PQ TechWatch

A product of the EPRI Solutions Power Quality Knowledge-Based Services program

Minimizing PQ Costs
by Taking Ownership

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Contents

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EXECUTIVE SUMMARY

Ask the manager of virtually any modern manufacturing facility about costs and productivity, and they will likely respond with some form of "Cutting costs and improving economic performance are our highest priorities." As such, it would seem obvious that every available opportunity to improve economic performance would be exploited, and that any newly identified opportunity would be pursued eagerly and aggressively. However, in the area of electric power supply, opportunities for increasing productivity by improving power quality (PQ) are often given short shrift. The stories are almost legend about end-users presented with strong evidence that a "modest" investment of a few thousand US$ in PQ mitigation would yield productivity improvements an order-of-magnitude greater, but choosing to do nothing. What can explain this phenomenon? The reasons are complex, but perhaps the single most significant reason is that many end users do not feel a sense of "ownership" of electric power supply and, therefore, are reluctant to invest in its improvement. However, just as manufacturers will purify water, air, and other raw materials for sensitive, high-precision processes, so also can they benefit from "purifying" their electric power to maximize the performance of their processes.

This PQ TechWatch first presents a case for why electric power end users would greatly benefit from having a sense of ownership of their facility's PQ strategy. It then goes further by presenting a powerful 6-step approach to implementing this strategy. The results of over 600 EPRI Solutions facility PQ audits provide compelling evidence that rich rewards await those electric power end users that take ownership and implement this strategy.

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.

For more information, please visit www.mypq.net.

About EPRI Solutions

EPRI Solutions, Inc. provides a complete portfolio of engineering and technical services, management consulting, and information products—serving more than 100 major energy-industry companies in North America and around the world. EPRI Solutions is a wholly-owned subsidiary of the Electric Power Research Institute (EPRI). For more information about EPRI Solutions, please contact us at 865-218-8000 or visit www.eprisolutions.com.

Every non-reactive ampere that passes through the utility meter represents energy now owned by the end user.

INTRODUCTION

Because of global competition, every manufacturer seeking to compete internationally, must continually search for ways to lower operating costs. Whether a plant produces semiconductor chips, plastic components, automobile parts, food, or paper, the ongoing challenge is to lower the cost of production and improve operating margins. Naturally, any unplanned production downtime is counter to these goals by reducing output, and increasing scrap and labor costs.

To create a product, most manufacturers first procure the highest-quality raw materials they can afford, and then further refine those materials on-site to make them suitable for processing. A common example is water—most manufacturers who use water in their processes will start not with raw lake or river water but, rather, with treated municipal water. Often, however, municipal water isn't adequate as is, and is filtered, purified, sanitized, and even de-ionized depending on the final application. As such, while the input water may be of good quality, the manufacturer recognizes that further treatment will produce a better end product. Paradoxically, however, most manufacturers rarely extend this type of consideration to the raw electric supply purchased from the utility—a circumstance that can increase the cost of a product and reduce its quality.

In contrast, many industrial end users clearly understand the benefits of taking ownership in matters of energy efficiency. They employ energy-efficient lighting, motors, and drives, or take measures to stop compressed air leaks and so on. Yet, when it comes to consideration of the quality, not just the quantity of power consumed, many fail to take ownership.

This *PQ TechWatch* seeks to remedy this dichotomy by setting out a case for manufactures (as well as the utility and original equipment manufacturers) to take ownership of their electrical power quality by applying the same quality control concepts they would use for any other raw process input. The results of such a transformation are likely to include lower operating costs and improved uptime and profitability.

WHAT IS "PQ OWNERSHIP"?

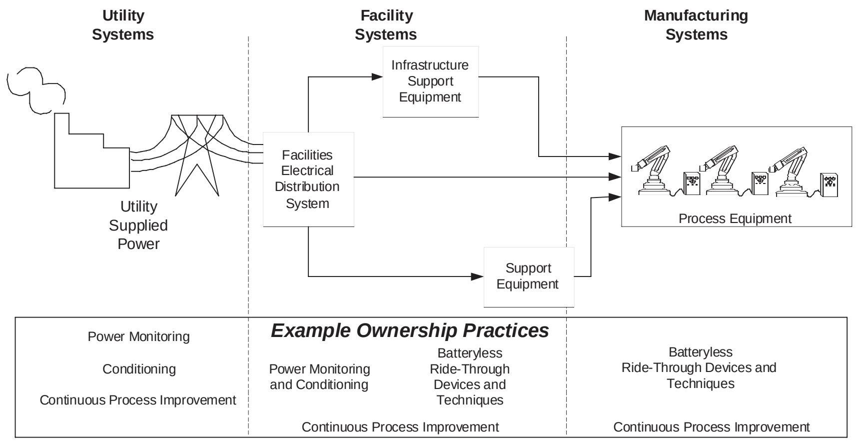
It's human nature—we take care of what we believe to be ours. Whether it's a home, a car, or a set of golf clubs, we coddle and maintain the things we own, more so than those we rent or borrow.

Unfortunately, many end users think of electric power as something they rent from the utility. In fact, every non-reactive ampere that passes through the utility meter represents energy now owned by the end user. Although the utility provides voltage, the amplitude and waveform of the electrical current is determined by the end use loads. How this power is conditioned, and consumed downstream of the meter becomes the end user's responsibility.

Taking ownership is best accomplished when the utility, the industrial end user, and original equipment manufacturers (OEM) all play a part. Real progress in taking ownership begins by avoiding the temptation to finger point. Instead, the electric power end user is best served by partnering with the utility and OEMs to understand why their process systems are sensitive to power quality phenomena, and to identify the most cost effective solutions. With a combined sense of responsibility for the outcome, everyone can benefit. Indeed, by cooperating, end users and OEMs can have a profound impact on how robust whole facilities and individual manufacturing systems can be in the face of power quality phenomena (see figure below).

Ownership of PQ at the Facility and Manufacturing Levels

Only the utility can tend to PQ issues at the "Utility Systems" level, which includes generation, transmission, and distribution. However, at the Facility and Manufacturing (or Process) levels, electric power end users have significant incentives to take ownership of power quality.

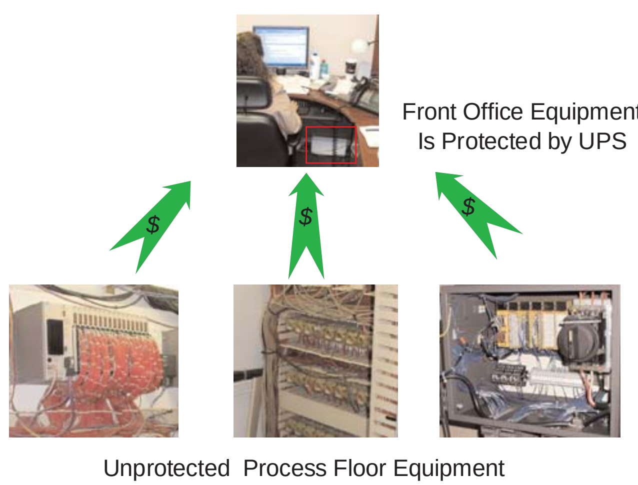


If an industrial end user asks the local electric utility to take special actions to improve power quality, the cost of these actions may be too much for the utility to bear alone. Furthermore, even if the utility improves PQ at the site, events such as voltage sags may still occur and affect processes (see sidebar, **Utility PQ Ownership**). For this reason, industrial end users often have ample incentive to make improvements on their side of the electrical meter to improve process performance. In most cases, the cost of improvements inside the industrial facility is only a fraction (10% to 20%) of the cost of utility-side solutions, and can be implemented much more quickly.

Most industrial plants consist of two distinct sections: the "front office" business operations and the production operations on the plant floor. From a power quality awareness standpoint, it's as if these two sections of the facility are miles apart even though they are just next door. Just look beneath the desk of every plant manager, plant engineer, or accountant and you will likely find a small UPS. In the many power quality audits EPRI Solutions has conducted, this is almost always the case. Despite the nearly ubiquitous recognition that it is beneficial to protect front-office computers and data from PQ phenomena, this level of concern is less frequently extended to the plant floor. Although programmable logic controllers (PLC) work tirelessly to create the revenue-producing product, they are often left to suffer the vagaries of unconditioned power (see figure below).

Front Office Equipment Often Get UPS Protection, But Not Process Floor Equipment

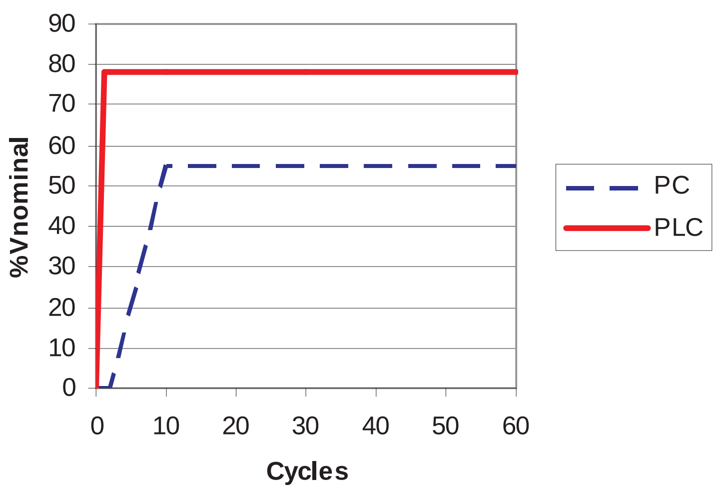
Although process controllers and other equipment are directly involved in making revenue-generating products, it is more likely one will find uninterruptible power supplies (UPS) on front-office computers, network servers, and even printers and photocopiers.



The first step in taking PQ ownership is developing an understanding of the facility's power quality environment.

Why are facilities applying power conditioning to the front-office equipment, but not the plant floor systems? The issue is ownership—because the output of front-office equipment is usually "owned" by one person (or a small group of people), this individual will take it upon themselves to improve the protection of their equipment. In contrast, while the process floor equipment is usually much more vulnerable to voltage sags and momentary outages than the front-office equipment, there is often no single owner. Ironically, front-office computers are usually more to PQ phenomena to begin with than their process floor counterparts. The figure below compares the voltage sag immunity of an unprotected desktop computer to that of an unprotected PLC. In fact, a typical facility may have twice as many minor voltage sags that would shut down the PLC versus the deeper and longer sags that would upset the front-office PC hardware.

Voltage Sag Immunity of Unprotected Desktop PC versus PLC System



Most personal computers (PC) can weather a voltage sag that doesn't go much below abut 55% of nominal. In contrast, programmable logic controllers (PLC) are often vulnerable to voltage sags that are just below 80% of nominal making them open to interruptions from a much higher percentage of voltage sags.

TAKING OWNERSHIP OF PQ—SIX STEPS TO IMPROVED PERFORMANCE

Taking ownership of power quality within the confines of a facility can provide dramatic improvement in facility performance. The six steps to achieving cost-effective ownership of PQ are:

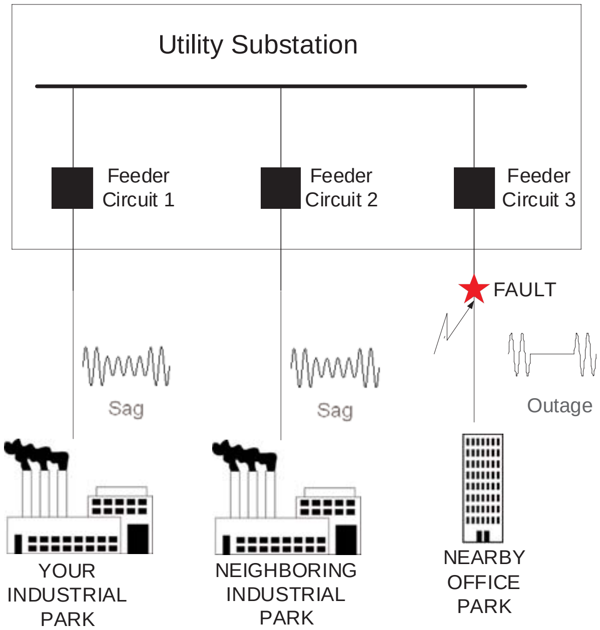
- Making full use of existing data
- Collecting your own data
- Determining the cost of PQ-related losses
- Finding a starting point
- Identifying interrelated processes
- Taking the lid off—one machine at a time

The six step method outlined shows the way to making this transition while taking full advantage of all resources and minimizing costs.

Step 1—Making Full Use of Existing Data

The first step in taking PQ ownership is developing an understanding of the facility's power quality environment. Utility resources may be available to help with this task. In some cases, the utility may have power quality monitoring at the substation feeding the end use plant or somewhere nearby. At a minimum, the utility will be able to provide information such as the number of faults that have occurred in the substation, including the feeder that serves the plant and adjacent loads. Faults that occur on the feeder will often cause interruptions in which the voltage drops out completely. Faults that occur on adjacent feeders will cause a voltage sag at most, if not all, nearby facilities. (See figure below on the following page)

Voltage Sags Caused by Electrical Faults



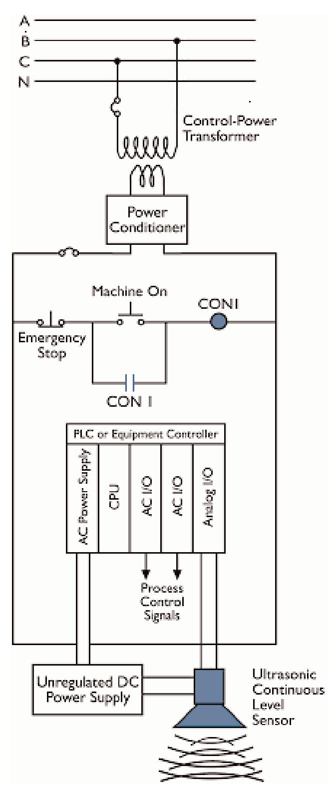
Faults are a normal part of day-to-day operations of electrical transmission and distribution systems. Unfortunately, one of the most common consequences of faults are voltage sags that can affect a wide area far beyond the point of the fault. There are few cost effective ways for electric utilities to avoid this circumstance. As such, it is usually beneficial for end users to take ownership of the task of hardening internal processes against voltage sags.

Based on power quality data from the Electric Power Research Institute (EPRI) Distribution Power Quality Study, most distribution-fed customers are likely to experience as many as 8 to 10 voltage sag events for every 1 complete interruption. This is due to the number of feeder circuits that are on the average distribution substation and the exposure in other parts of the distribution and transmission system. In other words, 80% or more of power quality events may be due to voltage sags alone and, therefore, most plant interruptions are due in large part to the inability of plant equipment to ride-through these events.

A utility substation circuit operation report can help facility managers understand the number of interruptions in voltage versus the number of voltage sags. An example report from a four-feeder substation is shown in the table on the following page.

If 75% or more of the events are voltage sags caused by faults on adjacent circuits (such as Circuits 1 and 3 in the table), there is a good chance that a minimal investment can solve the majority of the PQ problems. This typically involves supporting control power loads with batteryless power conditioning devices at an average price of $1,000 to $1,500 per kVA of protected circuit (see figure below). The good news is that most control power transformer loads are in the range of 1 kVA. When protecting critical loads only, the cost will be in the tens of thousands of dollars in most plants. Therefore, the approach is cost effective when compared to the alternatives. Other low-cost options include programming and setup of motor drives to enable the best voltage sag ride-through performance.

Cost Effective Control Power Solutions



Applying power conditioning at the control power level is often the most cost effective way of mitigating PQ related problems.

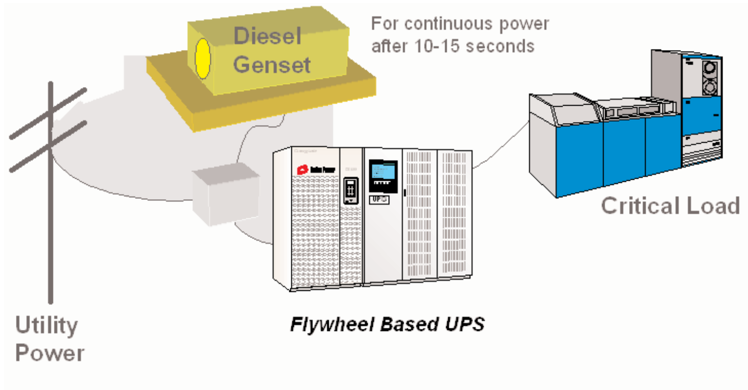
Example Utility Substation Circuit Operation Report

SUBSTATION CIRCUIT 1 OPERATIONS			
Date	**Time**	**Duration**	**Cause**
6/25/04	19:56	Instantaneous	Storm
4/22	19:00	Instantaneous	Lightning
SUBSTATION CIRCUIT 2 OPERATIONS			
Date	**Time**	**Duration**	**Cause**
7/10/04	18:55	Instantaneous	Lightning
10/3	14:18	Instantaneous	Lightning
10/6	11:35	Instantaneous	Underground Primary Failure
10/8	11:17	Instantaneous	Unknown
SUBSTATION CIRCUIT 3 OPERATIONS			
Date	**Time**	**Duration**	**Cause**
6/12/04	19:13	Instantaneous	Lightning
6/22	00:27	Instantaneous	Tree
7/10	18:54	Instantaneous	Lightning
SUBSTATION CIRCUIT 4 OPERATIONS			
Date	**Time**	**Duration**	**Cause**
7/2/04	21:28	Instantaneous	Unknown
4/9/05	00:59	Instantaneous	Tree
4/21	20:24	Instantaneous	Unknown
4/23	08:53	Instantaneous	Lightning
4/27	11:56	Instantaneous	Lightning
6/24/05	11:47	Instantaneous	Unknown
7/11	12:40	Instantaneous	Tree on the primary
TRANSMISSION FAULT			
Date	**Time**	**Duration**	**Cause**
6/30/05	20:36	7 minutes	Broken cross-arm

SUMMARY TOTALS:				
Customers on	**Momentary Interruptions**	**Sustained Interruptions**	**Voltage Sags**	**Percentage of Voltage Sags that are likely to cause Process Interruptions**
Feeder Circuit 1	2	1	14	82%
Feeder Circuit 2	4	1	12	71%
Feeder Circuit 3	3	1	13	76%
Feeder Circuit 4	7	1	10	58%

Utilities are often capable of providing a report on the causes of faults and other system occurrences. The frequency and location of these events can help facilities understand the types of PQ phenomena they are likely to face in the future.

Bridge Power Scheme with Flywheel and Backup Generator



End users can capably ride-through sags and brief power interruptions by employing a concept called "bridging power"—a combination of highly responsive short-term energy storage with longer term energy storage or back-up generation.

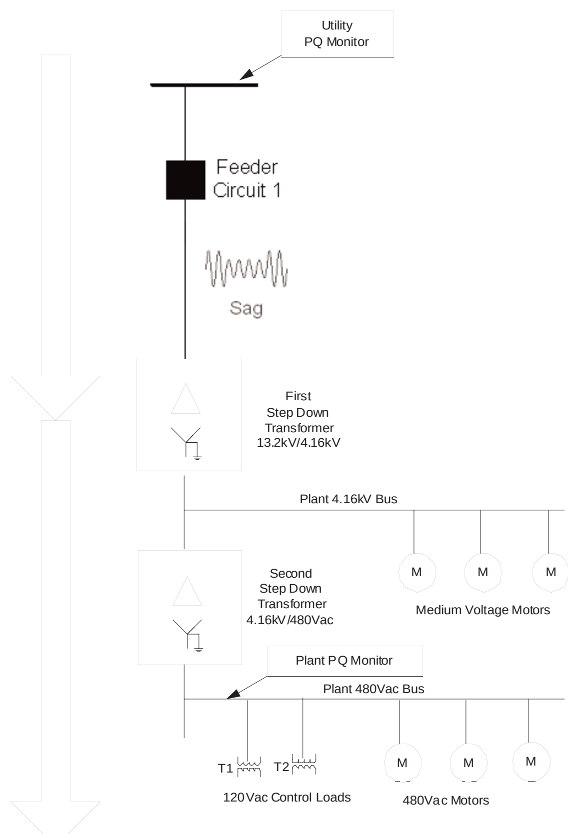
However, if an end user's facility sees almost as many interruptions as voltage sags (such as Circuit 4 in the table), it may be more appropriate to protect the plant's most critical processes at the panel level with a solution that incorporates energy storage, such as a flywheel-based system or the traditional three-phase UPS. In extremely critical applications, these solutions can be used in conjunction with a diesel generator to provide "bridge power" between the beginning of the event and when the diesel is on-line (see figure above). Because such solutions can cost upwards of $100,000, many customers choose the control power approach instead.

Step 2—Collecting Your Own Power Quality Data

Utility PQ monitoring data or breaker operation reports can help to correlate the PQ events a plant is experiencing with equipment sensitivities and the effectiveness of any solutions. However, there is no better way to understand the power quality in a plant than with dedicated internal PQ monitoring. A voltage sag on the utility side will have a given depth and duration. But after making several transformations down to the plant equipment and sensitive control loads, the magnitude of the waveform will be different. Therefore, monitoring at the equipment utilization voltage is important.

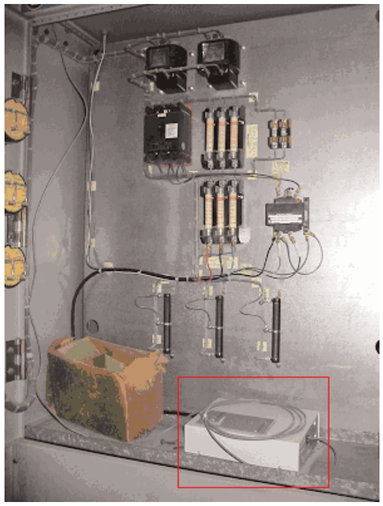
As illustrated below (see figure), a typical power supply system involves flow of power from one or more substations to the industrial facility service entrances, and from there through plant-internal distribution to plant floor loads such as motors, controllers, and control circuits. In the example shown, the 480 Vac bus has a dedicated monitor. Since the control voltage is most often connected across two phases of the 480 Vac supply voltage, three-phase monitoring at the 480 Vac can help characterize the voltage sag levels seen by the PLCs, relays, power supplies, and instrumentation.

Example Voltage Transformations from Substation to Plant Loads



A typical power supply system involves flow of power from one or more substations to the industrial facility service entrances, and from there through plant-internal distribution to plant floor loads such as motors, controllers, and control circuits. In the example shown, the 480 Vac bus has a dedicated monitor. Since the control voltage is most often connected across two phases of the 480 Vac supply voltage, three-phase monitoring at the 480 Vac can help characterize the voltage sag levels seen by the PLCs, relays, power supplies, and instrumentation.

Low-Cost 3-Phase Voltage Monitoring



Highlighted in the figure (red box) is a low-cost monitor, shown here watching over a plant's 480 Vac switchgear.

Many PQ monitors are currently on the market including some "utility grade" units that capture current and voltage at a high sample rate. Lower-cost power quality monitors, typically costing less than $1,000, are also available and some connect to the three-phase voltage and an analog phone line. When an event occurs, the user receives an e-mail with the time, depth, and event duration. Further details including the captured waveform are presented as well. An example of such an installation is shown in the figure above.

To provide a good idea of the power quality environment seen at the plant, the monitor needs to be installed and collecting data through at least three months. The longer the monitoring period, the better the data will represent the facility environment. Preferably, the monitor can be installed before the most challenging power quality periods, usually spring and summer.

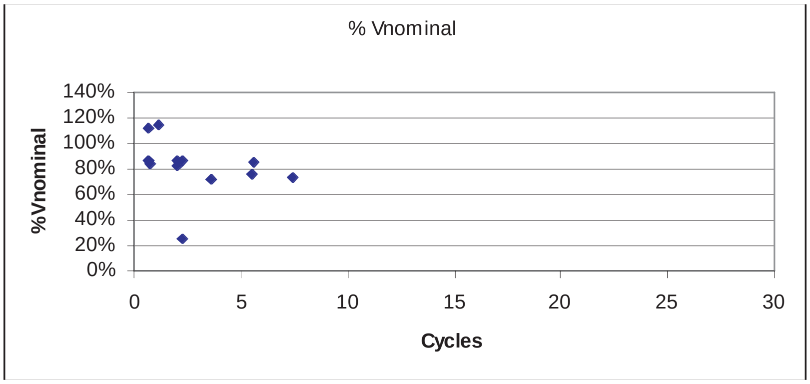
Armed with a representative sample of power quality data at the plant equipment utilization voltage, one can draw a direct correlation between power quality events and equipment performance. For example, the table below lists events captured by a low-cost power quality monitor and the accompanying figure on the following page, shows a scatter plot of the resulting data. The monitor may provide this output automatically via a software interface.

Event List from Power Quality Monitor

Duration	Event Type	Duration	Worst Case RMS Voltage	% Vnominal	Name or Location
7/20/2005 6:51	Instantaneous Sag	2.0 cycles	397.8	83%	Acme, Inc.
7/20/2005 6:51	Instantaneous Sag	2.0 cycles	414.5	86%	Acme, Inc.
7/16/2005 20:37	Instantaneous Sag	7.4 cycles	351.7	73%	Acme, Inc.
6/16/2005 11:42	Instantaneous Swell	1.1 cycles	552.7	115%	Acme, Inc.
6/16/2005 11:42	Instantaneous Swell	0.6 cycles	537.1	112%	Acme, Inc.
6/10/2005 17:32	Instantaneous Sag	2.2 cycles	413.4	86%	Acme, Inc.
6/2/2005 11:09	Instantaneous Sag	5.6 cycles	410.9	86%	Acme, Inc.
5/11/2005 17:11	Instantaneous Sag	0.6 cycles	414.5	86%	Acme, Inc.
5/11/2005 17:11	Instantaneous Sag	0.7 cycles	402.1	84%	Acme, Inc.
4/5/2005 16:19	Instantaneous Sag	3.6 cycles	343.9	72%	Acme, Inc.
4/3/2005 20:34	Instantaneous Sag	5.5 cycles	364.6	76%	Acme, Inc.
4/3/2005 20:34	Instantaneous Sag	0.6 cycles	419.2	87%	Acme, Inc.
3/1/2005 6:42	Instantaneous Sag	2.2 cycles	118.8	25%	Acme, Inc.

The data from a PQ monitor can be shown in tabular form

Scatter Plot of Power Quality Data



A more intuitive display form for data from a PQ monitor is graphically, showing voltage sag depth and duration

In addition, any shutdown data (frequently referred to as "stop tags") from the production floor should be recorded so that they can be compared to the power quality data to determine the kinds of PQ events that lead to process shutdowns.

Step 3—Determining the Cost of PQ-Related Losses

Once one has an understanding of a facility's PQ environment, the next step is to determine what these disturbances are costing. Without this key information, it is impossible to make the financial case for a solution. Consider the following five items:[1]

1. **Idled labor.** If the process is disrupted, some production workers may be paid while they wait for the processes to recover before they can work. Other workers may have to wait until their section of the production line has incoming product again due to a backup at bottleneck processes.
2. **Lost production**. When a process goes down due to a PQ problem, there may be multiple costs related to lost production. These include:
   a. Makeup production
   b. Overtime labor
   c. Overtime operating costs
   d. Expedited shipping
3. **Cost of equipment repair**. Damage to machines or tooling equipment can occur as a result of a PQ problem. In high-precision computer numerical control (CNC) processes, for example, the cutting head tool can be damaged. In a crystal pulling process, damage to the crucible can cost upwards of $50,000. Considerations in determining the cost of equipment damage include:
   a. Repair labor
   b. Repair supplies
   c. Repair parts
   d. Replacement part availability
   e. Expedited shipping of parts or carrying cost of having spare parts on-hand
4. **Cost of recovery**. This is the cost incurred to ramp the process back up. The time involved can range from minutes to days depending on the industry. In fact, a significant portion of unrealized profits can be attributed to the cost of recovery. Considerations when determining this cost include:
   a. Secondary equipment failures
   b. Recovery labor inefficiency
   c. Product quality
   d. Replacement value of scrap
   e. Blemished product lost profit margin
   f. Rework cost
   g. Labor
   h. Manufacturing supplies

5. **Miscellaneous costs.** Factors here include customer dissatisfaction — the next order may go to a competitor based on late delivery or quality issues. Also, longer lead times induced by an unexpected shutdown may lead to potential customers going elsewhere. Finally, the contract with the customer could include fines and penalties for late delivery.

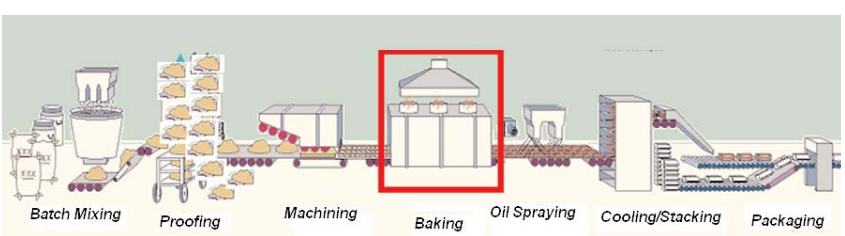
Step 4—Finding a Starting Point

A bottleneck is one in a chain of processes, such that its limited capacity reduces the capacity of the whole chain.

After learning what PQ problems are costing, one is ready to focus on fixing it. In every manufacturing environment, certain facility-level processes are fundamental to the entire plant. These can include process air, chilled water, exhaust, etc. Furthermore there are key process machines or areas in which interruptions are very costly. In an electronics assembly plant, it may be the surface mount machine or the wave solder machine. In an automotive assembly plant, one of the key areas is the paint department. In a semiconductor plant, a diffusion furnace holding 150 wafers is critical.

Besides looking at criticality and cost of shutdowns, another area to identify is any bottleneck processes. A bottleneck is one in a chain of processes, such that its limited capacity reduces the capacity of the whole chain. The figure below shows a food processing facility with a bottleneck in the baking section.

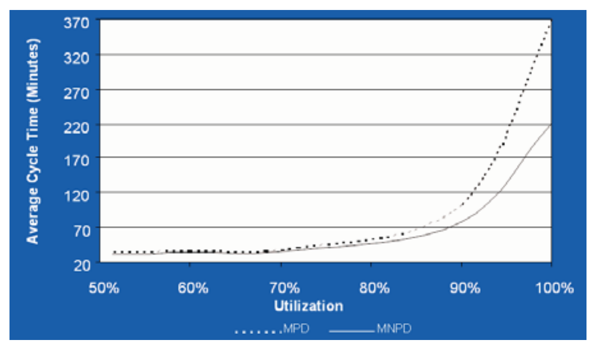
Baking Process is Sensitive Bottleneck in Food Processing Plant



Every manufacturing process has a bottleneck where capacity is (or is most likely to be) fully used. In the case of a bakery, the actual baking is usually the most time critical and sensitive process.

The limited capacity of these manufacturing areas is amplified when an unexpected shutdown occurs. As the utilization rate of a plant increases (such as moving from two to three-shifts a day or increasing the manufacturing speed of the entire process by reducing cycle times), the effect of an electrical disturbance is greatly magnified and the bottleneck scenario becomes more challenging. This concept is illustrated for an electronics assembly plant in the figure below. As the utilization rate of the electronics assembly plant increases, the average cycle time to move a product increases.[2] When a power disturbance occurs, the average cycle time to move a product from start to finish in the process increases due to the PQ disruption.

Process Cycle Time for Electronic Assembly Plant Versus Plant Utilization Rate



As the utilization rate of the electronics assembly plant increases, the average cycle time to move a product increases. When a power disturbance occurs, the average cycle time to move a product from start to finish in the process increases due to the PQ disruption. MPD denotes Cycle Time in Minutes with Power Disturbance, while MNPD denotes Cycle Time in Minutes without Power Disturbance.

For plants that run around the clock, the upset of a bottleneck process may lead to a backlog of product or "work in process" that cannot be moved through the system. As one might imagine, if the most sensitive and critical process is also a bottleneck, solving power quality problems related to this machine or area should be a priority.

A holistic approach must be used that takes into account the entire factory and its many interdependencies.

When looking at bottleneck issues, address the following possibilities:

- First consider solving power quality issues for bottleneck process equipment and those ancillary systems that support these processes.
- In a long manufacturing line with many sections, an upset of a section located early in the manufacturing process has a greater influence on system variability downstream. Therefore, these areas should be addressed secondly.

  If the plant is under utilizing its manufacturing processes (i.e., systems are not running at the highest utilization rate) then the effect of electrical disturbances may be limited. However, this does not mean that the process disruption is acceptable and does not warrant further attention.

Step 5—Identifying Interrelated Processes

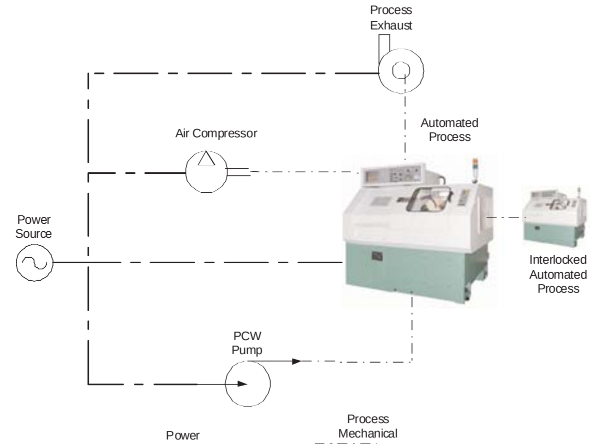
Once one has determined which processes or machines need improved power quality response, one must consider all interrelated processes. In modern automated equipment, process interlocks frequently exist between separate manufacturing process steps as well as between facility support systems and the automated process. If one aims to solve the PQ problems in the plant by focusing solely on the process machinery, but does not consider the related facility support systems, efforts could be in vain. A holistic approach must be used that takes into account the entire factory and its many interdependencies.

In the example process shown in the figure below, the automated process first must have adequate voltage to operate. This is normally measured either by a power monitoring relay that may be interlocked with power circuit on the machine or with some sort of monitoring.

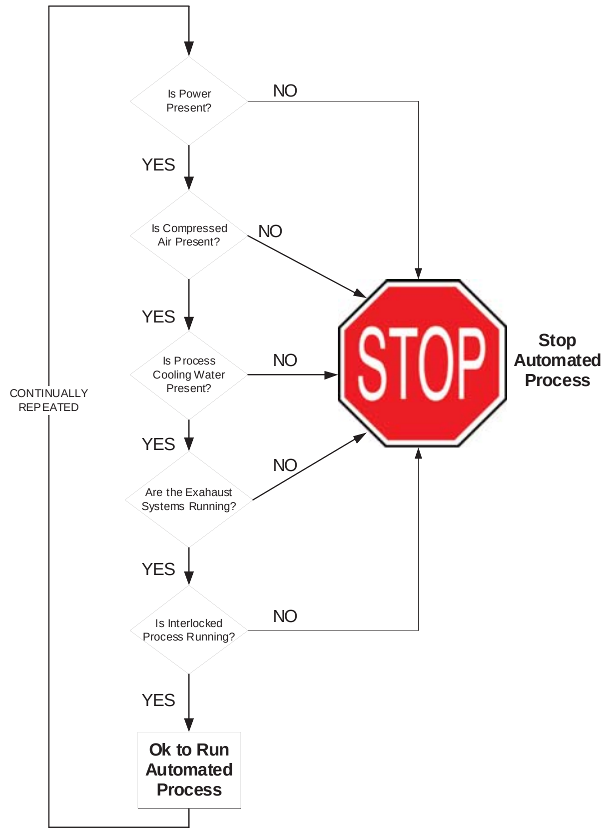
Next, the support systems such as compressed air, process cooling water (PCW), and exhaust must be running. The process machine will likely determine that these systems are running via flow or pressure sensors. Finally, if the process is dependent on other automated processes, the downstream machine must be up and running as well. Once all of these criteria are met, it is possible to run the automated process. The flowchart in the figure on the following page, summarizes the required interlocking logic. The same criteria that are required to make the machine or process begin are also critical in keeping the process running during a PQ event.

Interconnection of Facility Infrastructure Equipment and Automated Process Machine

Truly stand-alone equipment is a rarity in modern manufacturing facilities. As complex as most automated processes are, from a PQ standpoint the picture is even more convoluted when one takes into account ancillary systems whose failure or interruption can also spawn process shutdowns.



Example Automated Process Interlock Flowchart



Many interlocking features must be fully functional before processes can proceed. Interruption of any one is the same as all being interrupted.

Step 6—Taking the Lid Off-One Machine at a Time

It's not as difficult as it may seem to determine why process systems are vulnerable to voltage sags and momentary interruptions. There are some key items that can quickly be assessed to understand the vulnerabilities of control systems in particular. Internal assessments of the control cabinets can quickly point out vulnerabilities.

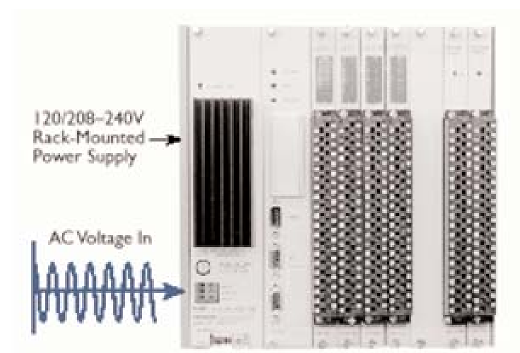
Does the Process Use AC-Powered PLCs?

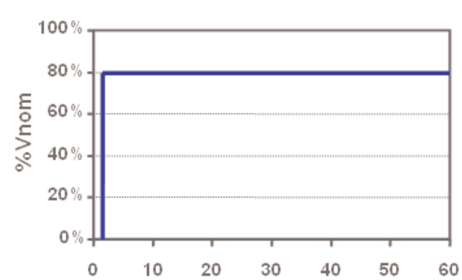
The quote following is from the AC power supply product literature of a well known PLC manufacturer that produces one of the most widely used PLCs in the United States.

"Each AC-input power supply generates a shutdown signal on the backplane whenever the AC line voltage drops below its lower voltage limit, and removes the shutdown signal when the line voltage comes back up to the lower voltage limit. This shutdown is necessary to ensure that only valid data is stored in memory."

PLC systems that are AC powered (see figure below) are often vulnerable to voltage sags. This is a very common power configuration for PLC systems. In previous EPRI power quality audits, some AC-powered PLCs were found to be upset by voltage sags as minor as 80 to 85% of nominal, 2 cycles, in duration. This level of vulnerability can be an Achilles heel to the control systems.

AC-Powered PLC and Voltage Sag Ride-Through



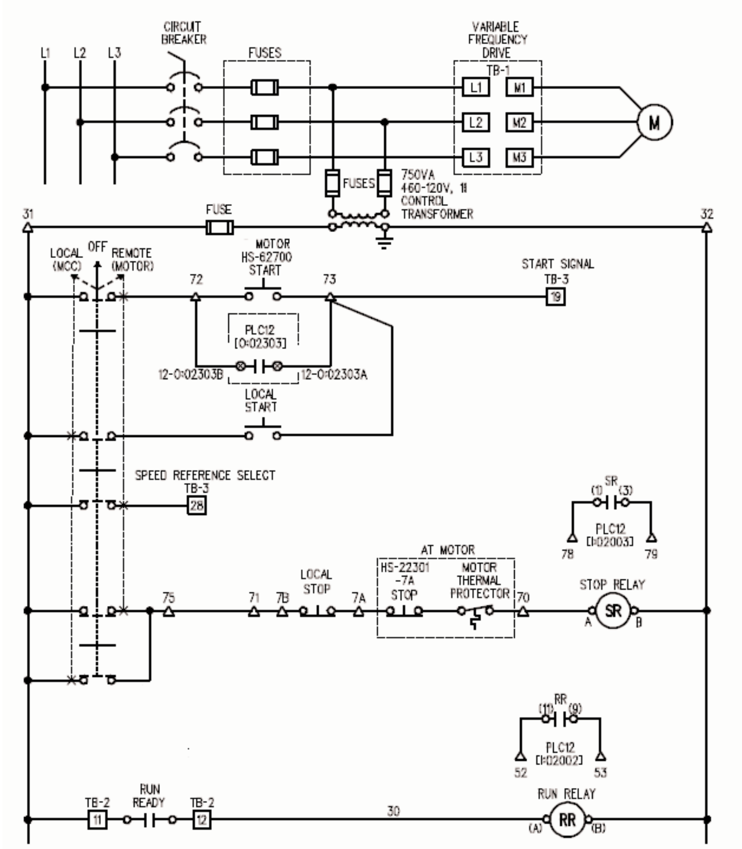


The most common powering scheme for programmable logic controllers (PLC) is direct AC power. Unfortunately, as illustrated in the sag-tolerance curve, direct AC powered PLCs are often particularly vulnerable to voltage sags. Even a relatively minor sag down to 80% of normal, and for as short as a couple of cycles can affect the operation of these devices .

Does the Plant Use AC-Powered Control Logic and Input/Output Devices?

If a plant uses AC-powered control logic such as relay logic or if automation circuits use AC input/output (I/O) devices such as motor starters, relays, solenoids, and sensors, then it is likely to have a high level of vulnerability to voltage sags and momentary interruptions. Take the hardwired drive control interface circuit shown in the figure below. The drive interface signals (usually run, emergency stop, and other interlocks) are dependant on 120 Vac control voltage derived from the control power transformer. Notice in the figure below that the adjustable-speed drive (ASD) can be stopped via stop pushbuttons at a local control interface which may be remote from the drive and other controls.

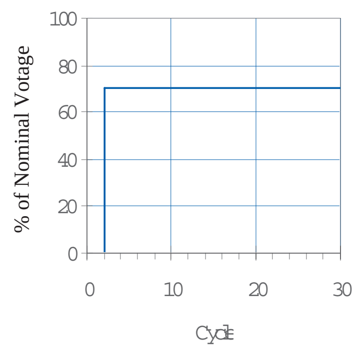
Example Control Interface for an Adjustable-Speed Drive (ASD)



While it is common to think of voltage sags or other PQ phenomena directly affecting sensitive devices like PLCs or ASDs, it is equally common for simple control circuit elements (such as motor contactors or small relays) to open, thereby causing unintended process interruptions.

If the relay in a local- or emergency-stop circuit is a simple AC "ice cube" relay (see figure below), a relatively minor voltage sag in the range of 70% of nominal for only a few cycles can easily cause the AC relay to change state, thus stopping process. That's why these types of AC-powered control circuits can be hypersensitive with respect to voltage sags.

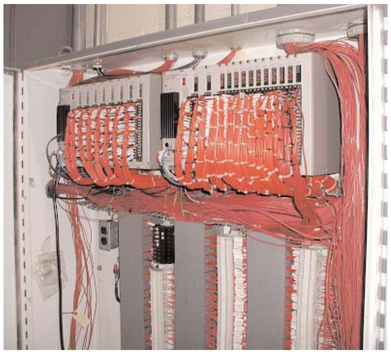
A Common Culprit: AC "Ice Cube" Relays



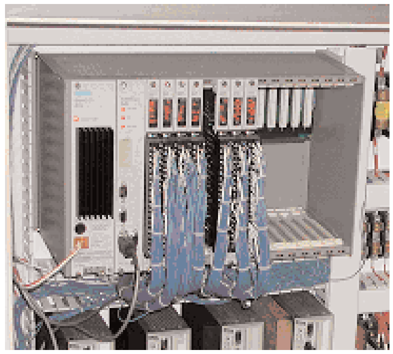
Although simple and otherwise inexpensive, the common "ice cube" relay can very quickly wear out its welcome in the presence of even minor voltage sags. Process controls have no way to differentiate between a true "emergency stop" event versus a relay opening because voltage has sagged.

PLCs are designed to sense events and react quickly. The control power used by the PLC can make a big difference in the voltage sag ride-through of the process that the unit is controlling. When a robust DC power supply is used, PLCs with DC I/O are typically hardier with respect to voltage sags.

PLC with All AC and DC Control Power Schemes



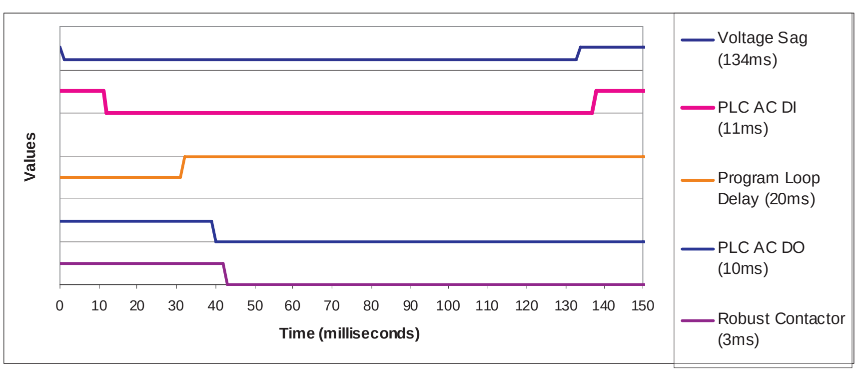
PLC with all AC I/O (Red Wires)



PLC with all DC I/O (Blue Wires)

Programmable logic controllers (PLC) feature a wide variety of I/O options, including AC (red wiring, as used on the left) or DC (blue wiring, as used on the right). While these two configurations may be equivalent when voltage is normal, AC I/O is known to be less robust in the face of voltage sags.

Cascading Effects of a Voltage Sag on an AC Input and PLC Control



llustrated here is the cascading effect of a voltage sag on different PLC system components. At t=0, a voltage sag begins (top trace, dark blue). Within about 10 milliseconds (msec), the PLC registers an AC input as a “0” instead of a “1” (second trace, magenta). This causes a cascade of events as the PLC proceeds to open the output to a motor contactor based on the now-erroneous AC input (subsequent traces).

However, utilizing AC I/O in the PLC can lead to problems related to how the PLC interprets a voltage sag event. The figure at top left shows a PLC (left) with all AC I/O, and a similar PLC (right) with all DC I/O. These two cabinets show the typical wiring color scheme (AC wiring is red, 24 Vdc wiring is blue). In the system on the left, you can easily see the preponderance of AC control signals going in and out of the PLC I/O.

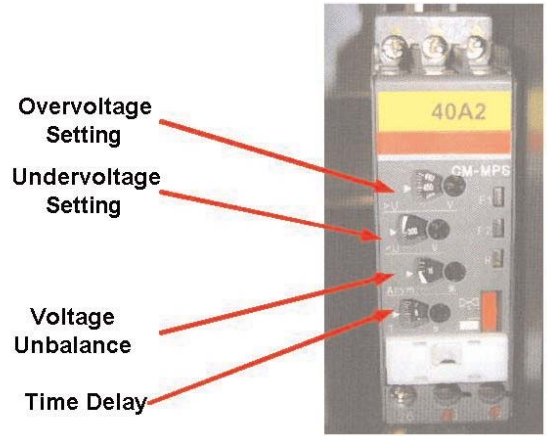
If a voltage sag event is low enough, inputs that are actually “on” can be misinterpreted as “off” due to sagging voltage. This false detection can lead to a cascading series of events that will stop process operations. Take the example shown in the figure at bottom left. The PLC logic has a simple discrete AC input (noted as PLC DI), which directly drives a discrete output point from the PLC to engage a contactor or starter (noted as PLC DO). In this example, an 8 cycle (134 ms) voltage sag occurs as represented by an RMS plot in the top of the graph. Only 11 milliseconds later, the PLC AC discrete input detects that the voltage at the input point has dropped to a point where a logic level “0” is detected. The program loop is solved, which takes about another 20 milliseconds, followed by turning off the discrete output point on the PLC to logic level “0”. Afterwards, the contactor disengages and shuts down the process operations. The cascading event and process shutdown occurred within 44 milliseconds or less than 3 cycles into the event.

Misapplication of Phase Monitoring Relays

Phase monitor relays (sometimes called 3-phase monitors, phase loss relays, protective relays, motor protection relays or phase failure relays) provide protection against premature equipment failure caused by voltage faults on 3-phase systems. Phase monitor relays protect against unbalanced voltages or single phasing regardless of any regenerative voltages. These relay units can protect against overvoltage, undervoltage, voltage unbalance, and phase reversal. They are available with or without time delay adjustments. Without time delay, phase monitoring relays can cause a process machine or entire bus to trip as a result of a voltage sag. Consider the scenario where this unit is applied on the 480 Vac bus in a manufacturing facility, as shown in the figure below. With unchangeable response time of 50 milliseconds, the relay will trip out an entire section of the plant for certain voltage sag events lasting more than 3 cycles.

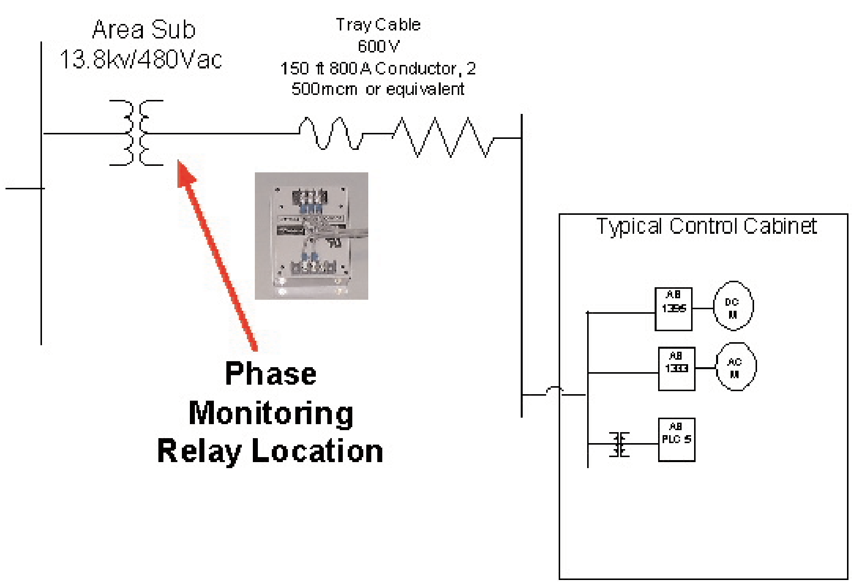
When using such protective relays, consider utilizing units with time delay. The unit shown in the figure at the right has settable trips for overvoltage, undervoltage, and voltage unbalance. Furthermore, the time delay setting can eliminate nuisance tripping of the equipment when transient conditions occur.

Configurable Phase Monitoring Relay with Adjustable Time Delay



Many electrical system monitors and relays have adjustable settings that can make them less sensitive to voltage sags while not compromising facility equipment protection or safety.

Phase Monitoring Tripping



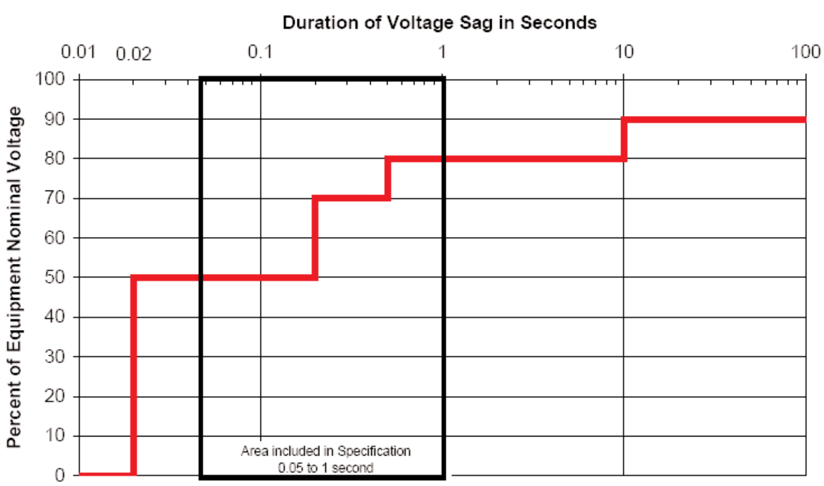
In one case investigated by EPRI Solutions, a Phase Monitoring Relay, reacting to a voltage sag, tripped and shutdown the entire electrical supply for a manufacturing plant. Such abrupt shutdowns are usually ungraceful and can lead to damaged equipment and big messes to clean up.

ENCOURAGING OEM OWNERSHIP OF PQ

Most manufacturers rely on original equipment manufacturers (OEM) for supply of critical manufacturing machines and, sometimes, entire manufacturing lines. In most cases, the details about electrical power and control equipment in OEM systems is not a direct concern of the manufacturer, being part and parcel of the OEM-supplied system. As such, OEMs must be brought to the table in taking PQ ownership, as their design and component decisions will otherwise create “weak links” in components and equipment and, thereby, affect the performance of the entire system. Embedded solutions are attractive since they in theory do not require add-on power conditioning equipment, but instead include more robust or improved components in the tool design. Furthermore, semiconductor tool suppliers are more comfortable with this approach since it does not require the addition of unfamiliar technologies.

One elegant approach to making OEMs part of the solution is to require all OEM-supplied equipment to meet specific voltage sag performance standards. The best and most frequently used of these standards is SEMI F47[3] (see figure below), which was adopted by the semiconductor industry in 2000. The actual requirements of meeting the specification are represented within the area outlined by the black box. However, a larger recommended area is also noted in the standard, which includes the durations from 0.01 to 100 seconds. Note that the voltage sag levels shown in the standard are relevant for single-phase and phase-to-phase voltage sags only. There are no three-phase requirements for SEMI F47 (such as 50% of nominal, 200 milliseconds for Vabc).

SEMI F47 Ride-Through Compatibility Curve



The semiconductor industry has made huge progress in making OEM-supplied equipment much more tolerant of voltage sags through creation and adoption of the SEMI F47 standard. The standard is, in many respects, a de facto agreement between the semiconductor industry and electric power providers of shared ownership of PQ.

Specific steps that end users can take to effectively bring OEMs to the PQ ownership table include:

1. **Use only SEMI F47-compliant devices in the design.** Since SEMI F47 became a standard, hundreds of control relays, safety relays, contactors, motor starters, power supplies, and motor drives have been certified as compliant with the standard. Learn more at www.f47testing.com or search the Internet for "SEMI F47".
2. **Avoid mismatched equipment voltages.** If the equipment used in a tool's design does not match the expected nominal input voltage, the tool will be more susceptible to voltage sags. This can occur when transformer secondary voltages do not match the rated voltage for the connected equipment, or when a tool subsystem such as a servo controller or power supply is rated for a higher voltage (i.e., 240 Vac equipment is used in a 208 Vac environment). For relays and contactors, a mismatch of 10% of voltage equates to an increase in susceptibility by 10%. However, in DC power supplies, the energy stored in the internal capacitors can be as much as 18% lower when the input voltage is mismatched by as little as 10% — directly equating to a reduction in ride-through time.
3. **Use three-phase switching power supplies in every location possible.** This type of power supply can survive single- and two-phase voltage sags while maintaining the output DC voltage. This type of supply should be specified for power safety circuits as well as DC power supplies for instrumentation and controls. In fact, the DC power supply

can be used to replace a control power transformer and build in robustness in the control system.

4. **Avoid the use of AC-powered "ice cube" general purpose relays.** Instead use a robust AC relay or use a DC power supply to power the control circuits as mentioned above.

5. **Consider Circuit Breaker Characteristics.** For equipment to be compliant with the SEMI F47 standard, circuit breakers and fuses should be selected to allow for higher inrush currents due to power quality variations within the SEMI F47 voltage sag range. This must be considered for constant power loads such as power supplies and variable frequency drives. Where possible, do not select breakers that have instantaneous trip characteristics.

6. **Do not use phase monitoring relays in the interlock circuit.** These devices will easily trip during a voltage sag and can lead to tool shutdown. Instead use these devices to log that a voltage sag or phase problem exists. If the concern is that a motor might run in the wrong direction, interlock only with motor controls.

7. **Use a non-volatile memory.** This type of backup technique for tool controllers ensures that the control system will not lose its place in the event of a voltage sag.

8. **Do not overload DC power supplies.** Since the amount of voltage sag ride-through time available from a DC power supply is directly related to the loading, DC power supplies should not be running at their maximum capacity. Oversizing by at least two times the expected load will help the power supply to ride-through voltage sags. This is only critical for systems that do not have a universal input front-end.

9. **Use robust ASDs.** When using adjustable-speed drives in the tool design, specify models that have good voltage sag ride-through. Check with drive supplier to make sure the drive firmware will support voltage sag ride-through. Flying restart, kinetic buffering, and the ability to have a low DC bus level trip point (50% of nominal is ideal) are essential. Be sure to configure the drive to take advantage of these features.

10. **Consider the software and control program issues.** System software developers should consider process variable fluctuations during voltage sags. Widening the bandwidth for certain process variables or adding time filter delays can help avoid tripping the process when voltage sags occur.

11. **Consolidate control power sources.** When designing the layout of process equipment, try to consolidate the control power feed such that they are fed from a common source or breaker where possible. If a small power conditioner is required to make the tool robust to voltage sags, this will make the implementation less painful.

12. **Use a targeted voltage conditioning approach.**[4] As the last resort, apply only targeted voltage conditioning devices to prop up weak link components on the tool that cannot be retrofitted with comparable robust components. Several kinds of products are available for selective mitigation. The most common devices are discussed below.

   - **The Voltage Dip Proofing Inverter (DPI).** The DPI falls into a class of devices referred to as batteryless ride-through devices (BRTD). Since the DPI operates only when a voltage sag is detected (off-line technology), it only needs to be sized for the nominal load. The device basically continually rectifies incoming AC voltage to charge the DC bus capacitors. When a voltage sag is detected that drops below an adjustable threshold, the line to the incoming power to the device is opened and the DPI supplies a square-wave output to the load for about 1 to 3 seconds. Care should be taken when applying this solution in that not all loads are compatible with a square-wave output produced by the DPI. The same basic advice also applies when utilizing small UPS systems that produce a square-wave output. The amount of time that the DPI will supply the load can be calculated based on the real power and the energy storage of the particular DPI.

- **Constant Voltage Transformer (CVT).** The CVT (a.k.a. ferroresonant transformer) is a device that maintains two separate magnetic paths with limited coupling between them. The output contains a parallel resonant tank circuit and draws power from the primary to replace power delivered to the load. The transformer is designed so that the resonant path is in saturation while the other is not. As a result, a further change in the primary voltage will not translate into changes in the saturated secondary voltage, and voltage regulation results. These devices will allow for much better voltage sag ride-through if they are sized to at least two and a half times the nominal VA requirement. Oversized in this manner, CVTs can supply a 100% of nominal voltage when the input voltage has dropped to as low as 40% of nominal.
- **The Uninterruptible Power Supply (UPS).** UPSs come in three basic types: standby, line-interactive, and rectifier/charger. The **standby UPS** switches to a battery and provides an inverter output to the load once it detects a voltage sag. If the transfer is fast enough (< 1 cycle) and is in phase with the incoming voltage, typical control components are not likely to be affected by the sag event. Careful selection of this type of UPS is required in order to guarantee that sensitive control loads will not drop out before the unit switches to the inverter. The **line-interactive UPS** is an on-line type that employs a regulating transformer (CVT) when the incoming voltage is nominal. When a voltage sag is sensed, the unit then switches to the inverter to power the load. High inrush loads must be taken into account when using this unit since the CVT output can collapse from overloading. The **rectifier/charger UPS** is also an on-line unit. The unit constantly rectifies the incoming AC line voltage. The resulting DC voltage is then used to charge the batteries and to feed the inverter circuit for the unit's output section. In the event of a voltage sag or outage, the unit switches to the battery for the source of the inverter's power.

One of the most important first steps is to understand the power quality environment at the industrial facility.

Ultimately, the determination of whether to use a UPS or some other voltage conditioning device depends on whether the load requires power during a brief outage and the end user's willingness to perform periodic maintenance on the unit's batteries.

- **The Dynamic Sag Corrector (DySC).** The DySC system is a BRTD that corrects voltage sags down to 50% of nominal, supplying a sine-wave output. By drawing additional current from the input line (voltage sags above 50%) or from internal storage caps (voltage sags below 50%) the DySC maintains the output to the load. The smaller single-phase versions of this product are called the "MiniDysc" while the larger three-phase units are called "Pro DySC". This product was developed in tandem with the SEMI F47 standard and is targeted specifically toward the semiconductor industry.
- Coil Hold-In Devices. Coil hold-in devices are BRTDs that are designed to mitigate the effects of voltage sags on individual relays and contactors. Two brands found on the market are the KnowTrip and the Coil Lock, one of which is UL listed. Typically, the coil hold in device is connected in-line with the incoming control signal for the relay or contactor. Available for coil voltages of 120 Vac, 230 Vac, and 480 Vac, the best application for this device is to prop up relays and contactors that are in an emergency off/master control relay, or motor control center circuits. Costing as little as $85, these units are very economical to support contactors and relays.

  Typical coil hold-in devices allow a relay or contactor to remain engaged until the voltage drops to around 25% of nominal. The unit installs between the relay or contactor coil connection terminals and the incoming AC control line.

Summary

This *TechWatch* focused primarily on helping the industrial end user and OEMs understand the basic concepts needed to take ownership of power quality. One of the most important first steps is to understand the power quality environment at the industrial facility. To do so, one can gather data from the utility and/or implement an internal power quality monitoring scheme inside the plant. Understanding the frequency of events and the cost of each event provides a basis to determine if action is justified. The cost of each event includes labor, production, repair, recovery, and other miscellaneous expenses.

If corrective action is warranted to solve vexing power quality problems, begin by tackling issues related to the bottleneck processes and then work outwards. Determine why the sensitive equipment trips during power quality disturbances. Interconnections and interlocks with process infrastructure equipment are an important consideration. Evaluate whether sensitive AC-powered control equipment and the set up and configuration of motor controls are contributing to the problem.

For an OEM or designer of new process controls, considerations must be given to the use of DC rather than AC in the control circuits or integrating robust AC components. As a last resort, low-cost, targeted power conditioning may be needed on the most sensitive circuitry.

NOTES

1. IEEE Recommended Practice for Evaluating Electric Power System Compatibility with Electronic Process Equipment, ISBN 0-7381-0184-2, IEEE 1998.
2. "Incorporating Power Quality Impacts into an Industry Process Modeling and Simulation Tool", Presentation by M. Howard, 1998.
3. PQA 2002: "Front-Line Application of Power Quality Research: Semiconductor Equipment Voltage Sag Immunity Improvements", Mark Stephens, April 15th, 2002.
4. EPRI *Task 24 Final Report: Power Quality in the Semiconductor Industry*, Mark Stephens, February 1999.