PQSoft Case Study

General Reference
Common Power Quality Problems and Solutions

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References			

Abstract:

Power quality is a frequently used term that means different things to different people. Common power quality problems include all of the issues that arise from the incompatibility between a utility's power and the customer's energy-using equipment that result in impaired operation. These include transients, sags and swells, harmonics, and short- and long-term voltage variations and outages. Also included under this broad area are issues of power reliability.

This document provides a brief summary of common power quality problems and solutions.

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RELATED STANDARDS

IEEE Standard 1159
IEEE Standard 1346
IEEE Standard 1250
IEEE Standard 1036
IEEE Standard 519

GLOSSARY AND ACRONYMS

ASD	Adjustable-Speed Drive
CVT	Constant Voltage Transformer
GPR	Ground Potential Rise
IEEE	Institute of Electrical and Electronics Engineers
MOV	Metal Oxide Varistor
PWM	Pulse Width Modulation
TVSS	Transient Voltage Surge Suppressors
UPS	Uninterruptible Power Supply
VCR	Video Cassette Recorder

COMMON POWER QUALITY PROBLEMS AND SOLUTIONS

Power quality is a frequently used term that means different things to different people. Common power quality problems include all of the issues that arise from the incompatibility between a utility's power and the customer's energy-using equipment that result in impaired operation. These include transients, sags and swells, harmonics, and short- and long-term voltage variations and outages. Also included under this broad area are issues of power reliability.

Power quality variations occur when the voltage waveform supplied to the customer deviates from normal. These deviations may involve changes in the voltage level (rms variations), changes in the voltage sinusoidal shape (harmonics, notching, and transients), or loss of power altogether (interruptions and outages). To some extent, the power system is constantly experiencing power quality variations because the supplied voltage is never a perfect sinusoid. When these variations are so significant, however, that customer equipment is adversely affected; the quality of service supplied becomes an issue that should be investigated. In addition, the current trend toward more energy efficient electronic devices has greatly increased the sensitivity of customer load equipment. As a result, power variations that once went unnoticed now result in mis-operation of customer devices. The impact of these power quality-related problems can vary significantly. For example, a VCR could miss recording a program or a semiconductor manufacturer could lose product worth hundreds of thousands of dollars during the same momentary interruption event. Events such as these adversely affect all involved parties. The customer must absorb the initial economic impact of the power quality disturbance, but the electricity supplier and the public are affected economically in the long run as well.

Characterizing the Power Quality Environment

The relative importance of a particular category of power quality phenomena for a specific customer will depend on the type of installed electrical equipment. The type of interaction 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 by IEEE Std. 1159, Recommended Practice for Monitoring Electric Power Quality.

Approaches for resolving equipment or process problems related to each category of phenomena vary widely. Causes, impacts, and appropriate solutions for this range of electrical phenomena have been analyzed in numerous research and study efforts, resulting in the development of proven solution techniques for many common power quality problems. These efforts have also contributed to a prioritization of the power quality phenomena categories. From the customer's point of view, the problem categories that are most important are those that:

- have the highest negative impact on productivity, or
- are difficult to diagnose and characterize, or
- are more difficult and/or expensive to resolve.

Using these criteria, research and case study investigations have identified the following categories of power quality phenomena to be of highest importance to customers:

- rms voltage variations, especially sags and interruptions
- transients, especially utility capacitor switching transients
- harmonic distortion , especially resonance conditions

This does not mean that there are never problems associated with other categories of power quality phenomena. Experience does indicate, however, that the majority of problems (especially from the custom's perspective) are those listed above.

RMS Voltage Variations

Most customers recognize that electric power outages can never be cost-effectively eliminated. Distribution system reliability in the United States is very high, reflecting the fact that actual electric service interruptions are very infrequent, perhaps just once or twice per year. Voltage variations of short duration are not as well understood and do occur with a much higher frequency that actual service interruptions. Sometimes the duration is so short as to be almost imperceptible to the naked eye. However, modern process equipment and processes are more discerning than the naked eye, and will misoperate or even shut down in response to such voltage variations. This reaction, coupled with the relatively high rate of occurrence and the general high cost and complexity of typical solutions, make 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, IEEE Recommended Practice for Evaluating Electric Power System Compatibility with Electronic Process Equipment, and IEEE Std. 1250, IEEE Guide for Service to Equipment Sensitive to Momentary Voltage Disturbances provide guidance for evaluating the impact of rms variation events on customer systems.

Figure 1 illustrates an example of a distribution system momentary interruption event. This waveform was recorded with a power quality disturbance analyzer.

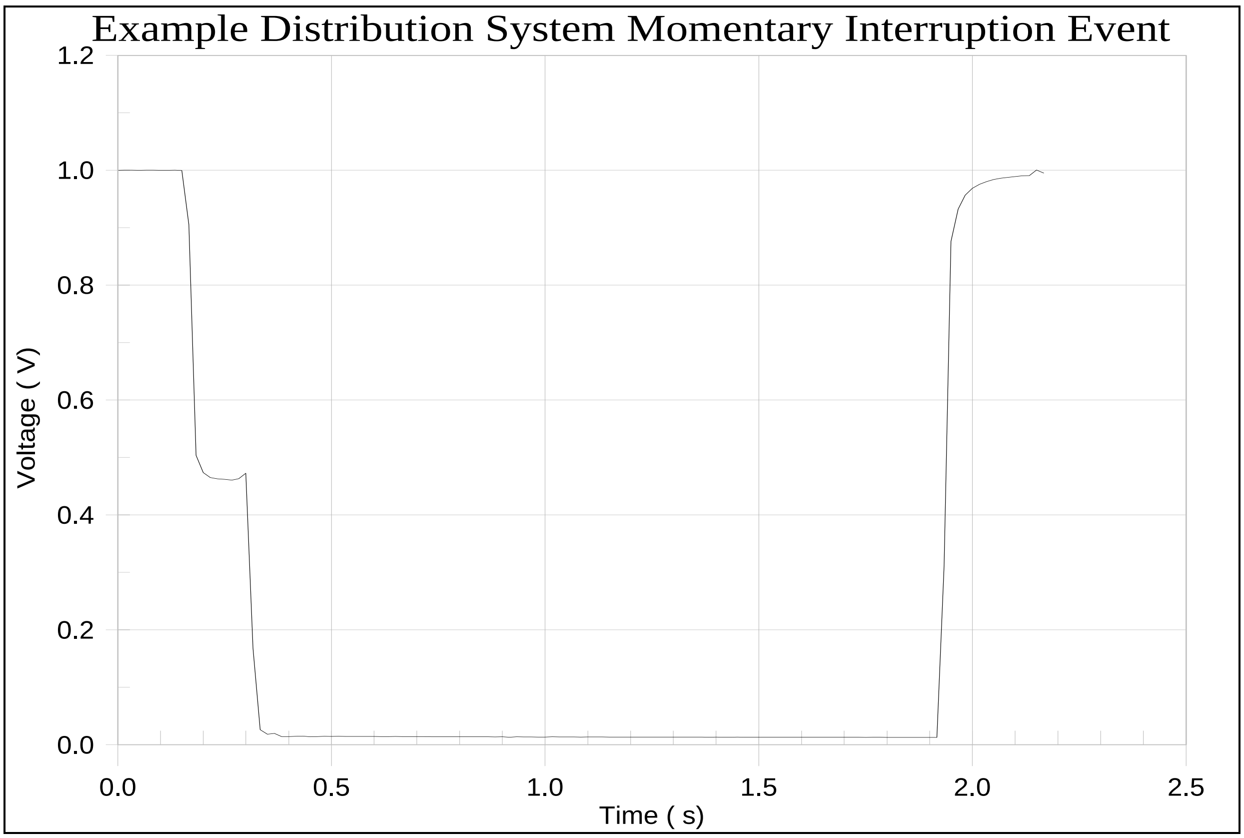

Figure 1 - Example Distribution System Momentary Interruption Event

Transients

Transient overvoltages caused by switching operations or lightning strikes to electric facilities have significant potential to damage electric power equipment or disrupt operation. High-frequency transients (most impulsive transients and low- and medium-frequency oscillatory transients) have been recognized from some time as a threat to electronic equipment, and have been blamed for a wide range of failures and misoperations. Fortunately, these transients are relatively easy to protect against, and a wide range of off-the-shelf and inexpensive transient voltage surge suppressor (TVSS) products can be applied by either the customer or equipment manufacturer.

Low frequency oscillatory transients, on the other hand, are more difficult to treat. Switching (energizing) of utility shunt capacitor banks is the most common source of low-to-medium frequency 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 effects can be felt quite far electrically from the point of origin. Low frequency transients have been strongly correlated with nuisance tripping of power electronic equipment, especially common types of adjustable-speed drives.

IEEE Std. 1036, Guide for the Application of Shunt Power Capacitors, provides a helpful overview to utility capacitor switching.

Figure 2 illustrates an example of a distribution bus voltage during a utility capacitor energizing event. The resulting overvoltage is approximately 1.35 per-unit (135%). Typical magnitudes for this type of event range from 1.2 to 1.8 per-unit and the resulting energizing frequencies generally fall in the range from 300 to 1000 Hz. This transient waveform was recorded with a power quality disturbance analyzer.

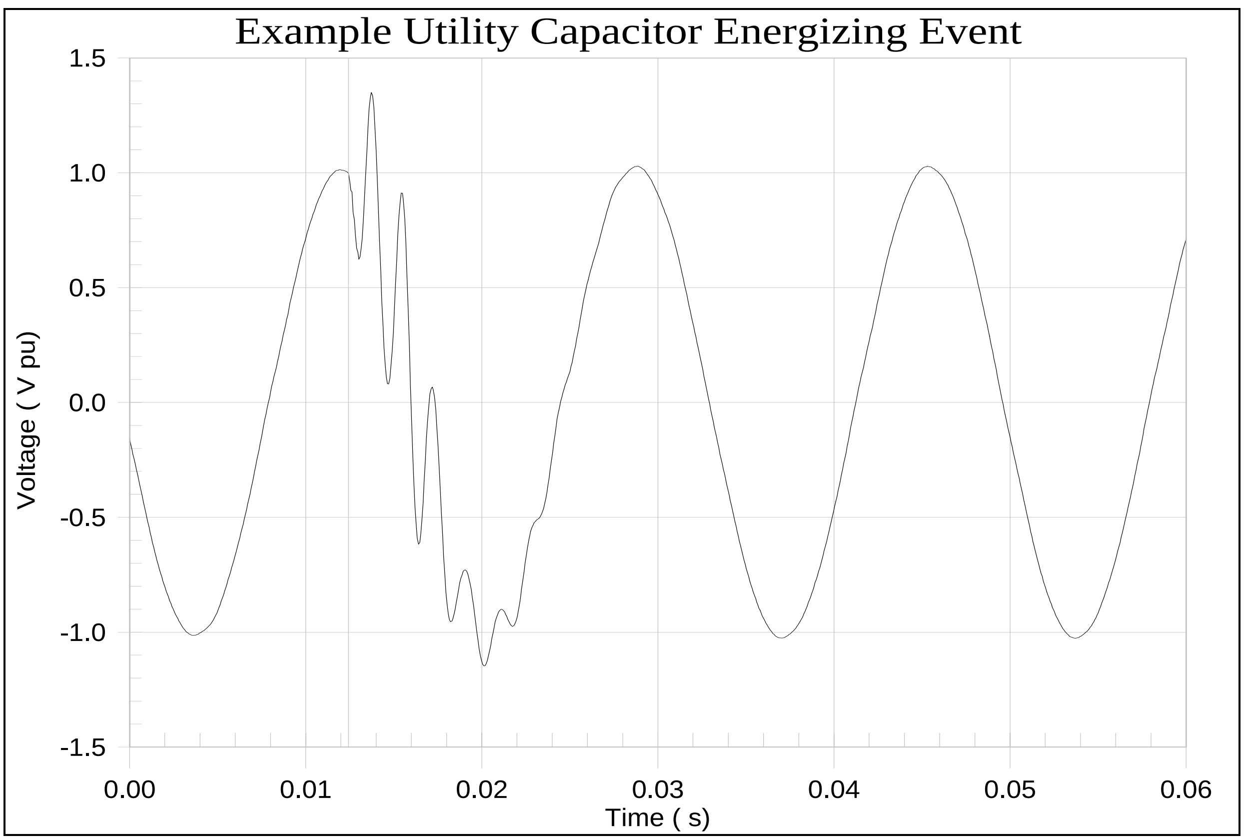

Figure 2 - Example Utility Capacitor Energizing Event

Harmonic Distortion

Harmonics are probably more strongly associated with power quality than any other category. It is somewhat surprising to those only casually involved in power quality that harmonics are not a chronic problem that the typical customer must deal with. Harmonics can cause equipment to misoperate, capacitor banks to fail, breakers to trip mysteriously, but in general, the electric power system has the ability to absorb substantial amounts of harmonic current with surprisingly little or no impact on connected equipment. Real problems from harmonics are usually confined to locations with high amounts of nonlinear, harmonic current-producing loads. Examples of this include a wastewater treatment plant where the entire load may be comprised of adjustable-speed motor drives powering pumps, or situations where power factor correction capacitors on the customer system or at the utility distribution level create resonances that amplify the effects of nonlinear loads. The fraction of electric power system load that produces harmonics currents has steadily increased over the past two decades.

IEEE Std. 519, IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems includes 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 onto 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).

Figure 3 illustrates an example of a dc drive current waveform. This waveform was simulated using Electrotek's SuperHarm™ program.

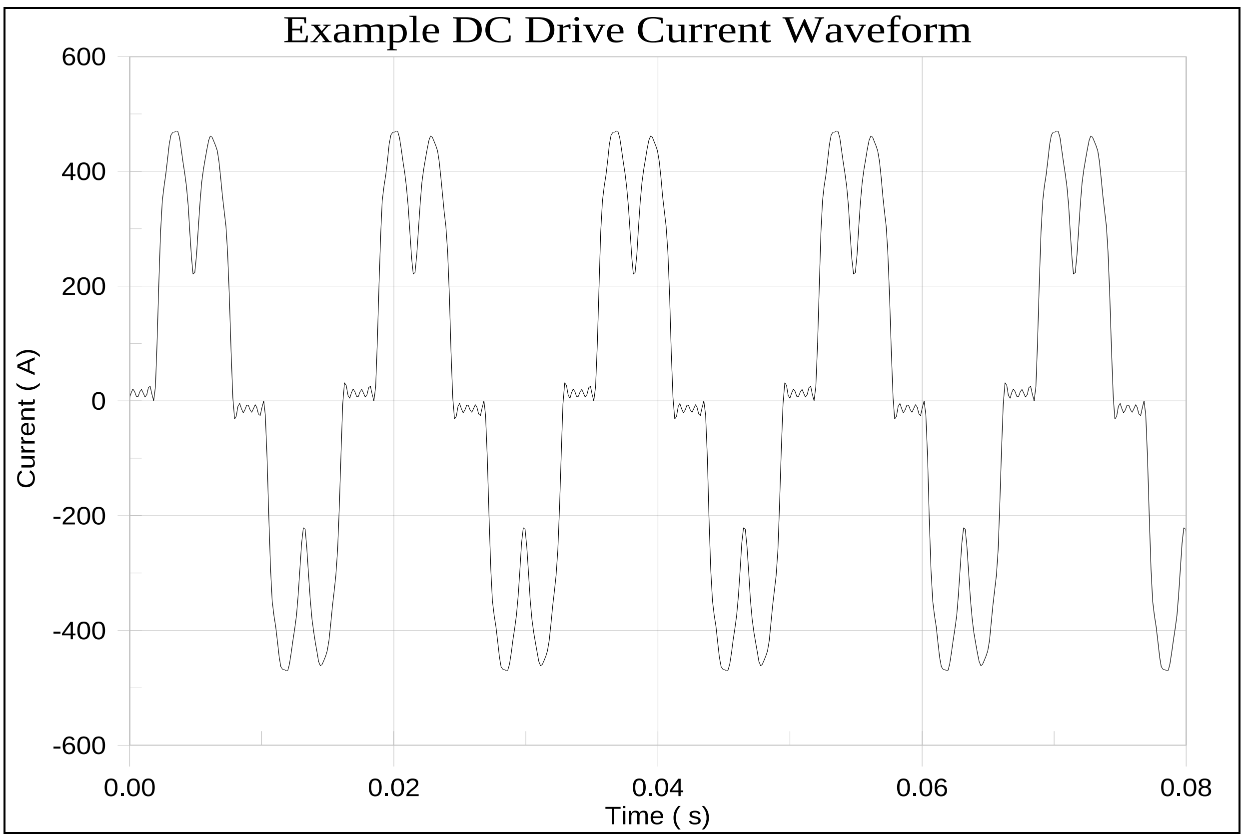

Figure 3 - Example DC Drive Current Waveform

Economic Impacts of Power Quality

The ultimate reason that we are interested in power quality is economic value. There are economic impacts on utilities, their customers, and suppliers of load equipment. The quality of power can have a direct economic impact on many industrial consumers. There has recently been a great emphasis on revitalizing industry with more automation. This usually means electronically controlled, energy-efficient equipment which is often much more sensitive to deviations in the supply voltage than its electromechanical predecessors (e.g., adjustable-speed drives vs. induction motors). Thus, like the blinking clock in residences, industrial customers are now more acutely aware of minor disturbances on the power system. There can be significant costs associated with these disturbances. For example, it is conceivable for a single, commonplace, momentary utility breaker operation to result in a $10,000 loss to an average-sized industrial customer by shutting down a production line that requires four hours to restart.

The electric utility is concerned about power quality issues as well. Meeting customer expectations and maintaining customer confidence is a strong motivator. With today's movement toward competition between utilities, it is more important than ever. The loss of a dissatisfied customer to a competing power supplier can have a very significant impact financially on a utility. Load equipment suppliers generally find themselves in a very competitive market with most customers buying on lowest cost. Thus, there is a general disincentive to add features to the equipment to withstand common disturbances unless the customer specifies otherwise. Many manufacturers are also unaware of the types of disturbances that can occur on power system.

The primary responsibility for correcting inadequacies in load equipment ultimately lies with the customers that must purchase and operate it. Specifications must include power performance criteria. Since many customers are also unaware of the pitfalls, one useful service that utilities can provide is dissemination of information on power quality and the requirements of load equipment to properly operate in the real world.

Factors that Influence Costs

Besides the obvious financial impacts on both utilities and industrial customers, there are numerous indirect and intangible costs associated with power quality problems. Residential customers typically do not suffer direct financial loss or the inability to earn income because of most power quality problems, but they can be a potent force when they perceive that the utility is providing poor service. The sheer number of complaints requires utilities to provide staffing to handle them. In addition, public interest groups frequently intervene with public service commissions, requiring the utilities to expend financial resources on lawyers, consultants, studies and the like to counter the intervention. While all of this is certainly not the result of power quality problems, a reputation for providing poor quality service does not help matters. As with many power quality problems, an economic evaluation is often difficult to complete since it is often very difficult to determine the cost of a particular event for an individual customer. In addition, these costs may vary drastically from customer to customer. There are a number of aspects of customer production that can be affected by a power quality event, including:

1. Lost Production - factory costs associated with the production process being disrupted.
2. Scrap - costs associated with product that must be scrapped and cannot be recovered by recycling the raw materials.
3. Restart - costs associated with restarting the production process.
4. Labor - extra labor costs associated with restarting the product line, reloading machines, cleaning up scrap, etc.
5. Repair - costs for repair of machines and equipment damaged during the transient event.
6. Replacement - costs for the replacement of machinery damaged during the transient event.
7. Process Inefficiency - costs due to the process not begin able to run to its optimal efficiency.
8. Demand Charges - increased utility charges because the customer is unable to operate equipment such as capacitors and adjustable-speed drives that might reduce demand charges.

Each event that impacts a customer's production will include a number of these costs. Predicting the exact economic impact is nearly impossible due to the large number of system parameters that can affect the characteristics of the event. It is entirely possible, however, that a single event could generate losses sufficient to justify the additional mitigation equipment expenditure.

Common Power Quality Problems and Solutions

Customers often blame utilities for most power quality problems, but the fact is that problems may originate on either side of the meter. There are four sources for most customer-encountered problems:

1. Natural phenomena (e.g., inclement weather)
2. Normal utility operations (e.g., automatic protection system operations)
3. Neighboring customers (e.g., welding equipment adjacent to an office)
4. Customer's own equipment and facilities (e.g., motor starting).

Within a customer's facility, poor power quality can result from incompatible equipment interactions or from poor wiring and grounding practices. In fact, many power quality problems are associated with customers' wiring and grounding practices. Problems such as voltage sags, however, generally originate on the utility's side of the meter. In addition, the proliferation of harmonic (nonlinear) producing loads is resulting in power quality problems for both customers and the utilities that serve them. These loads include adjustable-speed drives, electronic ballasts for fluorescent lighting, electric arc furnaces, computers distributed throughout commercial and industrial facilities, and other electronic technologies.

Identifying Power Quality Problems

The first step is to understand how customers perceive power quality problems. Customers rarely see or understand these problems. They see symptoms of them and the resulting difficulties in their businesses and homes. Some of the more common 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
- Static shock

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

- Adjustable-speed drives - harmonic distortion concerns
- Adjustable-speed drives - sensitivity to transient voltages
- Electronic controls, adjustable-speed drives, robotics, 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 capacitors - switching transients and magnification
- Power factor correction capacitors - harmonic distortion concerns (resonance)
- Motor contactors - sensitivity to voltage sags
- Power conditioning equipment selection - matching to requirements of protected equipment

- Data processing equipment - UPS system specification
- Electronic equipment - sensitivity to high frequency transients
- Transformers - harmonic heating
- Motors - voltage imbalances and harmonic heating

Once information regarding the symptoms and affected equipment is collected, the power quality event causing the problem can be determined. A number of common power quality issues include:

- Voltage sags due to faults on parallel circuits on the same distribution system or faults on the transmission system.
- Voltage sags due to motor starting.
- Momentary interruptions at industrial and commercial installations due to recloser operations on feeder circuit breakers.
- Voltage flicker from arc furnace and arc welding loads.
- Voltage transients caused by circuit switching and load switching within the customer facility.
- Transient voltage magnification at low voltage capacitor banks.
- Sensitivity of adjustable-speed drives and control systems to utility capacitor switching transients.
- Transients and notching associated with power electronics equipment operation.
- Coupled voltages at customer facilities due to lightning transients on the primary distribution systems.
- Harmonic distortion from adjustable-speed drives or other nonlinear loads.
- Transformer heating caused by harmonic current levels.
- Neutral conductor overloading due to harmonic producing loads in commercial installations.

Determining Power Quality Solutions

Lessons learned from numerous research and case study projects have revealed the following fundamental steps for optimized, cost-effective solutions to power quality problems:

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

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

Challenges for the Customer

Unfortunately, the range of required expertise and background knowledge is almost never immediately available to a customer unless there has been a previous and substantial internal investment in building such capability. Outside organizations with the requisite experience and skill must often be enlisted. When a 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. The urgency associated with resolving the problem and restoring production can lead to band-aid solutions, or worse, actions that result only in wasted effort and expense and do not improve the situation at all.

The solution process previously outlined is designed to prevent band-aids. Many of the steps and interim questions to answer can be beyond the skills and expertise of the customer. Examples of this include:

- In some cases, the customer may not be able to identify affected equipment; a single observation or problem may reveal only the most sensitive link in the process chain, where a solution specific to that component would only expose other parts of the production chain when more severe disturbances occur.
- While the customer most likely knows or could calculate the cost of a single event, they may not be able to project impact over time since this will relate to frequency and characteristics of electrical disturbance, for which they have no information.
- A customer may not have detailed specifications or electrical requirements for components or equipment that make up their process. Respective vendors may have such information, but seeking out each of them can be a daunting task.
- Customers may not be aware of the appropriate solution technologies, making them more susceptible to marketing claims from solution vendors.
- Customers may not have the necessary technical and/or engineering expertise to select, design, and specify a solution.
- With limited technical resources and staff that is often over utilized, there is often no evaluation or validation of a solution once commissioned.
- Power quality problems may not be isolated or stand-alone. For example, combinations of problems or careful analysis of equipment/process requirements versus electric supply characteristics sometimes points to a solution different than what might be indicated for a single observed occurrence.

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 affected equipment are many times the first contacts made for assistance.

Common Power Quality Solutions

The best power quality solutions are in general site-specific and potentially unique to the affected plant 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 is small in size 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 solution product, is it necessary to not only determine what type of technology, but also where it should be applied, in what size, 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.

A number of common power quality solutions include:

RMS Voltage Variations

- Faults on the power system are the ultimate cause of both momentary interruptions and voltage sags. Any measures taken to reduce the likelihood of a fault will help reduce the incidence of sags and interruptions to customers. These measures can include using underground circuits, tree trimming, insulator washing, and increased application of surge arresters for lightning protection on distribution circuits.
- It is possible to make the equipment being used in customer facilities less sensitive to voltage sags and momentary interruptions. Clocks and controls with low power requirements can be protected with a small battery or large capacitor to provide ride-through capability. Motor control relays and contactors can be selected with less sensitive voltage sag thresholds. Controls can be set less sensitive to voltage sags unless the actual process requires an extremely tight voltage tolerance. This solution requires coordination with equipment manufacturers but the trend seems to be in the direction of increased 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.
- Power conditioning equipment can be applied at the individual loads that are sensitive to voltage sags and/or interruptions. The power conditioning requirements depend on the types of voltage sags that can be expected and the possible durations of interruptions:
    - Voltage sags down to approximately 60% of nominal voltage can be handled with constant voltage transformers (CVTs - also known as ferroresonant transformers).
    - For voltage sag protection of larger loads, magnetic synthesizers or motor-generators can be used. Magnetic synthesizers can ride through voltage sags down to about 60% of nominal and provide voltage regulation.
    - Motor-generator 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.
    - For the most part, uninterruptible power supply (UPS) systems are required if equipment must be completely protected from interruptions. If momentary interruptions are the only problem (as opposed to long duration outages), the UPS system can be designed with minimum battery backup. Larger battery systems (to provide backup for interruptions lasting up to 15 minutes) can be designed if longer duration interruptions are anticipated.
    - For short duration interruptions and voltage sags (less than 2 seconds), superconducting storage devices and other power-electronic-based devices (Custom Power) are being developed to protect entire plants or portions of larger plants at the service entrance.
- Starting motors can cause voltage sags and other voltage variation problems such as flicker if the motor is started frequently. Alternative starting techniques, such as autotransformer starters, resistance and reactance starters, part-winding starters, and delta-wye starters may be applied if the voltage sag during starting impacts the system or adjacent equipment.

Transients

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

- Utility capacitor switching can also cause nuisance tripping of small adjustable-speed drives. These drives have dc capacitors that allow a current surge and resulting increase in the dc link voltage during the capacitor switching transient. The drive protection circuit trips on dc overvoltage. A series choke (or reactor or 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 (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 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.
- Lightning transients can be a particular problem for customer equipment. Lightning surge currents being conducted to ground create a ground potential rise (GPR) that can cause significant ground potential differences between different locations within a facility. When proper grounding practices are followed, this should not be a safety hazard. However, the ground potential differences can cause problems with communications and data processing equipment that has multiple ground references. Sometimes, only optical isolation can prevent these problems.
- Low voltage side current surge phenomena is a particular concern for residential customers. Currents in the transformer secondary winding during lightning surges also flow through the customer loads. Efforts to protect the transformer can make the surge at the customer service more severe. A coordinated approach involving secondary arresters at the pole and the service entrance is required to solve this problem.

Harmonic Distortion

- Almost all harmonic distortion problems occur when a resonant frequency exists near the 5^{th} or 7^{th} harmonic (11^{th} or 13^{th} harmonics can also be a problem if a large percentage of the load is nonlinear). Simple calculations can often be used to determine the system resonant frequencies. Existence of resonances near characteristic harmonic frequencies of loads that have been identified as harmonic sources is an early indication of potential trouble. If a harmonic resonance is discovered, possible solutions include
    - Ungrounding wye-connected capacitor banks (this is often used to solve telephone interference problems).
    - Changing capacitor bank sizes and/or locations (this is often one the least expensive options for both utilities and industrial customers).
    - Adding a reactor to an existing capacitor bank (has the effect of detuning the system).
    - Adding a harmonic filter bank - The most common filter is a single-tuned passive filter. The passive shunt filter works by short-circuiting the harmonic currents as close to the source of distortion as practical. This keeps the currents out of the supply system and alters the resonant frequency of the system.
    - Controlling the capacitor switching scheme to avoid the resonance.
- Harmonic distortion can also be reduced with the application of active filters. Active filters work by electronically supplying the harmonic component of the current into a nonlinear load.
- Harmonic currents magnitudes for a number of nonlinear customer loads can be reduced with the addition of a series choke.

- Transformer connections can be used to reduce harmonic currents in three-phase systems. Phase-shifting half of the 6-pulse power converters in a plant load by 30 degrees can approximate the benefits 12-pulse loads by reducing the 5^{th} and 7^{th} harmonic currents. Delta-connected transformers can block the flow of zero-sequence harmonics (typically triplens) from the line. Zigzag and grounding transformers can shunt the triplens off the line.
- Harmonic control on distribution feeders can often be achieved with the installation of a number of distributed harmonic filters near the end of the feeders.

REFERENCES

IEEE Standard 100. Terms and Definitions

IEEE Standard 1100. IEEE Recommended Practice for Powering and Grounding Sensitive Equipment (The Emerald Book).

IEEE Standard 1159. IEEE Recommended Practice on Monitoring Electric Power Quality.