EPRI

Infrastructure Quality and Reliability

September 22, 2003

EXECUTIVE SUMMARY

On August 14, 2003, 22 million customers lost power in the Northeast Blackout. This event brought worldwide attention to the issues of infrastructure security and reliability. Cost estimates for the impact of this single event are on the order of $6-8 billion. But many people don't realize that 0.5 million customers in the United States alone lose power every day for an average of about 2 hours. The number of customers affected by momentary interruptions and voltage sags is even greater. These shorter duration events are most important for industrial customers. Power disturbances ranging from milliseconds (voltage sags) to several seconds (momentary interruptions) impact industrial processes. A 1/10 second event, which literally is a blink of an eye, can cause a refinery to shut down or a semiconductor processing plant to stop production and it takes hours to get back to normal production. On any given day in a year approximately 30,000 industrial customers are impacted by such power disturbances.

Finding solutions to improve the performance of the supply infrastructure must be considered in combination with the requirements and designs of end use equipment and processes. CEIDS has the potential to make a dramatic impact on the achievement of compatibility between the supply infrastructure quality and reliability and the design of end use technologies and processes. This compatibility will be achieved not only by development of new, advanced technologies to improve performance of the supply system; but also by identifying market and regulatory structures that can facilitate flexible and tailored quality and reliability levels as a function of system, customer types, and contractual arrangements.

The importance of quality and reliability of power to the society, as the society embraces digital technologies in every facet of life, was highlighted in the recently published Electricity Sector Framework of the Future report [1]. This report, reflecting the thoughts of a broad range of stakeholders identified two main value creation opportunities for the grid of the 21st century, both of which are intimately tied to quality and reliability. These include:

- Stemming the cost of power disturbance to the society, estimated at 1% of GDP in 2002 and likely to grow in the future under status quo condition of grid quality and reliability.

- Facilitating economic growth through widespread adaptation of digital technologies – Improved quality and reliability of the electric grid in this case becomes an enabling factor for unleashing the productivity growth.

While quality and reliability are attributes of the electric grid, the value of these attributes can only be realized by the electricity consumer. Different consumers have different value assessments associated with quality and reliability of the supply. Good quality and reliable power to a residential consumer could mean loss of productivity to an industrial consumer. The different value assessments associated with different customers creates a challenge to design a system that can provide flexible levels of quality and reliability tailored to the needs of specific consumers.

The levels of quality and reliability are also a function of the type and location of the supply system. Distribution systems with radial feeders are not likely to have the same quality and reliability characteristics as urban networks. Significant benchmarking data is already available to characterize these differences and the levels that can be achieved for different system designs as a function of technology and investment must be understood.

Obviously, the quality and reliability of the electricity supply will only continue to grow in importance. But how will we define the actual quality and reliability requirements for the grid of the future and how will these levels of quality and reliability be achieved? These are complex tasks that depend on many factors; including regulatory environment, standardized indices for assessing performance, the economics of achieving different levels of quality and reliability, the economics of power quality and reliability impacts, new technologies for power quality improvement, end-use equipment technologies and standards, and the role of new automation and communication system infrastructures in achieving flexible quality and reliability levels.

This scoping study provides the background necessary to help define an appropriate role for CEIDS in developing the indices, benchmarking, technologies, supply infrastructure designs, and regulatory/market structures that are necessary to assure the system reliability and quality levels meet the requirements of the digital economy. A more detailed research initiative is recommended that will address three specific focus areas where CEIDS can play an important role in developing the quality and reliability characteristics and coordination for the infrastructure of the future. The research should complement existing and planned research at EPRI, DOE, utilities, state research organizations, universities, and other research organizations around the world. It should also coordinate and support standards development in IEC, IEEE, and other international standards organizations. The three focus areas that should be part of the initiative are summarized here and developed in more detail in this document.

1. **Infrastructure and Technologies for Flexible Quality and Reliability.** This development area will identify and develop the infrastructures and technologies to deliver flexible and tailored quality and reliability based on the specific requirements and characteristics of individual customers and systems. This will include use of new communications architectures (IECSA), consumer gateways (customer portal), and interfaces with equipment and processes within customer facilities. It includes the development and application of advanced power electronics technologies (solid state switch, DVR, etc.) that will facilitate flexible power quality and reliability levels (many of these development efforts are already under way and will continue in parallel to the CEIDS research). Some particular areas to emphasize that complement existing research include:

    - Technologies that address security issues and major disturbances. These are critical to the system reliability and will continue to grow in importance. Since this is an area worthy of a complete research initiative, the quality and reliability initiative should just focus on how security issues and technologies can affect reliability and identifying methods for characterizing this effect.

    - Technologies that facilitate self-healing of the grid through automated response to disturbances. This can include adaptive islanding, fast switching, and coordinated response of customer equipment through advanced communication architectures.

    - Automated distribution systems that manage quality and reliability in response to specific customer requirements and system capabilities.

2. **Assessment of Regulatory and Market Structures to Support Flexible Quality and Reliability.** Unfortunately, the development of innovative technologies and approaches for achieving improved quality and reliability has been slower than desired. A major reason for this is the lack of regulatory structures and profit opportunities that reward investments in technologies and designs that are focused on reliability and quality improvement. New innovations to facilitate quality and reliability levels that are tailored to particular circumstances are needed. Specific developments needed include:

    - Assessment of the effectiveness of existing market structures and regulations related to quality and reliability requirements. Various countries and utilities have requirements for both quality and reliability performance. These requirements are enforced through various economic penalties. The assessment should review the benefits of these different systems from a global economics perspective and identify characteristics of these systems that are effective and ineffective.

    - Indices that can accurately characterize the full range of quality and reliability concerns and benchmarking using these indices to define appropriate performance objectives as a function of important system characteristics. A probabilistic risk assessment approach is needed.

    - Flexible pricing structures that can address reliability and quality issues. These should identification of regulatory and market structures that provide for appropriate investment incentives related to providing flexible levels of security, reliability, and quality (based on the survey of existing systems and possible future approaches).

3. **Optimizing the Overall Economics of Reliability and Quality Levels.** This is the ultimate objective of developing the technologies and regulatory/market infrastructures to support flexible reliability and quality levels. The new technologies will allow optimization of service characteristics based on the costs and options for individual customers. Optimization procedures must be developed based on the technology options and infrastructure design options that will be available. Specific developments should include:

    - More complete understanding of all the costs associated with reliability and quality issues. These costs include utility system costs, customer costs, and society costs. Methods for characterizing these costs using analytical approaches are needed to facilitate the optimization process. The methodology should build on previous research characterizing reliability and quality costs and extend the characterization to individual end users and their performance optimization alternatives.

    - System level optimization that defines investment priorities between the supply system and customer systems to achieve performance compatibility. The development of standards like SEMI F47 is an illustration of a coordinated approach to supply side and customer side investment. This relative investment strategy can be extended to include a wider range of security, reliability, and quality issues and the diverse range of customer types.

These three focus areas should be addressed in a coordinated effort that characterizes previous and ongoing research and provides a detailed roadmap for achieving the optimum compatibility between the supply system performance and specific end-user system requirements. The end result of this research initiative will be indices, benchmarking results, technologies, infrastructure designs, and regulatory/market structures that will facilitate optimum compatibility between the supply system and customer systems in the digital economy. As the research results are turned into real systems, higher levels of productivity will be unleashed throughout the digital economy.

CONTENTS

1
INTRODUCTION

The quality and reliability of power are critical to the productivity and efficiency of the overall economy. A Primen study [2] estimates the costs of power interruptions and power quality problems at over $100 billion dollars per year in the United States alone. A key characteristic of the supply system in the future needs to be the ability to provide the level of quality and reliability required by different customers to maximize their productivity and efficiency of operation. This higher level of quality (for those customers that require it) will facilitate new production technologies and intelligent applications throughout the digital economy.

Indices are available for characterizing quality and reliability on the supply system. However, it is important to understand that, ultimately, quality and reliability must be characterized in terms of the effects on end-users. It is also important to note that different end-users have different impacts and costs associated with power quality and reliability variations. This will continue to be true as end-users become more automated. An important objective of the future power system infrastructure will be the ability to provide different levels of power quality and reliability to different end-users, depending on specific requirements. The regulatory and market structure must also support different cost structures based on the different quality and reliability objectives and requirements.

This scoping study evaluates the quality and reliability characteristics of today's electric supply infrastructures and how this must evolve in the future to meet the requirements of the digital economy. The evaluation must include an assessment of the quality and reliability requirements of different end-users and the economic impacts associated with power quality variations. Technologies to improve power quality at all levels of the system must be considered and the optimum strategy for providing the required power quality must be developed for each system.

The scoping study concludes with recommendations for further research that will define the requirements for the future grid in terms of power quality and reliability assessments and offerings coordinated with the requirements of end-users. Three areas of research are recommended:

1. **Infrastructure and Technologies for Flexible Quality and Reliability.** This research area will focus on the technologies and system design strategies that will be required to provide improved and flexible reliability and power quality, based on end-user requirements in the digital economy.

2. **Assessment of Regulatory and Market Structures to Support Flexible Quality and Reliability.** This research area will assess the effects of different regulatory and market structures on the quality and reliability characteristics of the supply system.

The objective will be to identify characteristics of the market and regulatory structures that are needed to support flexible and cost-justified quality and reliability supply system characteristics.

3. **Optimizing the Overall Economics of Reliability and Quality Levels.** This research area will develop a better understanding of true costs associated with quality and reliability problems and then extrapolate these costs to the end-users of the digital economy. These costs will then be the basis of optimizing the quality and reliability offerings as a function of customer requirements.

2

POWER QUALITY AND RELIABILITY

Power quality and reliability have many different definitions. They are often confused by end users. Electric utilities have specific definitions and indices for measuring reliability but many customers consider any event that disrupts their processes as a reliability problem. It is important to understand the terminology and different components of the quality and reliability of the electric service.

Reliability

The term reliability is used to indicate the ability of a system to continue to perform its intended function. Power systems are designed to provide electricity to end users. Power system reliability is, therefore, measured in terms of the ability of the power system to provide electricity to end users. It is usually measured at the service to the end users. For instance, the most commonly used indices of reliability [3] are the System Average Interruption Frequency Index – SAIFI – that measures the average number of outages per customer and the System Average Interruption Duration Index – SAIDI – that measures the average duration that a customer does not have electric service. These indices are influenced mostly by the distribution system. They are indices that are maintained by electric utilities and typically reported to regulators and commissions.

The differences between reliability and other measures of power quality are very important. Utilities measure reliability based on outages that last longer than the operating times of all automatic system reconfiguration equipment (e.g. reclosers). In the US, this is typically 5 minutes. Outages that last less than 5 minutes and momentary problems, such as voltage sags, are not considered in reliability indices. However, these shorter events can affect the reliability of end users. This is often a source of confusion.

Availability

In the engineering literature on power disturbances, the terms “availability” and “reliability” are often used interchangeably. However, availability is a term that can be applied to individual components that are part of the overall process of providing reliable power to the end-user. For instance, we can measure the availability of a transformer or a transmission line. When one of these components is unavailable, it may not result in an outage to any customers but it is important to understand because it is a factor in the overall reliability of the electric service (e.g. when the right combination of components are unavailable, the result is an outage to end users). Availability is a particularly important measure for transmission system components because transmission systems are usually configured as a network where outages of any single component will not result in an outage to end-users.

Security

Security has become another critical issue in the operation of the power system. It can be one of the important factors affecting the reliability of service. The recent Northeast outage on August 14th illustrates the vulnerability of today's power system to outages of critical components. Security issues can be critical factors in the availability of components and therefore influence the overall system reliability. Security is not specifically addressed in this scoping study but it should be remembered that it can be an important influence on reliability.

Power Quality

While reliability measures the availability of electric service to end-users (outages), power quality measures a wide range of power supply characteristics that can also influence the performance of equipment and processes. In other words, the reliability of end-use equipment and processes is dependent on both the reliability and quality of the electric service.

It is also important to note that many power quality characteristics are a function of both the supply system and the end-user system (and equipment) characteristics. For instance, harmonic distortion is typically caused by customer non-linear loads that draw distorted currents and interact with the supply system impedance to cause voltage distortion. This influences the need to achieve compatibility between the characteristics of the supply system and end-user equipment characteristics. It is not sufficient to just evaluate the performance of the supply system.

The important categories of power quality are discussed briefly here for reference. Definitions come from IEEE Standard 1159 [4] on Power Quality Monitoring and basic compatibility levels are defined in IEC Standard 61000-2-2 [5].

Steady State Power Quality Variations

These are characteristics of the supply voltage that may affect the performance of equipment on the supply system or end-use equipment. They include frequency variations, voltage variations, unbalances in the three phase voltages, flicker, and harmonic distortion. It is important to identify "compatibility levels" for these characteristics. These compatibility levels should be designed such that end-use equipment will operate properly and they should be feasible for the system to achieve. Most of these power quality characteristics require close coordination between the operation of end-use facilities and the performance of the power system. IEC has defined compatibility levels for these characteristics [5] and these compatibility levels are the basis of actual requirements for the power system performance in Europe [6].

Limits for steady state, or continuous, voltage variations can be specified in definite terms. However, these characteristics are continually varying and they are characterized with trends and probability distributions. The limits must also be specified taking into account the probabilistic nature of the variations. The important concepts for these types of voltage variations are shown in Figure 2.1.

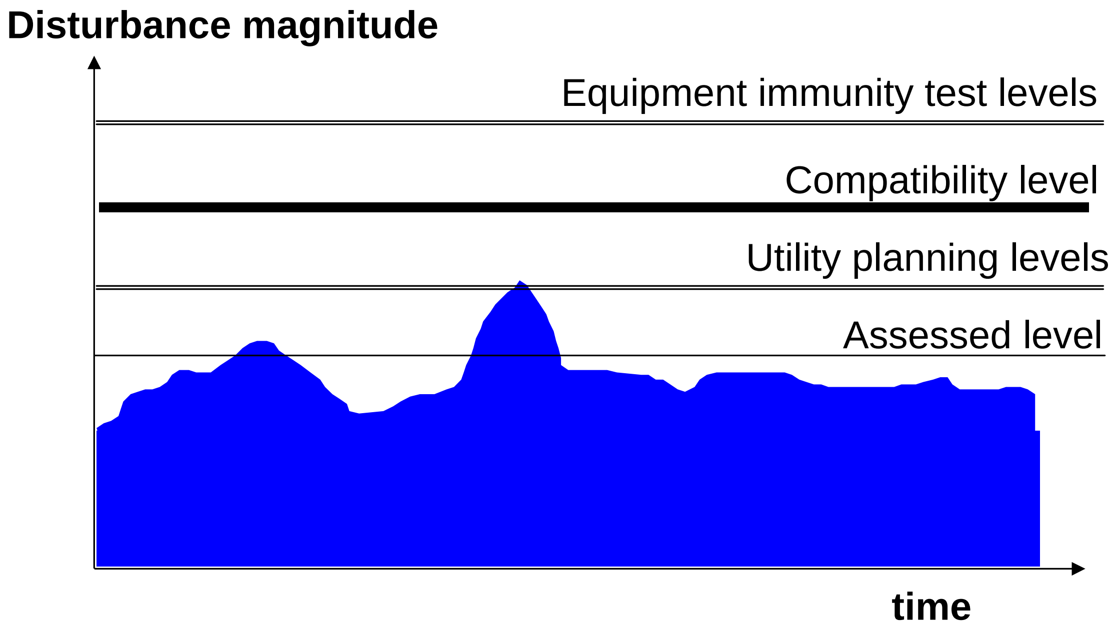

Figure 2.1. Important concepts for assessing power quality characteristics that can be characterised as continuous, or steady state, variations.

Table 2.1 gives the voltage variation characteristics for which definite limits have been specified in the European standard EN50160 [6]. Interharmonics are included even though specific limits have not yet been developed. Limits must be evaluated over a period of time due to the probabilistic nature of the variations. Generally an observation period of one week is chosen because it is the shortest interval to get representative and reproducible measurement results.

The limits are developed based on the concept of compliance for a percentage of the observation time, e.g. 95 % of the observations in any period of one week. No limits are specified for the remainder of the time. However, experience shows that the frequency of occurrence for disturbances outside the specified bands decreases very rapidly with the magnitude of these excursions.

The question for future research into optimising system performance and compatibility should involve the relationship between the performance levels that can be achieved for different types of supply systems and the immunity characteristics of end-use equipment. Equipment with different immunity characteristics may have different costs and the optimum “compatibility levels” may not be the same for all systems.

Table 2.2 summarizes typical objectives for the supply system performance at the point of common coupling (PCC) with end-users. These levels are not the same as the limits specified in

EN50160 but are more typical of objectives for actual system performance (EN 50160 limits can be considered to be worst case limits).

Table 2.1. Voltage variation characteristics with specific limits [6].

Voltage Characteristic	**Compliance with stated limits**	**Observation period**
frequency	99.5% 100%	year
slow variations of voltage magnitude	95% 100%	week
rapid voltage changes	some exceptions per day are admissible	day
fluctuations of voltage magnitude (flicker)	95%	week
unbalance of three phase voltages	95%	week
harmonic distortion of the voltage waveform	95 %	week
interharmonic voltages	to be defined	to be defined
mains-borne signalling voltages	99 %	day

Table 2.2. Summary of Typical Minimum Performance Requirements for Steady State Power Quality at the Point of Common Coupling with Customer Facilities (note that minimum requirements can vary significantly from one location to another and minimum requirements may not be defined for some of these categories).

Power Quality Category	**Limits**
Voltage Regulation	+/- 5% of nominal for normal conditions
	+/- 10% of nominal for unusual conditions
Voltage Unbalance	2% negative sequence
Voltage Distortion	5% total harmonic distortion
	3% individual harmonic components
Voltage Flicker	Pst* less than 1.0
	individual step changes less than 4%

* note - Pst is a measure of flicker where a value of 1.0 indicates that 50% of the people are likely to be able to notice flicker in a 60W incandescent lamp. Measurement procedures are defined in IEC Standard 61000-4-15 [7] and are being adopted by IEEE [8].

These characteristics depend on the operation of end-use equipment as well as the operation of the supply system. In order for the electric utility system to maintain these voltage quality levels, limits on the characteristics of end-use systems must also be developed. Various standards are in place for these limits. For example, requirements for harmonic performance of both the system and customer facilities are specified in IEEE 519 [9] and IEC 61000-3-6 [10]. Similar standards exist for other categories of steady state power quality variations.

Additional ongoing research is still needed in many of these areas to help define the optimum "compatibility levels" and the best places to invest in order to assure that the compatibility levels are maintained. For instance, there is still significant need for benchmarking of harmonic distortion levels on distribution systems around the world and the economics of controlling harmonic distortion in end-use equipment vs controlling the harmonic levels on the supply system. Similar issues are associated with controlling voltage variations (flicker) that result from load variations such as arc furnaces, welders, and motor starting.

Voltage Sags and Swells

A *voltage sag* is a short-duration decrease of the Root Mean Square (RMS) voltage (Figure 2.2). Voltage sags are typically caused by faults on the supply system. Sometimes a fault can result in an outage (a customer experiences an outage if they are supplied from the faulted portion of the system) but a fault almost always results in voltage sags over a wider portion of the supply system. As a result, customers experience many more voltage sags than actual interruptions. If the facility includes sensitive equipment, these voltage sags can have similar effects on the operation as actual interruptions.   The economic consequences can be severe.

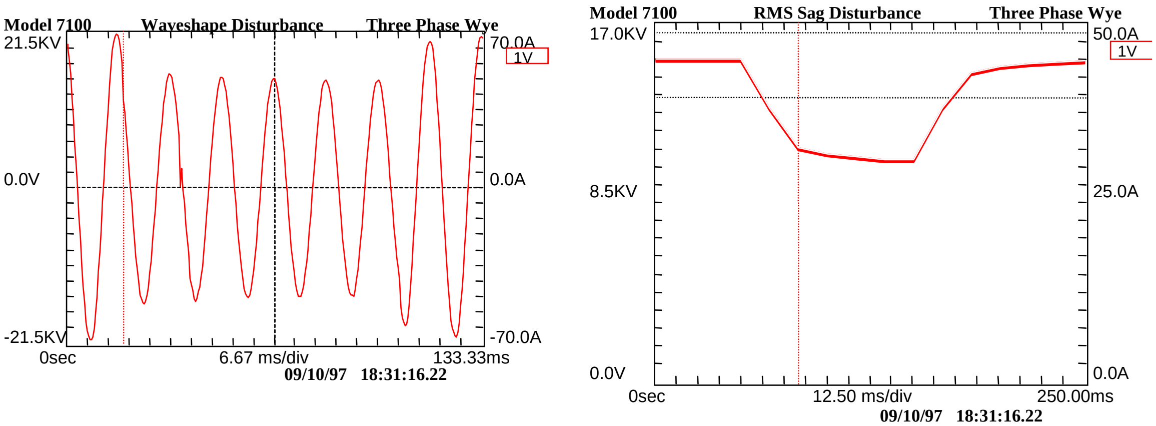

Figure 2.2. Waveform and RMS voltage during voltage sag

Many of the confusions between electric utilities and end users come from the fact that the electric utilities think of reliability in terms of 5 minute outages and many customers think of reliability problems as any events that interrupt the process. When this includes voltage sags, the difference can be tremendous.

It is important that the supply infrastructure be able to provide the quality needed by sensitive loads in the digital economy. Voltage sags will continue to be an important issue. Topologies and technologies that can provide service that is relatively free of voltage sags will improve the productivity of many industries and may be critical to a much wider range of customers in the future as automation reaches all the way down to the home. On the other hand, the economics of improving the performance of the supply infrastructure must be weighed against improving the immunity of the equipment to voltage sags. Electric utilities worked together with the semiconductor industry (both customers and manufacturers) to develop new standards for equipment performance that are based on the reality of the quality of power supplied from typical power systems [11]. This model may be important for many other industries to improve productivity and compatibility with the supply. However, research is still needed to understand the relative economics of the different approaches on a global scale. These economic evaluations must be based on the range of technologies that may be available for improving performance on both sides of the meter.

Transients

Transient disturbances are caused by the injection of energy by switching or by lightning. Lightning surges are a major issue throughout the power system. Surge arresters are used to protect equipment and insulation coordination procedures are used to minimize the impacts of lightning on power system equipment. Even with all these precautions, lightning surges still cause equipment failures and faults on the power system. Improving the immunity of both the power system and end user facilities to lightning transients is a continuous battle and research area. Fortunately, most end-use equipment can be effectively protected from lightning transients and it is standard practice to include this protection in virtually any power conditioning technology. Standards for test waveforms [12] and testing guidelines for surge suppression equipment [13] have made the application of these technologies very reliable.

However, there are still coordination problems associated with other types of transient overvoltages, such as those caused by capacitor switching (Figure 2.3). These transients can be magnified within customer facilities, cause adjustable speed motor drives to misoperate, and effect the operation of a wide variety of electronic equipment. The increased application of large capacitor banks to support transmission systems as transmission loading increases has further aggravated the problem. This is another area where compatibility research is needed to identify the most economical method of assuring compatibility (system investments to reduce these transients vs increased immunity of end-use equipment).

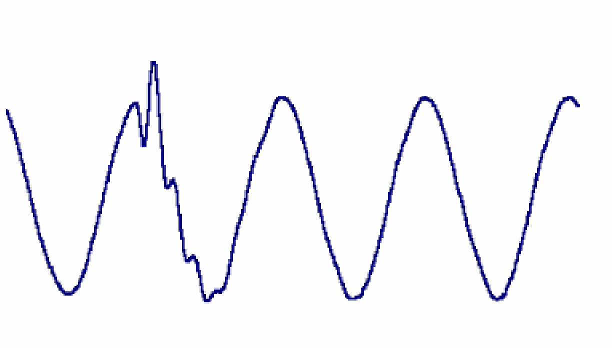

Figure 2.3. Example oscillatory transient waveform caused by capacitor energizing.

3

BENCHMARKING – UNDERSTANDING SYSTEM PERFORMANCE

Understanding system performance as a function of important parameters is a prerequisite to setting any standards for system performance. It is important that benchmarking efforts develop more complete pictures of the performance of the supply system as a function of different parameters:

- urban vs rural systems
- underground vs. overhead systems
- effect of different system topologies
- effect of different voltage levels, source strength, number of circuits from a common bus, etc.
- effect of lightning activity and other causes of system disturbances
- effect of investment in maintenance and equipment

Many other parameters may be important. As the cost of system monitoring continues to decrease, it is important that understanding the system performance in terms of quality and reliability characteristics be developed and maintained on a continuous basis. This information then provides the basis for evaluating the economics of system performance improvement investments vs investments in end-user technologies to improve their immunity to disturbances.

Previous Benchmarking Projects

Utilities do a good job of calculating and reporting system reliability performance (outages). This information is reported to regulators and other organizations that track reliability performance against objectives. Many regulators have instituted Performance Based Rates that are designed based on the benchmarking information.

Utilities are less effective in determining and reliability the performance of other power quality characteristics of the supply that can affect end-users. The most complete system performance benchmarking project to date is the EPRI Distribution Quality project [14]. This project characterized power quality based on two years of monitoring at almost 300 distribution system locations across the United States. Performance was characterized in all categories of power quality. Perhaps the most valuable part of the benchmarking was that assessment of expected voltage sag performance for end-users supplied from the distribution system.

Other benchmarking projects were performed in Canada, Europe, South Africa, and by other individual utilities. For instance, PowerGrid in Singapore conducted an extensive evaluation of expected voltage sag performance in Singapore and compared the performance with the results of other major benchmarking projects. PowerGrid is an example of a utility that has made tremendous investments in the system infrastructure to assure reliability and the highest quality of service for the variety of critical industrial processes (e.g. semiconductor manufacturers) that they supply. Table 3.1 summarizes the comparison [15,16,17]. Obviously, even with a completely underground system and high levels of investment, voltage sags can still be important.

Note that the benchmarking results in Table 3.1 are summarized in terms of the "System Average RMS Voltage Variation Index – SARFI". This provides a measure of the number of voltage sags per year that can be expected with a magnitude and duration below some threshold. In Table 3.1, only a magnitude characteristic is used. For instance, SARFI-70 is a measure of the number of voltage sags that can be expected with a minimum voltage magnitude below 70%. One of the important areas for research is in developing indices that measure system performance in a way that can be correlated with equipment sensitivity and equipment performance. Many different categories of indices are being considered. An IEEE working group is organizing this information into a guideline [18] but further work will be required as equipment characteristics continue to change.

Table 3.1. Comparison of expected performance levels estimated from different benchmarking projects

	SARFI-10	SARFI-70	SARFI-80	SARFI-90
Power Grid – Singapore	1.0	8.5	10.6	14.3
EPRI DPQ Project (US)	4.6	17.7	27.3	49.7
UNIPEDE Mixed Systems (Europe)	16.0	44.0	NA	103.1
UNIPEDE Cable Systems (Europe)	1.4	11.0	NA	34.6
South Africa	9.0	47.0	78.0	153.0

Using Benchmarking Results

As the expected performance of the supply system is better understood, standards for performance can be developed and the actual performance information can be used to prioritize maintenance and expenditures on system performance improvement technologies. For instance, United Illuminating monitors at all distribution substations and tracks voltage sag performance on a monthly basis. Figure 3.1 illustrates a chart that is used within the company to track performance at individual substations. The chart shows voltage sag performance at each substation over the past five years compared with performance for the last year. It also divides sags into events that are caused by transmission faults and events caused by distribution faults. This helps focus the areas where performance improvement can be expected with maintenance or investments in the distribution system. This is only one example of using monitoring results and benchmarking effectively. Research work in CEIDS and other organizations will help identify the uses of continuous system monitoring and performance assessment to optimize the performance and compatibility of the supply system for end-users.

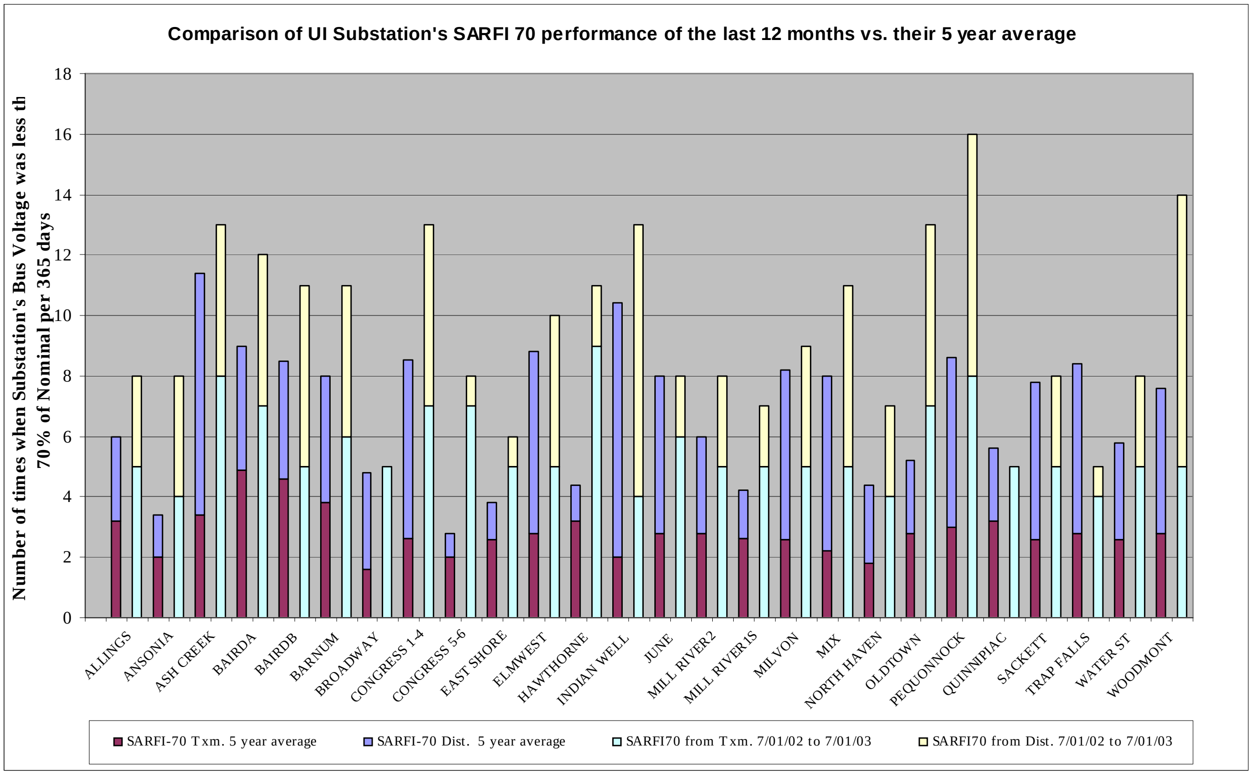

Figure 3.1. Example of using benchmarking information from continuous monitoring system to help prioritize system investments (courtesy of United Illuminating).

4

EQUIPMENT AND END USE SYSTEM CHARACTERISTICS

The concept of compatibility between the characteristics of the supply system quality and the end-user equipment immunity was described in Chapter 2 in terms of steady state power quality characteristics (e.g. voltage regulation, unbalance, flicker, harmonics). This concept is important to understand and optimum "compatibility levels" to assure that this compatibility is achieved in the most economical manner are needed.

This concept of compatibility doesn't apply in the same manner for disturbances like interruptions and voltage sags. It isn't possible to specify a number of interruptions that will be acceptable for equipment that will be disrupted by the interruption – even one interruption has an economic impact. The optimization problem is identifying the relative investments in design and technology for the system and the end-use equipment that results in the best possible performance for the lowest total cost. Not a simple problem!

Regulators are grappling with this problem in the area of reliability by setting standards for reliability that are based on historical performance. It is not clear that these historical performance levels are in any way related to the optimum performance with respect to the potential for relative improvement in performance of end-use equipment. These standards also do not typically recognize the different requirements of different types of customers for quality and reliability.

This is an area where further research by CEIDS and other organizations can provide substantial direction and value for the power system infrastructure of the future. The first requirement for this research is to develop an understanding of equipment characteristics, the costs of power quality problems for different types of customers, and the costs of improving the power quality performance through investments in either the equipment or local power conditioning technologies.

Some equipment manufacturers are doing a better job of describing the expected equipment performance for power supply variations. The ITI curve (Figure 4.1) was developed by the Information Technology Industry Council to define the expected performance of single phase information processing technologies (e.g. PCs, printers, monitors, etc.) for voltage sags [19]. This concept was taken up by the semiconductor industry, in cooperation with utilities, and a new standard for semiconductor production equipment was developed that will result in much more reliable performance for typical power systems. The SEMI ride through curve is shown in Figure 4.2 [20]. It specifies that these tools should ride through sags with a minimum voltage as low as 50% that last up to 200 msec.

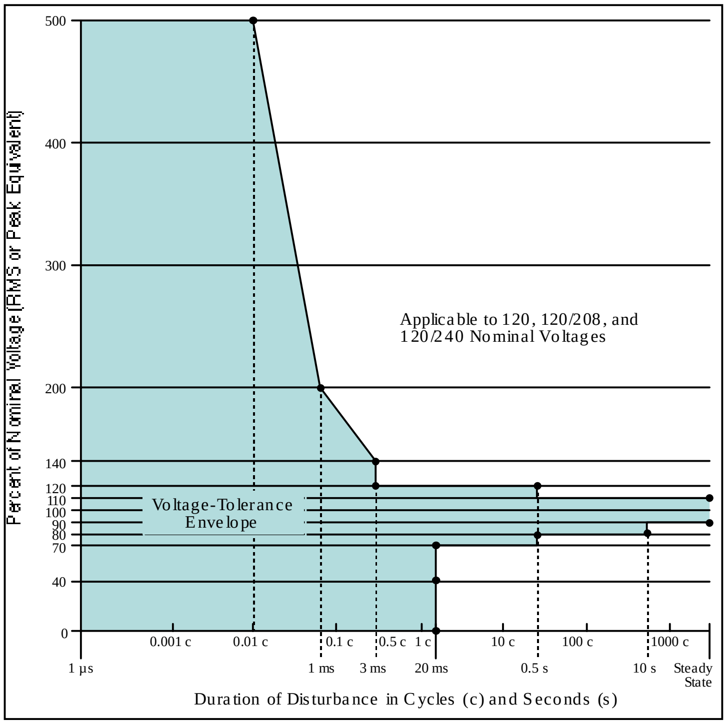

Figure 4.1. Curve defining voltage sag ride-through design goals for manufacturers of information technology equipment (applies to single phase 120/240 volt equipment).

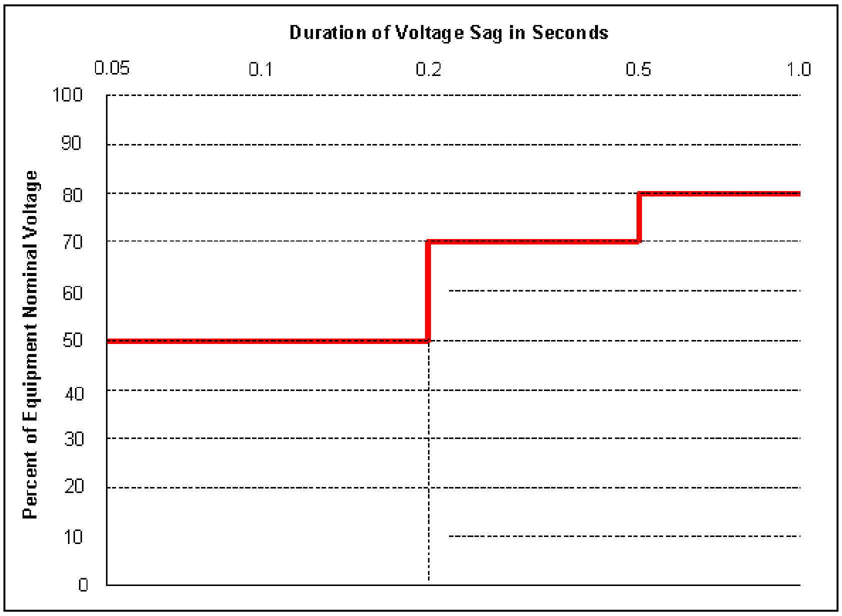

Figure 4.2. Required semiconductor equipment voltage sag ride-through capability curve (SEMI F47-1999)

The concept of addressing the compatibility from a system perspective was first developed effectively in IEEE Standard 1346 [21] which describes procedures for characterizing system performance in a way that can be used by customers to evaluate the likelihood of equipment impacts. It also describes the economic analysis procedure that customers should use to evaluate the expected impacts of this performance on their facilities so that they can optimize their local investments in power conditioning. Further research can take this concept to the next level so that the economic investment vs the expected benefits can be performed taking into account technologies for improvement on both sides of the meter.

5

ECONOMICS OF POWER QUALITY AND RELIABILITY IMPROVEMENT

As described previously, the costs associated with power outages can be tremendous. Manufacturing facilities have costs ranging from $10,000 to millions of dollars associated with a single interruption to the process. The costs to commercial facilities (banks, data centers, customer service centers, etc.) can be just as high if not higher. Unfortunately, these facilities can be sensitive to a wider range of power quality disturbances than just outages that are counted in utility reliability statistics. Momentary interruptions or voltage sags lasting less than 100 milliseconds can have the same impact as an outage lasting many minutes.

This has resulted in a wide variety of technologies for equipment protection and improving power quality. Utilities must also evaluate the need to improve the quality of supply if there are large numbers of customers impacted by power quality variations. The objective of further research will be developing advanced technologies that can be applied on both sides of the meter so that the quality characteristics of the supply system can be matched with the specific requirements of end-user systems.

The evaluation of power quality improvement alternatives is an exercise in economics. Facility managers and utility engineers must evaluate the economic impacts of the power quality variations against the costs of improving performance for the different alternatives. The best choice will depend on the costs of the problem and the total operating costs of the various solutions. Again note that the solutions should include options for improving performance on the supply system.

Improving facility performance during power quality variations can result in significant savings and can be a competitive advantage. Therefore, it is important for customers and suppliers to work together in identifying the best alternative for achieving the required level of performance.

The economic evaluation methodology consists of four basic steps [22]:

1. Characterize the system power quality performance.
2. Estimate the costs associated with the power quality variations.
3. Characterize the solution alternatives in terms of costs and effectiveness.
4. Perform the comparative economic analysis.

Characterizing the Power Quality Performance

Methods of characterizing the expected system performance were described previously (benchmarking). When defining performance indices, it is important to understand the characteristics of disturbances that can cause customer equipment to misoperate. Load susceptibility to rms voltage variations is very dependent on the specific load type, control settings, and application. Consequently, it is often very difficult to distinguish which characteristics of a given rms variation are likely to cause equipment to misoperate. This is an area where continued improvement in equipment performance characteristics is needed.

Figure 5.1 is an example of characterizing system performance using a chart of disturbances. The chart illustrates events that resulted in a process disruption. It also compares the disturbances with the ride-through specifications from the SEMI F-47 standard discussed in the previous section. A chart like this can be used to estimate the sensitivity of the overall process and evaluate the likelihood that supply disturbances will cause an expensive disruption.

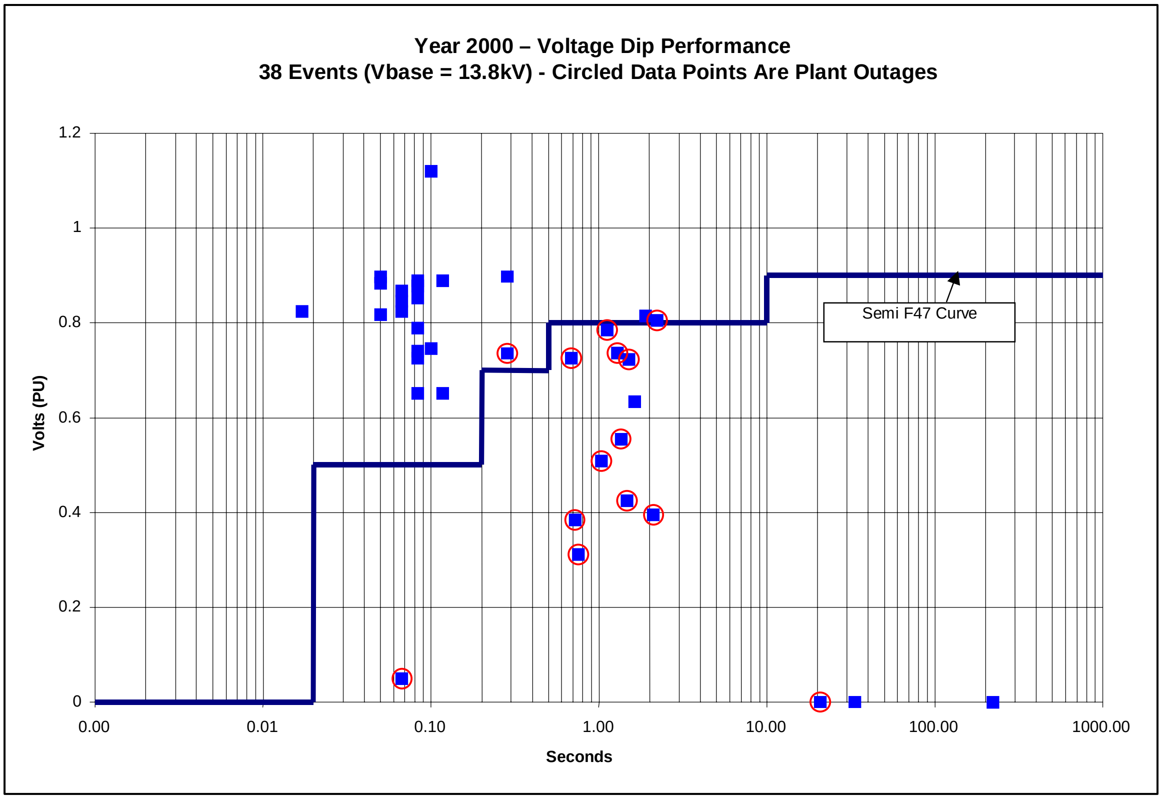

Figure 5.1. Example of characterizing system performance in terms of the impact on process operation.

Estimating the Costs for Power Quality Variations

The costs associated with supply disturbances 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

(24/7 operations). Not all costs are easily quantified or truly reflect the urgency of avoiding the consequences of a disruption. In fact, surveys often come up with widely varying estimates from end-users for the costs they are experiencing associated with supply disturbances. The end-users themselves often do not understand all the costs.

The cost of power quality disturbances can be captured primarily through three major categories:

- Product-related losses, such as loss of product/materials, lost production capacity, disposal charges, increased inventory requirements, etc.;
- Labor-related losses, such as idled employees, overtime, cleanup, repair, etc.
- Ancillary costs such as damaged equipment, lost opportunity cost, and penalties due to shipping delays.

Focusing on these three categories will facilitate the development of a detailed list of all costs and savings associated with a power quality disturbance. Appendix A of IEEE 1346-1998 provides a more detailed explanation of the factors to be considered in determining the cost of power quality disturbances.

Costs will typically vary with the severity (both magnitude and duration) of the power quality disturbance. 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. Voltage sags 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 C_i. If a voltage sag to 40% causes 80% of the economic impact that a momentary interruption causes, then the weighting factor for a 40% sag would be 0.8. Similarly, if a sag to 75% only results in 10% of the costs that an interruption causes, then the weighting factor is 0.1.

After the weighting factors are applied to an event, the costs of the event are expressed in per unit of the cost of a momentary interruption. The *weighted* events can then be summed and the total is the total cost of all the events expressed in the number of *equivalent momentary interruptions*.

Table 5.1 provides an example of these weighting factors. The weighting factors can be further expanded to differentiate between sags that affect all three phases and sags that only affect one or two phases. Table 5.2 is an example of combining the weighting factors with expected performance to determine a total annual cost associated with voltage sags and interruptions. The cost is 16.9 times the cost of an interruption. If an interruption costs $40,000 the total costs associated with voltage sags and interruptions would be $676,000/year for this example facility.

Table 5.1. Example of Weighting Factors for Different Voltage Sag Magnitudes

Category of Event	Weighting for Economic Analysis
Interruption	1.0
Sag with min voltage below 50%	0.8
Sag with min voltage between 50% and 70%	0.4
Sag with min voltage between 70% and 90%	0.1

Table 5.2. Example of combining the weighting factors with expected voltage sag performance to determine the total costs of power quality variations.

Category of Event	**Weighting for Economic Analysis**	**Number of Events/Year**	**Total Equivalent Interruptions**
Interruption	1	5	5
Sag with min voltage below 50%	0.8	3	2.4
Sag with min voltage between 50% and 70%	0.4	15	6
Sag with min voltage between 70% and 90%	0.1	35	3.5
Total			16.9

Characterizing the Cost and Effectiveness for Solution Alternatives

A wide range of potential solutions, with varying degrees of cost and effectiveness, are available to mitigate the consequences associated with poor power quality. Power quality solutions can be applied at different levels or locations within the electrical system. The four major options are:

- Supply system modifications and equipment that affect multiple customers.
- Service entrance technologies that affect a single targeted customer.
- Power conditioning at equipment locations within a facility.
- Equipment specifications and design.

In general, the costs of these solutions increases as the power level of the load that must be protected increases. This means that economies can usually be achieved if sensitive equipment or controls can be isolated and protected individually from equipment that does not need protection.

Ideally, the appropriate ride through will be part of the equipment design (thus the motivation for the new semiconductor manufacturing equipment standard). However it is often not a practical option when trying to improve the operation of an existing facility. Original equipment manufacturers may also be reluctant to incorporate "voltage sag ride through" capabilities in their equipment because the added costs may not translate into an appropriate perceived value for many of their customers. Manufacturers are more inclined to offer a "voltage sag ride through" option that could be purchased by those customers with the need.

Each solution technology needs to be characterized in terms of cost and effectiveness. In broad terms the solution cost should include initial procurement and installation expenses, operating and maintenance expenses and any disposal and/or salvage value considerations. A thorough evaluation would include less obvious costs such as "real estate" or "space related" expenses and tax considerations. The cost of the extra space requirements can be incorporated as a space rental charge and included with other annual operating expenses. Tax considerations may have several components and the net benefit or cost can also be included in with other annual operating expenses. Table 5.3 provides an example of initial costs and annual operating costs for some general technologies used to improve performance for voltage sags and interruptions. These costs are provided for example purposes only and are not necessarily accurate for any particular solution category.

Table 5.3. Example costs for different types of power quality improvement technologies

Alternative Category	**Typical Cost**	**Operating and Maintenance Costs (% of initial costs per year)**
Controls Protection (< 5 kVA)		
CVTs	$1000/kva	10%
UPS	$500/kva	25%
Dynamic Sag Corrector	$250/kva	5%
Machine Protection (10-300 kVA)		
UPS	$500/kva	15%
Flywheel	$500/kva	7%
Dynamic Sag Corrector	$200/kva	5%
Facility Protection (2-10 MVA)		
UPS	$500/kva	15%
Flywheel	$500/kva	5%
DVR (50% voltage boost)	$300/kva	5%
Static Switch (10 MVA)	$600,000	5%
Fast Transfer Switch (10 MVA)	$150,000	5%

Besides the costs, the solution effectiveness of each alternative needs to be quantified in terms of the performance improvement that can be achieved. Solution effectiveness, like power quality costs, will typically vary with the severity of the power quality disturbance. For voltage sags, this relationship can be defined by a matrix of "% sags avoided" values. Table 5.4 illustrates this concept for the example technologies from Table 5.3 as they might apply to an example process industry facility.

Table 5.4. Effectiveness of the power quality improvement options for a particular example case (the entries in the table represent the percentage of voltage sags or interruptions in each category that are corrected to levels that will no longer cause equipment impacts in the facility).

	Interruption	**Sags with min voltage below 50%**	**Sags with min voltage between 50% and 70%**	**Sags with min voltage between 70% and 90%**
CVT (controls)	0%	20%	70%	100%
Dynamic sag corrector/DVR	0%	20%	90%	100%
Flywheel Ride Through Technologies	70%	100%	100%	100%
UPS (Battery ride through technologies)	100%	100%	100%	100%
Static Switch	100%	80%	70%	50%
Fast Transfer Switch	80%	70%	60%	40%

Performing Comparative Economic Analysis

The process of comparing the different alternatives for improving performance involves determining the total annual cost for each alternative, including both the costs associated with the power quality variations (remember that the solutions do not typically eliminate these costs completely) and the annualized costs of implementing the solution. The objective is to minimize these annual costs (PQ Costs + Solution Costs).

Comparing the different power quality solution alternatives in terms of their total annual costs (annual power quality costs + annual power quality solution costs) identifies those solution(s) with lower costs that warrant more detailed investigations. The "do nothing" solution is generally included in the comparative analysis and is typically identified as the "base case". The "do nothing" solution has a zero annual power quality solution cost but has the highest annual power quality costs.

Many of the costs (power quality and O&M) are by their nature annual costs. The costs associated with purchasing and installing various solution technologies are one time "up front" costs that can be annualized using an appropriate interest rate and assumed lifetime or evaluation period.

Figure 5.2 gives an example of this type of analysis for a process industry facility. The facility has a total load of 5 MW but only about 2 MW of load needs to be protected to avoid production disruptions. The voltage sag performance was given in Table 5.2. The costs for an interruption are $40,000 per event and the costs for voltage sags are based on the weighting factors given previously. The six options given in Table 5.4 are analyzed and the annual costs are presented. The annualized costs are calculated based on a 15 year life and an interest rate of 10%.

It is interesting to note that all of the options reduce the total annual costs (in other words, any of these options would have a net benefit to the facility with the assumed interest rate and lifetime when compared to the existing conditions). It is also interesting that the best solution in this case involves applying equipment on the utility side (fast transfer switch). However, this has a major assumption that a backup feeder would be available and that there would be no charge from the utility for providing a connection to this backup feeder except the equipment and operating costs.

More commonly, the solution would be implemented in the facility and either a dynamic sag corrector or flywheel based standby power supply might make sense for protecting the 2 MW of sensitive loads. In this case, protecting just the controls with CVTs does not provide the best solution because the machines themselves are sensitive to voltage sags.

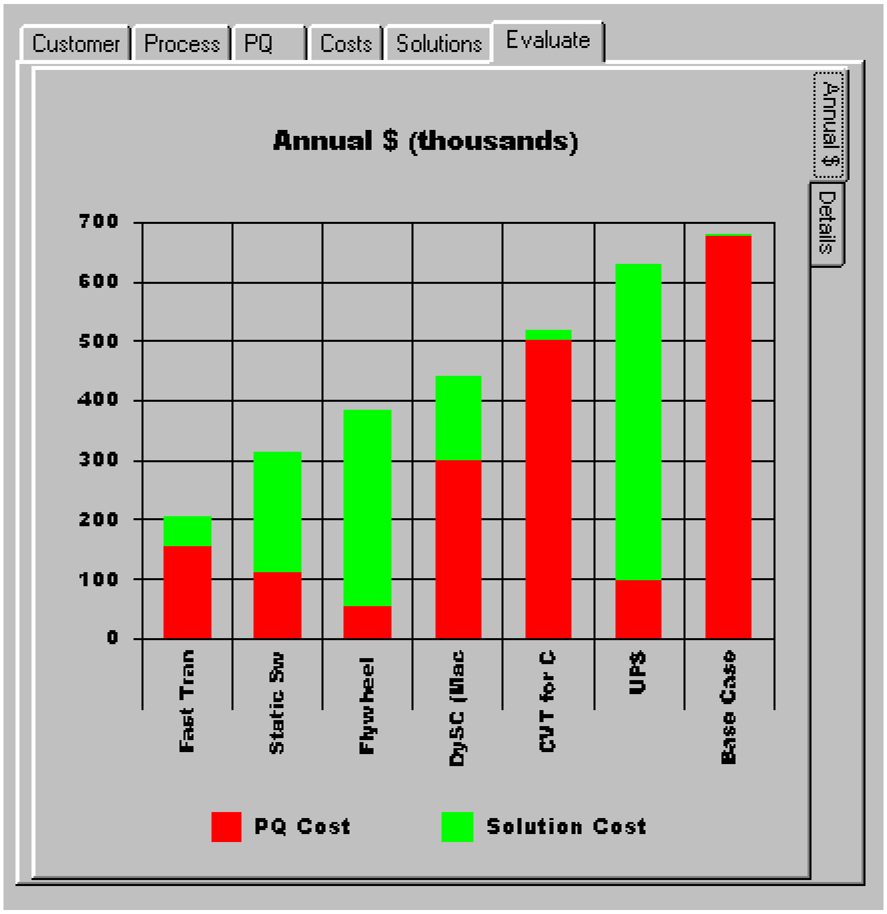

Figure 5.2. Example of comparing solution alternatives with the base case using total annualized costs.

A thorough economic analysis would also include a parameter sensitivity evaluation where the uncertain parameters could be characterized by minimum, maximum and average values. The probabilistic nature of power quality events coupled with market conditions that can greatly affect power quality costs would typically justify the need for the sensitivity evaluations.

Future Direction of the Economic Analysis

This example case is designed to illustrate the process that manufacturing and other critical facilities should be going through today to evaluate the best option for their individual facilities. This is not the global system optimum for achieving the highest level of productivity and performance. The future direction needs to focus on advanced technologies that can be applied at all levels of the system to improve compatibility (both supply side technologies and end-user technologies) and on the procedures to find the optimum places to make these investments from a system perspective.

These procedures will take into account the future technologies that will be available, the statistical nature of power supply performance, and the variety of different operating conditions for both the supply system and end-user facilities. The goal will be to develop the ability to continuously optimize performance by coordinating the performance of the supply system with the requirements of end-users on a custom basis and on a continuously changing basis.

New technologies may include the Intelligent Universal Transformer (EPRI research project), system automation technologies with communications all the way down to customer facilities (IECSA project), integration of distributed generation technologies, and advanced power electronics technologies to tailor system performance to specific requirements.

6

CONCLUSIONS

The previous sections described important concerns associated with the supply infrastructure quality and reliability. The recommended direction for future research was discussed throughout the document. The needed research can be summarized in three focus areas. These three focus areas should be addressed in a coordinated effort that characterizes previous and ongoing research and provides a detailed roadmap for achieving the optimum compatibility between the supply system performance and specific end-user system requirements (Figure 6.1).

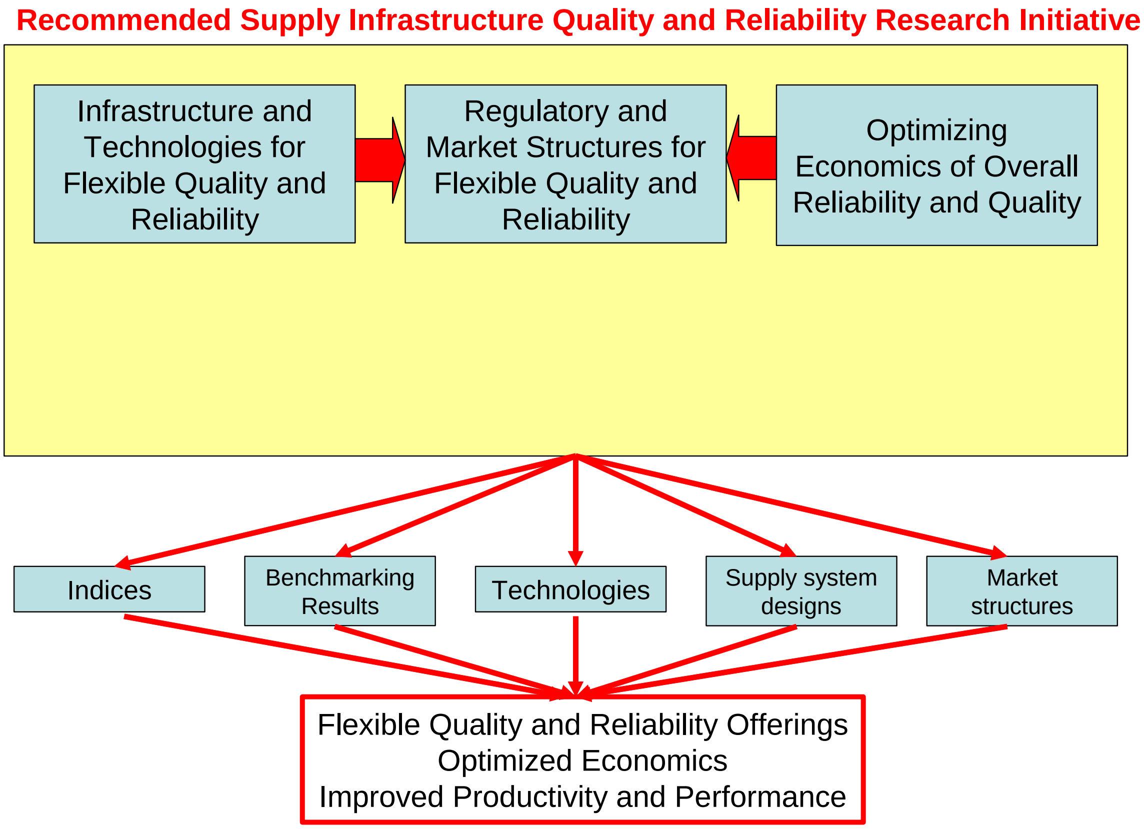

Figure 6.1. Components of CEIDS Supply System Reliability and Quality Research Initiative.

1. **Infrastructure and Technologies for Flexible Quality and Reliability.** This development area will identify and develop the infrastructures and technologies to deliver flexible and tailored quality and reliability based on the specific requirements and characteristics of individual customers and systems. This will include use of new communications architectures (IECSA), consumer gateways (customer portal), and interfaces with equipment and processes within customer facilities. It includes

the development and application of advanced power electronics technologies (solid state switch, DVR, etc.) that will facilitate flexible power quality and reliability levels (many of these development efforts are already under way and will continue in parallel to the CEIDS research). Some particular areas to emphasize that complement existing research include:

  - Technologies that address security issues and major disturbances. These are critical to the system reliability and will continue to grow in importance. This is a research area in itself and the focus with respect to the reliability and quality initiative should only be identifying major research under way and describing a methodology to account for security issues when characterizing system quality and reliability.

  - Technologies that facilitate self-healing of the grid through automated response to disturbances. This can include adaptive islanding, fast switching, and coordinated response of customer equipment through advanced communication architectures (i.e. IECSA).

  - Automated distribution systems that manage quality and reliability in response to specific customer requirements and system capabilities. This should build on initiatives at EPRI, DOE, EdF, and other research organizations to understand how automation can improve reliability and quality along with other operational and efficiency benefits.

The result of this research will be characterization of new technologies, automation systems, and system topologies with estimates of the possible impacts of these developments on the quality and reliability that can be provided by the grid along with cost estimates for achieving these improvements. The ability to provide customized quality and reliability as a function of end-user needs should also be characterized.

2. **Assessment of Regulatory and Market Structures to Support Flexible Quality and Reliability.** Unfortunately, the development of innovative technologies and approaches for achieving improved quality and reliability has been slower than desired. A major reason for this is the lack of regulatory structures and profit opportunities that reward investments in technologies and designs that are focused on reliability and quality improvement. New innovations to facilitate quality and reliability levels that are tailored to particular circumstances are needed. Specific developments needed include:

    - Assessment of the effectiveness of existing market structures and regulations related to quality and reliability requirements. Various countries and utilities have requirements for both quality and reliability performance. These requirements are enforced through various economic penalties. The assessment should review the benefits of these different systems from a global economics perspective and identify characteristics of these systems that are effective and ineffective.

- Indices that can accurately characterize the full range of quality and reliability concerns and benchmarking using these indices to define appropriate performance objectives as a function of important system characteristics. A probabilistic risk assessment approach is needed.

- Flexible pricing structures that can address reliability and quality issues. These should identification of regulatory and market structures that provide for appropriate investment incentives related to providing flexible levels of security, reliability, and quality (based on the survey of existing systems and possible future approaches).

The result of this research will be an understanding of the effectiveness of different market and regulatory structures in encouraging participation of the supply system in achieving optimum reliability and quality levels for the wide range of end-users. Approaches that can work towards an optimum mix of supply side and customer side investments will be identified. Any of the approaches require appropriate indices for benchmarking and assessing performance.

3. **Optimizing the Overall Economics of Reliability and Quality Levels.** This is the ultimate objective of developing the technologies and regulatory/market infrastructures to support flexible reliability and quality levels. The new technologies will allow optimization of service characteristics based on the costs and options for individual customers. Optimization procedures must be developed based on the technology options and infrastructure design options that will be available. Specific developments should include:

    - More complete understanding of all the costs associated with reliability and quality issues. These costs include utility system costs, customer costs, and society costs. Methods for characterizing these costs using analytical approaches are needed to facilitate the optimization process. There has been considerable work to characterize the overall costs associated with reliability and quality variations but future methodologies must be based on the specific costs and options for performance improvement for each end user and then being able to compare these options with system quality and reliability options.

    - System level optimization that defines investment priorities between the supply system and customer systems to achieve performance compatibility. The development of standards like SEMI F47 is an illustration of a coordinated approach to supply side and customer side investment. This relative investment strategy can be extended to include a wider range of security, reliability, and quality issues and the diverse range of customer types. System level optimization will be a function of end user types, system topologies, etc.

The end result of these research initiatives will be indices, benchmarking results, technologies, infrastructure designs, and regulatory/market structures that will facilitate optimum compatibility between the supply system and customer systems in the digital economy. As the research results are turned into real systems, higher levels of productivity will be unleashed throughout the digital economy.

7

REFERENCES

1. “Electricity Sector Framework of the Future”, EPRI, August, 2003.

2. Primen study evaluating the costs of quality and reliability.

3. IEEE 1366.

4. IEEE 1159 – Power Quality Monitoring.

5. IEC Publ. 1000-2-2, 1990 / EN 61000-2-2, 1994: „Electromagnetic Compatibility (EMC). Part 2: Environment Section 2: Compatibility levels for low-frequency conducted disturbances and signalling in public low voltage power supply systems“

6. EN 50160: Voltage characteristics of electricity supplied by public distribution systems, November 1994

7. IEC 61000-4-15. Flicker Measurement Equipment Specifications.

8. IEEE 1433. Voltage Flicker.

9. IEEE 519.

10. IEC 61000-3-6.

11. SEMI F47.

12. IEEE/ANSI Standard C62.41.

13. UL Standard for testing surge suppressors.

14. EPRI TR-106294-V2, An Assessment of Distribution System Power Quality; Volume 2: Statistical Summary Report, May 1996

15. NRS 048-2:1996, Electricity Supply - Quality of Supply Standards; Part 2: Minimum Standards.

16. F. W. T. Davenport, "Voltage Dips and Short Interruptions in Medium Voltage Public Electricity Supply Systems," UNIPEDE/DISDIP Report, 1990.

17. PowerGrid paper for CIRED 2001, Amsterdam.

18. IEEE 1564. Voltage Sag Indices, Draft 4.

19. ITIC.

20. SEMI F47.

21. IEEE Standard 1346.

22. “Economics of Power Quality,” Power Engineering Review, 2001.