Development of a Framework for a Service Quality Index

Technical Report

Development of a Framework for a Service Quality Index

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PRODUCT DESCRIPTION

This report describes a service quality index that may be more appropriate than traditional reliability indices for assessing the quality of power delivered to customers. The framework for this index, described in this report, provides an indication of performance that combines traditional reliability characteristics with power quality characteristics that also can affect customer operations.

Results & Findings

There are important characteristics of service quality that are not represented with traditional reliability indices. Indices like the System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI) provide basic information about service quality that is important to all customers. However, many customers also are sensitive to momentary interruptions and voltage sags and may even be impacted by steady state power quality characteristics like harmonic distortion levels in some cases. The proposed service quality index provides a more complete picture of service quality by combining important power quality characteristics with reliability levels and then providing a means of assessing the economic impacts to typical groups of customers.

Challenges & Objectives

Most utilities maintain detailed information about the reliability of service to customers. Historical data about number of interruptions and minutes interrupted can be calculated for most customers. However, actual economic impacts to customer operations may depend on characteristics other than interruptions that last longer than five (5) minutes. As a result, customer satisfaction may not correlate well with traditional reliability indices. This project's main objective was development of a service quality index framework that will provide the basis for a better assessment of the quality of power delivered to important customers. The framework for new service quality indices evaluates two categories of improvements to traditional reliability indices:

1. Characterization of all service quality parameters that can impact customer operations. Typically, this will include at least momentary interruptions and voltage sags along with longer interruptions. A method of including basic quality characteristics also is needed.
2. Better statistical characterization of performance so that customers can understand the risk of quality variations as a function of severity. This is needed to understand the expected economic impacts of the quality variations over time.

The resulting index can be combined with customer characteristics to assess actual economic impacts associated with the quality of service provided. These characteristics of service should have a much closer relationship with customer satisfaction.

Applications, Values & Use

The proposed service quality index is designed to better assess the quality of power delivered to customers. The index can be related to actual economic impacts experienced by different groups of customers and should provide a better measure of performance related to customer satisfaction than previous indices. The work in 2004 developed the basic framework for the service quality index, and continuing work in 2005 will assess the application for actual distribution system supply characteristics.

EPRI Perspective

The framework for a service quality index developed in this report builds on previous EPRI research evaluating important characteristics of reliability and power quality that can affect customer operations. Previous research developed a knowledge base about the sensitivity of customer equipment and processes to power quality variations as well as options for improvements. This report provides a consolidated framework for characterizing the performance of the supply system based on this knowledge and can be a valuable tool in developing priorities for system investment, premium power offerings, and customer services. The statistical characterization procedures provide the basis for more accurately assessing economic impacts to customers and evaluating benefits of system investments.

Approach

The project team's objective was to develop a service quality index framework that more accurately assesses the impact of service quality variations on customers and, therefore, is more likely to correlate with customer satisfaction. The team first identified different quality characteristics that can affect customer operations. These characteristics are divided into two general categories:

1. Steady state power quality characteristics. These characteristics include voltage regulation, harmonic distortion, unbalance, and flicker. These characteristics need to be within certain ranges to make sure that customer equipment is not affected.
2. Disturbances. These events can cause immediate impacts to customer equipment and operations. This report focuses on voltage sags, momentary interruptions, and long interruptions (reliability).

The relative importance of the different quality characteristics is based on typical economic impacts that customers experience. Standard methods of characterizing performance in these different categories are presented. These methods include statistical characterization approaches because all of these quantities vary significantly with time and system characteristics. The overall service quality index is developed by combining individual characteristics with appropriate weighting values. The project team will evaluate the combined index in more detail in 2005 with actual application examples.

Keywords

Power quality
Reliability
Performance indices
Customer satisfaction

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1
INTRODUCTION – WHY DEVELOP A SERVICE QUALITY INDEX?

Introduction

Customer equipment and processes continue to become more dependent on reliable and quality power. As a result, customer satisfaction is determined by a complex set of factors that are not adequately characterized with traditional reliability indices.

Utilities do an excellent job of characterizing system reliability and often have programs where executive bonuses are tied to overall system reliability performance. Regulators may establish reliability targets and some regulators have even implemented performance-based rates to help encourage utilities to meet specific targets.

However, customer satisfaction does not usually correlate with overall system reliability and often does not even correlate with the reliability of the specific circuit supplying the customer. Many customers are just as sensitive to momentary interruptions and possibly even voltage sags as they are to longer interruptions that are counted in reliability statistics. Also, customers that are experiencing problems with other types of power quality characteristics, such as excessive voltage distortion or lights flickering, are not likely to be satisfied until these problems are resolved.

There is clearly a need for characterization of system performance in a way that correlates better with the needs and expectations of customers. This report is an attempt to develop such a method – we will call it a *Service Quality Index*. This report describes the framework for such an index. The ongoing work in this research area in 2005 will develop baselines and example applications of the index using data from participating utilities and benchmark data from system surveys, such as the Distribution Power Quality (DPQ) and DPQ II projects [1,2].

The Basic Concept

The basic concept of the Service Quality Index is a measure of system performance that correlates better with the actual needs of customers. This characterization will include the steady state power quality characteristics, as well as important disturbance characteristics that can affect customer equipment and operations. The concept is illustrated in Figure 1-1. These different characteristics of the system performance must be addressed in a way that relates to their impacts on customer equipment and operations. The specifics of how this can be accomplished are discussed in the subsequent sections of this report.

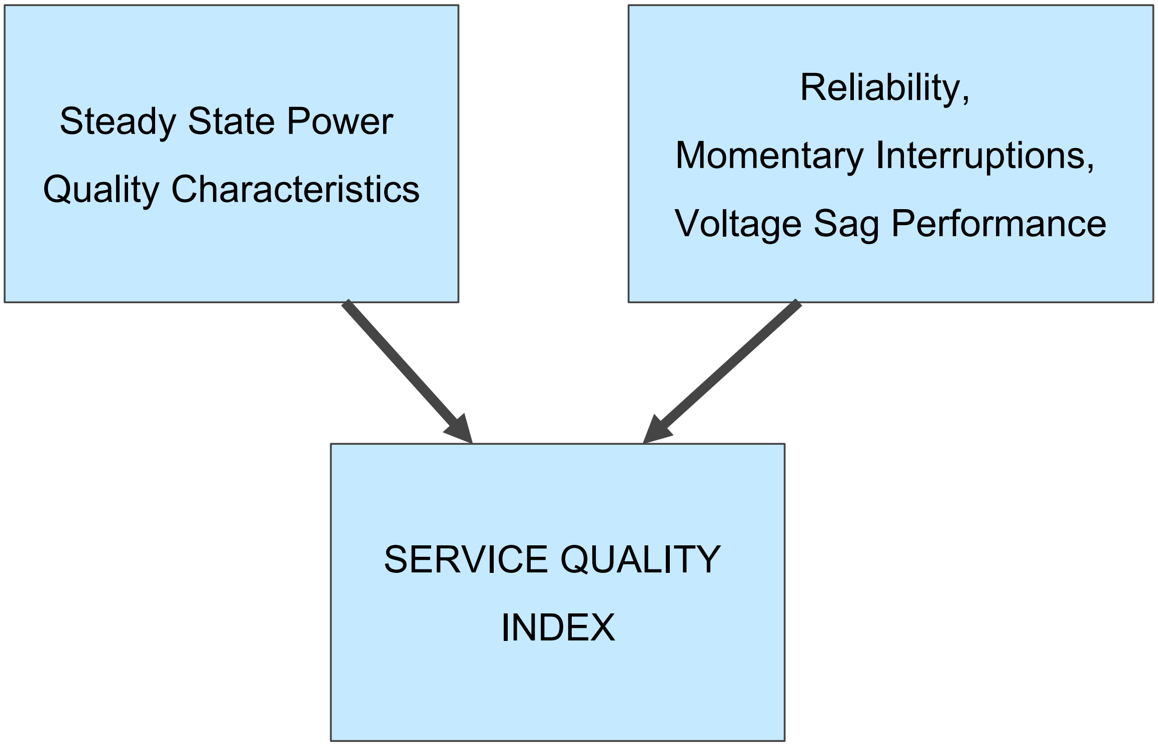

Figure 1-1
Simplified Concept for a Service Quality Index

Important Standards

The Service Quality Index should be based on recognized methods of characterizing the different components of power quality and reliability. This is accomplished by referencing the appropriate standards in each of these areas.

A recent effort by CIGRE/CIRED Working Group C4.07 [3] resulted in a valuable set of recommendations for power quality and reliability indices that are used as a basis for many of the recommendations associated with individual elements of power quality and reliability in this report. Other very important standards are described briefly here and referenced where appropriate in this report.

Reliability

Many indices have been defined as metrics for different aspects of reliability. Today there are in excess of 40 reliability indices in various documents. Some of the most common include SAIFI (System Average Interruption Frequency Index), SAIDI (System Average Interruption Duration Index), CAIDI (Customer Average Interruption Duration Index), and ASAI (Average Service Availability Index). SAIFI and SAIDI are system-oriented measures of frequency and duration of interruptions. CAIDI and ASAI are customer-oriented measures of outage duration (per outage) and fraction of demand satisfied. Definitions and methods for calculating these indices are established in the IEEE 1366 March 2001 Edition, *IEEE Guide for Electric Power Distribution Reliability Indices* [4].

Voltage Quality – Voltage Sags and Momentary Interruptions

Momentary Average Interruption Frequency Index (MAIFI), also defined in IEEE 1366, and the System Average RMS variation Frequency Index (SARFI) are indices often used for quantifying momentary interruptions and sags, respectively. The EPRI Reliability Benchmarking Methodology (RBM) defines an extensive set of service performance indices, including SARFI, which assess all areas of power quality based on monitored data [5].

IEEE Working Group 1564 is defining indices for characterizing voltage sag performance [6]. This work is also being coordinated with similar efforts in CIGRE so that there will be consistent recommended approaches to use worldwide.

Voltage Quality – Steady State Characteristics

The expected steady state voltage quality characteristics are defined in a variety of different standards. The basic international standard that defines the expected voltage quality characteristics is IEC 61000-2-2 [7]. This standard is the basis for many prescriptive standards that have been adopted by regulators around the world. Examples include EN 50160 [8] in Europe and NRS 048 in South Africa [9].

In the United States, there are individual standards for different aspects of steady state power quality. Important standards include:

- ANSI C84.1 [10] for definition of voltage regulation and unbalance characteristics.
- IEEE 519-1992 [11] for definition of harmonic voltage distortion characteristics.
- IEEE 1453 [12] for definition of flicker characteristics. This is a recently approved standard that adopts the international method of characterizing flicker, as defined in IEC 61000-4-15 [13].

Standard for Measuring Voltage Quality and Disturbances

There are two important standards that define the overall requirements of monitoring equipment and measurement methods for characterizing power quality characteristics and disturbances. The IEEE Standard 1159-1995 "Recommended Practice for Monitoring Electric Power Quality" [14] establishes a defined set of power quality disturbances and characteristics to describe the electrical environment in terms of voltage quality. Table 1-1 shows the categories of power quality disturbances with spectral content, typical duration, and typical magnitude. The standard also provides basic guidelines for measurement methods. Ongoing work on the IEEE 1159 Working Group is directed towards more detailed definition of instrumentation requirements and measurement methods.

IEC Standard 61000-4-30 [15] was recently completed and provides detailed requirements for power quality monitoring. It references important individual monitoring standards, such as IEC 61000-4-7 [16] for harmonics and IEC 61000-4-15 [13] for flicker. The standard defines accuracy requirements and specific measurement procedures for each of the power quality characteristics. Most of the indices recommended in this report (at least for steady state power quality characteristics) are based on use of the methods in IEC 61000-4-30 for measurement and calculation of the indices.

Table 1-1
Categories of Power Quality Variation – IEEE 1159-1995

Categories	Spectral Content	Typical Duration	Typical Magnitudes
1.0 Transients			
1.1 Impulsive			
1.1.1 Voltage	> 5 kHz	< 200 µs	
1.1.2 Current	> 5 kHz	< 200 µs	
1.2 Oscillatory			
1.2.1 Low Frequency	< 500 kHz	< 30 cycles	
1.2.2 Medium Frequency	300–2 kHz	< 3 cycles	
1.2.3 High Frequency	> 2 kHz	< 0.5 cycle	
2.0 Short-Duration Variations			
2.1 Sags			
2.1.1 Instantaneous		0.5–30 cycles	0.1–1.0 pu
2.1.2 Momentary		30–120 cycles	0.1–1.0 pu
2.1.3 Temporary		2 sec–2 min	0.1–1.0 pu
2.2 Swells			
2.1.1 Instantaneous		0.5–30 cycles	0.1–1.8 pu
2.1.2 Momentary		30–120 cycles	0.1–1.8 pu
2.1.3 Temporary		2 sec–2 min	0.1–1.8 pu
3.0 Long-Duration Variations			
3.1 Overvoltages		> 2 min	0.1–1.2 pu
3.2 Undervoltages		> 2 min	0.8–1.0 pu
4.0 Interruptions			
4.1 Momentary		< 2 sec	0
4.2 Temporary		2 sec–2 min	0
4.3 Long-Term		> 2 min	0
5.0 Waveform Distortion			
5.2 Voltage	0–100th Harmonic	steady-state	0–20%
5.3 Current	0–100th Harmonic	steady-state	0–100%
6.0 Waveform Notching	0–200 kHz	steady-state	
7.0 Flicker	< 30 Hz	intermittent	0.1–7%
8.0 Noise	0–200 kHz	intermittent	

Organization of the Report

This technical report is intended to provide the basic framework for development of a service quality index that includes both power quality issues and reliability issues that can be important to customers, especially in terms of economic impacts.

This report is organized into 10 chapters:

Chapter 1 provides a basic introduction to the issues being developed and the basic concept of a service quality index.

Chapter 2 outlines the important distinctions between reliability and power quality and why both of these issues can be important for customer satisfaction.

Chapter 3 provides the detailed background for characterizing steady state power quality performance. Important indices are introduced and defined for the individual characteristics that make up steady state power quality – voltage regulation, unbalance, harmonic distortion, and flicker.

Chapter 4 describes the methodology and indices for characterizing reliability. This is typically well-understood by most utilities since this is the one part of service quality that is usually well documented.

Chapter 5 extends the reliability concepts to include voltage sags and momentary interruptions. Important issues to consider when characterizing performance in terms of these important disturbances are discussed.

Chapter 6 describes the statistical methods for characterizing performance, particularly with respect to disturbances – reliability, momentary interruptions, and voltage sags. These statistical methods provide the basis for understanding the normal variations of these quantities and accounting for these normal variations in the indices.

Chapter 7 takes the analysis one step further to include the economic impacts of the disturbances. The concept of using the expected economic impacts as a way to weight the different components of the performance is introduced.

Chapter 8 summarizes the overall approach for combining the different indices into an overall service quality index.

Chapter 9 outlines the next steps for the research. In particular, the application of the proposed approach will be evaluated with actual data in 2005.

Chapter 10 gives the important references used in this research.

2
POWER QUALITY AND RELIABILITY

The proposed Service Quality Index combines reliability with important power quality characteristics. It is worthwhile to review some basic characteristics of reliability and power quality, illustrating the important differences and why the expanded approach is important to customers. Figure 2-1 illustrates the range of different characteristics that need to be considered in terms of the effects on customers. We will describe the important indices used for both reliability and power quality characteristics in the subsequent sections.

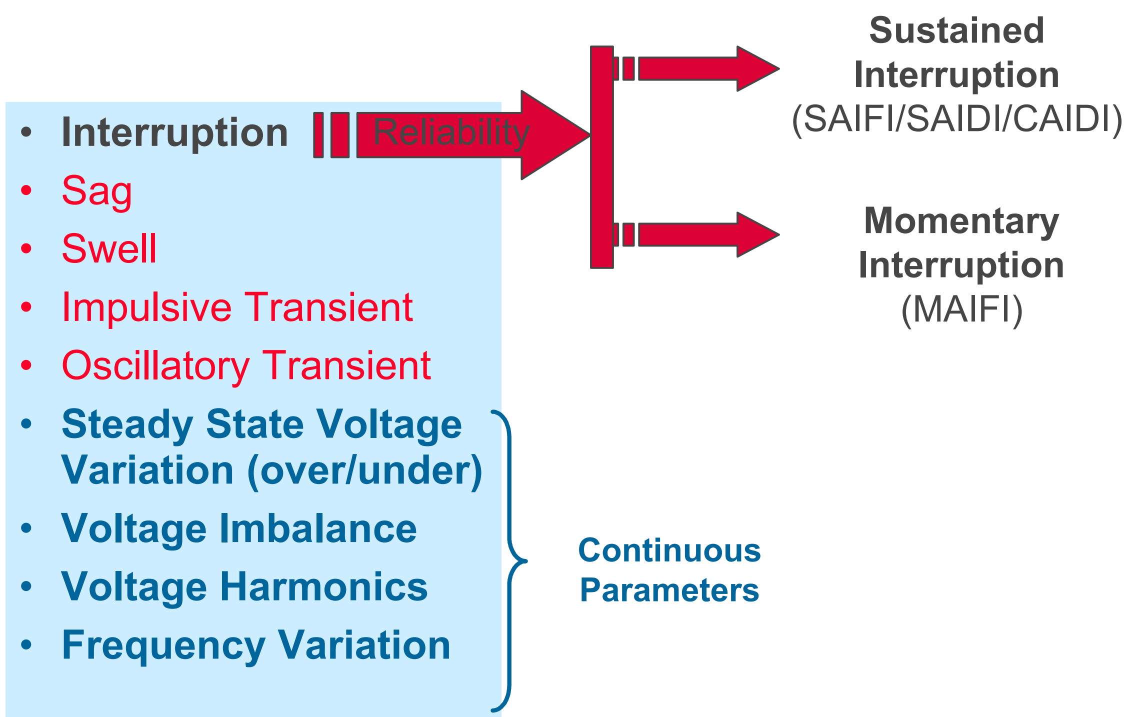

Figure 2-1
Reliability and Power Quality Characteristics That May be Considered as Part of a Service Quality Index

Traditional Reliability

Reliability indices are based on actual interruptions to customers, usually based on interruptions that last longer than five (5) minutes [4], although some utilities may use other durations, such as one (1) minute in Florida. The basic idea is that it will count as a reliability event if automatic reclosing and system reconfiguration is not successful for a fault condition. For power systems in most developed countries (like the United States), average number of these interruptions per year, excluding major events, is in the range of 0.5-5.0 interruptions per year (depending on factors such as weather, underground vs overhead systems, networked systems vs radial systems, etc.). The average number across the US is about 1.3 outages per year.

Approximately 50% of the states in the United States require reliability reporting and more than 75% indicate that reliability statistics and indices are maintained at the utility level (see Figure 2-2). The most common indices for reporting reliability at the system level are SAIFI and SAIDI (see definitions in Section 4). Table 2-1 summarizes example reliability levels for utilities in the United States and Canada from recent surveys and available data that is reported to public utility commissions, etc. Figures 2-3 and 2-4 illustrate that these average levels have not changed dramatically over the last ten years [17].

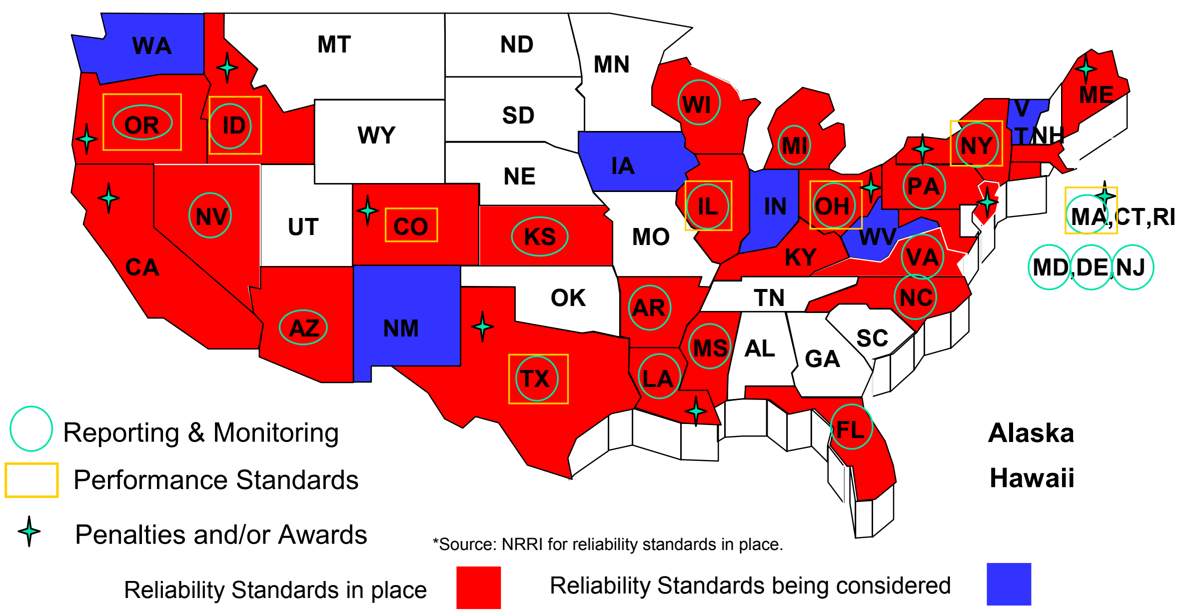

Figure 2-2
States With Reliability Reporting

Table 2-1
Reliability Levels Reported in Major Industry Surveys

	SAIFI, number of interruptions per year			SAIDI, hours of interruption per year		
	25%	50%	75%	25%	50%	75%
[IEEE Std. 1366-1998]	0.90	1.10	1.45	0.89	1.50	2.30
[EEI, 1999] (excludes storms)	0.92	1.32	1.71	1.16	1.74	2.23
[EEI, 1999] (with storms)	1.11	1.33	2.15	1.36	3.00	4.38
[CEA, 2001] (with storms)	1.03	1.95	3.16	0.73	2.26	3.28
[PA Consulting, 2001] (with storms)				1.55	3.05	8.35
Large City Survey [IP&L, 2000]	0.72	0.95	1.15	1.02	1.64	2.41

A B C represent the lower quartile A, the median B, and the upper quartile C of utility indices.

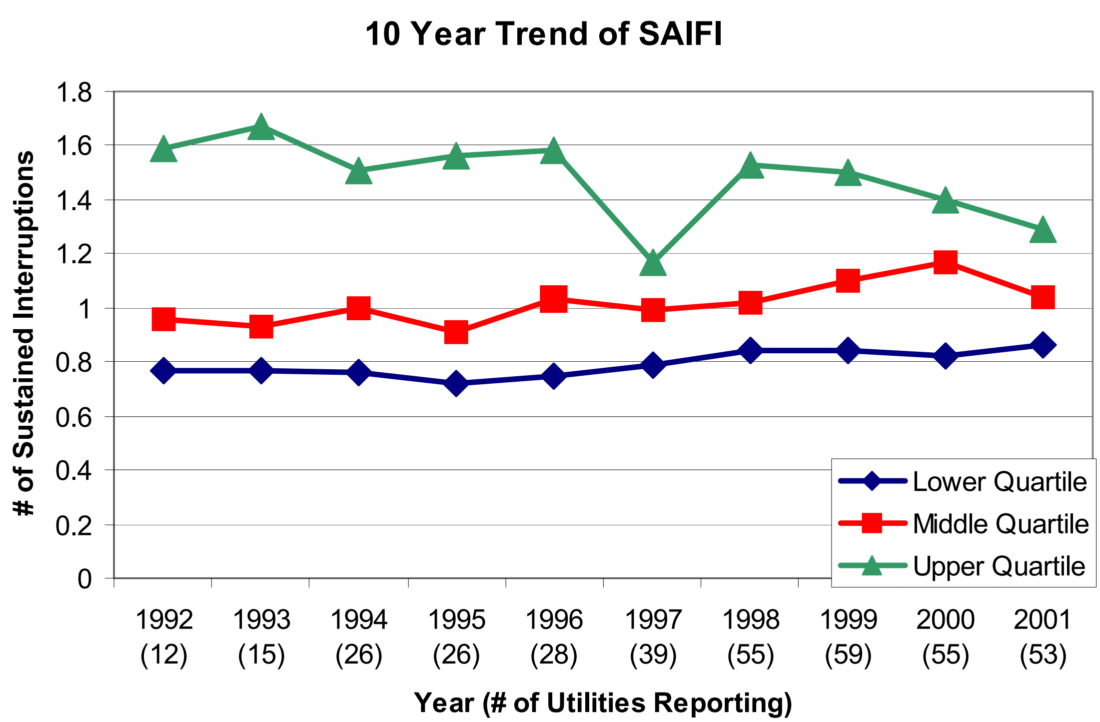

Figure 2-3
10 Year Trend of Average SAIFI Levels From Utilities Surveyed in an EPRI Survey. Note That These are SAIFI Levels EXCLUDING Major Events

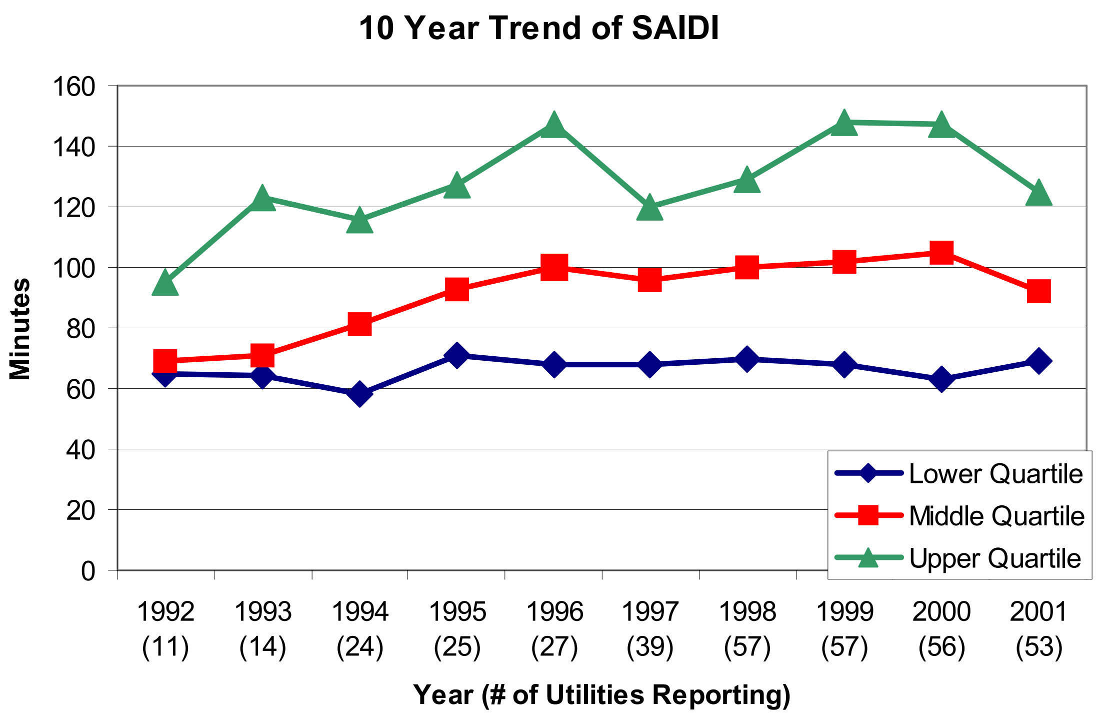

Figure 2-4
10 Year Trend of Average SAIDI Levels From Utilities Surveyed in an EPRI Survey. Note That These are SAIDI Levels EXCLUDING Major Events

It is important to note that these are system indices and the expected performance at individual locations can vary dramatically from these system average levels. Characterizing the probabilistic nature of the expected reliability levels in a way that will be more useful for end users is discussed in Section 6.

Another important note is that reliability indices are usually calculated with and without "major events" included. Many utilities may only report the indices with major events excluded because this is a more relevant indication of reliability that could be improved through better maintenance, design, and system operations practices. However, a customer-oriented index should include all of the events that can affect the customer operation and, therefore, the reliability component of the Service Quality Index, should include all events. With this in mind, it is important that the Service Quality Index not be the basis of regulations or requirements for the utility system performance – many of the factors influencing the performance will be outside of the control of the utility.

Steady State Power Quality

Steady state power quality refers to the quality of the normal voltage supplied to a customer. It includes characteristics like the rms voltage magnitude, the level of harmonic distortion, the amount of unbalance in the three phases, and the voltage variations that can be characterized as flicker. All of these characteristics can be quantified and limits for the variations can be developed.

These are the power quality characteristics that have received the most attention in terms of standards development. For instance, the European standard EN50160 [8] provides minimum performance requirements for the electric supply in all of the steady state power quality categories. EN 50160 is based on standards for power quality levels established in IEC Standard 61000-2-2 [7]. These power quality characteristics are evaluated using statistical procedures. Figure 2-5 illustrates the concept that applies for all the steady state characteristics. The power quality performance of the supply system is characterized statistically and this can be compared with the statistical characteristics of the equipment immunity to determine the likelihood that equipment will be affected by the power quality variations. The objective is to define a performance level that can be achieved with reasonable investment in the power system and will also have a low probability of causing equipment problems. This level is called the "compatibility level". It is defined with statistics. For instance, a typical way of defining the compatibility level for performance evaluations is the level that can be exceeded only 5% of the time (95% probability that the level will not be exceeded).

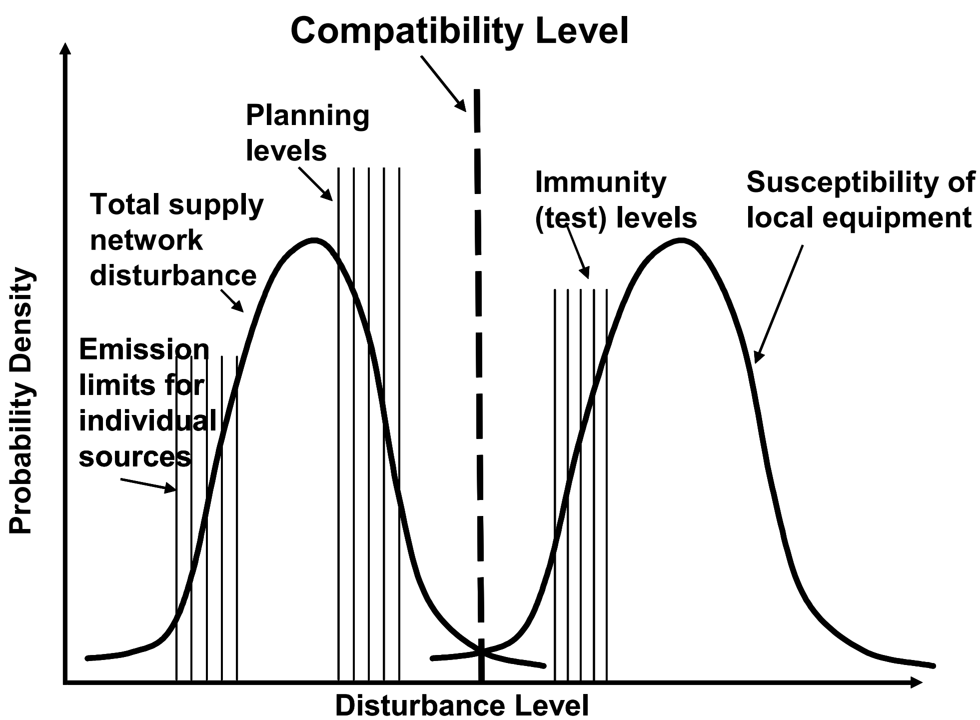

Figure 2-5
The Concept of "Compatibility Levels" for Steady State Power Quality Characteristics

Figure 2-6 illustrates the concept of the compatibility level compared to a time trend of a steady state power quality characteristic (for example, harmonic distortion). Other important power quality levels are also shown on both Figure 2-4 and 2-5:

- Equipment immunity level – this is the level of quality that may affect equipment performance if it is exceeded. It is also defined statistically. There should be some margin between the compatibility level for the supply and the equipment immunity level.
- Utility planning level – this is the level of quality that the electric utility establishes as a design objective. Usually, the planning level is defined at some level below the compatibility level to help assure that the actual compatibility level will not be exceeded. For instance, the compatibility level for harmonic voltage distortion might be 5% but the planning level might be 4% to help make sure that the 5% level is not exceeded.
- Assessed level – this is the actual level existing on the system, usually based on measurements. For instance, the evaluation of performance for the European standards requires measurements over a one week period and then the assessed level for comparison with the minimum performance requirements (based on the compatibility levels) is the level that is exceeded for 5% of the measurements (one measured value every ten minutes).

These concepts are explored in more detail in Section 4 for each type of steady state power quality. The objective is to define minimum requirements of the steady state power quality characteristics that should be achievable and also prevent customer equipment problems.

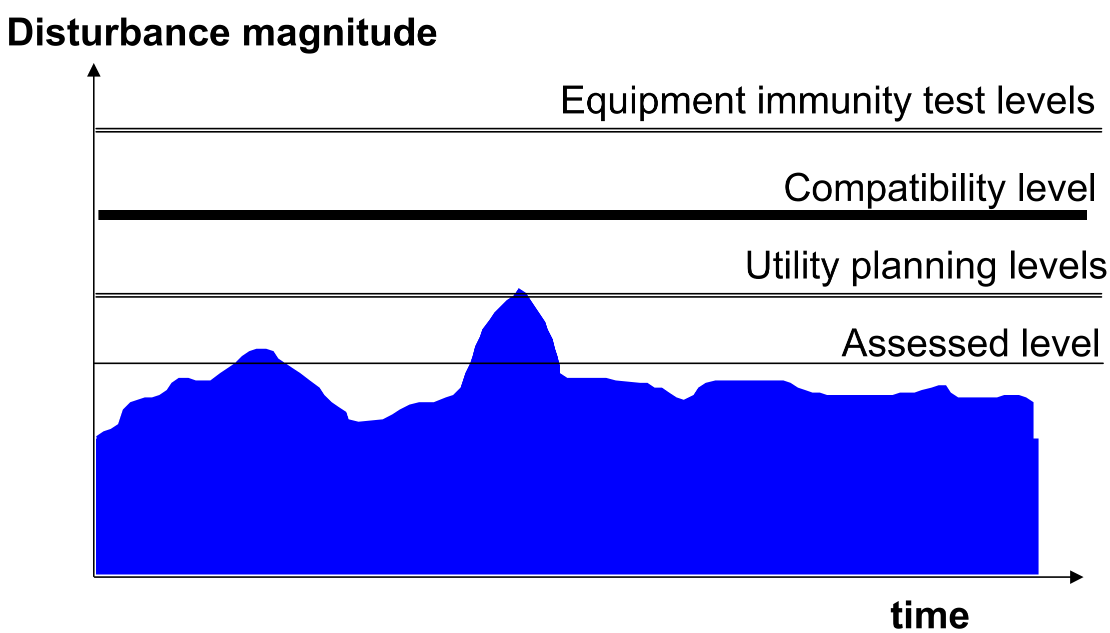

Figure 2-6
Illustration of Compatibility Levels Compared to an Actual Trend of a Steady State Power Quality Characteristic

Power Quality – Disturbances

Unfortunately, facility operations can be affected by more than just long duration outages. Momentary voltage sags, lasting less than 100 msec, are often sufficient to cause disruptions to sensitive equipment and operations (see example in Figure 2-7). Even though the effect of these disturbances can be the same as long duration outages, they can be more important because they occur much more frequently. These disturbances are caused by faults on distribution circuits and transmission circuits that may or may not result in actual outages that get counted in reliability indices. The interconnected nature of the system means that faults remote from a facility can still cause a momentary voltage sag that could be sufficient to affect operations.

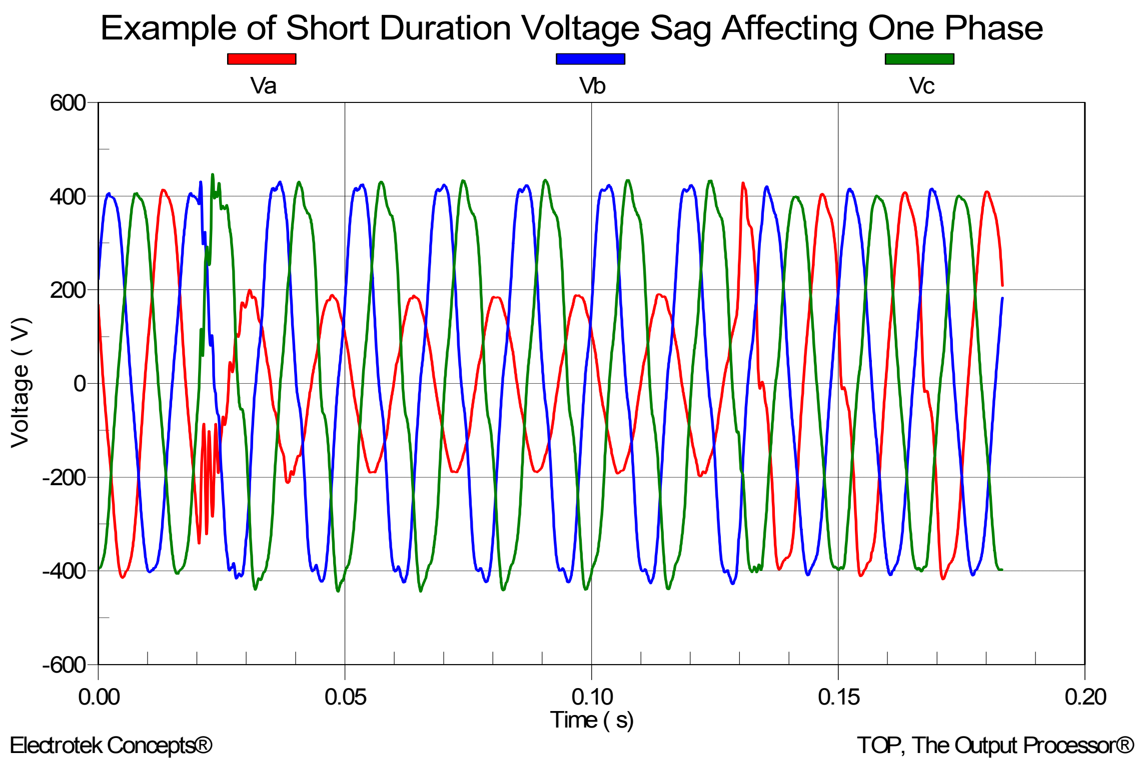

Figure 2-7
Example of Voltage Sag Disturbance That Can Affect Customer Equipment and Processes

Both voltage sags and momentary interruptions (interruptions that are shorter than the period used to define an outage for reliability reporting) should be considered in a Service Quality Index because of their important effects on customers. Other disturbances, such as normal capacitor switching transients and higher frequency transients that may be associated with lightning or switching events, are not considered for the Service Quality Index because they are less likely to affect customer equipment assuming that normal overvoltage protection practices are used.

Unfortunately, many utilities are unable to provide information about the expected number of voltage sags that a customer is likely to experience. EPRI conducted benchmarking projects that provided an estimate for the average number of voltage sags that customers experience on distribution systems across the US [1,2].

In order to present the results of this extensive benchmarking project, a new index to describe voltage sag performance was developed. It is called SARFI, or the System Average RMS (Variation) Frequency Index. This index represents the average number of voltage sags experienced by a customer each year with a specified characteristic. For SARFIx, the index would include all of the voltage dips where the minimum voltage was less than x. For example, $SARFI_{70}$ represents the expected number of voltage sags where the minimum voltage is less than 70%. Figure 2-8 illustrates expected performance of distribution systems across the United States for different SARFI levels.

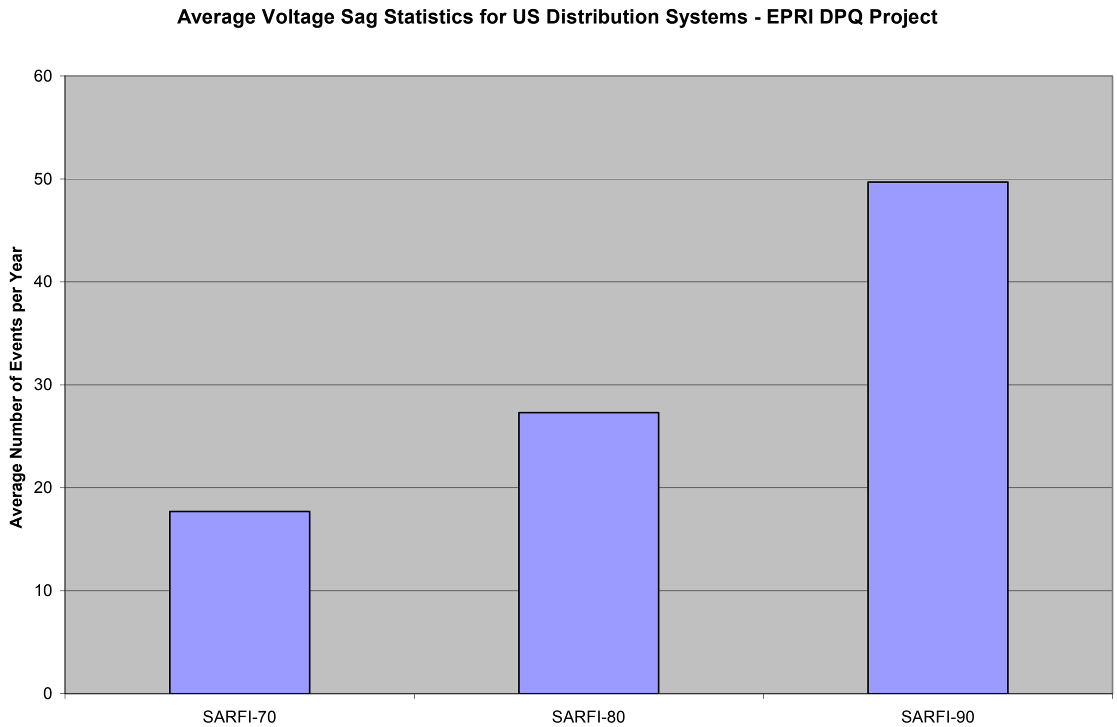

Figure 2-8
Average SARFI Statistics From Nationwide EPRI Benchmarking Project. These Show the Average Number of Voltage Sags That can be Expected for a Distribution System Customer in the United States as a Function of the Voltage Sag Severity (Minimum Voltage Magnitude)

This index is discussed in more detail in Section 6 along with the index for momentary interruptions – MAIFI.

SARFI indices become a very important consideration for many process industry customers because the indices represent events that impact the reliability of the process. There are typically very few actual outages. Therefore, voltage sags represent the most important power quality variation affecting industrial and commercial customers. The IEEE Gold Book (IEEE Standard 493) describes how a facility engineer should consider the impact of voltage sags as part of the economic evaluation of plant reliability [17]:

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

Obviously, these events are an important consideration for many customers.

Importance of Power Quality Characteristics – Equipment and Process Sensitivity

The components of a Service Quality Index will depend on the sensitivity of the equipment in facilities that are supplied from the system. This is different from customer to customer. Unfortunately, this information is usually not available without extensive monitoring and evaluation of equipment response to actual disturbances. Therefore, we have to look at typical characteristics to select the appropriate components to include in the indices.

The most difficult decision is how to address the issue of voltage sags in the indices. This is a topic that is currently being addressed in IEEE Working Group 1564 where a number of different approaches are being considered. There are a number of existing standards and guidelines that address equipment sensitivity to voltage sags. The two most important are the ITIC curve [19] and the SEMI F47 curve [20]. The ITIC curve is the most commonly referenced curve when describing typical equipment ability to ride through voltage sag conditions without being affected. The semiconductor industry used this as a starting point but developed a curve that specified improved ride through performance due to the high costs of disruptions to the process in this industry. Both curves are illustrated in Figure 2-9 with points representing actual voltage sag events superimposed. The improved performance that can be expected for equipment that meets the specifications of SEMI F-47 can clearly be seen.

The important thing to note is that the expected number of voltage sags and momentary interruptions is always much greater than the expected number of outages (reliability). Since much equipment is sensitive to these momentary events, it is important that they be addressed in the Service Quality Index. Specific recommendations for the appropriate index are developed in Section 5.

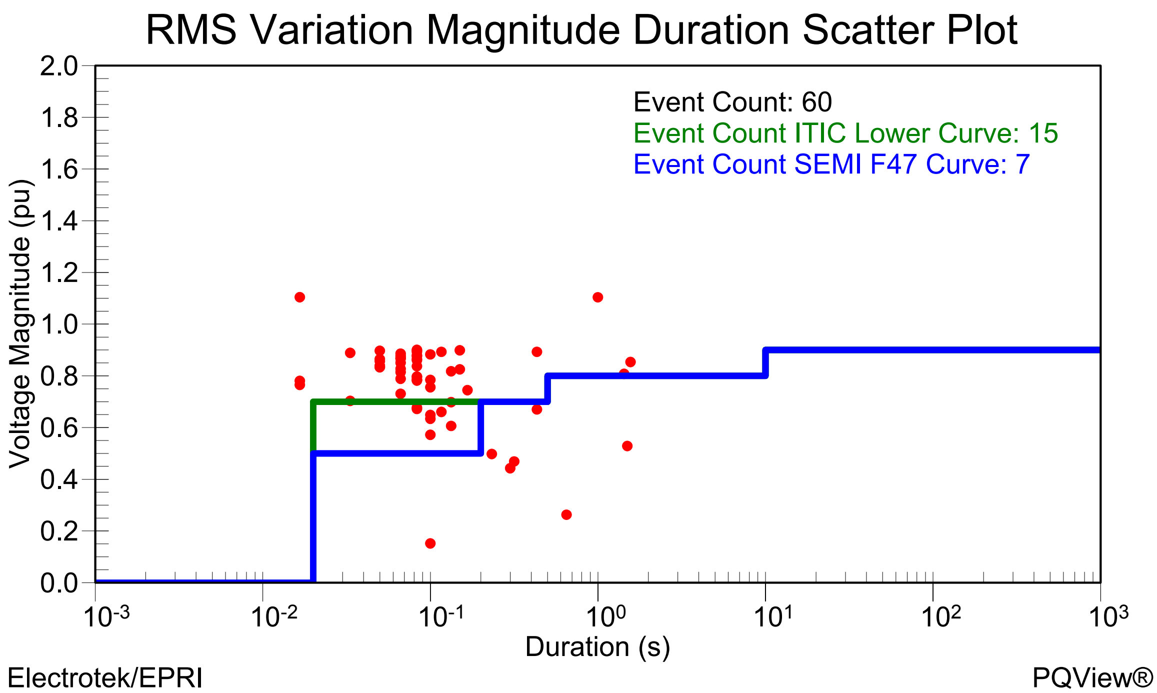

Figure 2-9
Plot of Rms Voltage Variations (Including 1 Minute Aggregation of Events) Illustrating the Number of Voltage Sags That Were Below the ITIC Curve and the Number That Were Below the SEMI-F47 Curve

Basic Approach for the Service Quality Index

It is clear that a Service Quality Index needs to include more than traditional reliability indices based on long duration outages. In order to include the full range of issues that could affect customer operations, the following approach is proposed:

1. Define minimum levels of steady state power quality that should be met so that customer equipment is not impacted. If these levels are met, then there should not be a problem unless there is an internal facility problem or a specific equipment design problem.
2. Define the expected performance for disturbances that could impact customer operations. These disturbances will include outages (reliability), momentary interruptions, and voltage sag performance. This expected performance can be described using appropriate probabilistic approaches and weightings for the individual components of the disturbance performance can be developed based on the expected economic impacts to customers. In this way, different weighting could be developed for different systems or overall typical weightings could be used.

The details of this approach are developed in the next sections.

3
STEADY STATE POWER QUALITY CHARACTERISTICS

Basic Concepts

Steady state power quality characteristics must meet minimum requirements to assure the proper operation of equipment. The basic concepts of compatibility levels (see Figures 2-5 and 2-6) are established in IEC 61000-2-2. This concept applies to all steady state types of power quality. It is not as applicable to disturbances, such as voltage sags (dips), interruptions, and transients. The normal variations of steady state power quality characteristics allow them to be characterized with trends over time and with statistical distributions. The statistical nature of these characteristics lends them to being represented by specific statistical levels. For instance, the limits in EN 50160 for steady state power quality are evaluated at the 95% probability level.

We are interested in defining the steady state power quality levels that should allow proper operation of virtually all customer equipment. Thus, if these power quality levels are met at the supply point, the steady state quality should be considered acceptable and should not result in customer problems. There is little value to providing even better power quality if these levels are not likely to cause problems. Extremely sensitive equipment that requires even better quality justifies special power conditioning and should not be the basis of the overall system requirements.

Recommendations for these minimum requirements for the steady state characteristics are developed in the following sections. Important standards and references that are the basis of the recommendations are cited and described as appropriate. In addition, typical levels of these steady state characteristics are provided from two important sources:

1. The DPQ project [1]. Steady state power quality characteristics were described for distribution systems in the United States. Note that these statistics are based on evaluation of single cycle samples of the three phase voltages. These samples are then analyzed to determine the rms voltage magnitudes, the unbalance, and the harmonic distortion levels. Flicker levels were not characterized in the DPQ project. This method of evaluating steady state power quality characteristics is different than the method recommended in IEC 61000-4-30 and related standards. These methods use 10 minute rms values as the basis for characterizing the steady state power quality. The 10 minute calculations can involve smoothing compared to the single cycle samples.
2. CIGRE C4.07 Working Group Report [3]. This working group gathered survey information describing both steady state power quality and disturbances from systems around the world. In general, the surveys referenced in this report used IEC methods for characterizing performance.

All of the recommended minimum steady state power quality levels developed in this report should be evaluated using the measurement procedures outlined in IEC 61000-4-30 [15]. This standard provides a convenient reference to make sure that all systems are being evaluated in the same manner. The IEEE 1159 working group is developing a similar set of recommended characterization procedures that will be consistent with the methods in the IEC standard.

Voltage Regulation

The ability of equipment to handle steady state voltage variations varies from equipment to equipment. The steady state voltage variation limits for equipment are usually part of equipment specifications. The Information Technology Industry Council (ITIC) specifies equipment withstand recommendations for IT equipment according to the ITIC Curve (formerly the CBEMA curve). The 1996 ITIC Curve specifies that equipment should be able to withstand voltage variations within +/- 10% (variations that last longer than 10 seconds).

Example Limits

Voltage regulation standards in North America vary from state to state and utility to utility. The most commonly applied standard in the United States is ANSI C84.1. Voltage regulation requirements are defined in two categories:

- Range A is for normal conditions and the required regulation is +/- 5% on a 120 volt base at the service entrance (for services above 600 volts, the required regulation is -2.5% to +5%).
- Range B is for short durations or unusual conditions. The allowable range for these conditions is -8.3% to +5.8%. A specific definition of these conditions is not provided.

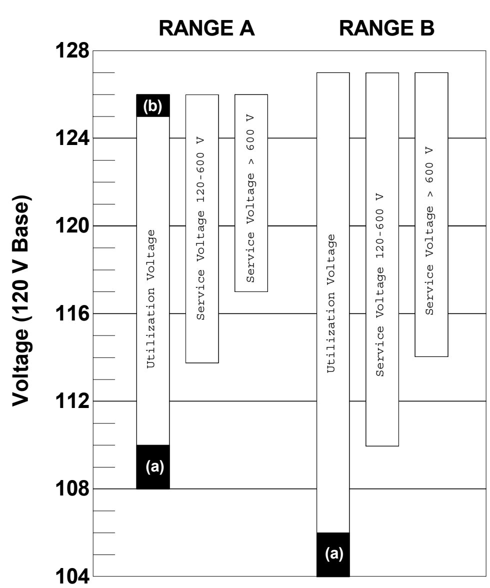

Figure 3-1
Voltage Regulation Requirements From ANSI C84.1

IEC 61000-2-2 mentions that the normal operational tolerances are +/- 10% of the declared voltage. This is the basis of requirements for voltage regulation in EN 50160 for the European Community. EN 50160 requires that voltage regulation be within +/- 10% for 95% of the 10 minute samples in a one week period. All 10 minute samples should be within -15% to +10%, excluding voltage dips.

Survey Results

Figure 3-2 illustrates the statistics of voltage regulation levels obtained in the DPQ project. Voltage regulation is described in this case as the range of voltage over the period of the day expressed as a percent of nominal. The voltage regulation was not described in terms plus or minus from nominal due to difficulties of defining the nominal voltage at different points on the distribution system. However, the results illustrate that almost all sites achieve a total variation level within 10%. The 95% for the entire sample of sites is a voltage regulation range of 8.5%.

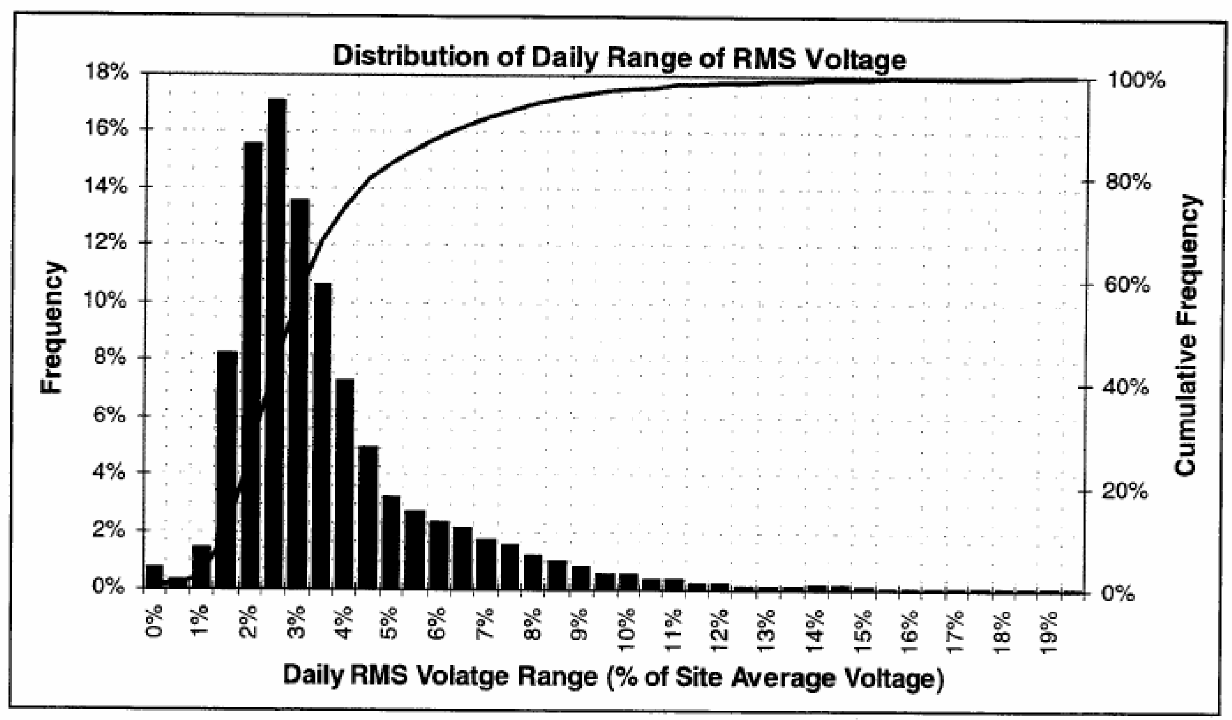

Figure 3-2
Voltage Regulation Statistics (Total Daily Voltage Variation Range) From DPQ Project (6/1/93-6/1/95)

Recommended Limit and Assessment Method

Since the objective is to define minimum acceptable requirements based on an evaluation at point of common coupling (realizing that the voltage variations inside a facility may be greater than the voltage variations on the system or at the supply point), the recommended level is +/- 5% with an evaluation at the 95% probability level.

The method of characterizing rms voltage recommended in IEC 61000-4-30 is based on 10 minute values over at least a one week monitoring period.

Voltage Unbalance

Voltage unbalance causes increased heating in motors and can result in unbalanced currents and non-characteristic harmonics for electronic equipment like adjustable speed drives. Figure 3-3 illustrates typical motor derating requirements for unbalanced voltages. High efficiency motors can be more susceptible to problems with unbalanced voltages due to lower negative sequence reactance values.

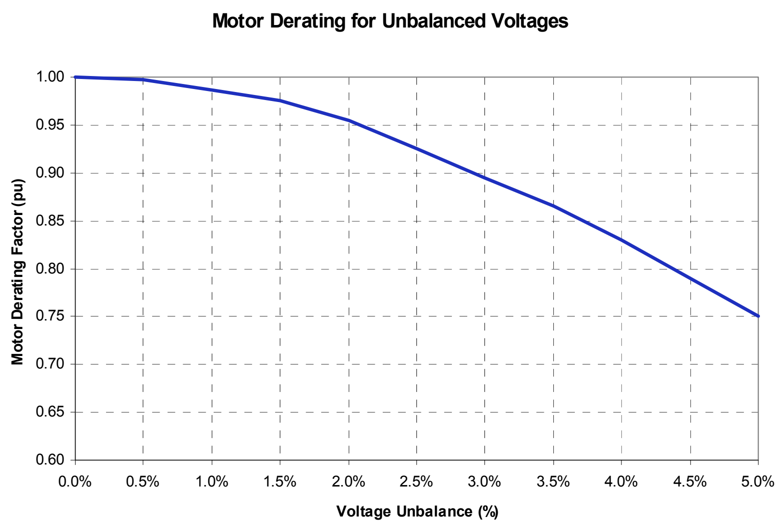

Figure 3-3
Typical Motor Derating as a Function of Voltage Unbalance (NEMA)

Voltage unbalance measured as the negative sequence component of the voltage divided by the positive sequence component is most important for motor loads and is the voltage unbalance quantity considered for this evaluation.

Example Limits

ANSI C84.1 recommends that voltage unbalance be limited to 2%. It is measured as the maximum deviation divided by the average of the three phases. This value can be influenced by the zero sequence voltage as well as the negative sequence voltage.

IEC 61000-2-2 specifies a compatibility level of 2% for voltage unbalance, recognizing that systems with large single phase loads may have voltage unbalance levels as high as 3%.

EN 50160 requires that European utilities maintain voltage unbalance less than 2% for 95% of the 10 minute samples in one week. For systems with significant single phase loads, the unbalance can be as high as 3%.

Survey Results

Negative sequence voltage unbalance statistics from the DPQ project are given in Figure 3-4. It shows that the 95% level for negative sequence unbalance over all the sites in the project was about 1.3%.

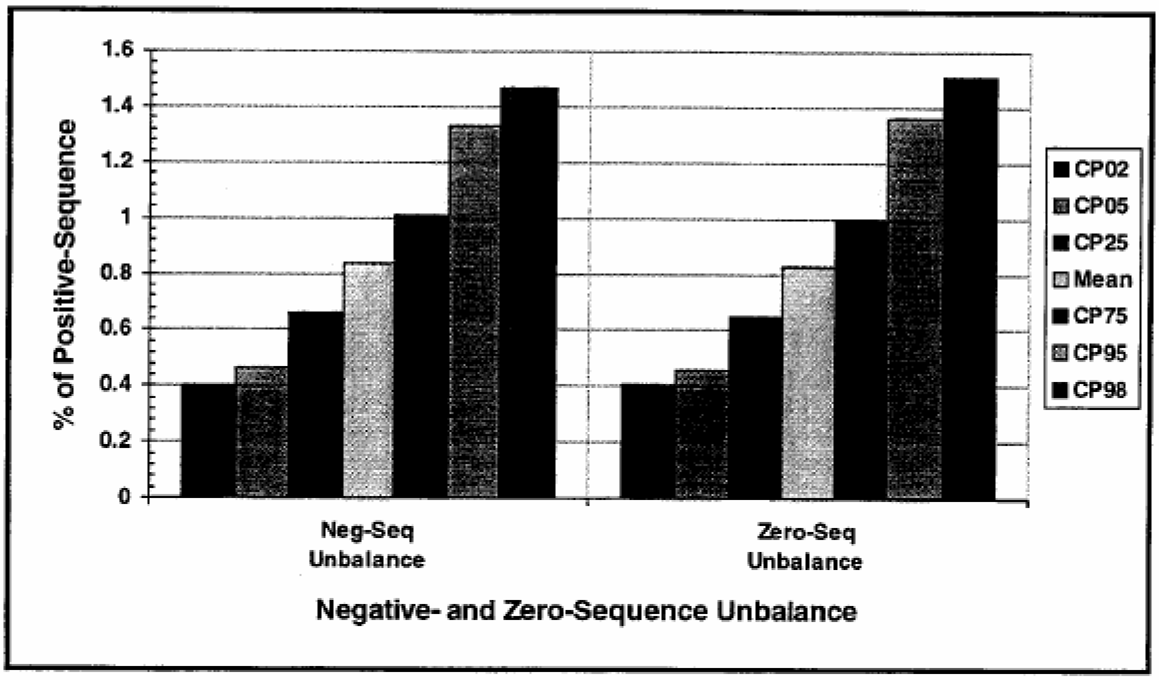

Figure 3-4
Voltage Unbalance Statistics From DPQ Project – Entire Data Set for all Sites (6/1/93-6/1/95)

The CIGRE C4.07/CIRED Working Group gathered survey data from around the world. Only a few surveys actually compiled information about unbalance but the results are still informative for developing a recommended minimum performance level. Figure 3-5 illustrates the results (95% probability level over one week of measurements at each site) for the different system voltage levels. We are most interested in the MV results. In this case, none of the sites had an unbalance level exceeding 2% at the 95% probability level.

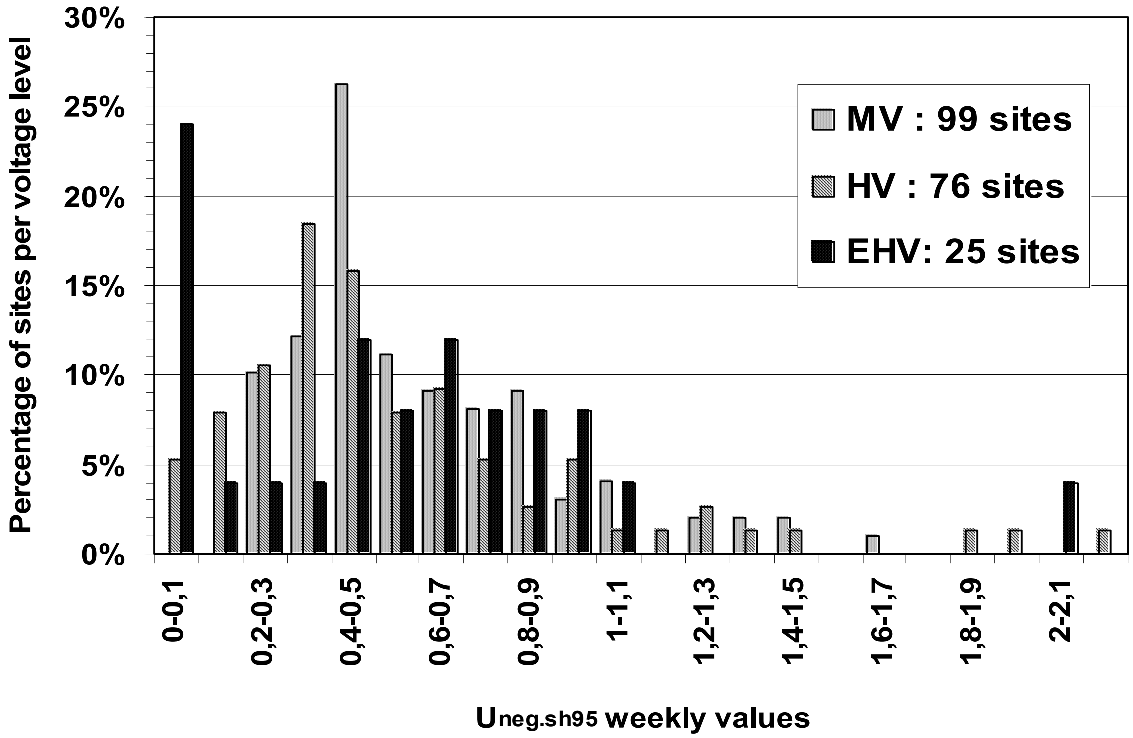

Figure 3-5
Measurement Data for Voltage Unbalance at MV, HV and EHV – All Sites (CIGRE C4.07/CIRED Report)

Recommended Limit and Assessment Method

The CIGRE working group recommends that the 95% value for weekly measurements of the 10 minute unbalance values be used for comparison with recommended unbalance limits (voltage characteristics). The most commonly used value for this characteristic is 2%. It seems to be a value that is very achievable and also has minimal consequences for customer equipment.

Harmonic Distortion

Harmonic distortion in the supply voltage results in increased heating in transformers, motors, capacitors, and conductors. This increased heating is usually the most important effect. However, voltage distortion in the supply system can excite resonances and overload customer power factor correction equipment. Sensitivity of customer equipment to voltage distortion may be dependent on both the magnitude of the distortion levels and the specific harmonic components. For instance, transformer eddy current losses increase with approximately the square of the frequency.

Very short term effects of harmonics can include misoperation of electronic controls or operation of uninterruptible power supplies. There may be a need for limits on the short term harmonics as well as the long term levels that cause heating.

Example Limits

IEEE 519 recommends voltage distortion limits of 5% for the total harmonic distortion (THD) and 3% for individual harmonic components. Measurement procedures for evaluation of performance with respect to these limits are not provided but it is generally considered that these limits would be applied at the 95% probability level.

IEC 61000-2-2 specifies harmonic distortion compatibility levels that are dependent on the harmonic order. The compatibility level for the voltage THD is 8%.

Table 3-1
Compatibility Levels for Individual Harmonic Voltages in Low Voltage Networks (Rms Values as Percent of the Rms Value of the Fundamental Component) – From IEC 61000-2-2

Odd harmonics Non-multiple of 3		Odd harmonics Multiple of 3		Even harmonics	
Harmonic Order h	Harmonic Voltage %	Harmonic Order h	Harmonic Voltage %	Harmonic Order h	Harmonic Voltage %
5	6	3	5	2	2
7	5	9	1,5	4	1
11	3,5	15	0,4	6	0,5
13	3	21	0,3	8	0,5
$17 \leq h \leq 49$	2,27 x (17/h) – 0,27	$21 < h \leq 45$	0,2	$10 \leq h \leq 50$	0,25 x (10/h) + 0,25
NOTE - The levels given for odd harmonics that are multiples of three apply to zero sequence harmonics. Also, on a three-phase network without a neutral conductor or without load connected between line and ground, the values of the 3rd and 9th harmonics may be much lower than the compatibility levels, depending on the unbalance of the system.					

These compatibility levels were used to develop the requirements for EN 50160. The EN 50160 requirements are applied for 95% of the 10 minute samples in a one week period with measurements according to IEC 61000-4-7. The EN50160 limit for voltage THD is 8%.

Table 3-2
Individual Harmonic Voltage Distortion Limits From EN 50160

ODD HARMONICS				EVEN HARMONICS	
not multiple of 3		multiples of 3			
Order h	Relative Voltage	Order h	Relative Voltage	Order h	Relative Voltage
5	6.0%	3	5.0%	2	2.0%
7	5.0%	9	1.5%	4	1.0%
11	3.5%	15	0.5%	6-24	0.5%
13	3.0%	21	0.5%		
17	2.0%				
19	1.5%				
23	1.5%				
25	1.5%				

Comparison of the IEEE 519 limits with the limits from EN 50160 show that the harmonic distortion limits in Europe are considerably relaxed compared to the IEEE limits. Even with these less severe limits, few problems related to harmonics are reported.

Survey Results

Harmonic levels were monitored in the DPQ project based on single cycle samples rather than 10 minute values. However, the statistics for large numbers of samples is likely to be similar to the statistics obtained with 10 minute values at the system level because the changes in harmonic levels are gradual. Larger differences could occur at individual locations with dynamic loads, such as arc furnaces.

Most of the DPQ results are reported as average harmonic levels. For instance, Figure 3-6 gives the distribution of average voltage distortion levels for all the sites in the DPQ project. The average distortion level across all the sites is 1.57%. No sites had an average voltage distortion level exceeding 5%. However, this can be misleading because the voltage distortion limits are meant to be compared with the 95% probability level for the harmonic distortion, not the average value. Figure 3-7 gives the distribution of 95% probability level voltage distortion (CP95) values for all the sites in the DPQ project. In this case, about 3% of the sites have distortion levels exceeding 5%. These cases usually involve resonance conditions associated with power factor correction on the distribution system.

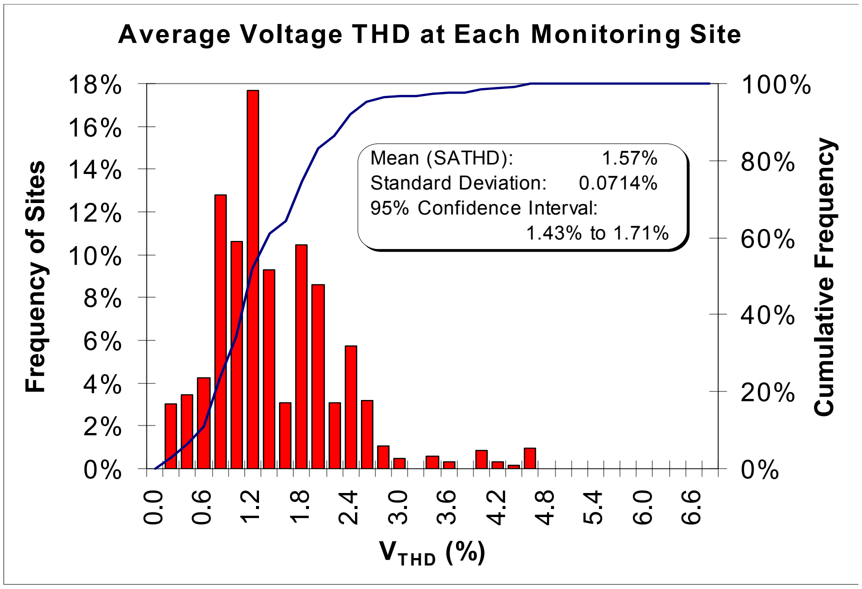

Figure 3-6
Distribution of Average Voltage Distortion Levels for all the Sites in the DPQ Project

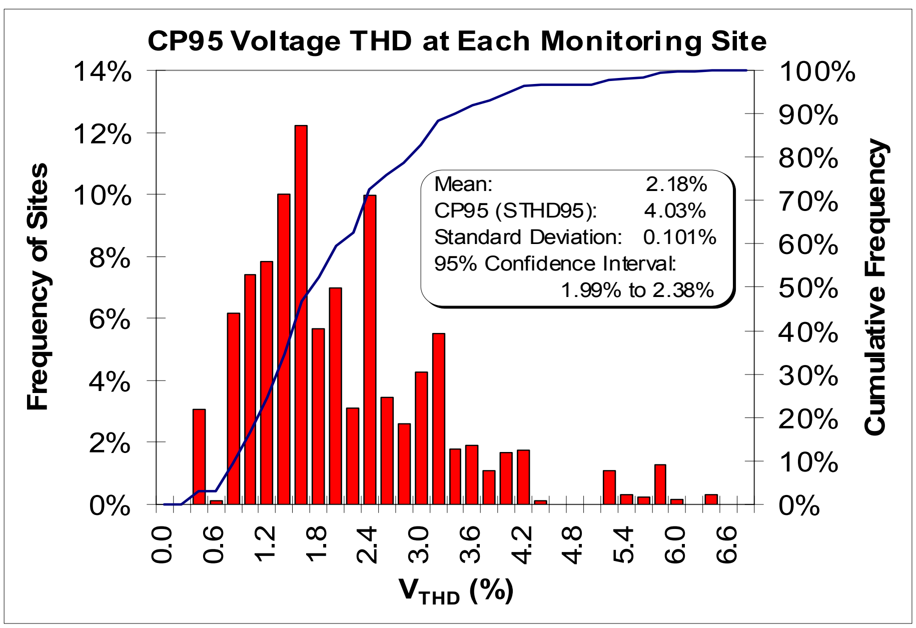

Figure 3-7
Distribution of CP95 Voltage Distortion Values (Level not Exceeded 95% of the Time) for all the Sites in the DPQ Project

Limited survey results were collected from MV systems in the CIGRE C4.07/CIRED effort. The results from two surveys are summarized in Table 3-3. These give the most important individual harmonic distortion levels and are very consistent with the DPQ survey results.

Table 3-3
MV Harmonic Survey Results From Two Surveys Totaling 178 Sites – Reported in CIGRE C4.07/CIRED Working Group Report

Harmonic Order	Measurement Results 95%-Site for $U_{h,sh95}$			Measurement Results Max-Site for $U_{h,sh95}$			Planning Levels
	Min	Max	Mean	Min	Max	Mean	
3	1,5	2,8	2,15	2	3,7	2,85	4
5	2,56	4,5	3,53	4,2	5	4,6	5
7	1,3	1,5	1,4	1,5	3,4	2,4	4
11	0,5	0,95	0,75	1	3,8	2,4	3

EPRI PEAC conducted a survey of harmonic levels at residential locations in eight (8) different countries in Europe [21]. Figure 3-7 gives the consolidated results from all 74 sites combined from this survey. Note that the results are actually very consistent with the results from the DPQ project. The 95% probability level for voltage THD across all the sites in the European survey project was 3.8%. This compares to a voltage THD level of 4.0% at the aggregate 95% level in the EPRI DPQ project. It would seen that overall harmonic distortion levels are very similar in the United States and Europe.

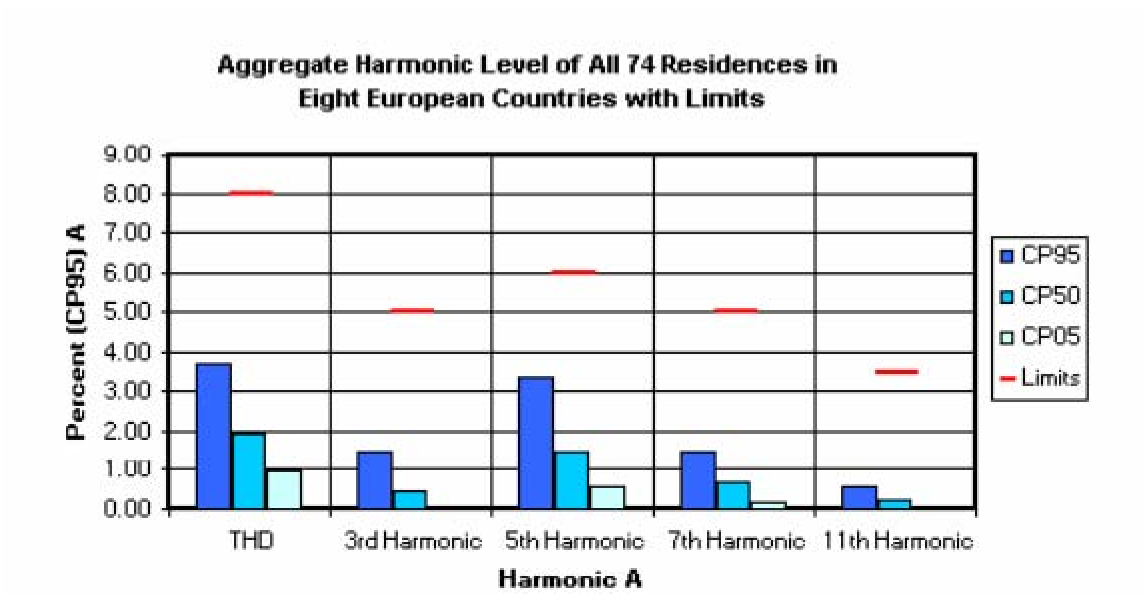

Figure 3-8
Results of Harmonic Survey at European Residential Locations

Recommended Limits and Assessment Method

The recommended limit for harmonic voltage distortion levels is 6% for the total harmonic distortion. This is higher than the recommended limit in IEEE 519 but significantly less than the recommended limit in EN 50160. Problems are not expected when voltage distortion levels are below 6%. New limits may be considered in the current revision work in IEEE 519 base don the international experience. It should not generally be necessary to assess the individual harmonics except as part of resolving problem conditions. In some cases, individual harmonic problems could occur at higher order harmonics without exceeding the 6% voltage distortion limits but these should be rare cases.

The recommended limit is compared to the 95% probability level of the 10 minute voltage distortion values measured over at least a one week period.

Flicker

It is not clear that voltage fluctuations that cause flicker need to be included in the service quality index. These fluctuations are usually not critical for customer equipment performance (although there are exceptions for sensitive equipment requiring voltage regulation and constant voltages, such as medical laboratory equipment). However, humans can be very sensitive to light flicker that is caused by voltage fluctuations and this may be enough justification to include it in the service quality index. Human perception of light flicker is almost always the limiting criteria for controlling small voltage fluctuations. Figure 3-9 illustrates the level of perception of light flicker from an incandescent bulb for rectangular variations. The sensitivity is a function of the frequency of the fluctuations and it is also dependent on the voltage level of the lighting.

Perception of flicker depends on the physiology of the eye-brain of the person subjected to the luminance fluctuation (flicker is a subjective perception). Flicker was originally related to the behavior of a 230 V, 60 W incandescent light bulb when subjected to voltage fluctuations. Other types of lighting may be less susceptible to light variations and flicker perception problems when subjected to the same voltage fluctuations. EPRI PEAC testing illustrated the different characteristics of other types of lighting and developed the concept of a gain factor for the lighting for comparison of susceptibility with that of a 60 W incandescent bulb (see Figure 3-10 for an example).

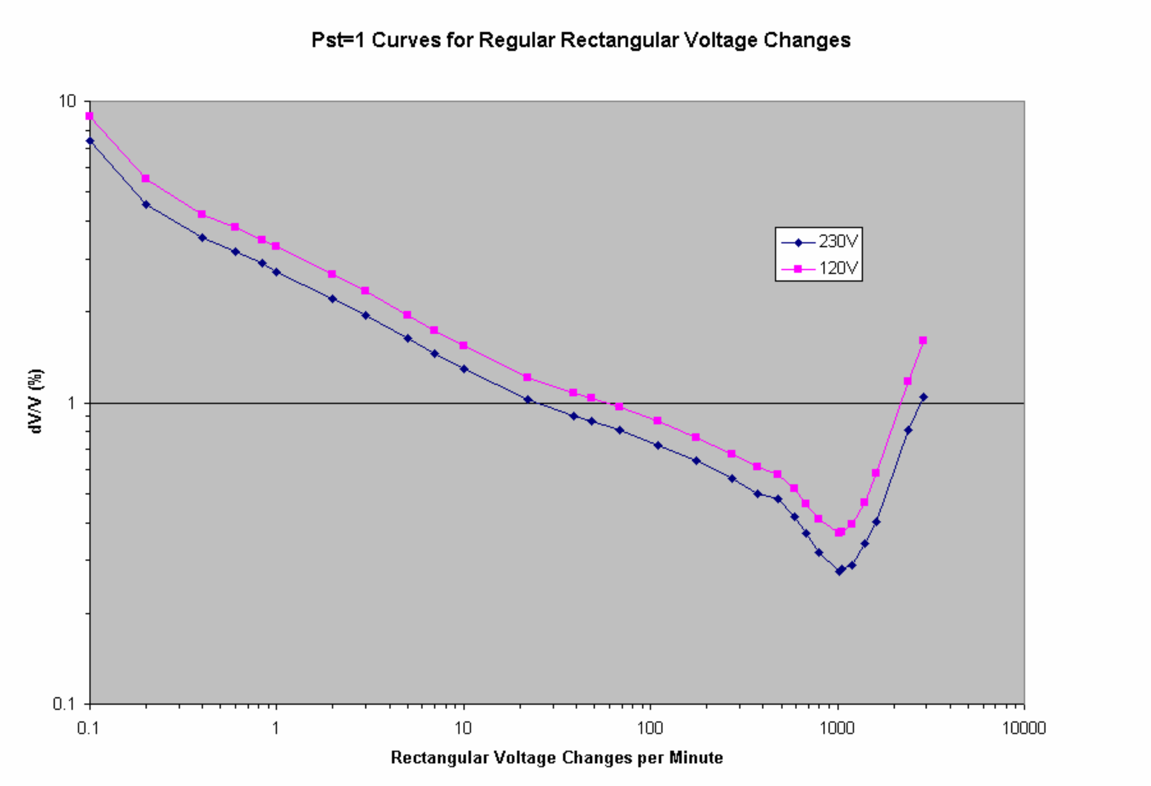

Figure 3-9
Curves illustrating the Level of Rectangular Voltage Fluctuations That Will Result in a Pst Value of 1.0 When Measured With the IEC flickermeter

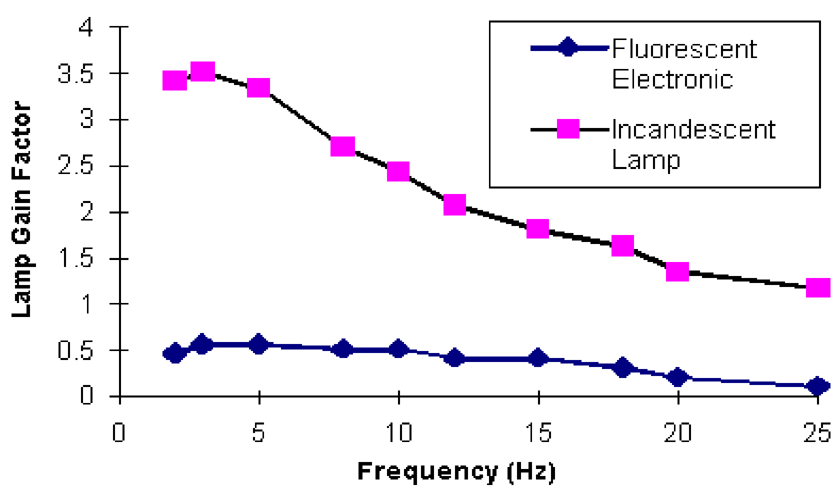

Figure 3-10
Lamp Gain Versus Flicker Frequency for Fluorescent Electronic and Incandescent Lamps

Example Limits

Limits for flicker levels are not specified in IEEE standards. Curves similar to the one shown above have been used by individual utilities as guidelines for controlling flicker.

Flicker levels in IEC standards are characterized by two parameters (both of these parameters are defined along with the measurement equipment to measure them in IEC 61000-4-15 [22]:

- 10-minute "short-term flicker severity - Pst. This value is obtained from a statistical analysis of the "instantaneous flicker value" in a way which models incandescent lamps and our observation of light intensity variations.
- 2-hour "long-term flicker severity - Plt. This is calculated by combining 12 successive Pst measurements using a cubic relationship.

Note that IEEE is also adopting this method of characterizing flicker (IEEE 1453).

IEC 61000-2-2 specifies flicker compatibility levels:

- Compatibility level for short term flicker (Pst) is 1.0.
- Compatibility level for long term flicker (Plt) is 0.8.

Recognizing that it is not always possible to maintain flicker levels within these compatibility levels, EN 50160 specifies less restrictive requirements for the supply system performance. The EN 50160 limit is that 95% of the long term flicker values (Plt) should be less than 1.0 in one week measurement period.

Note that individual step changes in the voltage, such as would be caused by motor starting or switching a capacitor bank, are often limited separately from the continuous flicker limits. IEC 61000-2-2 specifies a compatibility level of 3% for the individual voltage variations. EN 50160 specifies a limit of 5% for these variations but mentions that more significant variations (up to 10%) can occur for some switching events. Specific recommendations are not provided in IEEE but individual utilities usually have their own guidelines in the range 4-7%.

Survey Results

Survey results for flicker are very limited. Most measurement campaigns evaluating flicker are performed when there is a specific problem and the results are, therefore, not represented of the power system in general (most sites have very low flicker levels).

The results from a variety of surveys are provided in Figure 3-11, from the CIGRE C4.07/CIRED report. However, the report cautions that these results should not be considered to be statistically valid for the reasons described above.

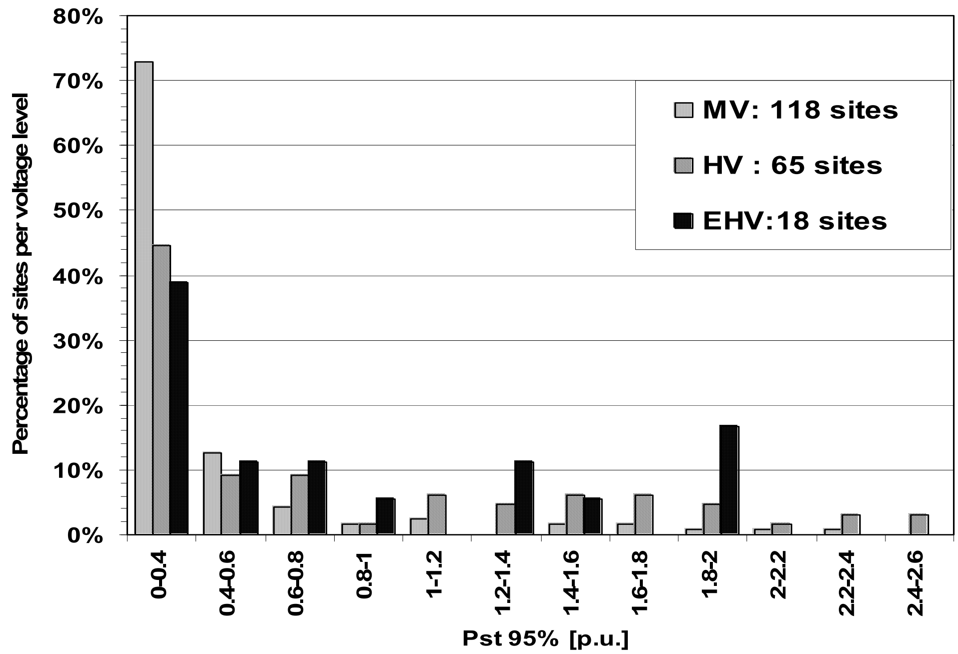

Figure 3-11
Measurement Data for Flicker $P_{st\ 95}$ at MV, HV and EHV – All Sites (From CIGRE C4.07/CIRED Working Group Report)

Recommended Limits and Assessment Method

The recommended limit for flicker is Pst=1.0 at the 95% probability level. This is consistent with the compatibility levels in IEC 61000-2-2 and is based on the actual design of the flickermeter. In other words, this flicker limit should prevent customer complaints associated with light flicker.

The limit is lower than the limit specified in EN50160. However, it is an appropriate limit when considering the philosophy of establishing a limit to prevent customer complaints rather than a limit that is a legal requirement for the utility to meet.

The Pst level is measured with a flickermeter that complies with IEC 61000-4-15 requirements. The Pst values are calculated for 10 minute intervals. 95% of these values should be below the limit in a one week measurement period.

Summary of Recommended Limits for Steady State Power Quality

Table 3-4 summarizes the recommended minimum steady state power quality requirements. All of these are based on 10 minute samples calculated according to IEC Standard 61000-4-30. They are evaluated based on the 95% probability level. In other words, these levels should be exceeded less than 5% of the time. Ideally, all locations on the power system should meet these minimum power quality requirements. However, there will always be some locations that have power quality characteristics that may exceed these requirements in one or more categories.

When a situation such as this is identified, the utility should work to solve the problem (that may be caused by one or more customers or may be related to a system condition).

Table 3-4
Summary of Minimum Performance Requirements for Steady State Power Quality Characteristics

Category	Requirement	Evaluation Method
Voltage Regulation	+/- 5%	95% 10 minute values in one week
Unbalance	<2%	95% 10 minute values in one week
Flicker	Pst<1.0	Pst 95% over one week period
Harmonic Distortion	6%	Voltage THD - 95% of 10 minute values - IEC 61000-4-7

4

RELIABILITY (LONG INTERRUPTIONS)

The system performance for disturbance events cannot be evaluated in the same manner as the system performance for steady state power quality. Different systems and different parts of the same system will have different expected disturbance characteristics. It is not useful from a customer perspective to define minimum requirements for disturbance performance that are based on the worst performing parts of the system. It is much more important to just accurately describe the expected performance at the individual customer location.

Reliability is a measure of the system performance for outages that last longer than five minutes (or some other duration determined to be longer than the time required for automatic reconfiguration devices to operate). This is perhaps the most important category of disturbances and it is one that most utilities maintain good records for. This section briefly summarizes the most important indices used for characterizing reliability and relates these indices to the objectives of the Service Quality Index. Discussion of the statistical characterization of reliability is deferred until Section 6 because this discussion applies to momentary interruptions and voltage sags in the same manner as it applies to long interruptions.

Reliability Indices

Reliability indices for distribution systems were defined as early as the 1970s when The Edison Electric Institute Transmission and Distribution Committee developed a *Guide for Reliability Measurement and Data Collection.* Although these system indices were originally developed for internal use by the distribution companies to quantify performance and identify opportunities for improvement (poor performing feeders) in planning and design, recent years have given way to many state regulatory authorities specifying the minimum reliability levels for utilities to maintain on a yearly basis. Illinois was first to mandate utility reliability reporting in 1998.

There are two characteristics of interruption performance that are important – the number of interruptions and the durations of interruptions. All of the reliability indices are related to these two characteristics in combination with characteristics of the system involved, such as the number of customers, the amount of load served, or other characteristics. We will focus on the simplest reliability indices and the most commonly used. They are defined in IEEE 1366-2003 Guide for Distribution Reliability Indices [4]:

SAIFI—System average interruption frequency index (sustained interruptions). SAIFI calculates how often the average customer experiences a sustained interruption over a pre-defined period of time. Mathematically:

$$\text{SAIFI} = \frac{\text{Total Number of Customer Interruptions}}{\text{Total Number of Customers Served}} \qquad \textbf{Eq. 4-1}$$

To calculate the index, use the following equation:

$$\text{SAIFI} = \frac{\sum N_i}{N_T} \qquad \textbf{Eq. 4-2}$$

SAIDI. System average interruption duration index. This index calculates the total duration of interruption for the average customer during a pre-defined period of time. It is commonly measured in customer minutes or customer hours of interruption. Mathematically:

$$\text{SAIDI} = \frac{\sum \text{ Customer Interruption Durations}}{\text{Total Number of Customers Served}} \qquad \textbf{Eq. 4-3}$$

To calculate the index, use the following equation:

$$\text{SAIDI} = \frac{\sum r_i N_i}{N_T} \qquad \textbf{Eq. 4-4}$$

CAIDI. Customer average interruption duration index. CAIDI represents the average time required to restore service. Mathematically:

$$\text{CAIDI} = \frac{\sum \text{ Customer Interruption Durations}}{\text{Total Number of Customers Interruptions}} \qquad \textbf{Eq. 4-5}$$

To calculate the index, use the following equation:

$$\text{CAIDI} = \frac{\sum r_i N_i}{\sum N_i} = \frac{\text{SAIDI}}{\text{SAIFI}} \qquad \textbf{Eq. 4-6}$$

The two most common indices and the indices discussed most in this report are SAIFI and SAIDI. SAIFI is the “system average interruption frequency index.” The system average interruption frequency index calculates how often the average customer experiences a sustained interruption over a predefined period of time. SAIDI is the “system average interruption duration index.” This index calculates the total duration of interruption for the average customer during a predefined period of time. It is commonly measured in customer minutes or customer hours of interruption.

Factors Affecting Reliability Performance

As mentioned above, reliability performance varies dramatically from one system to another and this is not necessarily an indication that one system has poor performance. Many factors influence the expected reliability at a particular location or for an entire system. Some of these factors are indicated in Figure 4-1 below.

Definition & Data Classification

- Major Events
- Interruption
- Planned/Unplanned
- Distribution/Transmission

Service Territory

- Geography
- Weather Pattern
- Vegetation Pattern
- Vehicle Access Pattern
- Animal Activity

Data Collection Process

- Outage Notification
- Outage Reporting
- Step Restoration Process
- Customer to Network Connectivity

System Design

- Urban/Rural/Downtown
- Load Characteristics
- Underground/Overhead
- Voltage Level
- Protection Scheme

Figure 4-1
Summary of Important Factors That Can Affect Reliability Levels

Obviously, a rural, overhead distribution system with significant exposure to trees, animals, and lightning cannot be expected to have the same reliability as an underground network. An important area of current research is attempting to quantify the effect of some of these parameters on expected reliability levels. However, for purposes of this report it is enough to recognize that different reliability levels should be expected at different locations.

Consideration of Major Events

One of the major developments in the latest version of IEEE 1366 (2003) was a new definition for major events. Many utilities report reliability indices with major events removed from the calculation. The result is less variability in the indices from year to year because major events can have dramatic effects on the overall indices.

In the U.S., most state PUCs allow exclusion of major events from reliability indices calculations. The idea is that the major events are not a reflection of the system performance that could be influenced with better maintenance and operations practices. However, prior to the new major event definition in IEEE 1366-2003, there was no uniformity to the way utilities were defining major events. This made it even more difficult to compare reliability indices being reported for different systems.

A common definition for major events was an incident in which more than 10% of customers are affected in any 24 hr period. The latest version of IEEE 1366 (2003) provides a new definition of major events based on events that are more than 2.5 standard deviations away from the mean with the assumption of a log-normal distribution of daily interruption statistics. It is beyond the scope of this report to describe this method in detail. It is recommended that utilities adopt the method for reliability reporting for overall system evaluations – it will provide more consistency in calculations throughout the industry.

However, for purposes of the service quality index, it is recommended that the reliability indices include all events and that major event exclusion not be applied. Customers are affected regardless of whether or not the outage was associated with a widespread problem. The Service Quality Index is a customer-focused index and should, therefore, include all events. This is also consistent with the Canadian philosophy for reliability reporting in general.

Using Reliability Indices for the Service Quality Index

For the Service Quality Index, the reliability index is being calculated at a specific location. Essentially, the indices SAIFI and SAIDI simplify in this case to the number of outages at the location of interest and the total minutes interrupted at the location. For a single location, there is no distinction between SAIDI and CAIDI because the number of customers involved is essentially one.

As mentioned above, the reliability indices for a service quality index should include all events. Events should not be excluded regardless of whether or not hey were associated with a major event.

5

VOLTAGE SAGS (DIPS) AND MOMENTARY INTERRUPTIONS

For many customers, voltage sags and momentary interruptions can result in similar impacts to long interruptions. The difference is that there are many more voltage sags and momentary interruptions than long interruptions. Therefore, the economic impacts of these momentary events can be much greater than the impact of long interruptions.

Therefore, it is recommended that both momentary interruptions and voltage sags be included in the Service Quality Index. The performance for these disturbances can be described with indices that are very similar to the basic indices for describing long interruptions. Recommended approaches are developed in this chapter.

Momentary Interruption Index

Momentary interruptions are defined along with long interruptions in IEEE 1366-2003.

MAIFI. Momentary average interruption frequency index. This index calculates the average frequency of momentary interruptions. Mathematically:

$$\text{MAIFI} = \frac{\text{Total Number of Customer Momentary Interruptions}}{\text{Total Number of Customers Served}} \qquad \textbf{Eq. 5-1}$$

To calculate the index, use the following equation:

$$\text{MAIFI} = \frac{\sum IM_i N_i}{N_T} \qquad \textbf{Eq. 5-2}$$

It is important to note two definitions associated with momentary interruptions:

- **momentary interruption**: A single operation of an interrupting device that results in a voltage zero. For example, two circuit breaker or recloser operations (each operation being an open followed by a close) that momentarily interrupts service to one or more customers is defined as two momentary interruptions.
- **momentary interruption event**: An interruption of duration limited to the period required to restore service by an interrupting device. NOTE—Such switching operations must be completed within a specified time of 5 min or less. This definition includes all reclosing operations that occur within five minutes of the first interruption. For example, if a recloser or circuit breaker operates two, three, or four times and then holds (within 5 min of the first

operation), those momentary interruptions shall be considered one momentary interruption event.

Sometimes, the impact of multiple reclosing events on a customer may be more severe than a single momentary interruption. However, a customer is usually affected or not affected by a momentary interruption. If he is affected, even a single interruption will be enough to cause the problem. Multiple interruptions in this case are not likely to make the problem worse.

Therefore, the recommendation for the Service Quality Index is that MAIFI be calculated using momentary interruption events.

Also, in a similar manner to the calculation of SAIFI and SAIDI, the calculation of MAIFI for the Service Quality Index is at a single location so it is essentially just a count of the Momentary Interruption Events.

Voltage Sag Indices

Characterizing the Voltage Sag Event

Calculation of voltage sag indices is a little more complicated than either momentary or long interruption indices. This is due to the fact that we have the additional task of characterizing the voltage vs time in a consistent manner in order to develop the basic characteristics of the sag – the magnitude and duration for each phase voltage.

It is important that the voltage sag performance be characterized in a consistent manner for describing voltage sag performance at a site or for an entire system. The following procedures should be used when characterizing voltage sag performance (based on recommendations in IEC 61000-4-30):

- The voltage sag magnitude should be characterized according to IEC 61000-4-30. That is, the magnitude should be based on the minimum one cycle voltage magnitude based on updates every half cycle.
- The minimum voltage magnitude during a voltage sag should be based on the minimum line-to-line voltage at the location being evaluated for three phase locations. There are other options that could be considered, such as using the "characteristic voltage" defined by Math Bollen [23]. However, using the line-to-line voltage provides some consistency and is a simpler calculation. This is a topic that could be revisited based on future recommendations in standards.
- Multiple events that occur within one minute of each other should be counted as a single event. This is to prevent multiple sags from reclosing events being counted as multiple events. This is often referred to as one minute time aggregation. It is a similar concept to using Momentary Interruption Events described above.
- The duration of a voltage sag will be the duration from the time when one phase of the voltage drops below 90% magnitude until the time when all three phases of the voltage return

to 90% magnitude. When multiple events are aggregated, the duration will be the longest duration of the individual events being aggregated.

For each event, the important characteristics to calculate are the minimum voltage and the duration for the voltage sag on each phase. The minimum voltage for all three phases and the overall event duration should also be calculated.

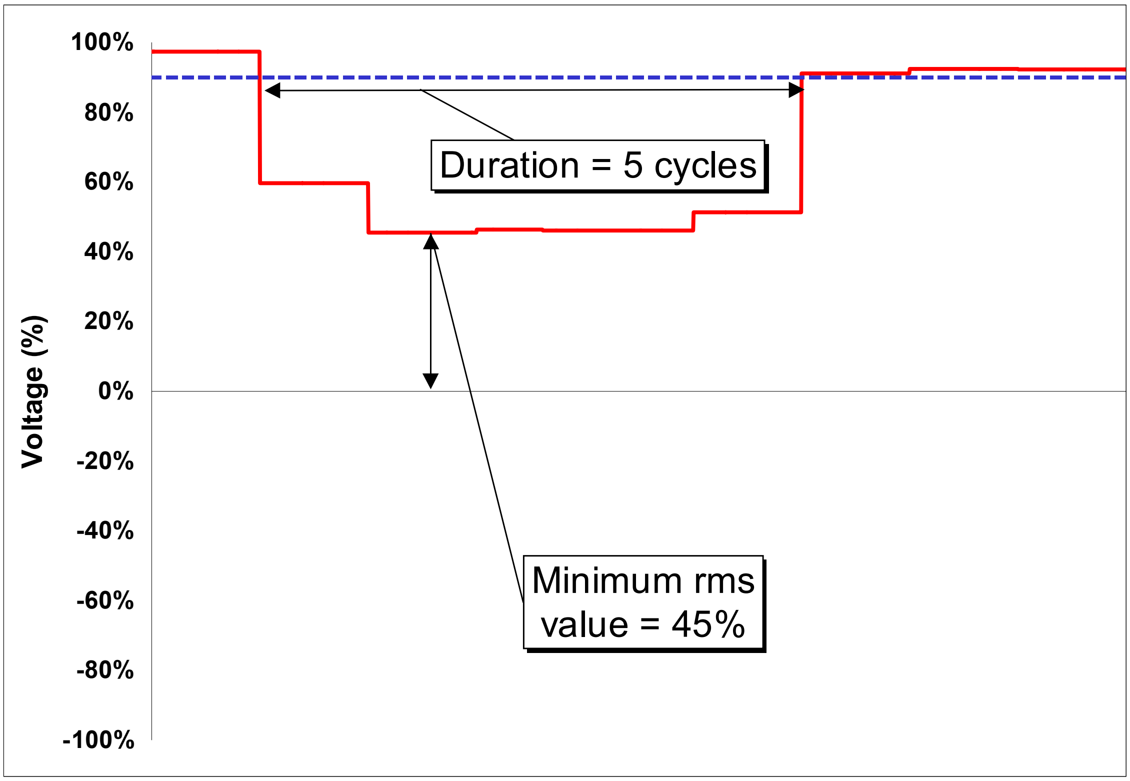

Figure 5-1
Basic Calculation of the Magnitude and Duration From the rms Waveform for a Voltage Sag Event

Note that characterizing the duration of a voltage sag is very dependent on the choice of a threshold voltage. The threshold can be a percentage of either nominal or declared voltage, or a percentage of a sliding voltage reference, which takes into account the actual voltage level prior to the occurrence of a dip. The user should indicate the reference voltage in use.

A number of other characteristics for voltage dips are mentioned in an annex to IEC 61000-4-30 including phase angle shift, point-on-wave, three-phase unbalance, missing voltage and distortion during the dip. The use of additional characteristics and indices may be valuable and needed for individual investigations such as determining the source of the event and the impacts on equipment. However, they are not generally needed for general indices describing voltage sag performance.

Voltage Sag Site Indices

The calculation of site indices is an intermediate step in the calculation of system indices. Site indices are used namely for compatibility assessment between sensitive equipment and the power supply and can be used as an aid in the choice of a voltage-dip mitigation method. They can also be used to provide information to local customers on the voltage quality. In the case of the Service Quality Index at a particular location, the voltage sag site index is an important component.

Site indices are calculated from single event indices. At locations where seasonal variations in the number of dips can be expected, the monitor period should be an integer multiple of one year. For locations with a strong seasonal variation in the event frequency, a three to five-year monitoring period is recommended to incorporate year-to-year variations in the seasonal effects.

Site indices can be presented in a number of different ways:

- As a voltage-dip table in accordance with the UNIPEDE-disdip [25] recommendation or the recommendations in IEC 61000-2-8 [26];
- As a contour chart according to IEEE 1346 [27];
- As the number of events more severe than a certain curve, e.g. ITIC or SEMI F47 curve [20], or below a certain retained voltage (e.g. SARFI indices)
- In any other way most suitable for the specific site and application.

It is recommended that site indices be based on the remaining voltage in percent and the duration in milliseconds for individual events. It should be indicated if the pre-event or nominal voltage is used as a reference to calculate the relative remaining voltage. When using pre-event voltage, the sliding reference, as defined in IEC 61000-4-30, should be used. The sliding reference window may be used in HV and EHV systems with a relatively large variation in normal-operation voltage, when HV/MV transformers are equipped with on-line tap changers.

In many cases time aggregation is used to prevent double counting of events close together in time. Different methods of aggregation are in use, each with their advantages and disadvantages.

The monitor availability needs to be considered in calculating the event frequencies for the site indices from measurement data.

IEEE P1564 draft 5 [24] proposes a five-step procedure for characterizing voltage dip performance, starting with actual waveforms and progressing to the characterization of system voltage dip performance. The procedure is illustrated in Figure 5-2.

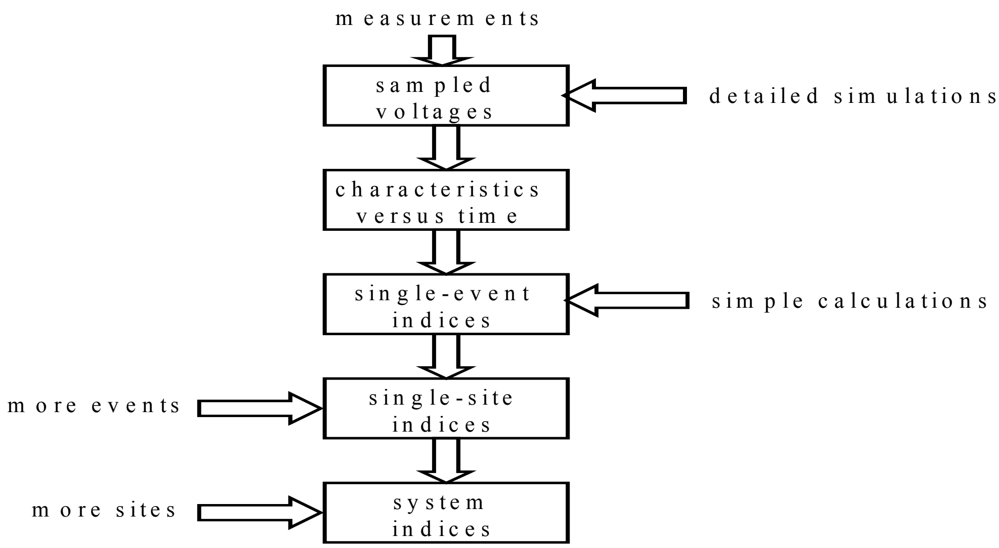

Figure 5-2
The Procedure for Obtaining Voltage Sag System Indices According to IEEE P1564 Draft 5

The voltage sag site index is most critical for the Service Quality Index so that is the focus of this discussion.

SARFI Indices

SARFI is an acronym for *System Average RMS Variation Frequency Index*. It is a power quality index that provides a count or rate of voltage sags, swells, and/or interruptions for a system. The size of the system is scalable: it can be defined as a single monitoring location, a single customer service, a feeder, a substation, groups of substations, or for an entire power delivery system. There are two types of SARFI indices: *SARFI-X* and *SARFI-Curve*. For our purposes, SARFI will be used as a single-site index (a one-site system).

SARFI-X corresponds to a count or rate of voltage sags and/or interruptions below a voltage threshold. For example, SARFI-90 considers voltage sags and interruptions that are below 0.90 per unit, or 90% of the reference voltage. SARFI-70 considers voltage sags and interruptions that are below 0.70 per unit, or 70% of the reference voltage. The SARFI-X indices are meant to assess short-duration rms variation events only, meaning that only those events with durations less than the minimum duration of a sustained interruption (5 minutes) are included in its computation.

As an example of calculating SARFI-x indices, consider the rms variation event summary table in Table 5-1, which was hypothetically measured at a single site. The count of voltage sags and interruptions that would be included in the SARFI-90 is 8, as there were 8 voltage sags and interruptions measured at this location that had a retained voltage below 0.9 per unit (90 percent) and between ½ cycle and 5 minutes in duration. This can be expressed as a rate of 31.3 events per year. This is computed by dividing the 8 events by the 92 days between July-01-2000 and Oct-01-2000, and then multiplying by 365/92 to normalize the index to events per year.

Table 5-1
Example rms Event Summary Table for Calculation of SARFI Indices

Time Stamp	Retained Voltage	Duration
Jul-01-2000 09:48:52	73%	9 cycles
Jul-01-2000 09:50:16	73%	9 cycles
Jul-07-2000 14:20:12	0%	82 cycles
Jul-10-2000 15:55:23	13%	100 cycles
Jul-21-2000 09:48:52	0%	2.6 seconds
Aug-08-2000 07:35:02	49%	34 cycles
Sep-02-2000 08:30:28	0%	41 seconds
Sep-08-2000 10:30:40	59%	40 cyc

Table 5-2
SARFI-x Indices Calculated for the Events in Table 5-1

Index	Count	Events per year
SARFI-90	8	31.7
SARFI-70	6	23.8
SARFI-50	5	19.8
SARFI-10	3	11.9

Another way to use the SARFI index is to count all the voltage sag events that are below a specified compatibility curve. This is referred to as the SARFI-curve approach. For example SARFI-CBEMA considers voltage sags and interruptions that are below the lower CBEMA curve. SARF-ITIC considers voltage sags and interruptions that are below the lower ITIC curve. SARFI-SEMI considers voltage sags and interruptions that are below the lower SEMI curve. An example is shown in Figure 5-3, where each recorded sag is indicated as one point in the magnitude-duration plot (note that "magnitude" is used here as a synonym to retained voltage). The SARFI-90 value is 87 in this case; SARFI-CBEMA is 43; SARFI-ITIC is 26 and SARFI-SEMI is 12.

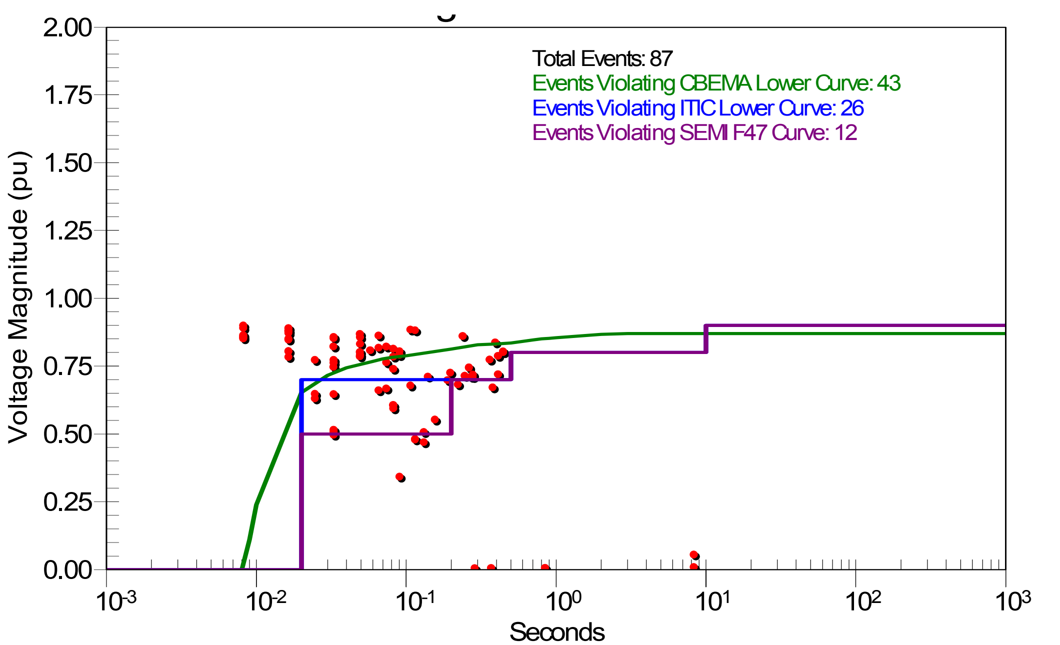

Figure 5-3
Scatter Plot of Voltage Sag Events Superimposed With Compatibility Curves for Calculation of SARFI Indices

Time aggregation is very important with voltage sag events, just as it is in using Momentary Interruption events. Tables 5-3 and 5-4 below illustrate the process of time aggregation for an example set of data. One minute aggregation is used in this case. The results are plotted in a scatter plot and compared to the SEMI F47 curve in Figure 5-4.

Table 5-3
Example Table of Voltage Sag Events That Does Not Include Time Aggregation (Note That The Events do Include Phase Aggregation – That is There is Only One Entry Per Event Regardless of How Many Phases Were Affected)

Time Stamp	Retained Voltage (pu)	Duration (s)
05/02/2000 09:39:55	0.694	0.25
05/02/2000 09:39:58	0.878	0.1
05/08/2000 08:22:45	0.631	0.25
05/08/2000 08:22:48	0.858	0.15
05/08/2000 08:22:50	0.459	0.1
05/08/2000 08:23:11	0.853	0.117
05/08/2000 08:23:14	0.542	0.517
05/08/2000 08:23:37	0.552	0.483
05/08/2000 08:36:12	0.772	0.033
05/08/2000 08:45:24	0.838	0.167
05/08/2000 08:45:54	0.545	0.233
05/08/2000 08:46:00	0.47	0.133
05/08/2000 08:46:19	0.892	0.15
05/08/2000 08:46:24	0.545	0.483
05/08/2000 08:46:42	0.861	0.117
05/14/2000 08:03:00	0.831	0.067
05/14/2000 09:06:59	0.828	0.05
05/17/2000 14:39:05	0.891	0.067
05/29/2000 03:33:54	0.013	0.2
05/29/2000 03:34:17	0.068	0.133
05/29/2000 03:34:42	0.008	0.067
05/30/2000 07:53:14	0.721	0.067
05/30/2000 07:53:18	0.76	0.1
05/30/2000 08:00:09	0.684	0.033
05/30/2000 13:15:03	0.763	0.033

Table 5-4
Example Table of Voltage Sag Events After Applying Time Aggregation of One Minute (Based on Data in Table 5-3)

Time Stamp	Retained Voltage (pu)	Duration (s)
05/02/2000 09:39:55	0.694	0.25
05/08/2000 08:22:45	0.459	0.1
05/08/2000 08:36:12	0.772	0.033
05/08/2000 08:45:24	0.47	0.133
05/08/2000 08:46:24	0.545	0.483
05/14/2000 08:03:00	0.831	0.067
05/14/2000 09:06:59	0.828	0.05
05/17/2000 14:39:05	0.891	0.067
05/29/2000 03:33:54	0.008	0.067
05/30/2000 07:53:14	0.721	0.067
05/30/2000 08:00:09	0.684	0.033
05/30/2000 13:15:03	0.763	0.033

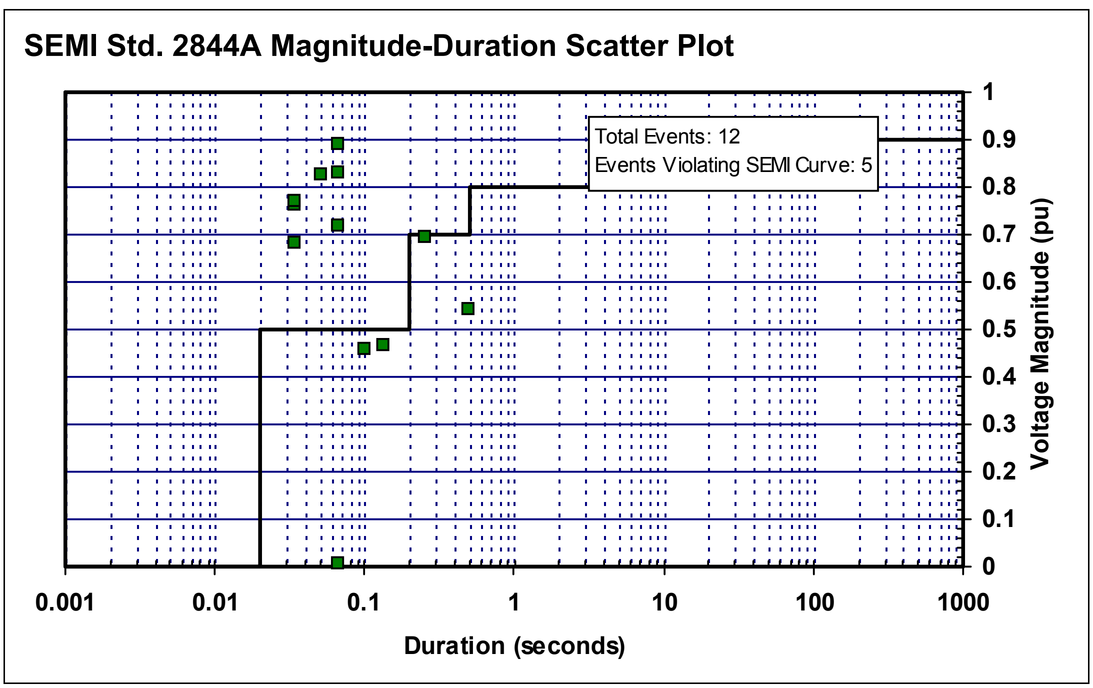

Figure 5-4
Scatter Plot of Voltage Sag Events Superimposed With SEMI F47 Curve for Calculation of SARFI-SEMI After Applying Time Aggregation of One Minute

Voltage Sag Tables

A commonly used method of presenting the performance of a site is by means of a voltage sag table. The columns of the tables represent ranges of voltage sag durations; the columns represent ranges of retained voltage. Each cell in the table gives the number of events with the corresponding range of retained voltage and duration. Each event, i.e. each combination of retained voltage and duration fits in only one cell of the table. Different values are in use for the boundaries between the cells.   The most popular voltage sag tables in use around the world are described briefly here.

Measured voltage sags may have a duration or retained voltage value that corresponds exactly with the border between two cells. These events should be placed in a cell according to recommendation in IEEE Std.493 [28]: a voltage sag with an index value on the border between two cells will be added to the cell with the most severe sags. Thus a sag with 500 ms duration will be added to the (0.5-1 s) duration range; a sag with a retained voltage of 85% will be added to the (70-85%) range.

Unipede Table

The Unipede table has been commonly used for characterizing voltage sag performance from surveys in Europe. The cells of the table are shown in Table 5-5.

Table 5-5
Voltage Dip Density Table Recommended by UNIPEDE

retained voltage	DURATION OF THE VOLTAGE SAG						
	<1 cycle	1 cycle-0.1 s	0.1-0.5 s	0.5-1 s	1-3 s	3-20 s	20-60 s
85-90%							
70-85%							
40-70%							
10-40%							
≤10%							

IEC 61000-4-11

IEC 61000-4-11 recommends a set of magnitude and duration values for testing equipment ride through characteristics. These specifications can be used as the basis for a sag density table, as shown in Table 5-6.

Table 5-6
Voltage Dip Density Table Based on Testing Recommendations in IEC 61000-4-11

Retained voltage	DURATION OF THE VOLTAGE SAG				
	<1 cycle	1 cycle-200 ms	0.2-0.5 s	0.5-5 s	5s-1 min
70-80%					
40-70%					
10-40%					
≤10%					

South-African Standard NRS 048-2:2003

The South African standard NRS 048-2:2003 defines a voltage sag table with five ranges of retained voltage and duration, as shown in Table 5-7.

The aim of that standard is to give compatibility levels for voltage sags in the form of a maximum number of voltage sags per year for defined ranges of voltage sag duration and retained voltage, designated as sag window categories.

Table 5-7
Voltage Dip Density Table From Standard NRS-048:2003

<table>
<tr><td rowspan="2">retained voltage</td><td colspan="4"></td></tr>
<tr><td><150 ms</td><td>150-600 ms</td><td>0.6-3 s</td><td>3 s – 1 min</td></tr>
<tr><td>85-90%</td><td colspan="3"></td><td>I1</td></tr>
<tr><td>80-85%</td><td colspan="2">Y</td><td rowspan="2">Z1</td><td rowspan="5">I2</td></tr>
<tr><td>70-80%</td><td></td><td rowspan="3">S</td></tr>
<tr><td>60-70%</td><td>X1</td><td rowspan="3">Z2</td></tr>
<tr><td>40-60%</td><td>X2</td></tr>
<tr><td>≤40%</td><td colspan="2">T</td></tr>
</table>

IEC 61000-2-8

The voltage-sag table as proposed in draft IEC 61000-2-8 is shown in Table 5-8. This table is basically an expansion of the UNIPEDE table to provide better definition of voltage sag categories. The disadvantage is the added complexity.

Table 5-8
Voltage Dip Density Table Recommended in IEC 61000-2-8

	<0.1 s	0.1-0.25 s	0.25-0.5 s	0.5-1 s	1-3 s	3-20 s	20-60 s	1-5 min
80-90%								
70-80%								
60-70%								
50-60%								
40-50%								
30-40%								
20-30%								
10-20%								
≤10%								

Voltage Sag Energy Index

The voltage sag energy is defined as:

$$E_{VS} = \int_0^T \left[1 - V(t)^2\right] dt \qquad \textbf{Eq. 5-3}$$

where

V(t) is the rms voltage in per unit.

The integration is taken over the duration of the event, thus for all values of the rms voltage below the threshold.

The sag energy method of characterization uses three site indices: number of events per site; "total lost energy" per site and "average lost energy" per event.

The "Sag Energy Index" (SEI), is the sum of the voltage sag energies for all qualified events at a given site during a given period. The indices are usually calculated monthly and annually.

$$SEI = \sum_{i\_1}^{n} \mathrm{E}_{VS\_i} \qquad \textbf{Eq. 5-4}$$

where

i is the sag event number and *n* is the number of qualified events during the given period at a given site. The sag-energy index, when expressed in units of time, can be interpreted as the length of the equivalent interruption with the same lost energy as all sags together that occurred during the observation period.

The " Average Sag Energy Index" or ASEI is the average of the voltage sag energies for all qualified events measured at a given site during a given period:

$$ASEI = \frac{1}{n}\sum_{i=1}^{n} \mathrm{E}_{VS\_i} \quad \textbf{Eq. 5-5}$$

The ASEI is dependent on the triggering of the monitor. A sensitive setting will result in a large number of shallow events (with a low sag energy) and thus in a lower value for ASEI. The SEI on the other hand will increase for sensitive setting of the monitor. To compare results from site to site and from one period to another, a standardized trigger setting needs to be defined. A value of 0.9 pu sag voltage for qualifying the sag events is recommended.

The SARFI-90 index is used as a third index to quantify the number of events at the site. Note that only two of the three indices are needed as they are related according to:

$$\mathrm{SEI} = \mathrm{ASEI} \times \mathrm{SARFI90} \quad \textbf{Eq. 5-6}$$

When using voltage sag energy indices it is recommended to not include momentary interruptions, as one momentary interruption may have a larger contribution to the index than all voltage sags together. The user of the index may decide to add a separate voltage sag energy index for momentary interruptions or to use the definitions as recommended in IEEE Std.1366.

For purposes of the Service Quality Index, we are recommending that momentary interruptions be treated separately from voltage sags.

Voltage Sag Severity Index

The voltage-sag severity S_e is defined from the retained voltage V in per-unit and the duration d by comparing these values with the SEMI F47 curve or some other compatibility curve. The algorithm for calculating the voltage-sag severity proceeds as follows (assuming the severity is based on the SEMI F47 curve):

$d \le 1$ cycle: $S_e = 1 - V$

1 cycle $< d \le 200$ ms: $S_e = 2(1 - V)$

200 ms $< d \le 500$ ms: $S_e = 3.3(1 - V)$

500 ms $< d \le 10$ s: $S_e = 5(1 - V)$

$d > 10$ s: $S_e = 10(1 - V)$

The calculation of site indices for the voltage sag severity method is very similar to the calculation of site indices based on the voltage sag energy.

Three site indices are introduced to characterize the site performance:

- total voltage-sag severity: $S_{SITE} = \sum_{i=1}^{N} S_{e-i}$
- average voltage-sag severity: $S_{average} = \frac{S_{SITE}}{N}$
- the number of events for the site: N

Note that N is equal to SARFI-90 and that the same relation between the indices holds as for the voltage-sag energy method:

$$S_{SITE} = S_{average} \times \text{SARFI90} \qquad \textbf{Eq. 5-7}$$

The user of the index may decide to not include short interruptions in the voltage-sag severity indices but instead quantify that aspect of power quality by means of the indices defined in IEEE Std.1366.

Voltage Sag Coordination Charts

A method for reporting site information from event magnitude and duration is described in IEEE Std.1346-1998 [27] and in IEEE Std.493-1997 [18]. The method uses a "voltage sag coordination chart" to represent the expected voltage sag performance of the supply system. An example of such a chart is shown in Figure 5-5. The chart gives the number of events per year (sags and interruptions) as a function of the severity of the event. For the example shown here there is on average 1 event per year where the voltage drops below 50% for 100 ms or longer. There is also on average 1 event per year more severe than 80%, 200 ms and on average 0.1 event per year below 70% for longer than 500 ms.

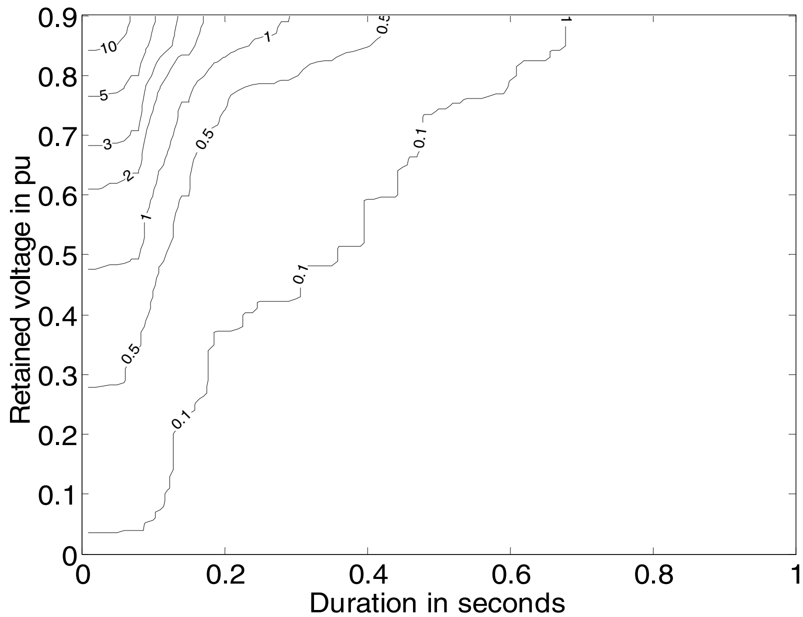

Figure 5-5
Example of a Voltage Sag Coordination Chart Representing Voltage Sag Performance of HV Sites (Based on Procedure Defined in IEEE 1346)

Future Directions

New methods are being proposed in the literature to determine direction (upstream, downstream) and cause (fault, motor, transformer, other) of a voltage-dip event. In addition, there are new indices based on phase-angle jump, symmetrical component voltages, point-on-wave, etc. Methods need to be developed to present site indices when additional single-event indices like phase-angle jump and symmetrical component voltages are included. Site indices for three-phase characterization of dips may consist of one set of indices or of different sets of indices for different types of dips. Implementation of these new methods and indices could provide systematic indications on the causes of dips and allow better prediction of the effects of voltage dips on different type of sensitive equipment. The effect on the site indices of the propagation of voltage dips to lower voltages should be investigated.

Stochastic prediction methods are needed to obtain voltage dip site indices and system indices, thus avoiding long and expensive monitoring programs. Recommendations to that effect are given in IEEE Std.493. Methods for voltage-dip state estimation need to be developed, where the site indices for non-monitored sites are estimated from the site indices for monitored sites.

Recommended Voltage Sag Site Index

Many different methods of summarizing voltage sag performance are used and this makes it difficult to compare results between systems. System characteristics result in widely different voltage sag performance anyway and methods of accounting for system characteristics are needed in addition to consistent reporting methods.

For purposes of the Service Quality Index, there is a need to keep the voltage sag performance index as simple as possible while still including the important factors determining whether or not a sag is likely to have an impact on customer operations. It is also useful if the index chosen has a similar characteristic to the other indices that will be used in conjunction with the sag index (SAIFI, SAIDI, MAIFI).

Based on these requirements, the best approach for characterizing sag performance using a simple index is one of the SARFI-curve indices. Possible choices would be the SARFI-ITIC index or the SARFI-SEMI index. The SARFI-SEMI index is attractive because it effectively encourages customers to move towards equipment that has better ride through characteristics (according to the specifications of the SEMI-F47 standard). However, there is still a great deal of equipment that is more sensitive than the specifications of SEMI F47 and many of the events that could affect this equipment would not be counted in the SARFI-SEMI index. **Therefore, the recommendation is to use the SARFI-ITIC index as the basis for evaluating voltage sag performance.** This is applied on a site basis and is a count of the expected sags per year that would be more severe than the ITIC curve specification.

Since momentary interruption events will be counted separately with the MAIFI index, it is important that these events not get counted twice. Therefore, a modified SARFI-ITIC index is proposed that counts all of the voltage sags more severe than the ITIC curve but subtracts the MAIFI performance based on momentary interruption events.

6
DESCRIBING THE STATISTICS OF RELIABILITY AND VOLTAGE SAG PERFORMANCE

Characterization is a process in which existing levels of service quality are determined as well as the levels of quality that can be reasonably expected. *Benchmarking* is the process of comparing the supply quality characteristics of the power delivery system of a utility or multiple utilities that defines a geographic region with external performance. Thus, characterization and benchmarking are two specific activities in which data is obtained to help define and compare the quality of supply.

The final step in the supply quality characterization process is the statistical analysis and presentation of the data. All of the supply quality parameters are stochastic in nature. Describing these characteristics is particularly important for the disturbance components of the supply quality (SAIFI, SAIDI, MAIFI, SARFI-ITIC). Variability and uncertainty analysis is critical in defining baseline threshold levels and also in identifying the range of quality of supply parameters that can be expected.

Utilities typically use deterministic analysis methods to assess the risks associated with disturbances to electric power systems. Traditionally, the average and/or median of an index are used to reflect performance. Data analysis using a single estimate such as an average is called *deterministic approach*. However, a deterministic method often produces overly conservative results. While improvements in modeling the system behavior might lead to more accurate estimates of the *average* values for power quality indices, the deterministic approaches do not consider the *variability* and *uncertainty* in the data. Conversely, a probabilistic approach provides the ability to view the full range of variability and uncertainty as opposed to presenting service quality indices as simple point values.

This chapter provides insights into the concepts of variability and uncertainty in data and provides the basics of probabilistic methods that can be used to assess quality of service from monitored data and its application to the Service Quality Index.

Variability and Uncertainty Analysis

Variability represents heterogeneity or diversity, which is not reducible through further measurement or study. Fundamentally a *property of nature*, variability arises due to the differences in the value of a quantity among different members of a population. For example, variability might refer to different feeders in a distribution system having different performance in terms of voltage interruptions. In essence, some feeders will perform better than the others due to differences in topology, weather, and existing system conditions, and so on.

Additionally, some years will be more severe in terms of storms, lightning flashes, tornados, and so on than other years that can greatly impact the quality of supply. Regardless of the level of measurement accuracy, this variability cannot be reduced with further measurement. Variability is an intrinsic property of distribution systems that makes each feeder unique in its performance. Therefore variability is present across the system data (spatial variation) as well as over a period of time (temporal variation). Statistical indices such as CP05 (5^{th} percentile), CP50 (50^{th} percentile), CP95 (95^{th} percentile) represents variability in a dataset.

Uncertainty represents lack of knowledge about a poorly characterized phenomenon that is sometimes reducible through further measurement or study. Fundamentally a *property of the risk assessment*, uncertainty might be reduced through further measurement. For example, one-year voltage sag measurements at a substation provide an indication of the expected voltage sag performance at the substation for that given year. However, it does not accurately represent the "expected" voltage sag rate in the future. Further measurement over a longer period of time will reduce, but not necessarily eliminate the uncertainty in quantifying the expected voltage sag rate at that substation.

As a result, uncertainty is unavoidable in any service quality dataset. In general, utilities do not have the resources to monitor all the feeders in its service territory. System performance therefore can and should be predicted from the limited information available. Also, monitored data at a feeder will be available only for a limited period of time. Uncertainty is quantified using a desired confidence level (C.I.) or probability band, which also is representative of risk (e.g., 95% C.I. level and 50% C.I. level).

A sample two-dimensional analysis of variability and uncertainty is illustrated in Figure 6-1. Proxy data, which is representative of a 10-year system-wide variation in average SAIDI of a utility, was used for this example. The intent of Figure 6-1 is to emphasize the basis for shifting towards a probabilistic framework in order to better assess risk. This framework, unlike a deterministic approach, can be used to account for variability and uncertainty in a dataset and thereby reduce risk associated with using the Service Quality Index to make decisions about investment.

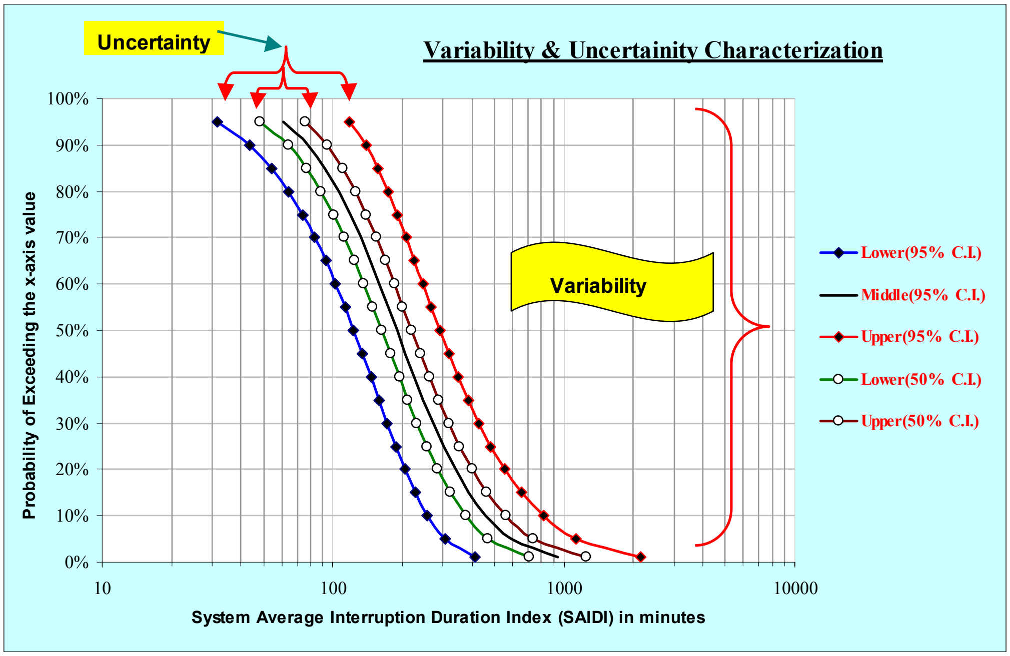

Figure 6-1
Characterizing Variability and Uncertainty for Reliability and Quality Disturbance Data

Analysis of the dataset using a deterministic framework would suggest that the *average* and *median* of SAIDI for this system would be 242.86 and 149.57 minutes, respectively. However, as can be seen in Figure 6-1, significant variability and uncertainty exists in this dataset. The variability is not captured when the data is only described with a single statistic (e.g. mean). Distributions illustrate the variability of the data and the uncertainty is characterized with different confidence levels that provide a picture of the risk associated with using a oarticular estimate.

As an example, consider 50% probability of exceeding x-axis. Using 95% confidence level, the lower and upper bounds of SAIDI (median) were found to be 123 and 289 minutes. This means that one is 95% confident that the 50^{th} percentile will lie between 123 and 289 minutes. Similarly, based on a 50% confidence level, the 50^{th} percentile will lie between 163 and 219 minutes. Simply put, one is 50% confident that the 50^{th} percentile will lie between 163 and 219 minutes.

This approach of probabilistic risk assessment enables risk managers to assess the full range of variability and uncertainty instead of being misled into thinking that PQ parameters are point values.

Methods for Variability and Uncertainty Analysis

There are several statistical measures that can be used for variability and uncertainty analysis. Statistical approaches, which can be used to quantify variability and uncertainty include:

- Normalized Standard Deviation
- Poisson Distribution (Discrete)
- Weibull Distribution (Continuous)
- Log Normal Distribution (Continuous)
- Non Parametric Bootstrap method

A comprehensive explanation of all these methods can be found in most statistical reference books and software manuals. Subsequent sections in this chapter will focus on illustrating the use of some of these techniques in assessing uncertainty in the components of a Service Quality Index.

The following section will illustrate the use of normalized standard deviation for assessing variability within a 10-year dataset of SAIFI, SAIDI and MAIFI for three utilities. The same concepts would apply to the SARFI calculations. Additional sections in this chapter will illustrate the application of more advanced statistical techniques for assessing variability.

Normalized Standard Deviation for Assessing Variability

Standard deviation is a measure of the spread of a data set around its mean. The use of standard deviation implies that the dataset has a normal distribution. One characteristic for a normally distributed dataset is that the mean and the median are equal or close in value. In a perfectly symmetrical distribution such as the normal distribution, the mean and median converge at the same point as shown in Figure 6-2. Normalized standard deviation is the ratio of standard deviation and mean for a data set. Normalized standard deviation allows comparison of the variability of two different data sets with different mean or datasets that have different units of measure. An example of this is comparing the variability in SAIDI, which has a unit of minutes, and SAIFI, which has a unit of frequency of occurrences per year.

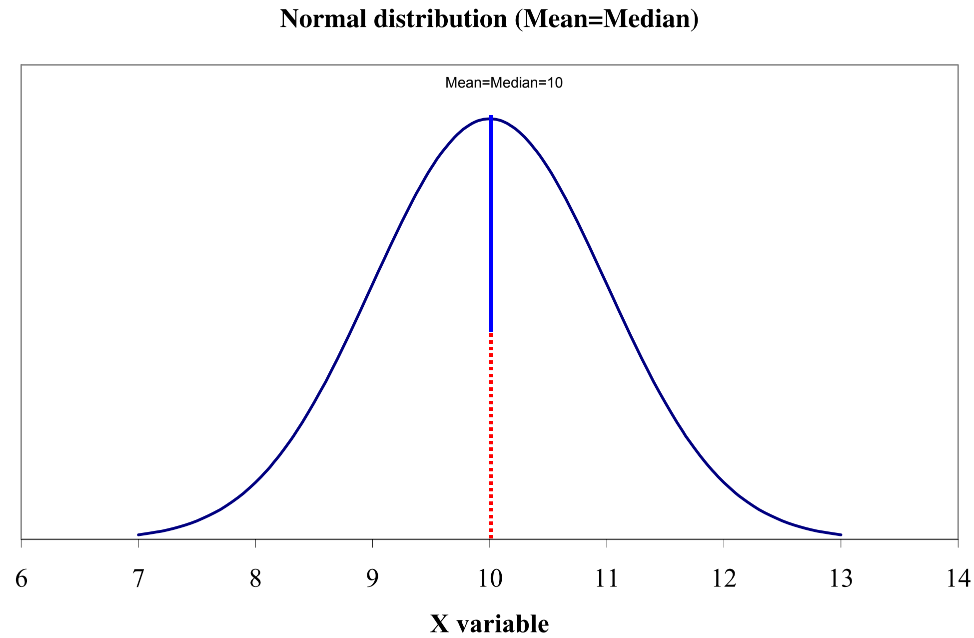

Figure 6-2
Normal Distribution

Sample Data Set Used for Variability Analysis

Publicly available historical data for SAIDI, SAIFI, and MAIFI from four utilities in the west coast of the United States was used as a sample data set. These utilities also report these indices with and without inclusion of major events. This allows a comparative analysis to evaluate the impact of major events in overall performance indicators as well as the variability of the performance indicator. Table 6-1 summarizes the data for these four utilities and the mean, median, standard deviation, and normalized standard deviation for each dataset. While the mean and median for each dataset are not equal in all cases, the values are relatively close and an assumption of normal distribution is valid.

Table 6-1
Variability Analysis (Using Normalized Standard Deviation) for Four Utilities Long Term Reliability Indices

		1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	Mean	Median	Std Dev (SD)	Normalized SD
Utility 1	SAIFI (Major Events Excluded)	1.61	1.61	1.57	1.55	1.62	1.63	1.66	1.48	1.39	1.43	1.56	1.57	0.092	5.90%
Utility 2		1.00	0.87	0.92	0.72	1.04	0.93	0.94	0.67	0.57	0.64	0.83	0.87	0.165	19.93%
Utility 3		1.61	0.84	2.44	4.04	2.68	1.82	3.15	1.81	1.65	1.22	2.13	1.82	0.959	45.09%
Utility 4		0.77	0.72	0.53	0.71	0.76	0.79	0.91	0.68	0.71	0.65	0.72	0.72	0.098	13.49%
Utility 1	SAIDI (Major Events Excluded)	143.30	151.60	152.90	164.90	167.50	160.90	180.10	156.80	166.40	215.60	166.00	164.90	20.187	12.16%
Utility 2		72.80	83.60	57.80	56.90	81.90	89.30	91.60	65.20	51.90	52.90	70.39	70.39	15.404	21.88%
Utility 3		100.60	64.10	214.30	244.80	168.60	124.80	164.33	137.56	118.86	153.24	149.12	149.12	52.972	35.52%
Utility 4		65.41	58.02	41.15	63.30	57.80	69.95	69.13	40.42	37.98	41.03	54.42	57.80	12.925	23.75%
Utility 1	MAIFI (Major Events Excluded)	1.37	1.31	1.39	1.27	6.30	4.25	3.11	2.58	2.24	2.08	2.59	2.24	1.615	62.37%
Utility 2						1.53	1.41	1.09	0.80	0.75	0.86	1.07	1.07	0.331	30.81%
Utility 3								3.78	1.80	2.78	0.90	2.32	2.32	1.242	53.64%
Utility 4		1.43	1.29	1.30	1.25	1.61	1.64	1.79	1.59	1.64	1.55	1.51	1.55	0.180	11.89%
Utility 1	SAIFI (Major Events INcluded)	1.61	1.74	1.76	2.63	2.37	1.70	2.13	1.48	1.39	1.56	1.84	1.74	0.407	22.14%
Utility 2		1.00	0.87	0.92	0.87	1.48	0.93	0.94	0.67	0.57	0.87	0.91	0.91	0.239	26.16%
Utility 3		2.02	1.21	2.44	4.89	3.11	2.62	3.15	1.81	2.37	1.22	2.48	2.44	1.082	43.57%
Utility 4		0.90	0.72	0.68	0.71	1.19	0.79	0.91	0.68	0.71	0.65	0.80	0.72	0.167	20.98%
Utility 1	SAIDI (Major Events Included)	143.30	176.70	157.70	572.40	322.50	170.60	317.30	157.30	166.90	252.80	243.75	176.70	133.510	54.77%
Utility 2		72.80	83.60	67.80	98.50	133.90	89.30	91.60	65.20	51.90	68.50	82.31	82.31	23.021	27.97%
Utility 3		161.40	160.10	214.30	463.31	638.03	323.01	164.33	137.94	219.30	153.24	263.50	214.30	165.659	62.87%
Utility 4		91.73	58.02	119.87	63.30	120.94	69.95	69.13	40.42	37.98	41.03	71.24	69.13	30.671	43.05%
Utility 1	MAIFI (Major Events Included)	1.37	1.36	1.46	1.71	6.52	4.37	3.49	2.59	2.24	2.21	2.73	2.24	1.651	60.44%
Utility 2						1.53	1.41	1.09	0.80	0.75	0.87	1.08	1.08	0.329	30.65%
Utility 3								3.78	1.80	2.78	0.90	2.32	2.32	1.242	53.64%
Utility 4		1.64	1.29	1.42	1.25	1.63	1.64	1.79	1.59	1.64	1.55	1.54	1.59	0.170	10.98%

Observations From the Variability Analysis

The simple normalized standard deviation analysis allows for some powerful observations to be made. These observations can help in determining appropriate use of these statistical procedures in the Service Quality Index.

- Utility 3 has a significantly higher variability in its year-to-year SAIFI and SAIDI index (excluding major event) compared to the other utilities as shown in Figure 6-3. Additionally as can be seen from Figure 6-4, Utility 3 also is the smallest utility in terms of number of customers and therefore most likely has the least number of feeders. Variability of year-to-year system wide numbers will be larger for smaller utilities than larger utilities. This would imply that dead bands for performance indicators should be set wider for smaller utilities.

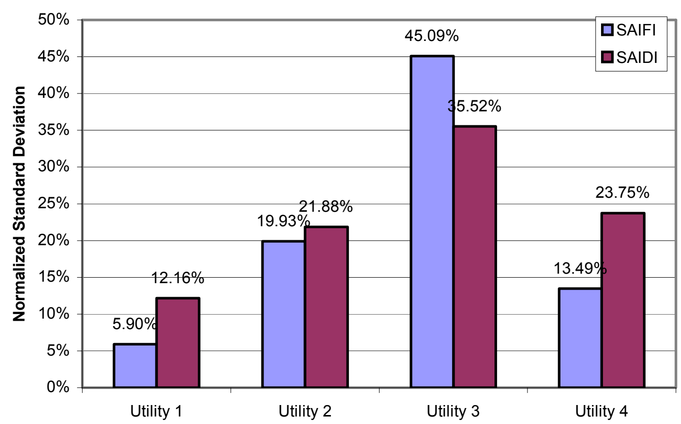

Figure 6-3
Year-to-Year Variability for SAIFI and SAIDI Indices

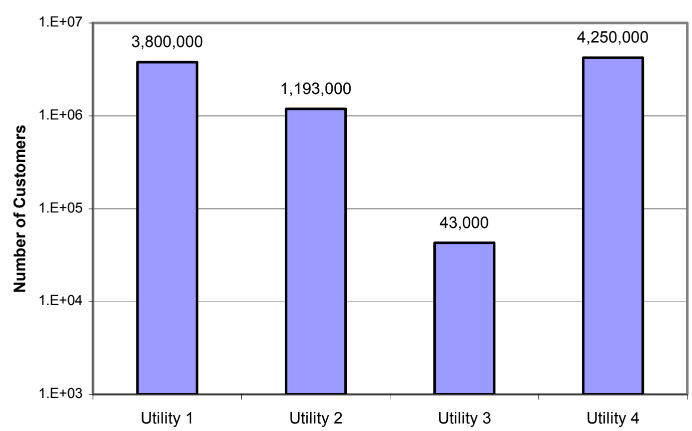

Figure 6-4
Number of Customer for the Four Utilities in the Sample Dataset

- Figure 6-5 illustrates the year-to-year variability in MAIFI indices. This variability is much higher than SAIFI or SAIDI. This illustrates that characterizing MAIFI with appropriate probability distributions may be even more important than SAIFI and SAIDI.

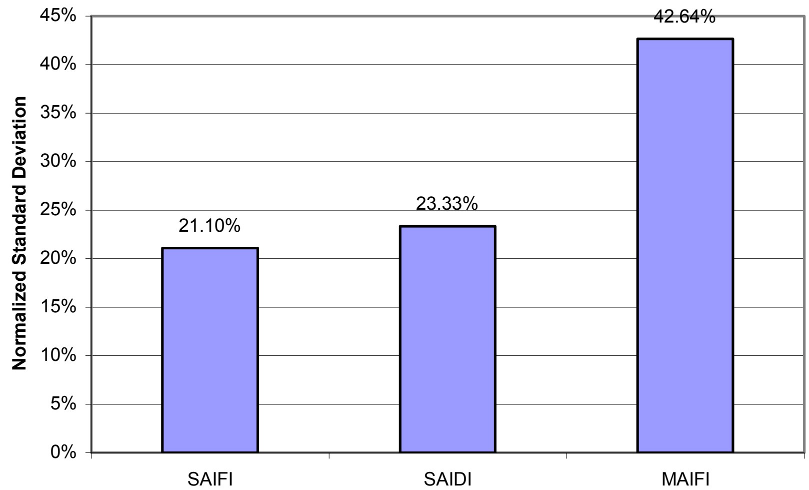

Figure 6-5
Variability of SAIFI, SAIDI and MAIFI Indices

- Inclusion of major events increases the year-to-year variability of SAIDI much more than SAIFI or MAIFI. Figure 6-6 indicates that the variability in SAIDI may double with the inclusion of major events. This is another important observation because we are proposing to include major events in the site indices for use in a Service Quality Index.

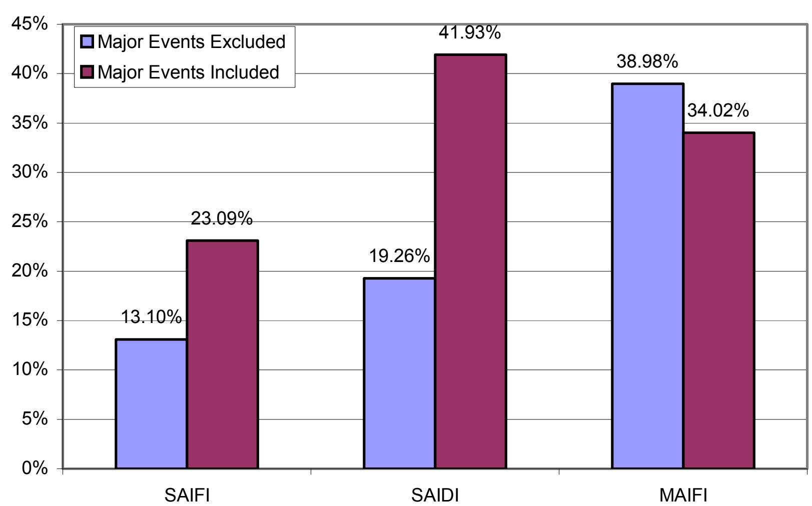

Figure 6-6
Impact of Major Events on Year-to-Year Variability

Probabilistic Framework Based on Poisson Distribution

There are a number of factors that make it difficult to use the "average" values of reliability and quality indices for prediction of future performance. This is one of the important objectives of the Service Quality Index – provide information that is useful in evaluating expected performance and the impact on customers. If we cannot use the average values for this purpose, we must develop appropriate methods of characterizing performance.

Reasons that the average value has limited use for prediction purposes:

- A large fraction of faults (the ultimate cause of outages, momentaries, and voltage sags) are directly attributable to bad weather: lightning, heavy wind, thunderstorms, and so on. The "average" fault performance is therefore not at all constant but follows the annual weather patterns. Moreover, the amount of weather activity also varies significantly from year to year.
- Power systems themselves are not static but change continuously from year to year. Load characteristics, feeder characteristics, protection equipment and philosophies, grounding, arresters, the environment (trees, animals) can all change from year-to-year. The result is different expected performance even for similar weather conditions.

Obviously, to obtain a more accurate estimate of long-term *average* values of power quality indices, a long-term monitoring period is required. Statistical data-analysis techniques based on Poisson distribution can be used to predict the following:

- For a certain accuracy level, one can estimate the minimum monitoring period that is required to obtain accurate long-term "averages" of power quality indices.
- For different power quality indices, one can observe that a less frequently occurring index needs a longer monitoring period to achieve the same level of accuracy. Simply put, the minimum monitoring period that is required to obtain an accurate long-term "average" of SARFI-ITIC will be less than MAIFI.
- For a given confidence level, 100(1-α[1])%, one can predict the uncertainty intervals (also commonly called in textbooks as error bands or confidence intervals) to better analyze and characterize supply quality and understand the risks of specifying a particular level.

The main characteristic of Poisson distribution is that *time between the events is exponentially distributed* (see Figure 6-7). This occurs when events are completely independent from each other. Under that condition, the number of events captured within a certain period is a stochastic variable with a so-called Poisson distribution.

[1] For a 95% confidence level, the error level/uncertainty level, alpha (α), is equal to 5%

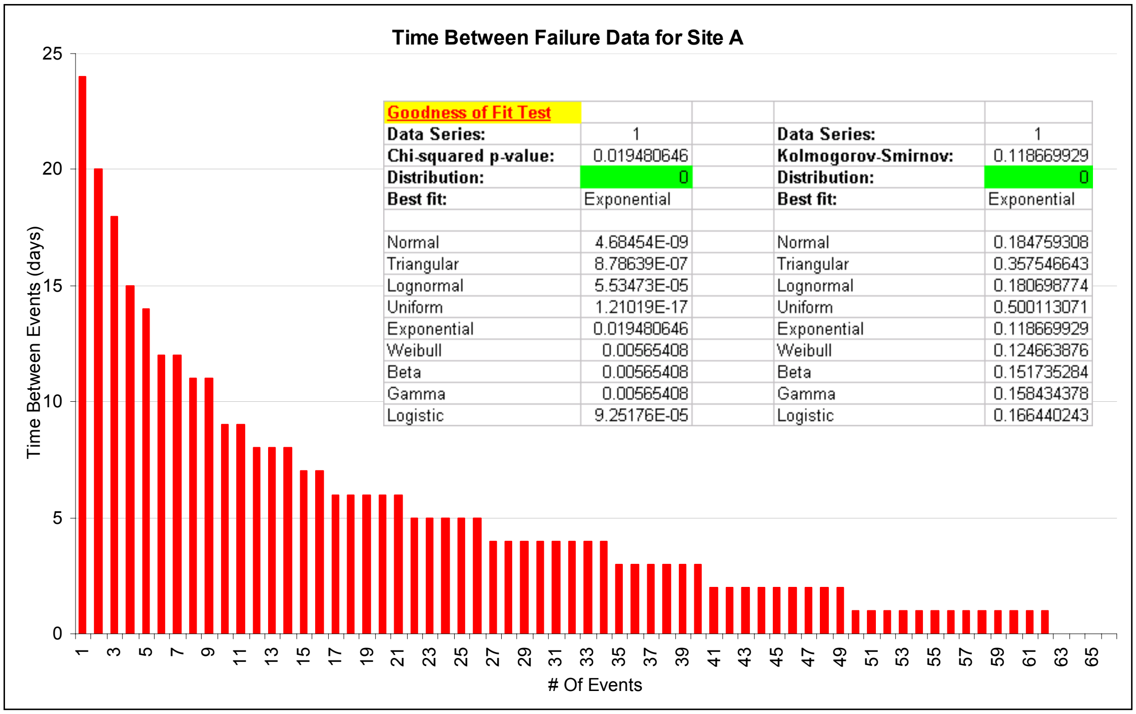

Figure 6-7
Frequency Distribution of Time-Between-Failures for Power Quality Events

For purposes of this section, an event is any power quality occurrence where the nominal voltage falls below a user-defined value or percent. It is assumed that the following two items are available from the data: 1) average number of power quality events (λ) per interval, expressed in either days, or weeks, or years; and 2) total monitoring period. Proxy data from a Distribution Power Quality study (DPQ) study [2] were used as a sample dataset.

Required Monitoring Period Estimation

The mathematical expression for the Poisson distribution is given in Equation (6-1). Symbols λ and $P(X)$ represent the expected number of events per interval (days, weeks, or years) and the probability of exactly X events given a knowledge of λ, respectively. It should be noted that the distribution has only one parameter, λ, which is the average or expected number of occurrences per unit (such as a day, week, month, or year). As an example, consider that $SARFI_{70}$ at a site recorded over a monitoring period of 600 days ("n") is 12. Then λ, the expected number of events/year, will be computed as (12/600) * 365 = 7.3 events/year.

$$P(X) = \frac{e^{-\lambda}\lambda^X}{X!} \qquad \textbf{Eq. 6-1}$$

The minimum required monitoring period (y) can be found as shown in Equation (6-2), where:

Y = Required minimum monitoring periods expressed in years/months/weeks

λ = Average number of fault per year/months/weeks/days

ε = Inaccuracy levels (for example to calculate 90% accuracy ε will be 1-0.9)

The symbol n denotes the monitoring period over which a sample site was monitored, expressed in years/months/weeks/days. The numerator “t-distribution parameter” is a factor obtained from Student’s t-distribution with (λ*(n-1)) degrees of freedom. If (λ*n) is large (>10), Student’s t-distribution can be approximated by a normal distribution with mean, μ, equal to (λn) and standard deviation, σ, equal to $\sqrt{\lambda}$. Note that a (λ*n) greater than 10 is considered a reasonably accurate approximation.

$$y \geq \frac{(t - distribution\ \ parameter)^2}{\varepsilon^2 \lambda} \qquad \textbf{Eq. 6-2}$$

For a 95% confidence interval with a large enough value of λn, Equation (6-2) can be re-written as shown in Equation (6-3).

$$y \geq \frac{(1.96)^2}{\varepsilon^2 \lambda} \qquad \textbf{Eq. 6-3}$$

Table 6-2 shows the analysis of power quality data obtained from the DPQ study to estimate the minimum monitoring period required to obtain accurate (95% confidence interval) long-term “averages” of power quality indices based on the Poisson distribution. The results obtained using the data collected from 7 substation sites in the DPQ study is shown in Table 6-2. Power quality index $SARFI_{70}$ is used here for illustrative purpose. Symbol λ represents $SARFI_{70}$ per year.

It is clear from the results obtained in Table 6-2 that as the event frequency increases, the minimum monitoring period required to obtain accurate long-term “average” of $SARFI_{70}$ reduces. Also, as accuracy increases (inaccuracy is lower), a longer monitoring period is required to get more accurate estimates.

Table 6-2
Minimum Monitoring Period as a Function of Accuracy Desired for $SARFI_{70}$ – "Substation Level" Sites From DPQ Study (Accuracy at the 95% Confidence Level)

Site ID #	$SARFI_{70}$	MD[2]	λ (Events/yr)	Accuracy 90% (in Years)	Accuracy 75% (in Years)	Accuracy 50% (in Weeks)	Accuracy 25% (in Weeks)
1	22	525	15.30	25.12	4.02	52.39	23.28
2	34	760	16.33	23.53	3.76	49.07	21.81
3	42	575	26.66	14.41	2.31	30.05	13.36
4	66	811	29.70	12.93	2.07	26.97	11.99
5	62	731	30.96	12.41	1.99	25.88	11.50
6	64	598	39.06	9.83	1.57	20.51	9.12
7	88	750	42.83	8.97	1.44	18.71	8.32

Table 6-3 provides the minimum monitoring period required to obtain an accurate long-term "average" of $SARFI_{50}$. The same sites as those used in Table 6-2 were chosen for comparative purposes. Comparing these results with those obtained in Table 6-2, it is clear that different $SARFI_X$ will have different rates of occurrence. Therefore, the monitoring time needed to achieve the same accuracy is different. For the same site and the same level of accuracy, because there will be more $SARFI_{70}$ events than $SARFI_{50}$, the minimum monitoring period required with $SARFI_{70}$ will be lower.

Table 6-3
Minimum Monitoring Period as a Function of Accuracy Desired for $SARFI_{50}$ – "Substation Level" Sites From DPQ Study

Site ID #	$SARFI_{50}$	MD	λ (Events/yr.)	Accuracy 90% (in Years)	Accuracy 75% (in Years)	Accuracy 50% (in Weeks)	Accuracy 25% (in Weeks)
1	5	525	3.48	110.51	17.68	230.50	102.44
2	10	760	4.80	79.99	12.80	166.84	74.15
3	9	575	5.71	67.24	10.76	140.25	62.33
4	37	811	16.65	23.07	3.69	48.12	21.39
5	42	731	20.97	18.32	2.93	38.21	16.98
6	21	598	12.82	29.97	4.80	62.51	27.78
7	40	750	19.47	19.73	3.16	41.16	18.29

[2] MD – Monitoring Days

Accounting for Uncertainty and Variability

In practice, monitoring periods are generally limited. This means that λ obtained from the monitored data is not the true value but only a *point estimate* obtained from the data. Besides, λ obtained from the monitored data differs from the true mean value. Therefore, it is important to account for uncertainty in the dataset as a result of limited monitoring period. This is obtained by constructing an uncertainty interval for λ.

Approximating the Poisson distribution with a normal distribution, an uncertainty/error interval (based on a 95% confidence level) is obtained as shown in Equation (6-4). This approximation is quite good if (λ*n)[3] is large (>20). Otherwise, a more accurate estimate of confidence intervals could be obtained using a chi-square distribution, as shown in Equation (6-5). Once the lower and upper bounds of λ are obtained from either Equation (6-4) or Equation (6-5), Equation (6-1) can be applied to find lower and upper bounds for the probability of *X* faults occurring in a given period. This will account for variability that is inherent in the dataset. These probabilities can then be converted into risk associated with the estimate.

$$\left[\lambda_{Upper}, \lambda_{Lower}\right] = \lambda \ \pm \ z_{(1-\alpha/2)}\left(\frac{\lambda}{n}\right)^{1/2} = \lambda \ \pm \ 1.96\left(\frac{\lambda}{n}\right)^{1/2} \qquad \textbf{Eq. 6-4}$$

$$\left[\lambda_{Upper}, \lambda_{Lower}\right] = \left[\frac{0.5*\chi^{2}_{((1-\alpha/2),2\lambda n)}}{n}, \frac{0.5*\chi^{2}_{(\alpha/2,(2\lambda n+2))}}{n}\right] \qquad \textbf{Eq. 6-5}$$

Figure 6-8 illustrates the uncertainty bands of $SARFI_{70}$ for seven substation sites. The same sites as those used in Table 6-2 were chosen. Note that different sites have different uncertainty characteristics and this relationship is not related directly to the calculated average levels.

[3] Symbol *n* is the monitoring period over which a sample site was monitored expressed in years/months/weeks/days, and symbol λ is the average number of faults per year/months/weeks/days.

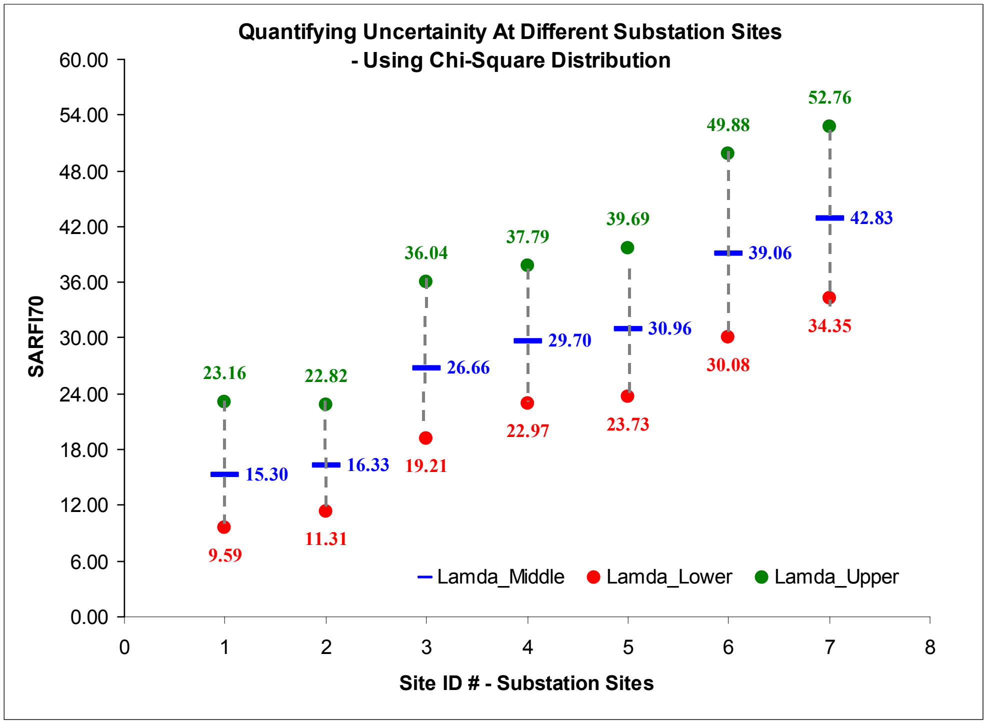

Figure 6-8
Accounting for Uncertainty in $SARFI_{70}$ – Substation Sites (95% Confidence Interval Shown)

The uncertainty in predicting the expected (average) level can be reduced through longer monitoring or sample periods. Table 6-4 illustrates the uncertainty in predicting the average rate for SARFI-90 over six years of monitoring. The results show that the uncertainty decreases with each year of monitoring. This is illustrated in Figure 6-9.

Table 6-4
Power Quality (SARFI-90) Monitored for Six Consecutive Years at an Individual Site (95% Confidence Level Indicated)

Year	$SARFI_{90}$	λ^*	λ_Lower	λ_Upper	λ_Upper - λ_Lower
1994	15	15.00	8.40	24.74	16.34
1995	23	19.00	13.45	26.08	12.63
1996	10	16.00	11.80	21.21	9.42
1997	33	20.25	16.08	25.17	9.09
1998	13	18.80	15.19	23.01	7.81
1999	6	16.67	13.56	20.27	6.71

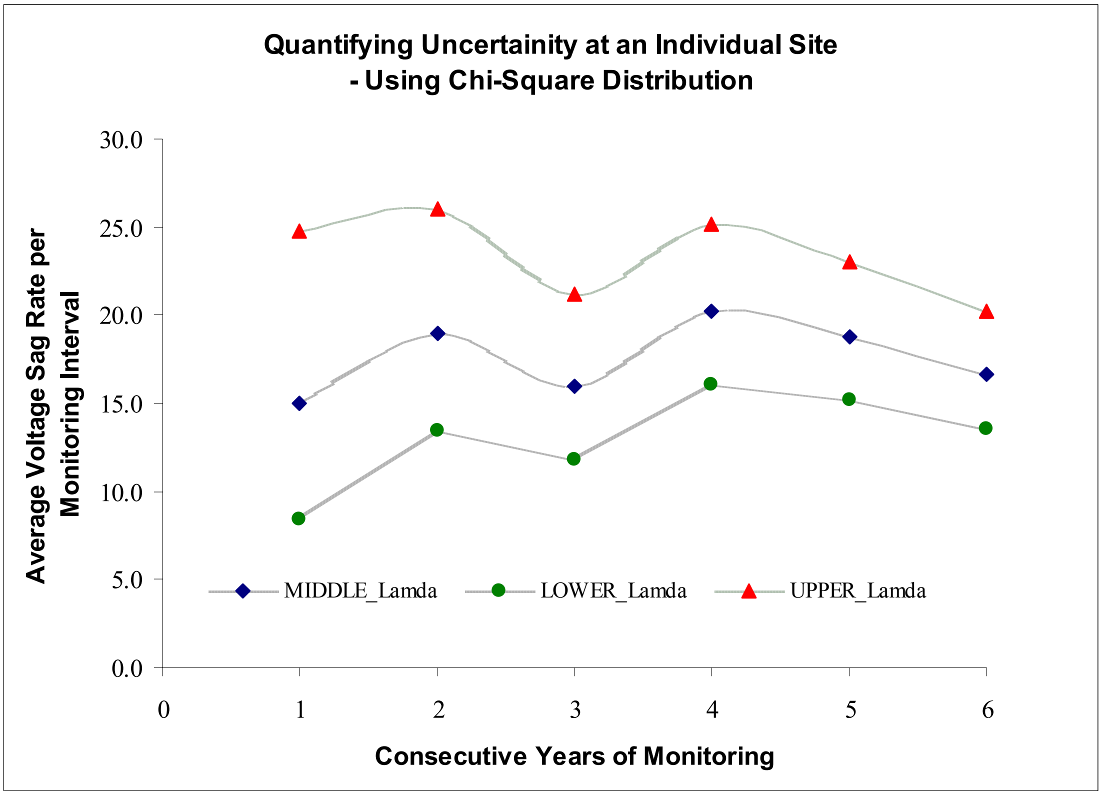

Figure 6-9
Reduction in Uncertainty as a Function of the Monitoring Period (Illustration Using SARFI-90 Performance Monitored for Six Years)

General Guidelines to Account for Uncertainty and Variability

As discussed earlier in this chapter, reliability and power quality disturbance indices exhibit a variability that is not adequately captured using a deterministic approach. Limited monitoring durations also give rise to an uncertainty in predicting the average value or the distribution of performance index values. This chapter has described methods that can be used to represent typical reliability and power quality indices with appropriate distributions and then apply statistical methods to describe the uncertainty in predicted performance levels.

Reliability indices typically have a characteristic distribution like the one shown in Figure 6-10 below. There is a large peak at lower values of the index and then a long tail representing the few sites that have poor reliability performance. In a skewed distribution like this, the average is higher than the median. Additionally, poor performing sites and anomalies such as severe storms skew the average upward. Since the distribution is not normal, all the characteristics derived based on the assumption that the distribution is normal are invalid.

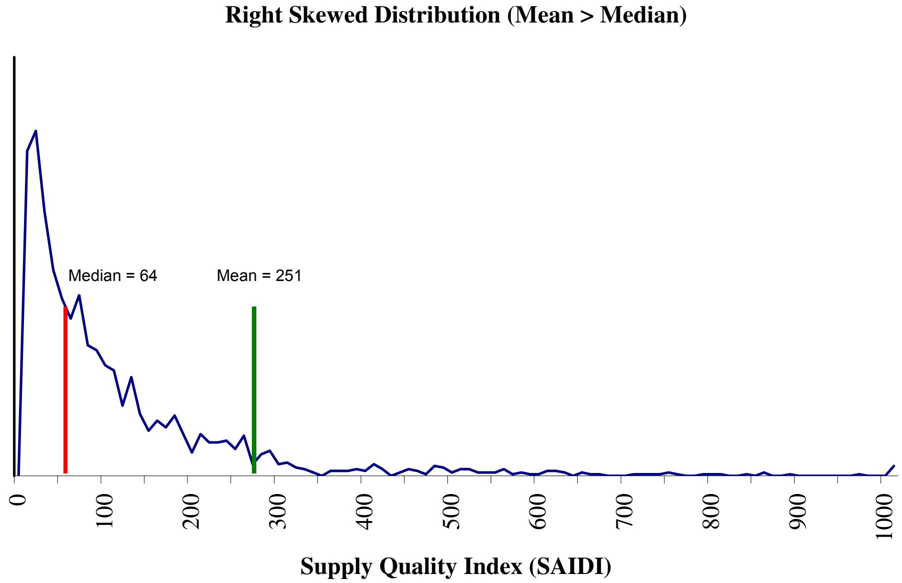

Figure 6-10
Right Skewed Distribution Typical of Many Reliability Distributions

With this in mind, the average of a small number of data points (often a typical PUCs baseline) is quite likely to be less than the real long-term average. This is especially unfortunate when only penalties are implemented and there is no upper limit regardless of whether major events are allowed to be excluded. Advanced probability techniques such as parametric and nonparametric [2-7] can be used to account for the inherent skew that may exist for a dataset and thereby can provide a more accurate estimate of spatial and temporal variability and uncertainty. Advanced probability methods enable the reporting of indices based on probability/percentile representation that is more accurate than a simple deterministic use of numbers such as an *average* or *median* of the given index.

General procedures that can be used to estimate variability and uncertainty using probabilistic techniques are summarized below. The steps include:

Performance Indicators of Interest: Identify the metrics (SAIFI, SAIDI, MAIFI, SARFI-ITIC) to characterize expected performance at the site of interest.

Simple Tests to Account for Variability: Normalized Standard Deviation techniques can be used to estimate variability in a dataset. Note, however, that this technique cannot be used to account for data uncertainty.

Advanced Analysis: If advanced statistical software is available, more advanced techniques can be used to account for spatial and temporal variability and uncertainty. Parametric or nonparametric techniques may be appropriate depending on whether the data can be represented with a specific distribution, such as a lognormal distribution.

- ***Applying Parametric-Based Techniques:*** If a given dataset fits a standard statistical distribution (Lognormal, Weibull, etc.) with reasonable accuracy, use parametric methods to estimate variability and uncertainty by 1) Constructing the cumulative distribution function (CDF), 2) Constructing confidence bands around the CDF, and 3) Calculating the range of expected performance at specific confidence intervals.

- ***Applying Non Parametric-Based Techniques:*** If a given dataset does not fit a standard statistical distribution, apply non-parametric methods (Bootstrap, Monte-Carlo, etc.) to estimate variability and uncertainty by 1) Constructing the cumulative distribution function (CDF), 2) Constructing confidence bands around the CDF, and 3) Calculating the range of expected performance at specific confidence intervals.

Using Poisson distribution for prediction: The Poisson distribution can be used to represent power quality and reliability data sets for characterizing both variability and uncertainty characteristics.

Example Application of Probabilistic Characterization

Duke Power funded the development of a service characterization tool to calculate expected power quality and reliability (PQ&R) levels for individual sites on the Duke system. The system uses system-wide reliability data for the years 1992-2001 (data is updated annually). The characterization methodology developed is a predecessor to the framework developed in this report.

Duke Power keeps track of frequency and duration of outages to track system wide reliability indices such as SAIFI (interruption frequency) and SAIDI (interruption duration). Some of the drawbacks of this approach are:

- These numbers do not represent an individual customer's PQ&R level.
- SAIFI/SAIDI indices do not represent customer perception of service quality. These indices are necessary but may not be sufficient to characterize the service level.
- Power quality events have temporal (number of events vary from year to year) as well as spatial (number of events vary from region to region, sub-station to sub-station within the system). Current data presentation methods do not consider these variations.
- Most of the PQ&R reporting is done using a single number such as average per year or median. This form of reporting is not adequate to characterize the service level of the entire system.
- To overcome these limitations, this new approach was designed and implemented.
- Instead of reporting system wide indices, a three-tiered approach was adopted with each tier reporting a more detailed and location specific information regarding PQ&R level. The three tiers are:
  - System level
  - Boundary level
  - Site level

System level reporting includes system wide PQ&R statistics. The Duke system has been divided into regions and each region has been divided into different zones. Boundary level reporting includes PQ&R characteristics at regional level or an individual zone characteristic within a region. Site level reporting includes even more specific information. At this tier, substation, feeder or customer specific information can be obtained. Also, at each tier reporting can be done for one or more years depending on the study requirement.

Apart from reporting number of outages and duration per year, following indices are reported:

- Number of momentary events per year.
- Number of voltage sags per year.
- Steady state power quality information (regulation, harmonics, unbalance, flicker) is considered for future inclusion).

A lognormal distribution is used to represent the distributions of reliability and voltage sag data. This distribution is then used to estimate probabilities based on historical data.

The data is maintained in an Access database and a software front-end application was developed to analyze the data based on the requirements of specific investigations. The results are displayed as a cumulative distribution plot (CDF). Values of 5th, 25th, 50th, 75th and 95th percentiles are tabulated. The main menu for the application is shown in Figure 6-11. For purposes of the Service Quality Index, the site level calculations are the most important so we will focus on that part of the application for this discussion.

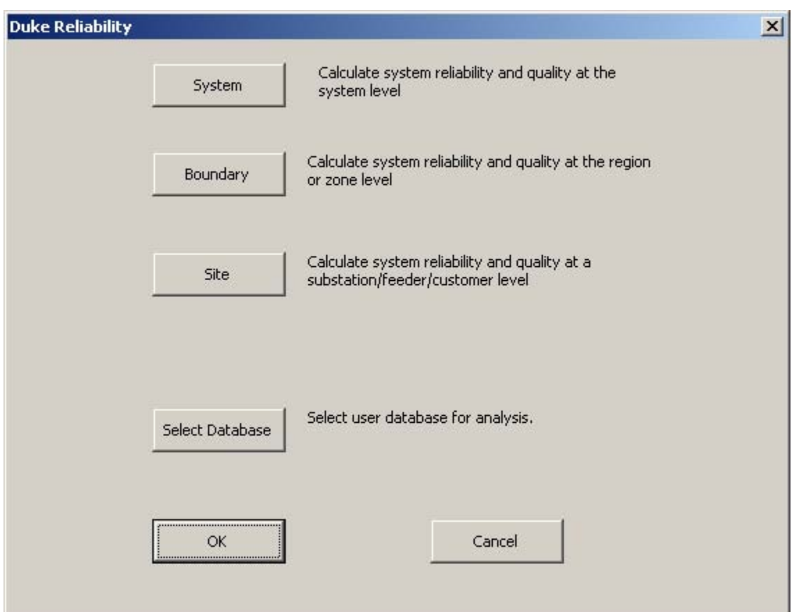

Figure 6-11
Main User Interface for the Duke Power Reliability Calculation Application

At the site level, three options are available:

- Substation level
- Feeder level
- Customer level

The substation level menu is shown in Figure 6-12 as an example.

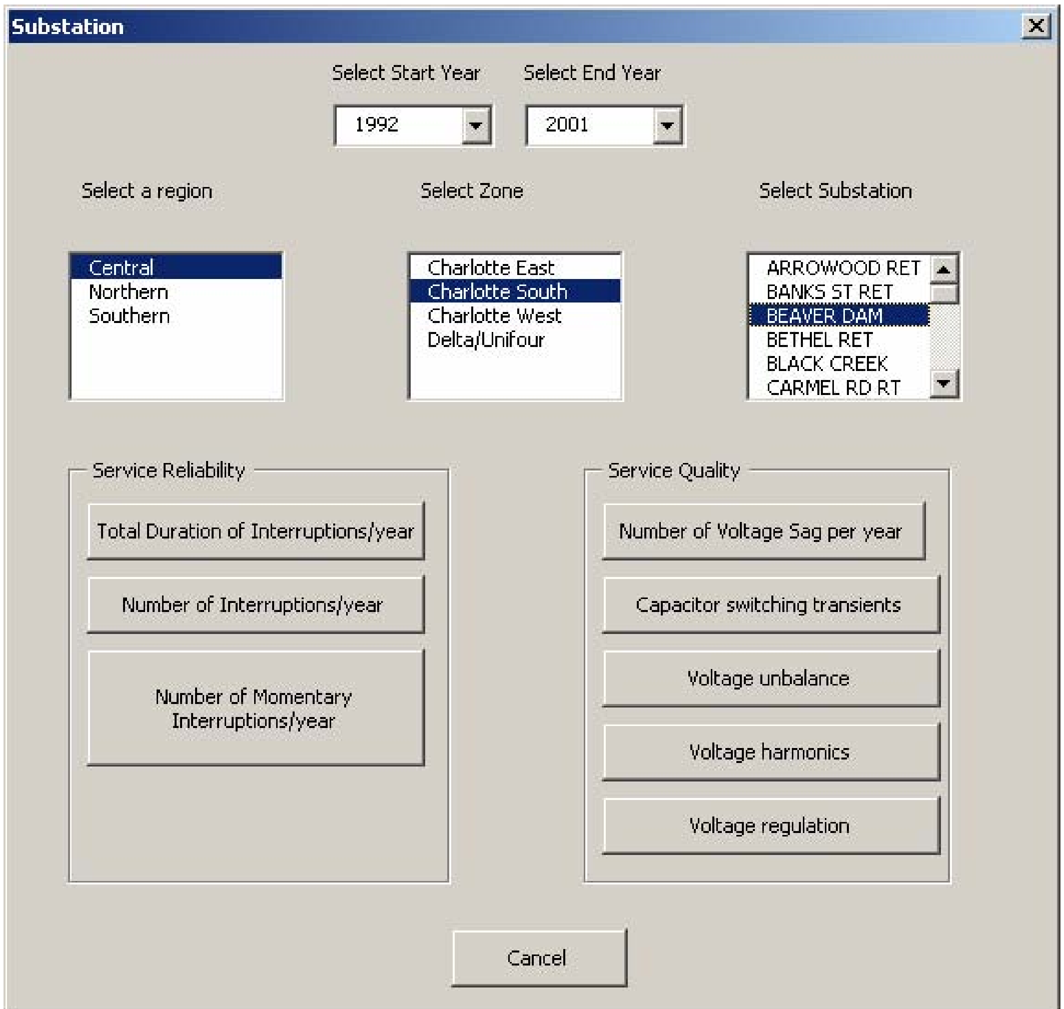

Figure 6-12
Substation Level Menu for the Duke Power Reliability Calculation Application

For a given site, the application will access the historical performance information for the site and calculate a lognormal distribution that best fits the data. The distribution illustrates the variability that can be expected and provides much more information than a simple average value for the expected performance. Then confidence bands around the calculated distribution are calculated to illustrate the uncertainty based on the limited monitoring data available.

Figure 6-13 is an example of the results for a specific evaluation of momentary interruption performance.

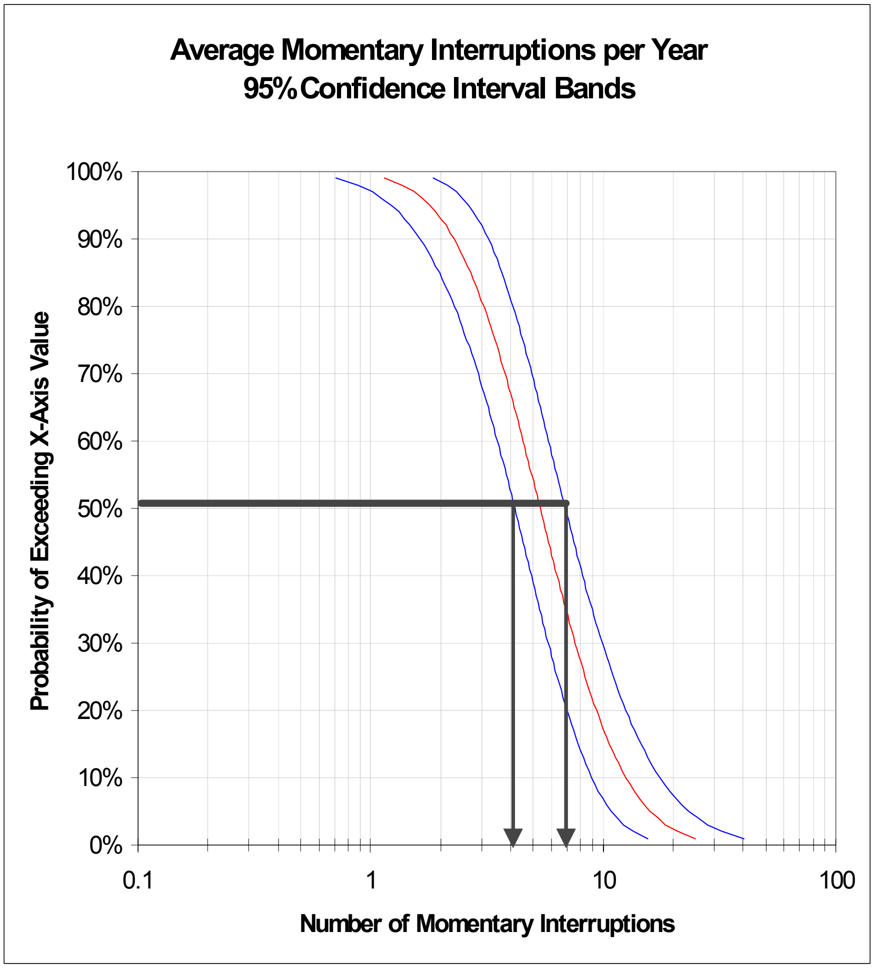

Figure 6-13
Example of Probability Density Function Representing Momentary Interruption Performance at the Selected Site With Bands Illustrating the 95% Confidence Intervals. The Arrows Indicate the Range of Average Values That an be Expected Based on the Uncertainty in the Data (4-7 Momentary Interruptions Per Year at the 95% Confidence Level)

This is an example of the type of tool that is needed for the implementation of the Service Quality Index. The next step for a tool like this will be to combine the different components of the Service Quality Index into a convenient report and to include appropriate weightings for the different components (see next section).

7 USING ECONOMIC IMPACTS AS A METHOD OF WEIGHTING DIFFERENT COMPONENTS OF SERVICE QUALITY

The objective of the Service Quality Index is that it should represent the impact of the supply quality on customer operations. The best measure of the impact of different disturbances is the economic impact experienced by the customer. In this chapter, we explore possible weightings that could be used for different components of the Service Quality Index based on the customer economic impact.

Costs of Interruptions

The most basic disturbances affecting industrial and commercial facilities are interruptions. These events virtually always cause disruption to industrial and commercial loads that are not explicitly protected. The costs associated with power interruptions represent the basic costs of an interruption to the process. These costs can be characterized for different industry categories. A number of surveys have been performed to characterize these costs [29-31].

Once we understand the costs of interruptions, we can also estimate the costs of less severe power quality variations, such as voltage sags. The costs associated with these events can generally be expressed as some portion of the costs associated with an interruption. This again shows the importance of understanding the interruption costs.

Factors Affecting the Costs of Interruptions

The costs associated with interruptions can vary significantly from nearly zero to several million dollars per event. The cost will vary not only among different industry types and individual facilities but also with market conditions. Higher costs are typically experienced if the end product is in short supply and there is limited ability to make up for the lost production. Not all costs are easily quantified or truly reflect the urgency of avoiding the consequences of an interruption.

The cost of a power quality disturbance can include costs in a number of different categories. These are some of the most important categories that should be considered:

- **Lost Production.** Costs represent the value of the shortfall in product shipped due to power quality variations. An interruption does not necessarily prevent a plant from meeting production quotas. However, when it does, these costs are generally some of the larger cost impacts of power quality variations.

- **Scrap Cost.** Costs associated with product that must be scrapped. This can be very important for some processes that involve long production times and very valuable product.
- **Restart.** Costs associated with restarting a production process not accounted for in the other categories.
- **Labor Cost.** Extra labor costs associated with restarting the product line, reloading machines, cleaning up scrap, etc.
- **Equipment Damage and Repair Costs**. Costs for repair of machines and equipment damaged as a result of power interruption.
- **Equipment Replacement.** Costs for the replacement of machinery damaged by power interruption.
- **Other Costs.** A miscellaneous "catch all" field that can account for any unique costs that a customer may have. This can include "lost opportunity" costs, penalties for shipping delays, lost goodwill with customers, etc.

Interruptions will almost always result in an impact to the facility. However, the impact may be different for a momentary interruption than it is for an interruption that lasts for an hour. Some critical elements of the process may have short duration ride through capabilities but are not protected for longer interruptions. Therefore, it is important to understand the impacts of interruptions with different durations as well as the impacts of a simple momentary interruption.

Interruption Costs for Different Types of Customers

Various surveys have been performed around the world to characterize the costs of interruptions to different types of industrial, commercial, and residential customers. We will focus primarily on industrial and commercial customer costs because these tend to be orders of magnitude higher than costs to residential customers. However, cost relationships should be developed for residential customers as well.

Some types of facilities can have interruption costs in the millions of dollars per event. These can include some data processing facilities, communication centers, semiconductor manufacturing processes, and some pharmaceutical processes. These facilities must be supplied from an extremely reliable supply or they must invest in local ride through protection and/or backup generators to assure reliable supply to the process.

The discussions here focus more on the facilities where the investment in improving the reliability of supply is not so clear-cut. These are facilities where the costs of interruptions and the expected reliability of the supply must be weighed carefully with the costs for improving performance in order to determine the optimum level of investment.

As mentioned above, the interruption costs will be somewhat dependent on the duration of the individual interruption. Curves have been developed, known "damage functions" that describe the costs as a function of the duration of the interruption.

The costs also depend on the size of the facility. One way to describe this function is to normalize the costs by the peak kW demand for the facility. This is not always a linear function across facilities with different demands in the same type of industry but it provides a better estimate than ignoring the size of the facility completely.

Costs for Momentary Interruptions

Momentary interruptions are the most basic power quality event that must be characterized in terms of the impact on facilities. These events involve a total loss of power to the facility for a period less than 5 minutes. For standardization internationally, a one minute event is used as the basic definition of a momentary interruption. Unfortunately, most utilities do not publish system performance statistics for momentary interruptions – these are not part of the traditional "reliability" indices.

Table 7-1 summarizes typical costs of momentary interruptions for different types of customers. The results are normalized by the kW demand of the facility. These costs are based on published services and Electrotek experiences with individual case studies. Note that the costs are without major investments in technologies to ride through the momentary interruptions. Facilities that have made these investments will have reduced costs but are incurring the costs of the solution investment.

Table 7-1
Typical Costs of Momentary Interruptions in $/kW Demand for Different Categories of Industrial and Commercial Facilities

	Cost of Momentary Interruption ($/kW Demand)	
Category	**Minimum**	**Maximum**
INDUSTRIAL		
Automobile Manufacturing	$5.0	$7.5
Rubber and Plastics	$3.0	$4.5
Textile	$2.0	$4.0
Paper	$1.5	$2.5
Printing (newspapers)	$1.0	$2.0
Petrochemical	$3.0	$5.0
Metal Fabrication	$2.0	$4.0
Glass	$4.0	$6.0
Mining	$2.0	$4.0
Food Processing	$3.0	$5.0
Pharmaceutical	$5.0	$50.0
Electronics	$8.0	$12.0
Semiconductor Manufacturing	$20.0	$60.0
COMMERCIAL		
Communications, information processing	$1.0	$10.0
Hospitals, banks, civil services	$2.0	$3.0
Restaurants, bars, hotels	$0.5	$1.0
Commercial shops	$0.1	$0.5

Cost as a Function of the Interruption Duration

The impacts to a facility increase as the duration of the interruption increases. Figure 7-1 gives an example of the "damage function" for industrial and commercial customers. The curve was developed as an average of the interruption costs as a function of duration for a variety of different industrial and commercial customer types.

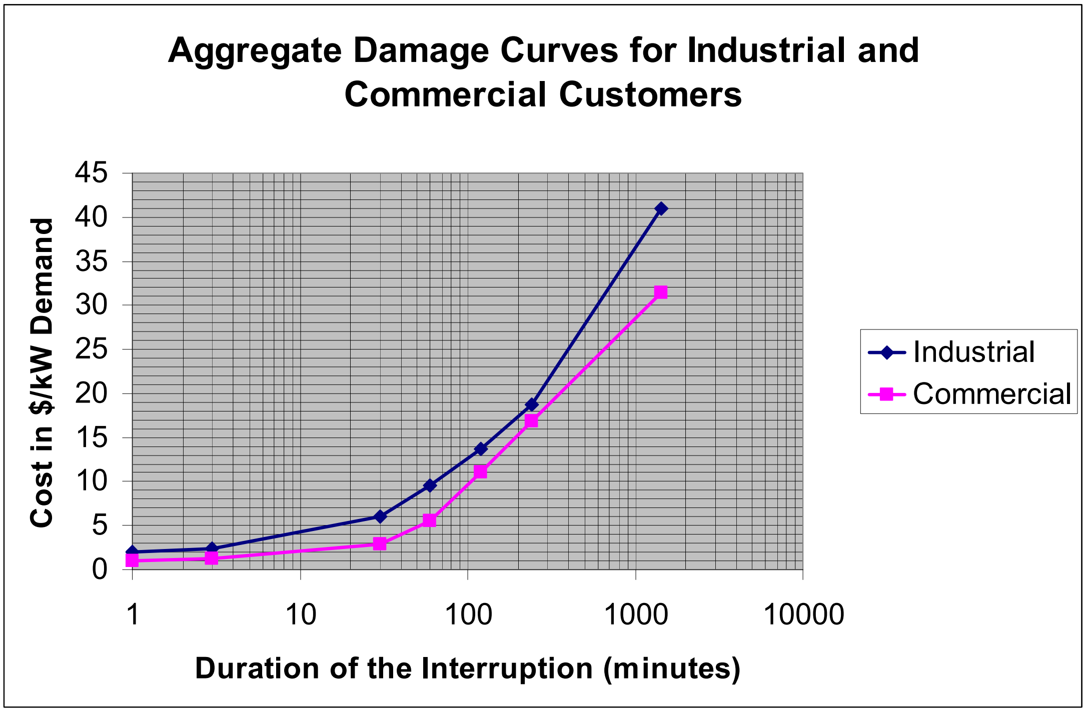

Figure 7-1
Industrial and Commercial Customer Damage Functions (Costs are in $/kW Demand as a Function of the Interruption Duration)

Costs of Voltage Sags

Costs associated with voltage sags and other power quality variations are even more difficult to characterize. This relationship can often be defined by a matrix of weighting factors. The weighting factors are developed using the cost of a momentary interruption as the base. Usually, a momentary interruption will cause a disruption to any load or process that is not specifically protected with some type of energy storage technology. Even the new SEMI F-47 specification does not require that equipment be able to ride through a momentary interruption. Voltage dips and other power quality variations will always have an impact that is some portion of this total shutdown. The base costs associated with a momentary interruption can be designated as Ci. If a voltage dip with a minimum voltage of 40% causes 80% of the economic impact that a momentary interruption causes, then the weighting factor for this voltage dip would be 0.8. Similarly, if a dip with minimum voltage of 75% only results in 10% of the costs that an interruption causes, then the weighting factor is 0.1.

Table 7-2 provides an example of weighting factors that were used for one investigation. The weighting factors can be further expanded to differentiate between voltage sags that affect all three phases and sags that only affect one or two phases. The weighting factors shown in Table 7-2 were derived after developing an understanding of plant costs and equipment sensitivities. Testing indicated that only a small percentage of the equipment was sensitive to voltage sags with minimum voltage levels of 80 – 90% so a weighting factor of 0.1 was assigned to this category. However, many loads in the plant are affected for voltage sags with a minimum voltage below 80%. For minimum voltages in the range of 70-80%, a weighting factor of 0.6 is assumed and for voltages in the range of 50-70%, a weighting factor of 0.8 is assumed (these are more severe). Almost all loads that are not protected will be impacted for voltage sags with a minimum voltage below 50% of normal. Even motor contactors are dropping out at these voltage magnitudes. Therefore, a weighting factor of 0.9 was used for voltage sags with minimum voltages below 50% (still not quite as severe as a complete interruption). A weighting factor of 1.0 is used for actual interruptions (minimum voltage below 10%).

Table 7-2
Example of Weighting Factors Used to Characterize the Costs of Voltage Sags in Terms of the Costs for Momentary Interruptions

Category of Event	Weighting for Economic Analysis
Interruption (voltage below 10%)	1.0
Voltage sag with min voltage below 50%	0.9
Voltage sag with min voltage between 50% and 70%	0.8
Voltage sag with minimum voltage between 70% and 80%	0.6
Voltage sag with min voltage between 80% and 90%	0.1

For purposes of the Service Quality Index where we have decided to use a single voltage sag index (SARFI-ITIC is recommended), a single weighting factor for the voltage sag component is needed. The majority of voltage sags more severe than the ITIC curve will have minimum voltages in the range of 50-70%. It is reasonable to select a weighting factor that reflects customer costs for sags in this range.

Summary of Weighting Factors for Service Quality Index

The previous sections provide some background on typical costs. This report will not recommend actual cost numbers to use since the objective is to define the framework for the Service Quality Index. The cost weightings can also be expressed as a range. Once the cost weightings have been applied to the components of the power quality index (weightings applied to the probability distribution of events, a curve of the probability of cost impacts from the site being considered can be developed. An example is shown in Figure 7-2.

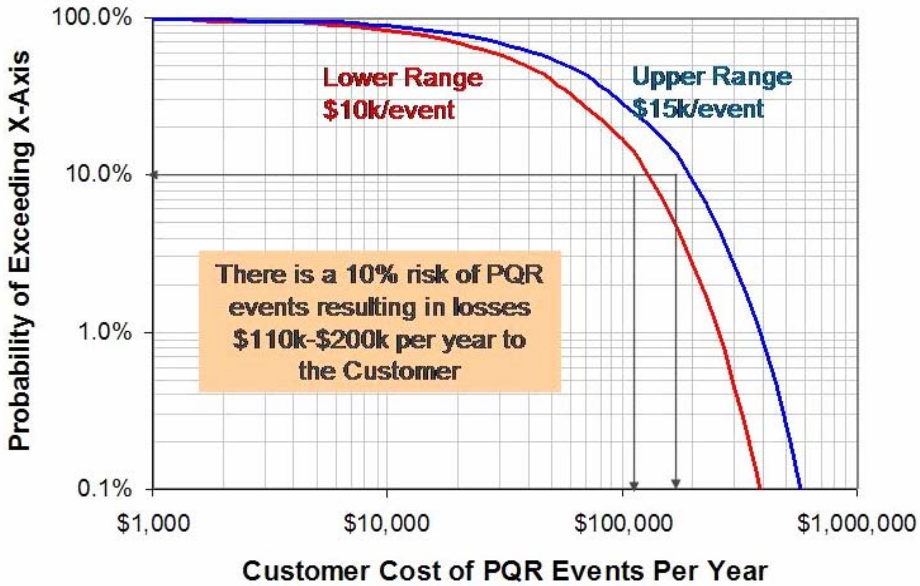

Figure 7-2
Example of Calculation of the Probability Density Function for Cost Impacts Associated With Power Quality and Reliability Events

Calculating this probability function requires the cost weightings summarized in Table 7-3 that can be applied in combination with the associated probability functions for the indices.

Table 7-3
Summary of Cost Functions Needed for Weighting of the Service Quality Index Components

Service Quality Index Component	Cost Function Needed	Units
Reliability - expected number of outages (SAIFI)	Base Cost per outage lasting longer than 5 minutes	$/kW demand
Reliability - expected duration per outage (SAIDI/SAIFI)	Incremental cost per outage as a function of duration of the outage	$/kW demand/minute
Momentary Interruption Events (MAIFI)	Cost per momentary interruption	$/kW demand
Voltage Sag Events (SARFI-ITIC)	Cost of voltage sag more severe than ITIC curve	Per unit of momentary interruption cost

8
COMBINING THE PERFORMANCE INFORMATION TO CHARACTERIZE SERVICE QUALITY

This section summarizes the components of the Service Quality Index and how they can be presented to describe the performance at individual system locations. The overall procedure is summarized in Figure 8-1 and summarized in the following sections.

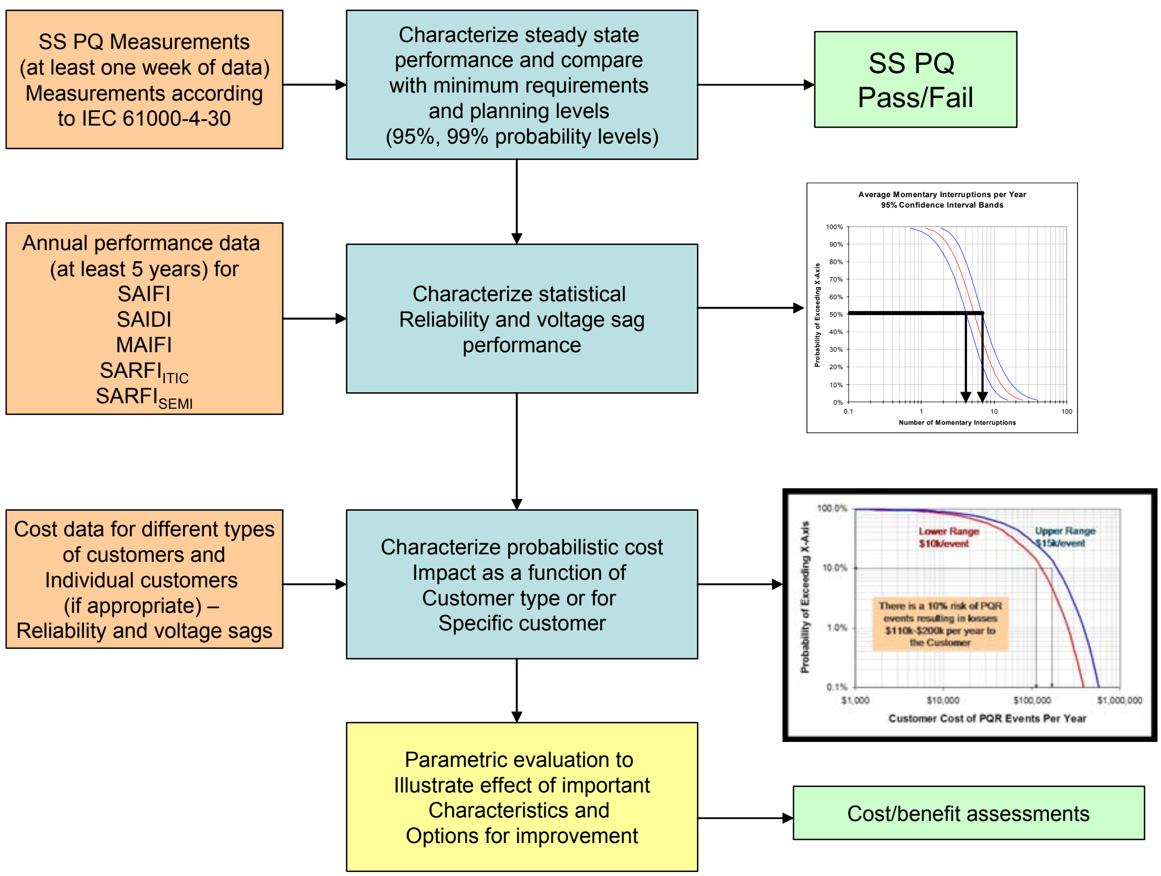

Figure 8-1
Overall Procedure for Describing the Service Quality Performance

Steady State Power Quality

Steady state power quality characteristics are evaluated for minimum compliance requirements. The concept is that equipment should perform without problems if the quality of supply meets these minimum requirements and, therefore, there will not be economic impacts. If the minimum requirements are not met, remedial measures should be considered. This could involve working with customers that may be causing the problem (e.g. harmonic production) or it may involve system changes to solve the problem (e.g. fixing a resonance problem).

Important aspects of characterizing and evaluating the steady state power quality characteristics include:

- Definition of minimum requirements. Recommendations for minimum requirements are outlined in Section 3.
- Measurements according to IEC 61000-4-30 procedures. This involves characterizing steady state power quality with 10 minute values that can be trended and evaluated as statistical distributions.
- Evaluate compliance at the 95% probability level. This prevents evaluation based on the worst case conditions that may be exceptional circumstances and not representative of the normal system conditions and performance.

Reliability Including Momentary Interruptions

Indices for reliability performance are well defined in IEEE 1366. The Service Quality Index should include momentary interruptions in addition to traditional interruptions lasting longer than five minutes.

Important considerations when characterizing reliability:

- Include major events. Reliability reporting for regulatory purposes should exclude major events, as defined in IEEE 1366-2003. However, impacts on customers should include major events.
- Maintain multiple years of reliability performance data and use the data to understand the uncertainty in the probability density functions for the reliability indices.

Voltage Sags

Many customers are affected by voltage sags in a similar manner to momentary interruptions. Understanding the service quality should, therefore, include voltage sag performance. For simplicity, a single index is recommended for characterizing the voltage sag performance – SARFI-ITIC. The description of performance using this index is basically the same as using MAIFI functions to describe momentary interruption performance.

Economic Impacts for Weighting

The different components of the Service Quality Index can be combined using weighting functions based on the economic impacts of the disturbances to customers. This requires an understanding of typical economic impacts for different groups of customers and a method for combining these impacts for the customers supplied from a particular location. Example data is provided in Section 7.

9
NEXT STEPS

This section lists some important next steps that will help further develop the Service Quality Index concept:

- Develop data collection and management recommendations for the Service Quality Index.
- Develop cost functions for use with the Service Quality Index.
- Use the DPQ data and estimated reliability data to develop baseline information for the Service Quality Index.
- Apply the framework with actual historical performance data from example systems to illustrate the range of characteristics that can be obtained.
- Develop recommendations for application of the Service Quality Index.

The 2005 effort will accomplish some of these next steps by applying the Service Quality Index concept to the DPQ data and to example systems for a few participating utilities. It is expected that additional recommendations will de developed from this experience.

10
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