Power Quality Contracts in a Restructured Competitive Electricity Industry

Barry W. Kennedy – Bonneville Power Administration, Portland, OR 97209
Mark McGranaghan – Electrotek Concepts, Knoxville, TN 37923

Abstract. Who will be responsible for the quality of power being delivered in the deregulated utility industry? The characteristics and sensitivity of end use equipment within customer facilities ultimately define power quality requirements. Improving the energy efficiency and productivity of industrial and commercial facilities can sometimes result in the use of technology that either causes power quality problems or is sensitive to power quality variations. Historically, utilities have only gotten involved in power quality problems that they caused to their customers. In the deregulated industry the concepts of utilities and their customers are blurred. What are the power quality requirements at the interface between the transmission company and the distribution company? What is the base level of power quality that must be supplied by the distribution company to the end use customers? What kinds of enhanced power quality services can the energy service company offer to the end use customers? The answers to all of these questions must be developed in terms of the contracts between the different entities resulting from the utility industry deregulation. This paper describes some of the requirements for these contracts and ways of measuring performance to evaluate compliance with the contracts.

The New Structure

The traditional model for an electric utility is a vertically integrated, regulated company that includes generation of electricity, transmission systems, distribution systems, and retail services. The prices and service terms are set by uniform, regulated tariffs that are approved and controlled by a utility regulatory commission. The company is allowed to obtain a specified rate of return on the capital investments in generation, transmission, and distribution required to provide reliable electric service to all the customers.

Figure 1 illustrates the shift in utility structure that is resulting from deregulation. In this new structure, customers will have the option to purchase electricity from a variety of retail marketers, just as you can select from a variety of suppliers for your long distance telephone service. In this model, the price and terms of the electric service will be determined in the competitive marketplace and will be negotiated on a case-by case basis. The retail marketers will have to arrange for the required power supply to meet their contractual requirements, the physical delivery of the electricity (transmission and distribution), and any other services that may be part of their contracts with customers.

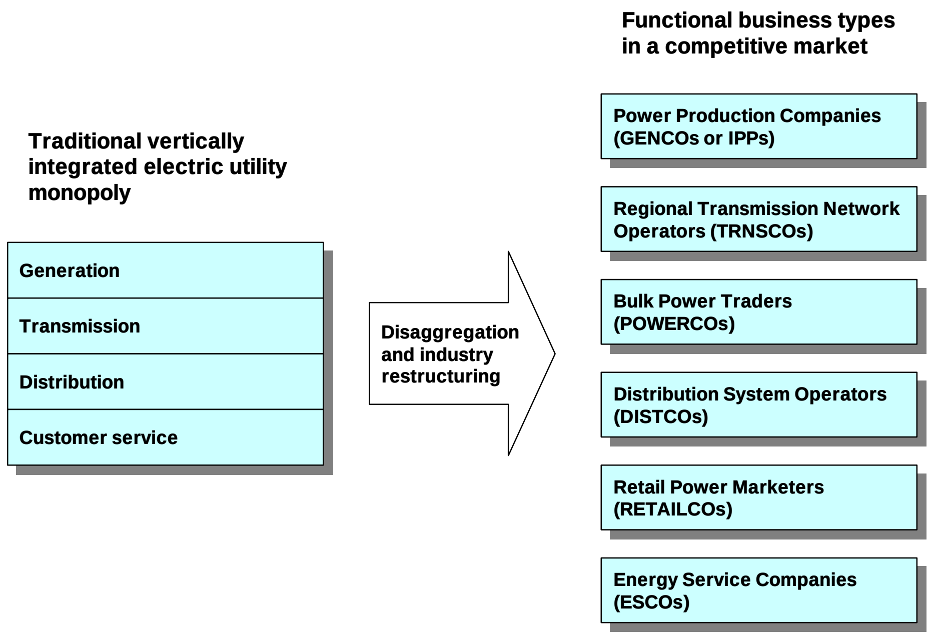


Figure 1. Changes in the utility industry structure resulting from deregulation and competition.

The retail marketer is just one of the separate entities that results from the restructuring. Power production companies (GENCOs or IPPs) will sell power in contracts to bulk power traders. Regional transmission network operators (TRANSCOs) will provide transmission access to get the power to the distribution systems supplying the customers. Finally, distribution companies (DISTCOs) will provide the final delivery of the electricity to individual end use customers. These distribution companies, or lines companies, will likely still be the sole provider of delivery services and the access charges and terms for these services will probably still be regulated.

One interesting result of the new structure is the opportunity for unbundled customer services as new revenue producing opportunities. Utilities are creating unregulated subsidiaries at a tremendous pace in order to tap this potential market for customer services. These business could be part of the retail energy marketing business or they can be separate energy service companies (ESCOs). Evaluation of power quality concerns and implementation of power quality improvement technologies are very clear opportunities for these businesses. Note that these businesses do not hava any geographic boundaries. When technologies and expertise are developed to offer a range of services, the services can be offered worldwide, not just in a traditional service territory. Power quality enhancement is one of these services.

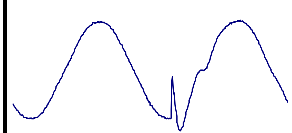
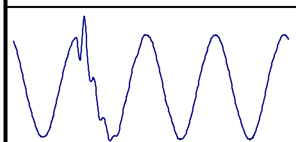
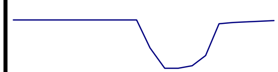
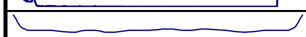
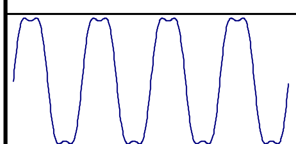
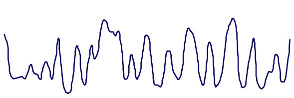
This new model for the electric utility industry creates many needs for contracts between the different entities involved. The contracts will have to address issues of reliability and power quality, as well as the obvious issues of prices and delivery requirements.

Power Quality and Reliability

Obviously, reliability will be a key issue in this restructured utility industry. We must not allow the introduction of competition to create disincentives for maintaining a reliable electric system. In fact, there is significant discussion of performance-based rate structures for the distribution companies or lines companies. But what is reliability?

As competition takes hold, defining reliability and standardizing methods of reporting will be one of the most important tasks facing industry regulators. Methods for characterizing all power quality variations are needed so that system performance can be described in a consistent manner from one utility to another and one system to another. Electric utilities already have standardized *reliability indices* that are used to report on system performance. These indices are based on sustained interruptions that last longer than a certain period (1-5 minutes, depending on the state and the utility). However, there are many power quality variations other than sustained interruptions which can cause misoperation of customer equipment. These include sags, swells, harmonic distortion, transient overvoltages, and steady-state voltage variations (see Table 1).

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

The Electric Power Research Institute (EPRI) has been developing a set of indices which provide a more complete picture of system performance to address the broader definition of reliability. All or some subset of these indices can be used in contracts between suppliers and customers or between companies representing different parts of the system (e.g. transmission and distribution) to define expected system performance. The extent of the system being evaluated will depend on the particular agreement being evaluated (see Figure 2).

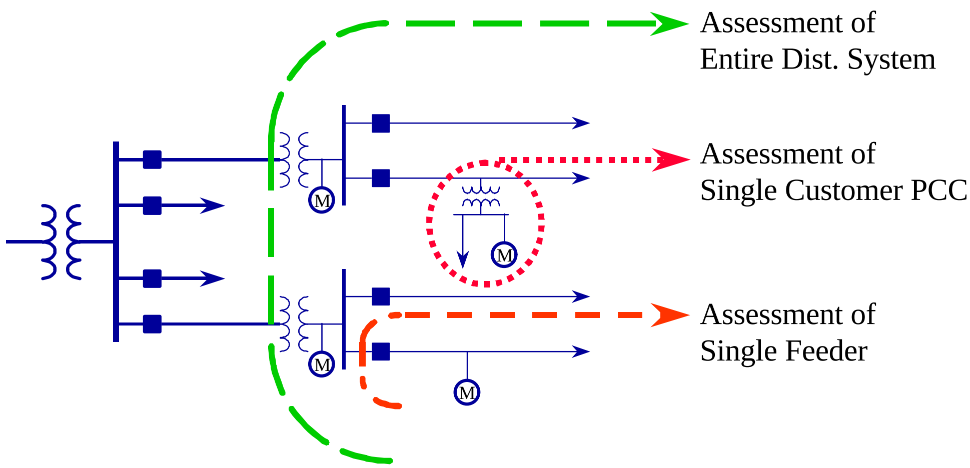


Figure 2. Application of Reliability/Power Quality Indices at Different Levels of the System

One of the most important indices relates to the system voltage sag performance. Voltage sags are typically the most important power quality variations affecting industrial and commercial customers. The IEEE Gold Book (Standard 493-1990) already includes voltage sags in the definition of reliability:

> *Economic evaluation of reliability begins with the establishment of an interruption definition. Such a definition specifies the magnitude of the voltage dip and the minimum duration of such a reduced-voltage period that results in a loss of production or other function of the plant process.*

The most basic index for voltage sag performance is the *System Average RMS (Variation) Frequency Index*$_{voltage}$ (*SARFI*$_x$). *SARFI*$_x$ represents the average number of *specified* short-duration rms variation events that occurred over the monitoring period per customer served from the assessed system. For *SARFI*$_x$, the specified disturbances are those rms variations with a voltage magnitude less than *x* for voltage drops or a magnitude greater than *x* for voltage increases. *SARFI*$_x$ is defined by equation 1.

$$SARFI_x = \frac{\sum N_i}{N_T} \qquad (1)$$

where

$X \equiv$ rms voltage threshold;
possible values - 140, 120, 110, 90, 80, 70, 50, and 10
$N_i \equiv$ number of customers experiencing voltage deviations with magnitudes above X % for $X > 100$ or below X % for $X < 100$ due to event i
$N_T \equiv$ number of customers served from the section of the system to be assessed

$SARFI_x$ is calculated in a similar manner as the System Average Interruption Frequency Index (SAIFI) value that many utilities have calculated for years (proposed IEEE Standard P1366). The two indices are, however, quite different. $SARFI_X$ assesses system performance with regard to short-duration rms variations, whereas, SAIFI assesses only sustained interruptions. $SARFI_X$ can be used to assess the frequency of occurrence of sags, swells, and short-duration interruptions. Furthermore, the inclusion of the index threshold value, *x*, provides a means for assessing sags and swells of varying magnitudes. For example, $SARFI_{70}$ represents the average number of sags below 70% experienced by the average customer served from the assessed system.

SARFI can be broken down into sub-indices by the causes of the events or by the durations of the events. For instance, it may be useful to define an index related to voltage sags that are caused by lightning-induced faults. Indices have been defined for subcategories associated with instantaneous, momentary, and temporary voltage sags, as defined in IEEE 1159.

It is also useful to introduce the concept of aggregated events. Multiple voltage sags often occur together due to reclosing operations of breakers and characteristics of distribution faults. Once a customer process is impacted by a voltage sag, the subsequent sags are often less important. To account for this effect, $SARFI_x$ uses an aggregate event method that results in only one count for multiple sags within a one minute period (aggregation period).

These indices can be estimated based on historical fault performance of transmission and distribution lines but system monitoring is required for accurate assessment of performance at specific system locations. Many utilities (Consolidated Edison, United Illuminating, Northeast Utilities, San Diego Gas & Electric, TVA, Entergy, Baltimore Gas & Electric) have already installed extensive monitoring systems to help characterize system performance on a continuous basis. Detroit Edison and Consumers Power have installed monitoring systems to track performance at specific customers (automotive plants) as part of the contractual requirements associated with serving these customers.

The information obtained using these indices can be valuable for many different purposes. For instance, United Illuminating (UI) has installed power quality monitoring at 92% of their distribution substations and will have all the substations monitored by the end of this quarter. Data from the monitoring is available in real time to customer engineers, protection engineers, and operations engineers through the UI network. The data is used to calculate performance indices that become part of monthly and quarterly reports. SARFI is included as one of UI's company performance drivers along with SAIFI, SAIDI, and CAIDI (interruption-based indices). SARFI-based ranking of substations is used for prioritizing expansion and maintenance. If $SARFI_{90}$ exceeds specified thresholds in any period, a PQ investigation is recommended. In the future, steady state performance indices (voltage regulation, unbalance, harmonics) will also be included.

Other indices are also being defined to characterize steady state voltage regulation, unbalance, flicker levels, harmonic distortion (voltage and current), and transient disturbance performance. Steady state variations are characterized by statistical distributions that define the percentage of time the values are within specified ranges. The 99% and 95% probability levels for these distributions provide good indices for evaluation. Disturbances, like voltage sags and transients, are characterized by the expected number of events per period of time that exceed specified thresholds. Different thresholds are used for different applications.

Requirements for Power Quality Contracts

The requirements of particular power quality contracts and the concerns that must be addressed will depend on the parties involved and the characteristics of the system. These are typical areas that will be addressed in a power quality contract:

- Reliability/power quality concerns to be evaluated
- Performance indices to be used
- Expected level of performance (baseline)
- Penalty for performance outside the expected level and/or incentives for performance better than the expected level (financial penalties, performance-based rates, shared savings, etc.)
- Measurement/calculation methods to verify performance
- Responsibilities for each party in achieving the desired performance
- Responsibilities of the parties for resolving problems

In this section, the most important concerns that should be addressed are summarized for each type of contract. Under each concern, important factors that should be included in the contract are described. Figure 3 illustrates some of the important relationships where power quality considerations will be included in the contracts.

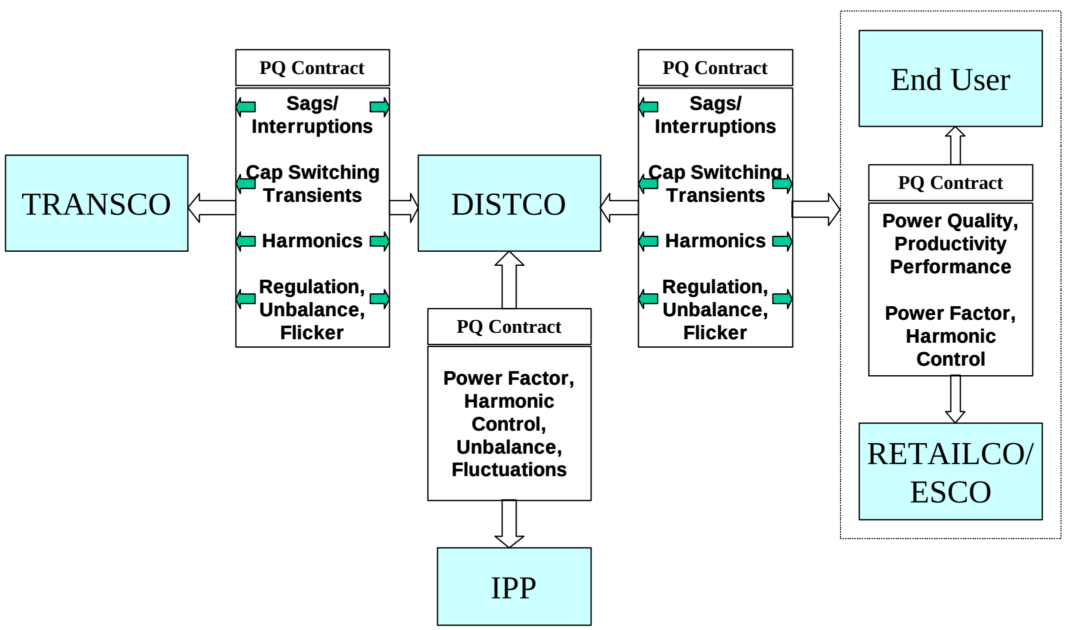


Figure 3. Power quality contracts in the new electric utility industry structure.

Contracts between TRANSCO and DISTCO or Direct Serve Customer

Contracts between transmission companies and distribution companies (or large direct serve customers) will define the power quality requirements and responsibilities at the distribution substation interface between the two systems.

Voltage Regulation, Unbalance, Flicker.
The steady state characteristics of the voltage being supplied by the transmission system should be described. Responsibilities for the voltage regulation between the two companies will be defined. Control of flicker levels requires limits on both parties. The supplying transmission system is responsible for the overall flicker levels in the voltage. However, the distribution company or the direct serve customer is responsible for controlling fluctuating load characteristics. This is particularly important for contracts between the transmission company and a large arc furnace customer.

Harmonic Distortion.
The transmission supply company is responsible for the quality of the voltage being supplied. The distribution company or end use customer is responsible for the harmonic loading of their system. This will typically be defined in terms of harmonic current limits at the point of common coupling, as described in IEEE 519-1992 or similar standard.

Transient Voltages.
Many utilities are applying capacitor banks at the transmission level for system voltage support and to improve power transfer capabilities. Switching these capacitor banks creates transient voltages that can impact distribution systems and end use customers due to magnification or sensitive loads. This problem was encountered in England after deregulation and there was no definition of responsibility for controlling the transient voltages. The transmission company declared that the transient voltages were not excessive and the distribution companies that served the customers declared that the transients causing the problem were being created on the transmission system. With integrated utilities in the United States, these problems are usually solved with switching control in the transmission capacitor banks (synchronous closing or closing resistors). Requirements for control of switching transients should be defined at the point of common coupling (the supply substation) in a power quality contract. Transients from capacitor switching should be limited to very low levels (e.g. less than 1.1 pu) at this point due to their potential for causing problems at lower voltages.

Voltage Sags and Interruptions
Expected voltage sag and interruption performance at the point of common coupling should be defined. It is important to recognize that voltage sags can be caused by faults on the transmission system or faults on the downline distribution system. Contracts that include voltage sag limits between utilities and large customers supplied from the transmission system have already been implemented by Detroit Edison, Consumers Power, and Centerior Electric with the large automotive manufacturing companies. Payments or rate structures that provide compensation for voltage sag and interruption performance outside of the specified levels should be defined.

Contracts between DISTCO and End Users (or End User Representative)

The power quality requirements at the point of common coupling between the distribution system and end use customers must be defined. In some cases, the end user may be a customer of the distribution company. In other cases, the end user may be represented by a retail marketer or an energy service company. The basic power quality requirements at this interface will probably be defined by regulations. However, opportunities for performance-based rates or enhanced power quality service from the distribution system will create the need for more creative contracts.

Voltage Regulation, Unbalance, Flicker.
These steady state characteristics of the voltage being supplied will be defined. Customer requirements to control fluctuating loads, unbalanced loads, and motor starting will be part of this contract.

Harmonic Distortion.
IEEE 519-1992 describes the split of responsibility between the customer and the distribution system supplier in controlling harmonic distortion levels. The distribution company is responsible for the voltage distortion and the customer is responsible for harmonic currents being created by nonlinear loads within the facility.

Transient Voltages.
Capacitor switching transients could be important due to their impact on sensitive loads. The distribution system supplier should control the capacitor switching transient magnitudes but the customer should be responsible for avoiding magnification problems created by power factor correction capacitors within the facility. Basic requirements and responsibilities for surge suppression should also be defined to avoid problems with high frequency transients associated with lightning.

Voltage Sags and Interruptions
The contract should define expected voltage sag and interruption performance. This is an area where enhanced performance options may be offered in cases where it may be more economical to improve performance through modifications or power conditioning equipment applied at the distribution system level.

Contracts between RETAILCO or ESCO and End User

The retail energy marketer or the energy service company will have separate contracts with the end use customers. These contracts may be much more creative and complicated than the contract that defines the basic distribution company interface with the customer. The energy service company may offer a whole range of services for improving the power quality, efficiency, and productivity that dictate the contract requirements. A couple of categories that are of particular interest are discussed here.

Enhanced Power Quality Requirements to Improve Productivity.
At this level, the power quality requirements must be defined in terms of the characteristics of the equipment being used within the facility. The power quality may be defined in terms of the performance of the process, rather than the electrical characteristics of the voltage and the current. The energy service company can take responsibility for the interface with the distribution company and provide the necessary power conditioning to assure proper operation of the facility. Payment terms for this power quality guarantee can be in terms of shared savings from improved productivity (similar to many contracts that specify payments to energy service companies from the shared savings of energy efficiency improvements) or they can be fixed payments based on the power quality improvement requirements.

Power Factor and Harmonic Control.
The supplying distribution system will have requirements for harmonic control that must be met by the customer. The tariffs for the distribution system supply will probably also include power factor penalties. The retail energy marketer or the energy service company will have to deal with these requirements, possibly integrating harmonic control and power factor correction with power conditioning equipment for voltage sag and transient control.

Contracts between DISTCO and Small IPP

Deregulation also creates more opportunities for small independent power producers (IPPs) to generate and sell electricity. Many of these smaller producers may be located on distribution systems, creating a need to define the power quality requirements for this interface (along with protection and reliability requirements). The power quality contracts will define the expected power quality that the IPP can expect at the interface (similar to the contract with end users) and will define the requirements for the IPP in terms of the quality of the generated power. Important areas to consider for the IPP requirements are the power fluctuations (e.g. startup for motor/generator systems, power fluctuations for wind or photovoltaic systems), harmonic characteristics of the generated current, power factor characteristics, balance.

Monitoring and Analysis to Evaluate Compliance

Power quality contracts will require some means of evaluating compliance. This will usually involve a combination of system monitoring and analytical tools. System monitoring is required to accurately assess system performance but this is just one of the important objectives for a system monitoring project.

1. **Monitoring to characterize system performance.** This is the most general requirement. System performance must first be determined to establish baseline power quality levels. System characterization is a *proactive* approach to power quality monitoring. Once baseline characteristics are determined, ongoing performance measurements are used to identify problem areas and assure that adequate performance is maintained.
2. **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.
3. **Monitoring as part of an enhanced power quality service.** Enhanced power quality services will be part of the service offerings of many retail marketers (RETAILCOs) and energy service companies (ESCOs). Performance-based rates may also be built into the contracts with distribution companies (DISTCOs) or transmission companies (TRANSCOs). 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 supplier achieves contracted levels of power quality.

Equipment Requirements

The monitoring equipment requirements will depend on the specific power quality variations that must be characterized to evaluate system performance. Some important requirements are summarized as a function of the type of power quality variation in Table 2.

Table 2. Equipment Requirements for Various Types of PQ Variations

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

With the extent of the monitoring requirements continually increasing, it is becoming imperative to automate the data collection functions and provide easy-to-use data analysis and reporting features as part of the overall system. The system should have automatic downloading of data and characterizing of the data into a database that can be used for data analysis purposes. Data should be available to w wide variety of people – the World Wide Web provides a convenient mechanism for this purpose.

Figure 4 illustrates a system monitoring configuration that takes advantage of the World Wide Web for data access (either intranet for internal access or internet for ecternal access). 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.

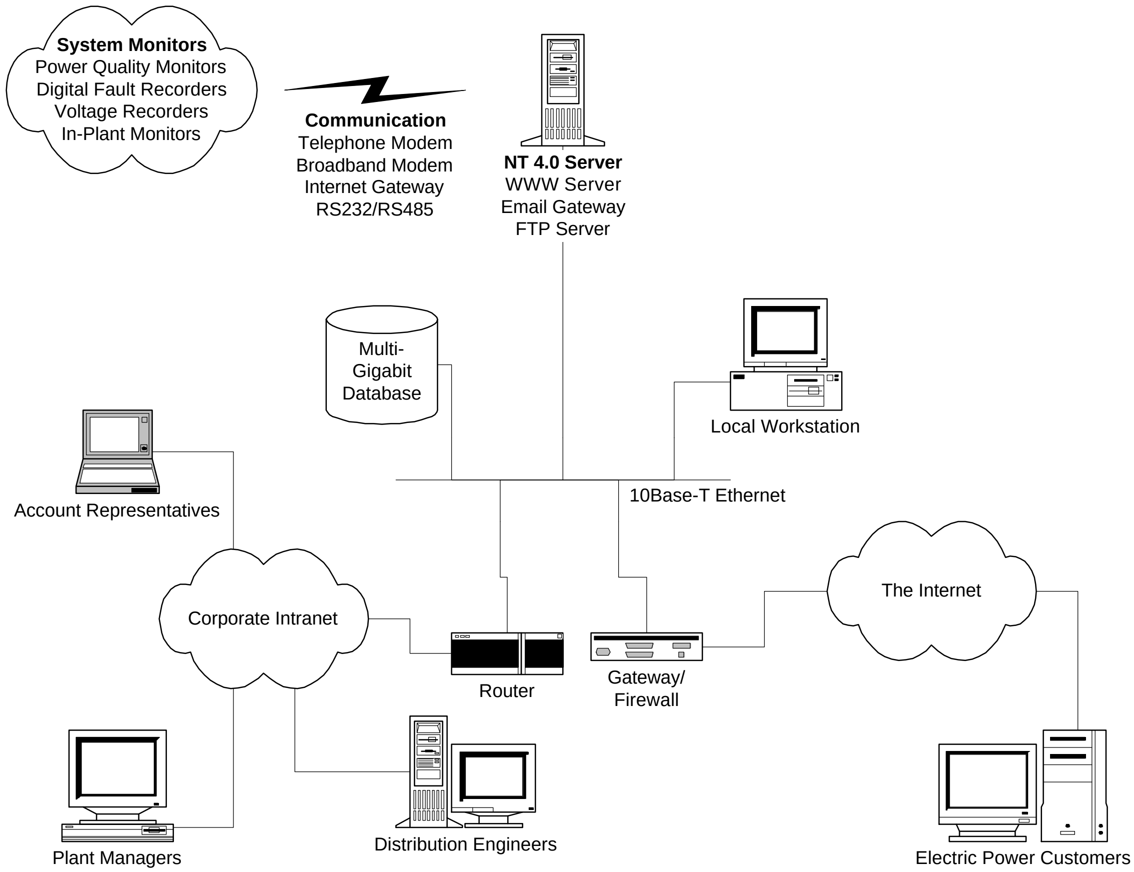


Figure 4: Configuration for a System Type Power Quality Monitoring System

Data Analysis Functions

Once the data has been collected, it must be analyzed and presented in summary form for evaluation of contract compliance. In order to facilitate changing hardware capabilities, the system should be able to characterize data from a variety of different monitoring devices. Electrotek and EPRI have developed a data interchange format (PQDIF) to facilitate data collection and data analysis from different kinds of instruments.

Figure 5 illustrates different kinds of data reporting features that can be used for both steady-state power quality variations (trends and histograms) and disturbances (event lists, summary histograms, performance indices). These kinds of reports can be made available via a World Wide Web interface for sharing with field personnel or customers as part of a power quality contract performance evaluation and verification effort.

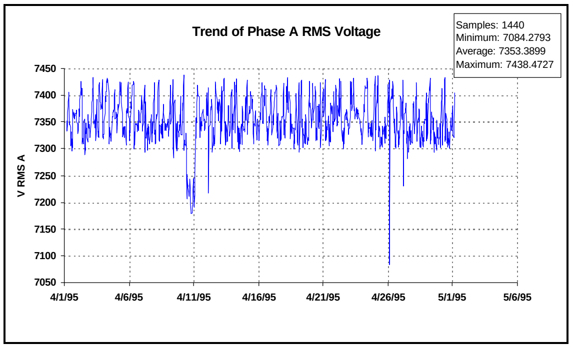


Figure 5a: Trend of Steady-State Sampled Data

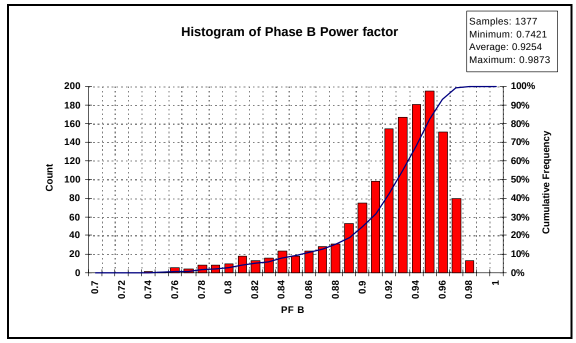


Figure 5b: Histogram of Steady-State Sampled Data

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 5c: Event Summaries

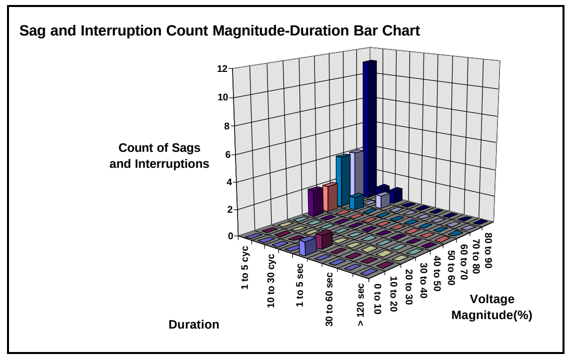


Figure 5d: Voltage Sag Statistical Analysis

Analytical Methods

It may not be practical to install monitoring equipment at every customer or every location of interest on the system. In these cases, it is possible to use simulation techniques to estimate the power quality characteristics at system locations that are not specifically being monitored. The simulations can be used to essentially perform a state estimation function with input from the power quality monitoring results that are available. Figure 6 illustrates this approach in block diagram form. Using this state estimation technique, power quality performance indices can be calculated for any system location.

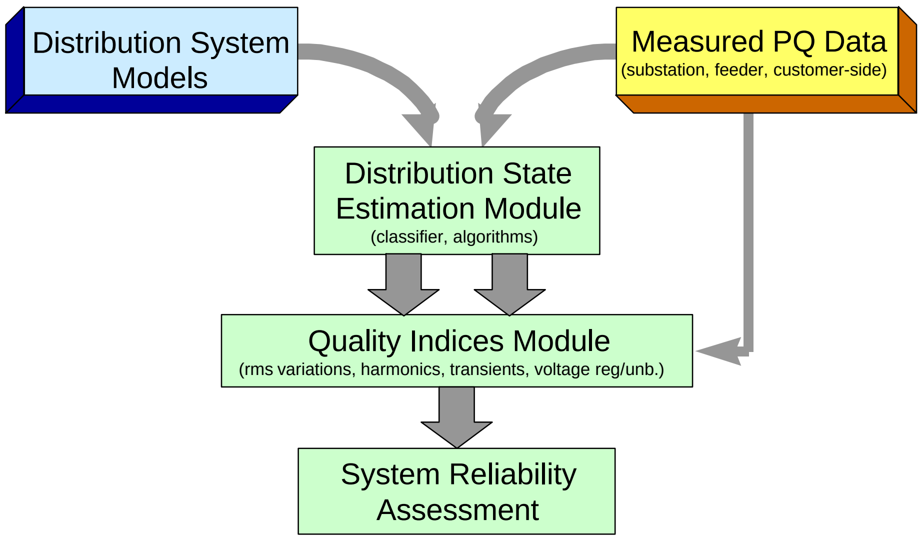


Figure 6. Block diagram illustrating state estimator approach to calculate system performance indices.

Summary

Basic power quality requirements will have to be regulated. As deregulation takes over the industry, the temptation to let the level of service and investment in the system deteriorate is obvious. Regulators will want to prevent this be requiring some basic level of quality and reliability. Indices are being developed and standardized to facilitate the characterizing of power quality levels on the system (IEEE 1159-1992 provided a starting point by standardizing the definitions). EPRI recently completed a 2 year monitoring project to provide benchmark indices describing power quality levels on distribution systems in the United States. The Europeans have already started the process with the Euronorms (EN50160) that define levels of power quality that can be expected in a number of important categories (harmonics, flicker, regulation, unbalance, disturbances).

Utilities will have to report power quality performance statistics and make sure that the performance does not significantly deteriorate over time. The regulations governing power quality will be part of the overall regulations for operating the distribution part of the electricity supply business (often called the lines company). This will require more system monitoring and analytical tools to predict performance as part of the system design process.

The regulations will only address a base level of power quality and will probably be evaluated on a system-wide basis. They will not change the need for power quality investigations and services that are targeted to individual customers. Opportunities for enhanced power quality options and performance-based rates will be created for the distribution companies and opportunities for a wide variety of services related to power quality and energy efficiency improvement are already being created for retail energy marketing companies and energy service companies. These new services and rate structures require standard definitions and performance measures that can be used in contracts and performance evaluations.