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Review of Power Quality Applications of Energy Storage Systems

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Abstract

Under the sponsorship of the U.S. Department of Energy (DOE) Office of Utility Technologies, the Energy Storage Systems Analysis and Development Department at Sandia National Laboratories contracted Sentech, Inc., to assess the impact of power quality problems on the electricity supply system. This report contains the results of several studies that have identified the cost of power quality events for electricity users and providers. The large annual cost of poor power quality represents a national inefficiency and is reflected in the cost of goods sold, reducing U.S. competitiveness. The Energy Storage Systems (ESS) Program takes the position that mitigation merits the attention of not only the DOE but affected industries as well as businesses capable of assisting in developing solutions to these problems. This study represents the preliminary stages of an overall strategy by the ESS Program to understand the magnitude of these problems so as to begin the process of engaging industry partners in developing solutions.

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Sandia National Laboratories would like to thank Dr. Christine E. Platt of the U.S. Department of Energy's Office of Utility Technologies for the support and funding of this work. We would also like to acknowledge the National Power Laboratories, which conducted a study that provided data summaries for four types of power quality events and input from 130 user sites, and Duke Power, which conducted a study that provided detailed data from 198 industrial and commercial users, making it possible to derive approximations of the national impact of power quality events. Thanks are also due to Paul Butler of Sandia's Energy Storage Analysis and Development Department for providing valuable technical review before the final study was published.

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Acronyms and Abbreviations

ASD	adjustable speed drive
CBEMA	Computer Business Equipment Manufacturers Association
CEA	Canadian Electrical Association
DOE	U.S. Department of Energy
EPRI	Electric Power Research Institute
ESS	Energy Storage Systems
IEEE	Institute of Electrical and Electronics Engineers
NPL	National Power Laboratories
PC	personal computer
PG&E	Pacific Gas & Electric
RMS	root mean square
UPS	uninterruptible power supply
Var	volt-ampere reactive

1. Executive Summary

In America, electricity has become ubiquitous. It is present virtually everywhere there is a need, it is available in seemingly limitless quantities, and it performs an uncountable variety of tasks. However, unnoticed by most users, the electricity supply often exhibits imperfections. The magnitude and prevalence of these imperfections, together with the occasional total interruption or outage, constitute the ingredients of power quality.

Increased automation in homes and factories has increased the impact of power quality deviations. Power quality has been defined as any problem manifested in voltage, current, or frequency deviations that results in failure or misoperation of utility or end-user equipment. Examples of power quality events and of devices capable of protecting against their effects are shown in Table 1-1. Storage systems are seen to provide by far the broadest range of power quality protection.

While storage provides comprehensive protection, it may not be the economic choice for each of the power quality events listed in the table. However, because of their ability to detect and respond to the energy deficiency in the supply source rapidly, energy storage systems are the preferred solution for voltage sags, undervoltages, and interruptions.

Data on the frequency of power quality disturbances are not widespread and are often proprietary. Three surveys conducted to determine the extent of power quality issues have been identified. While the detailed results of the surveys are not available in the public domain, data summaries have been published. The most useful summary for this study was published by the National Power Laboratories (NPL) and included data on 130 user sites consisting of 31% industrial, 24% small business, 18% multistory buildings, 17% residential, and 10% institutional. Table 1-2 summarizes NPL data for four types of power quality events. Because the data show great variance between the number of events in the best locations (zero) and the number in the worst locations (over 1,000 per month for three of the disturbances), it is likely that the median, rather than the average, is more representative of typical performance. Consequently, for this study, the more conservative median is used in subsequent analyses.

Table 1-1. Mitigation Capabilities of Protection Devices

	Power Quality Event								
	Impulsive Transient	Oscillatory Transient	Sag/ Swell	Under-/Over-voltage	Interruption	Harmonic Distortion	Voltage Flicker	Noise	Electrostatic Discharge
Surge arrestor	x	x							
Filter	x	x				x		x	x
Isolation transformer	x	x				x			
Constant voltage transformer			x	x					
Dynamic voltage restorer			x	x					
Backup generator					x				
Humidity control									x
Energy storage									
- Off-line	x	x	x	x	x		x	x	
- Line-interactive	x	x	x	x	x		x	x	
- On-line	x	x	x	x	x	x	x	x	x

Table 1-2. NPL Summary of Disturbances

	Best Locations (events/month)	Worst Locations (events/month)	Median (events/month)	Average (events/month)
Sags/Undervoltages (low RMS)	0	1,660	4.1	27.9
Swells/Overvoltages (high RMS)	0	1,450	3.4	13.9
Transients	0	1,166	15.7	63.5
Interruptions	0	10	1.0	1.3

Information regarding the cost to electricity customers of power imperfections is even less widely available than data on the imperfections. However, a survey conducted by Duke Power has been published that contains information suitable for deriving approximations of national impact. Duke surveyed 198 large industrial and commercial customers and collected information on the components of interruption costs under varying outage conditions. Analyzing the average interruption costs of the various outage conditions showed that the most costly occurrences resulted from electricity outages and voltage sags. The costs for these occurrences are summarized in Table 1-3, in which the greater impact of longer-duration events and the benefits of prior notice are clearly evident.

Few estimates of the national cost of power quality events have been attempted. An article in *Spectrum*, a publication of the Institute of Electrical and Electronics Engineers (IEEE), suggested a cost of $25 billion, and an Electric Power Research Institute (EPRI) report estimated a cost of $400 billion. The first value was based on 1.5–3% of sales of the U.S. manufacturing industry, and the second was based on estimates of idled employee-hours due to power quality problems in the commercial sector.

The combination of NPL and Duke Power data provides a third opportunity to estimate national impact, in particular to estimate the national cost of power quality events that energy storage systems could resolve. Using the frequency of events from the NPL survey and extrapolating the Duke Power data to a national electricity level, a total cost (to large industrial customers) of U.S. power outages and voltage sags—and thus a potential power quality market for storage—can be developed. As shown in Table 1-4, the resulting estimate is approximately $150 billion annual cost.

The $150 billion value is developed using only undervoltage/sag and interruption data because these are the two categories of power quality problems in the Duke Power survey for which storage systems are a likely solution. Costs resulting from power quality problems in other categories are excluded. Thus the estimate is conservative in the sense that there may be cases where storage could provide cost-effective solutions for other power quality problems, possibly some not covered in the Duke survey.

It should be recognized that computing a national loss number with data from a single region can be a risky undertaking; opportunities to introduce error are relatively high. Nevertheless, it is noteworthy that the $150 billion estimate falls between the estimates of $25 billion and $400 billion cited earlier. Whatever the actual number, one can postulate with increasing

Table 1-3. Duke Power Survey on Cost of Power Quality Events

	Event				
	4-Hr Outage, No Notice	1-Hr Outage, No Notice	1-hr Outage with Notice	Momentary Outage	Voltage Sag
Average cost of event	$74,835	$39,459	$22,973	$11,027	$7,694

Table 1-4. National Cost Estimate for Large Industrial Customers

	Average Annual Cost to Large Industrial Customers	Estimated Cost for Duke Power Customer Group	Estimated Cost for National Customer Group
Undervoltages/sags	$377,000	$ 3.2B	$ 114B
Interruptions	$132,000	$1.1B	$39B
		Total estimated U.S. cost (rounded):	$150B

confidence that the market value of energy storage systems addressing power quality problems could total tens of billions of dollars annually.

The market for such systems has grown in the recent past because of the proliferation of microprocessor-controlled equipment and power electronic motor controls, which are susceptible to distortions in supply waveform. At present, part of the market is served by a variety of uninterruptible power supplies. Largely overlooked, however, are energy storage systems capable not only of meeting large industrial loads during interruptions but also of correcting for voltage magnitude variances and waveform imperfections. Such systems have been installed in recent years, but large gaps persist in power ratings, protection durations, performance capabilities, flexible siting and operation, cost, and installation ease. Until these shortcomings are overcome, manufacturers and their customers will continue to experience higher than necessary costs.

The large annual cost of poor power quality represents a form of national inefficiency and is reflected in the cost of goods sold, reducing U.S. competitiveness. This cost is ultimately paid by consumers, both domestic and foreign. Its mitigation merits the attention of the affected industries as well as businesses capable of developing solutions and the U.S. Department of Energy (DOE).

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2. Overview

The electric utility industry is expected by the public to provide a reliable and uninterrupted supply of electricity—a goal that the industry has achieved to a great extent. Although the reliability of the electricity supply system is high, there are occasional unscheduled outages caused by a variety of unpredictable events. Industries such as telecommunications that cannot tolerate unscheduled outages have installed backup generation and/or energy storage systems in order to alleviate the problem.

In recent years, with increased automation and greater use of microprocessor-controlled processes, industries have begun to realize that unscheduled outages are only one of many power quality problems. Very short perturbations (measured in milliseconds) in the supply waveform sometimes affect sensitive equipment, resulting in significant losses in productivity. The utility industry has begun to feel increased pressure from industrial customers not only to supply reliable and uninterrupted power, but also to ensure that the quality of the power supply is adequate for their equipment to operate smoothly. The deregulation pressures on the electric utility industry and the associated increases in customer choices only exacerbate the utility industry's need to provide the higher-quality power that their customers are demanding. EPRI has undertaken a major effort to analyze the nature and causes of the power quality problems.

A major thrust of the DOE's Energy Storage Systems (ESS) Program at Sandia is to minimize or eliminate power quality and reliability problems that cost U.S. companies productivity and revenues. To accomplish this, the ESS Program conducts its own analyses and exchanges analyses with industry partners and various industry organizations. It then develops suitable projects to address power quality and reliability problems using energy storage technologies/solutions. For example, a mid-voltage power quality system is being developed to solve power quality problems at the substation (15-kV) level. The PQ2000, a 2-MW/15-sec power quality system, has demonstrated its ability to address power quality problems by protecting a lithograph plant in Homerville, Georgia, against short-duration power outages; it was designed to do the same at the utility level, and will soon do so at a Virginia utility. Power quality problems will also be mitigated with modular energy storage systems such as the 250-kW PM250 system and the Advanced Battery Energy Storage System (ABESS). These technologies are being advanced by the ESS Program and its partners and will offer benefits such as improved power plant operation and higher-reliability power for utility customers.

This study reviews the existing literature dealing with power quality issues and summarizes the nature, scope, and costs associated with poor power quality. It also discusses the technology options available to address power quality issues and identifies the role energy storage systems can play in mitigating these power quality problems.

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3. Problem Description

The term power quality often means different things to different people. Electric utilities are primarily responsible for a reliable and uninterruptible supply of electricity, but this is just one facet of good power quality. The manufacturers of equipment define power quality as the characteristics of a power supply that are required to make end-user equipment work properly. These characteristics can be very different depending on the type of equipment and the manufacturing process in question. Since end users are ultimately affected by poor power quality, the definition of power quality must accommodate their concerns. Thus, an EPRI Power Quality Workbook[1] defines power quality as any problem manifested in voltage, current, or frequency deviations that results in failure or misoperation of utility or end-user equipment.

An ideal voltage supply is a pure sinusoidal waveform with constant magnitude and frequency. Several types of distortions in the power supply can be the cause of power quality problems. These distortions result from a wide variety of events ranging from switching events within the end-user facility to faults hundreds of miles away on the utility transmission line. Perturbations that fall within the category of power quality events can be categorized as transient disturbances, fundamental frequency disturbances, and variations in steady state. Table 3-1 lists power-quality-related events and defines the characteristics of those events. Graphical descriptions of these perturbations are provided in Appendix A.

The phenomena listed in Table 3-1 affect different equipment in different ways. Switching an air conditioner on may cause a sag in voltage, which might dim the lights momentarily. However, plugging in a coffee pot to the same receptacle as a PC might cause a voltage sag that could scramble data every time the heater of the coffee pot is turned on or off.[2]

Industrial equipment with microprocessor-based controls and power electronic devices that are sensitive to disturbances are affected most by poor power quality. Control systems can be affected by momentary voltage sags or small transient voltages, resulting in nuisance tripping of important processes. Furthermore, many of these sensitive loads are interconnected in extensive networks and automated processes. This interconnected nature makes the whole system dependent on the most sensitive device when a disturbance occurs. Examples of industries with such interconnections include steel, plastic, glass, paper, and often chemical manufacturers.

A growing percentage of loads utilize power electronics in some type of power conversion process. Such systems generate harmonic currents that result in voltage distortion when they interact with the system impedance. Adjustable speed drives (ASDs), for example, can generate harmonics that can excite resonance with low-voltage capacitors and cause equipment failure. In addition to ASDs, factory efficiency upgrades and demand-side management initiatives often involve the application of equipment such as high-efficiency motors and electronic ballasts. These devices also have significant power quality compatibility issues. Changes in the load characteristics that result from the use of such equipment contribute further to the problems encountered by the end user.

Because microprocessor-based controls and power electronic devices are most susceptible to disturbances in voltage, the Computer Business Equipment Manufacturers Association (CBEMA)[3] has defined the operational design range of voltage for computers. The CBEMA curve given in Figure 3-1 defines the tolerance of microprocessor-based equipment to voltage deviations.

Microprocessor-based equipment is typically designed to withstand and operate normally during disturbances as long as the event is within the shaded portion of the curve. The curve depicts the ability of equipment to withstand large voltage swings (100–200% under/over nominal voltage) for short durations (given in microseconds) and smaller voltage swings for longer durations.

Scope of Power Quality Problems

The types of power quality disturbances that may be present are highly dependent on location. If a facility is located at the end of a distribution feeder,

[1] "Power Quality—Electric Power Research Institute's Power Quality Workbook," TR-105500, April 1996.

[2] *EPRI Journal*, July/Aug 1991.

[3] Presently known as the Information Technology Industry Council.

Table 3-1. Categories of Power Quality Variations

Major Category	Specific Category	Defining Characteristics
Transient Disturbances	IMPULSIVE TRANSIENTS	Unidirectional Typically <200 microseconds
	OSCILLATORY TRANSIENTS - low-frequency - medium-frequency - high-frequency	Decaying Oscillations <500 Hz 500–2000 Hz >2000 Hz
Fundamental Frequency Disturbances	SHORT-DURATION VARIATIONS - sags - swells	Duration 0.5–30 cycles 10%–90% nominal 105%–173% nominal
	LONG-DURATION VARIATIONS - undervoltages - overvoltages	>30 cycles
	INTERRUPTIONS - momentary - temporary - long-term	Complete loss of voltage <2 sec 2 sec–2 min >2 min
Variations in Steady State	HARMONIC DISTORTION	Continuous distortion (V or I) Components to 50th harmonic
	VOLTAGE FLICKER	Intermittent variations in 60-Hz voltage magnitude; frequency component <25 Hz
	NOISE	Continuous high-frequency component on voltage or current; freq: >3000 Hz

* Source: Power Quality Assessment Procedures, EPRI CU-7529 (December 1991).

depending on the loading level of the feeder, undervoltage may be prevalent at the location. Areas with high isokeraunic levels (high incidences of lightning) are more prone to surges. The reverse is also often observed; regions with high isokeraunic levels have transmission and distribution systems better designed to cope with lightning surges, resulting in lower incidences at the customer end. In addition, harmonics created by neighboring facilities may affect each other. Voltage sags could be experienced when large motors, like those in a sawmill, start up, drawing 2 to 3 times full load current, and dipping the voltage well below acceptable levels for up to 5 seconds. Table 3-2 lists the causes of the power quality events listed in Table 3-1.

In order to ascertain the impact of power quality problems, one must ascertain the frequency of these occurrences as well as determine how severe these disturbances must be to cause disruption of service and production.

There are three surveys of power quality problems that form the basis for much of the discussion related to power quality issues. Table 3-3 provides an overview of the scope of the surveys as well as the parameters measured. Detailed results of these surveys are not available in the public domain. The surveys conducted by the Canadian Electrical Association[4]

[4] Canadian National Power Quality Survey, Canadian Electrical Association, Project 220 D 711A, August 1995.

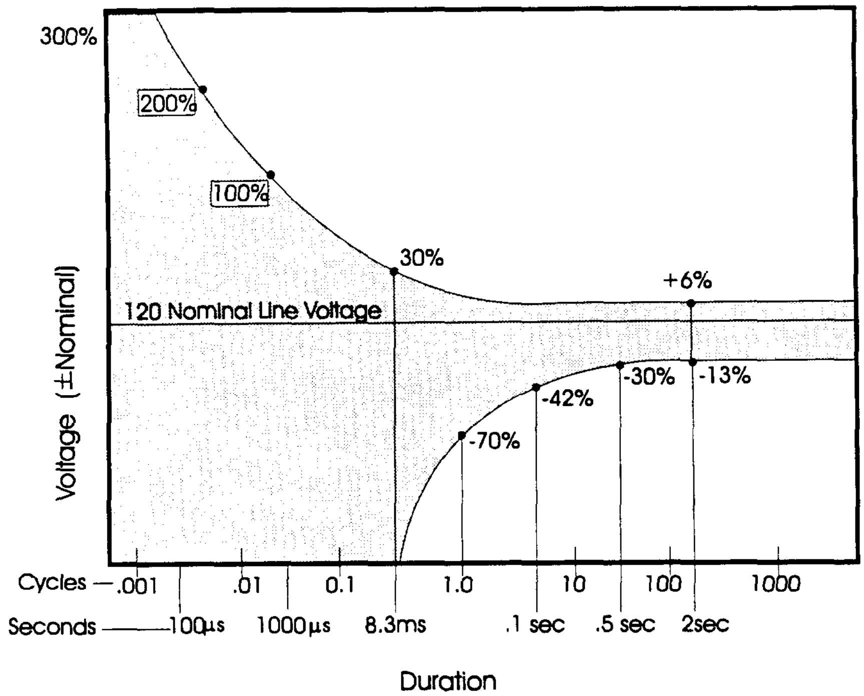

Figure 3-1. The CBEMA Curve.

Table 3-2. Summary of Power Quality Variation Categories and Causes*

Category	Method Of Characterization	Cause
IMPULSIVE TRANSIENTS	Magnitude Duration	Lightning, load switching
OSCILLATORY TRANSIENTS	Waveforms	Lightning, line/cable switching, capacitor switching, transformer switching, load switching
SAGS/SWELLS	Waveforms, RMS vs. Time	Remote faults
UNDERVOLTAGES/ OVERVOLTAGES	RMS vs. Time	Overloading of feeder/motor starting, load changes, compensation changes
INTERRUPTIONS	Duration	Breaker operation/fault clearing, maintenance
HARMONIC DISTORTION	Waveforms, Harmonic Spectrums	Nonlinear loads, system response characteristic
VOLTAGE FLICKER	Magnitude Frequency of Modulation	Intermittent loads, arcing loads, motor starting
NOISE	Noise, Coupling Method, Frequency	Power electronic switching, arcing, electromagnetic radiation

* Source: Power Quality Assessment Procedures, EPRI CU-7529 (December 1991).

Table 3-3. Summary Overview of the CEA, NPL, and EPRI Power Quality Surveys

Survey	Monitor Period	Quantity of Data (Monitor Months)	Number of Sites	Measured Parameters
CEA	1991 to 1994	530	550	Voltage
NPL	1990 to 1995	1200	130	Voltage
EPRI	1993 to 1995	5691	277	Voltage & Current

(CEA) and the NPL[5] can be purchased, while the most extensive survey conducted by EPRI[6] is not available to non-EPRI members. Summary reports are available in the public domain for each of the three studies, with NPL reporting most of its survey data in an IEEE Industrial Application publication.[7]

The CEA survey, conducted in the service territories of 22 Canadian utilities, monitored residential, commercial, and light industrial customers for 25 days at their 120-V or 347-V service entrance panels. Heavy electricity users connected at voltages over 29 kV were not included in this study. The NPL study, in contrast, monitored a smaller number of sites over a longer period of time. It also included heavy industries (8 heavy industries and 33 light industries, in a survey sample of 130). Single-phase, line-to-neutral data were collected at the standard wall receptacle.

While the CEA and NPL surveys focused on the end user, the objective of the EPRI study was to describe the power quality levels on primary distribution systems in the U.S. The feeders monitored represented a diverse sampling of U.S. distribution systems, with voltage ratings from 4.16 kV to 34.5 kV and line lengths from 1 to 80 kilometers. The feeders also represented a wide geographic sampling of the nation, and included rural, suburban, and urban load densities and residential, commercial, and industrial load types. The feeder selection process identified a population of monitoring locations that would be an unbiased representation of the types of distribution feeders present across the U.S.

[5] National Power Laboratory Power Quality Study, Best Power Technology, Inc., Necedah, WI.

[6] "An Assessment of Distribution System Power Quality," EPRI TR-106249, May 1996.

[7] Douglas Dorr, "Point of Utilization Power Quality Study Results," *IEEE Transactions on Industrial Applications*, Vol. 31, No. 4, July/August 1995.

The NPL Survey Results

The sites surveyed in the NPL study included a wide range of building locations, building types, building ages, and population areas. It included locations where participants felt they had power quality problems and also those where a problem was not perceived. Of the 130 locations surveyed, 31% were industrial, 17% residential, 24% small businesses, 10% institutional, and 18% multistoried building customers. Table 3-4 defines the four events studied. The definitions of these events conform to the American National Standards Institute's ANSI C84.1-1989 standard, which defines normal conditions of voltage.

Table 3-5 lists the variations in event duration for the four types of disturbances recorded in the NPL survey. In interpreting the summary statistics in Tables 3-5 and 3-6, one should note that the distribution and site event occurrence rates for each category are highly skewed; thus, average or median values for these parameters clearly do not represent any kind of "typical" performances and should not be interpreted as such. However, for a preliminary estimation of the national cost of poor power quality, some of these numbers will be used later in this chapter under "Estimation of National Cost of Poor Power Quality."

Table 3-6 describes the frequency of events on a monthly basis at individual locations. It is apparent from Table 3-6 that transients are the most prevalent events, whereas interruptions account for less than 1% of all recorded disturbances. However, the table statistics do not reveal whether the event caused a disruption; nor do they describe the extent of losses.

Since the differences between the best and worst locations in Table 3-6 reflect highly skewed data, the average numbers do not necessarily represent typical performance. It is likely that the median values are more typical. The survey results also do not provide any indication of the variation of the frequency of occurrences between different customer classes.

Table 3-4. Definition of Events in NPL Survey

Event/Disturbance	Voltage Level	Duration
Sag/Undervoltage (Low RMS)	<104 Vrms	>2048 µs
Swell/Overvoltage (High RMS)	>127 Vrms	>2048 µs
Transient	>100 Vpeak	≥5-2048 µs
Interruption (Outage)	0 Vrms	≥4 ms

Table 3-5. Duration Summary Statistics for All NPL Data

	Minimum	Maximum	Median	Average
Sags/Undervoltages (Low RMS)	0.01 s	1.75 hr	0.26 s	2.1 s
Swells/Overvoltages (High RMS)	0.01 s	170 hr	60 s	44.2 min
Transients	< 1 µs	>2048 µs	21 µs	63.4 µs
Interruptions	0.004 s	71.1 hr	2.4 s	21.1 min

Table 3-6. Events per Month Based upon All NPL Data and Individual Location Statistics

	Best Locations (events/month)	Worst Locations (events/month)	Individual Location Median (events/month)	Average (events/month)
Sags/Undervoltages (Low RMS)	0	1,660	4.1	27.9
Swells/Overvoltages (High RMS)	0	1,450	3.4	13.9
Transients	0	1,166	15.7	63.5
Interruptions	0	10.2	1.0	1.3

Since the differences between the best and worst locations in Table 3-6 reflect highly skewed data, the average numbers do not necessarily represent typical performance. It is likely that the median values are more typical. The survey results also do not provide any indication of the variation of the frequency of occurrences between different customer classes.

A CBEMA curve analysis of these events, as shown in Figure 3-2, results in 289 power line deviations per site per year (~24 events/site/month) falling somewhere outside the high and low threshold limits of the curve. Nineteen of such events lying outside the shaded region were transients, 164 were swells or overvoltages, 90 were sags or undervoltage conditions, and 16 were interruptions. The median of the number of events given in Table 3-6 is comparable to this CBEMA curve analysis.

Cost of Poor Power Quality to Customers

Costs associated with power quality problems arise from lost production as well as other related disruptions suffered by customers, such as equipment damage, startup costs, etc. The costs of power-quality-related disruptions are largely dependent on the industrial and commercial activities that are impacted, the time of occurrence, and the duration of the event. Many electric utilities have conducted surveys of

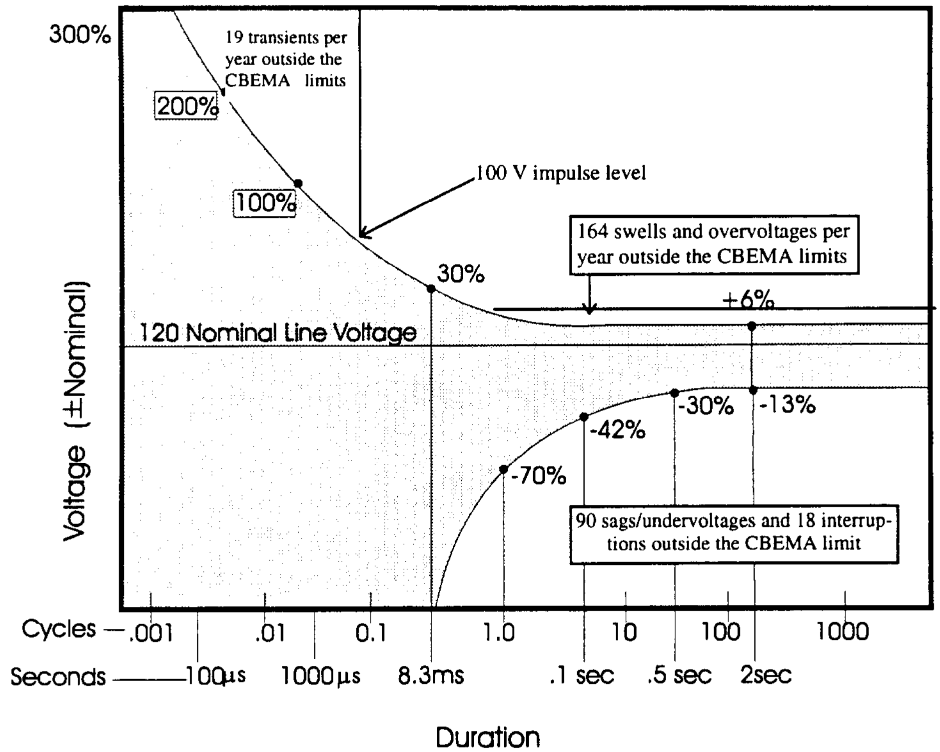

Figure 3-2. CBEMA Curve Analysis of the NPL Survey (number of line deviations per site per year).

power-quality-related costs within their service territories. The detailed results are proprietary; however, summaries have been published.

The summary of a survey conducted by Duke Power[8] is presented in Table 3-7. The utility surveyed 198 of its industrial and commercial customers and reported the results in terms of five types of reliability and power quality events. The magnitude and composition of the interruption costs change dramatically as a function of outage duration and type of problem.

The largest impact is obviously from long-duration outages, where approximately 90% of all production-related activity in a facility is affected. The corresponding numbers for voltage sags and momentary outages are 37% and 57% respectively. In all outage categories, more than 50% of the average total cost of the outage is due to lost product revenue (revenue change), with the remainder coming from damage to input feedstock and equipment.

[8] Mike Sullivan, "Power Interruption Costs to Industrial and Commercial Consumers of Electricity," Commercial and Industrial Systems Technology Conference, 1996.

Figure 3-3 illustrates the cost of distribution for industrial and commercial customers for a 1-hour outage on a summer afternoon without advance notice. The commercial and industrial customers of Duke Power surveyed had interruption costs ranging from $0 to $100,000 and from $0 to over $1 million, respectively.

Figure 3-3 illustrates that greater than 35% of all industrial and about 8% of all commercial customers surveyed experienced an interruption cost of greater than $10,000 on a hot summer day. The sample size for this survey consisted of 210 large industrial and commercial customers and 1,080 small/medium industrial and commercial customers. It may be fair to assume that most of the 210 large customers surveyed will experience a loss of greater than $10,000 per interruption lasting 1 hour and will experience at least the average costs listed in Table 3-7.

One must be extremely cautious in generalizing about the costs associated with power quality problems on the basis of only one survey's results. The costs are very site- and time-specific and depend to a very large extent on the type of equipment and industrial processes that are impacted. To add further perspective to the cost of power quality disturbances, references to two additional studies were located. A

Table 3-7. Components of Outage Costs by Scenario (average of 198 large customers in the Duke Power service territory)*

Cost Element	4-Hr Outage, No Notice	1-Hr Outage, No Notice	1-Hr Outage With Notice	Momentary Outage	Voltage Sag
Production Impacts					
Production Time Lost (Hours)	6.67	2.96	2.26	0.70	0.36
Percentage of Work Stopped	91%	91%	91%	57%	37%
Production Losses					
Value of Lost Production	$81,932	$32,816	$28,746	$7,407	$3,914
Percentage of Production Recovered	36%	34%	34%	19%	16%
Revenue Change	$52,436	$21,658	$18,972	$5,999	$3,287
Loss Due to Damage					
Damage to Raw Materials	$13,070	$8,518	$3,287	$2,051	$1,163
Hazardous Materials Cost	$323	$269	$145	$136	$90
Equipment Damage	$8,421	$4,977	$408	$3,239	$3,143
Cost to Run Backup and Restart					
Cost to Run Backup Generation	$178	$65	$65	$22	$22
Cost to Restart Electrical Equipment	$1,241	$1,241	$171	$29	$29
Other Restart Costs	$401	$368	$280	$149	$74
Savings					
Savings on Raw Materials	$1,927	$645	$461	$166	$114
Savings on Fuel and Electricity	$317	$103	$85	$12	$9
Value of Scrap	$2,337	$874	$450	$228	$140
Labor Management Approach During Recovery					
Percentage Using Overtime	33%	26%	25%	7%	6%
Percentage Using Extra Shifts	1%	1%	0%	1%	1%
Percentage Working Labor More Intensively	3%	4%	4%	7%	4%
Percentage Rescheduling Operations	4%	5%	5%	0%	0%
Percentage Other	1%	2%	2%	1%	0%
Percentage Not Recovering	59%	62%	64%	84%	89%
Labor Costs and Savings					
Cost to Make Up Production	$4,854	$1,709	$1,373	$254	$60
Cost to Restart	$665	$570	$426	$192	$114
Labor Savings	$2,139	$644	$555	$0	$0
Average Total Costs					
Total Costs	**$74,800**	**$39,500**	**$23,100**	**$11,000**	**$7,700**

* Source: Mike Sullivan, Commercial and Industrial Systems Technology Conference, 1996.

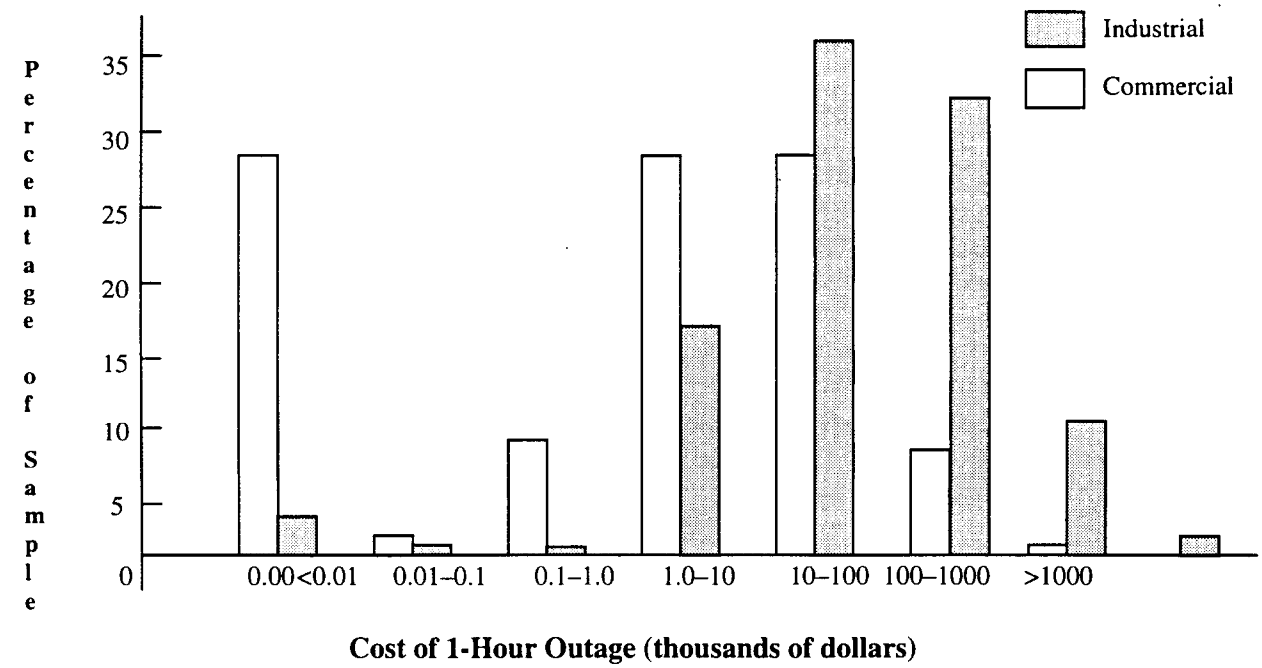

Figure 3-3. Difference in Commercial and Industrial Customer Interruption Cost (Duke Power data).

survey carried out by Pacific Gas & Electric (PG&E) covered 51 industrial customers ranging from electronics, automotive, instrument, apparel, and transportation equipment manufacturers to petroleum refineries, metal mines, and real estate offices. The cost of a 15-second interruption at these facilities was estimated to average $70,000 per customer, with the cost ranging from $25,000 to $270,000 per customer.[9] Finally, a survey of residential customers in the New England Electric System indicated that 3% of homes in their service territory had PCs primarily for business. The study found a momentary interruption for a home-based business costs about $25 per interruption. A survey of small commercial customers in Canada[10] also provides useful insights, with that survey finding losses in the range of hundreds of dollars for interruptions lasting up to 1 hour.

Estimation of National Cost of Poor Power Quality

The foregoing discussion illustrates the difficulty of developing precise estimates of the national impact of power quality problems. Prior estimates of the cost of poor power quality have ranged from $25 billion to $400 billion per year. The estimate of $25 billion[11] was based on the assumption that 1.5 to 3 cents of every sales dollar in the U.S. manufacturing industry was spent on correcting power quality problems. The $400 billion figure[12] was based on the estimate that employees were idle 37.3 million hours in 1991 due to power quality problems experienced by commercial customers. This idle time translates to an employee productivity loss, and therefore a loss to U.S. businesses, of $400 billion.

Utilizing the NPL survey data on the frequency of power-quality-related events and Duke Power's estimation of its large industrial and commercial customers' productivity losses, it is possible to develop an estimate of the national cost of poor power quality in this sector. For purposes of this study, the loss incurred in the large industrial sectors as a result of momentary outages and voltage sags is of most interest, since energy storage systems provide the preferred comprehensive solution for these power quality problems. Thus the estimate provides a basis on which to assess this market segment for storage sys-

[9] *EPRI Signature*, Summer 1995.

[10] R.K. Subramaniam, "Understanding Commercial Losses Resulting from Electric Service Interruptions," *IEEE Transactions on Industrial Applications*, January/February 1993.

[11] Carel DeWinkel, "Storing Power for Critical Loads," *IEEE Spectrum*, June 1993.

[12] "Power Quality in Commercial Buildings," EPRI-BR105018.

tems. In the interest of taking a conservative approach, Sentech's estimate is limited to the industrial/large customer sector, because the disruptions caused in this sector are the costliest (as discussed earlier under "Cost of Power Quality to Customer"), and hence investment in storage systems by this sector may be justifiable.

The NPL survey data in Table 3-6 provide the average and median interruptions and sags/undervoltages recorded in all 130 sites surveyed but do not differentiate between customer classes. Comparison of averages and medians indicates that there are a disproportionately smaller number of sites experiencing very poor power quality compared to the greater number of sites with good power quality records. The use of the median number instead of the average removes much of this distortion in the survey data and will indicate the extent of disturbance experienced by at least 50% of survey participants. Therefore, the survey medians will be assumed to be representative of what is experienced by at least 50% of the larger industrial customers. Hence, from Table 3-6 it may be concluded that at least 50% of industrial customers experience 12 interruptions and 49 sags/undervoltages per year.[13]

The figures in Table 3-7 indicate that it is fair to assume that the large industrial customers (excluding large commercial customers) in Duke Power's service territory will incur an average cost of $11,027 and $7,694 for each occurrence of momentary outage and voltage sag, respectively. Multiplying the loss for each of these occurrences with the frequency of their occurrence[14] results in an average loss of $509,000 per year for each of Duke Power's large industrial customers. Given that there are 8,700[15] large industrial customers in Duke Power's service territory, the total loss by this customer class will be on the order of $4.4 billion.

The total industrial electricity sales in the U.S. and within Duke Power's service territory are 1,004 TWh and 28.2 TWh, respectively. If one were to extrapolate the estimated $4.4 billion loss experienced by large industrial customers in Duke Power's service territory to the entire U.S. using electricity sales to the industrial sector as a base, the result would be an estimated national loss of $150 billion per year. This is summarized in Table 3-8.

It should be recognized that computing a national loss number with regional data can be a risky undertaking; the opportunities to introduce error are relatively high. Nevertheless, it is interesting to note that the $150 billion value derived from the Duke Power and NPL data falls between the $25 billion and $400 billion figures cited earlier.

The extent of the $150 billion loss that storage systems can address at present/near-term prices can be estimated as follows. The median loss incurred by each of the customers is $509,000,[16] which implies that 50% of the customers experienced a loss greater or equal to $509,000 per year. Assuming that an annual loss of at least $500,000 would have to be incurred for a large industrial customer to be able to justify the installation of large protective storage systems, the national market for storage equipment will be at least one-half the losses incurred annually by all large industrial customers, namely $75 billion. The cost-benefit analysis for installing a storage system is provided later under "Cost-Benefit Analysis Example."

Whatever the actual number, one can postulate with increasing confidence that the annual market potential of energy storage systems addressing power quality problems should total tens of billions of dollars.

Unserved markets of this size beg explanation. The market for such systems has grown in the recent past because of the proliferation of versatile microprocessor-controlled systems and power electronic motor controls, which are susceptible to distortions in the supply waveform. At present, part of the market is served by a variety of uninterruptible power supplies. Largely overlooked, however, are energy storage systems capable not only of meeting large industrial loads during interruptions but also of correcting for voltage magnitude variances and waveform imperfections. Such systems have been installed in recent years, but large gaps persist in power ratings, protection durations, performance capabilities, flexible siting and operation, cost, and installation ease. Until

[13] Twelve interruptions (12 months/year*1 event/month) and 49 sags/undervoltages (4.1 events/month*12 months/year) per year.

[14] [(12 * $11,027) + (49 * $7,694) = $509,000]

[15] The EL&P Electric Utility Industry Directory—1995 indicates that Duke Power has 8,693 industrial/large customers among its total customer base of 1.7 million.

[16] Median number of power quality disturbances experienced each year × average loss per disturbance.

Table 3-8. National Cost Estimate for Large Industrial Customers

	Average Annual Cost to Large Industrial Customers	Estimated Cost for Duke Power Customer Group	Estimated Cost for National Customer Group
Undervoltages/ sags	$377,000	$ 3.2B	$ 114B
Interruptions	$132,000	$ 1.1B	$ 39B
		Total estimated U.S. cost (rounded):	$ 150B

these gaps are overcome, manufacturers and their customers will continue to experience higher than necessary costs.

The large annual cost of poor power quality represents a form of national inefficiency and is reflected in the cost of goods sold, reducing U.S. competitiveness. The cost is ultimately paid by consumers, domestic and foreign. The mitigation of these costs merits the attention of the affected industries, businesses capable of developing solutions, and the DOE.

4. Technology Options

There are three general approaches to solving power quality problems:

- Eliminate or modify the source of the disturbances.
- Eliminate or modify the path for the disturbances between the source and the affected equipment.
- Protect the affected equipment.

Generally, consideration of all three options is necessary to develop a cost-effective solution. Determining the least-cost approach to mitigating power quality problems often requires that an industrial customer initiate an extensive internal survey to determine the nature of the problem. Such a survey is commonly done in partnership with the local utility, and the solutions that are implemented are often developed with strong input from the utility and in some instances even with financial assistance from the utility.

Many technology solutions exist to deal with the different power quality events. Devices that are commonly used for this purpose include the following:

- Surge arrestors
- Isolation transformers
- Uninterruptible power supply (UPS)/energy storage systems
- Static Var systems
- Wiring and grounding
- Shielding
- Filters
- Constant voltage transformers
- Backup generators
- Series capacitors
- Dynamic voltage restorer
- Humidity control

Energy storage systems can be placed off-line, in a line-interactive mode, or on-line to deal with power quality problems. Off-line (also called standby) energy storage systems (see Figure 4-1) are cost-effective for small, less critical, stand-alone applications such as isolated PCs and peripherals. However, when an outage occurs in the utility supply, this configuration may not be able to switch to its storage power supply fast enough to prevent disturbances in highly sensitive equipment. If filters are present, standby systems will protect against most transients by limiting excess voltage, but their ability to protect against sags and surges is significantly less than on-line or line-interactive designs.

Line-interactive systems (see Figure 4-2) provide highly effective power conditioning and energy storage backup. Their voltage boost circuitry and fast-acting transfer switches protect against most voltage sags and surges and provide extremely quick response to disturbances. Transfer switches with response times of ~1/4 power cycle provide adequate protection for the most sensitive devices. The energy efficiency of line-interactive storage systems is higher than that of on-line systems and becomes an important cost-saving advantage when protecting hundreds of kilowatts of critical loads.

The on-line configuration (see Figure 4-3) provides the highest level of protection for critical loads. Off-line and line-interactive storage systems reduce the impact of transients, surges, and sags by either clipping the peaks, boosting power, or switching to storage backup. In contrast, on-line energy storage systems regenerate the sinewave and do not involve switching. The configuration protects against all utility disturbances because the system completely isolates the load from the utility supply at all times. Since on-line systems continuously condition input supply, they have relatively large parasitic losses.

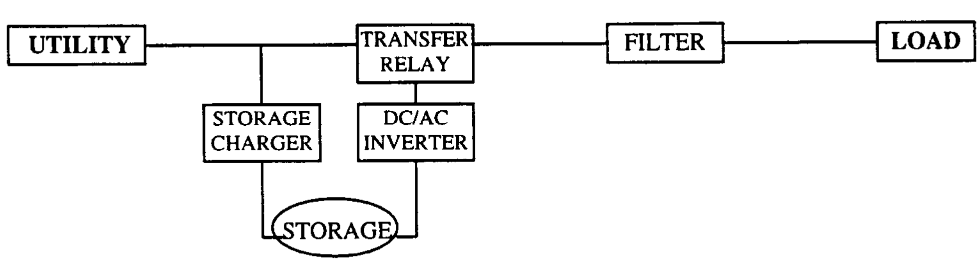

Figure 4-1. Off-Line Configuration of Energy Storage Systems.

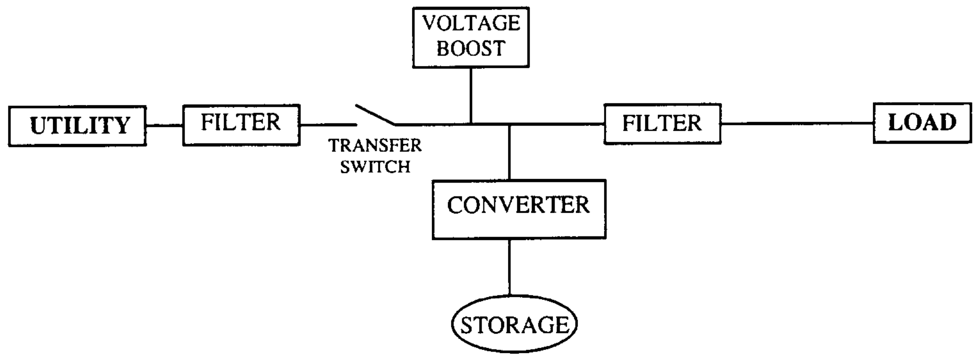

Figure 4-2. Line-Interactive Configuration of Energy Storage Systems.

Each of these energy storage configurations for power quality applications has its advantages and disadvantages. Prior to selecting a solution, the electricity provider or end user needs to define the power quality events that are most prevalent at the location and must estimate the damages caused by the events. The different solutions, including the storage option, can then be assessed in order to determine the most cost-effective solution.

To determine which device or combination of devices is appropriate, systematic monitoring of the facility, with the help of monitoring equipment and analysis of recorded data, is necessary.

Matching the Power Quality Problem with the Technology Solutions

Table 4-1 matches power quality events to the preferred technology solution to mitigate that particular event. Thus if impulsive transients were the only type of power quality event that was experienced by an industrial facility, Table 4-1 would indicate that surge arrestors, filters, and isolation transformers are the technology options available to the customer to deal with the problem. Table 4-1 also lists the power quality events that only an energy storage system can address. These include interruptions, sags/swells, and over-/undervoltages. In each of these cases, supply of the electrical energy from external sources, such as a storage system, is required to deal with the problems.

Often a mitigation technology can provide solutions to multiple power quality events. Table 4-2 illustrates this point by showing the different power quality events that can be handled by each of the technology options discussed in Table 4-1. An energy storage system is only essential when an external source of electrical energy is necessary to deal with the power quality event, such as with an interruption. However, the same energy storage system can also service all of the other power quality events shown in Table 4-2.

Cost-Benefit Analysis Example

For illustrative purposes, the cost-effectiveness of energy storage systems is analyzed using the loss estimates given in Table 3-7 and the frequency of supply disturbances obtained from the NPL survey and listed in Table 3-6.

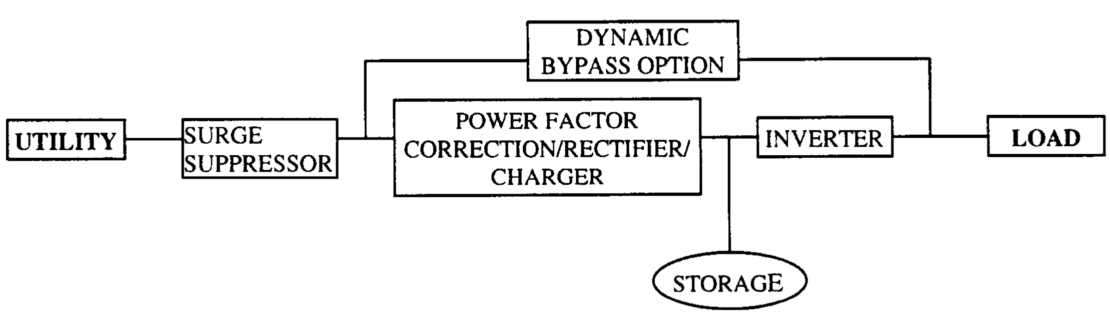

Figure 4-3. On-Line Configuration of Energy Storage Systems.

Table 4-1. Individual Solutions to Single-Category Power Quality Events*

Event Category	Method Of Characterization	Cause	Power Quality Solution
Impulsive Transients	Magnitude, Duration	Lightning, load switching	Surge arrestors, filters, isolation transformers
Oscillatory Transients	Waveforms	Lightning, line/cable switching, capacitor switching, transformer switching, load switching	Surge arrestors, filters, isolation transformers
Sags/Swells	Waveforms, RMS vs. Time	Remote faults	Constant voltage transformer, storage systems
Undervoltages/ Overvoltages	RMS vs. Time	Motor starting, load changes, compensation changes	Dynamic voltage restorer, constant voltage transformer, storage systems
Interruptions	Duration	Breaker operation/fault clearing, equipment failure, maintenance	Backup generator, storage systems
Harmonic Distortions	Waveforms, Harmonic Spectrums	Nonlinear loads, system response characteristic	Filters, isolation transformer (zero sequence)
Voltage Flicker	Magnitude, Frequency of Modulation	Intermittent loads, arcing loads, motor starting	Static Var system, series caps
Noise	Coupling Method, Frequency	Power electronic switching, arcing, electromagnetic radiation	Wiring and grounding improvement, chokes, filters, shielding

* Source: Power Quality Assessment Procedures, EPRI CU-7529 (December 1991).

Table 4-3 shows the benefit an energy storage system can bring to a large industrial customer if the storage system can handle both momentary outages and voltage sags. Duke Power data show the average losses for these types of events to be $11,027 and $7,694 per event, respectively, while the power quality survey data in Table 3-6 indicate that the median number of momentary outages was 1 per month and the median number of voltage sags/swells was 4.1 per month.

Systems based on batteries or on superconducting magnetic energy storage that protect megawatt-scale loads for durations in seconds are now commercially available at a cost of $1 to $2 million. With an annual avoided cost of $500,000 dollars and a payback period of 2 to 4 years, close to 50% of the large industrial customers (described earlier under "Estimation of National Cost of Poor Power Quality") in the U.S. may find storage systems economically attractive.

Table 4-2. Power Quality Solutions and Their Ability to Protect against Events in Multiple Power Quality Categories

Power Quality Solutions \ Power Quality Categories	Impulsive Transients	Oscillatory Transients	Sags/ Swells	Under-voltages/ Over-voltages	Inter-ruptions	Harmonic Distortions	Voltage Flicker	Noise
Surge Arrestors	✓	✓						
Filters[a]	✓	✓				✓		✓
Isolation Transformers	✓	✓				✓		
Constant Voltage Transformers			✓	✓				
Dynamic Voltage Restorer			✓	✓				
Backup Generator					✓			
Energy Storage[b]								
- Off-line	✓	✓	✓	✓	✓		✓	✓
- Line-interactive	✓	✓	✓	✓	✓		✓	✓
- On-line	✓	✓	✓	✓	✓	✓	✓	✓

[a] Different kinds of filters will be required to mitigate the different power quality problems.

[b] For sags/swells, under-/overvoltages, and interruptions, the level of protection increases from off-line to line-interactive to on-line.

Table 4-3. Competitiveness of Energy Storage Systems for Power Quality Applications

BENEFIT: ANNUAL AVOIDED COST	
Momentary Outage: Avoided Cost (1 event per month * 12 months * $11,027)	$132,000
Voltage Sags: Avoided Cost (4.1 events per month * 12 months * $7,694)	$377, 000
Total benefits per year	$509,000
COST: CAPITAL COST OF EQUIPMENT	
Cost of commercially available 1-MW energy storage system capable of providing protection for a few seconds	$1 million (1 MW = $1M)
SIMPLE PAYBACK PERIOD	~2 years

5. Conclusions

Power quality issues have come to the forefront recently mainly because of the increased use of sophisticated microprocessor-controlled equipment in industrial processes. Systems with loads that are highly sensitive and interconnected in extensive networks are vulnerable because they are dependent on the most sensitive device in the system when a disturbance occurs. Surveys conducted by the electric utility industry demonstrate that manufacturers incur large losses as a result of poor power quality.

Power quality problems arise from a variety of events. There are a number of technology options that electricity suppliers as well as end users can use to mitigate power quality problems. It is imperative that careful investigation of the frequency of events and their economic impacts be undertaken. Often it would be most cost-effective to implement solutions only for those power quality problems that have severe economic impacts rather than installing systems capable of dealing with all power quality events.

Data on the frequency of system disturbances and their economic impacts can be obtained through systematic monitoring at end-user sites. Several such studies have been conducted; however, most of the results are considered to be proprietary and are thus not available in the public domain. Summaries of some of these surveys have been published that contain enough information to permit tentative conclusions to be drawn regarding the nature and frequency of power quality disturbances and the role energy storage systems can play in mitigating them. The survey data suggest that storage systems are well suited to handle problems arising from unscheduled momentary outages. These types of events, although less frequent, cause the most severe economic impact. An energy storage system installed to handle outages can also reduce the impacts of voltage sags, undervoltages, and other disturbances. On-line storage systems are capable of eliminating all power quality-related problems, but such a comprehensive solution may be justified only for the more critical processes.

Preliminary estimates based on both the NPL and Duke Power surveys indicate that a 2-to-4-yr payback period for commercially available energy storage systems is feasible for the industrial customer experiencing typical disturbances. The data from these two surveys were used to obtain a rough estimate of $150 billion as the annual losses incurred nationally by the industrial sector because of momentary outages and voltage sags, two events for which storage systems are the primary solution. This number is between the $25 billion estimate made in an IEEE publication and the $400 billion estimate made in an EPRI publication.

This study suggests that the accrued national benefit from mitigating power quality losses is very large. This conclusion is supported by studies conducted by EPRI and other entities. However, it is important to note that the numerical estimates of the benefits developed in this study are based on limited data and on extrapolation from the available information. The numerical estimates therefore serve only to establish an order of magnitude of the accrued benefits of mitigating power quality problems. To establish more precise estimates, it would be necessary to further refine the analysis with better, more complete data obtained through more detailed surveying or through greater access to surveys already conducted by electric utilities.

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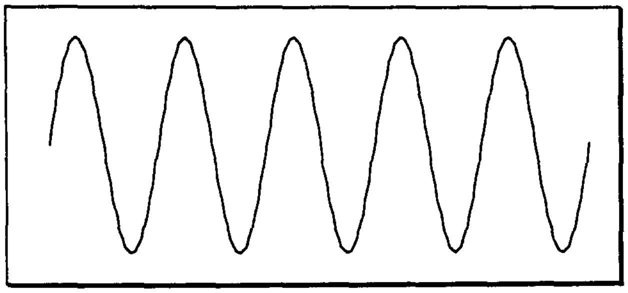
Graphical Illustration of Power Quality Events

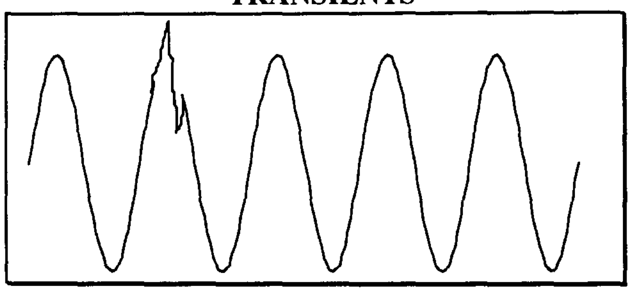
Appendix A
Graphical Illustration Of Power Quality Events

IDEAL SUPPLY WAVEFORM



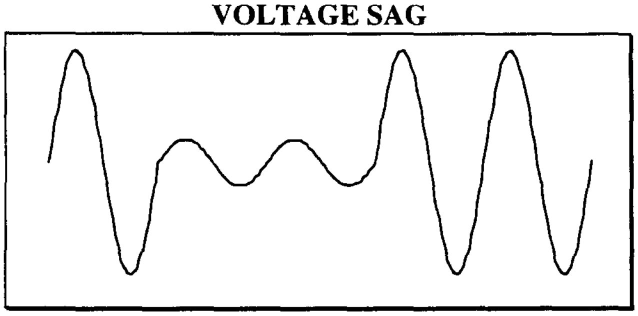
1. IDEAL SUPPLY WAVEFORM: An ideal supply waveform is a pure sinusoidal waveform with a constant amplitude and frequency.

TRANSIENTS



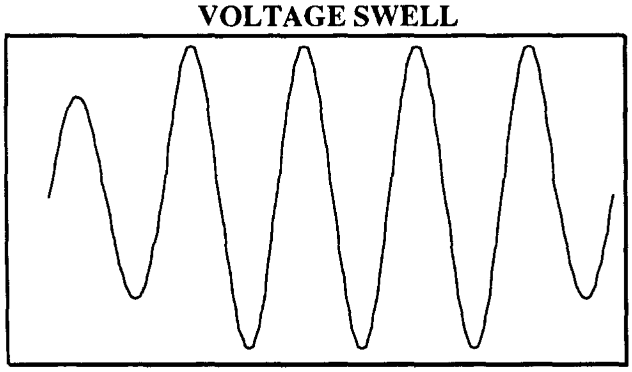
2. TRANSIENTS (Impulsive and Oscillatory): A transient is a surge in voltage or current that can have extremely short duration and high magnitude. Typically, surges are caused by switching operations or lightning. Surges can be generated by customers switching their own loads or may be caused by utility switching of capacitors, breakers, etc. Surges have always existed in power systems, but it is only in recent years that they have received attention mainly because of the sensitivity of electronic devices like VCRs and personal computers.

VOLTAGE SAG



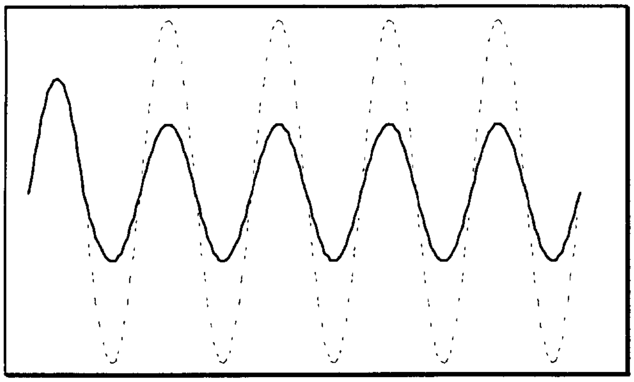
3. VOLTAGE SAG: A momentary voltage dip that lasts for a fraction of a second or less is classified as a voltage sag. Voltage sags may be caused by faults on the transmission or distribution system or by the switching of loads with large amounts of initial starting/inrush current. Voltage sags may be sufficiently severe, especially in the case of faults, to cause sensitive loads to reset.

VOLTAGE SWELL



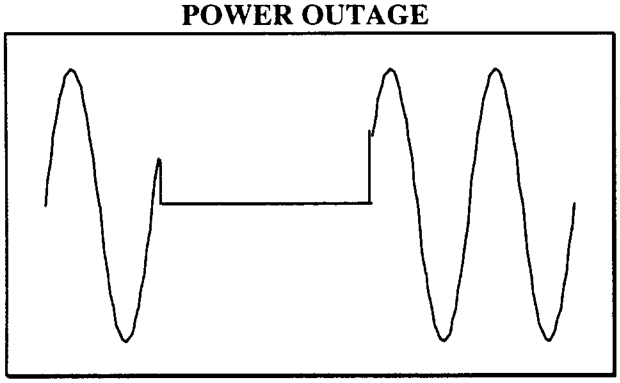
4. VOLTAGE SWELL: When a fault occurs on one phase of a 3-phase, 4-wire system, the other two phases rise in voltage relative to ground (about 20%). This steady-state rise in voltage is referred to as a swell. Voltage swells usually have duration of a fraction of a second or less.

UNDER/OVERVOLTAGE



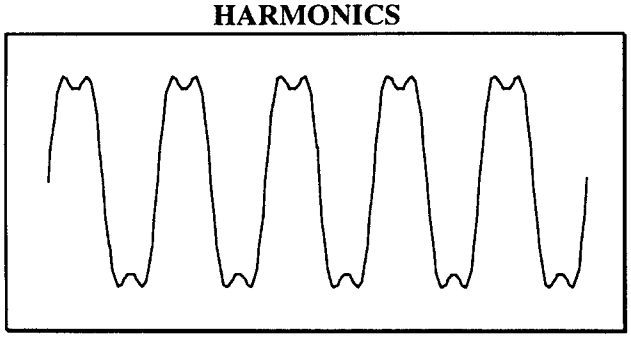
5. UNDER/OVERVOLTAGE (Voltage Drop): A customer who experiences a long-duration (several seconds or longer) service voltage less than the proper nominal operating voltage limit can be considered to be experiencing an undervoltage situation. Similarly, a customer experiencing higher than nominal operating voltage can be considered to be experiencing overvoltage. Such a condition may be caused by a number of factors, such as overloaded or poor internal wiring, poor connections, compensation changes, and/or voltage drop/gain on the utility system.

POWER OUTAGE



6. INTERRUPTION (Power Outage): A power outage is a complete loss of voltage usually lasting from as short as a quarter cycle up to several hours, or in some cases even days. Outages are usually caused by the fault-induced operation of circuit breakers or fuses. Some of these interruptions might be classified as permanent, while others may be classified as temporary.

HARMONICS



7. HARMONICS: These are the nonfundamental frequency components of a distorted 60-Hz power wave. They have frequencies that are integral multiples of the 60-Hz fundamental frequency. Harmonics are not generally produced by the utility but rather by the customer's equipment. For example, a large nonlinear industrial load may produce harmonics that, if they are of sufficient magnitude, can travel back through the power system and affect other customers.

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