Reliability and Power Quality Indices for Premium Power Contracts

Mark McGranaghan   Daniel Brooks
Electrotek Concepts, Inc.
Phone 423-470-9222, Fax 423-470-9223, email markm@electrotek.com
408 North Cedar Bluff Road, Suite 500
Knoxville, Tennessee 37923

Abstract

Deregulation creates new opportunities for utilities to offer premium services to customers. The premium services can be justified based on better customer service for important customers or as a means to generate additional revenues from the existing customer base. One of the premium services being considered by many utilities is an enhanced power quality service. This service will provide a higher level of power quality for customers with equipment sensitive to momentary voltage variations, such as momentary interruptions and voltage sags. Offering such a service requires a means of characterizing the system performance. This paper describes indices and a methodology developed to characterize system power quality levels. An example of applying this methodology as part of a premium service contract is also described.

Introduction

What is reliability? As competition in the utility industry takes hold, defining reliability and standardizing methods of reporting on reliability will be one of the most important tasks facing industry regulators. Electric utilities have developed a variety of *reliability indices* that are used to report on system performance to reliability councils. These indices are based on sustained interruptions (different utilities use different definitions for a sustained interruption but it is usually somewhere in the range of one to five minutes).

However, there are many power quality variations other than sustained interruptions which can cause misoperation of customer equipment. Variations such as sags, swells, harmonic distortion, transient overvoltages, and steady-state voltage variations all need to be considered and coordinated with the specifications for equipment operation. A working group in IEEE was organized specifically for this purpose (IEEE P1346) and has already developed guidelines for evaluating the compatibility of equipment operation with the expected voltage sag performance of the power system.

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. EPRI has sponsored a project to develop a draft set of indices that could be used for this purpose and a methodology for calculating the indices (Reliability Benchmarking Methodology - RBM).

For purposes of this discussion, let's focus on voltage sags. 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.*

Voltage sags are generally the most important power quality variations affecting industrial and commercial customers. Characterizing voltage sag performance has become increasingly important as industries have automated their processes and become more dependent on sophisticated electronic equipment. Costs associated with a voltage sag event can range from tens of thousands of dollars at a plastics plant to millions of dollars at a semiconductor manufacturing facility. How can we describe the system performance so that customers can make economic evaluations of power conditioning requirements and evaluate alternative power supply proposals?

Indices for Voltage Sag Performance

In defining indices for assessing voltage sag performance, we can use the work that has already been done in IEEE to define indices for both sustained and momentary interruption performance. These indices have been used by utilities for years, although they are just being standardized by the IEEE. They are included in the proposed IEEE Standard 1366.

We should also work to coordinate the definitions used for these indices with the definitions in IEEE Standard 1159-1995*, Recommended Practice on Monitoring Electric Power Quality.* A sustained interruption is defined as a reduction in the rms voltage to less than 10% of nominal voltage for longer than 1 minute. P1366 uses 5 minutes for this definition.

The most basic index for voltage sag performance is described below. It provides the basis for most of the other indices as well.

System Average RMS (Variation) Frequency Index$_{Voltage}$ ($SARFI_x$)

$SARFI_x$ represents the average number of *specified* short-duration rms variation measurement 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 the equation:

$$SARFI_x = \frac{\sum N_i}{N_T}$$

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 measurement 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. 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.

Figure 1 is a summary of SARFI levels for an example customer that can then be used to evaluate different methods of improving performance of a facility. The levels shown in Figure 1 are divided into voltage sags that are caused by faults on the distribution system and faults on the transmission system – this can be very important if a static switch is being considered as one of the power quality improvement technologies. The levels shown in Figure 1 are for a specific customer but the levels are inline with the average performance numbers found in the EPRI DPQ project.

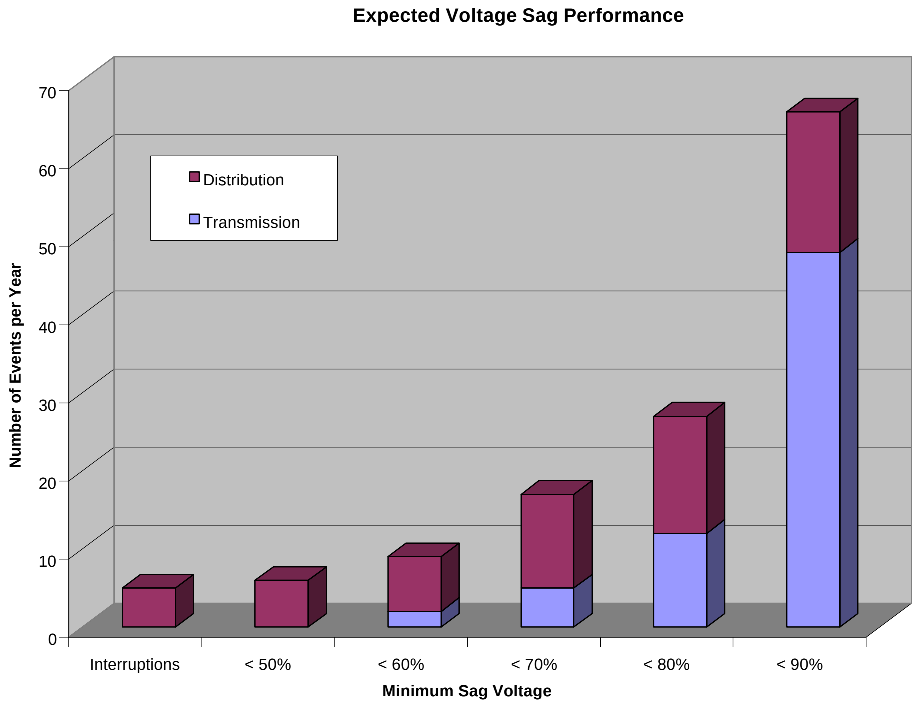


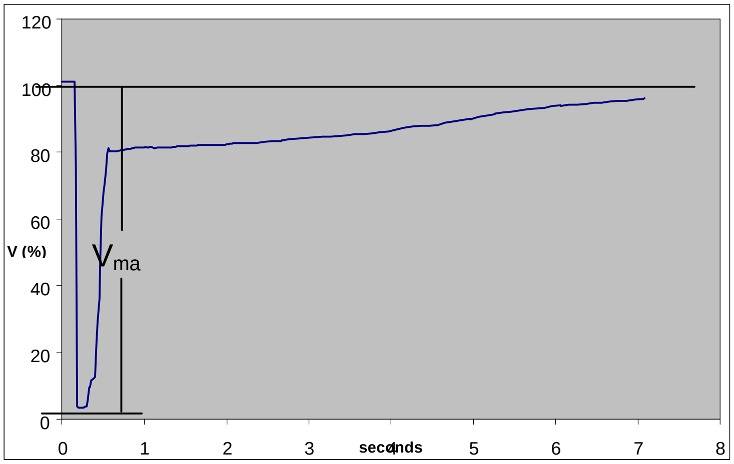
Figure 1. Voltage Sag Performance at an Example Customer

Important Characteristics of Voltage Sags

The basic SARFI calculation described above focuses on the minimum magnitude of the voltage during the sag. However, other characteristics of the voltage sag can be important in terms of the impact on customer equipment and the effectiveness of remedial measures.

Characterizing the magnitude and duration

Most methods for characterizing the voltage sag magnitude use the maximum deviation magnitude of the measurement. This method is illustrated by the measurement shown in Figure 2. Notice that the magnitude, V_{mag}, is assigned as the maximum deviation from nominal without regard to the duration of the event. This is also the technique recommended by the EPRI RBM.



F

Figure 2. Characterization of the sag magnitude for an example measurement.

Duration of the sag can also be important. IEEE Std. 1159 provides convenient duration categories for classifying voltage sags (instantaneous, momentary, and temporary) but does not define the methodology for determining the duration. There is currently an IEEE 1159 task force charged with developing these methodologies. Consider the duration to be assigned to the sag shown in Figure 2. Some methods suggest that the duration assigned to the dip should be the time period for which the voltage is below the 90% threshold (T_{dip} shown in Figure 3). Other methods suggest that if the dip is non-rectangular, the duration should be only the time period associated with rectangular component for which the magnitude is assigned.

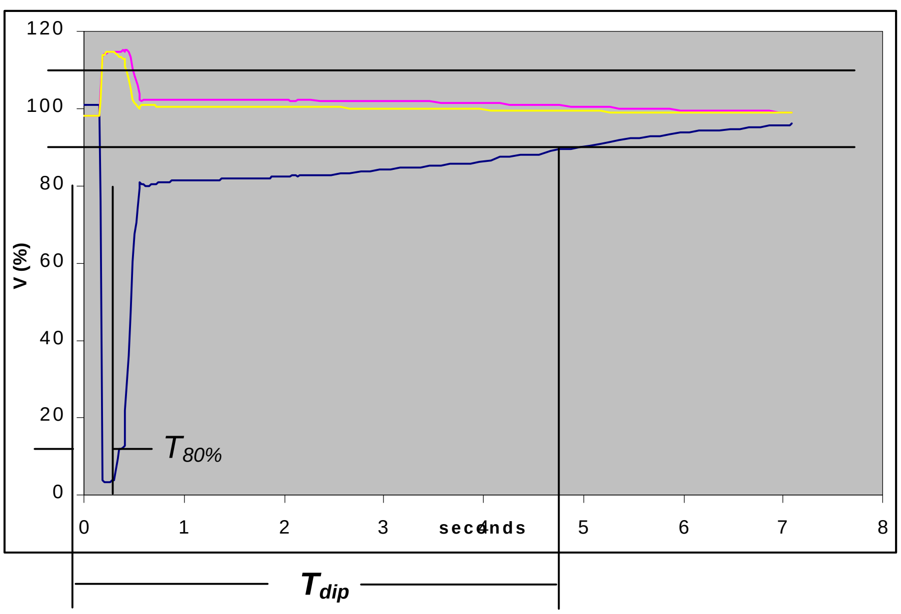


Figure 3. Three-phase, non-rectangular rms variation measurement comparing the characterized duration using the UNIPEDE method and the time below threshold method.

The EPRI RBM method for characterizing rms variation duration is called the "Time Below Specified Voltage Threshold" method. *This method designates the duration as the period of time that the rms voltage is below a specified voltage threshold level used to assess the disturbance*. Thus, the assigned duration of a given non-rectangular rms variation will differ depending on the specified voltage threshold being used for assessment. Using this method, the duration of the dip shown in Figure 3 would be $T_{80\%}$. Figure 4 illustrates the "Time Below Specified Voltage Threshold" method for a single-phase rms variation measurement assessed at three voltage levels; 80%, 50%, and 10%.

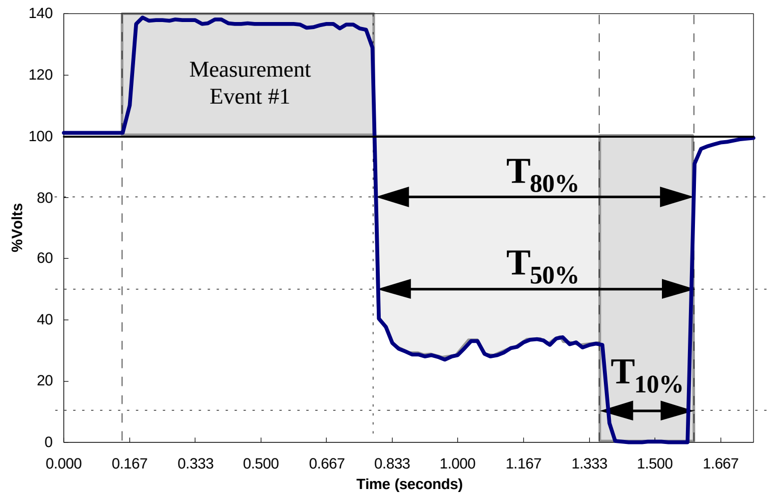


Figure 4. Illustration of "Time Below Specified Voltage Threshold" characterization of rms variation duration.

The Concept of Aggregation

A single three-phase fault at the distribution level can result in multiple rms variation measurements, which in turn can be counted in many ways. The resulting count of the number of rms variations associated with a single fault can vary from one to tens depending on the counting method used. Consequently, when counting sags for the purpose of mediating service contracts, it is necessary that a tabulation method be used which is equitable to both the utility and the customer.

Measurement aggregation is the process of representing multiple measurements associated with a single power system event as a single measurement. The intent of measurement aggregation is to relate the disturbance events to the possible impacts on a facility. Figure 5 shows the rms variation measurements that would be recorded as a result of the semi-permanent three-phase fault shown on the medium voltage system of Figure 5. The proper operation of the network protective system (sequencing of the recloser used to isolate the fault from the network), result in multiple voltage sag measurements upline of the operating recloser. Assume that the recloser sequences twice before locking out, resulting in two three-phase sags. The number of voltage sags associated with this single fault varies drastically depending on how the measurements are aggregated.

Any monitored customer service upline of the operating recloser could count as many as six voltage sags resulting from the one three-phase fault illustrated in Figure 5. Counting each phase measurement as an individual voltage sag, the two three-phase measurements result in six sags. However, the event is only likely to impact customer processes one time.

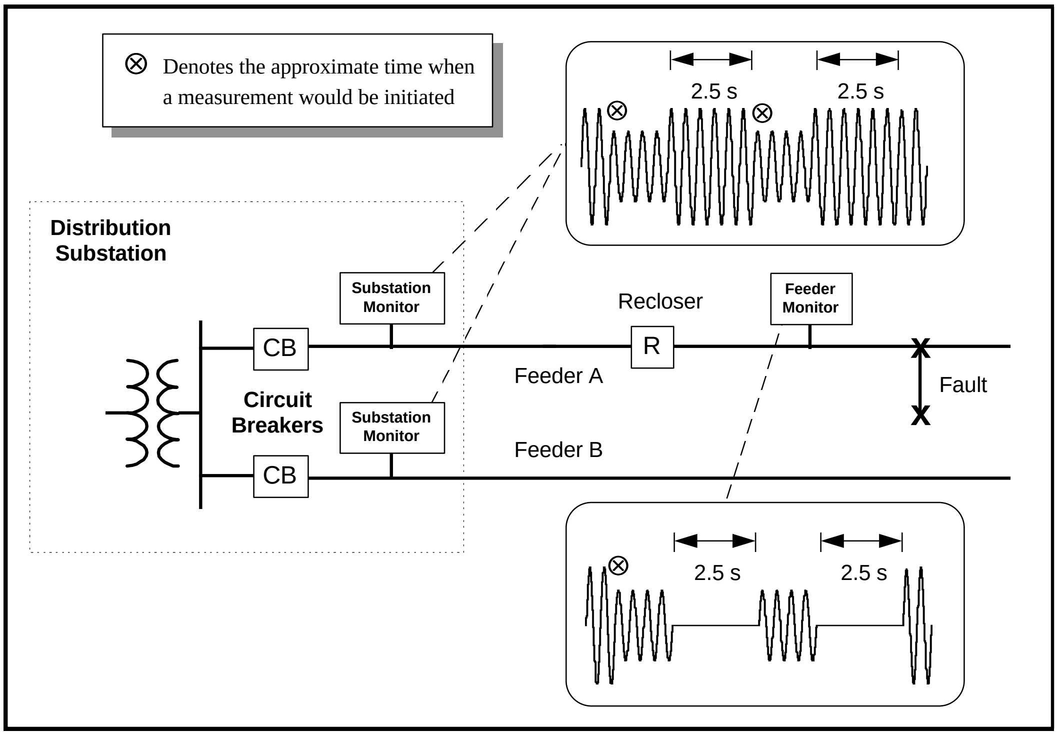


Figure 5. Illustration of rms variation measurements resulting from a three-phase fault at the MV level.

The EPRI RBM Indices define aggregation at three levels for the purpose of characterizing voltage sags.

Component Level. Aggregation at the component level is the process of assigning a single magnitude-duration set to a single phase measurement which may or may not consist of multiple rectangular components. For instance, the event in Figure 2 has two components. The first is a short sag with a minimum magnitude of close to zero. The second component has a minimum magnitude of about 80% and lasts much longer as the voltage recovers. The EPRI RBM use the minimum magnitude during the whole event to characterize the voltage sag magnitude but the duration is the duration below a specified threshold.

Measurement Level. Aggregation at the measurement level is the assignment of a single magnitude-duration set to represent all of the phase measurements comprising a multi-phase measurement. With this aggregation, an event that affects all three phases does not get counted as three events. The number of phases affected can be important. This is handled by defining sub-indices with characteristics such as the number of phases impacted during the voltage sag.

Temporal Level. Aggregation at the temporal level is the process of assigning a single magnitude-duration set to represent all of the three-phase measurements resulting from a single power system occurrence. Figure 5 illustrates how a single distribution system three-phase fault can result in multiple sag measurements being recorded by the same monitor. Temporal aggregation summarizes multiple measurements associated with a single originating event into a single set of characteristics (magnitude, duration, etc.). Many different time periods could be appropriate for temporal aggregation, depending on the customer processes and equipment that could be impacted. For the RBM indices, an aggregation period of one minute is used (corresponds to the IEEE 1159 definition of the minimum duration for a sustained interruption). Other aggregation periods could be appropriate for specific contracts. The voltage sag is characterized by the minimum voltage magnitude during the entire aggregation period.

Example Application of Voltage Sag Indices for Premium Service Contracts

Detroit Edison and other utilities have developed service contracts with major customers that include consideration of voltage sags in their performance requirements.

Rather that use just a frequency of occurrence index based on the magnitude of a voltage dip, Detroit Edison calculates a voltage dip score for its customer monitoring points. This metric takes into account the voltage lossed on each of the three phases. The calculation uses a 15 minute aggregation period for the calculations due to the characteristics of the large loads that are impacted by these events. This index is defined as follows:

$$DIPScore = \sum_{i} \frac{3 - \sum_{p=1}^{3} V_{i\,p}}{3}$$

where

i ≡ dip event number occurring during assessment period
$V_{I\,p}$ ≡ phase voltage magnitude for the three-phase dip measurement event i

Detroit Edison compares the DIPScore for a given customer site with a target value developed from a combination of historical monitoring data and the sensitivity of the customer processes. This measure allows Detroit Edison to mediate its Special Manufacturing Contracts.

The Role of System Monitoring

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, Consumers Power, Southern California Edison, Carolina Power & Light) have already installed extensive monitoring systems to help characterize system performance on a continuous basis. Detroit Edison, Consumers Power, and First Energy 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. A customer survey at United Illuminating found that commercial and industrial customers consider PQ as the second highest service priority. UI found that the customer concerns were based on a perception of poor PQ rather than quantified assessment. In response to this perception, UI has installed power quality monitoring at all of their distribution substations. 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.

We are in for a period of rapid change. Electric utilities need to take a customer focus in everything they do if they are going to survive in the deregulated world. Characterizing system performance in a manner that relates to the impacts on customer equipment is one good example. In order to provide good information about the quality of power being delivered to customers and the causes of disturbances, we need to monitor voltages and currents at least at the system substations and the service entrance to important customers. The substation sites provide basic information that is applicable to all customers connected to the station (voltage sags, some transient information, harmonic distortion at the substation). The customer sites provide more detailed information closer to the actual loads that can be impacted, including the effects of transformer connections, lower voltage capacitors that can cause harmonic resonance and magnification of switching transients, and customer loads. With these sites being monitored, indices can be calculated for characterizing system performance and performance at individual locations for contracts.

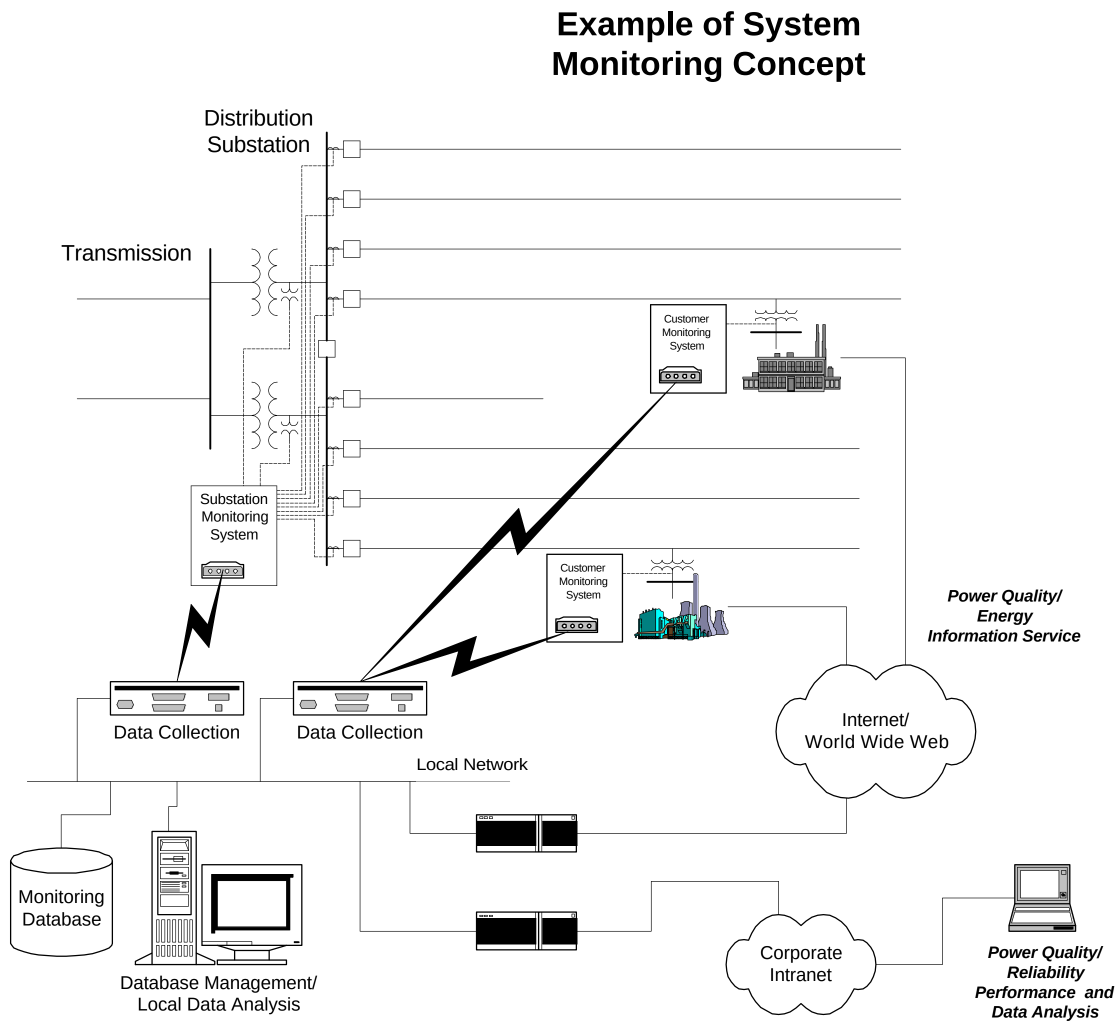


Figure 6. Overview of Power Quality Monitoring System

Many utilities are considering offering premium service contracts to customers that need higher levels of power quality. These contracts start with an information service that provides the customer with summaries of overall power quality levels and specifics of disturbances that may be impacting the process. The technology is already in place for you to collect the data remotely and provide it to the customer in summary form via the World Wide Web. As an initial step, you can provide the information to your customer service personnel and they can interface with the customer. When there are problems with the production process, they can be related to specific power quality conditions. Power conditioning equipment can be optimized and, in the long run, equipment specifications can be improved to prevent problems in the future. When a problem occurs, there is an opportunity to help solve the problem (service opportunity, equipment sales opportunity).

Customers may not be able to justify paying for this service initially but realizing the benefits of improved productivity will justify the value over time.

An information service that starts based on monitoring at the service entrance can be expanded to include monitoring within the facility. Many customers already have sophisticated monitoring systems throughout the facility but they do not have the expertise to review the information or summarize it effectively. This is an opportunity for the power supplier to offer a service that tracks both energy use and power quality throughout the facility and summarizes the information in terms of equipment performance and opportunities for improvement. It may even be possible to structure fees based on savings as was popular with energy service companies in the initial energy efficiency craze.

Summary

Reliability and power quality are closely related. Reliability is really the measure of the ability to provide service that is adequate for customers to operate their facilities. Many customer facilities are sensitive to momentary voltage variations, such as voltage sags, and may even be sensitive to transients, harmonic distortion, and other power quality variations. Indices to characterize these variations are needed so that adequacy of service for customers can be evaluated.

Indices that define power quality performance have been developed. They are already being used by many utilities to characterize their own system performance and some utilities are already using them to evaluate performance with respect to contracts with individual customers. The indices are absolutely essential in order to offer enhanced power quality services that many utilities are considering under deregulation.

The first step is to understand the performance of the existing system. Many utilities have put monitoring systems in that allow them to characterize the system power quality performance on a continuous basis. With an accurate picture of existing performance, contracts that define performance requirements are very realistic and can be developed without unnecessary risk.