PQ Case Study

A product of the EPRI Power Quality Knowledge program

Mitigating PQ-Related Process Delays at an LCD Display Manufacturer

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CONTENTS

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SUMMARY

Liquid crystal display (LCD) manufacturing is on an upswing. One leading supplier plans to sell as many as 10 million flat-panel LCD-TV sets in 2008 alone, which requires boosting factory capacity as much as 50%. Because U.S. broadcasters shut off analog television broadcasts in February 2009, many consumers are planning ahead to switch over to flat-panel TVs that can receive digital signals.[1]

EPRI conducted a power quality (PQ) audit at an LCD manufacturer to help the company decrease unscheduled process delays caused by voltage sags. Thirteen separate process machines were examined and recommendations were made to decrease the voltage sag sensitivity of the LCD manufacturing equipment. Although many of the operations are similar to those used by the semiconductor industry in wafer processing, the LCD manufacturing equipment was not compliant with SEMI F47-0706.

This case study examines the utility PQ environment, the LCD manufacturing process, and the recommended solution strategies. It also illustrates the lack of adherence to PQ standards for LCD manufacturing equipment in general and the need for this growing industry to adopt PQ standards.

About the EPRI Power Quality Knowledge program

The EPRI Power Quality Knowledge 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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Mitigating PQ-Related Process Delays at an LCD Display Manufacturer

INTRODUCTION

When a liquid crystal display (LCD) manufacturer was experiencing production problems due to voltage sags, the local utility asked EPRI to help find a solution. The company manufactures LCDs for mobile phones, digital cameras, printers, and digital copiers. Like semiconductor processing, LCD production involves deposition followed by photolithography and etching.

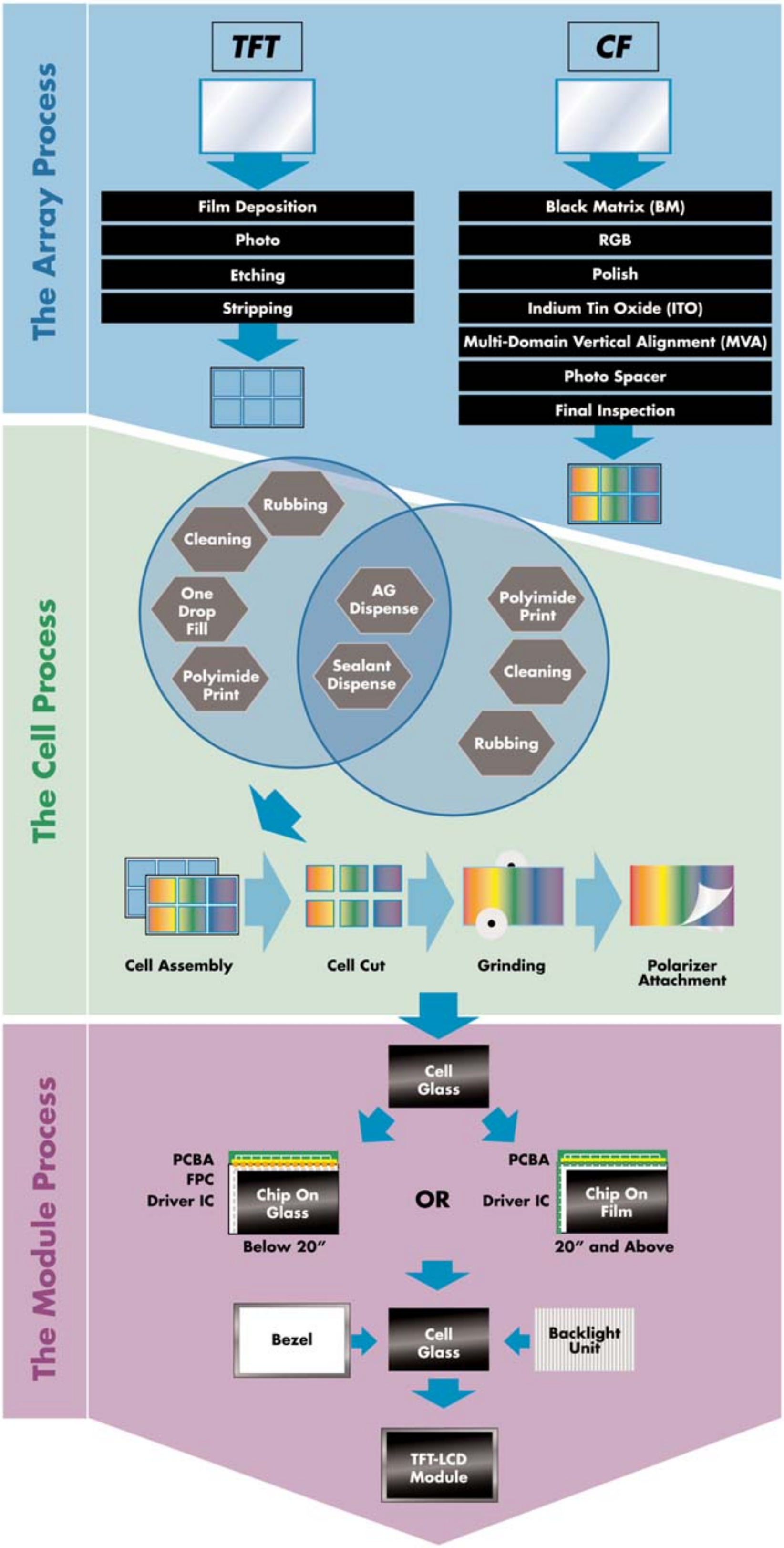
Figure 1 illustrates the typical processing steps for manufacturing a thin-film transistor liquid crystal display (TFT-LCD). The entire process can be separated into three stages: the array process, the cell process, and the module assembly process.

The array process consists of the following sequence of subprocesses: preparing the thin film, photolithography, etching, and stripping. As a first step, a thin sheet of glass is cleaned and coated with chemicals to enhance the deposition process. The glass is then coated with a photo resist material and exposed to ultraviolet (UV) light through a light mask such that only certain areas are exposed to the UV light. Each nonexposed section is approximately equal to a pixel. The exposed areas are washed out using a chemical bath. The glass is then baked and etched to remove the photo resist material not exposed by UV light. Any remaining photo coating is removed using an organic solvent. This forms completion of one mask process. Typically, five process are needed to complete the TFT-LCD array process. The end of this process prepares the glass substrate for the cell process.

The cell process consists of polyimide printing, rubbing, spacer spread, sealant patterning, liquid crystal dispensing, assembling and sealing, and polarizer lamination. This process stage involves the coating of the thin film and color filter substrates. Two plates are prepared simultaneously, a TFT plate and a color filter (CF) plate. A sealant is patterned on the glass substrate to glue the two plates together. The glass substrate from the array process is cleaned and coated with a polyimide coating to form the CF substrate. The liquid crystal material is then filled between the sealant edges, and the two substrates are glued together, trapping the liquid crystal material between the substrates in unique cell blocks. The substrates are then cut to dimensions, and a polarizer material is affixed to the surface. This completes the second stage.

The module assembly process consists of the following stages: chip-on-glass (COG) process, flexible printed circuit (FPC) attachment, printed circuit board (PCB) mounting, backlight mounting, and age testing. During this process, driver ICs, contacts, and PCBs are affixed to the module coming out of the cell process. The backlight is then mounted and the module is packaged for final delivery. The module is then put through stringent tests to detect any defects before it is shipped for delivery.

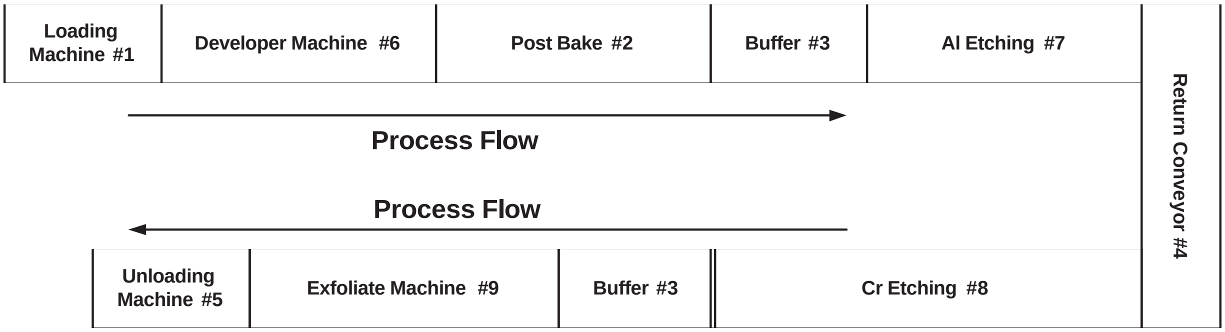
Figure 1. Typical LCD Manufacturing Process



The PQ audit examined LCD process equipment that was either known to be sensitive to voltage sags or known to be involved in bottleneck processes. Thirteen LCD process machines—used for deposition, photo resist, exposure, developing, and etching processes—were selected for a PQ audit to reduce the plant's susceptibility to production losses from voltage sags.

The LCD manufacturer's metal etching process is depicted in **Figure 2**. The goal of the PQ audit was to evaluate the most sensitive equipment in the plant and formulate the best approach for hardening that equipment to voltage sags and momentary outages. This was accomplished by inspecting drawings, on-site testing, physically examining the plant equipment and specifications, talking to equipment technicians and operators, and analyzing plant PQ data.

Figure 2. Display Manufacturer's Metal Etch Line

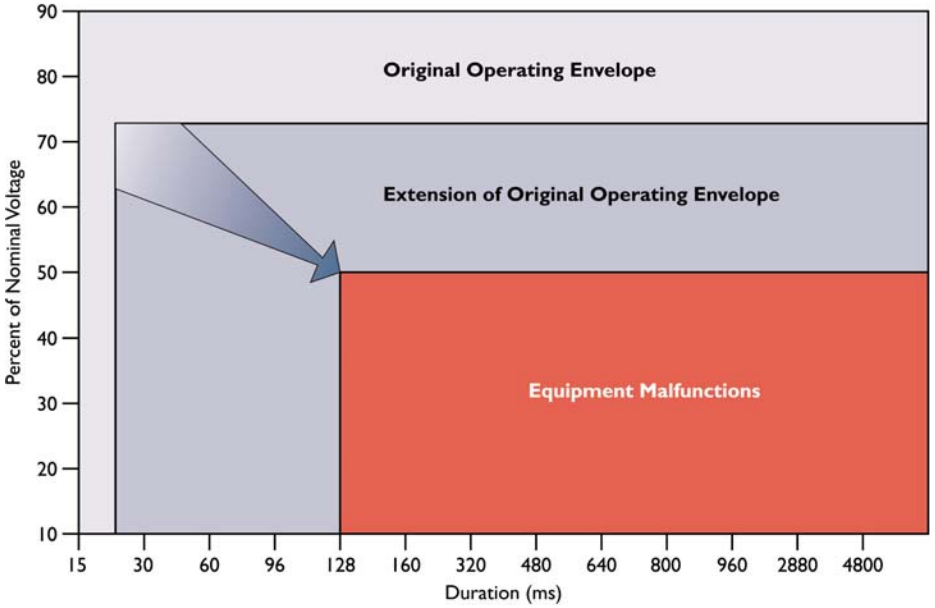


This concept of hardening plant processes to PQ disturbances is sometimes referred to as *extending the operating envelope*. Extending the operating envelope of equipment simply means making the equipment more tolerant of voltage sags. The sag-tolerance curve shown in **Figure 3** has two areas. The area under and to the right of the curve represents the area in which voltage sags cause the equipment to malfunction. The area above and to the left of the curve is called the *operating envelope*, which encompasses the voltage sags that the equipment can tolerate.

Extending the operating envelope of equipment equates to reducing the area of equipment malfunctions by enabling the equipment to ride through deeper and longer voltage sags. For example, the programmable logic controller (PLC) in **Figure 3** was modified by adding power conditioning to enhance its ability to ride through voltage sags. Before the modification, sags less than 72% of nominal voltage lasting longer than 25 milliseconds (ms) would cause the PLC to malfunction. After the control-level solution was implemented, the PLC could ride through voltage sags as low as 50% of nominal voltage and as long as 128 ms.

EPRI research has shown that low-cost modifications can be made to existing process equipment to make manufacturing processes more robust against voltage sags. This investigation identified voltage sag-sensitive components in manufacturing process equipment and applied techniques to make the equipment more compatible with the electrical environment.

Figure 3. Example of Extending the Operating Envelope of a Programmable Logic Controller



BACKGROUND: PQ DATA

As a part of this study, EPRI reviewed voltage sag power quality data supplied by the local utility. A total of 247 voltage sag events were recorded by the utility from April 1, 1997 through March 31, 2004. The PQ data was recorded at the substation that feeds the LCD plant. The LCD plant is one of several loads fed from the 66-kV subtransmission-level voltage, as shown in **Figure 4**.

Because the PQ data is recorded at the secondary of the substation that feeds the LCD plant, it is a good representation of events that would be seen at the plant’s service entrance. A scatter plot of the recorded voltage sag data is shown in **Figure 5**.

Figure 4. Site Feeder Arrangement

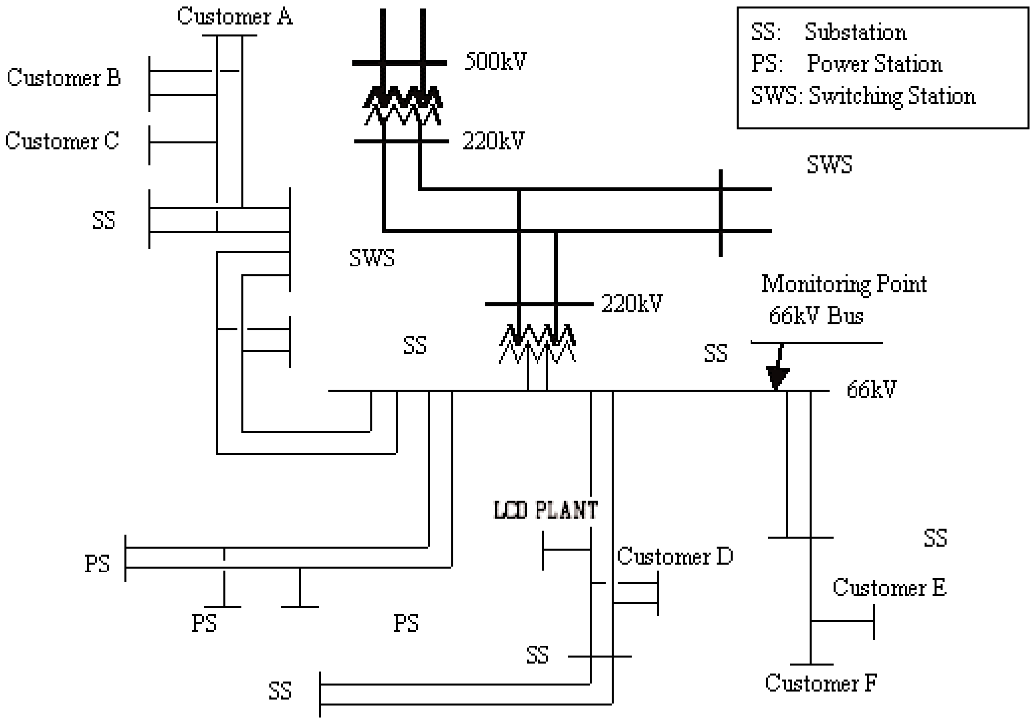
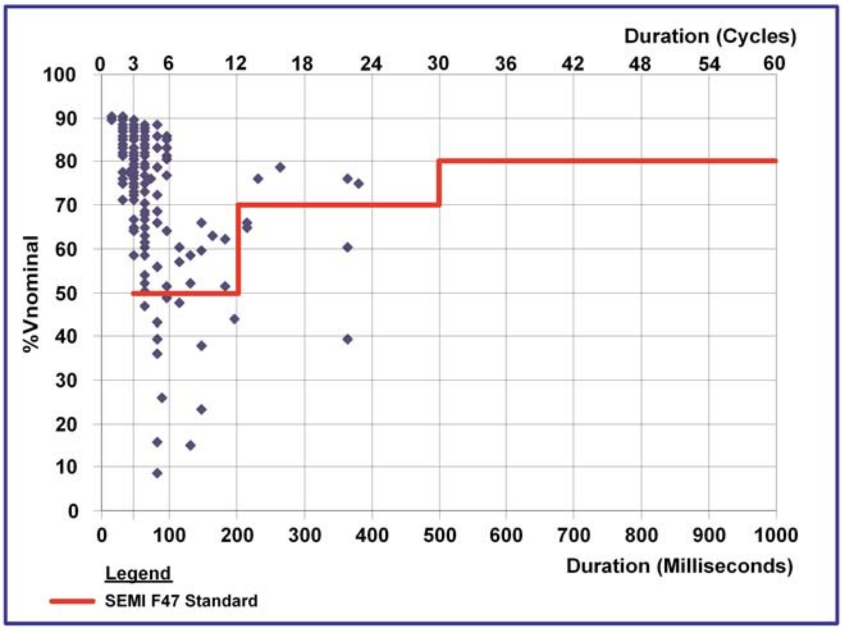


Figure 5. LCD Plant's Seven-Year Voltage Sag Dip History



Seven years' worth of PQ data is summarized in Table 1. Because no outages are recorded in the data, one can determine that the local utility power supply to the plant is highly reliable. However, there are numerous PQ events during the monitoring period. The data summary shows that the average voltage sag seen by the facility is 7 ms in duration with a magnitude of 76% of nominal voltage.

Table 1. Summarized PQ Data for LCD Plant

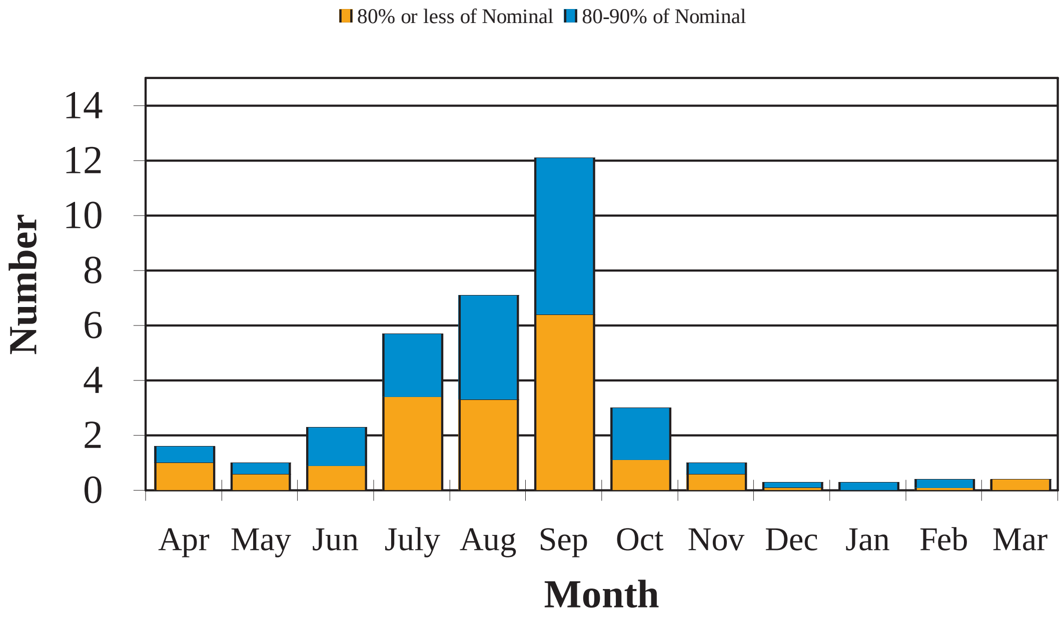
Site	LCD Plant Substation
Designation	LCD Plant
Monitor Years	7
SARFI 50	2.3
SARFI 70	7.3
SARFI 80	17.0
SARFI 90	32.9
SARFI SEMI	2.9
Average Sag Magnitude (%)	76.1
Average Sag Durations (ms)	6.6
Median Sag Magnitude (%)	80.0
Median Sag Duration (ms)	49.0
Maximum Sag Duration (ms)	383.0

The System Average RMS (Variation) Frequency Index (SARFI) is also shown for various levels. SARFIx represents the average number of specified RMS variation measurement events that occurred over the assessment period per customer served, where the specified disturbances are those with a magnitude of less than x for sags or greater than x for swells. For the purposes of this study, these indices will be used to calculate SARFI for sag event data only.

For example, SARFI 50 will produce the average number of voltage sags that occurred over the assessment period that were below 50% of nominal. Furthermore, one can apply the same concept to evaluate the number of events that would occur below a voltage sag standard curve such as SEMI F47. This index is typically referred to as $\text{SARFI}_{\text{SEMI}}$. Based on analysis of the dataset, 2.9 events per year are expected to fall below the SEMI F47 curve.[3] Therefore, if all equipment were SEMI F47-compliant, there would still be about three events per year that could shut down the process. It is also important to note that the longest voltage sag recorded during the seven-year period was 383 ms.

The frequency of voltage sags at the LCD plant is related to seasonal changes. Historically, voltage sags increase in the spring months, occur throughout the summer, and peak in September (**Figure 6**). During this time frame, the number of events above 80% of nominal is roughly equal to the number of events below 80% of nominal voltage.

Figure 6. Number of Voltage Sag Occurrences at the Local Utility's Substation Near LCD Plant (Apr. 1, 1997-Mar. 31, 2004)



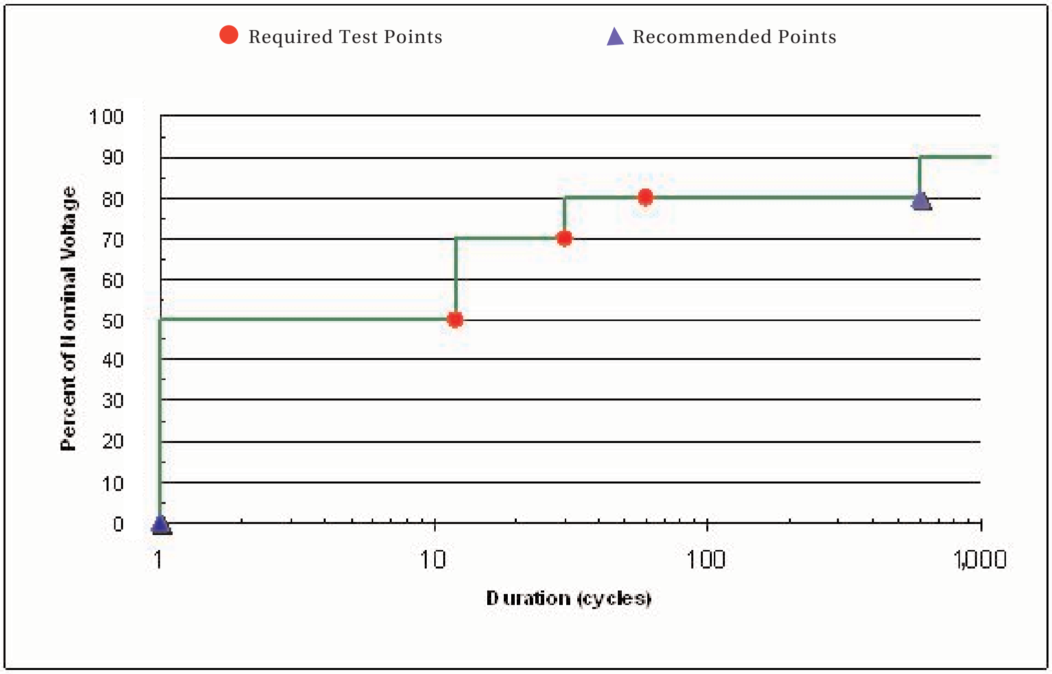
PQ STANDARDS AND THEIR APPLICABILITY TO THE DISPLAY INDUSTRY

The most well-known PQ voltage sag immunity curves are those provided by ITIC, IEC 61000-4-11/34, and the SEMI F47 standards. The Information Technology Industry Council (ITIC) curve was specifically developed for single-phase data-processing equipment. It is an update to the curve developed previously by the Computer Business Equipment Manufacturers Association (CBEMA) that also appears in IEEE Standard 446 (Orange Book). These curves apply to single-phase equipment operating at 120 volts. The IEC 61000 is a European standard that defines the immunity test methods and range of preferred test levels for electrical and electronic equipment connected to low-voltage power supply networks for voltage sags, short interruptions, and voltage variations.[3] This curve is similar to the ITIC curve and the SEMI curve that is explained next.

The SEMI organization represents manufacturers of semiconductor chips. This industry utilizes equipment in critical processes; disruptions to those processes have very expensive impacts. The SEMI F47 curve shown in **Figure 7** was adopted by the semiconductor industry in 1999.[4] The standard applies to single- and two-phase voltage sags at the desired test levels. Many devices in the marketplace meet this standard. In developing this ride-through specification, SEMI evaluated actual disturbances at semiconductor manufacturing facilities from around the world and identified that there was a significant number of voltage sags where the minimum voltage is less than the 70% specified on the ITIC curve. Therefore, the ITIC ride-through specification was modified so that equipment should be able to tolerate voltage sags with a minimum voltage down to 50% as long as the voltage sag duration lasts less than 200 ms. This duration is selected because most faults (especially faults on transmission lines and cables) are cleared in less than 200 ms.

Though the standards mentioned above are excellent ones for hardening plant processes to PQ disturbances, especially voltage sags, it is important to note that they were developed to address specific classes of electrical equipment (as in the case of ITIC and IEC 61000-4-11/34) or specific industry sectors (SEMI F47 for the semiconductor industry). It would therefore be prudent to assume that the display manufacturer industry should be examined to study the potential susceptibility of equipment used in its plants. This would allow either the development of a standard more specifically suited to the LCD industry or the adaptation of SEMI F47 for this industry. Selecting an appropriate standard is especially important as the display industry ramps up production to meet the accelerating popularity of LCD TVs and displays. Because the display industry uses processes similar to those in the semiconductor industry, SEMI F47 was used as the applicable standard for this PQ study.

Figure 7. The New F47-0706 Standard



PQ EVALUATION OF PLANT

A detailed, two-stage investigation of the susceptibility of the plant was carried out as part of the audit. Stage one consisted of on-site and off-site testing of critical components; stage two entailed a detailed PQ walk-through of the plant.

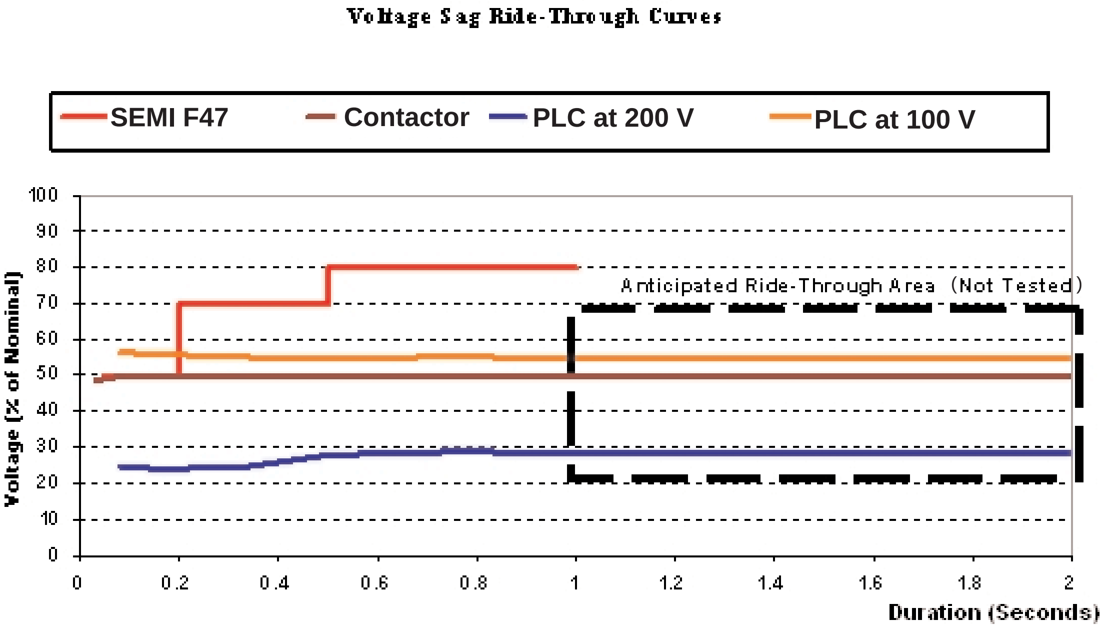
On-Site and Off-Site Component Testing

Many of the plant lines share components that are identified as being susceptible to voltage sags. During the on-site visit, EPRI conducted voltage sag testing of representative components in order to estimate the ride-through of the process equipment.

On-site testing consisted of one power supply, one PLC, and one electric contactor. The voltage sag testing showed that the contactor could ride through voltage dips down to 50% nominal, starting at 2 cycles. The PLC, at 200 V, could ride through voltage dips down to 25% to 30% nominal. The same PLC was tested at 100 V and could only ride through voltage sags down to 55% nominal. The ride-through curve in **Figure 8** shows the sensitivity of the contactor and PLC at 100 V and 200 V. Testing showed that connecting the 100-V to 200-V power supply to a 200-Vac power source would increase ride-through of the PLC from 55% nominal to 25% nominal.

All the machines evaluated during the audit had PLCs from the same manufacturer, but not all were the same type. Even though they differed, the results can be used to correlate how PLCs in the field would respond to similar voltage sags.

Figure 8. On-Site Voltage Sag Testing: Test Component Ride-Through Curve



At EPRI, additional components for some of the machines investigated were tested after the on-site visit. The ride-through curve for some of the relays tested at EPRI can be found in **Figures 9** and **10**. The testing revealed that some of these relays are susceptible to voltage sag disturbances similar to the ones that occurred at the display manufacturer’s plant.

Figure 9. Off-Site Voltage Sag Testing: Relay A Ride-Through Curve

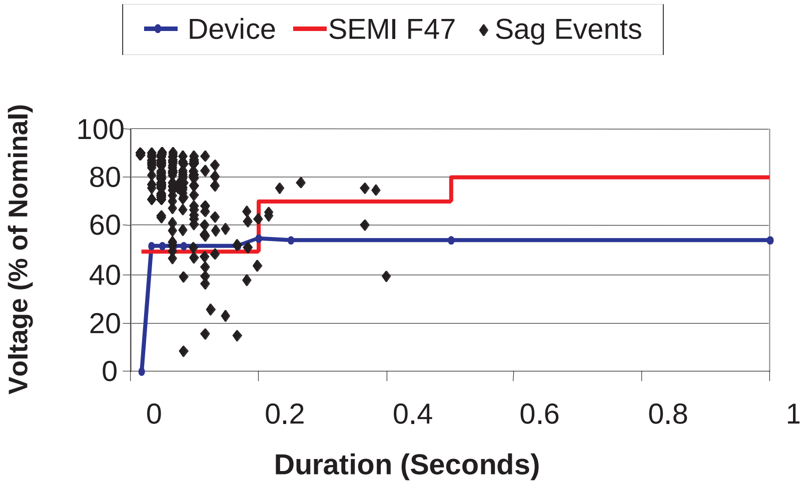
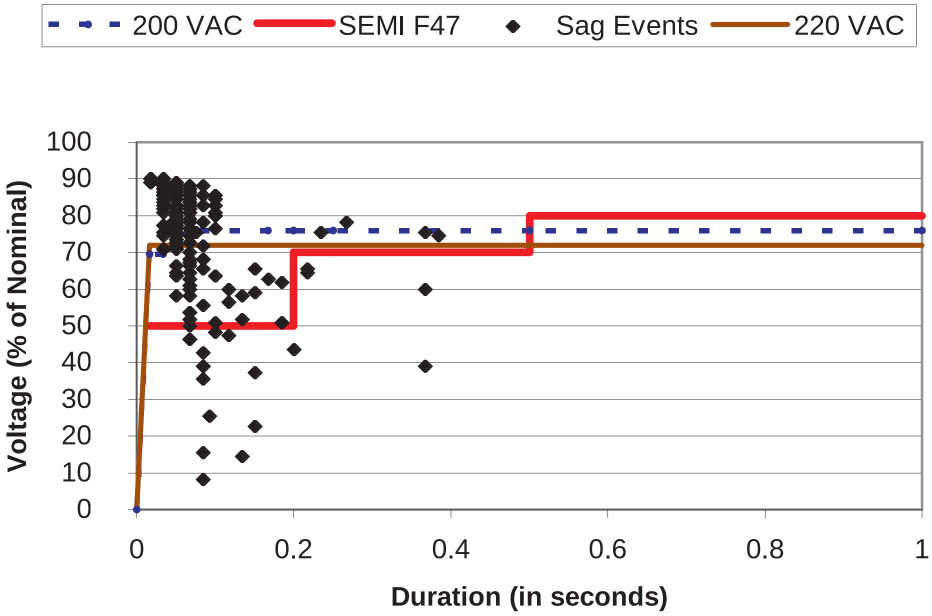


Figure 10. Off-Site Voltage Sag Testing: Relay B Ride-Through Curve



PLANT WALK-THROUGH INVESTIGATION

Next, the PQ team visited the site to verify the accuracy of prints, take power measurements, and confirm their prior identifications of “weak link” circuits and components. This on-site visit was invaluable in that it enabled the engineers to better understand the machines, the plant’s processes, and the customer’s concerns and philosophy. Most importantly, the visit provided the opportunity to meet with plant operators and technicians who could describe the machines’ dynamic performance when subjected to voltage sags—critical information that can’t be found in electrical drawings. A total of 13 machine process (depicted in **Figure 2**) were analyzed. As an example, the audit of one machine, the loading machine, is presented here.

During the on-site visit, the loader was “loading” material into the metal etch processing line. Some of the components identified as being potentially sensitive to voltage sags include PLCs, critical relays, AC power supplies, circuit breakers, and robots. Some of this equipment, especially the robot (**Figure 11**), is considered critical for the manufacturing process and must be protected from PQ disturbances. Similar sensitive equipment can also be expected on other processes.

Figure 11. Robot Used in Loading Process

IDENTIFYING MITIGATION MEASURES

Following the site visit, the PQ team got to work on finding the best technical and most cost-effective power quality solutions for the 13 process machines. Three possible approaches were considered:

- *Control-level solutions—the lowest-cost option*. This approach involves installing small power conditioners only on specially selected critical control circuits.
- *Machine-level solutions—using three-phase power conditioners to protect an entire machine*. This approach is considerably more expensive because solutions must be sized for the power drawn by the entire machine, not just its controls.
- *Panel-level solutions—strategically placing large-scale power conditioners on distribution panels to protect entire processes*. Although generally much more costly than other options, this solution is not as expensive as conditioning power for an entire facility.

The example of the loading process explained in the previous section is again presented here as an example. Recommendations were made to address three different areas of protection. The first recommendation was made at the control level, the second addressed the machine level, and the third addressed the panel level.

R1: Control-Level Recommendation for Loading Process

The objective of the control-level recommendation is to protect sensitive components of the machine by placing power conditioners as close to the identified sensitive component as possible. The most critical control loads are the PLC power supply and the DC power supply (which provides 24-Vdc power to all PLC I/O cards and sensors). On-site testing of the PLC showed that this PLC is likely to ride through voltage sags down to 25% nominal. The PLC and DC power supply are both powered from a common circuit breaker. The current on the breaker was measured at 0.5 A and 207 V. The calculated full load current of the breaker is 1.72 A. The manufacturer's rated current for this load is 2 A. The recommendation is to install either a 5-A momentary line-drop protector (MLP) (rated at 200 V) or a 3-A, 750-VA dynamic sag corrector (rated at 208 V) after the circuit breaker, as shown in **Figure 12**. Both power conditioners are offered because the nominal voltage during the on-site visit was measured between 205 Vp-p and 209 Vp-p. The estimated ride-through curve with either recommended power conditioner is shown in **Figure 13**.

Figure 12. Loader Circuit Breaker: Single-Phase Power Conditioner Location

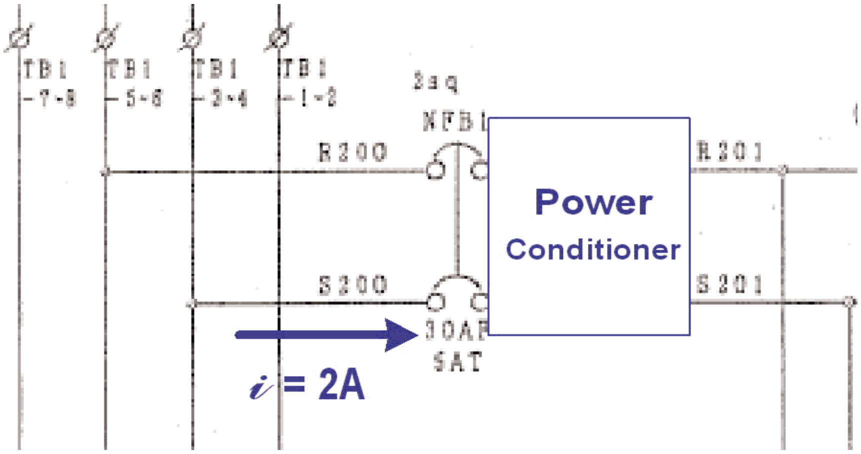
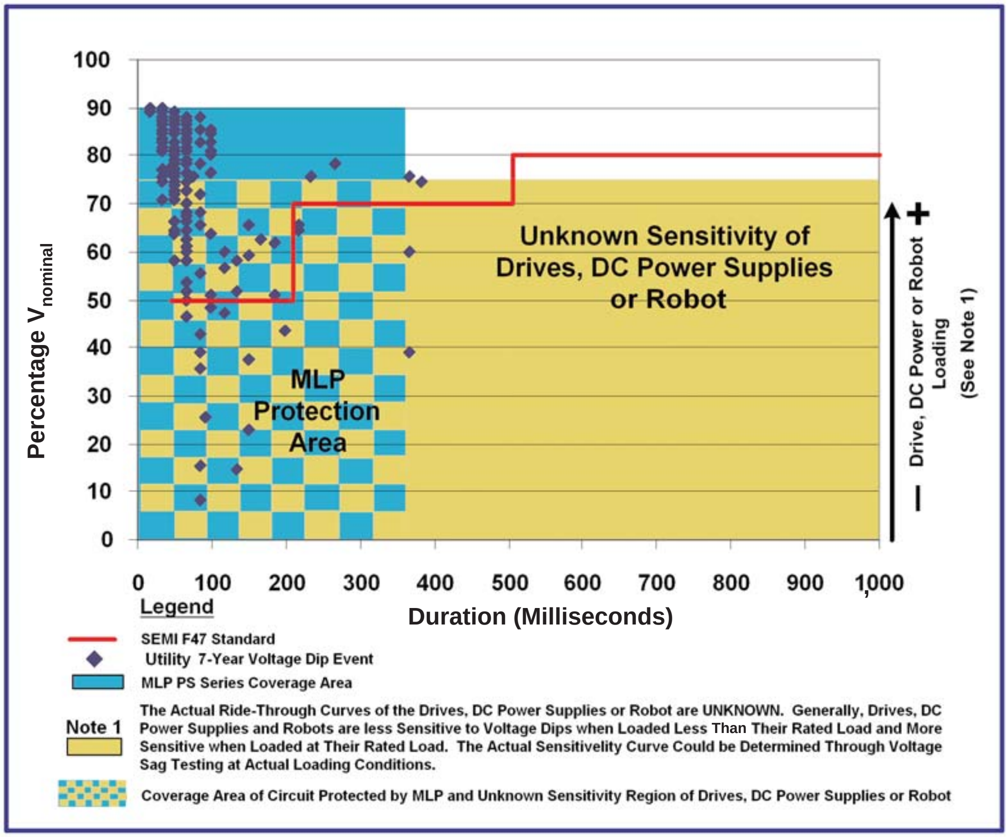


Figure 13. Estimated Ride-Through Curve of Loader with MLP as Recommended in R1



The Actual Ride-Through Curves of the Drives, DC Power Supplies or Robot are UNKNOWN. Generally, Drives, DC Power Supplies and Robots are less Sensitive to Voltage Dips when Loaded Less Than Their Rated Load and More Sensitive when Loaded at Their Rated Load. The Actual Sensitivelity Curve Could be Determined Through Voltage Sag Testing at Actual Loading Conditions.

The robot is rated at 2 kVA, 200 V, three-phase. A three-phase 5-kA MLP could protect just the robot. The 5-kVA MLP could be installed in series with the three-phase power as shown in **Figure 14**. The estimated ride-through curve of the loader with the MLP on the robot is shown in **Figure 15**.

Figure 14. Loader Robot: Three-Phase Power Conditioner Location

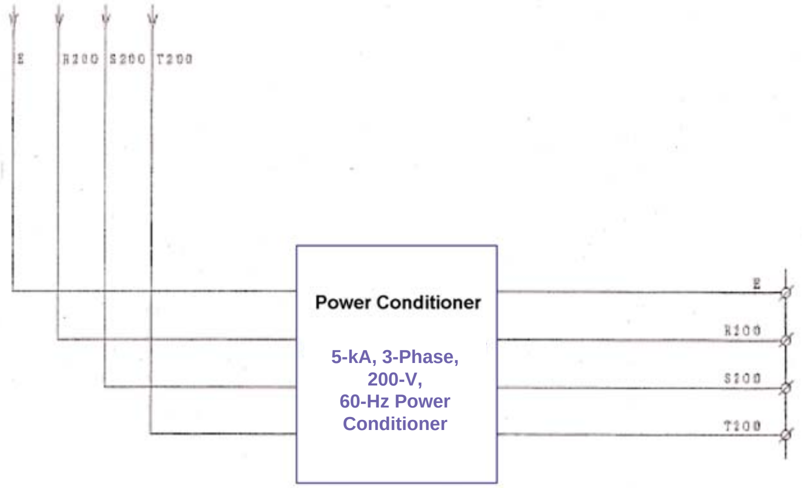
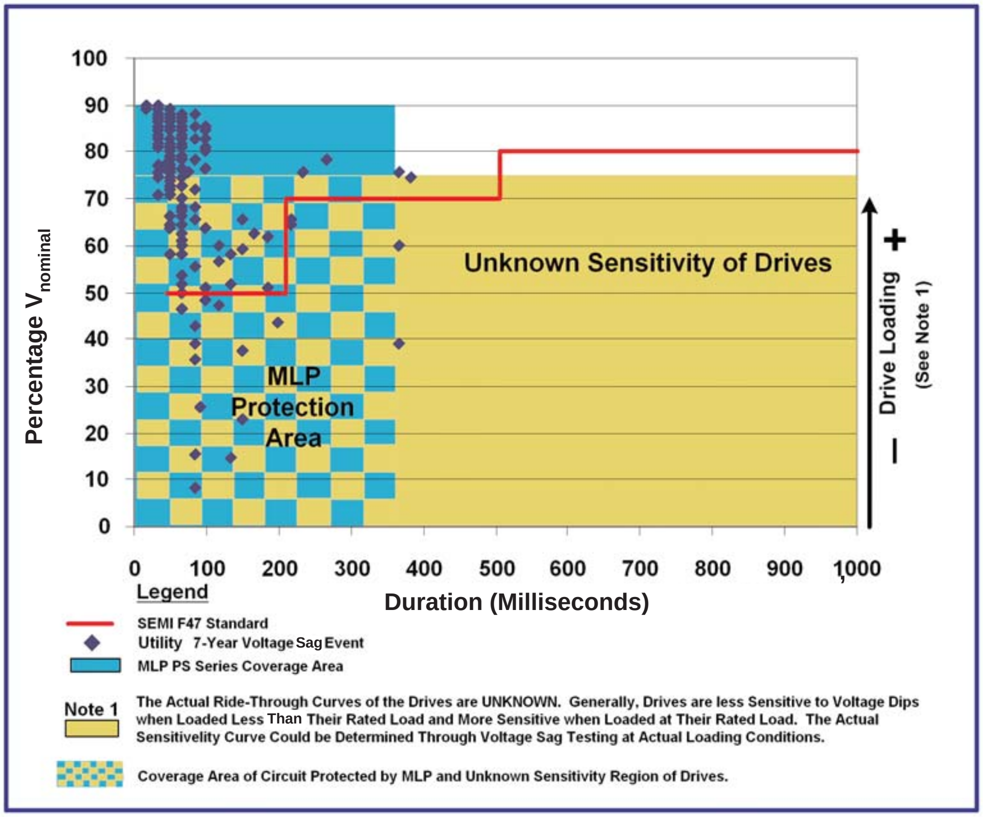


Figure 15. Estimated Ride-Through Curve of Robot with MLP as Recommended in R1



R2: Machine-Level Recommendation for Loading Process

The loading machine can be protected with a three-phase power conditioner installed between the metal etch power distribution panel, shown in **Figure 16**, and the 30-A breaker. There are two companies that provide three-phase batteryless power conditioners (MLP and dynamic sag corrector) at the 5-kVA level. The difference between the two conditioners is the area of protection and cost, which also corresponds to the area of protection. The protection offered by the dynamic sag correction device is shown in **Figure 17**.

Figure 16. Metal Etch Loader: Power Feed Circuit Breaker (from Metal Etch Distribution Panel)

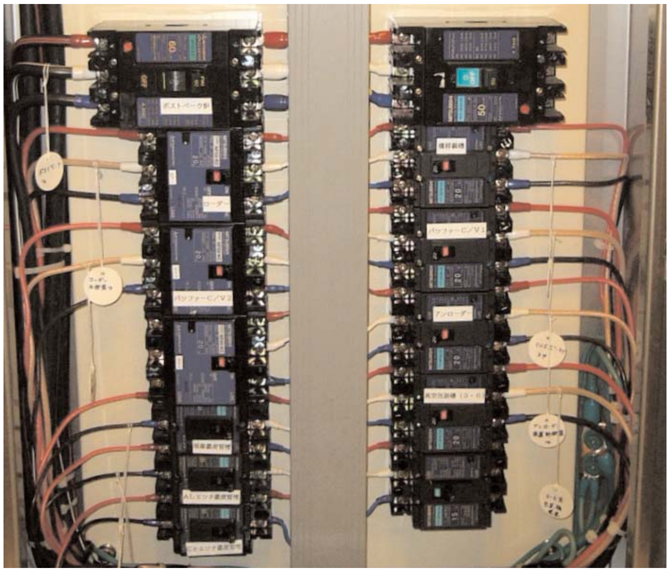
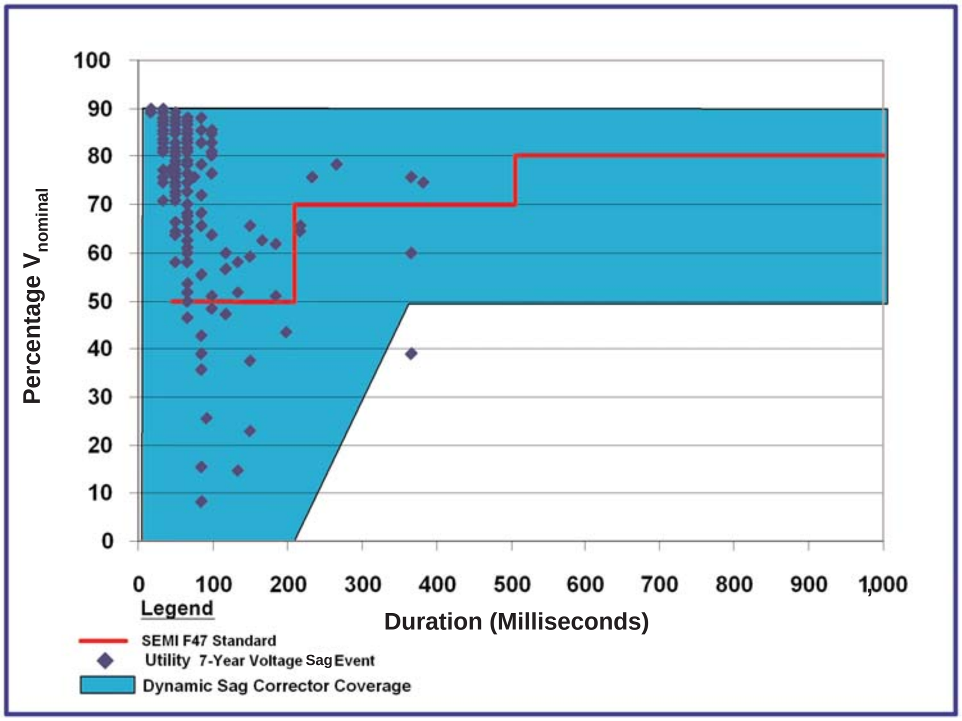


Figure 17. Estimated Ride-Through Curve of the Loader with a Dynamic Sag Corrector Associated with Recommendation R2



R3: Panel-Level Recommendation for Complete Line

This level of protection protects the entire metal etch line, including the loading process. The entire line is fed from a single distribution panel. All the processes, including loading, constitute a total load of 118 A. In addition to the 118-A load, there are three other three-phase loads protected by 20-A circuit breakers, fed from the same panel. Including all loads, the total current rating for the metal etch panel is 178 A. The metal etch power distribution panel can be protected with either a 72-kVA, 200-A, 208-V dynamic sag correction device or a 75-kVA uninterruptible power supply (UPS). The estimated ride-through curve for the panel-level recommendation—which includes the unloading, post bake, buffer 1 and 2, return conveyor, and unloading machine—is shown in **Figure 18** for the UPS and **Figure 19** for the dynamic sag corrector.

Figure 18. Estimated Ride-Through Curve for the UPS Metal Etch Panel-Level Recommendation

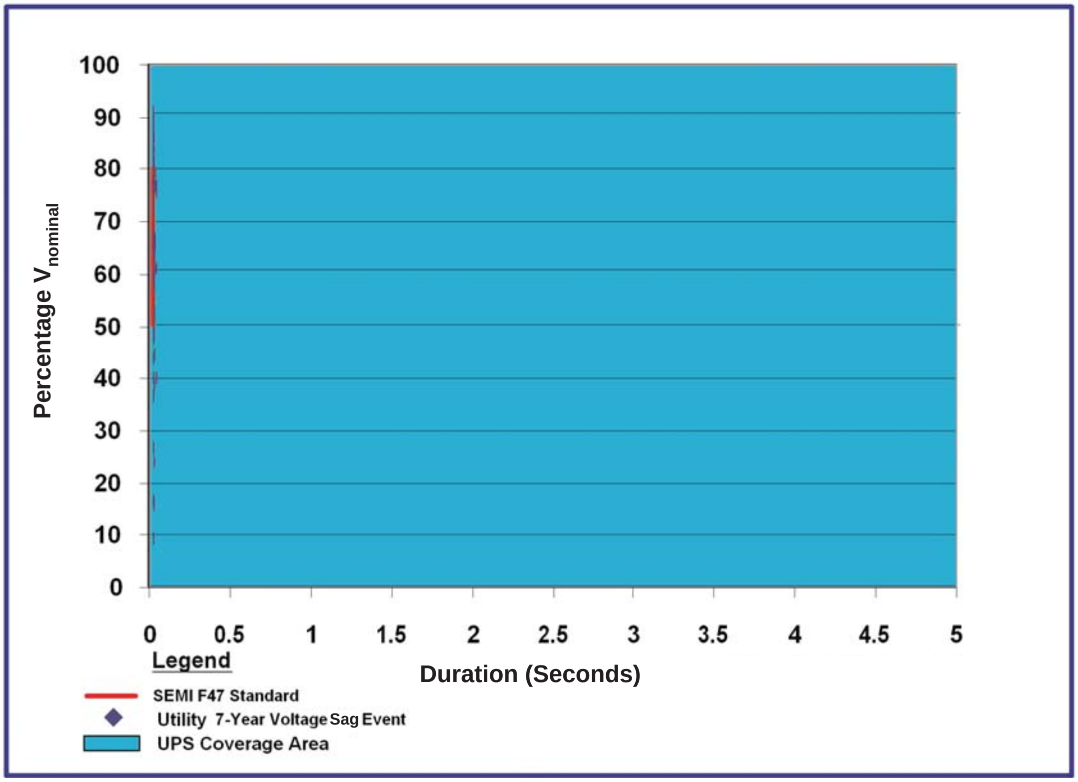
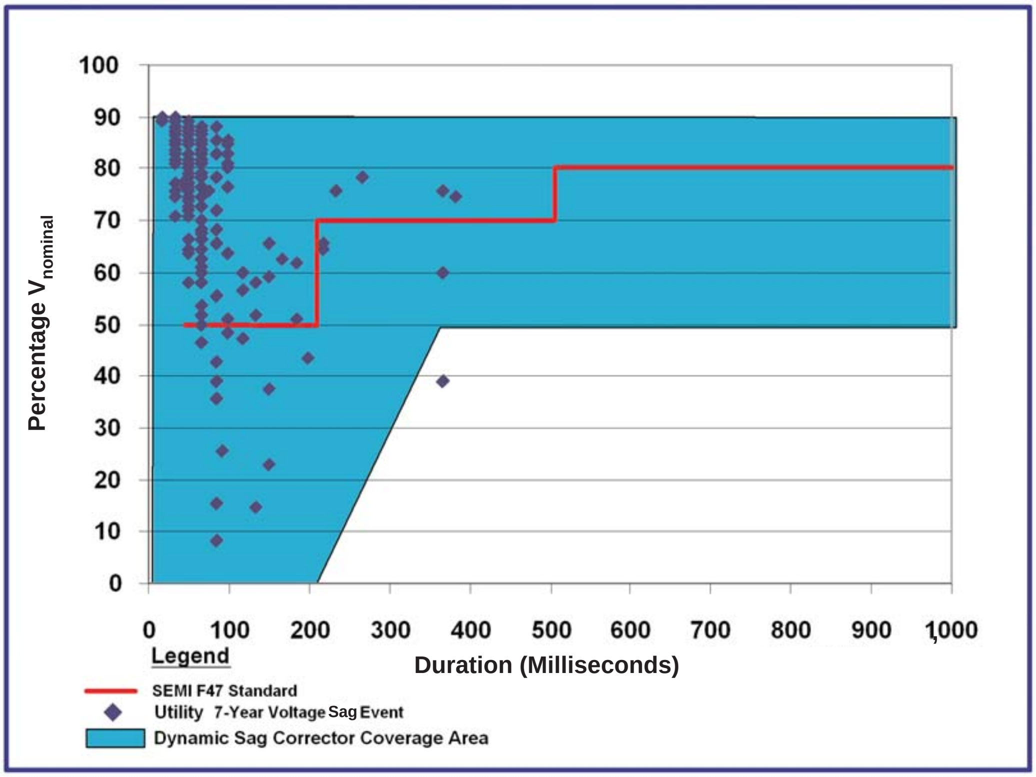


Figure 19. Estimated Ride-Through Curve for the Dynamic Sag Corrector Metal Etch Panel-Level Recommendation



COST AND IMPLEMENTATION OF SOLUTIONS

Figure 20 shows how the cost of power quality solutions can range from the thousands of dollars to millions of dollars. **Figure 21** compares the protection levels provided and costs of the three approaches explained in the previous section. Most notable is that machine-level and panel-level solutions protect against a greater number of voltage sags, albeit at higher cost. Table 2 provides a summary of the costs for mitigating voltage sags on the display manufacturer's equipment within six cost categories.

Initially, the manufacturer had indicated that it wanted to protect the 13 process machines against all of the voltage sags shown in **Figure 21**. The PQ team explained that the cost of doing so would be very high and possibly cost-prohibitive. However, if the customer could accept coverage against all but the most severe voltage sags, the cost could be a fraction of the cost of a solution to protect against all events.

Figure 20. Cost of Implementing Power Quality Solution Varies Greatly Relative to Knowledge of Equipment Sensitivity

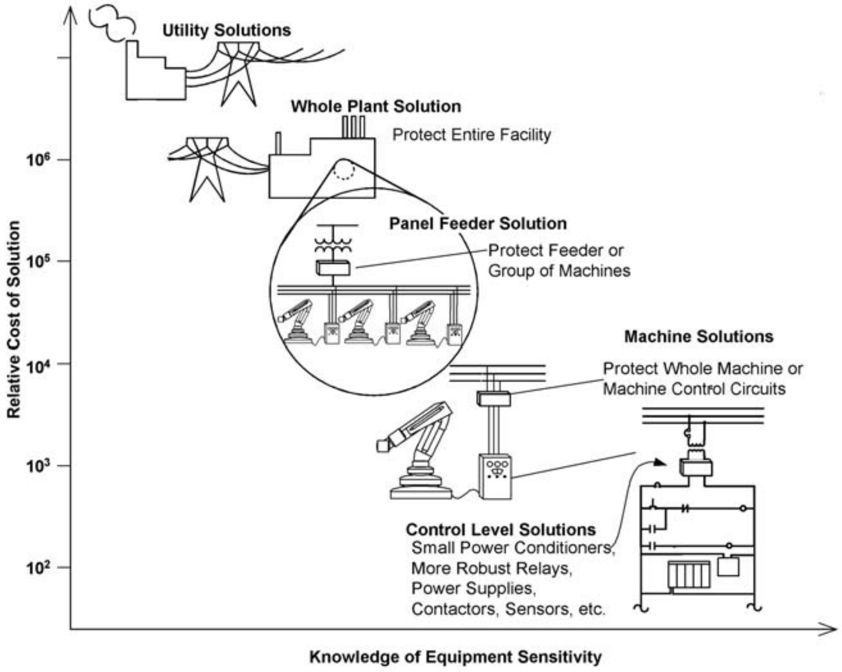
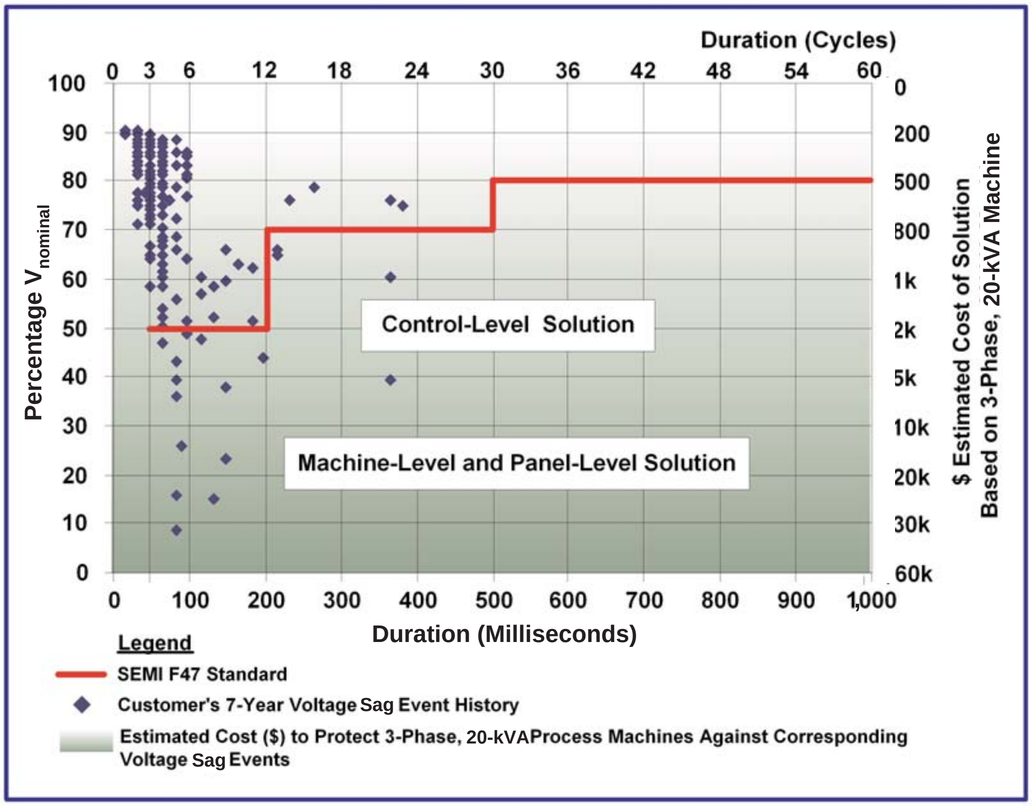


Figure 21. Cost of Solution Relative to Area of Protection



The customer was pleased with the PQ team's recommendations and decided to implement three machine-level solutions and 10 solutions at the control level. **Table 3** summarizes the customer's selections and their costs. The estimated cost for all 13 machines totaled $107,300, representing a savings of over $1 million compared with the option of employing all machine-level solutions. This illustrates the clear economic benefit of employing PQ audits to optimize the selection of solutions that most cost-effectively match the needs of diverse process facilities and the various machines within those facilities.

Table 2. Total Cost Summary for Recommendations

Category	Total Cost for Solutions Presented	Notes
Lowest Cost		
Control-level solutions: Assuming lightly loaded drives, DC power supplies and controllers (mix of different solutions).	$58,239	Assumes lightly loaded system. May still be vulnerable.
Low Cost		
Control-level solutions: Assuming heavily loaded drives, DC power supplies and controllers and using lowest-cost power condition option. (In most cases this is the dynamic sag corrector.)	$149,373	Provides power conditioning for vulnerable circuits. Systems should be greatly improved.
Medium Cost		
Metal etch line distribution panel power conditioning plus all other equipment protected at machine level with lowest-cost option presented.	$350,533	This method is easier to install since the metal etch line loads (all machines) are consolidated.
High Cost		
Machine-level solutions: Machine-level power conditioning on all machines with lowest-cost power conditioner. (In most cases this is the dynamic sag corrector.)	$374,871	This method is comprehensive but requires a machine-level power conditioner at each of the 13 machines.
Higher Cost		
Control-level solutions: Assuming heavily loaded drives, DC power supplies and controllers and using highest-cost power conditioner. (In most cases this is the MLP.)	$457,980	If the MLP is used exclusively for control-level loads, it is not an economical choice since the price per unit is high compared to the dynamic sag corrector.
Highest Cost		
Machine-level power conditioning on all machines with highest-cost power conditioner. (In most cases this is the MLP.)	$657,912	This method is comprehensive but requires a machine-level power conditioner at each of the 13 machines.

Table 3. Solution Recommendations Selected by Customer

Process Equipment	Solution Selected	Total Three-Phase Load of Machine	Cost of Solutions Selected by Customer	Estimated Cost for Machine-Level Solutions
Machine 1	Machine-level	4 kVA	$24,000	$24,000
Machine 2	Control-level	22 kVA	$4,000	$55,000
Machine 3	Control-level	4 kVA	$2,400	$24,000
Machine 4	Control-level	3 kVA	$4,100	$24,000
Machine 5	Machine-level	4 kVA	$24,000	$24,000
Machine 6	Control-level	55 kVA	$3,500	$150,000
Machine 7	Control-level	72 kVA	$2,500	$150,000
Machine 8	Control-level	45 kVA	$2,500	$115,000
Machine 9	Control-level	45 kVA	$2,500	$115,000
Machine 10	Control-level	103 kVA	$800	$170,000
Machine 11	Machine-level	22 kVA	$24,000	$75,000
Machine 12	Control-level	5 kVA	$3,000	$24,000
Machine 13	Control-level	140 kVA	$10,000	$200,000
Total			$107,300	$1,150,000

SUMMARY

This case study details the audit of an LCD display manufacturer that was facing PQ-related disturbances resulting in significant interruptions to the manufacturing process. The audit entailed a detailed investigation that involved on-site plant walk-through and inspection of select process machines as well as simultaneous PQ testing of electrical equipment deemed most susceptible.

The outcome of this investigation resulted in three levels of solution recommendations: low cost (control level), higher cost (machine level), and highest cost (panel level). The audit focused on analyzing solutions at all three levels to provide multiple options, ranging from protecting only the most sensitive control circuits to protecting the entire line. The manufacturer was given the opportunity to select the degree of coverage desired based on the solution's cost. In this case, the manufacturer picked a combination of different levels of protection, thereby optimizing the cost/reward ratio.

The LCD display industry is a fast-growing industry and, like all other industries, needs to mitigate process delays caused by power disturbances. There are several PQ standards that define equipment immunity to voltage sags. Most of these standards—such as the ITIC, IEC 61000-4-11/34, and SEMI F47—were developed for specific voltage classes or industries. Though the LCD display manufacturing processes are similar to semiconductor processes, it would be useful to conduct a detailed investigation of the PQ immunity requirements for display manufacturers to determine if a new standard should be developed or if an existing standard could be applied to this growing industry.

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