Power Quality Reference Guide for Customers and Utility Representatives

Power Quality & Advanced Technologies Interest Group
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Background

This brochure is intended to serve as a quick reference guide for utilities and their customers on identifying common power quality problems and their causes, and how to select appropriate power conditioning measures. This guide includes a review of some of the most important power quality phenomena, including voltage unbalance, voltage sags and swells, momentary interruptions, transients, switching surges, harmonics, notching, and voltage flicker.

A section on best practices for characterizing and diagnosing power quality problems is included, with a utility supply point and customer site survey, and an effective communication process overview. As well, a review of power quality symptoms and economic factors for determining the effect of power quality variations on utility and customer power system equipment is given. Finally, this brochure includes a review of relevant power quality standards, representative waveform signatures, and a summary of the various mitigation and power conditioning measures that can be utilized on utility and customer power systems.

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The use of certified practitioners for the application of the information contained herein is strongly recommended.

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Acronyms

ASD	adjustable-speed drive
CEATI	CEA Technologies, Inc.
CT	current transformer
CVT	constant voltage transformer
DVR	Digital Video Recorder
EMTP	Electromagnetic Transients Program
FFT	fast Fourier transform
hp	horse power
Hz	Hertz
IEC	International Electrotechnical Commission
ITIC	Information Technology Industry Council
MCOV	maximum continuous operating voltage
MOV	metal oxide varistor
MTBF	mean time between failures
MVAr	mega-volt-amperes reactive (106)
NESC	National Electric Safety Code
NEC	National Electrical Code
PC	personal computer
PCC	point of common coupling
PES	Power and Energy Society (IEEE)
PIV	peak inverse voltage
PLC	programmable logic controller
PQ	power quality
PT	potential transformer
pu	per-unit
PWM	pulse width modulation
RMS	root mean square
SCR	silicon controlled rectifier
SMES	superconducting magnetic energy storage
SMPS	switch-mode power supply
SSD	superconducting storage device
TDD	total demand distortion
THD	total harmonic distortion
TIF	telephone influence factor
TVSS	transient voltage surge suppressors
UL	Underwriters Laboratories
UPS	uninterruptible power supply

Introduction

Why is Power Quality Important?

Power quality is important because many customer power-electronic devices and appliances are designed to operate at a specific voltage and frequency. In North America, power is delivered at standard voltages (e.g., 120V, 240V, and 480V) and frequency (e.g., 60 Hz or cycles-per-second). Deviations in these quantities may cause customer or utility equipment to malfunction or get damaged.

Power quality is a frequently used term that can mean different things to different people. Common power quality problems include all of the issues that arise from the incompatibility between the power delivered by the utility at a customer connection point, and the customer's energy-using equipment that results in impaired operation. These include transients, voltage sags and swells, harmonics, and short- and long-term voltage variations and momentary power supply outages. The power quality problems is difficult to evaluate as the causes can be so varied, ranging from switching events within the customer facility, to faults hundreds of miles away on the utility transmission system.

Power quality issues occur when the voltage magnitude and waveform supplied to the customer deviates from normal. These deviations may involve changes in the voltage magnitude (e.g., rms variations), changes in the voltage sinusoidal shape (e.g., transients), or loss of power altogether (e.g., outages). To some extent, the power system is constantly experiencing power quality variations because the supplied voltage is practically never a perfect sinusoid of constant magnitude. However, when these variations are so significant that customer equipment is adversely affected, the quality of service supplied becomes an issue that should be investigated (e.g., through a site survey).

The present trend towards more energy efficient electronic devices has greatly increased the sensitivity of customer load equipment. It has also increased the injection of harmonic currents to the supply system. As a result, power variations that once went unnoticed now result in the misoperation of customer devices. The impact of these power quality-related problems can vary significantly.

Common Power Quality Problems and Causes

Electric utilities and their customers have long been concerned with power quality. The need for constant voltage and frequency has always been recognized as important. However, recent trends towards energy conservation, the growing penetration of distributed "green energy" generating technologies, the increasing utilization of power-electronic loads, and the proliferation of sensitive customer electronic equipment are changing the definition of what is meant by "constant voltage." Considering all interested parties, the following definition for power quality has been developed:

> *"Any power problem manifested in voltage, current, or frequency deviations that result in failure or misoperation of utility or end user equipment"*

Characterizing Power Quality Phenomena

Over the years, power quality (PQ) parameters specified by utilities have been based on the requirements included in the Transmission and Distribution System Codes or guidelines, applicable in their supply areas, which referred to various Standards (e.g., IEEE 519 1992, CSA 235). These parameters characterize various power quality phenomena, such as steady state voltage (long term), flicker, harmonics, and transients. However, short-duration rms voltage variations such as voltage sag characteristics are not well defined.

The relative importance of a particular category of power quality phenomena for a specific customer will depend on the type of electrical equipment installed in the facility. The nature of interactions between customer equipment and the power quality phenomena – equipment damage, equipment/process trip, compromised product quality, etc. – and the frequency at which it occurs or could be expected to occur are also critical factors in the evaluation process, once the cause has been identified. The range of power quality phenomena is defined in IEEE Std. 1159-2009 Recommended Practice for Monitoring Electric Power Quality (refer to Appendix A). A review of the important power quality categories follows.

Transients

Transient overvoltages and overcurrents are classified by peak magnitude, frequency, and duration (see Table 1). These parameters are useful indices for evaluating potential impacts of transients on power system equipment. The absolute peak voltage, which is dependent on the transient magnitude and the point on the fundamental frequency voltage waveform at which the event occurs, is important for dielectric breakdown evaluation (e.g., insulation strength). Some equipment and types of insulation may also be sensitive to rates of change in voltage or current. The transient frequency, combined with the peak magnitude, can be used to estimate the rate of change.

Transient overvoltages and overcurrents caused by equipment switching operations or lightning strikes to electric facilities have a significant potential to damage electric power equipment or disrupt operations. High-frequency impulsive transients and low-to-medium frequency oscillatory transients have been recognized for quite some time as a threat to power electronic-based customer equipment. They have also been blamed for a wide range of equipment misoperation and failures. To mitigate such transients, a wide range of off-the-shelf and inexpensive transient voltage surge suppressor (TVSS) products can be applied by either the customer or the equipment manufacturer.

Low frequency oscillatory transients, such as those caused by the switching (energizing) of utility shunt capacitor banks (which are essential for power system voltage control) are the most common source of low-to-medium frequency oscillatory transients on the electric power system. Unlike the other subcategories of transient phenomena, these are usually of modest magnitudes but contain substantial energy, so their electrical effects can be "felt" quite far from the point of origin. Low frequency transients caused by capacitor bank switching have been generally correlated with nuisance tripping of power-electronic equipment, especially common types of adjustable-speed drives.

A representative low frequency oscillatory transient is shown in Figure 1. The figure shows the measured utility distribution substation bus voltage and current waveforms during energization of a capacitor bank. The maximum transient overvoltage was 15.560kV or 1.38 per-unit (138%). The principal energizing frequency was 660 Hz (11th harmonic) and the resulting steady-state voltage rise was approximately 1.5%. The maximum transient current was 2,076 amps.

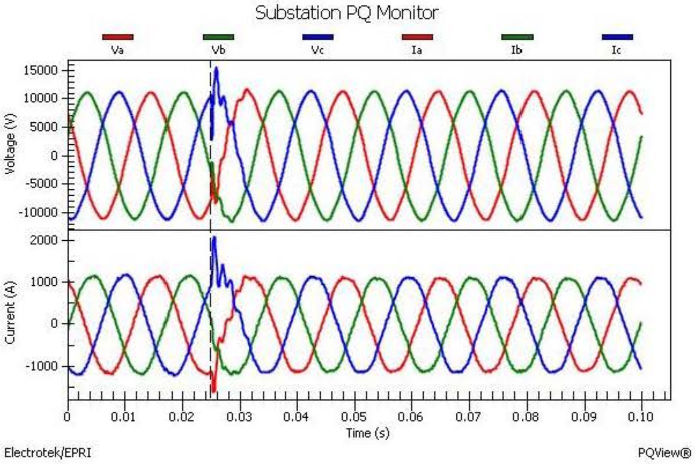

Figure 1 - Example of a substation capacitor bank energization transient

Voltage Variations

Voltage variations, such as voltage sags and momentary interruptions, are often the most important category for customers. These conditions are characterized by short duration changes in the rms voltage magnitude supplied to the customer (see Table 1). Voltage sag is a short duration decrease in the rms voltage magnitude from the nominal voltage, usually caused by a fault on the power system or due to large motor starting. Voltage sag caused by motor start is of low variation in magnitude with a longer duration in the range of few seconds to minutes. Voltage sag caused by a fault on the power system is of large variation in magnitude with shorter duration in the range of few to tens of cycles. The effect on the customer depends on the voltage magnitude during the disturbance, the duration of the disturbance, and the sensitivity of the customer's equipment. Although utilities continuously strive to provide reliable power to their customers, a number of factors may cause voltage variation events.

It is important to differentiate between an interruption and voltage sag:

- An interruption refers to the complete loss of supply voltage (i.e., power is off).
- Voltage sag refers to voltage drops below 90% of the nominal value (as per IEEE Std 1159 2009) while the load still has power supply (i.e., power is on, but may not be compatible with some sensitive electronic equipment).

Voltage variations and interruptions are inevitable on the electric power system. Voltage sags, being an inherent result of the faults, are impossible to completely eliminate because utilities can only take limited actions to minimize the frequency of faults' occurrences. Typical causes of faults on the supply system include inclement weather (lightning, snow, ice, high winds), and third party intervention (vegetation, animal intrusion, accidents, etc.). Other important sources of voltage variations include unbalance, induction motor starting, and voltage flicker. Most customers recognize that electric power outages and voltage variations can never be cost-effectively eliminated

Voltage sags or short duration voltage variations caused by faults on the supply system can misoperate or even shutdown customer's sensitive electronic equipment. This reaction, depending on the rate of occurrence and the general high cost and complexity of mitigation alternatives, makes short-term voltage variations one of the most - if not the most - important categories of power quality phenomena from the customer's point of view.

IEEE Std. 1346 and IEEE Std. 1250 provide guidance for evaluating rms variations on customer systems. A representative customer voltage sag event is shown in Figure 2. The figure shows a measured three-phase secondary voltage sag waveform with a magnitude of 47.9% and duration of about 7.0 cycles (0.12 seconds). The voltage sag was caused by a short-duration fault and subsequent fuse clearing on a feeder branch circuit during a storm.

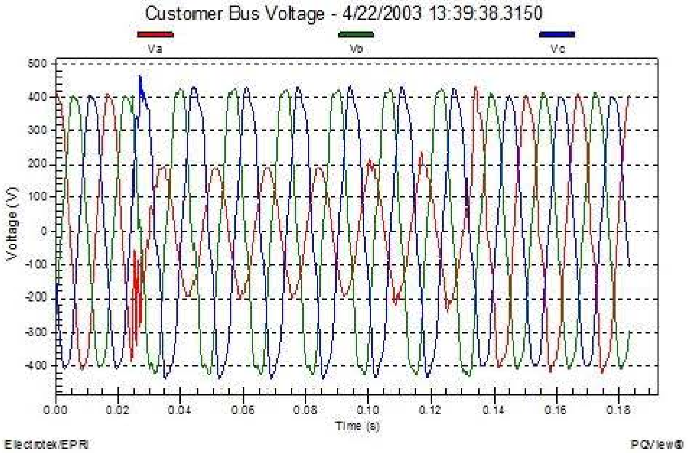

Figure 2 - Example of a measured customer secondary voltage sag event

A special, voltage variations related phenomenon is called "voltage flicker". This condition is caused by rapidly changing load currents, for instance electric arc furnace loads, and results in relatively small but rapid supply voltage variations due to voltage drops across network impedances. The voltage variations can in turn cause rapid changes in light output of lighting devices (i.e., a "flicker"). The voltage flicker is not associated with equipment malfunction, but can cause irritation to a customer's eyes.

Waveform Distortion

Waveform distortion is defined as a steady-state deviation from an ideal sine wave of power frequency, principally described by the spectral content of the deviation. The principal types of waveform distortion include dc offset, harmonics, interharmonics, notching, and noise (see Table 1). Harmonics are the most significant subcategory of waveform distortion. Harmonics are sinusoidal voltages or currents with frequencies (e.g., 180 Hz) that are integer multiples (e.g., 3rd) of the fundamental frequency of the supply system (e.g., 60 Hz). Harmonic distortion is a steady-state voltage or current that originates in the nonlinear characteristics of devices (e.g., adjustable speed drives) connected to the system. Harmonic distortion levels are often characterized using rms trends over longer periods of time (e.g., 24 hours).

Harmonics can create many problems, such as causing equipment to misoperate, capacitor banks to fail, circuit breakers to trip mysteriously, transformer overheating, etc. Problems from harmonics are usually associated with high amounts of nonlinear, harmonic current-producing loads. Examples of this include a facility where a significant portion of the load may be comprised of adjustable-speed motor drives, or situations where power factor correction capacitors in the customer facility or on the utility distribution system create resonances that amplify the effects of nonlinear loads.

IEEE Std. 519 and CDN/CSA C61000-3-6 include guidelines on establishing and using harmonic voltage and current limits on the power system. The basic philosophy of the standard is that the customer is responsible for limiting the amount of harmonic currents injected into the overall power system, and the utility is responsible for avoiding conditions on the power system that could create unacceptable voltage distortion levels (e.g., resonance). A representative harmonic voltage waveform is shown in Figure 3. The figure shows an example measured three-phase industrial customer secondary bus voltage waveform with severe harmonic distortion. The total harmonic distortion (V_{THD}) of the waveform was 10.4%.

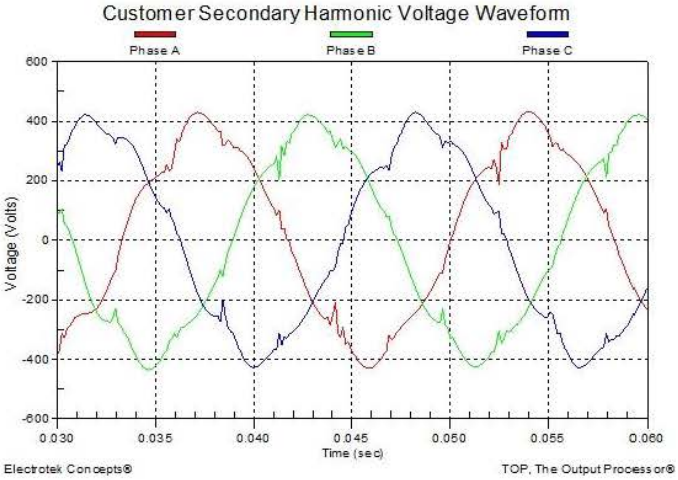

Figure 3 - Example of a measured customer secondary harmonic voltage

Causes of Common Power Quality Problems

Power quality problems may originate from utility supply system or from customer facilities. Common sources for many customer problems include:

1. Natural phenomena (e.g., inclement weather).
2. Normal utility operations (e.g., automatic protection system operations to clear faults).
3. Neighbouring customers (e.g., welding equipment adjacent to an office building).
4. The customer's own equipment and facilities (e.g., large induction motor starting, electric arc furnaces, sensitive electronic equipment, etc.).

Within a customer's facility, poor power quality can result from incompatible equipment interactions or from poor wiring and grounding practices. Problems such as short duration voltage sags and momentary interruptions, however, generally originate from the utility's side of the meter. In addition, the proliferation of harmonic-producing loads is causing power quality problems for both utilities and their customers. These loads include adjustable-speed drives, electronic ballasts for fluorescent lighting, electric arc furnaces, computers distributed throughout commercial and industrial facilities, and other power-electronic technologies.

Figure 4 - Electrical distribution feeder damaged by ice-storm. Even regular tree trimming programs cannot always prevent power outages.

Identifying Power Quality Symptoms

The first step to identifying power quality symptoms is to understand how customers perceive power quality problems. Some of the more common equipment symptoms include:

- Equipment damage,
- Blinking digital displays,
- Data or information loss / software glitches,
- Loss of instructional programming and controller timing,
- An abnormal number of service calls on sensitive equipment,
- Disk drive problems,
- Computers re-booting, etc.

Once information regarding the equipment symptoms is collected, the power quality disturbance that is causing the problem can be determined. Many common power quality issues include:

- Voltage sags due to faults on parallel circuits on the distribution system or faults on the transmission system,
- Voltage sags due to induction motor starting,
- Momentary interruptions at industrial and commercial facilities due to fault-clearing and reclosing operations of feeder circuit breakers and reclosers,
- Voltage flicker from arc furnace and arc welding loads,
- Voltage transients from load or circuit switching within the customer facility,
- Transient voltage magnification at low voltage power factor correction capacitor banks,
- Sensitivity of adjustable-speed drives and control systems to utility capacitor bank switching transients,
- Transients and notching associated with power-electronic equipment operation,
- Coupled voltage surges at customer facilities due to lightning transients on the primary distribution system,
- Harmonic distortion from adjustable-speed drives or other nonlinear loads,
- Transformer heating caused by harmonic currents, and
- Neutral conductor overloading due to harmonic loads.

Figure 5 - Large 5000HP electric motor. Start, stop or cyclical loading of such motors may cause noticeable short duration sags in supply feeder voltage

Determining Customer Equipment Susceptibility to Power Quality Problems

Customer equipment can have drastically different sensitivities to power quality variations. Equipment sensitivity is very dependent on the specific load type, control settings, and application. Consequently, it is generally difficult to identity which characteristics of a given power quality event are the most likely to cause equipment to misoperate. Event characteristics include magnitude, duration, phase shift, unbalance, and point-in-the-wave at which the event initiates and terminates. For customers with sensitive equipment and processes, the ride-through capability is often the most important characteristic to determine.

In addition to the observed symptoms, it is important to determine the customer equipment that is affected by the power quality disturbance. Some important equipment categories to consider include:

- Adjustable-speed drives - harmonic distortion concerns and sensitivity to transient voltages,
- Electronic controls, adjustable-speed drives, and programmable logic controllers - sensitivity to voltage sags,
- Switch-mode power supplies - harmonic current generation and neutral current concerns,
- Fluorescent lighting (especially with electronic ballasts) - harmonic generation,

- Power factor correction capacitor banks - harmonic resonance and switching transients (voltage magnification),
- Motors and motor contactors - voltage imbalances, harmonic heating, and sensitivity to voltage sags, and
- Electronic equipment - sensitivity to high frequency transients.

Equipment Susceptibility Curves

Equipment sensitivity is the key factor that determines if a power quality variation will disrupt a customer load or process. Some loads may be sensitive to just the magnitude of a voltage variation event, while other loads may be sensitive to both the magnitude and duration of the event. Currently, no single international standard includes equipment characteristics for all types of customer loads. However, a number of different industries have created equipment susceptibility curves that may be used to evaluate the potential for load disruption during voltage variation events. The susceptibility curves described below are voluntarily agreed-upon guidelines for the identified manufacturing sectors, but they do not (and cannot) represent general power delivery standards for the electric utilities:

1. **CBEMA:** The curve, which is illustrated in Figure was originally developed by the Computer Business Equipment Manufacturers Association (CBEMA) to describe the tolerance of mainframe computer equipment to the magnitude and duration of voltage variations on the power system. While many modern computers have greater tolerance than this, the curve has become one possible standard design target for sensitive equipment. The curve was first published in IEEE Std. 446-1995.
2. **ITIC:** The successor organization to CBEMA is the Information Technology Industry Council (ITIC). This organization has developed a newer recommended capability curve for single-phase data processing equipment operating at 120 volts. The intent was to develop a curve that more accurately reflects the performance of 60 Hz computers and their peripherals, and other information technology items such as copiers, fax machines, and point-of-sales terminals. The ITIC curve provides an easier graphical format to reproduce, and does provide improved ride-through capability for minor voltage sags.
3. **SEMI:** The Semiconductors Equipment and Materials International (SEMI) organization has developed a power quality need curve that provides a voltage vs. time characteristic that their equipment is expected to ride-through during voltage variation events. Several related standards include SEMI F42-0699 "Test Method for Voltage Sag Susceptibility of Semiconductor Processing Equipment" and SEMI F47-0706 "Specification for Semiconductor Processing Equipment Voltage Sag Immunity." SEMI F47 specifies the minimum voltage sag ride-through capability design requirements for equipment used in the semiconductor industry, while SEMI F42 defines a test method used to characterize the susceptibility of semiconductor-related equipment.

Equipment Sensitivity and Characteristics

Power quality disturbances have always existed on the power systems. In the past, there were not too many complaints about these conditions because residential customers had analog clocks and industrial customers had standard induction motors. Now, residential customers have digital clocks, DVRs, electronic coffee makers, and many other electronic gadgets that rely on continuous power to operate correctly. In addition, rural and farming customers now utilize sensitive digital equipment, such as automated milking machines on dairy farms. Many of these devices must be manually reset whenever there is a power quality event. It is important for customers to understand the sensitivity of their equipment to different power quality variations. Different categories of equipment and even different brands of equipment within a category can have significantly different sensitivities to these events. This makes it difficult to develop a single standard that defines the sensitivity of industrial process equipment.

The wide range of equipment sensitivities underlines the importance of working with the manufacturer to ensure that the equipment can work in the environment where it will be used, and to develop specifications based on realistic power system conditions.

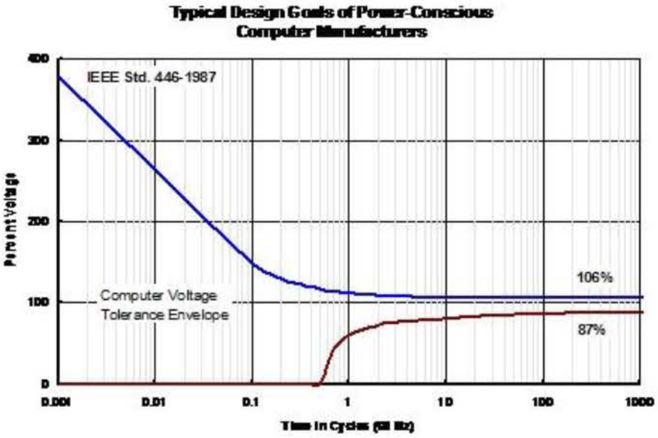

Figure 6 - Example of an equipment (CBEMA) susceptibility curve

Analyzing PQ Problems

Effective Methods for Diagnosing Problems

Monitoring is often used to characterize power quality problems at various locations on utility and customer power systems. The monitoring duration is dependent on the nature of the power quality problem being investigated. For example, harmonic distortion levels may need to be monitored for weeks, months, or even years to show the influence of load and seasonal variations. The objectives of the monitoring program determine the choice of measurement equipment, the method of collecting data, disturbance thresholds, data analysis requirements, and the overall effort required. Common screening procedures for determining a particular power quality problem for a utility or customer include:

- Characterize the problem - which customer equipment is misoperating or failing.
- Correlate problems with changes in the system, such as capacitor bank switching, bad weather, etc.
- Characterize the magnitudes, durations, and frequencies of the disturbances causing the problem. This may require monitoring at different voltage levels including the distribution system, customer service entrance, and at the affected equipment.
- Identify possible solutions. Characterizing problems and causes will lead to a range of possible solutions.

A representative harmonic monitoring data analysis for a utility substation bus is shown in Figure 7. The figure shows an example measured one-week 12.47kV substation bus voltage harmonic distortion (V_{THD}) trend.

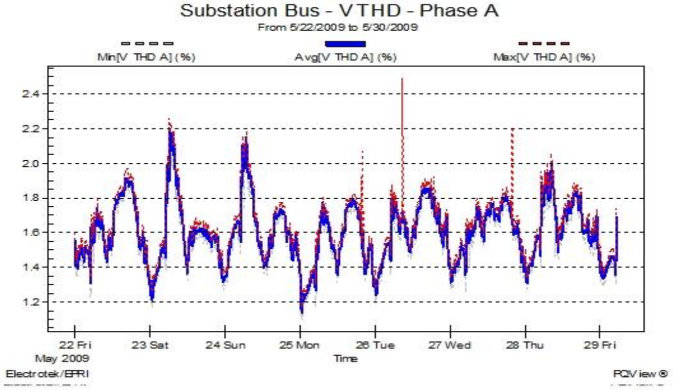

Figure 7 - Example of a measured substation bus voltage distortion trend

Selecting Appropriate Power Quality Monitoring Instruments and Transducers

Although instruments have been developed to measure a wide variety of power quality disturbances, a number of different instruments are generally necessary, depending on the phenomena being investigated.

Basic categories of instruments that may be applicable include:

- Wiring and grounding test devices,
- Multimeters,
- Oscilloscopes,
- Disturbance analyzers,
- Harmonic analyzers and spectrum analyzers,
- Combination disturbance and harmonic analyzers,
- Flicker meters, and
- Energy monitors.

A number of factors should be considered when selecting an instrument, including:

- Number of measurement channels (e.g., voltage and/or current),
- Temperature specifications of the instrument,
- Input voltage range (e.g., 0-600 volts) and power requirements,
- Ability to measure three phase voltages,
- Data sample rate,
- Ability to measure currents,
- Housing of the instrument (e.g., portability, rack-mount, etc.),
- Ease of use (e.g., user interface, graphics capability, etc.),
- Communication capability (e.g., modem, network interface), and
- Documentation and analysis software.

The flexibility of the instrument is also important. More functions that can be performed with a single instrument will result in fewer instruments being required for the monitoring effort. Disturbance analyzers and disturbance monitors form a category of instruments that have been developed specifically for power quality measurements and site surveys. They can typically measure a wide variety of system disturbances from very short duration transient voltages to long duration outages or undervoltages. Measuring thresholds can be set and the instruments left unattended to record disturbances over a long period of time.

Figure 8 - Monitoring voltage distortion at feeder capacitor installation. Excessive level of harmonics may damage capacitors and negatively affect the feeder supply voltage profile.

Selecting Monitoring Locations, Quantities to Monitor, and Instrument Thresholds

In general, it is advisable to begin monitoring as close as physically possible to the sensitive equipment being affected by the power quality disturbances. It is important that the monitor sees and captures the same variations as the sensitive equipment. High-frequency transients, in particular, can be significantly different if there is large separation between the monitor and the affected equipment.

The main service entrance is another important monitoring location. Transients and other voltage variations measured at that location can be experienced by all of the equipment in the facility.

Selecting a monitoring site to solve many power quality problems is usually straightforward, as it has been established by customer complaints, equipment failure reports, and other external factors.

When monitoring some power disturbances, it may be sufficient to only measure voltages. However, this is not adequate for harmonic evaluations. In order to characterize harmonic problems, it is critical to measure both voltages and currents. For the evaluation of power quality problems caused by capacitor bank applications, both voltage and current should be monitored. Voltages are used to characterize transients that can damage utility and customer equipment and cause nuisance tripping of sensitive power-electronic equipment (e.g., ASDs). Currents are used to identify series and parallel harmonic resonances on the system. Other quantities that may need to be collected include voltage (V_{THD}) and current (I_{THD}) harmonic distortion levels. These may be required for compliance evaluations with utility or industry standards (e.g., IEEE Std. 519, IEC 61000-3-6).

Disturbance monitors are designed to detect abnormal conditions. Therefore, it is necessary to define the range of conditions that can be considered normal. Some disturbance monitors have pre-selected (default) thresholds that can be used as a starting point. The best approach for selecting thresholds is to match them with the specifications of the equipment that is affected. This may not always be possible due to a lack of specifications or application guidelines. An alternative approach is to set the thresholds tight for a period of time (collecting a large amount of disturbance data) and then use an analysis of the data collected to select appropriate thresholds for longer duration monitoring.

Figure 9 - Monitoring power quality at customer electrical installation

Measurement Data Collection and Analysis Process

The monitoring data collection and analysis effort involves the periodic downloading of measurements from the instruments and collecting system event data. Maintaining a record of important events is required to correlate with the measurement data. At a minimum, the time and location of the following system events should be recorded:

- Weather conditions – e.g. lightning activity, high winds, snow, icing, etc.
- Feeder switching overcurrent protective device operations,
- Capacitor bank switching operations,
- Transmission system disturbances,
- Equipment failures (e.g., transformers, lightning arresters, capacitor banks, overcurrent protective devices, etc.),
- Customer complaints, and
- Changes in configuration/operation on utility and customer facilities.

The interval required for downloading measurement data from a monitor depends on the frequency of disturbances at the monitored location, how the instrument is configured to record each disturbance, and, if steady-state measurements are recorded, the sample interval. The download interval should be selected to suit the monitoring instrument memory.

Utility and Customer Site Survey Process

Power quality investigations often require monitoring to identify the exact problem and then to verify the implemented solutions. Before embarking on extensive monitoring programs, it is important to develop an understanding of the customer facility, the equipment being affected, wiring and grounding practices, and operating considerations. Power quality problems can often be solved without extensive monitoring by asking the right questions when talking to the customer and performing an initial site survey. The initial site survey should be designed to obtain as much information as possible about the customer facility and the problems being experienced. Specific information that should be obtained at this stage includes:

- Nature of the problems (e.g., data loss, nuisance trips, component failures, control system malfunctions, etc.),
- Characteristics of the sensitive equipment experiencing problems (e.g., equipment design information or at least application guide information),
- Time at which problems occur,
- Coincident problems or known operations (e.g., arc furnace operation) that occur at the same time,
- Possible sources of power quality variations within the facility (e.g., motor starting, capacitor bank switching, power electronic equipment operation, arcing equipment, etc.),

- Existing power conditioning equipment (e.g., ferroresonant transformers) being used,
- Electrical system data (e.g., one line diagrams, transformer ratings and impedances, load information, capacitor bank information, cable data, etc.),
- Changes in configuration and operation of utility or customer facilities.

Once this basic data is obtained through discussions with the customer, a site survey should be performed to verify the one-line diagrams, electrical system data, wiring and grounding integrity, load levels, and equipment characteristics.

Data Collection and Review

A site survey may be used to verify the initial data collected and to perform detailed wiring and grounding checks at a customer facility. Generally, a significant percentage of power quality problems are related to issues with wiring and grounding. For example, loose connections and improper grounding techniques for noise control can be identified without an extensive measurement program. Information that can be obtained during the customer site survey includes:

1. **Customer information:**
    a. Company and contact name
    b. Address and phone / fax / e-mail / etc.
2. **Nature of the problems:**
    a. Data or information loss
    b. Nuisance trips of motor drives or other power electronic devices
    c. Electronic component failures and equipment damage
    d. Control system malfunctions
3. **Influence on operations:**
    a. Stopped or slow production
    b. Lost production or sales
    c. Reduced product quality
    d. Scrap / restart
4. **Characteristics of the sensitive equipment experiencing problems:**
    a. Equipment design information
    b. Equipment ride-through characteristics
    c. Equipment application guides or installation/user manuals
5. **Frequency and timing:**
    a. Time of day, day of week/month, dates of occurrence
    b. Repetitive (same time every day)
6. **Coincident problems or known operations that occur at the same time:**
    a. Motor starting or slowing down
    b. Capacitor bank switching
    c. Lights blink on-and-off momentarily
    d. Weather conditions
7. **Possible sources of power quality variations within the facility and their power rating:**
    a. Motor starting
    b. Capacitor bank switching
    c. Power-electronic equipment operation (e.g., adjustable-speed drives, electronic lights, etc.)
    d. Arcing equipment (e.g., magnetic ballast fluorescent lights, arc furnaces, etc.)
    e. Copy machines, HVAC
8. **Power conditioning equipment being used:**
    a. Surge suppressors (TVSS)
    b. Motor-generator sets
    c. Ferroresonant transformers (CVTs)
    d. UPS systems
    e. Isolation transformers / chokes
9. **Electrical system data:**
    a. One-line or facility wiring diagrams
    b. Load and transformer information (e.g., rating and impedance)
    c. Capacitor unit and bank information (e.g., rating, connection, and placement)
    d. Feeder/cable data

Effective Communication with Customers

It is important that customers maintain a log detailing equipment problems that occur during the power quality monitoring and site survey using a standardized disturbance recording form. An example of a recording form is provided in Appendix B. This allows for the correlations of disturbances and system switching events with actual equipment power quality problems. The log should also indicate any major changes in the system configuration that are implemented during the measurement period (e.g., power factor correction capacitors, circuit configurations, new equipment, etc.). There may also be disturbances recorded that do not have any direct effect on customer equipment. It is important to distinguish these disturbances from the events that actually cause problems.

Meetings and discussions between all interested parties can be useful for identifying the particular power quality problem. Disturbance recording forms maintained by the customer can be reviewed for discussing disturbance cause(s) and relevant mitigating measures.

Solving PQ Problems

Utility and Customer Power Quality Problems Mitigation

Power conditioning for mitigating common power quality problems includes a number of alternatives for utilities, customers, and equipment manufacturers. The power conditioning options may have somewhat higher costs because an energy storage medium (e.g., battery) is required to hold all of the required energy for a critical load when the utility system falters. Determining which devices of an electrical load or process are sensitive to power quality variations will allow the selection of the appropriate type and rating for the power conditioner(s).

Modifications to the design of sensitive customer equipment may be the least expensive option, yet it is not always practical to implement. In addition, modifying the utility system may not be practical and can be quite expensive (e.g., fault current limiters). Power conditioning equipment, applied at or near sensitive customer equipment, may be the most cost-effective solution for many common power quality problems.

Methodology for Selecting Appropriate Mitigation Measures

The best power quality solutions are generally site-specific and potentially unique to the affected facility or process. Most problems involving one of the aforementioned power quality phenomena are difficult to resolve with off-the-shelf solution products, except for instances where the load rating is small and has no or limited interaction with other process equipment. This is, however, a trivial case, and most real problems involve a range of equipment interconnected in some fashion to constitute the process.

In applying a mitigation solution product, is it necessary to not only determine what type of technology should be used, but also where it should be applied, in what rating, and to what portions of the overall process. Sometimes determining what needs to be protected is a difficult challenge. Once determined, how and where the solution should best be applied can be a difficult proposition. The financial objective in solving power quality problems is to earn an acceptable return on investment or meet certain payback criteria. The following fundamental steps for optimized and cost-effective solutions to power quality problems include:

1. Identify the affected equipment/process.
2. Identify the nature of the electrical disturbance affecting equipment.
3. Calculate or approximate economic impact.
4. Select mitigation technologies based on nature of the electrical disturbance.
5. Determine the benefit/cost ratio for solution alternatives.
6. Select an appropriate solution based on technical and economic evaluation.
7. Design a solution application.
8. Specify and procure the selected solution product.
9. Install and commission the solution equipment.
10. Evaluate/validate the performance.

Not every step is necessarily mandatory or even applicable in every case. Sometimes the correct solution is more obvious, and possibly even based on previous experience, and therefore much of the problem identification/characterization effort can be omitted. The outlined procedure illustrates the breadth and depth of knowledge required to maximize the chances of a cost-effective solution.

Challenges for the Customer

The range of required expertise may not be immediately available to a customer unless there has been a prior substantial internal investment in building such a capability. Outside organizations with the requisite experience and skills often need to be enlisted.

When a power quality problem is encountered, customers have an immediate feel for the impact on the bottom line, and sometimes may be able to trace the problem down to specific equipment components of the overall affected process.

When a customer experiences production problems that are suspected to be related to power quality, the electric service provider (utility) and the manufacturer(s) of the sensitive equipment are often the first to be contacted for assistance.

Utility Power Quality Solutions

Utility power quality mitigation alternatives include reducing the number of faults on the power system, reducing the number and severity of transient voltages and currents, and taking steps to reduce harmonic distortion levels on distribution feeders.

Faults on the power system are the primary cause of both momentary interruptions and voltage sags. Any measure taken to reduce the likelihood of a fault will help reduce the incidence of sags and interruptions for customers. These measures can include using underground circuits, tree trimming, and increased application of surge arresters for lightning protection on distribution circuits.

The utility distribution system protection philosophy can also affect the problems experienced by customers during faults. It is possible that residential and commercial customers could be affected by momentary interruptions, but not by voltage sags. The number of interruptions experienced by customers can be reduced by clearing faults farther out on the distribution feeder with fuses and downline protective devices (e.g., reclosers), rather than by interrupting the entire feeder at the substation. Faults cannot be completely eliminated; however, there are steps that can be taken to reduce the number of faults, including:

- **Tree trimming:** This is one of the most effective methods for reducing the number of faults on overhead distribution lines. Power utilities have regular tree trimming programs; in some cases, an increase in the tree trimming frequency may be warranted.
- **Insulator washing:** Like tree trimming in wooded regions, insulator washing is necessary in coastal and dusty regions. Otherwise, there will be numerous insulator flashovers for even a mild rainstorm without lightning.
- **Shield wires:** Shield wires for lightning are common for utility transmission systems. They are generally not applied on distribution feeders except where lines have an unusually high incidence of lightning strikes. Some utilities construct their feeders with the neutral on top, perhaps even extending the pole, to provide shielding.
- **Modified conductor spacing:** Employing different line spacing, including conductor phase spacers to control conductor galloping, can sometimes increase the ability to withstand flashover or reduce the susceptibility of trees to touch the line.
- **Tree wire (insulated/covered conductor):** In areas where tree trimming is not practical, insulated or covered conductor can reduce the likelihood of tree-induced faults.
- **Underground (UD) cables:** Fault prevention techniques in UD cables are generally related to preserving the insulation against voltage surges. The insulation degrades significantly as it ages, requiring increasing efforts to keep the cable sound. This generally involves arrester protection schemes to divert lightning surges coming from the overhead system, although there are some efforts to restore insulation levels through injecting fluids into the cable.
- **Line arresters:** To prevent overhead line faults, the insulation level of the line must be raised, prevent lightning from striking the line, or prevent the voltage from exceeding the insulation level. The last idea is becoming

popular with improving surge arrester designs. To accomplish this, surge arresters are placed every two or three poles along the feeder as well as on distribution transformers. Some utilities place them on all three phases while other utilities place them only on the phase most likely to be struck by lightning.

- **Animal guards:** Animal guards are non-conductive devices installed on energized electrical equipment to minimize customer outages due to animal contact. Adding these devices will often reduce the likelihood of animal-induced faults.

Transient Disturbance Mitigation

Utility transient mitigation techniques include switchgear options. Devices for transient control on the utility system either attempt to minimize the overvoltage (or overcurrent) at the point of application, or limit (clip) the overvoltage at local or remote locations. These include:

- Synchronous closing control (also known as zero voltage closing),
- Pre-insertion devices (resistors and/or inductors),
- Fixed inductors/reactors, and
- Arresters (metal oxide varistors – MOVs).

The effectiveness of these methods is usually system-dependent and detailed transient analysis is often required to select the optimum control scheme and device ratings. Each of the methods has various advantages and disadvantages in terms of transient overvoltage reduction, cost, installation requirements, operating and maintenance requirements, and reliability. A number of utility distribution capacitor banks are installed without any transient overvoltage control.

Harmonics Mitigation

Utility alternatives for harmonic mitigation include eliminating harmonic resonances or reducing harmonic current distortion levels by strict adherence to connection standards. There are a number of methods for modifying the power system to reduce or eliminate harmonic resonances that can cause very high current or voltage distortion levels. A passive shunt harmonic filter may be added to the utility system to divert the troublesome harmonic currents off the system and into the filter. However, installing filters may not always be possible due to space limitations. Also, harmonic filters completely change the system frequency response characteristic, most often, but not always, for the better. A reactor may also be applied to de-tune the system. Harmful resonances are generally between the system inductance and shunt power factor correction capacitor banks. The reactor must be added between the capacitor and the supply system source.

Figure 10 - In-line voltage regulators used by power utilities to improve voltage profiles on long distribution feeders

Customer Power Quality Solutions

A number of different power conditioning alternatives exist for any given load. Therefore, it is very important to understand the type and nature of the disturbances that are causing problems, as well as the capabilities of the sensitive equipment that is to be protected. Power conditioning equipment is used to isolate sensitive equipment from disturbances such as lightning and switching transients, voltage sags, interruptions, or to provide voltage regulation to certain loads.

Figure 11 illustrates a common approach for power conditioning for sensitive equipment, where the power conditioner is placed in front of the sensitive load. Figure 12 shows that this location can be interpreted in several different physical locations: anywhere from inside the facility to out on the utility system. It also shows that the cost of this protection increases as the location moves toward the utility system.

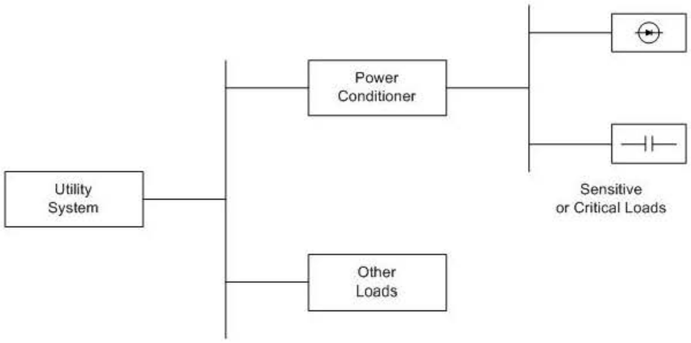

Figure 11 - Approach for power conditioning

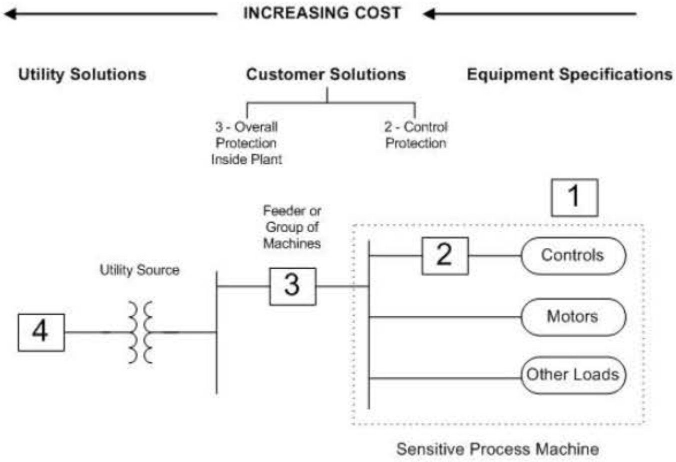

Figure 12 - Locations for power conditioning equipment and relative costs

The cost of protecting customer equipment from disturbances increases dramatically as one moves away from the critical load locations. For example, a power conditioner that can be used to protect process controls as opposed to the entire process is smaller and much more economical. Therefore, it is very important to first understand the process completely before any power conditioning equipment is applied. Protection of an entire facility, for instance, is often very costly and generally not required. Ideally, a customer site survey should be completed to characterize sensitive and critical loads. Many facility loads may not be critical and, therefore, may not need power conditioning equipment.

Another key factor in the application of power conditioning equipment is a cost/benefit study. This refers to the economic justification and payback of applying power conditioning equipment. A cost/benefit analysis should be done as part of any more complex power conditioning application project.

Customer Power Conditioning Equipment Summary

Customer power quality mitigation alternatives include taking steps to make equipment less sensitive to common power quality variations, modifying equipment procurement specifications, and the addition of power conditioning equipment at individual loads within a commercial or industrial facility. The customer is responsible for evaluating and specifying power conditioning equipment that is appropriate for its facilities.

Voltage sag mitigation

It is possible to make the equipment used in customer facilities less sensitive to voltage sags, momentary interruptions, and a number of other common power quality variations. Clocks and controls with low power requirements can be protected with a small battery or a large capacitor to provide greater ride-through capability. Motor control relays and contactors can be selected with less sensitive voltage sag thresholds. Controls can be set to be less sensitive to voltage sags unless the actual process requires an extremely tight voltage tolerance. This solution requires coordination with equipment manufacturers. However, the trend seems to be increasing ride-through capability. For instance, most programmable logic controllers use switched-mode power supplies that have a ride-through capability of about four cycles. Therefore, it should not be necessary to trip these controllers under short voltage sag conditions.

Another way that customers can combat voltage sags and other power quality problems is through their equipment procurement specifications. This essentially means keeping problem equipment out of their facility, or at least identifying ahead of time power conditioning requirements. Several ideas, outlined below, could easily be incorporated into any company's equipment procurement specifications to help alleviate problems associated with voltage sags.

1. Equipment manufacturers should have voltage sag ride-through capability curves (see *Equipment Susceptibility Curves* section), available for their customers so that an initial evaluation of the equipment can be performed. Customers should consider requesting these types of capability curves to properly evaluate new equipment.
2. The company procuring new equipment should establish a procedure that rates the importance of the equipment. If the equipment is critical in nature, it will be necessary to make sure adequate ride-through capability is included when the equipment is purchased. If the equipment is not important or does not cause major disruptions in manufacturing or jeopardize facility and personnel safety, voltage sag protection may not be justified.
3. Since the relative probability of experiencing a voltage sag to 70% (0.70 per-unit) or less of nominal is much less than experiencing a sag to 90% or less of nominal, it makes sense to choose an upper limit for a ride-through capability specification within the 70-75% range. A reasonable selected value would be around 50%.

The final method is the addition of power conditioning equipment in a facility. This method involves adding specific power conditioning equipment at individual loads that are sensitive to voltage sags, momentary interruptions, and other power quality variations. The power conditioning requirements depend on the types of voltage sags that can be expected and the possible durations of interruptions. A brief review of various options for customer power conditions for the different power quality categories is provided below.

Transients - Disturbance Mitigation

Power conditioning for transient protection requires knowledge of the type of transient that is occurring. Generally, short term monitoring is all that is required to characterize switching transients, since these tend to occur frequently. If the problem is lightning, the time of equipment failure and misoperation is also important. Monitoring will often indicate lightning induced problems, and there is technology that can locate lightning strikes. Lightning transient protection often requires a review of wiring and grounding practices as well, since this is important in determining how the transient propagates. This section includes a review of customer power conditioning alternatives for mitigating transients.

High-frequency impulsive and lightning induced transients can generally be solved by applying surge suppression devices. However, these types of devices typically do not provide adequate protection for low-to-medium frequency switching transients, such as those caused by utility capacitor bank energizing.

Utility capacitor bank switching can be a particular problem for customers that have low voltage power factor correction capacitor banks. These low voltage capacitor banks can magnify the switching transients, causing failure of arresters and electronic equipment within the facility. Using a tuned harmonic filter for shunt compensation can often solve this problem.

Utility capacitor bank switching can also cause nuisance tripping of small adjustable-speed drives and other power-electronic devices. These drives have dc capacitors that allow a current surge and resulting increase in the dc link voltage during the capacitor bank switching transient. The drive trips on dc overvoltage. A series choke (or reactor/isolation transformer) can be used to solve this problem.

Most high frequency transients occurring within customer facilities do not have significant energy associated with them (e.g., less than 1 Joule). This means that equipment can be protected with simple surge protection devices (e.g., varistors, silicon avalanche diodes, etc.). It is important that the transient voltage withstand capabilities of the equipment be coordinated with the protective levels of the devices used for protection.

Power-electronic devices and other electronic equipment can be sensitive to the transient voltage rate-of-rise, as well as to the magnitude. These devices can be protected with a series filter (choke) in addition to standard surge protectors. Many hybrid types of surge protectors include a series choke for this purpose.

As previously shown in Figure , customers have the option to protect equipment from transient phenomena at a number of locations, including the point-of-entry (e.g., meter panel or service entrance) and point-of-use (e.g., computer, adjustable-speed drive, etc.). Generally, a combination of point-of-entry and point-of-use devices will provide the greatest level of protection. Point-of-entry protection may include meter-based surge protective devices that are attached to the electric meter or panel-mount surge suppressors that are installed in electrical distribution panels. Point-of-use protection may include isolation transformers, transient voltage surge suppressors (TVSSs), line reactors, hybrid protectors and low-pass filters, and power conditioners. Some equipment manufacturers include transient protection as part of their standard equipment design.

Low-pass filters pass signals with low frequencies and reject signals with high frequencies. These filters can improve power quality by reducing the effect of the transient energy and by removing noise from the electrical system. Low-pass filters can be used to provide even better protection than inductive reactors for high frequency transients. Generally, low pass filters are composed of series inductors and parallel capacitors. This LC combination provides a low impedance path to ground for selected resonant frequencies. For this configuration, the inductor must be sized for the rated load current. Refer to UL 1283 for safety information regarding electromagnetic interference filters.

Hybrid protectors combine one or more surge suppressors with a gap-type protector and a low-pass filter to provide maximum protection. The gap-type protector handles high-energy transients. The low-pass filter limits transfer of high frequency transients (rate-of-rise). Finally, the MOV limits transient magnitude at the protected equipment. A schematic diagram for an example hybrid transient protector is shown in Figure 13.

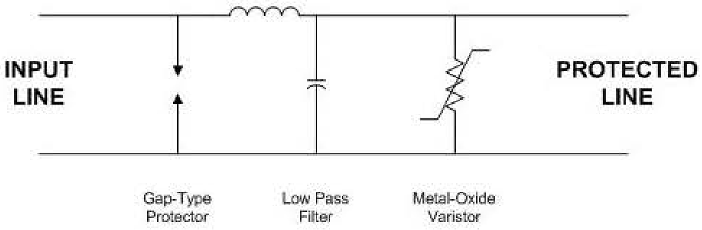

Figure 13 - Schematic diagram of a hybrid transient protector

Isolation transformers are used to attenuate high frequency noise and transients as they pass from winding to winding. However, some common mode and normal mode noise can still reach the load. An electrostatic shield is effective in eliminating common mode noise. However, some normal mode noise can still reach the load due to magnetic and capacitive coupling.

Isolation transformers are high impedance devices that essentially separate the load from the power system. Therefore, noise and transients are prevented from reaching the load and any load-generated noise and transients are prevented from reaching the rest of the power system. Voltage notching due to power electronic switching and other load-generated problems can then be limited to the load side of the isolation transformer. Capacitor switching transients from the utility system and other transient overvoltages can be attenuated, thereby limiting nuisance tripping of adjustable-speed drives and other sensitive equipment. An additional benefit of isolation transformers is that they can define a new ground reference, or a separately derived system. This neutral-to-ground bond limits neutral-to-ground voltages in sensitive equipment.

Voltage Variations

Power conditioning for voltage variation protection involves the addition of equipment at individual customer loads that are sensitive to voltage sags and/or momentary interruptions. The power conditioning requirements depend on the types of voltage sags that can be expected and the possible durations of the interruptions. Power conditioning equipment applied between the utility system and sensitive customer equipment may be the most cost effective solution for many common voltage variation problems. This section includes a review of customer power conditioning alternatives for mitigating voltage says and interruptions.

A voltage sag is a short duration of a reduction in rms voltage caused by faults on the power system and motor starting in a facility. Ferroresonant transformers, coil-lock devices, magnetic synthesizers, and a number of power-electronic based power conditioners can be used for protection against voltage sag events. Voltage sag protection may be implemented on a single coil or piece of equipment. Correction may also be chosen for large portions of a facility or even for the entire facility. The selection of voltage sag mitigation will consist of engineering aspects as well as a cost versus benefit evaluation.

A major component of many voltage sag mitigation devices is electrical or mechanical energy storage. During voltage sags or brief interruptions, a power converter draws the stored energy to synthesize nominal system voltage for the protected load. When the supply voltage is restored, the load is transferred back to the incoming source. An alternate approach uses a series injection transformer coupled to the line as a means of boosting the incoming voltage during a voltage sag event.

Voltage sags down to approximately 60% of nominal voltage can be handled with constant voltage transformers (CVTs) or ferroresonant transformers. These transformers can provide a constant voltage to the load for even more severe voltage sags if they are oversized. These power conditioners function by operating a transformer in its saturated region to make it less sensitive to variations in the input voltage. Ferroresonant transformers can protect equipment for virtually all voltage sag conditions that can be caused by single-line-to-ground faults on parallel distribution feeders or on the transmission system.

Coil-lock devices are another option for voltage sag protection. Coil hold-in devices are designed specifically to mitigate the effects of voltage sags on individual relays and contactors. They work on the principle of injecting a rectified dc voltage from the remaining voltage during a voltage sag to keep a contactor coil energized. They are connected in line with the incoming control signal for the relay or contactor and are particularly useful in emergency-off circuits, master control relays or motor control circuits. The rating of the device is typically based on the resistance of the coil, which usually decreases with the rating of the relay or contactor. This can be a very economical method to prevent unnecessary drop out of contactors during voltage sags. They generally provide ride-through for a voltage sag as low as 25% for up to 20 cycles. The devices may also provide some level of surge protection. A general schematic diagram for a coil hold-in device is shown in Figure 14.

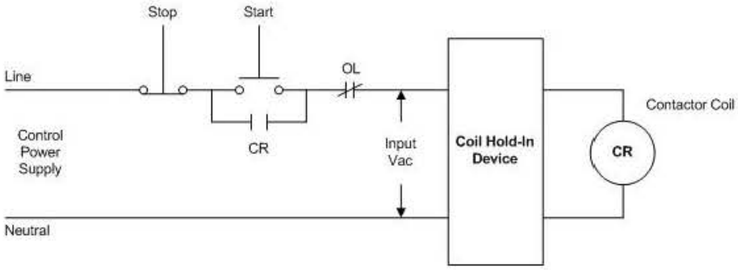

Figure 14 - Schematic for a coil hold-in device

For voltage sag protection of larger loads, magnetic synthesizers or motor-generators can be used. Magnetic synthesizers use saturated transformers to construct a new, clean, three-phase 480-volt source. Magnetic synthesizers can ride-through voltage sags down to about 60% of nominal and provide voltage regulation.

Motor-generator sets (M-G sets) also help ride-through voltage sag conditions due to the inertia of the motor and generator. However, standard motor-generators can only ride-through a couple cycles of a complete interruption. The addition of a flywheel (increased inertia) can increase the ride-through capability to 1-2 seconds. This may be sufficient to handle many momentary interruption problems.

An interruption is a short duration loss of rms voltage that occurs when circuit breakers and reclosers clear faults on the power system. For critical customer operations that must ride-through severe interruptions or voltage sags, motor-generators (M-G) sets, uninterruptible power supplies (UPS), or superconducting magnetic energy storage devices may be applied.

M-G sets can be used to provide 15 seconds of ride-through up to about 35 kVA. On-line and rotary UPSs can be used for long duration outages, generally up to 15 minutes in duration for very large loads. For short duration outages of 2 seconds or less, and for total facility protection (up to about 750 kVA) a superconducting magnetic energy storage device can be used. Diesel-based UPS protection can be employed for outages greater than 15 minutes in duration.

An uninterruptible power supply (UPS) is a power-electronic based device that provides a continuous voltage to a load by supplying power from a separate source (e.g., battery) when utility power is lost. A UPS is often used to protect computers, telecommunication equipment, or other critical electrical equipment where an unexpected power disruption could cause severe business disruption or data loss. UPS ratings range from units that will back up a single computer to units that will power entire data centers or buildings. Larger UPS systems are often applied in conjunction with back-up generators.

Historically, UPSs were used with large computer systems and in areas where the power supply was interrupted frequently. However, UPS units are now a commonly applied power-conditioning alternative for business and personal computers, as well as other sensitive customer equipment.

There are a number of different types of UPSs, including on-line, standby, hybrid, and parallel. A standby power supply is sometimes termed off-line UPS since the normal line power is used to power the equipment until a disturbance is detected and a switch transfers the load to the battery-backed inverter. A typical configuration for a standby UPS is shown in Figure 15.

The transfer time from the normal source to the battery-backed inverter is important. The CBEMA curve shows that 8 ms is the lower limit on voltage sag ride-through for power-conscious manufacturers. Therefore, a transfer time of 4 ms would insure continuity of operation for the critical load. Typical ride-though times range from five to 20 minutes.

A standby power supply does not typically provide any transient protection or voltage regulation, as does an on-line UPS. This is the most common configuration for commodity UPS units available at retail stores for the protection of small computer and entertainment system loads.

UPSs specifications include kVA capacity, dynamic and static voltage regulation, harmonic distortion of the input current and output voltage, surge protection, and noise attenuation. The specifications should indicate (or the supplier should furnish) the test conditions under which the specifications are valid.

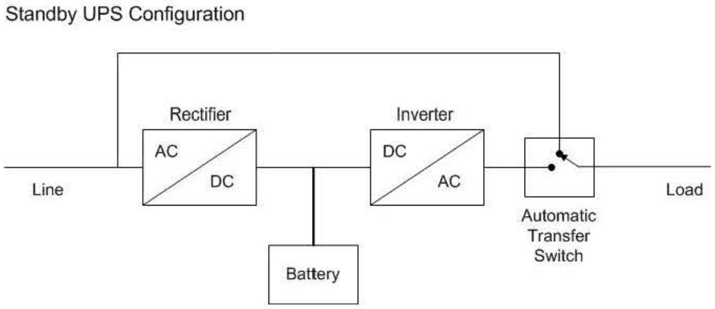

Figure 15 - Block diagram for a standby UPS

Harmonic Distortion

Power conditioning for harmonic protection requires knowledge of the type of problem that is occurring. Harmonic distortion is present to some degree on all power systems, however, solutions are generally applied only when there is a harmonic-related problem, or standards compliance is required. Common mitigation alternatives for controlling harmonics include reducing the harmonic currents produced by loads, adding filters to control the flow of harmonic current, and modifying the frequency response of the system to reduce voltage distortion levels. This section includes a review of customer power conditioning alternatives for mitigating common power system harmonic problems.

There are a number of methods for modifying the power system to reduce or eliminate harmonic resonances that can cause high current or voltage distortion levels. Almost all of the harmonic distortion problems occur when a harmonic resonant frequency exists near the 5th or 7th harmonic (though 11th or 13th harmonics can also be a problem). Simple hand-calculations can often be used to estimate system resonant frequencies for some circuits. The existence of resonances near characteristic harmonic frequencies of nonlinear loads that have been identified as harmonic sources is an early indication of potential trouble. If a harmonic resonance is discovered, possible solutions include:

- Change capacitor bank ratings or locations (often one of the least expensive options for customers),
- Add a reactor to an existing power factor capacitor bank (effect of detuning the system),
- Add a harmonic filter bank, and
- Controlling the power factor capacitor bank switching scheme to avoid the resonance.

When the mitigation of harmonic distortion is required, one option is to install a harmonic filter bank at the source of harmonics or at a location where the harmonic currents can be effectively removed from the system. The most cost-effective filter is generally a single-tuned passive filter in the majority of cases. Filters should be carefully designed to avoid unexpected interactions with the system.

For industrial customers, the need for filters is often precipitated by an adverse system response due to the addition of power factor correction capacitor banks, resulting in a harmonic resonance. These adverse system responses to harmonics can be corrected by changing the capacitance or the reactance. Two methods that require the addition of intentional reactance are:

- Adding a shunt filter. Not only does this shunt troublesome harmonic currents from the system, but it also changes the system response, often (though not always) for the better. This is the most common type of filtering applied because of the economics and as it tends to smooth the load voltage in addition to removing the unwanted current.
- Adding a reactor to the system to tune it away from resonances. Harmful resonances are generally between the system inductance and shunt power factor correction capacitor banks. The reactor must be added between the capacitor bank and the power source. One method is to install a reactor in series with the capacitor bank to move the system resonance without actually tuning the capacitor bank to create a filter.

Passive harmonic filters are made of inductive, capacitive, and resistive elements. They are relatively inexpensive compared with other means for eliminating harmonic distortion, but they have the disadvantage of potentially adverse interactions with the power system. They are employed either to shunt the harmonic currents off the line or to block their flow between parts of the system. This is done by tuning the elements to create a resonance at a selected harmonic frequency.

The most common type of passive filter is the single-tuned notch filter. Other, less common types of filters include series passive, low-pass broadband, and c-type. A c-type filter may be used for complex loads such as cycloconverters and electric arc furnaces. An example of an industrial customer 480-volt single-tuned notch filter arrangement is shown in Figure 16. The notch filter is series-tuned to present low impedance to a particular harmonic current. It is connected in shunt with the system. Thus, harmonic currents are diverted from their normal flow path on the line into the filter.

One important side effect of adding a filter is that it creates a sharp parallel resonance point at a frequency below the notch frequency. This resonant frequency must be placed safely away from any significant harmonic. In practice, filters are typically tuned slightly lower than the harmonic to be filtered (e.g., 4.7th vs. 5th) to provide safety margin in case there are some unforeseen changes in system parameters. If they were tuned exactly to the harmonic, changes in either capacitance or inductance with temperature or failure might shift the parallel resonance closer to an important harmonic.

This could present a situation worse than having no filter because the resonance is generally very sharp. For this reason, filters are often rated for the lowest problem harmonic (e.g., 4.7th for a six-pulse adjustable-speed drive).

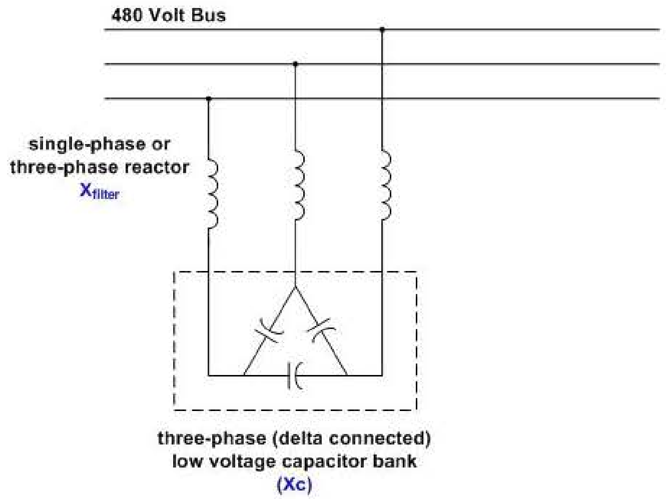

Figure 16 - Example of a low voltage single-tuned notch filter

Harmonic distortion in customer facilities can also be reduced by using active filters. Active filters work by electronically supplying the harmonic component of the current to a nonlinear load. Active harmonic filters are based on sophisticated power electronics for reducing harmonic levels. They also have a distinct advantage over passive filters in that they do not resonate with the system. They can be used in very difficult circumstances where passive filters cannot operate successfully because of where the parallel resonance lies. They can also address more than one harmonic at a time and combat other power quality problems such as voltage flicker. They are particularly useful for large, distorting loads fed from relatively weak points on the power system.

The active filter uses power-electronic switching to generate harmonic currents that cancel the harmonic currents from a nonlinear load. The basic idea is to replace the portion of the sine wave that is missing in the current from a nonlinear load. An electronic control monitors the line voltage and/or current, switching the power electronics very precisely to track the load current or voltage and force it to be sinusoidal. There are two fundamental approaches to achieve this: one that uses an inductor to "store-up" current to be injected into the system at the appropriate instant, and one that uses a capacitor. As a result, while the load current is distorted to the extent demanded by the nonlinear load, the current seen by the system is much more sinusoidal. Active filters can typically correct for power factor as well as harmonics.

The active filter does not need to provide any real power to cancel harmonic currents from the load. The harmonic currents that are cancelled show up as reactive power. Reduction in the harmonic voltage distortion occurs because the harmonic currents flowing through the source impedance are reduced. Therefore, the dc capacitors and the filter components must be rated based on the reactive power associated with the harmonics to be cancelled, and on the actual current waveform (rms and peak current magnitude) that must be generated to achieve the cancellation.

Harmonic currents magnitude for a number of nonlinear customer loads can be reduced with the addition of a series choke (or reactor or isolation transformer). Isolation transformers are used to attenuate high frequency noise and transients as they pass from winding to winding. However, some common mode and normal mode noise can still reach the load. An electrostatic shield is effective in eliminating common mode noise. However, some normal mode noise can still reach the load due to magnetic and capacitive coupling.

Isolation transformers are high impedance devices and essentially isolate the load from the system. Therefore, noise and transients are kept from reaching the load and any load-generated noise and transients are kept from reaching the rest of the power system. Voltage notching due to power electronic switching and other load-generated problems can then be limited to the load side of the isolation transformer. Capacitor bank switching transients from the utility system and other transient overvoltages can be attenuated, thereby preventing nuisance tripping of adjustable-speed drives and other equipment. An additional benefit of isolation transformers is that they can define a new ground reference, or separately derived system. This neutral-to-ground bond limits neutral-to-ground voltages at sensitive equipment.

Inductive reactors (a.k.a., chokes) perform functions similar to isolation transformers, except that they do not define a separately-derived system. Inductive chokes provide additional impedance in the circuit in much the same manner that an isolation transformer does, but at a much-reduced cost. They are often applied to the front-end of adjustable-speed drives to protect the drives from nuisance tripping caused by capacitor bank switching and other normal power system switching operations. Some motor drives have been found to be sensitive to overvoltages as minor as 1.2 per-unit. Inductive chokes limit these overvoltages to below the trip setting of the drive. They are generally rated as 3% impedance, based on the drive kilowatt (or hp) rating. Some drive manufacturers now produce drives with chokes as part of their standard design. Chokes also help prevent voltage notching, caused by power electronic switching, from disturbing other equipment. They can limit notching to the drive side of the inductive choke.

Transformer connections can be used to reduce harmonic currents in three-phase systems. Phase-shifting half of the six-pulse power converters in a facility load by 30 degrees can approximate the benefits of 12-pulse loads by reducing the 5th and 7th harmonic currents. Delta-connected transformers can block the flow of zero-sequence triplen harmonics from the line (triplen harmonics are odd multiples of the 3rd, e.g., 3rd, 9th, 15th, etc.). Zig-zag and grounding transformers can shunt the triplens off the line.

Zig-zag transformers are often applied in commercial facilities to control zero sequence harmonic components. A zig-zag transformer acts like a filter to the zero-sequence current by offering a low-impedance path to neutral. This reduces the amount of current that flows in the neutral back toward the supply by providing a shorter path for the current. To be effective, the transformer must be located near the load on the circuit that is being protected. A schematic diagram for one example zig-zag transformer design is shown in Figure 17.

Two possible harmonic problems in commercial facilities are overloaded neutral conductors and transformer heating. Both of these problems can be solved with proper zig-zag transformer placement. Some new commercial buildings include zig-zag transformers on the 480/208V supply transformer secondary to prevent transformer overheating. A zig-zag transformer located at the supply transformer secondary does not provide any benefit for neutral conductors supplying the loads.

Typical results with a zig-zag transformer show that it can shunt about 50% of the third harmonic current away from the main circuit neutral conductors. Thus, the zig-zag transformer can almost always reduce neutral currents to acceptable levels due to zero-sequence harmonics. The largest zero-sequence harmonic will nearly always be the third harmonic in office buildings with many computers and related equipment.

Zig-zag transformers are an excellent choice for existing facilities where neutral conductor problems and possible transformer heating are concerns, assuming that there is a convenient place to install the transformer between the neutral circuit of concern and the actual loads. In new facilities, it may be better to simply design the circuits with sufficient current-carrying capacity in the neutrals and with higher-capacity transformers.

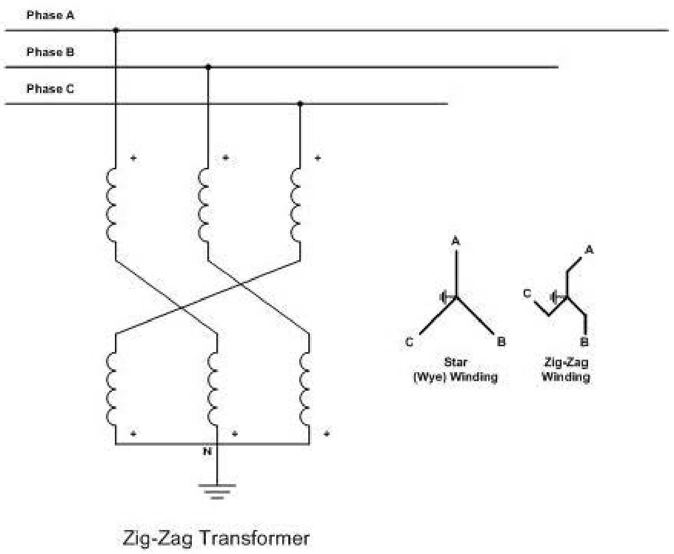

Figure 17 - Example of a zig-zag transformer schematic diagram

Summary

Comparing Mitigation Best Practices and Current Power Quality Standards

The electric power system is constructed for a reliable supply of power. Together with modern devices, it still utilizes many of the same elements that it did fifty years ago. However, the end-user equipment powered by this electricity has changed significantly, especially with advances in power electronics. Therefore, the requirements of electricity customers have also changed tremendously as the equipment being used now has become much more sensitive to power quality variations. The ability of equipment to operate during disturbances can be described as its immunity to power supply variations. There is interest to establish international power quality standards to deal with these problems. Standards are important because they can define the quality requirements of electricity, limit emissions from disturbing loads, and determine the immunity levels of customer equipment.

Customer equipment sensitivity is the primary factor that determines if a power quality variation will disrupt a load or process. Some loads may be sensitive to just the magnitude of the event, while other loads may be sensitive to both the magnitude and duration of the event. Currently, there is no single standard that includes equipment characteristics for all types of customer loads. However, a number of different industries have created equipment susceptibility curves that may be used to evaluate the potential for load disruption during power quality events.

The wide range of equipment sensitivities underlines the importance of working with the manufacturer to insure that the equipment can work in the environment where it will be used, and to develop specifications based on realistic power system conditions. It is also important to recognize that an entire process in a customer facility can depend on the sensitivity of a single piece of equipment. The overall process involves controls, adjustable-speed drives, motor contactors, robotics, etc., that are all integral to the facility's operation. This can make it very difficult to identify the sensitive piece of equipment after the entire process shuts down.

Some sensitive equipment requires very clean and constant voltage to operate properly. There are several different types of power conditioners available for this purpose, but care should be taken not to install a power conditioner that is more sensitive than the load it is designed to protect. There is also considerable overlap between different areas with some power conditioning equipment, so it is vitally important to look at all the options when specifying equipment.

Summary and Conclusions

This guide is intended to provide a quick and useful reference for utilities and their customers, by helping them identify common power quality problems and select effective mitigation measures. An introduction to power quality phenomena is given, as well as best practices for characterizing and diagnosing power quality problems. The guide includes a review of power quality standards, representative waveform signatures, and a summary of mitigation and power conditioning measures that can be used on utility and customer power systems.

Common power quality problems include all of the issues that arise from the incompatibility between a utility's power system and the customer's energy-using equipment that result in impaired operation. These include transients, voltage sags and swells, momentary interruptions, harmonics, and short- and long-term voltage variations and outages. Power conditioning for specific power quality problems requires knowledge of the type of problem that is occurring.

Harmonic distortion is often named by customers as the cause of power quality disturbances, but often it is actually a problem with transients. A measurement of the event may show a distorted waveform with obvious high frequency components. Although transient disturbances contain high-frequency components, transients and harmonics are distinctly different phenomena and are analyzed differently. Transient waveforms exhibit the high frequencies only briefly after there has been an abrupt change in the power system. The frequencies are not necessarily harmonics; they are the natural frequencies of the system at the time of the switching operation. These frequencies are not related to the system fundamental frequency. In contrast, harmonics occur in the steady state and are related to the system fundamental frequency.

Power quality issues may emerge from one or a combination of events on transmission system, distribution system, or customers' equipment. Joint co-operation of various stakeholders, such as electrical utilities, customers and electrical equipment manufacturers is important in order to address power quality problems.

Appendix A

Categories of Power System Electromagnetic Phenomena

IEEE Std. 1159-2009 *Recommended Practice for Monitoring Electric Power Quality* (see Table 1) defines power quality variation categories. Some of the categories include subcategories to more accurate describe a particular power quality variations. There are three primary attributes which are used to differentiate between the categories and subcategories: frequency components, magnitude, and duration. These attributes are not equally applicable to all categories of power quality variations.

The diagram below is graphical depiction of the time domain of various electromagnetic disturbances categorized in more details in Table1.

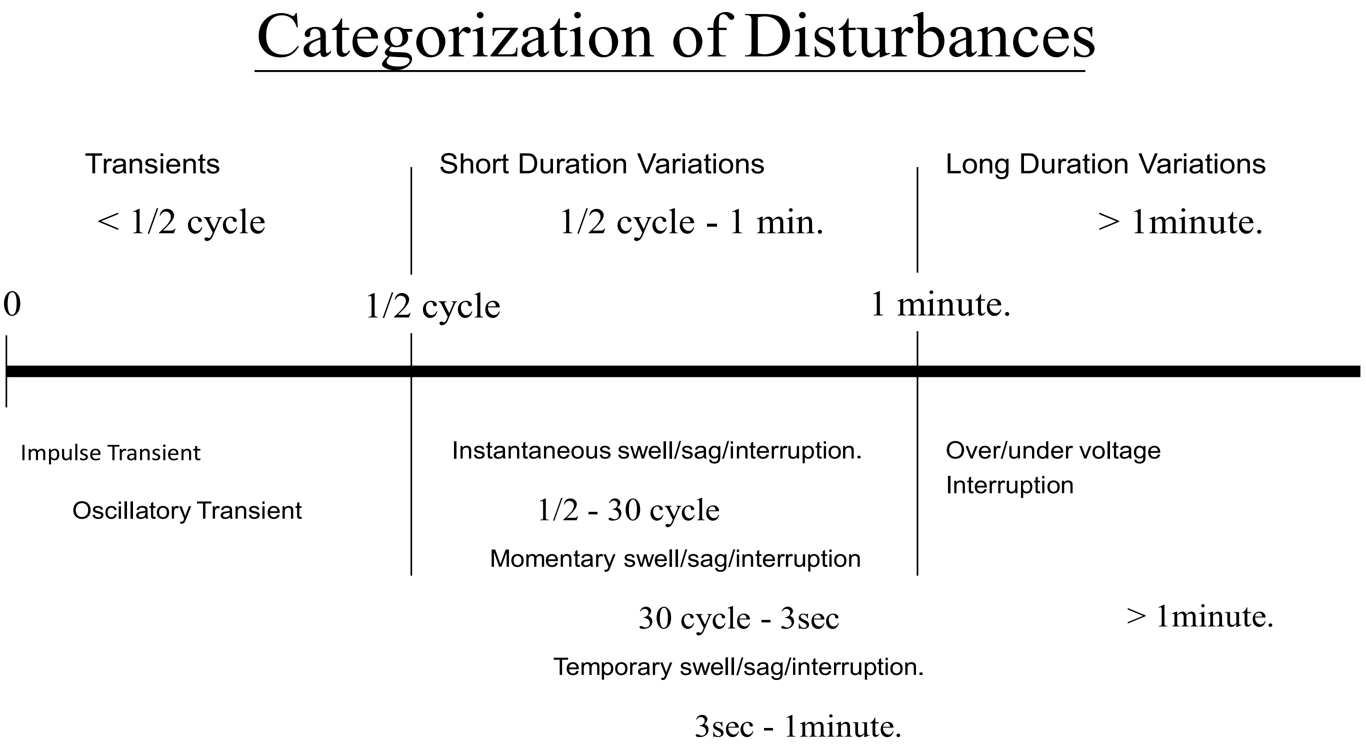

Figure 18 – Categories of electromagnetic phenomena

Categories	Typical Spectral Content	Typical Duration	Typical Voltage Magnitude
Transients			
Impulsive			
Nanosecond	5 ηs rise	< 50 ηs	
Microsecond	1 μs rise	50 ηs -1 ms	
Millisecond	0.1 ms rise	> 1 ms	
Oscillatory			
Low Frequency	< 5 kHz	0.3 - 50 ms	0 - 4 per-unit
Medium Frequency	5 - 500 kHz	20 μs	0 - 8 per-unit
High Frequency	0.5 - 5 MHz	5 μs	0 - 4 per-unit
Short Duration RMS Variations			
Instantaneous			
Sag		0.5 - 30 cycles	0.1 - 0.9 per-unit
Swell		0.5 - 30 cycles	1.1 - 1.8 per-unit
Momentary			
Interruption		0.5 cycles - 3 sec	< 0.1 per-unit
Sag		30 cycles - 3 sec	0.1 - 0.9 per-unit
Swell		30 cycles - 3 sec	1.1 - 1.4 per-unit
Temporary			
Interruption		3 sec - 1 min	< 0.1 per-unit
Sag		3 sec - 1 min	0.1 - 0.9 per-unit
Swell		3 sec - 1 min	1.1 - 1.2 per-unit
Long Duration RMS Variations			
Interruption, Sustained		> 1 minute	0.0 per-unit
Undervoltages		> 1 minute	0.8 - 0.9 per-unit
Overvoltages		> 1 minute	1.1 - 1.2 per-unit
Current Overload		> 1 minute	
Voltage Imbalance		Steady-state	0.5 - 2%
Current Imbalance		Steady-state	1.0 - 30%
Waveform Distortion			
DC Offset		Steady-state	0 - 0.1%
Harmonics	0 - 9 kHz	Steady-state	0 - 20%
Interharmonics	0 - 9 kHz	Steady-state	0 - 2%
Notching		Steady-state	
Noise	Broadband	Steady-state	0 - 1%
Voltage Fluctuations	< 25 Hz	Intermittent	0.1-7%, 0.2-2 P_{st}
Power Frequency Variations		< 10 sec	± 0.10 Hz

Table 1 Categories of power system electromagnetic phenomena

Appendix B

Customer Electric Disturbance Log

A customer electrical disturbance log can be a valuable tool when solving power quality problems. The log can be used in conjunction with power quality monitoring to compare electric disturbances with disruptions to equipment or processes within a customer facility. Kept properly, the disturbance log will contain information that will help determine patterns such as times-of-day, areas within a facility, and the frequency of the occurrences. It can also help to determine if the origin of the electrical system disturbance is the utility or customer equipment.

Customer Contact Information:

Company: ____
Address: ____
Contact Name: ____
Phone Number: ____
Fax Number: ____
E-mail Address: ____

Equipment or Process Affected:

Equipment Type: ____
Manufacturer: ____
Equipment Rating: ____
Mitigation Equipment: ____

Symptoms (√ all):

Dimming Lights ☐
Error/Fault Code ☐
Control Problem ☐
UPS Beeping ☐
Breaker Tripping ☐
Harmonic Problem ☐
Short Power Loss ☐
Equipment Overheating ☐
Capacitor Bank Failure ☐
Drives/PLC Tripping ☐
Equipment Damage ☐
Other ☐

Other Details: ____

Disturbance Information:

Date: ____
Time: ____
Event Description: ____
____
Weather Conditions: ____

Duration (√): < 2 seconds ☐ 2-120 seconds ☐ > 2minutes ☐ > Unknown ☐
Regularity (√): Daily ☐ Hourly ☐ Weekly ☐ > Unknown ☐

Lost Production Time (hrs): ________________________
____

Additional Comments: ____
____

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