EPRI SOLUTIONS

Conducting a Power Quality Audit

Chapter 3

CONTENTS

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The first stage in most power quality-related sagas is usually the occurrence of one or more PQ events that result in downtime, scrap, and lost production. The second stage in this scenario should be a PQ audit—a process by which the sensitive portions of an end-use facility are identified, the PQ phenomena characterized, and, hopefully, the ideal and most cost-effective methods for mitigation discovered. As such, a sound PQ audit strategy is perhaps the single best investment that a utility or end user can make on the PQ solution path.

The PQ audit is broken down into six steps, with detailed descriptions of how to complete each one. This overview of PQ auditing includes highlights of the two most common types of power quality audits: reactive and proactive. The former is conducted in response to equipment failure or damage caused by either a steady-state or momentary power disturbance, while the latter is intended to identify potential sources of power disturbances and eliminate them before they can become a nuisance.

About the EPRI Solutions Power Quality Knowledge-Based Services program

The EPRI Solutions Power Quality Knowledge-Based Services program provides a wealth of resources in well-designed, readable, and accessible formats. Paramount among these are documents covering a wide range of PQ topics, written not only for use by busy PQ professionals, but also to be shared with important end-use customers and internal utility management. The program's website, www.mypq.net, is the most comprehensive electronic PQ resource available, providing 24-7 access to proven expertise via the PQ Hotline, hundreds of PQ case studies, over 200 PQ technical documents, PQ standards references, indexes, conference presentations, and a wealth of other resources.

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INTRODUCTION

Although the vast majority of electric power is reliable and of excellent quality, dealing with the inevitable vagaries of electric power supply is part and parcel of operating a modern business. Savvy electric power end users usually try to take into account power disturbances and the electrical environments in which their equipment is intended to operate when building new plant or installing new equipment. However, predicting and anticipating all possible PQ phenomena is not possible. Because end-use equipment is expected to have electric power supplied within a somewhat narrow range of voltages, most equipment manufacturers do not offer troubleshooting scenarios for equipment affected by power disturbances beyond the common "±10% of nominal voltage" operating range.

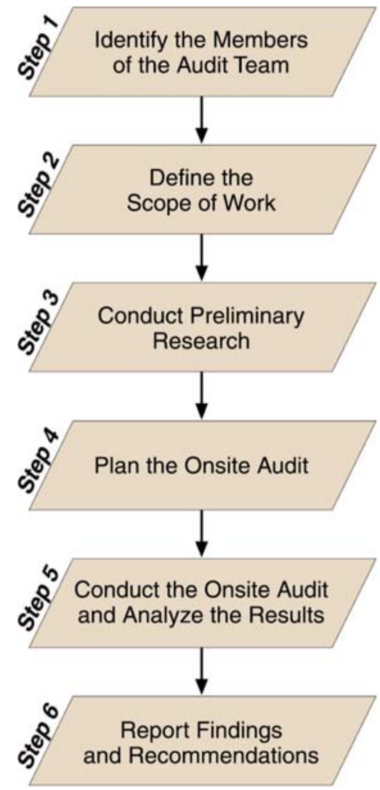
Troubleshooting equipment problems resulting from PQ phenomena is a common task for companies that rely on business or process machines for their livelihood. When power disturbances cause unplanned downtime or premature equipment failure, a unique set of skills is required to determine the root cause and to recommend solutions to prevent further shutdowns. This chapter provides basic PQ auditing and troubleshooting techniques that can significantly help end users identify, isolate, and mitigate troublesome power disturbances.

The Six Basic Steps for Executing a PQ Audit

The six basic steps for troubleshooting power disturbances are shown in the figure at top right.

This chapter examines each of these steps in turn, providing the motivated end user or PQ professional with all the tools necessary to conduct a successful PQ audit.

Six Steps for a Successful Power Quality Audit



STEP 1—IDENTIFY THE MEMBERS OF THE AUDIT TEAM

Selecting the members of the audit team is the first and most important step of a successful PQ audit. To be effective, both in the investigation and analysis phases, the PQ audit team should be composed of personnel representing *all* groups directly responsible for or involved with the operating and maintenance of the end-use equipment. Doing so ensures that the PQ audit team has access to all pertinent information. Perhaps even more importantly, it greatly enhances the feeling of ownership and enthusiasm for going forward with the audit's eventual results and recommendations.

Some likely members of a successful PQ audit team include a site or process line manager, an equipment operator, an equipment maintenance technician, a utility technical representative, a lead PQ auditor, and the original equipment manufacturer.

Assembling the Right Team is Essential for a Successful PQ Audit

Having the right personnel on a PQ Audit team is the first step to a successful audit.

Site or Process Line Manager

The site or process line manager should serve both as a member of the audit team and as the primary point of liaison between the team and the rest of the organization. This person will be the formal recipient of the team's findings. As liaison, the site manager is responsible for coordinating the transfer of equipment and site data to the audit team and is also responsible for scheduling, allocating resources for the audit, and formalities such as obtaining permission for access to sensitive areas and operations and maintenance (O&M) personnel. Finally, it is the responsibility of the site manager to closely define the scope of the PQ audit—for example, what equipment is and is not included, etc. (see figure).

The person first aware of equipment malfunction is most often the operator of that equipment.

Understanding the Process

Knowledge of the process is vital for the PQ Audit team. Representatives from management, operations, and maintenance are critical to bring a full understanding of how the process functions (or is intended to function) to the audit.

Equipment Operator

The person first aware of equipment malfunction is most often the operator of that equipment. As such, the equipment operator possesses information vital in troubleshooting PQ problems and is an essential member of the investigative team.

Equipment Maintenance Technician

In most cases, next in the communication chain is the technician responsible for maintenance and repair of the misoperating piece of equipment. Although not every hiccup in operations is necessarily immediately reported to technical personnel, it is likely that persistent and costly interruptions eventually will be. The frequency of shutdowns is recorded at the operation level, thereby spawning an audit. To ensure that good quality information is available to the audit team—and that root causes of problems can be more directly identified—it is imperative that the maintenance technician be part of the audit team.

It is also desirable that the lead auditor have no vested interest in any particular PQ mitigation technology or specific proprietary technique.

Utility Technical Representative

A thorough PQ audit should, naturally, include an analysis of the power-delivery system, both inside and outside the facility that is experiencing power disturbances. A utility technical representative can provide important information about the configuration of the electrical supply system and operational details such as capacitor switching practices, recloser operation, etc. The utility representative also likely has access to additional sources of information. If there is insufficient PQ monitoring capability at or inside a facility, the utility might be able to provide data gathered from a nearby power quality monitor or other pertinent information such as circuit recloser operations, which could then be correlated with equipment malfunctions.

Lead PQ Auditor

Each PQ audit will have a lead PQ auditor who is responsible for managing and organizing the audit team, analyzing data, identifying the root causes of power quality problems, and ultimately recommending solutions. A good set of qualifications for a lead auditor include the following:

- Experienced in solving a variety of PQ problems
- Knowledgeable in electric power transmission and distribution configuration and operation
- Familiar with most reliability and PQ standards
- Good at maintaining access to other experts for consulting and advice
- Familiar with the operation, capabilities, and limitations of a wide range of power quality measurement devices such as voltmeters, harmonic analyzers, waveform generators, spectrum analyzers, and voltage-sag simulators

In addition, it is also desirable that the lead auditor have no vested interest in any particular PQ mitigation technology or specific proprietary technique.

Original Equipment Manufacturer

An optional but often useful addition to the PQ audit team is the manufacturer of the misoperating equipment, particularly if the piece of equipment is sophisticated (see figure below). Depending on the date of installation and service agreement purchased by the equipment owner, the original equipment manufacturer (OEM) may or may not be able to be consulted regarding problems with the equipment. Whenever possible, the OEM should be contacted as a resource for the audit team. If a PQ audit recommends changes to a piece of equipment (including firmware or software changes), in some cases these must be approved or even performed by the OEM. If circumstances are such that the OEM can be included in the PQ audit, the OEM may be more receptive to supplying useful information and providing approval (should such be necessary) for implementation of any changes necessary to improve the performance of OEM equipment in the face of PQ phenomena.

An OEM Representative May be Required for Particularly Sophisticated End-Use Equipment

The owner, auditors, and utility define the method of investigation, and all parties work together to schedule all the tasks.

STEP 2—DEFINE THE SCOPE OF WORK

The objective of a PQ audit is defined by the equipment owner. However, all members of the audit team should contribute to the development of the statement of work (SOW). The owner, auditors, and utility define the method of investigation, and all parties work together to schedule all the tasks. The document that declares the scope of work should include the following sections:

- ***Background.*** This is a brief description of the problems with the equipment and the objective of the audit.
- ***Project description.*** This section should include a list of the equipment included in the PQ audit, and more details about the project objective. Limits should be defined in this section. Is the focus of the audit restricted to only the affected equipment? Or does the audit include the entire facility and utility power-distribution system?
- ***Method of investigation.*** The method of investigation should be explained, including a list of power quality equipment required by the audit, such as voltmeters, spectrum analyzers, ground testers, or voltage-sag generators.
- ***Schedule.*** All important milestones should be included in this section, such as submission of electrical drawings, utility drawings, and PQ data; onsite visits; preliminary findings; and final report.
- ***Deliverables.*** Deliverables are based on the objective of the audit. If the equipment owner is looking for the root cause and a recommendation for mitigation solutions, a final report could be the deliverable. If the objective is to mitigate the power disturbances on the utility side of the meter, this could be beyond the scope of the present audit and require a proposal of further work. Another deliverable might be an evaluation of how the recommendations were implemented after the audit was performed.

STEP 3—CONDUCT PRELIMINARY RESEARCH

Preliminary research is performed to effectively target the onsite audit. Information gathered in this step is designed to transfer pertinent data to the auditors so that either the root causes of equipment problems can be identified or the efforts of the auditors can be focused in the right directions. The auditors should gather drawings that will be required for the audit and conduct research, such as reviewing standards and research reports. Millions of dollars have been spent researching the effects of power disturbances on all types of business, commercial, and manufacturing equipment. The research findings can be found in studies, papers, and books available through the Institute of Electrical and Electronics Engineers (IEEE) and EPRI.[1]

Equipment Selection

The success of a PQ audit depends in part on the identification of all of the owner's equipment that is experiencing malfunctions, shutdowns, or even damage. If the audit is initiated because of ongoing equipment malfunctions, shutdowns, or damage, the audit is called a *reactive power quality audit*. On the other hand, if the objective is to prevent future problems, it is called a *preventative power quality audit*. In either case, the list of the affected equipment must be complete. If the affected equipment is part of a manufacturing process, it may be interlocked with facility support equipment —such as air compressors, chillers, and hydraulic pumps—or other process equipment. In this case, all interlocked equipment must be considered with the same emphasis as the primary equipment. Each piece of equipment involved in the PQ audit is detailed in an equipment audit sheet, such as the one shown in the figure below. The audit sheets are used for reference.

Equipment Audit Sheet

Manufacturer: ____________________
Type of equipment: ____________________
Model: ____________________
S/N: ____________________
Date of Mfg: ____________________
Rated Voltage: ____________________
Rated Current: ____________________
Short Circuit Current: ____________________
Control Circuit Rated Voltage: ____________________
Control Circuit Rated Current: ____________________
Facility Support Subsystem(s): ____________________
Interlocked WITH (Equipment Name): ____________________
Interlocked TO (Equipment Name): ____________________

Each piece of equipment involved in the PQ audit should be detailed in an equipment audit sheet.

The primary voltage level of a facility can help the auditors determine what kinds of power disturbances are affecting the facility equipment.

Preliminary Questions

Finally, the auditors should craft a list of questions designed to better understand the equipment and the electrical environment (see Appendix). Examples of questions pertinent to preliminary research are shown below. After the list of questions has been answered and drawings analyzed, the probable causes of equipment problems should be determined by the auditors. This determination should be achieved by the entire audit team based on the experience of each team member, case studies, and preliminary research.

What Is the Category of the Facility in Which the Affected Equipment Operates?

Is the audit site a residential, commercial, or industrial facility? The complexity of the audit typically depends on the type of facility in which the audit will be performed. Each type of facility has its own set of typical loads. For example, in a residential facility, one is likely to find appliances, TVs, stereos, and DVD players. Industrial sites contain more complex loads, such as chillers, extruders, centrifuges, ion implanters, and process controllers. A typical commercial facility has computers, copiers, routers, and uninterruptible power supplies (UPSs).

Does the Facility or Utility Monitor Power Disturbances?

If monitor data and equipment shutdown logs are available to the auditors, the root cause of equipment problems can be identified by correlating equipment logs with recorded power disturbances.

Does the Utility Have a Record of Relay or Reclosure Operations?

If these records are available, it is often possible to correlate an equipment problem to the operation of a utility protective device. If the protective device is on an adjacent circuit or the subtransmission system, then the cause of the equipment problem is likely voltage sags.

What Is the Facility's Voltage Level (Transmission/Distribution)?

The primary voltage level of a facility can help the auditors determine what kinds of power disturbances are affecting the facility equipment. For example, voltage sags are more prevalent at the distribution level than at the transmission level. Plus, a transmission-powered facility will typically be a very large manufacturing facility.

What Equipment Will Be Included in the Audit?

A list of equipment included in the audit will help the auditors with project organization. The equipment list can also be used to determine whether any of the auditors have investigated the same or similar equipment in previous audits. One advantage of selecting a power quality consultant who has performed many PQ audits is that knowledge gained from previous audits and testing are available for reference.

What Are the Equipment Specifications, and Are Schematics Available?

The auditors should request all relevant drawings prior to the onsite visit. Types of drawings needed for analysis include:

- ***Equipment specifications.*** The electrical and performance specifications are helpful in determining the OEM's intended use and design specifications.
- ***Equipment power and control (single-line drawings, if available).*** The auditors should use these drawings to identify potential sources of disturbances (unfiltered adjustable-speed drives [ASDs], power supplies, relays, and so on) and components that are sensitive to voltage sag (see figure at top right).
- ***Facility single-line drawings.*** Facility single-line drawings should be used to determine how loads are powered and distributed throughout the facility. Facility single-line drawings are necessary for wiring and grounding investigations.
- ***Utility single-line drawings.*** During the onsite audit, the auditors may perform an inspection of the distribution feeders, equipment, and substations. If so, the utility single-line drawings should be used to plan onsite monitoring, plan the testing, and select measurement points.

Ice Cube Relays–Often a Sensitive Component

The simple ice cube electrical relay is ubiquitous in industrial controls. Unfortunately, it is also a common culprit in facility shutdowns due to mild voltage sags. Knowing where these devices are located in a plant is essential information for a PQ audit.

How Is the Equipment Affected?

This is a very important question to ask, because the answer could point the auditor in the right direction. For example, if ground fault circuit interrupter (GFCI) circuit breakers trip when certain processes are running, attention should be focused on identifying nonlinear loads, the source of harmonics that produce leakage current on grounds. Sometimes this question can only be answered by an equipment operator or technician during the onsite audit. Is the equipment damaged? If equipment damage is caused during an electrical disturbance, the auditor should focus attention on sources of overvoltages or transients. Do other machines shut down at the same time or in the same manner?

If many or all machines are affected at the same time, the auditors should investigate all systems common to all affected machines. A momentary interruption could cause all or most equipment to shut down. If only a few are affected, voltage sags could be the cause. If only one machine is affected, the auditors should look for harmonics or wiring and

A momentary interruption could cause all or most equipment to shut down.

grounding problems. If all affected equipment are interlocked together, fed by the same transformer, or rely on facility systems like compressed air or cooling water, the cause may not be apparent.

Can the Shutdowns Be Associated with Any Other Event?

The answer to this question alone can save many hours investigating the type and source of the power disturbance. For example, when asked this question, an operator might state that sometimes the lights blink when a machine shuts down, while at other times the machine's emergency machine off (EMO) circuit trips but the lights do not noticeably blink. This type of information should direct the auditors toward voltage sags and sag-sensitive components in the equipment's EMO circuit for all affected equipment. Example questions to ask include:

- Did the lights blink?
- Can equipment problems be correlated with the time of day, weather, or season of the year?
- Can equipment problems be correlated with the startup or shutdown of other loads in the facility (such as large motors)?
- Are the problems random or predictable?

Is This a New Problem?

If the experienced problem is new, then the auditors should focus on recent changes, such as the addition of loads or changes to the power-distribution network. The auditors should discuss changes to and configurations of the power system with the local utility. If the utility is not part of the audit team, then the equipment owner is responsible for establishing a utility contact for the auditors. Changes that could affect the quality of power include:

- Changes in the facility, such as new processes or loads. If nonlinear loads such as power supplies or ASDs have been added, the total harmonic distortion may have increased beyond a safe level.
- Changes to the utility power system. Has the utility added new loads on the feeder that powers the facility under investigation?
- Changes in power factor–correction capacitors or load-switching operations. Oscillatory transients created by switching loads or power factor–correction capacitors can cause loads with silicon-controlled rectifiers (SCRs) on their front ends to trip (such as ASDs).

Does the Equipment Require a Program Upload After the Event Occurs?

The programs that run process machines reside in the volatile memory of many process controllers, such as programmable logic controllers (PLCs). Batteries are installed to maintain the program in the event of a power failure. If the batteries are not functioning correctly, the program may be lost during a voltage sag or interruption. Batteries should be replaced as soon as this condition is recognized. Notify the equipment owner immediately regarding this finding. Do not wait until the final report is completed.

What Is the Most Important Aspect of the Shutdown: Product Quality or Production Delay?

This information is critical in determining recommendations for installing mitigation devices. If the equipment owner wants to reduce the long delay time caused by a shutdown, an effective low-cost, control-level

A plan of action should define the schedule, personnel, types and locations for measurements, test equipment, and data-collection equipment.

solution should be recommended. However, if the owner's objective is to prevent both production delays and reduced product quality, then all control and power components must be protected.

What Are the Average Process Delay (Restart Time) and Costs Associated with the Unplanned Shutdown?

The equipment owner may not want to share this type of confidential information with the audit team. However, if such information is available, the auditors should use it to determine recommendations for mitigation solutions. For example, take a manufacturer that experiences five unscheduled shutdowns per year at $2,000 per hour of loss, with an average delay of two hours. This manufacturer would not purchase a $50,000 or $100,000 power conditioner to eliminate the delays. In this case, the auditors should try to identify the most cost-effective solution with a low capital expenditure.

If This Problem Has Been Investigated Before, What Were the Findings?

If this issue has been evaluated before, any findings and reports should be shared with the auditors. If the auditors determine that the present problems and previous problems are the same, the efficacy of the recommendations made in the first report should be investigated. The auditors may determine that the mitigation device installed was different from the one recommended or that the characteristic of the actual power disturbance is different or more severe than first estimated.

STEP 4—PLAN THE ONSITE AUDIT

The next major step is an onsite audit to verify the theory of equipment problems and gather information not obtained during preliminary research. Time onsite is valuable to all parties; therefore, a plan must be developed to organize that time. A plan of action should define the schedule, personnel, types and locations for measurements, test equipment, and data-collection equipment. It is likely that more employees at the equipment owner's facility will be involved in the onsite audit than were contacted for the preliminary research. For the benefit of audit participants who were not involved in the preliminary research, the plan of action should include a summary of the scope of work. Sections of the plan of action should include:

- Summary of the scope of work
- Preliminary findings
- Audit participants
- Onsite audit schedule
- All collected data
- Test plan (if necessary for analysis)
- Audit worksheets

Because some of the auditors will have unique skills and equipment, at times, the utility or facility will take advantage of the opportunity for training. This is why a plan of action should be a working document that requires approval from all participants.

Power Quality Instruments

The type of measurements and power quality equipment vary from site to site. However, a typical audit will require a standard set of instruments, tools, safety apparel, and other implements. It is imperative that the PQ auditors have a reliable plan for gathering and recording onsite data. Analysis of onsite data is performed after the audit is complete; therefore, the methods used to gather onsite information will ultimately determine the success of the audit. Examples of data-gathering equipment are:

- Digital voice recorder
- Digital camera

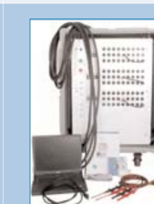
- Multimeter
- Harmonic analyzer
- Flashlight
- Business cards for distribution to equipment operators, engineers, and managers
- Safety apparel (NFPA 70E-1995[2] and OSHA[3])

Some of these examples are shown in the figure below.

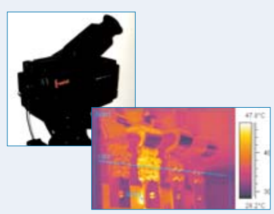
Typical Equipment Used by a Power Quality Auditor

Depending on the probable power quality disturbances causing equipment problems, measurements will need to be taken to classify the disturbances (see IEEE Standard 1159-1995) and identify their sources. The type of suspected disturbances and audit determine the types of instruments and clothing that the auditors will require (see Table).

Typical Power Quality Audit Instruments

Type of Instrument/ Apparel	Use	Example
Safety gloves	Safety gloves are required when accessing low-voltage cabinets (NFPA 70).	
Flashlight	One of the most important tools of an audit.	
Digital voice recorder	Necessary to use onsite to record information like measurements and notes from operators, meetings, and equipment specifications.	
Voltage sag generator	The voltage sag generator is used to simulate voltage sags to characterize equipment sensitivity.	 EPRI Solutions PortaSag
Voltage sag meter	Measures and records voltage disturbances such as voltage sags.	 SoftSwitching Technologies I-Sense
Power quality monitor (analyzer)	Monitors and analyzes power	 Dranetz BMI  HIOKE 3196

Typical Power Quality Audit Instruments (continued)

Type of Instrument/Apparel	Use	Example
Three- and four-point ground tester	Takes three-point measurements of resistance to ground of ground rods and grids. Three-point measurements are generally used when the electrode or grid can be easily disconnected, if corrosion is suspected, or in circumstances where ground faults are unlikely to occur.	 AEMC Instruments Model 4630
High potential (hi-pot) or insulation tester	Used for testing motors, transformers, electrical wiring, and cable insulation for damage.	 B+K Precision Model 308
Power frequency survey meter	Measures 30-2,000 Hz magnetic fields: 0.2 mG to 20 G (20 nT to 2 mT); Electric fields: 1 V/m - 200 kV/m.	 Holaday Instruments HI-3604 ELF
Circuit analyzer	Measures ground impedance, neutral impedance, and ground-to-neutral voltage false grounds.	 SureTest Model ST-1D
Infrared camera/ thermal imaging system	Used to inspect wiring and equipment. Example to the right shows bus bar straps where phase B is warmer at the joint than the joints at phases A and C and neutral.	
AC current probe	Measures current in a range from 100 mA to 2,000 A (AC).	 AEMC SR 661
Harmonic analyzer and current probe	Measures harmonics, power, waveforms, power factor, and frequency.	 Fluke 41B
Oscilloscope	Captures transient data to 10 MS/s resolution and analyzes waveforms.	 Nicolet Odyssey XE or Tektronix THS720P

STEP 5—CONDUCT THE ONSITE AUDIT AND ANALYZE THE RESULTS

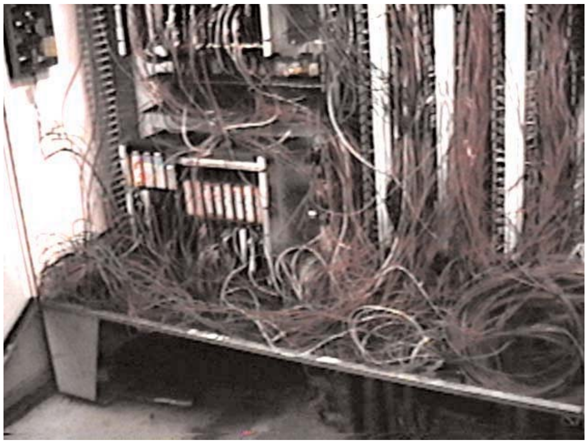
The onsite audit is the most important step in the audit process. The onsite audit gives the auditors the opportunity to learn more about the application and use of the affected equipment, wiring and grounding conditions and practices, maintenance and operational procedures related to equipment shutdowns, and configurations of power systems (utility, facility, and equipment). During the audit, investigators are able to check theories about equipment problems born during the preliminary research.

An onsite audit focuses on both general and specific investigations. General investigations typically include inspection of wiring, grounding, and the electric utility's power-delivery system related to the facility. Other onsite investigations depend on the specific PQ disturbance identified in preliminary research. This section explains tasks performed during general investigations and describes the most common power disturbances that cause equipment malfunctions, shutdowns, or damage.

Wiring and Grounding Investigation

The characteristics of equipment in a facility electrical system are never *completely* understood during the design process—the equipment's response to static and dynamic changes in voltage at the input terminals is almost never considered. In addition, stresses occur due to everyday operations and maintenance plus upgrades that result in changes in both the load profile and power distribution. Design miscalculations, stress, age, and any equipment modifications may result in poorly grounded equipment, loose connections, premature equipment malfunctions, equipment shutdowns, or equipment damage (see figure on the following page).

Panel Wiring can be Source of PQ Problems



The wiring in control panels is usually orderly and even labeled once a process line is first completed. However, subsequent modifications or troubleshooting can result in what is commonly referred to as a "Spaghetti Panel." Loose connections, short circuits, and other problems can be extremely difficult to find in such a setting.

In EPRI Solutions' experience with over 600 site investigations, the root cause of approximately 90% of all power quality problems in a typical facility are caused by wiring and grounding errors within the facility's electrical system. Examples of equipment responses to wiring and grounding problems are listed in the following table.

Equipment Response to Wiring and Grounding Errors

Equipment Response	Possible Causes
Damaged equipment	Loose, inadequate, or multiple ground system.
Loss of data	Loose or elevated ground.
Nuisance tripping of circuit breakers with GFCI protection	Neutral or ground current caused by inductive/capacitive (LC) filters and nonlinear loads.
Fire or electronics damage	Shielded communication cable grounded at one end (see National Electrical Code [NEC], Article 250).[4]
Damaged modems, telephones	The absence or ineffective bonds between communication and building ground electrodes not only could cause damaged equipment in the event of transients but also could cause a fire.
Abnormal operating temperatures	Loose cable connections, excess current on neutral caused by nonlinear loads, or harmonics.

Wiring and grounding investigations are targeted at identifying any design or installation issues that either caused or have the potential to cause PQ disturbances if left unchanged. A wiring and grounding investigation consists of visual inspections and measurements of phase, neutral, and ground conductors starting at the affected equipment and going to the service entrance. A single-line power-distribution drawing for the facility is required for this investigation. The following are example inspections and measurements included in a wiring and grounding investigation:

- Check for one common grounding electrode. All enclosures and equipment within a building should be bonded to a common grounding electrode. See NEC, Article 250-54.
- Check for proper ground bonding. Are all elements of the grounding electrode system bonded, such as water pipe, building steel, and ground ring? See NEC, Article 250-81.
- Is the resistance of the grounding electrode more than 25 ohms? If so, it should be augmented by one additional electrode. See NEC, Article 250-84.
- The conductor used to connect the grounding electrode system to equipment grounding conductors and the grounded conductor at the service entrance and at any separately derived source should be sized per NEC, Article 250-94.
- Verify that the grounding path complies with NEC, Article 250-51.
- Are all metallic enclosures (conduits, raceways, and panel boards) bonded? See NEC, Article 250-71.
- Is there a neutral-to-ground (N-G) bond at the main service per NEC, Article 250-23?

The goal of a voltage-sag investigation of the power system is to identify opportunities to reduce faults.

- Are there N-G bonds on every separately derived power source? See NEC, Article 250-26. If this bond is not present, an unsafe condition could exist, and equipment could malfunction.
- Check the wiring in isolated ground receptacles. All metallic enclosures should be bonded to the grounding electrode.
- Check the root mean squared (RMS) voltage levels.
- Check for ground loops and apply protection to data and communication lines if a ground-loop potential exists.
- Check for overloaded neutral conductors.
- Check for extra N-G bonds. The neutral should not be bonded to ground at any other location. See NEC, Article 250-26.
- Check the condition of wires, looking especially for insulation breakdown.
- Check the tightness of connections.
- Check the types of terminations to make sure they are appropriate for their applications.
- Check overall load and circuit configurations. Look for unbalanced voltage and current.
- Check the distribution of single- and two-phase loads that could cause imbalance.
- Check for continuity of conduit and enclosure grounds.
- Check for appropriate transformer sizing.
- Check for ground bonds on both ends of shielded communication lines. If only one end is bonded, a hazardous condition could exist.

Useful wiring and grounding references can also be found from IEEE and EPRI.[5]

Voltage Sag and Interruption Investigation

A voltage sag is defined as a reduction of the rated RMS voltage at power frequency for durations from a half cycle to a few seconds. Voltage sags are caused by faults on the power-delivery system, both inside and outside a facility. Sags can also be a result of load changes, such as a large motor starting. Voltage sags are unpredictable, can happen any time of the day or year, and can be quite expensive to eliminate. This is why voltage sags are the most costly power disturbance known to manufacturers.

The impact of voltage sags on equipment depends on the characteristics of the sag coupled with the sensitivity of the equipment. The goal of a voltage-sag PQ audit is to try to reduce the number of sags by investigating the power-delivery system of the local utility and by decreasing the sag sensitivity of equipment through a voltage-sag investigation of the equipment or testing of the equipment.

Electric Utility Power Delivery System Study

Because voltage sags are often caused by faults on the electric power delivery system, reducing the number of faults would also reduce the number of voltage sags. Faults on a power system could be caused by storms (such as lightning and trees contacting lines), animals (such as birds and snakes contacting transformer terminals), broken insulators, and human errors (such as car crashes and digging into underground conductors).

The goal of a voltage-sag investigation of the power system is to identify opportunities to reduce faults. Economically, faults cannot be totally eliminated; however, they can be reduced through design and maintenance procedures. A visual inspection of the power system should be performed by the auditors, including a representative of the local electric utility, to identify opportunities to reduce the number of sags. Forms for recording information during such an investigation are shown below.

PQ Audit Form: Configuration Parameters of the Electric Utility Power-Delivery System

Facility voltage level	______ V
Substation name	______
Substation and/or distribution transformer size	______ MVA
Substation loading and configuration (single mainline, expressed feeder, branched mainline, or very branched)	______
Number of feeders on substation bus	______
Facility feeder name	______
Distribution transformer size	______ MVA
Distance from substation to facility distribution transformer	______ miles

PQ Audit Form: Targeted Areas for Fault Reduction

Equipment	Are fast relaying techniques used to reduce the duration of voltage sags?	______
	Is the voltage regulated? If so, what method of voltage regulation is used?	______
	What is the condition of overhead structures?	______
	Are bus ties present? If so, what is the method of operation?	______
	Check age and operation of equipment. Outdated or poorly performing hardware should be replaced.	______
	Visually inspect insulators for breakage, excessive dust, and arc marks.arc marks. name	______
	Use radio frequency to check for failing splices, connections, and insulators.marks.	______
	Are grounds placed away from phase conductors?	______
Tree Faults	What is the estimated tree density of the area?	______
	If the electric service to the facility is overhead, what is the distance from substation to facility?	______
	Are tree-wire insulated conductors used?	______
	Is there any damage to the conductor insulation?	______
	Inspect for preventable faults caused by tree contact. Are trees or branches near or touching distribution lines?	______
	What is the frequency of the utility's tree-trimming maintenance cycle?	______
Lightning Faults	Are arresters installed?	______
	Arresters should be located on every sixth structure or every ¼ mile.	______
	Arresters should be installed on every equipment pole and on both the line and load sides of each equipment switch.	______
	Is the equipment old, such as expulsion arresters?	______
	Are riser brackets grounded or ungrounded?	______
	Are equipment tanks grounded properly?	______
	Are current-limiting fuses used properly?	______
	Look for old or burned arresters.	______
	Are shield wires used on transmission and/or distribution structures?	______
Faults Caused by Animals	Are animal guards on every arrester?	______
	Are jumpers and grounds covered?	______
	Are bushings, arresters, or cable terminations unprotected against animals?	______
	Are polymer arresters covered?	______
	Are there ground leads or grounded guys near phase conductors?	______
	Look for poor clearances with polymer arresters.	______
	Are guy wires insulated properly?	______
	Do jumpers have proper clearance?	______

Test Equipment for Characterizing Voltage-Sag Sensitivity

The request for a voltage-sag investigation is often initiated by the equipment owner (residential, commercial, or industrial) because the equipment has a history of malfunctions or shutdowns related to voltage sags. The goal of the voltage-sag investigator is to identify a low-cost solution to decrease the number of shutdowns. Five proven tasks can be followed by an investigator to improve the equipment's tolerance.

Task 1: Characterize Equipment Sensitivity to Voltage Sags

To decrease the number of sag-related shutdowns, an investigator must know the actual sensitivity of the affected equipment. Equipment sensitivity can be determined one of three ways:

- **Voltage-sag testing.** Equipment tolerance can be characterized by exposing the equipment to voltage sags generated by a voltage-sag generator. A precise tolerance can be determined by injecting voltage sags with increasing depths and durations while measuring and recording the response of the tested equipment.
- **Voltage-sag correlation.** If accurate shutdown records and historical records of voltage sags are both available, a sag-tolerance curve can be estimated. The accuracy of the curve depends on the accuracy of the shutdown records and the point at which voltage sags were recorded (location of the power quality monitor). The closer the monitor is to the equipment, the more accurate the tolerance curve.
- **Estimation based on typical tolerance curves.** The tolerance curve can be estimated by identifying the affected equipment's most sag-sensitive components and using existing tolerance curves of similar components to generate a tolerance curve for the equipment. Although this type of curve will only be an estimate, it could be quite close to the actual tolerance of the affected equipment.

Task 2: Define Objective Tolerance Curve

What is the goal of the equipment owner? The equipment owner must decide how tolerant the affected equipment must be. For example, if ten shutdowns per year can be attributed to voltage sags, what is an acceptable number of shutdowns? Does the owner want to totally eliminate voltage sags to its facility, eliminate shutdowns for specific equipment only, or just reduce the number of shutdowns by 70% to 80%? Another option for the owner is to use an existing voltage-sag standard, such as SEMI F47-0200 or the ITIC (96) curve.[6]

It's imperative that the equipment owner know the costs associated with mitigating voltage sags before the objective is determined. The most cost effective method of mitigation is a small, dedicated device conditioning the power for only the sensitive system component. On the other hand, conditioning power for an entire facility or process line can be quite expensive. For example, a facility-level solution for a 1-MVA facility could cost $500,000 to $1,000,000. Applying a machine-level solution to eliminate sags on one 50-kVA three-phase machine could range from $25,000 to $50,000. If an investigator has the knowledge and experience to recommend a control-level solution, a 70% to 80% reduction of shutdowns could cost between $1,000 and $2,000.

Task 3: Test and/or Recommend Solution to Meet Objective

Based on the equipment owner's tolerance objective, the voltage-sag investigator can select a mitigation solution to meet the objective. In an effort to select the most efficient mitigation solution, power quality monitoring data is necessary. The term *efficient* here does not apply to the actual efficiency of the mitigation device but to the coverage area. For example, if the machine has 10 events that shut the machine down, but no events are less than 50% of nominal and none longer than 20 cycles, it's inefficient to purchase and install a power conditioner capable of protecting the machine against 2-second interruptions.

Task 4: Implement Recommended Solution

Depending on the project's deliverables, an investigator may be responsible for providing only general recommendations or details such as part number, cost, dimensions, and installation diagrams for the recommended mitigation device. Typically, the investigator does not provide a turnkey installation of recommendations. If the investigator supplied the recommended power conditioner, the choice could be biased towards the investigator's own equipment. As a service to the equipment owner, the investigator should be available to manage or help with the installation process, especially for recommendations at the control level.

Task 5: Verify the Effectiveness of the Recommended Solution

The effectiveness of a mitigation device can be measured by comparing equipment tolerance curves before and after recommendations are implemented. The same methods used in Task 1 to obtain the original tolerance curve can be used to measure the effectiveness of the recommendations. If the recommendation does not meet the objective, return to Task 3 and reevaluate mitigation solutions.

Harmonic Investigation

Harmonics are the third major cause of equipment shutdowns for commercial and industrial facilities. Harmonics are caused by all kinds of nonlinear loads, meaning that the current waveform is a different shape from the voltage waveform. Examples of nonlinear loads are devices with rectified front ends, such as DC power supplies and ASDs. Other sources of harmonics are devices that operate on ferromagnetic induction, such as magnetic lighting ballasts, solenoids, and transformers, in addition to loads that change impedance with increased voltage, such as constant-voltage transformers, high-pressure sodium lighting, and fluorescent lighting.

Power systems of large facilities with many different types of nonlinear loads can be a challenge to an investigator faced with identifying a single or a combination of harmonic sources contributing to a particular problem. The challenge comes not only from the amount of total harmonic distortion but also from interactions between harmonics with different frequencies that can magnify (resonate) or cancel one another. This is why a harmonic investigation requires a methodical approach. A reference for harmonic investigations is IEEE Standard 519-1992.[7] To help with the investigation, the table below lists characteristics that affect the frequency response of a power system.

Common harmonic investigation tasks, detailed below, include identifying all nonlinear loads, harmonic measurements, and existing harmonic-mitigation devices (such as filters and chokes), as well as reducing harmonics through filters and/or changes in reactance. The basic tool needed is a portable harmonic analyzer that can monitor and record harmonic voltages and currents. Voltage measurements can be made at capacitor control circuits or at metering points.

Characteristics That Affect the Frequency Response of a Power System

Characteristic	Effect on power system
Short-circuit capacity	Short-circuit capacity is an indication of the system impedance at the fundamental frequency. The higher the short-circuit capacity, the lower the voltage distortion than the same distorted current level on systems with lower short-circuit capacities.
Capacitor banks	Capacitor banks can contribute to series and parallel resonance that magnify harmonic levels.
Load characteristics	Resistive portions of a load can help dampen the effects of parallel resonant frequencies. Motor loads and other dynamic loads contribute to the short-circuit capacity.
Balanced and unbalanced systems	If phases of a three-phase power system balanced, it can be assumed that all frequencies are positive sequence. However, real-world systems are often unbalanced. The greater the unbalance, the larger the impact of positive and negative sequences.
Resonant conditions	When inductive and capacitive reactances are equal at a particular frequency, an amplified harmonic current can oscillate between a capacitor bank and system inductance source, causing large harmonic currents and, often, commensurate voltage distortion.
Normal flow of harmonic currents	Harmonic currents are drawn by nonlinear loads the lowest impedance power, typically the utility power system. Capacitors, often installed for power factor correction, are particularly prone to drawing high-frequency harmonics.
Frequency response of industrial systems	If the nonlinear load is close to the capacitive source, at resonant condition, voltage distortion can be severe.

Tasks for Identifying and Correcting Sources of Distortion and Resonance

Task 1: Load characteristics

- Identify all 500-kVA or higher ASDs, rectifiers, or induction furnaces.
- Identify power electronic devices, such as converters, DC drives, and AC drives.
- Identify arcing devices, such as arc furnaces, fluorescent lights, and metal halide lights.
- Identify ferromagnetic devices (transformers).
- Identify capacitor banks.
- Characterize lines and cables on the system.
- Identify all step-down and isolation transformers.

Task 2: Measurements

- To track down the source of harmonics, take measurements at successive points in the system, such as capacitor banks, all transformers, and branch circuits.
- If the problem is new, identify all changes in load configuration.
- If possible, capacitor banks should be turned off during measurements to prevent resonance from clouding the measurements.
- Harmonic problems come up when power-factor-correction capacitors are added. Consider tuned banks to avoid problems.
- Measure current RMS levels and distortion levels in all feeders to the above busses.

- Measure neutral current levels at the secondaries of wye-connected transformers.
- Use spectrum analyzers that compute harmonic power.
- Use testing equipment that generates harmonics with and without filters.
- Measure system short-circuit equivalent impedance.

Task 3: Examine Existing Filters

- Check for choke inductance built in or added to the front ends of ASDs.
- Identify all filter systems.
- To determine total harmonic levels for a facility, measurements should be taken at the point of common coupling.
- Perform the same measurements at all branch circuits.
- The best place to solve harmonic problems is at the source. Review equipment specifications and design.

Task 4: Analysis and Action

- If a feeder has one large distorting load, then that load could be the main source of all harmonic power on the feeder.
- When comparing bus harmonics, typically the circuit with the largest 5th harmonic component is the largest harmonic load.
- Control voltage distortion to less than 8% by controlling current harmonics and/or reducing system impedance.

Much research has been performed to investigate the maximum acceptable levels of harmonics of the electrical environment where the equipment is installed. Both the IEE and the International Electrotechnical Commission (IEC) have developed standards that define acceptable harmonic levels.[8] According to Table 3.2.1 in EPRI's *Power Quality Workbook for Utility and Industrial Applications*,[9] all individual voltage harmonic components should not exceed 3% of the fundamental and the total harmonic distortion (THD) level should not exceed 5%.

A common rule to achieve 5% THD is to keep nonlinear loads of a transformer at or below 30% of the total load. If THD is greater than 5% and nonlinear loads approach 50% of the total transformer load, power-factor-correction capacitors and filters tuned for frequencies between the 4th and 5th harmonic can reduce resonant conditions. A range of common filters to reduce harmonics are listed in the table below.

Example Harmonic Filters and Typical Application at the Branch Circuit or Equipment

Filter Type	Typical Applications
Series inductor	Switch-mode power supplies (SMPSs)
Boost converter power-factor correction	SMPSs
Parallel-connected resonant filter	SMPSs
Series-connected resonant filter	SMPSs
Neutral current filter	Load centers, SMPS
Zigzag filter	Loose cable connections, excess current on neutral caused by nonlinear loads, or harmonics.
Active filter	Pulse-width Modulated (PWM) Adjustable-speed Drives (ASD), SMPSs, Uninterruptible Power Supplies (UPS), and other storage systems.
Choke upstream of motor drives	ASDs
Passive three-phase filter upstream of motor drives	ASDs

The table below is designed to suggest possible causes for common problems but should not be relied on as solutions for specific problems.[10] All shutdowns should be investigative, using well-defined troubleshooting techniques.

Example Equipment Responses to Harmonic Conditions

Equipment Response	Possible Harmonic Cause	Investigative Solutions
ASD DC bus capacitor failure	Even harmonic voltage (2nd and 4th)	Apply even-order harmonic filter to harmonic source.
Generator control malfunction	Voltage distortion	Change sensitivity setting to a less sensitive switching setting.
UPS switching on without apparent cause and running batteries down	Voltage distortion	Change sensitivity setting of UPS.
Overheating of neutral conductor	Excessive currents on neutral conductors	Usually caused by odd triplen harmonics (3rd, 9th, 15th, etc.). See NEC, Article 310-15 B4c
Heating in three-phase, dry-type transformers	Excessive currents on neutral conductors	Excessive currents on neutral conductors. See NEC 310-15 B4c
Harmonic voltage-related heating in other equipment, such as motors	Excessive currents on neutral conductors	Excessive currents on neutral conductors. See NEC 310-15 B4c
Harmonic voltage stress on system capacitors and equipment capacitors	Excessive currents on neutral conductors	Excessive currents on neutral conductors. See NEC 310-15 B4c - Neutral Conductor and Note 1.
Resonance with power-factor-correction capacitors	Excessive currents on neutral conductors	Excessive currents on neutral conductors. See NEC 310-15 B4c - Neutral Conductor and Note 1.
Voltage distortion at the PCC	Excessive currents on neutral conductors	Excessive currents on neutral conductors. See NEC 310-15 B4c - Neutral Conductor and Note 1.
Motor overheating or premature failure	Caused by high-frequency harmonics that cause losses in copper windings or fifth-harmonic components causing a negative-sequenced magnetic field	Derate the motor or install filters at various locations.
Capacitor fuse blowing	Fifth or seventh harmonic resonant caused by numerically equal capacitive reactance and system inductive reactance	Check harmonic resonance whenever shunt capacitors are installed with ASDs or other harmonic-producing loads. Identify 1) new nonlinear loads and 2) changes in power-factor-correction capacitors.
Audible capacitor noise ("singing"), transformers, problem with neighboring communication circuits, excessive N-G voltages	Resonance condition due to shunt capacitors	Change capacitive reactance or inductive reactance.
Overheating of rotors or pulsating or reduced torque of rotors	Positive and negative harmonic sequences	Check motor type. A wound motor is most susceptible, followed by deep-bar squirrel cage, and then squirrel cage.
Capacitor increased heating and voltage stress, shortened capacitor life	Harmonics at high frequencies with large magnitudes	Look for components that produce high-frequency harmonics with large magnitudes.
Communication errors, signal interference introduced into logic or communication circuits	Voltage notching	Voltage notching is caused when current is commutated in rectifiers.

If harmonic current is greater than 1.73 times the balanced phase current, potential exists for overheating of conductors. Recommended corrective actions are doubling the size of the neutral conductor, installing a third-harmonic filter at each load, installing a zigzag transformer close to loads, installing a series-blocking filter in the neutral conductor, or installing an active filter. The table below is a simple worksheet for recording harmonic measurements.

Harmonic Measurements Worksheet to Document a Circuit's Current Spectrum

Order	1st	3rd	5th	7th	9th	11th	13th
Frequency (Hz)	60	180	300	420	540	660	780
Current (A)							

Transient Investigations

The immunity of end-use electrical equipment and electronic devices to voltage transients is vital to their reliability. Immunity varies with equipment design and the types and levels of protection implemented at the utility power system level, at the facility level, and at the point of use (or equipment-to-facility interface). The condition of the utility distribution system and the facility power system also impacts immunity. Systems, whether utility or facility, that have not been maintained will place the facility and its equipment at a higher exposure level to damage from transients.

Transients can be periodic or random electrical disturbances.

Sources of Transients and Related Phenomena

The duration of transients, also referred to as surges, is less than one-half the period of the normal mains voltage waveform. Transients can be periodic or random electrical disturbances. They can appear across any of the electrical conductors—lines, neutrals, and grounding. The characteristics of transients include amplitude, duration, and rate of change. Transients may cause equipment damage or operational upset. Voltage transients may also originate inside or outside a facility.

In low-voltage AC power circuits, surge voltages and surge currents originate from two major sources: lightning strikes and load switching. Interactions between such systems as the power system and a communication system can also produce transients in one of the systems.

- *Lightning surges.* A direct flash to the power system, to the structure of interest and nearby structures, or to the soil may result in lightning surges. Lightning flashes occurring in the distance can also induce voltage surges in the circuits of a facility.
- *Switching surges.* Intentional actions on the power system, such as load or capacitor switching, may result in surges. Switching surges can also be the result of unintentional events, such as power system faults and the subsequent by utility protective equipment like reclosers.
- *Multiple-system interaction overvoltages.* Overvoltages can occur between different systems during the flow of surge currents in one of the systems. In the context of power quality, these are limited to AC power systems; however, their occurrence can impact multi-port equipment connected to the mains. Therefore, knowledge of these events and how to mitigate them is important to equipment reliability.

For additional information on the sources of transients (surges), please see IEEE C62.41.1-2002.[11]

Causes of Equipment Failure

Possible causes of equipment failure due to transients are many. Transients that cause equipment failures may originate from inside or outside a facility. When it is suspected that transients may be causing failures, inspection of the damaged equipment may reveal what part of the equipment failed. This may lead one to determine how the transients entered the equipment—through the power port, network port, or perhaps a combination of both. Examples of equipment responses to transients are listed in the table below.

Responses of End-use Equipment to Voltage Transients and other PQ Phenomena

Equipment Response	Possible Causes
Damaged equipment: damage to the AC input circuitry and/or power-factor-correction circuitry in power supplies	Voltage transients occurring between line and neutral or between line and ground
Damaged equipment: damage to the AC input circuitry and/or electromagnetic interference (EMI) filters within power supplies	Voltage transients occurring between neutral and ground
Damaged equipment: damage to network or other communication ports	No ground reference equalization between power ground and communication ground; voltage transients occurring between the two grounds
Sporadic equipment operation	Voltage transients occurring between line and neutral, line and ground, or power and communication grounds
Loss of data	Voltage transients occurring between power ground and communication ground
Fire or smoke emitting from AC input circuitry	Maximum continuous operating voltage of surge protective device (such as a metal oxide varistor) exceeded by temporary overvoltage
Damaged equipment: failure of circuit cards (power or signal)	Component failure due to transients, but also overheating, corrosion, or electrical shorts resulting from buildup of dust, soot, or other foreign material on components and printed circuit boards.

The presence of wiring and grounding errors in a facility that is exposed to internally or externally generated transients will more than likely exacerbate the transients. The functionality of appropriately sized and well-coordinated surge-protective devices (SPDs) also depends on correct wiring and grounding practices. In an audit where transients are suspected as the cause of equipment failures, the wiring and grounding system should also be inspected for errors. The following are recommended visual inspections of equipment and facility infrastructure when transients and other types of overvoltages are suspected as the cause of equipment malfunction, shutdown, or damage.

- Inspect the front-end AC input circuitry of equipment for signs of overvoltages, tracking, and arcing.
- Inspect the power-factor-correction circuitry for signs of components affected by overvoltages (such as cracks, swelled cases, and burn marks).
- Inspect printed circuit boards for signs of breakdown of board materials and melted solder.
- Inspect metal oxide varistors (MOVs) for burn marks caused by overvoltages.
- Inspect the facility electrical system for wiring and grounding errors.
- Inspect service entrance, main switchgear, all subpanels, and all points-of-use interfaces for the presence of SPDs.
- Record the model, serial, and nameplate information for all SPDs.
- Check for contactor-controlled equipment (such as HVAC equipment, silicone-controlled rectifier-based heaters, and motor loads) circuited with non-contactor equipment that may be sensitive to transients.

- If the facility used lightning protection, inspect the lightning rods, inspect the conductors that lead from the rods to the down-conductors, and ensure that none of the down-conductors are routed close to other electrical equipment or conduits. The lighting-protection system should be grounded to the building ground system at only one point.
- Inspect the lead length of panel-mounted SPDs. The lead length should be no longer than 3 feet.
- Check for improperly bonded ground conductors inside switchgear and subpanels evidenced by the use of multiple ground bars or lugs mounted at different locations on inside metal surfaces.
- Check for single ground bars or lugs mounted on the inside of painted metal surfaces of panels. Proper mounting techniques include the removal of paint on metal surfaces before bars or lugs are mounted.
- Inspect for the use of SPD-based power strips with electronic equipment that uses network, telephone, or cable TV cables that are plugged directly into their respective ports. These applications should use SPD-based power strips that contain ground reference equalizers, evidenced by input and output network, telephone, and/or cable TV ports designed into the power strip.

If it is suspected that transients are impinging upon a facility or equipment at a rate great enough to warrant the installation of a power-line monitor, then install a monitor at the service entrance or at the offended load. One may base this rate upon the number of times that one or more pieces of equipment have failed. Ensure that the monitor of choice has the capability of recording transients, and monitor for at least seven days.

Surge-Protective Devices

Surge-protective devices should be applied from the service entrance all the way down to the point of use (where the equipment interfaces with the facility power system at the branch circuit level). SPDs act primarily on the amplitude of the transient voltage and are often applied to divert potentially damaging surges. Upsetting surges may require remedies other than the application of SPDs. An SPD may be installed at the service entrance, at the main switchgear, at the first subpanel, at the second subpanel, and finally at the point-of-use interface. SPDs at the service entrance may be meter-based or panel-mounted. SPDs at the main switchgear and at subpanels may be breaker-mounted (that is, consume the space for one or more breaker slots) or may be panel-mounted on the outside of the panel. In any installation, the lead length between the SPD and its connection to the facility power system should be as short as possible. If excessive lead length is identified, the SPD may need to be remounted to shorten its lead length. SPDs may also be installed only at the service entrance and the point-of-use interface with none at the switchgear or subpanel levels.

While many facilities use some type of SPD, most transient protection will not incorporate SPD coordination. Coordination of SPDs helps to ensure that each SPD installed from the service entrance to the point-of-use interface, absorbs some part of the surge energy. Some noncoordinated SPD installations end up allowing the last SPD near the load to absorb all of the surge energy while none of the upstream SPDs absorb any energy. This exposes other upstream parts of a facility electrical system to transients and places undue stress on the last SPD. In properly coordinated SPDs, the first SPD should absorb approximately 80% to 90% of the surge energy, while the remaining SPDs farther down the circuit divide the remaining

Even if SPDs are installed in a facility, equipment failures may be caused by the inability of one or more of the SPDs to mitigate the transients.

energy. The first SPD should also be sized to handle the majority of the energy.

Another important general applications rule for SPDs is the selection of the maximum continuous operating voltage (MCOV). For 120-volt systems, the MCOV for the first SPD should be about 175 volts, with a 150-volt rating for the remaining SPDs down the line. For 208- and 277-volt systems, the MCOV for all SPDs should be about 125% of the nominal operating voltage. Even if SPDs are installed in a facility, equipment failures may be caused by the inability of one or more of the SPDs to mitigate the transients. If no SPDs are installed and if the facility experiences equipment failures from transients, the appropriately sized SPDs should be installed.

If an SPD contains some type of indicator, such as an LED, indicating the status of the SPD or a counter that counts transients, one should not base the functionality of the SPD protection on the status of the indicator, nor should one assume that no transients have entered the facility, panel, or equipment if the counter reads zero. Tests at EPRI Solutions have indicated that indicators and counters on SPDs are not always reliable.

STEP 6—REPORT FINDINGS AND RECOMMENDATIONS

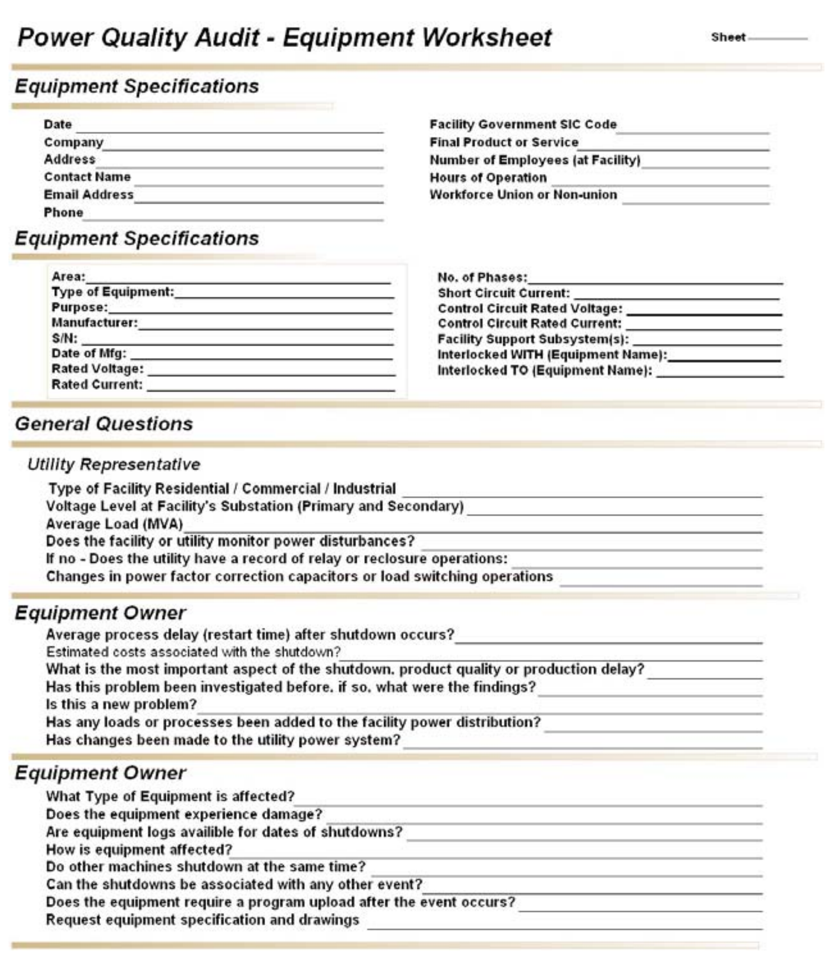
The final report resulting from a power quality audit conveys all findings and recommendations for the audit. The report might be formal, informal, printed, electronic, in the form of a presentation, or all of the above. The point of this section is to discuss how to present findings and recommendations to the equipment owner.

Actual contents of a final report are based on the audit's scope of work and deliverables, which vary from project to project. However, the basic structure of the report should be consistent. Sections of the final report should contain at least the following sections:

- **Executive summary.** The executive summary should include a brief summary of each section of the final report. The audience for the executive summary is someone who may not have the time read the entire report or may not have the technical background to appreciate the details.
- **Background (including summary of scope of work).** The background section should be a brief summary of the scope of work and plan of action developed in Step 3 of the audit process.
- **Findings and recommendations.** This is the main section of the final report. It should include test results, measurements, onsite findings, and recommendations for mitigation solutions. Recommended solutions should include enough detail to allow the equipment owner to purchase and install the recommended equipment. The estimated cost of the mitigation solution should also be included so that the equipment owner can perform a payback analysis to determine the recommendation's feasibility.

Appendix

The following is a typical PQ audit equipment worksheet used by EPRI Solutions to create an overall picture of the electrical environment and equipment loads.



Power Quality Audit - Equipment Worksheet Sheet ______

Equipment Specifications

Date ______
Company ______
Address ______
Contact Name ______
Email Address ______
Phone ______

Facility Government SIC Code ______
Final Product or Service ______
Number of Employees (at Facility) ______
Hours of Operation ______
Workforce Union or Non-union ______

Equipment Specifications

Area: ______
Type of Equipment: ______
Purpose: ______
Manufacturer: ______
S/N: ______
Date of Mfg: ______
Rated Voltage: ______
Rated Current: ______

No. of Phases: ______
Short Circuit Current: ______
Control Circuit Rated Voltage: ______
Control Circuit Rated Current: ______
Facility Support Subsystem(s): ______
Interlocked WITH (Equipment Name): ______
Interlocked TO (Equipment Name): ______

General Questions

Utility Representative

Type of Facility Residential / Commercial / Industrial ______
Voltage Level at Facility's Substation (Primary and Secondary) ______
Average Load (MVA) ______
Does the facility or utility monitor power disturbances? ______
If no - Does the utility have a record of relay or reclosure operations: ______
Changes in power factor correction capacitors or load switching operations ______

Equipment Owner

Average process delay (restart time) after shutdown occurs? ______
Estimated costs associated with the shutdown? ______
What is the most important aspect of the shutdown, product quality or production delay? ______
Has this problem been investigated before, if so, what were the findings? ______
Is this a new problem? ______
Has any loads or processes been added to the facility power distribution? ______
Has changes been made to the utility power system? ______

Equipment Owner

What Type of Equipment is affected? ______
Does the equipment experience damage? ______
Are equipment logs availible for dates of shutdowns? ______
How is equipment affected? ______
Do other machines shutdown at the same time? ______
Can the shutdowns be associated with any other event? ______
Does the equipment require a program upload after the event occurs? ______
Request equipment specification and drawings ______

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NOTES

1. Citations for standards and similar documents are provided in either the Reference Reading List or Notes sections at the end of this document.
2. NFPA 70E - 2000, “Standard for Electrical Safety Requirements for Employee Workplaces,” (February 11, 2000).
3. OSHA Standard 29 CFR, Part 1910, “Occupational Safety and Health Standards,” and Part 1926, “Safety and Health Regulations for Construction.”
4. NFPA 70, National Electrical Code (NEC) 2005 (Quincy, MA: National Fire Protection Association, 2005).
5. For example, IEEE Standard 1100-2004 and the EPRI report Capacity Planning, Power Quality, Reliability, and Availability for Internet Facilities, Volume 2.
6. The ITIC (96) curve was created by the Information Technology Industry Council and represents the power quality sensitivity of a broad range of industrial IT equipment. This curve can be used for gauging the susceptibility of loads to PQ events and the effectiveness of PQ solutions in protecting against deviations in supply. SEMI F47-0200, developed by Semiconductor Equipment and Materials International, expands upon the ITIC curve to give stricter requirements for electronic equipment used within the semiconductor industry.
7. IEEE Std. 519-1992, “IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems,” (January 4, 1993).
8. [7] and IEC 61000-3-6, “Electromagnetic Compatibility (EMC) - Part 3: Limits - Section 6: Assessment of emission limits for distorting loads in MV and HV power systems,” (1996).
9. Mark McGranaghan, “Power Quality Workbook for Utility and Industrial Applications,” (October 1995), EPRI, TR-105500.
10. Table developed by the authors with case studies and examples drawn from [7], [9], and the IEEE Emerald Book, “IEEE Standard 1100-1999: IEEE Recommended Practice for Powering and Grounding Electronic Equipment,” (1999).
11. IEEE Std C62.41.1 - 2002, “IEEE Guide on the Surge Environment in Low-Voltage (1000 V and Less) AC Power Circuits,” (November 11, 2002).

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