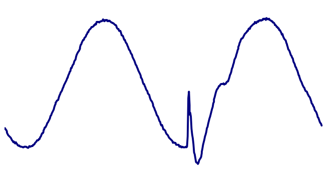
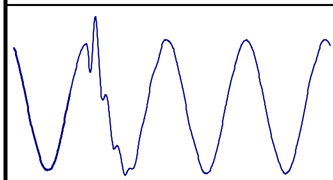
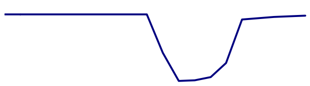
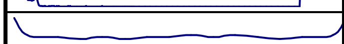
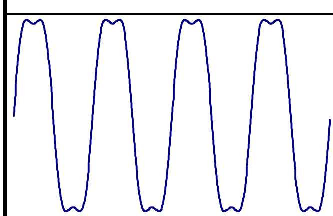
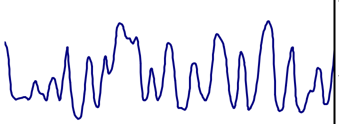
What to Monitor?

Power quality encompasses a wide variety of conditions on the power system. Important disturbances can vary in duration from very high frequency impulses caused by a lightning stroke, to long-term overvoltages caused by a regulator tap switching problem. The range of conditions that a power quality instrument must characterize creates problems both in terms of the monitoring equipment complexity and in the data collection requirements. Table 1 provides a brief summary of important categories of power quality variations along with typical causes of the variations, power conditioning alternatives, and methods of characterizing the variations.

The methods of characterizing are important for the monitoring requirements. For instance, characterizing most transients requires high frequency sampling of the actual waveform. Characterization of voltage sags involves a plot of the rms voltage versus time. Outages can be defined just by a duration. Monitoring to characterize harmonic distortion levels and normal voltage variations requires steady-state sampling with trending of the results over time.

It may be prohibitively expensive to monitor all the different types of power quality variations at each location. The priorities for monitoring should be determined up front based on the objectives of the effort. Projects to benchmark system performance should involve a reasonably complete monitoring effort. Projects designed to evaluate compliance with IEEE Std. 519-1992 for harmonic distortion levels may only require steady-state monitoring of harmonic levels. Other projects focused on specific industrial problems may only require monitoring of rms variations, such as voltage sags or momentary interruptions.

Table 1: Summary of Power Quality Variation Categories

Example Waveshape or RMS variation	Power Quality Variation and Category	Method of Characterizing	Typical Causes	Example Power Conditioning Solutions
	Impulsive Transients Transient Disturbance	• Peak magnitude • Rise time • Duration	• Lightning • Electro-Static Discharge • Load Switching • Capacitor Switching	• Surge Arresters • Filters • Isolation Transformers
	Oscillatory Transients Transient Disturbance	• Waveforms • Peak Magnitude • Frequency Components	• Line/Cable Switching • Capacitor Switching • Load Switching	• Surge Arresters • Filters • Isolation Transformers
	Sags/Swells RMS Disturbance	• RMS versus time • Magnitude • Duration	• Remote System • Faults	• Ferroresonant Transformers • Energy Storage Technologies • UPS
	Interruptions RMS Disturbance	• Duration	• System Protection • Breakers • Fuses • Maintenance	• Energy Storage Technologies • UPS • Backup Generators
	Undervoltages/ Overvoltages Steady-State Variation	• RMS versus Time • Statistics	• Motor Starting • Load Variations • Load Dropping	• Voltage Regulators • Ferroresonant Transformers
	Harmonic Distortion Steady-State Variation	• Harmonic Spectrum • Total Harmonic Distortion • Statistics	• Nonlinear Loads • System Resonance	• Active or Passive Filters • Transformers with cancellation or zero sequence components
	Voltage Flicker Steady-State Variation	• Variation Magnitude • Frequency of Occurrence • Modulation Frequency	• Intermittent Loads • Motor Starting • Arc Furnaces	• Static Var Systems

Where to Monitor?

Obviously, distribution system power quality monitoring can be a very expensive proposition due to the number of possible locations. It is very important that the monitoring locations be selected carefully based on the project objectives to minimize the costs involved.

Our primary objective during EPRI's national power quality study was to characterize power quality on primary distribution feeders. Therefore, we located monitoring locations on the actual feeder circuits. We arbitrarily installed one monitor near the substation and randomly placed instruments at two other downline sites. By choosing the remote sites randomly, we strove to obtain project results which represented power quality on typical distribution feeders nationwide.

However, it is not realistic to assume that three sites selected on any feeder can completely characterize power quality. More commonly, a typical monitoring project has objectives that involve characterizing the power quality that is actually being experienced by customers on the distribution system. In this case, we prefer monitoring at actual customer service entrance locations on the feeder because it includes the effect of step down transformers supplying the customer. Data collected at the service entrance can also characterize the customer load current variations and harmonic distortion levels. Monitoring at customer service entrance locations has the additional advantage of reduced transducer costs. Frequently, the monitoring instrument obtains voltages by direct connection, while the metering CTs provide current measurements.

A good compromise approach is to monitor at the substation and at selected customer service entrance locations. The substation is important because it is the point of common coupling for most rms voltage variations. The voltage sag experienced at the substation during a feeder fault is experienced by all the customers on other feeders supplied from the same substation bus. Customer equipment sensitivity and location on a feeder together determine the service entrance locations for monitoring. For instance, it is valuable to have a location immediately downline from each protective device on the feeder.

Selecting the Monitoring Equipment

There are many different types of monitoring equipment that form part of a power quality monitoring project. We find four basic categories of equipment particularly useful:

1. **Digital Fault Recorders.** These may already be in place at many substations. DFR manufacturers do not design the devices specifically for power quality monitoring. However, a DFR will typically trigger on fault events and record the voltage and current waveforms that characterize the event. This makes them valuable for characterizing rms disturbances, such as voltage sags, during power system faults. DFRs also offer periodic waveform capture for calculating harmonic distortion levels.
2. **Voltage Recorders**. Power providers use a variety of voltage recorders to monitor steady-state voltage variations on distribution systems. We are encountering more and more sophisticated models fully capable of characterizing momentary voltage sags and even harmonic distortion levels. Typically, the voltage recorder provides a trend that

gives the maximum, minimum, and average voltage within specified sampling window (for example, 2 seconds). With this type of sampling, the recorder can characterize a voltage sag magnitude adequately. However, it will not provide the duration with a resolution less than two seconds.

3. **In-Plant Power Monitors.** It is now common for monitoring systems in industrial facilities to have some power quality capabilities. These monitors, particularly those located at the service entrance, can be used as part of a utility monitoring program. Capabilities usually include waveshape capture for evaluation of harmonic distortion levels, voltage profiles for steady-state rms variations, and triggered waveshape captures for voltage sag conditions. It is not common for these instruments to have transient monitoring capabilities.

4. **Special-Purpose Power Quality Monitors**. The monitoring instrument developed for the EPRI DPQ project was specifically designed to measure the full range of power quality variations. This instrument features monitoring of three-phases and current plus neutral. A 14-bit A/D board provides a sampling rate of 256 points per cycle for voltage, and 128 points per cycle for current. The high sampling rate allowed detection of voltage harmonics as high as the 100^{th} in order and current harmonics as high as the 50^{th}. Most power quality instruments can record both triggered and sampled data. Triggering should be based upon rms thresholds for rms variations and on waveshape for transient variations. Simultaneous voltage and current monitoring with triggering of all channels during a disturbance is an important capability for these instruments. Power quality monitors have proved suitable for substation, feeder locations, and customer service entrance locations.

Clearly the monitoring equipment requirements depend on the specific types of power quality variations that the monitoring objectives require. Table 2 summarizes the instrument requirements as a function of the type of power quality variation.

Table 2. Equipment Requirements for Various Types of PQ Disturbances

Concern	Instrument/Software Measurement and Control	Instrument/Software Analysis and Display
Harmonic Levels	• voltage and current • three-phase • single-phase acceptable for balanced three-phase loads • waveform sampling • configurable periodicity • synchronized sampling	• FFT capability • trending • waveform and spectral plots
Long Term Voltage Variations	• three-phase voltage • rms sampling • configurable periodicity	• trending • magnitude versus duration plots
Short Term Voltage Variations, Interruptions	• three-phase voltage • rms sampling • configurable threshold level • one cycle rms resolution	• magnitude versus duration plots
Low Frequency Transients	• three-phase voltage and current • Waveform sampling • frequency response ≥ 5 kHz • configurable threshold level	• waveform plots showing pre-event and recovery
High Frequency Transients	• three-phase voltage & current • frequency response ≥ 1 MHz • impulse peak and width detection • configurable threshold level	• waveform plots showing position of impulse on power frequency sinusoid

Monitoring System Configuration

The configuration complexity of a monitoring system depends primarily upon the number of instruments used to acquire information and the number of people who need to utilize it. The simplest monitoring system could be a self-contained circuit monitor or power profiling device built into a sensitive load. However, the real value of a monitoring system is in automatic data downloading from the measuring instruments. Sometimes a single computing workstation can fill that task by using a telephone modem or RS232 port to communicate with a number of monitors. Two-way communication between the workstation and the monitors is becoming more and more important. Either the workstation's programming instructs it to regularly poll its remote monitors, or the instruments themselves can alarm the workstation when a significant event has occurred.

On the other hand, a complete monitoring system should fully utilize the networking infrastructure becoming commonplace in today's corporations. Data can also be downloaded from monitoring instruments by way of broadband (cable system) modems, as well as through Internet or intranet connections. Upon downloading important data, a notification application can automatically send email or pager messages to account representatives or plant managers. Anyone with access to the data through an Ethernet connection can use workstation applications to analyze the database of collected information. Another option for data access is to use a standard World Wide Web browser to query a database server over a corporation's intranet. Similarly, customers of a utility given permission to access the data could view event summaries and reports via the Internet. The Internet offers an effective vehicle for providing power quality monitoring as an enhanced level of service.

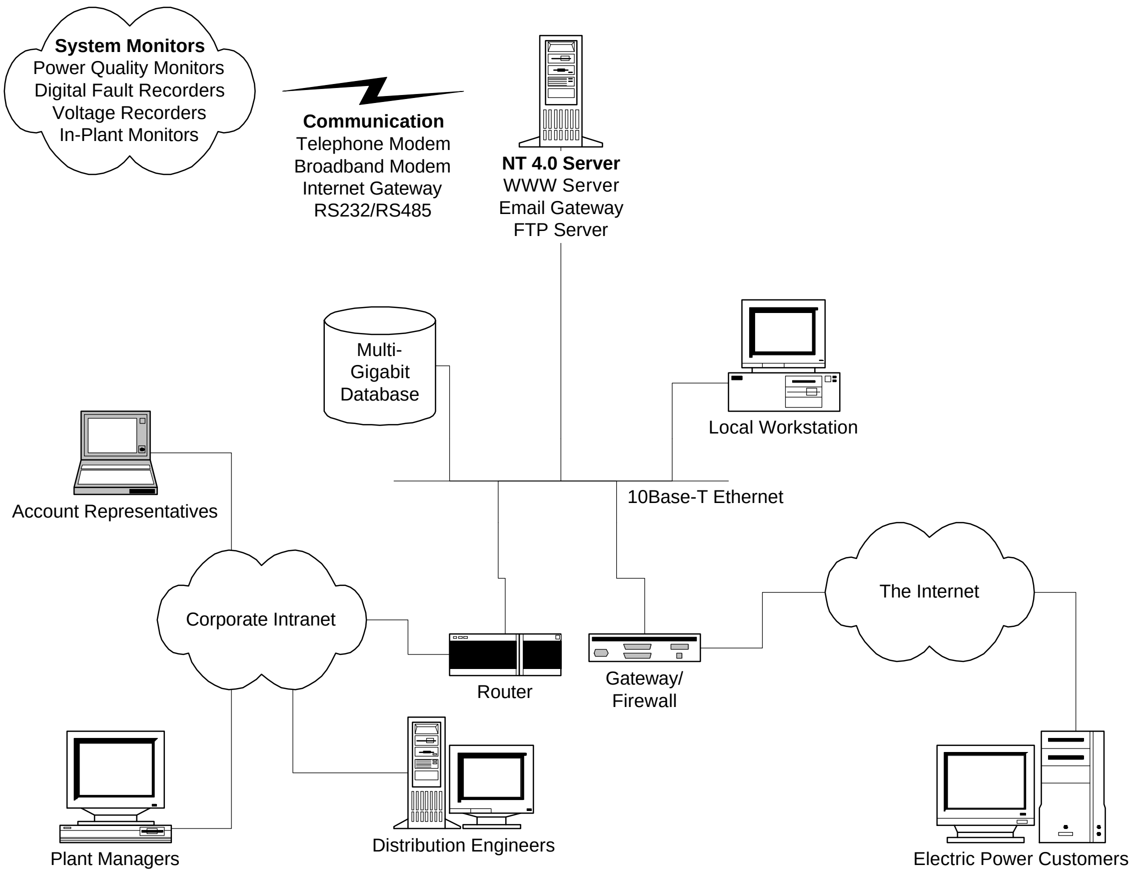


Figure 1: Advanced Configuration for a Power Quality Monitoring System

At the heart of the monitoring system is a server computer optimized for database management and analysis. The Microsoft NT 4.0 operating system is proving more than adequate for maintaining World Wide Web and FTP services, email and paging notification, and handling capacity of hundreds of gigabytes of monitoring data.

Easing Data Collection and Analysis

The data collected during the EPRI DPQ Project was enormous, considering the technology available to us at the project's onset. Its analysis would have been an all but insurmountable task without a software system for automatically characterizing measured events and storing the results in a well-defined database. PQView® is the tool we developed to pull together all of the facets involved in that and other monitoring projects. PQView has now become part of the EPRI Power Quality Diagnostic System (PQDS).

PQDS is a general purpose tool being developed by Electrotek Concepts and funded by EPRI that helps a utility organize the data collection, processing, and analysis tasks associated with power quality issues. It should orchestrate a much more efficient power quality investigation, allowing a power provider better customer support with less work force. A PQDS user will be able to use various modules to help conduct a case study with the results being stored in an Investigation Database. Two modules completed for 1997 included a Measurement Module and an Event Identification Module.

PQView is the PQDS Measurement Module. It fulfills data collection, characterizing, analysis, and reporting roles. This module maintains the database of all monitoring results utilized by the PQDS, including both raw measurement data and data characterized for statistical analysis and reporting. PQView allows a user to create any number of power quality databases and to decide which information should be loaded into a database. This provides flexibility in deciding how to organize the information. The power quality database created and managed by PQView can also include data from other sources, such as site surveys. Input filters have already been developed for PQView to incorporate measurement results from a variety of commonly used instruments and a data interchange format (PQDIF) has been developed to make interfacing with instruments even easier in the future.

With PQView, a power quality investigator can choose from a number of pre-defined charts and reports. For steady-state analysis, PQView provides a *Steady-State Wizard* which can generate both trends and histograms. Figures 2a and 2b provide examples of steady-state analysis. For analyzing sags, swells, and interruptions, we provide *an RMS Variation Analysis Panel* which gives the user flexibility in analyzing and displaying statistical graphs. Figure 2c and 2d furnish illustrations of some rms variation reporting features.

Power quality problems are customer problems. Since customers are an integral part of the power quality equation, it is often vital to include them in the power quality monitoring effort. We have designed the PQView power quality monitoring system to include customer and utility field personnel through direct communication. Although the data management tasks are still performed by PQView's data manager module, the data analysis tasks can be performed by a server computer that accepts remote instructions from a World Wide Web browser such as Netscape™ or Microsoft's Internet Explorer.™ By using a web browser, PQView becomes a multi-platform application, being able to cross boundaries based on incompatible operating systems.

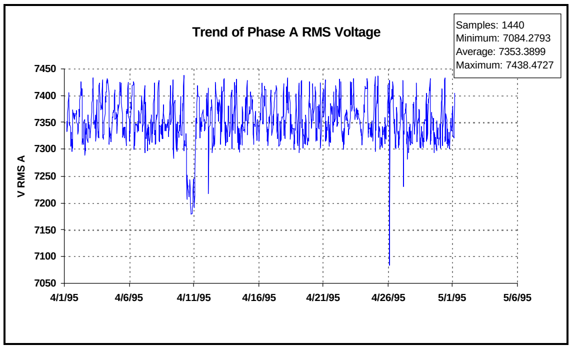


Figure 2a: Trend of Steady-State Sampled Data

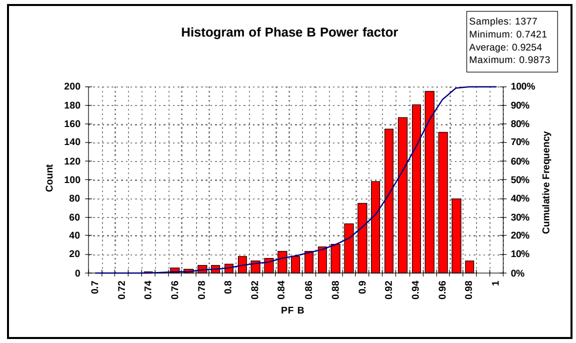


Figure 2b: Histogram of Steady-State Sampled Data

Monitoring Site	Time Stamp	Time Stamp (msec)	Phase	Magnitude (pu)	Duration (cyc)
SITE3	04/02/95 04:11:31	690	A	0.893	4
SITE1	04/03/95 07:13:40	127	C	0.702	5
SITE3	04/04/95 10:31:49	127	B	0.889	12
SITE1	04/04/95 10:57:05	377	A	0.547	5
SITE2	04/05/95 11:15:10	127	A	0.46	4
SITE1	04/08/95 07:35:58	127	C	0.714	15
SITE3	04/08/95 11:09:35	377	A	0.148	162
SITE2	04/08/95 23:30:08	377	A	0.004	117
SITE2	04/09/95 00:07:01	315	B	0.82	6
SITE2	04/09/95 00:49:49	940	C	0.566	2
SITE3	04/10/95 04:55:21	252	A	0.628	5
SITE2	04/12/95 12:35:37	377	C	0.769	2
SITE2	04/14/95 10:22:49	65	A	0.478	4
SITE2	04/15/95 16:12:48	127	C	0.888	3
SITE3	04/18/95 15:40:33	690	A	0.623	3
SITE3	04/18/95 15:44:05	377	B	0.893	5

Figure 2c: Event Summaries

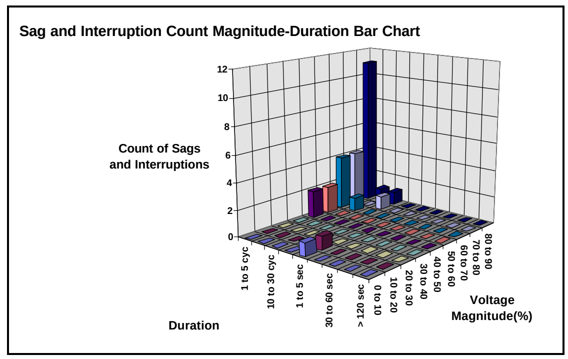


Figure 2d: Voltage Sag Statistical Analysis

Summary

Power quality monitoring is fast becoming an integral component of general distribution system and customer service entrance monitoring. Power producers will integrate power quality monitoring with monitoring for energy management, evaluation of protective device operation, and distribution automation functions. The requirements of instruments for power quality monitoring may dictate more sophisticated instruments than would be required for simple voltage recording or energy use. However, these instruments can incorporate power quality capabilities along with their other functions.

A power quality monitoring system should make use of the wide variety of available networking infrastructure. However, the actual power quality database must be maintained with data in standard formats for comparisons, analysis, and reports. As standards bodies define performance indices for power quality, utilities will want to benchmark system performance using these indices so that they can offer differentiated services for customers that have special requirements.

Communication and customer participation will be an important factor determining the success of a power quality monitoring project. The Internet and the World Wide Web provide an excellent opportunity to involve customers at minimal additional cost to the utility. Try the World Wide Web interface to PView at *www.electrotek.com/pqweb.*