Relevant Case Studies from EPRI’s Power Quality Audits

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Case Studies

1. Case Study Magnet Wire Plant Resolves PQ Issues
2. Industrial Case Study: Monitor Manufacturer
3. Gypsum Board Manufacturer Experiences Sudden Downtime
4. Power Quality Investigation of a Manufacturing Plant
5. Automotive Part Supplier Case Study – Flywheel Applications
#1) Case Study Magnet Wire Plant Resolves PQ Issues
Introduction

• A magnet wire plant experienced voltage-sag-related process upsets on several of its wire manufacturing lines.

• The plant load was approximately 5 MVA and was fed from three 2-MVA transformers.

• In addition to the wire lines, other important process sections of the plant include a rod mill and enamel, lubricant, and mechanical-room systems.

• In order to decrease the susceptibility of the plant to power quality (PQ) disturbances, the local utility supplying the magnet wire plant requested that EPRI provide a detailed PQ audit.

• The PQ audit revealed that several controls were susceptible to power quality disturbances.
Background (1)

• The need to provide reliable power with a steady voltage and frequency has been recognized since the inception of the electric utility industry.

• Voltage sags are the most important power quality variation affecting equipment because statistically they are the most frequent.
  – This was determined in the EPRI Distribution Power Quality (DPQ) study.
  – Lightning strikes, animals, fires, equipment failure, auto and construction accidents, and wind are some of the causes for power system faults.
Background (2)

• Voltage sags, a decrease in RMS voltage at the power frequency for durations of 0.5 cycles to 1 minute, and interruptions are caused by faults (short circuits) on the power system.

• The location of the fault and the power system configuration determine the severity of voltage sags, while the power system protection scheme usually determines the duration.

• Below is a voltage sag characterized by a duration of four cycles and a depth of 50%.

![Voltage Sag Diagram]
Background (3)

- In the United States, a typical voltage sag is:
  - 6–10 cycles (100–167 milliseconds) in duration
  - Greater than 60% to 70% of nominal voltage in magnitude
  - Typically single-phase and appears in either one or two phases inside the plant.

- A momentary interruption occurs when the supply voltage decreases to less than 10% of nominal for a period of time not to exceed 1 minute.
  - These Interruptions are measured by duration since the voltage magnitude is always less than 10% of nominal.
  - Typical duration for interruptions is 30–120 cycles (0.5–2.0 seconds) and depends on recloser fault clearing time.
Background (3)

• The magnet wire plant is supplied by a local substation that is fed from a tapped 115-kV transmission line jointly owned by two other utilities.

• The “scatter plot” below shows the voltage sags experienced by the plant from April 2000 to October 2001.
  – It is a composite of single-phase data from the 115-kV line and the plant’s incoming transformer voltage.
  – The PQ data was recorded by two digital fault recorders (A and B).

• Analysis of the data reveals that the magnet wire plant had reported upsets for voltage sags ranging from 3 cycles, 78% of nominal voltage to 18 cycles, 89% of nominal.
The magnet wire plant utilizes programmable logic controllers (PLC) and AC drive technology as the backbone of the control systems.

Typically, the characteristics of a robust PLC-based control system are:
- DC-powered PLC power supply
- DC-powered input/output (I/O) and control power
- Robust AC drives

A scoring system was used to evaluate the susceptibility of various manufacturing lines in the plant to power quality disturbances.

### Summary of Power Quality Attributes for PLCs and AC Drives

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Power Quality Influences</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLC</td>
<td>DC-Powered Rack Power Supply Enhances PQ Robustness (+1)</td>
</tr>
<tr>
<td></td>
<td>AC-Powered Rack Power Supply Decreases PQ Robustness (−1)</td>
</tr>
<tr>
<td></td>
<td>DC Powered I/O Enhances PQ Robustness (+1)</td>
</tr>
<tr>
<td></td>
<td>AC Powered I/O Decreases PQ Robustness (−1)</td>
</tr>
<tr>
<td>AC Drive</td>
<td>DC Bus Trip Level Set Low (60% Range) Enhances PQ Robustness (+2)</td>
</tr>
<tr>
<td></td>
<td>DC Bus Trip Level Set High (80% Range) Decreases PQ Robustness (−2)</td>
</tr>
<tr>
<td></td>
<td>Lightly Loaded AC Drive Enhances PQ Robustness (+1)</td>
</tr>
<tr>
<td></td>
<td>Heavily Loaded AC Drive Decreases PQ Robustness (−1)</td>
</tr>
</tbody>
</table>
Plant Power Quality Assessment (2)

• Based on this summary table, it is apparent that the magnet wire plant uses a large number of drives.

• The PQ audit revealed that several PLCs and I/Os are AC powered, making them susceptible to voltage sag events.

<table>
<thead>
<tr>
<th>System</th>
<th>Plant Area</th>
<th>Number of Lines</th>
<th>PLCs (total per system)</th>
<th>AC Drives (total per system)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process Systems</td>
<td>Rod Mill</td>
<td>1</td>
<td>3</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Horizontal Oven Lines</td>
<td>56</td>
<td>70</td>
<td>352</td>
</tr>
<tr>
<td></td>
<td>Vertical Oven Lines</td>
<td>12</td>
<td>16</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>Enamel System</td>
<td>1</td>
<td>1</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Lubricant System</td>
<td>1</td>
<td>1</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Machine Room</td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>91</td>
<td>426</td>
<td></td>
</tr>
</tbody>
</table>
The weighted calculations for each process area’s PQ performance is scored based on the system discussed earlier.

Scores of zero or less are susceptible to voltage sags and all others have some degree of robustness.

### Weighted Score Assessment of Various Manufacturing Lines in Magnet Wire Plant

<table>
<thead>
<tr>
<th>Plant Area</th>
<th>Number of Lines</th>
<th>PLCs</th>
<th>AC Drives</th>
<th>Plant Area PQ Score</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>AC I/O?</td>
<td>DC I/O?</td>
<td>DC PLC Rack Power Supply?</td>
</tr>
<tr>
<td>Rod Mill</td>
<td>1</td>
<td>No</td>
<td>Yes +1</td>
<td>Yes -1</td>
</tr>
<tr>
<td>Horizontal Oven Lines</td>
<td>56</td>
<td>No</td>
<td>Yes +1</td>
<td>No</td>
</tr>
<tr>
<td>Vertical Oven Lines</td>
<td>12</td>
<td>No</td>
<td>Yes +1</td>
<td>No</td>
</tr>
<tr>
<td>Enamel System</td>
<td>1</td>
<td>Yes -1</td>
<td>Yes +1</td>
<td>Yes -1</td>
</tr>
<tr>
<td>Lubricant System</td>
<td>1</td>
<td>Yes -1</td>
<td>Yes +1</td>
<td>Yes -1</td>
</tr>
<tr>
<td>Mechanical Room PLC</td>
<td>1</td>
<td>Yes +1</td>
<td>Yes -1</td>
<td>No</td>
</tr>
</tbody>
</table>
Recommendations for Hardening Magnet Wire Plant to Power Quality Disturbances

- A detailed assessment and inspection of various electrical controls in the magnet wire plant revealed that several manufacturing lines were susceptible to power quality disturbances.
- The audit recommended all possible options with particular emphasis on low-cost modifications by changing AC drive firmware and adding small power conditioners to control circuits in the plant.
- Power quality solutions can range from thousands of dollars to millions of dollars.
Recommendations for Hardening Magnet Wire Plant – Distributed Power Conditioning

- A number of controls in the magnet wire plant are fed from AC power.
  - One recommendation is to provide small “batteryless” power conditioners for equipment supplied by AC control transformers.
  - The power conditioners can be installed on the secondary side of the control power transformers.

Example Batteryless Power Conditioners

CVT and PowerRide RTD, DPI and VDC, DySC
Recommendations for Hardening Magnet Wire Plant – Firmware Upgrade

- The magnet wire plant uses several AC drives of a single make.
- AC drives are susceptible to voltage sags in which the DC bus level drops to 81% of nominal or less.
  - Test results at EPRI in the past indicate lowering the DC bus trip level will greatly increase the ride-through.
- Each drive must be retrofitted with a new language module firmware revision to allow a lower DC bus voltage trip setting to 50%.
- This is a typical low-cost solution as firmware upgrades are relatively inexpensive.
Cost-Benefit Analysis of Recommended Power Quality Improvement Solutions

• Below is a summary of the recommendations and estimated typical costs based on the first two recommendations in the previous slides (distributed power conditioning and firmware upgrades).

• For the purposes of cost calculation for the third recommendation (using a centralized power conditioning system), a mid-range price of $300 per kVA will be used.
  – The centralized method equates to roughly $600,000 per 2-MVA transformer or $1.8 million for 3 transformers.

Cost for Distributed Power Conditioning and Firmware Update Recommendations

<table>
<thead>
<tr>
<th>Area</th>
<th>Recommendation</th>
<th>Number Required</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rod Mill</td>
<td>Small batteryless power conditioners</td>
<td>2</td>
<td>$2,780</td>
</tr>
<tr>
<td>Horizontal Lines</td>
<td>Drive firmware upgrade kit</td>
<td>352</td>
<td>$70,400</td>
</tr>
<tr>
<td>Vertical Lines</td>
<td>Drive firmware upgrade kit</td>
<td>72</td>
<td>$14,400</td>
</tr>
<tr>
<td>Enamel System</td>
<td>Small batteryless power conditioners</td>
<td>1</td>
<td>$1,690</td>
</tr>
<tr>
<td>Lubricant System</td>
<td>Small batteryless power conditioners</td>
<td>1</td>
<td>$1,690</td>
</tr>
<tr>
<td>Mechanical Room Systems</td>
<td>Small batteryless power conditioners</td>
<td>1</td>
<td>$1,690</td>
</tr>
<tr>
<td></td>
<td>Drive firmware upgrade kit</td>
<td>2</td>
<td>$400</td>
</tr>
</tbody>
</table>

**Total Cost** $93,050
Test Validation of Recommendations (1)

- PQ testing was performed on one selected line to evaluate the actual line susceptibility as well as to validate the low-cost recommendation of upgrading firmware and setting drive bus trip level to 50%.
  - Line testing was conducted to prove firmware upgrades improved the ride-through performance.

- The testing strategy was to characterize the AC drives with the firmware upgrade installed and then test again without the existing firmware revision.

- The voltage sag generator was placed in series with the 480-Vac source and the take-up control.
Test Validation of Recommendations (2)

- The oven was tested at various voltage levels and durations to characterize the ability of the equipment to ride through voltage sags.
- Below lists the test points agreed upon by the team and all voltage sags were performed phase to phase.

### Horizontal Line Take-Up Drive Cabinet

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Sag Duration (60-Hz cycles)</th>
<th>Sag Duration (seconds)</th>
<th>SEMI F47 Ride-Through Curve Sag Depth (% Vnominal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>0.05</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>0.1</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>0.2</td>
<td>50</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>0.5</td>
<td>50</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
<td>1</td>
<td>50</td>
</tr>
</tbody>
</table>
Test Validation of Recommendations (3)

- During the sag testing of the horizontal line with the firmware upgrades, it was discovered that a two-phase sag of any duration to 60 cycles with a magnitude down to 35% nominal would not trip AC drives off-line.
  - Testing below 35% of nominal was discontinued as the inrush current was in excess of 90 amps and might destroy the rectifiers in the drive.

- Similarly, the test was repeated on a line with no firmware updates installed.
  - The unprotected drive yielded its first trip at 12 cycles, 70% nominal by shutting down the drive, thus breaking the magnet wire.

- Repeated testing revealed that the unprotected AC drives tripped more often.
Test Validation of Recommendation (4)

- Based on the testing, sag ride-through curves were compiled.
- **These curves show that a simple update to the drive firmware and resetting of the DC bus trip levels to 50% will significantly harden the line’s susceptibility to voltage sags.**
#2) Industrial Case Study: Monitor Manufacturer
The “Engineering” of Embedded Solution

• Initial dialogue established between plant personnel and utility PQ group.

• Remote gathering of information, plant/equipment one-line diagrams, process upset logs, PQ monitoring data.

• One week investigation at the plant
  – Get buy-in from the process managers
  – Understand the process
  – Talk with the process floor people
  – Evaluate sensitivity
  – Investigate hidden weak links
  – Evaluate solution options
  – Cost benefit analysis
  – Recommendation to process managers
Production Lines

- Line A manufactures 19" CRTs for monitors with provisions for 21"
- Line B manufactures flat panel 19" CRTs for monitors with provisions for 17”.
- Pegasus Line manufactures 17” CRTs for PC monitors.
- 32” line manufactures TV CRTs.
- 27” Line manufactures TV CRTs
- 20” Line manufactures TV CRTs.
## Financial Impact of Three Events

<table>
<thead>
<tr>
<th>Date</th>
<th>Impact</th>
<th># of Units Rejected (A)</th>
<th>Downtime in Minutes</th>
<th># of Units missed due to downtime (based on 28 second Mercury Index time) (B)</th>
<th>Total # of Units missed (A) + (B)</th>
<th>Total Cost (based on $180 per unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11/19/98</td>
<td>Power fluctuation caused CS light houses to trip</td>
<td>30</td>
<td>20</td>
<td>43</td>
<td>73</td>
<td><strong>$13,140</strong></td>
</tr>
<tr>
<td>11/23/98</td>
<td>Power Glitch AG, SCR, PII, Lost all screening</td>
<td>73</td>
<td>48</td>
<td>103</td>
<td>176</td>
<td><strong>$31,680</strong></td>
</tr>
<tr>
<td>01/26/99</td>
<td>Power glitch in screening process</td>
<td>44</td>
<td>10</td>
<td>22</td>
<td>66</td>
<td><strong>$11,880</strong></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>147</td>
<td>78</td>
<td>168</td>
<td>315</td>
<td><strong>$56,700</strong></td>
</tr>
</tbody>
</table>
Voltage Sag Characteristics Inside the Plant

Cumulative Histogram for 208V

RMS Voltage Magnitude (in % of Nominal)

Number of Events

110 Total Events

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Type of Events

![Bar chart showing the number of events by type and year from 1994 to 1999. The chart indicates the number of momentary, 3-phase, 2-phase, and 1-phase events for each year.]
Critical Process: Screening

Screening Process Flow Diagram
Sensitive Equipment
How Sensitive?

(Higher Bar Means More Sensitive)

% of Nominal Voltage

<table>
<thead>
<tr>
<th>Component</th>
<th>% of Nominal Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>24V DC PS</td>
<td>1</td>
</tr>
<tr>
<td>24V DC PS</td>
<td>2</td>
</tr>
<tr>
<td>24V DC PS</td>
<td>3</td>
</tr>
<tr>
<td>PLC @ 208V</td>
<td>4</td>
</tr>
<tr>
<td>PLC @ 120V</td>
<td>5</td>
</tr>
<tr>
<td>PLC @ 208V</td>
<td>6</td>
</tr>
<tr>
<td>PLC @ 120V</td>
<td>7</td>
</tr>
<tr>
<td>PLC @ 120 &amp; 208V</td>
<td>8</td>
</tr>
<tr>
<td>Servo Drive</td>
<td>9</td>
</tr>
<tr>
<td>AC Contactor</td>
<td>10</td>
</tr>
</tbody>
</table>
Embedded Solution

Change PLC Input from AC to DC input.

Use a 3-Phase AC input to 24VDC output Power supply.

If PLC AC power supply is integrated to the Module use a small power conditioning (e.g., Dip Proofing Inverter or CVT).
AC Versus DC Input for PLCs

Figure 1. A rack-mounted PLC power supply that requires AC voltage (120/208-240 volts)

Figure 2. External power supply that provides 24 volts DC to the rack-mounted PLC power supply.
# How Effective is a 3-Phase AC Input to 24V DC output

## Phoenix Contact PS PLC Power Supply unit

<table>
<thead>
<tr>
<th>PLC Power Supply unit</th>
<th>24V DC Source</th>
<th>Loading on 24V DC Source</th>
<th>Voltage Sensitivity Threshold (in %) for 30 Cycle Ride-Through</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Three Phase Sags</td>
</tr>
<tr>
<td>CV500-PS211</td>
<td>Phoenix Contact</td>
<td>20%$^1$</td>
<td>0%</td>
</tr>
<tr>
<td>CV500-PS211</td>
<td>Phoenix Contact</td>
<td>35%</td>
<td>45%</td>
</tr>
<tr>
<td>CV500-PS211</td>
<td>Phoenix Contact</td>
<td>60%</td>
<td>50%</td>
</tr>
</tbody>
</table>

---

1. **CV500-PS211**

   - **PLC Power Supply unit**: Phoenix Contact
   - **24V DC Source**: Phoenix Contact
   - **Loading on 24V DC Source**: 20%
   - **Voltage Sensitivity Threshold (in %) for 30 Cycle Ride-Through**:
     - Three Phase Sags: 0%
     - Two-Phase Sags: 0%
     - Single-Phase Sag: 0%

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### Diagram

- **3-Phase Sag Tester**
- **208V 3-Phase Utility Source**
- **Phoenix Contact 24V DC Power Supply**
- **PLC Power Supply PS211**
- **PLC CPU**
- **I/O Racks**
- **Wire Spool (Additional Load)**
- **31**
How Effective is this Solution?

Impact of Decreasing Voltage Sag Sensitivity of PLC

<table>
<thead>
<tr>
<th>Year</th>
<th>With No Improvement</th>
<th>Reducing Sensitivity of PLC to 50% of Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>1995</td>
<td>12</td>
<td>1</td>
</tr>
<tr>
<td>1996</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>1997</td>
<td>18</td>
<td>1</td>
</tr>
<tr>
<td>1998</td>
<td>15</td>
<td>3</td>
</tr>
</tbody>
</table>
## Targeted Recommendation Based on PLC Type

<table>
<thead>
<tr>
<th>PLC Types</th>
<th>Existing 100-240V AC PLC, I/O Rack Power Supply</th>
<th>Replacement 24V DC Power Supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>CQM1 (Small Range)</td>
<td>• CQM1 PA-203</td>
<td>Not required; Existing power supply can withstand sags down to 30% of nominal voltage</td>
</tr>
<tr>
<td></td>
<td>• CQM1 PA-206</td>
<td></td>
</tr>
<tr>
<td>C200H&lt;sub&gt;α&lt;/sub&gt; (Mid Range)</td>
<td>• PS223</td>
<td>PA204</td>
</tr>
<tr>
<td></td>
<td>• PS22E</td>
<td></td>
</tr>
<tr>
<td>CV Series: 500, 1000, 2000, M1 (Large Range)</td>
<td>• CV500-PS221</td>
<td>• CV500-PS211</td>
</tr>
<tr>
<td></td>
<td>• CV500-PS221</td>
<td>• 3G2A5-PS212-E</td>
</tr>
<tr>
<td></td>
<td>• CVM1-PA208</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• 3G2A5-PS22-E</td>
<td></td>
</tr>
<tr>
<td>C200H, C200HS, C1000H (older model PLCs)</td>
<td>Power Supply Integral to CPU Unit</td>
<td>Not available for PLCs with integral power supply; Requires 500VA DPI unit for PLC and I/O Rack power supply</td>
</tr>
</tbody>
</table>
Lessons Learned

• In designing new process lines use DC input controllers wherever possible.

• Use a robust DC source for all your DC inputs (such as, 3-Phase AC to 24V DC power supply)

• Know the sag immunity of your DC power supplies in your plant.
#3) Gypsum Board Manufacturer Experiences Sudden Downtime
Introduction

• A large gypsum board manufacturer began experiencing voltage sag-related shutdowns in a critical part of its production line related to its paper edge heater (PEH) controls on the front-end of the quarter-mile-long manufacturing line.

• The line had experienced six events in a one-month period that were now shutting down the associated variable frequency drives and controls.

• The puzzling aspect of this problem was that this section was not problematic in the past.

• Working in cooperation with the local utility, EPRI was called in to look at the manufacturing process, determine why these sensitivities were occurring, and offer a solution.
THE MANUFACTURING PROCESS

- In order to make drywall, the gypsum core material must be placed between layers of paper and then dried, finished, and cut into standard sizes.
  - The process takes about 35–45 minutes from initial forming of the sheet in the slurry section to the cutting of the final product to the standard length.

- The manufacturing begins by blending additives together in a slurry. Next the mixture is sandwiched between layers of paper, and edges are formed on the continuous sheet of drywall. It is then cut and dried.

- It was immediately after this initial “sandwich” section that the manufacturer was experiencing shutdowns with the PEH section.
The plant is fed 161 kV from a local substation, which is stepped down to 4.16 kV for distribution throughout the facility.

The plant is fed in a wye-wye arrangement. Therefore, the magnitude of the voltage on the 161-kV side will translated directly to the 4.16-kV side.

The utilization voltage in the plant is stepped down to 480 Vac by other transformers, which are delta-wye in configuration.

The utility had power quality monitoring data from nearby substations, not right at the plant.

The data from the closest substation was used, which was located about 2.5 miles from the gypsum plant’s 161/4.16kV service entrance transformers.
PEH Control Panel Test Setup

- Conducted Voltage Sag Tests from nearby MCC room.
- Due to distance, used a local Dranetz meter setup to trigger on the voltage sag at the panel. Communicated by phone.
- Tests Conducted such that voltage sags were induced on the front end of the UPS that is supporting the control cabinet load.
- Started Tests at 90%, 6 cycles and decreased in 5% increments until trip.
- Continued until controls were found to trip.
PEH Control Panel

- PEH Control panel includes many relays, contactors, and six burner control units.
- Interfaces to separate PLC and Drive via hardwired connection.
- Control voltage supported by a line-interactive UPS.
- A local line conditioner abandoned in place (not used) that was previously for a printer.
- Very dusty environment
PEH Control Panel Test Results

- Control Panel was found to shutdown for an 85% of nominal, 6 cycle voltage sag!
- UPS switched in during voltage sag but was not able to support load for more than 2 cycles.
- Process line was upset and had to be restarted.
• With the UPS malfunctioning, it is not surprising that all of the recent voltage sags seen at the plant had upset this panel.
Why did UPS Fail?

- **The UPS did not show any external signs that there were any operation problems.**
  - The Best Fortress is a line-interactive UPS with tap changer.
  - Voltage is normally passed directly through to the output.
  - The line-fault detection circuit continuously monitors the input and during an outage will seamlessly transfer to inverter (battery power).
  - This inverter is very fast and can actually correct input voltage on a sub-cycle basis.
  - Also located inside is an autotransformer with a boost tap. When a voltage sag appears, the unit will transfer to inverter, change from the nominal to the boost tap, then transfer back to utility power. This is what appears to have happened in this case.
- Theory 1: The boost tap is not working. One reason for this could be a blown fuse on the boost tap. We are not sure if the relays are sealed or not, if not then the dusty environment may have effected the relay. Perhaps a good vacuuming is needed.
- Theory 2: There is a welded relay contact caused a fuse to blow. This seems to be supported by the high frequency pulse near the peak of the first negative half cycle in the plot, which could be due to a shorted turn between the normal and boost taps with the nominal tap winning (the boost tape fuse blows first). Then, near the peak of the second negative half cycle, which starts out looking good on inverter, the UPS transfer to the boost tap and the output collapses.
Other Tests

- Other tests were performed on the associated variable frequency drive, programmable logic controller (PLC), relays, and contactors.

- From the power quality data, it is clear that the malfunctioning UPS that powers the PEH control cabinet was the most significant impact.

- This is followed by the high susceptibility of the 120-Vac input cards, and the various 120-Vac “ice cube” style relays used in the control systems and the motor starters.

- Surprisingly, the most robust sections of the control system are AC variable frequency drives and the PLC rack power supplies.
To make the PEH system more robust to voltage sags, the following recommendations were provided:

1. The UPS used to support the PEH control cabinet must be replaced. The malfunctioning UPS will drop out for voltage sags of 85% of nominal or less, leading to a shutdown of the PEH controls.
   - A new UPS or properly sized CVT would be effective. The estimated cost of the CVT is US$1200.

2. Power conditioning should be provided for both the PLC power supply and the control voltage used by the I/O circuits.
   - In the current scheme used at the facility, only the PLC power supplies are protected by power conditioning.
   - Without power conditioning on the I/O and control power, the controls will remain susceptible.
   - The budgetary cost should be from $1200 to $2500 per each CVT installation.

3. The plant uses many variable frequency drives of the same model that was tested.
   - In order to maximize the driver performance, it was recommended that drive momentary power loss parameters be enabled.
CONCLUSIONS

• The gypsum plant experienced a sudden downturn in the ability of its process systems to ride through voltage sags.

• Specifically, the PEH control area began tripping off-line where it had been historically more robust.
  – Testing and analysis of the related controls revealed that the UPS was not functioning properly even though it showed no external signs of a fault condition.

• This case study reveals a common issue with small UPS systems that begin to malfunction.

• In this case, bypassing the UPS would have allowed the line to ride through two of the power quality events in which it actually shut down.

• **When new power quality problems begin to arise on an existing system, a malfunctioning power conditioner should be considered a likely scenario.**
#4) Power Quality Investigation of a Manufacturing Plant
Introduction (1)

• A manufacturer’s plant had experienced a series of equipment and process downtimes in the second half of 2005 as a result of power quality problems.

• The basic purpose of the power quality audit was to evaluate the most sensitive equipment in the plant and formulate the best approaches that could be taken for hardening the equipment to voltage sags and momentary outages.

• The power quality audit was accomplished by inspecting drawings, doing on-site testing, physically examining the plant equipment and specifications, as well as analyzing plant power quality data.

• The facility contained five critical product lines, numbered as Process Lines 1 through 5.
  – All five product lines were susceptible to PQ disturbances, most notably voltage sags.

• In addition to the product lines, several other areas were vulnerable to voltage sags, including boiler systems, air compressors, conveyor controls, as well as the computer control areas.
Introduction (2)

• Three process lines (1–3) are used as the prime examples for this case study.

• Process line 2 uses an Allen Bradley programmable logic controller (PLC), which is fed by a small, local uninterruptible power supply (UPS).
  – The controls also contain several National Electrical Manufacturers Association (NEMA) style starters as well as six TB Wood’s E-trAC drives.

• In addition, one of the sub panels is powered by a generator that controls four small 120-Vac motors that are use to pull the product out of the oven if the power is lost.
  – This control requires that the PLC remain on-line (via UPS).
  – The PLC operates the small motor starters using generator power through the output card to turn on the motor starters.
Process Line 2 Controls

PLC remote I/O racks, burner controls, numerous AC “ice cube” relays

Drive racks
Process Line 4 and 5

- Process Line 4 and 5 each use a 5-kVA constant voltage transformers (CVT) to provide conditioned power to only a few of the control cabinets.
Power System Overview

• Plant is supplied from a 12-kV industrial feeder.
  – Derived from a 69-kV substation

• Plant is located approximately 0.5 miles from substation.

• Three single-phase reclosers were added on a lateral upstream circuit in July 2005, which should increase the power quality as seen by the manufacturer.
PQ Data and Analysis (1)

• The utility reported events during the time frame from June 25, 2005, through December 2, 2005.
  • These events are tabulated and plotted on the following slide.

• If the equipment in the plant were compliant with the SEMI F47 power quality standard, then only 9 out of 20 events would have affected the plant.

• Furthermore, if the equipment could survive voltage sags down to 30 percent of nominal for 1 second, then only one out of 20 events would have affected the plant
  • Squirrel fault (December 1, 2005, 200-cycle Interruption)
Summary of Power Quality Attributes for PLCs and AC Drives

<table>
<thead>
<tr>
<th>Data</th>
<th>Seg Duration (Cycles)</th>
<th>Worst Case Magnitude of Event</th>
<th>Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/28/2006</td>
<td>2</td>
<td>65%</td>
<td>Storm in area, 165 kW load, wire down</td>
</tr>
<tr>
<td>6/29/2006</td>
<td>6</td>
<td>75%</td>
<td>Storm in area, 165 kW load, wire down</td>
</tr>
<tr>
<td>6/29/2006</td>
<td>5</td>
<td>96%</td>
<td>Storm in area lightning, capacitor bank alarm</td>
</tr>
<tr>
<td>7/2/2006</td>
<td>10</td>
<td>25%</td>
<td>Storm in area lightning</td>
</tr>
<tr>
<td>7/2/2006</td>
<td>11</td>
<td>30%</td>
<td>Storm in area lightning</td>
</tr>
<tr>
<td>7/20/2006</td>
<td>7</td>
<td>60%</td>
<td>Storm in area lightning, fuses blown on East West Circuit</td>
</tr>
<tr>
<td>7/28/2006</td>
<td>9</td>
<td>65%</td>
<td>Storm in area lightning, fuses blown on East West Circuit</td>
</tr>
<tr>
<td>8/3/2006</td>
<td>5</td>
<td>32%</td>
<td>Storm in area lightning</td>
</tr>
<tr>
<td>8/3/2006</td>
<td>6</td>
<td>59%</td>
<td>Storm in area lightning</td>
</tr>
<tr>
<td>8/10/2006</td>
<td>6</td>
<td>82%</td>
<td>Storm in area lightning, trip 6kV line</td>
</tr>
<tr>
<td>8/10/2006</td>
<td>39</td>
<td>93%</td>
<td>Storm in area lightning, trip 6kV line</td>
</tr>
<tr>
<td>8/19/2005</td>
<td>3</td>
<td>52%</td>
<td>Storm in area lightning</td>
</tr>
<tr>
<td>8/19/2005</td>
<td>5</td>
<td>71%</td>
<td>Storm in area lightning</td>
</tr>
<tr>
<td>8/20/2005</td>
<td>38</td>
<td>81%</td>
<td>Storm in area lightning</td>
</tr>
<tr>
<td>8/20/2005</td>
<td>48</td>
<td>67%</td>
<td>Storm in area lightning</td>
</tr>
<tr>
<td>8/20/2005</td>
<td>12</td>
<td>40%</td>
<td>Connector failure on 12kV circuit</td>
</tr>
<tr>
<td>8/22/2005</td>
<td>22</td>
<td>60%</td>
<td>Connector failure on 12kV circuit</td>
</tr>
<tr>
<td>11/27/2005</td>
<td>4</td>
<td>93%</td>
<td>Unknown (subtransmission fault cleared itself)</td>
</tr>
<tr>
<td>12/17/2005</td>
<td>300</td>
<td>0%</td>
<td>Switch in customer substation</td>
</tr>
<tr>
<td>12/20/2005</td>
<td>0</td>
<td>50%</td>
<td>Tree contact with 6kV line</td>
</tr>
<tr>
<td>12/20/2005</td>
<td>8</td>
<td>50%</td>
<td>Racking to try and find fault</td>
</tr>
</tbody>
</table>

*One 200-cycle interruption not shown
PQ Data and Analysis (3)

Based on the equipment used in Process Lines 2 and 3 and the results from previous EPRI tests, it is possible to create an expected ride-through curve.

- Process Lines 2 and 3 would be expected to survive only 5 of the 22 recorded events based on its configuration.
- This worst-case estimate assumes that voltage sags always occur on the most vulnerable phase.

![Expected Response of Process Lines 2 and 3 to Voltage Sags](image.png)

*One 200-cycle interruption not shown*
PQ Data and Analysis (4)

- As a part of this project and recommended by EPRI, an I-Grid power quality monitor has been installed by the manufacturer.
  - Connected to a 480-Vac bus in the generator room.
- The I-Grid has been monitoring power quality information since it was installed on December 14, 2005.
Analysis of Plant Susceptibilities (3)

• The final tests involved using a 1.5-kVA MiniDySC power conditioner on the control loads.

• With the dynamic sag corrector (DySC) installed, the cabinet controls survived a 30-cycle interruption before shutting down.
Summary of Plant Analysis

• The audit revealed that several pieces of equipment had control power sourced from control power transformers (CPTs) or through ice-cube relays, both of which are very susceptible to sags.

• Moreover, the analysis showed that a UPS is not necessarily an effective solution as both a bad and/or slow UPS could result in line trips.
  – A better solution would be to provide a voltage ride-through solution or an active sag corrector, as demonstrated during the tests.
Recommendations

• Based on the results of the analysis, several recommendations were made to improve the plant response to voltage sags such as:
  – Power Conditioners
  – Consolidation of Loads
  – Adjusting Control Parameters
Power Conditioners (1)

- The product lines are spread out with control racks in various locations.

- Ideally, one larger power conditioner would be best; however, with the spread out arrangement, several separate power conditioners may have to be used.

- One recommendation is to use the PowerRide ride-through device (RTD) at appropriate locations.
  - For example, Process Line 4 would need three of these.
    - The first unit would be wound to have both 120-Vac and 480-Vac outputs. The 480-Vac output section will feed the existing CPTs (estimated not to exceed 2.5 kVA), while the 120-Vac output can feed the 120-Vac loads (estimated not to exceed 2.5 kVA).
    - The other two units would be installed in or near the cabinets and are rated at 2 kVA each.
Power Conditioners (2)

PowerRide RTD Recommendation
Power Conditioners (3)

• The PowerRide RTD is basically a three-phase input, single-phase output CVT.
  – Allows the controls to survive single-phase voltage sags and momentary interruptions.
  – For events as severe as momentary interruptions on phases A-B and B-C, the output remains at 100% as long as Phase A-C remains at 66% or more.
  – For voltage sags on phase A-C, one expects a typical CVT response with the voltage dropping off at about 50% of nominal or less.
Power Conditioners (4)

- Given the response of the unit, it is likely that only the one momentary interruption event would have affected the process if this unit were installed on the controls.

*One 200-cycle interruption not shown*
Power Conditioners (5)

- Another option would be to use multiple DySC products.
- It is likely that the units in the plant would only be lightly loaded, therefore pushing the voltage sag ride-through closer to the half-loaded line.
- All but the one momentary interruption would be protected.
- With the use of any of these power-conditioning equipment, the UPS can be removed.

Expected Voltage Sag Response of DySC Power Conditioner

*One 200-cycle interruption not shown*
Consolidation of Loads

• Several loads in the plant are dispersed all over the place.
• These loads can be combined together as several panels are only lightly loaded.
• Such a consolidation would allow more effective use of power-conditioning equipment.
Adjusting Control Parameters

- It is recommended that the adjustable-speed drives be set up for the best voltage sag ride-through performance possible.
- This would allow the adjustment of voltage trip points as well as enabling any voltage sag ride-through features that may have been inherently built into the drive.

**Magnatek GPD 305**

- When a fault occurs during operation, the GPD drive can be programmed for auto-restart using parameter n47.
- The setting of this parameter either enables or disables the ride-thru feature of the GPD 305. The three settings are:
  - 0 = Disabled (Factory setting)
  - 1 = Enabled with a 2 sec ride-thru
  - 2 = Enabled with indefinite ride-thru, provided the control power is maintained.
- When set to “0” there will be no ride-thru available
- If enabled, the 305 will continue to operate during a momentary power loss of up to 80%, but if the loss exceeds the identified time period, the 305 will stop.
Implementation Results (1)

• The plant ultimately decided to deploy the PowerRide RTD technology as the solution.
  – Familiarity of the constant voltage transformer to the maintenance staff played a key role in the decision.

• When the product was installed, a few initial problems were encountered related to matching the peak voltage output of the larger size power-conditioning units with the required peak voltage input for the PLCs.
  – From a root-mean-squared standpoint, the voltages matched.
  – The peak voltage requirement of the PLC was higher than the output of the conditioner.
  – The power conditioning provider and the manufacturer found a workable solution to boost the output to an acceptable level.

• Subsequently, the power conditioner manufacturer changed the design for future builds of the larger power conditioner to provide a higher peak voltage to avoid a reoccurrence in future installations.
Implementation Results (2)

• The plant estimated yearly losses in the $300,000 range due to downtime induced by problems related to power quality.

• Since installation of the recommendations in early June of 2006, the site experienced a total of 103 events as reported by the I-Grid system.

• Of those events:
  – 6 were outages that were mostly weather related
  – The remaining 97 recordings were aggregated into a subset of 40 actual events.
    • Of those 40 events, 18 to 19 would have shut the plant equipment down based on the previous history and the expected vulnerability of the unprotected equipment.

• However, none of the voltage sag events were found to affect production after the installation of the solutions.
Conclusions (1)

• A detailed PQ audit of the plant revealed several controls on the process lines were vulnerable to voltage sags.

• Based on the recommendation of EPRI, the manufacturer purchased an I-Grid monitor, which was remotely set up and configured by EPRI.
  – The plant quickly realized that unless you can see the PQ data, you cannot correlate the process vulnerabilities and the effectiveness of any installed solutions.
  – The installation of the I-Grid system provided valuable data that served to enhance the recommendations put forth for improving power quality response of the plant's manufacturing lines.
Conclusions (2)

• It was determined that providing conditioned power to the controls would significantly improve the tolerance of the process lines to PQ-related problems.

• Individual power conditioners were recommended; however, a consolidation of several of these loads to a common point of coupling can alleviate the need for multiple power conditioner units.
  – The latter approach would be significantly less expensive.

• Among the various types of power conditioners available, the PowerRide RTD and the DySC were proposed as viable choices.
  – The RTD was selected by the plant and installed.

• Besides power conditioning, the plant process could be hardened by maximizing utilization of features already present in the controls.
  – The successful adaptation of the proposed drive changes by the plant resulted in a significant decrease in PQ-related problems.
#5) Automotive Part Supplier Case Study – Flywheel Applications
1.1 Overview (1)

- Located in Tennessee, an automotive parts supplier has been experiencing interruption related shutdowns of their process equipment.

- The majority of equipment downtime issues have been caused by Interruptions of power and the effect on:
  - Two Kiln Lines in building 801

- The Utility hired EPRI to conduct a Power Quality Audit at the site to help formulate possible solutions.
1.1 Overview (2)

• EPRI and the Utility worked closely with the Automotive Parts Supplier to review the critical Kiln and Stick Coil Ovens power schemes.

• This work included:
  – Reviewing Installation Drawing
  – Physically walking down the power scheme to locate switchgear, Automatic Transfer Switches (ATS), Power Distribution Panels and Generators.
  – Discussed downtime issues with plant engineers and maintenance personnel.
  – Pre-sighting the location of possible flywheel based power conditioning that could be installed at the site.
  – Temporarily installing 4 PQ monitors at ATS locations in building 801 and 601.
1.1 Overview (3)

• The 801 Kiln Lines have diesel generator back-up for the processes.
  – The dead time between a power interruption event and the generator start-up still causes equipment shutdown and significant downtime.
  – Bridge Power solutions are needed to allow the process equipment to ride-through the events while the generator systems come on-line.

• This report contains the findings and recommendations from the PQ Audit.

[Image: Two 250kVA/200kW Diesel Gens for Kilns 1 and 2 in Bldg 801]
1.2 Electrical Environment Summary

- Since 2000 there have been a total of 17 interruptions at the site.
- Of those 17, many were caused by issues at the local distributors sub.
- The majority of the interruptions were weather related (53%) followed by those caused by Non-Utility equipment (29%).
1.3 Approach

• In order to determine a solution to bridge the gap between a power interruption and the generator start-up, determination of the power profile is needed for the critical loads.

• EPRI and the Utility worked with the Automotive Supplier to install 4 power quality meters at the site in the Automatic Transfer Switch (ATS) Locations.

• Another critical consideration is footprint and ambient environment. These items were noted as well during the PQ Audit as described within this report.

• EPRI and The Utility evaluated two separate flywheel technologies for consideration by the Automotive Supplier.
  – CAT UPS
  – Pentadyne Flywheel with Liebert UPS
Temporary Power Monitoring Locations at in ATS Units (one week of monitoring at each location)

- Kiln 2 ATS #2
- Hioki 3196 Power Quality Analyzers
- BLDG 801 Mechanical Room ATS Units
- Kiln 1 ATS #1
- Fluke 435 Power Quality Analyzers
- BLDG 601 Curing Oven 1 ATS
- BLDG 601 Curing Oven 2 ATS
Bldg 801 Kiln Analysis
Bldg 801 Generators

- EPRI Examined the two Diesel generators used for back-up power for Kilns 1 and 2.
- The two units are 250kVA/200kW CAT units.
Load Measurements in Bldg 801

Diagram of electrical system with switches, transformers, and power monitoring locations.
Kiln 1 Power profile

- Over 1 week of monitoring data showed the Average max power is 62.4kW and 75.1kVA
- The beginning part of this graph shows a power outage that caused the meter to reset.
- The maximum power seen was 92kVA
Kiln 2 Power profile

- Over 1 week of monitoring data showed the Average max power is 51.8kW and 68.2kVA
- The maximum power seen was 99.8kVA
Bldg 801 Kiln Data Monitoring Summary

- Over 1 week of monitoring data showed the Average max power of both kilns combined is 114.3kW/143.4kVA
- Kiln’s did not appear to shut down for weekend shutdowns
- Power Factor for the ovens are as follows
  - Curing oven 1:
    - Min PF: 0.76
    - Average PF: 0.84
    - Max PF: 0.86
  - Curing oven 2:
    - Min PF: 0.55
    - Average PF: 0.75
    - Max PF: 0.81
Bldg 801 Mechanical Room Layout (1)

- There is sufficient space in the Bldg 801 mechanical room to install two flywheel systems.
- The 10 x 10 area blocked in red is currently used for filter storage.
- This should be sufficient for installation space needed for Flywheel UPS units.
• The filter storage boxes can be relocated.
• There is more than enough room for a 10x10 concrete pad.
Bldg 801 Mechanical Room Temperature

• The Bldg 801 Mechanical room is not air conditioned.

• Prior to the installation of curtains around the Kilns, the temperature in the room reached extremes:
  – 103.8F 6/15/05
  – 106 F 6/27/05
  – 110 F 7/26/05

• Now, the temperature is expected to stay below 103 degrees on the worst case day per the Automotive Supplier.

• Installed solutions must be able to operate in the 103 degree environment.

CAT UPS:
104F Alarm Only
132F Shutdown

Pentadyne + UPS:
? Alarm Only
?F Shutdown
Solution Approach 1: (2) 150kVA Flywheel UPS Systems

- The loads for Kiln 1 and Kiln 2 are each below 99kVA maximum.
- Both the CAT UPS and Pentadyne systems have 150kVA sized units.
- This is the most economical approach.
- Both systems should be able to maintain output for at least 15 seconds at this loading level.
Solution Approach 1: (2) 150kVA Flywheel UPS Systems

- Note: Flywheel UPS units maintenance bypass not shown for simplicity.
Approach 1 Details and Costs

- **CAT UPS:**
  - 150kVA Unit X 2
  - $99,895 for each unit
  - $199,790 total for two
  - Two Units Back to Back should fit in proposed area
  - Price includes maintenance bypass
  - See Attached Quote and Data Sheets from Stowers

- **Pentadyne/Liebert FS + UPS:**
  - (130kVA UPS with 190kW Liebert FS flywheel) X 2
  - $105,078.5 For each unit
  - $210,157 Total for two
  - Two Units Back to Back should fit in proposed area
  - Price includes maintenance bypass
  - See Attached Quote and Data Sheets from Liebert
Solution Approach 2: (2) 300kVA Flywheel UPS Systems

- Upsizing the Flywheel UPS systems to 300kVA allows for redundancy.
  - Addition of manual bypass switch and two isolation switches on the output of the flywheels would allow for operation if there is a failure of a generator.
  - Flywheel UPS systems built with manual bypass so that they can be bypassed in the event of maintenance or failure of unit.
- While not the most economical approach, this method will allow for load growth and is could provide be beneficial in the long rung.
- Under normal circumstances (without bypassing), the 300KVA UPS systems should provide prolonged interruption covered in the 20+ second range if needed since they would be less than 50% loaded.
Solution Approach 2: (2) 300kVA Flywheel UPS Systems

- 300kVA Flywheel Based UPS
- "EDP-2" 277/480V 3Ph. 4W.
- "EDP" 277/480V 3Ph. 4W.
- 300kVA Flywheel Based UPS
- 250kVA/200kW 277/480V Diesel Generator
- 250kVA/200kW 277/480V Diesel Generator

ATS #2 ASCO 7000 Series 300A

Normal Open Manual Bypass

Normal Closed Isolation Switch

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Approach 2 Details and Costs

- **CAT UPS:**
  - 300KVA Unit X 2
  - $116,770 for each unit
  - $233,540 total for two
  - + Plus additional cost for new bypass and isolation switches
  - Price includes maintenance bypass
  - Two Units Back to Back should fit in proposed area

- **Pentadyne/Liebert FS + UPS:**
  - (300kVA UPS with 190kW Liebert FS flywheel) X 2
  - $142,805 for each unit
  - $285,610 total for two
  - + Plus additional cost for new bypass and isolation switches
  - Price includes maintenance bypass
  - Two Units Back to Back should fit in proposed area