Power Quality Mitigation Technology for Industrial Processes

Volume 1: Guidebook for Identifying and Implementing PQ Solutions

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REPORT SUMMARY

As a result of the growing use of sensitive electronic equipment in modern process control industries, industrial facilities have become increasingly vulnerable to a variety of power quality

productivity due to downtime. EPRI developed this two-volume guide in the interest of helping utility customer service representatives as well as industry operation and maintenance personnel

into screening industrial processes for power quality events as well as selecting and implementing mitigation technologies. Volume 2 provides a database of the available mitigation technologies, including a brief description of each one and its appropriate application.

Background

Voltage aberrations indicative of power quality problems include voltage transients, sags, fluctuations (flicker), regulation, and unbalance as well as frequency variations, harmonics and interharmonics, noise, and notching. When such power quality disruptions repeatedly occur, the industrial customer may turn to the utility for solutions. Some mitigation solutions available today, however, are so new and unfamiliar that the utility may not be aware of their proper application. The purpose of this guide is to provide a systematic approach for helping both utilities and industries cost-effectively mitigate and resolve industrial power quality disruptions.

Objectives

- To develop a screening process for industries experiencing repeated power quality disruptions.
- To present a comprehensive description of mitigation technologies for power quality disruptions.
- To provide guidelines for specification and successful implementation of mitigation solutions.

Approach

EPRI's Adjustable Speed Drive Demonstration Office developed a detailed six-step process for screening for power quality disturbances that impact industrial processes. Next, they illustrated the steps with real-world case studies and presented a comprehensive list of available mitigation technologies.

Results

Before going to the extent of bringing in the utility or outside sources to monitor incoming electrical service, several steps should be taken by in-house personnel to ensure that other

problem sources have not been overlooked. In fact, the steps described in this guide do not suggest in-depth study of power quality aberrations until other problems, such as improper grounding and mechanical failures, have first been ruled out. The guide will also provide direction so that if the utility is called to perform power quality monitoring, the appropriate documentation is in place to record events and make informed decisions based on the data received.

Volume 1 presents two case studies that illustrate the six-step process, beginning with process descriptions, stepping through the screening process, and concluding with the resulting solutions that made the processes run as intended. The guide compares mitigation technologies for various power quality events to help utilities and their customers select the appropriate technology for a particular process symptom. Included is direction for performing a cost-benefit analysis for a given technology installation. Construction issues such as equipment footprint, floor loading, access, and ventilation requirements are also addressed. Finally, once a mitigation technology has been selected, Volume 1 provides guidelines for project management and implementation, including areas such as budgeting, scheduling, and project team roles and responsibilities. Checklists address construction of mitigation equipment, design information, power quality equipment specifications, and power quality tests. Volume 2 presents reference material on current and emerging power quality mitigation equipment, an in-depth discussion of the capabilities of emerging technologies, and a listing of major mitigation equipment manufacturers.

EPRI Perspective

By providing utilities with a clear road map for applying industrial sector power quality mitigation technologies, EPRI is enabling utilities to better service one of their key customer segments. Due to their understanding of electric service power quality characteristics, utilities are in a unique position to help customers understand and implement such technologies. Widespread acceptance of new power quality mitigation technologies will ultimately benefit utilities and their customers by providing an opportunity to obtain specified levels of power quality from standard service distribution systems.

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Keywords

Power quality
End-use mitigation systems
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EXECUTIVE SUMMARY

The Adjustable Speed Drive Demonstration Office of the Electric Power Research Institute has developed a guide titled “Screening for Power Quality Events in Industrial Processes”. The purpose of this guide is to provide a systematic approach to providing a solution to power quality events which disrupt industrial processes. The intended user of this guide is the maintenance person or plant engineer responsible for determining a solution to recurring electrical events associated with the industrial process.

This guide was developed around the Statement of Work tasks for the project. The Introduction (Section 2) provides background for the project, discusses the purpose of the guide, and denotes the intended reader. Section 3 is the fundamental section of the guide. It provides discussion of the steps required for screening for power quality events affecting the industrial process. The sequence of steps does not verify the existence of power quality aberrations until other problem sources, such as improper grounding and mechanical failures, have been ruled out first.

Section 4 is provided to give illustration to the steps outlined in Section 3. Two case studies are discussed, beginning with the process descriptions, stepping through the screening process, and ending with the resulting solutions that made the processes run as intended. Section 5 discusses the comparison of mitigating technologies for various power quality events. Section 5 also provides a comparison between new and conventional mitigation technologies for various process symptoms.

Section 7 discusses feasibility considerations of a mitigation solution. A guide for performing a cost/benefit analysis for a given technology installation is provided. Constructibility issues such as footprint, floor loading, access, and ventilation requirements are also addressed. Once a mitigation technology has been selected, Section 8 provides guidelines for implementation of a project to install the mitigation equipment.

2
INTRODUCTION

Background

As a result of the growing use of sensitive electronic equipment in modern process control industries, industrial facilities have become increasingly vulnerable to a variety of power quality disturbances. Disruptions to critical industrial processes have resulted in lost revenue and productivity due to downtime. When such disruptions repeatedly occur, the industrial customer will typically turn to the utility to help provide a solution. Depending on the resources available from the utility, this approach may or may not result in the successful implementation of a mitigating solution. Some of the mitigation solutions available today are so new and unfamiliar that the utility may not be aware of their proper application.

Objective

The objective of this guide is to provide assistance to the utility and their connected customers as follows:

- To provide a screening process for industrial processes experiencing repeated disruptions, in the interest of obtaining a solution.
- If it is deemed that a mitigation solution is required, to determine which mitigating technology is best suited for the particular industrial facility and the application.
- To provide guidelines for the specification and successful implementation of the resulting mitigation solution.

This guide is divided into two volumes. Volume I will provide insight into screening of industrial processes for power quality events, as well as the selection and implementation of a mitigating technology. The Appendices of Volume I provide expanded detail of certain sections and will be referred to when applicable. Volume II provides a database of the available mitigating technologies, including a brief description of each and their appropriate application.

Intended Audience

This guide is geared toward the plant maintenance or operations person who may be called on to find a solution for recurring problems associated with electrical disruption of process equipment. The reader is not required to have a thorough understanding of electrical theory or be versed in troubleshooting electrical equipment to benefit from this guide. This guide will suggest a systematic approach to finding a solution to process disruptions, and will require the reader to work with qualified personnel within their facility and possibly outside sources to perform the tasks described.

This guide is also provided as a reference for the utility customer service representative. It is anticipated that deregulation of the utility industry will spur utilities to become more involved in the day to day power quality problems experienced by connected customers. The utility will typically be one of the first resources that the plant operations person calls for assistance or direction, and this guide will help to provide that direction.

3
SCREENING FOR POWER QUALITY EVENTS

The Process Disruption Scenario

The effects of industrial process disruptions can impact all levels of personnel in an industrial facility. The following scenario illustrates these effects:

Upper management conducts their quarterly production reviews, and finds that their main product line is falling way short of the forecasted business plan. Management is looking for ways to exceed the forecast so they can add to their profits, while currently they are actually behind on their expected earnings because the real rate of production is not even meeting the forecast. The Operations Manager is asked to find out why the production rates are so low and report back.

The Operations Manager meets with the maintenance crew assigned to that particular product line. The maintenance crew tells of seemingly regular tripping of the equipment in the line each week. They are increasingly frustrated with the cleanup required each time the line goes down. Drives were added in the line several months ago to increase efficiency in the process, but since then the downtime has resulted in decreased efficiency overall. In an effort to update the older equipment in the line, the motors have been replaced with new high efficiency motors, but the process trips have continued to occur.

The Operations Manager decides to check into the situation further and calls a meeting with the maintenance persons associated with other product lines in the facility. He hears more of the same stories of process disruptions; time spent working on machines, hours of cleanup, and overall frustration from the crew.

How the Utility Gets Involved

Upon hearing this feedback, the Operations Manager has strong reason to believe that power quality events are responsible for the process disruptions, and may want to blame the utility for providing a lower quality of power than they have received in the past. The utility typically provides a guarantee of a quality of incoming electricity, usually –6% +13% of nominal voltage, and continues to fall within those guaranteed limits. Additions to the process, however, notably sensitive electronics like those found in drives, require a tighter tolerance of power quality than the utility is historically able to provide.

Larger utilities today have the resources to provide monitoring of a facility's incoming power at various points within the facility. Smaller utilities, such as co-ops in rural areas, may not have resources to provide this service from within, but they will know which outside sources to contact for providing this service. A fee is typically involved, ranging from $1,000 to $2,000 up to $10,000, depending on the size of the facility and extent of the problems.

Before going to the extent of bringing in the utility or an outside source to monitor the incoming electrical service, there are several steps that should be taken by in-house personnel.

These steps will be outlined in an effort to ensure that other sources of problems within the facility have not been overlooked. This approach provides peace of mind for plant personnel, knowing that a more costly blanket solution wasn’t arbitrarily chosen without first investigating more cost-effective, simpler fixes that could have solved their process problems. The guide will also provide direction so that if the utility is called to perform power quality monitoring, the appropriate documentation is in place to record events and make informed decisions based on the data received. If an introductory review of power quality events is needed, refer to Appendices A & B.

The flowchart in Figure 3-1 lists the major steps required for screening of power quality events. Discussion of each of these steps will follow.

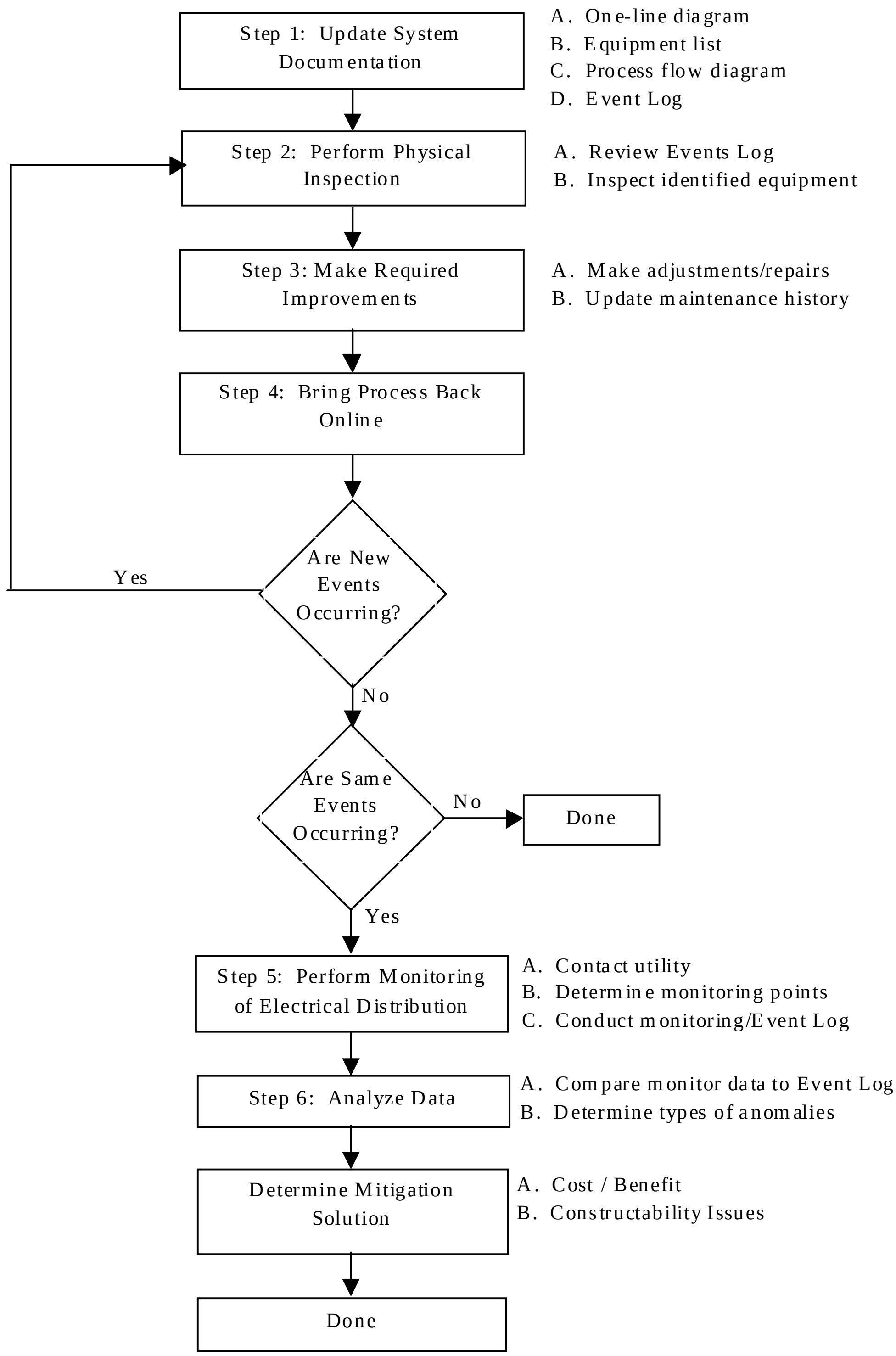

Figure 3-1
Steps for Screening of Power Quality Events

STEP 1: UPDATE SYSTEM DOCUMENTATION

A. Update One-Line Diagrams

The One-Line Diagram will be the base reference document for troubleshooting the system. Therefore, accuracy of the one-line is imperative. Verify inclusion on the one-line of all electrical equipment, including distribution equipment, such as panelboards, and loads, such as motors and drives. Verify ratings of electrical distribution equipment, such as impedance ratings of transformers. Also include any mitigation equipment, such as surge suppressors, capacitor banks, and ferroresonant transformers, etc. which may have been added to the system subsequent to development of the one-line.

B. Develop an Equipment List

When developing an equipment list, include as much information as is available, such as:

- Equipment number
- Manufacturer
- Model number
- Nameplate data
- Voltage
- kW or HP rating

Include a column for describing condition of equipment. This column will be used to note equipment condition during the inspection process.

Include a column to denote whether the equipment is a contributor to poor power quality, such as drives, arc furnaces, induction heating units, welders, and electronic rectifiers.

Include a column to denote whether the equipment is sensitive to poor power quality, such as drives, electronic process controls, computers, PLCs, and robotics.

C. Develop a Process Flow Diagram

The Process Flow Diagram will show the relationship of equipment in the process, even if electrically fed from different sources. Along with the major pieces of equipment, it should show instrumentation and control loops associated with the process as well.

D. Develop a Log of Disruption Events

Ask the operators and maintenance personnel to keep a log of all unexpected events for a given period of time. The time period required might vary from one week to sixty days, depending on how often these events recur. The description of events should include as much detail as possible, such as:

- Specific equipment that behaves unexpectedly
- Detailed description of event
- Date and time
- Coincidental events that occur simultaneously
- Weather

Steps 1A and 1D above will be essential to an organized an efficient resolution to the facility's process disruptions. Whether all or part of the remaining effort is handled in-house or by outside sources, all parties will be able to contribute most efficiently from the complete collection of required system documentation.

STEP 2: PERFORM A PHYSICAL INSPECTION

CAUTION: It is anticipated that the majority of tasks in Step 2 will be performed by in-house personnel. Safety procedures should be observed during the inspection, testing, and maintenance of electrical and mechanical equipment. Only qualified personnel should perform these tasks.

A. Review the Events Log

Filter out equipment that showed erratic operation during the monitoring period and mark this equipment on the Equipment List to be visually inspected. Look for coincidences of events, such as a drive tripping simultaneous to a chiller coming on line or lights flickering simultaneous to a process shutdown. It is anticipated that most events will fall under the following categories:

- Motor Failure
- Dry Type Transformer Failure
- Adjustable Speed Drive Trip
- Erratic Operation of Electronic Controls
- Failed or Inoperable Auxiliary Electrical Components (small control relays)

B. Inspect the Identified Equipment

- Pull off equipment covers and look for obvious signs of a problem, such as overheating, excessive wear insulation breakdown, etc.
- Inspect transformers and electrical equipment upstream of erratic loads, checking for signs of overheating.
- Check for proper grounding of equipment and proper termination of all wiring at terminal strips. Also check for wiring insulation wear.

- Check control loops for proper tuning of controllers and proper shielding of instrumentation.
- Contact drive vendors and describe the observed occurrences with them to determine if they have seen the particular action before and have a solution. Also determine what voltage tolerances must be maintained for continuous operation. This information can be compared to the quality of power provided by the utility if and when monitoring of the distribution is performed.

Equipment in most instances will need to be disassembled to perform the inspection. Certain tests may need to be conducted also. Troubleshooting assistance and example checklists for inspection of equipment types can be found in Appendix C.

A proper checkout of the equipment as noted above will typically lead to several findings of improper installation. Fixing the anomalies found will often make a significant difference in the operation of the process.

STEP 3: MAKE REQUIRED IMPROVEMENTS

A. Make Adjustments/Repairs

Make adjustments or repairs based on the physical anomalies found in Step 2. This may include such things as:

- Tightening loose terminals in a control panel.
- Tightening ground wires for process equipment.
- Resizing motor overload relays so that motor doesn’t prematurely trip.
- Review condition of motors.
- Ensuring shields are grounded at only one end of the control loop.

B. Keep a Maintenance History

If not already part of the maintenance program, develop a Maintenance History for each piece of equipment, identifying what the problems found and what specific changes or maintenance was performed. This will be similar to the chart a doctor has for each of his/her patients. The Maintenance History will prove valuable as an ongoing reference beyond the scope of this guide.

STEP 4: BRING THE PROCESS BACK ONLINE

Rerun the process for an adequate period of time to determine if the adjustments made in Step 3 remedied the disruptions. Again, the operator will need to keep a log of events that occur so they can be compared with earlier events to see if the adjustments made a difference in the smooth running of the process.

As will often be the case, equipment that was failing originally may no longer show signs of failure. Yet, other equipment that did not previously experience problems now may begin to do so. If this occurs, it will be necessary to start back at Step 2, performing a physical inspection of this equipment. This cycle should be repeated until the problems are solved or the same problems are continuing to occur. Once it is determined that the same problems are occurring, it will be necessary to move on to Step 5.

STEP 5: PERFORM MONITORING OF ELECTRICAL DISTRIBUTION

A. Getting Started

This is the time that the utility can step in and offer assistance, by either performing the monitoring with their own resources or providing reference to a power quality consultant versed in monitoring of electrical distribution. Considerations such as fee, schedule, etc. can typically be negotiated at this time.

B. Determine Monitoring Points

Reviewing the one-line diagram should give some insight into appropriate monitoring points. The most obvious monitoring connection is at the service entrance. However, it is suggested that points within the facility, as close to the process as possible, be monitored also to ensure exactly what quality of power is seen at the instant of process shutdowns. For additional information on monitoring equipment and the monitoring procedure, refer to Appendices E, F, and G.

C. Conduct Monitoring Program

The length of time needed for conducting the monitoring program will vary depending on the process cycle and typical intervals of time between events. The utility or power quality consultant can offer advice on how long to monitor the system.

An event log should continue to be kept by the process operators during the monitoring program. Information obtained from the event log will later be compared to the voltage fluctuations picked up by the monitoring program.

STEP 6: ANALYZE DATA

The utility representative or power quality consultant will sit down with the plant engineering staff to analyze the results, and make recommendations of possible solutions. System documentation, including the one-line, equipment list, event logs, maintenance histories, and technical data gathered from vendors, will prove invaluable during the review of the monitoring program. For more information on specific power quality events and their effects on process equipment, refer to Appendix D.

4
CASE STUDIES FOR POWER QUALITY ANALYSIS

To more fully illustrate the steps outlined in the screening process, two case studies will be analyzed. These studies, consisting of process models in the synthetic fiber and pharmaceutical industries, will demonstrate the systematic approach for determining the most cost-effective solution for solving process disruptions.

Case Study No. 1: Plastic Strip Production for Carpet Backing

Background

A synthetic fiber plant operates a continuous process to produce plastic strips for carpet backing. The continuous operation consists of extrusion and slitting, stretching, shrinking, and winding of plastic strips.

The process would experience disruptions several times each week. Any or all of the components would trip on a given occasion. The most costly component in the process line was the extruder. Cleanup and restart time due to the extruder tripping was approximately eleven hours, with an estimated cost of $15,000 in lost production and downtime per event. On this basis, the annual cost of these shutdowns was estimated to be $150,000.

System Documentation

The Plant Engineer began the investigation by updating the system documentation. Refer to Figures 4-1 and 4-2 for the one-line diagram and process flow diagram associated with this process line.

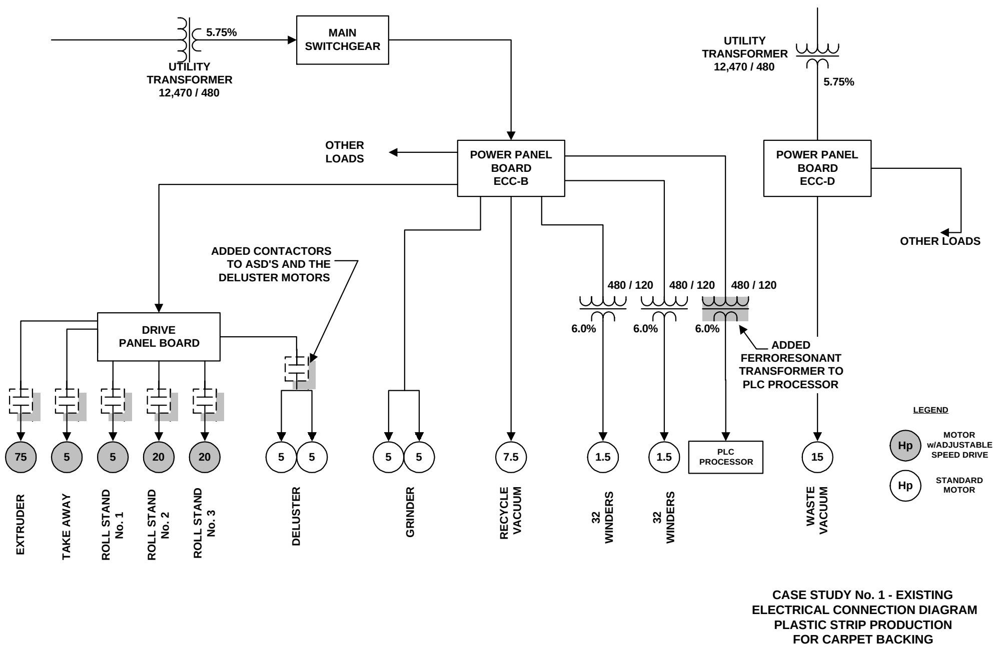

Figure 4-1
One-Line Diagram

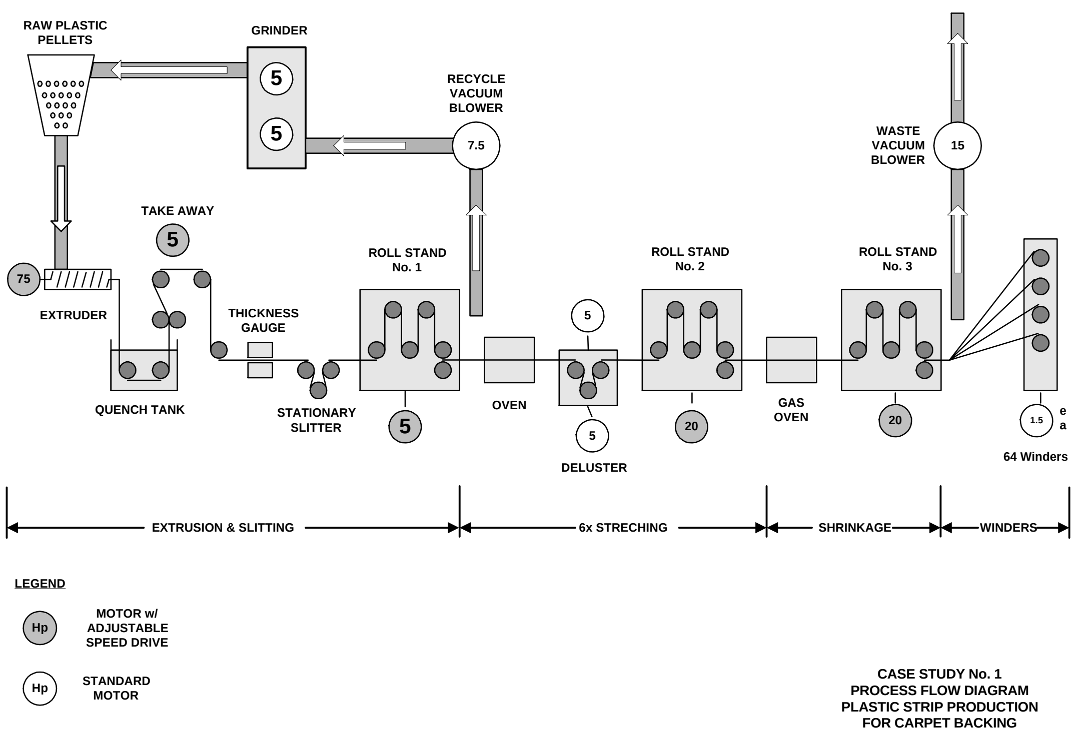

Figure 4-2
Process Flow Diagram

The Plant Engineer provided an Events Log to the Operators of the process line and asked them to record any disruptions seen. A short training session was conducted to ensure that the operators understood what was required and how to record the events as completely as possible. Over the following two weeks, the operators recorded the events that had occurred, summarized as follows:

- On three occasions, winder motors (64 total) dropped out, causing the knife to automatically fall, cutting the strips. The material could not be recycled and was then conveyed away by the waste vacuum blower as scrap.
- On one occasion, the deluster motors (2 total) tripped causing the luster of the plastic stripping to fall out of range. Material which had moved beyond the deluster at the time of the trip was scrapped.
- Adjustable speed drives for the three roll stand motors tripped on a daily basis. The ASD alarm panel indicated the cause to be an overvoltage condition.
- On two occasions, the PLC processor controlling the continuous process tripped and lost its memory. The process sequence had to be reset and material was scrapped.
- On several occasions the extruder slowed down or tripped off line completely. If the material had not moved past Roll Stand No. 1, it could be recycled back into the process. If the material had moved beyond Roll Stand No. 1, it had to be scrapped. On the occasions where the extruder tripped off line, major downtime was experienced for cleanup and getting the extruder back on line.
- *The operators noted a simultaneous event that occurred when the equipment would fail: the lights in the building would flicker.*

Physical Inspection/Repairs

The maintenance crew performed a physical inspection of the equipment in the process line. Grounding of the electrical distribution system and process equipment were checked and deemed to be in good shape. Equipment wiring terminations were checked and tightened to ensure continuity.

However, no one felt that the corrections to wiring were going to make the difference. Due to the simultaneous occurrence of flickering lights, it was thought that the problems were of poor power quality in nature. The Plant Engineer had several discussions with vendors of equipment, who offered inexpensive solutions for ride-through of voltage fluctuations in the electrical supply. Before going to the effort of bringing in the utility to monitor the electrical distribution, it was deemed economical to implement solutions suggested by the equipment vendors. These changes to the system were made as follows:

- No-trip components were added to the contactor coils on all of the adjustable speed drives and the deluster motors to provide sag protection.
- A ferro resonant transformer was installed upstream of the PLC to provide ride-through and galvanic isolation.

Testing the Low-Cost Solutions

The process line was brought back on-line, and the operators again recorded any unusual events that occurred. A summary of the events noted is as follows:

- The PLC did not trip and lose memory after the ferro resonant transformer was installed.
- The ASDs tripped less often with the no-trip components on the contactor coils.
- The extruder would still run slow or trip offline in its usual manner, interrupting production.

Monitoring the Electrical Distribution

At this point, the Plant Engineer contacted the utility to discuss monitoring of the electrical distribution. He explained to the utility representative the events that were occurring and the efforts that had been made to solve the problems. The utility representative agreed that power monitoring was the next logical step.

The utility representative contacted a power quality consultant, who supplied the power monitoring equipment and the simulation software. The monitoring equipment was installed at the service entrance to the facility and upstream of the power panels feeding the process equipment (ECC-B and ECC-D in Figure 4-1).

The monitoring was performed for a period of two weeks, with shutdowns to the process occurring in usual fashion. The process operators continued to maintain the Events Log to provide a means of comparison between the timing of shutdowns and the occurrence of voltage fluctuations as seen through the monitoring equipment.

Analyzing the Results

The power quality consultant along with the Plant Engineer and his staff analyzed the monitoring data and the system documentation, including the one-line diagram; the event logs, and design parameter feedback obtained from equipment vendors. The team came to the following conclusions based on comparison of data:

- The winder motors were susceptible to transients and would trip on voltage sags of 30% for 0.5 cycles.
- The deluster motors were susceptible to transients and would trip on voltage sags of 20% for 0.25 cycles.
- The ASDs for the roll stand motors would trip on voltage sags of 10% for 10 cycles. This indicated that the overvoltage alarm shown on the alarm display after tripping was not accurate.
- The extruder was determined to be extremely susceptible to voltage sags of only 20% for less than 30 cycles. The extruder requires large amounts of energy relative to the other electrical components in the system, and ride-through ability on its own is practically nonexistent.

- The PLC processor had been receiving a voltage spike of 200 volts for less than 20 microseconds as often as twelve times during an eight hour shift. This could happen any time of the day or night and was an independent event from the events causing other process equipment to shut down. Installation of the ferroresonant transformer remedied the effects of the voltage spike.
- The recycle and waste vacuum blower motors, as well as the two grinder motors, had sufficient ride-through and were not affected by power quality events.
- Certain transients that occurred were noted to have originated from the process equipment itself, but their magnitude did not exceed the design parameters of the equipment and therefore were not attributable to the process shutdowns.

Determining a Mitigation Solution

A solution providing for mitigation of voltage sags was needed. Low-cost integrated solutions such as the no-trip components on the ASD contactor coils had helped the situation but did not completely mitigate the problem. The extruder, the largest load in the process line, was also the most sensitive to voltage fluctuations. It was evident in this case that a system solution was required.

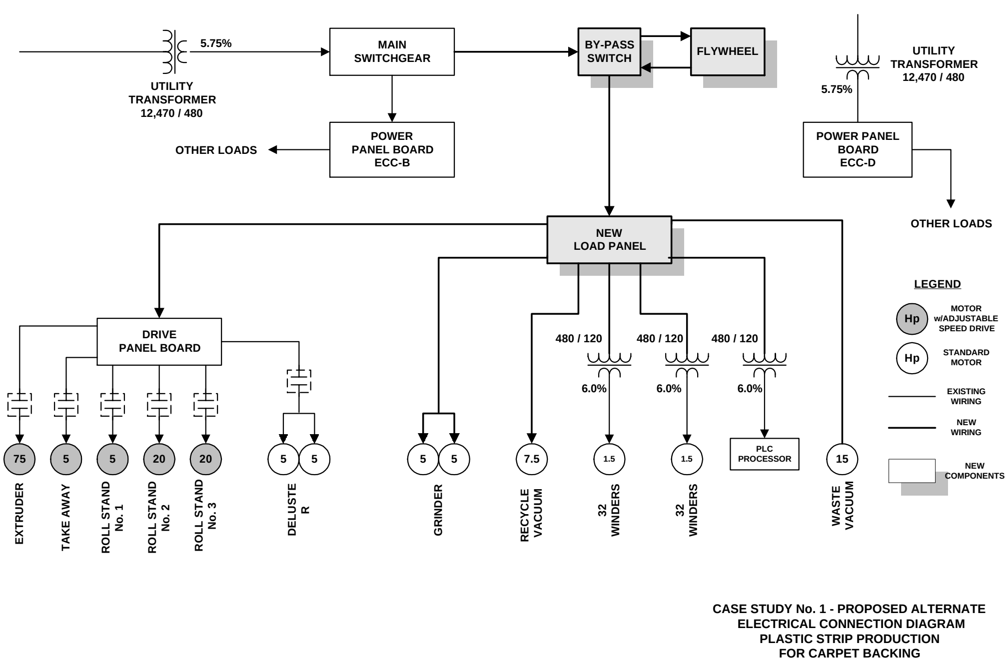

Figure 4-3
Revised One-Line for the Mitigation Solution

A cost/benefit analysis was performed on available mitigating technologies, and constructability and implementation issues were considered. The resulting solution (and see Figure 4-3) was determined as follows:

- A new load panel for the process loads was installed. All process loads currently fed from power panels ECC-B and ECC-D were moved to the new load panel
- A low-speed flywheel and bypass switch was installed between the main switchgear and the new load panel. The 250 kW flywheel was rated to provide ride-through of power quality events for 12 seconds.
- The utility, through a partnership agreement with the flywheel vendor and the industrial customer, took ownership of the flywheel, charging the customer a “clean power” rate on the electric bill. The utility took ultimate responsible for the operation of the flywheel, and kept the customer from having to provide capital funding for the purchase and installation of the unit.

Case Study No. 2: Batch Process in a Pharmaceutical Facility

Background

A new batch process was initiated by Company “A” six months ago to provide the proper mixture of ingredients for the manufacture of a new drug. There are precise requirements for the timing of ingredient addition, mixing speeds and duration during the various stages of the batch process.

Company A prepares the batches and ships them to Company “B” for tablet formulation and packaging. The FDA has strict record keeping procedures for the blending and fermenting process. The final batch product is tested for quality assurance and validation prior to being transferred to Company “B”.

The production schedule calls for three batches to be completed per day, one batch per shift, 7 days per week, to fulfill the contract between Company “A” and Company “B”. Each batch represents $50,000 of final packaged product. If the quota of 21 batches is not met, regardless of the reason, Company “B” back charges Company “A” $5,000 per batch for the lost revenue.

Several times during the last six months, there have been failures of the electrical equipment. The timing of the trips and the duration of the outage determine whether a batch has to be scrapped or not, so all is not lost every time a failure occurs. To date, however, five batches have been scrapped because they did not pass the quality inspection tests, and during all five batches it was observed that an electrical equipment failure had occurred.

System Documentation

After four months of operation, it became apparent that Company A was losing money by not meeting its quota. The Plant Manager asked the Operations Engineer to find the problem and determine a solution. The Operations Manager verified that the one-line (Figure 4-4) for the facility, the equipment list, and process flow diagram (Figure 4-5) were updated. Refer to Figures 4-4 and 4-5 for these documents for this process line.

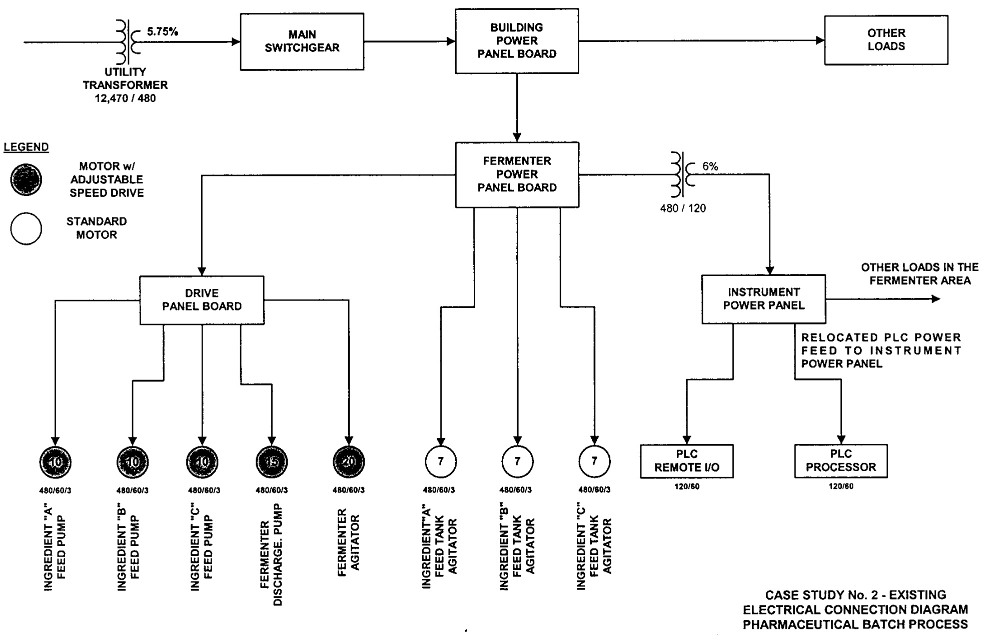

Figure 4-4
One-Line Diagram

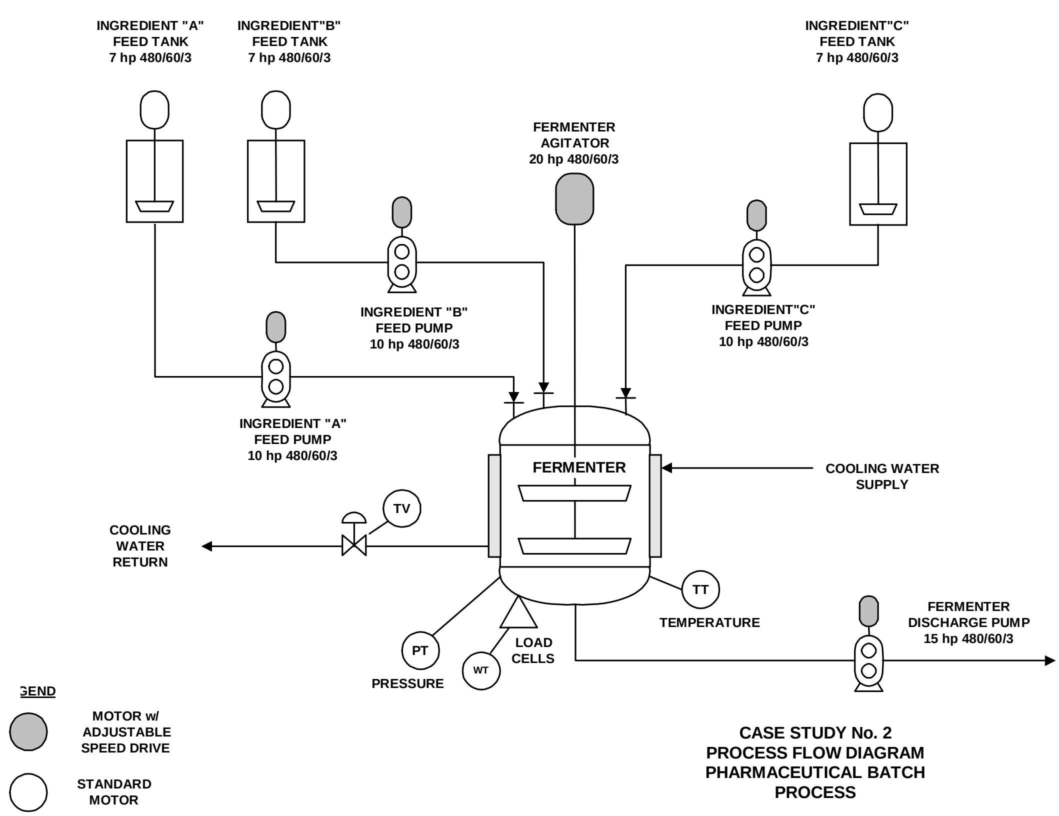

Figure 4-5
Process Flow Diagram

The Operations Manager also created an Event Log and asked the process operators to keep records of any unexpected events that occur. The operators kept the Event Log for two months and recorded several events, summarized as follows:

- The pump motor used to transfer Ingredient A from an intermediate holding tank to the Fermenter has a tendency to overheat and trip after several minutes of operation. The motor was installed with the new batch process six months ago. Fortunately, this event does nothing to spoil the batch, because the ingredient it is pumping is done so at the beginning stage and is not time sensitive. This does slow the production schedule because they have to wait as long as 30 minutes to restart the motor and complete the Ingredient A transfer.
- The Adjustable Speed Drive for the Fermenter agitator will trip randomly; averaging three or four times a week. Depending on what stage the batch is in; this could be a critical situation, because the agitation speed and duration must be precise during certain stages of the batch process. Those batches scrapped over the past six months coincided with the agitators ASD tripping during particular stages.
- The sequence and timing of ingredients added and timing of agitation speeds and duration are controlled through an existing PLC. Three times over the past six months the PLC processor has shut down and lost its memory. Twice the associated batches were unable to be saved due to the timing of the PLC memory loss.

Physical Inspection

- The maintenance crew performed a physical inspection of the equipment identified in the Event Log. They began by pulling the cover off of the Ingredient A pump motor to look inside. Although this motor was less than one year old and in service for only six months, the inside of the motor was brown, and looked and smelled aged. The maintenance electrician thought the damage inside the motor indicated that the motor had been running hot. After checking the thermal overload, it was found that the overload relay had been improperly specified. It was also determined that the motor duty was undersized for the application.
- The maintenance crew decided to inspect the agitator motor also, even though the drive, not the motor, had been recorded on the event log. Upon removing the cover, they found that the motor still looked relatively new, even though it was a much older motor than the Ingredient A pump motor. Closer inspection by means of megohmmeter testing revealed holes in the insulation. The maintenance electrician noted that the insulation breakdown was possibly a symptom of a ground fault. The insulation breakdown had not been obvious in the Ingredient "A" pump motor because it was already so damaged inside.
- The PLC processor was checked out for proper wiring and grounding, and no problems were found. In reviewing the one-line, it was noted that the processor was fed from the same 120V panel as several store room lighting circuits.
- Discussions with the agitator ASD vendor yielded no concrete reasons for the tripping that had been occurring, other than the possibility of voltage sags larger in magnitude than the ASD was designed for. The vendor suggested installing no-trip coils to see if they solved the problem before trying a more rigorous approach.

Equipment Repairs/Adjustments

- The Ingredient A pump motor was replaced with a properly sized high efficiency motor. The thermal overload relay was checked for the proper setting also.
- After analyzing the agitator motor and verifying insulation breakdown, the Plant Engineer consulted with the motor testing service to determine the causes of such an occurrence. Review of the facility one-line showed that the distribution system was an ungrounded system. An ungrounded system is known to cause motor windings to fail over time. It was decided to install a high resistance ground for the distribution system to remedy the breakdown effects occurring with motors.
- The PLC feeder was switched to an instrument power panel that contained no lighting circuits. In addition, a ferroresonant transformer was installed in the line to provide additional power conditioning for the sensitive load.
- A no-trip component was installed for the agitator adjustable speed drive.

Testing the Low-cost Solutions

The batch process was brought back online, and the operators again prepared to record any unusual events that occurred. To date, the batches have been running consecutively for four weeks without a process shutdown.

If in the future, however, process shutdowns do begin to occur, plant personnel will be able to review the maintenance history of the work done on the various components and determine appropriate action.

5
COMPARISON OF POSSIBLE SOLUTIONS

Mitigation equipment exists for all of the power quality aberrations that might be discovered through monitoring of the electrical distribution. Refer to Appendix H for a table of mitigation solutions for various power quality events. This table will provide the narrowing of mitigation choices before a full-scale inquiry into each technology is performed. For more detailed descriptions and applications of new technologies, refer to Volume II of this guide.

When determining a mitigation solution, the question may arise as to whether conventional or new technology is best suited to provide the solution. Table 5-1 was developed as a sample means of comparison between conventional and new technologies for given process equipment symptoms. The symptoms identified in the table were extracted from the case studies depicted in this guide.

Table 5-1
Comparison of Conventional vs. New Technologies

Symptom	Conventional	New Technology
Contactor trip	Change component	Add "no trip" device
Components failing on over voltage	Add external surge arrestor and linear R&C networks	Use TVSS and envelope following surge arrestors
ASDs tripping and board failures	Pull a neutral connection	High resistance ground using zigzag transformer
Logic problems and wrong indications	Ferro resonant transformer	Ferro resonant transformer
Power factor penalty	Add solidly connected power factor correction capacitor	Add solidly connected power factor correction capacitor
PLC loses program	Double conversion UPS	Single conversion UPS
Extruder stops on power outages	None	Power electronics controlled low speed flywheel
Extruder stops on power outages	Electrolytic capacitor (very large volume)	Ultra capacitor with power electronic chopper (small cubicle)
Extruder stops on power outages	None	PQ 2000 (much to large for this application)
Extruder stops on power outages	None	Micro SMES (much too large for this application)
Extruder stops on power outages	None	Run system continuously on fuel cell
Extruder stops on power outages	None	Run on 3 paralleled micro turbines
Extruder stops on voltage sag	None	Dynamic Sag Corrector

6
PROJECT FEASIBILITY

Before proceeding with a power quality mitigation installation project, feasibility issues should be considered. There may be several potential devices to help solve the problem of process shutdowns in an industrial facility. Key issues for determining the best solution for the process and physical parameters of the facility should be considered, as follows:

Cost/Benefit Analysis

Completing a cost benefit analysis for the proposed project will require a detailed investigation of all aspects of the particular plant. The information gathered will be specifically relevant to this one project. The following cost and benefit sections are intended to be guidelines accumulated from past experience with demonstration projects. The authors acknowledge that each project has its own special features that must be captured in a tabular form and dollars assigned to each line.

Cost

Identify all the cost elements that can be associated with the project

	$
Site Survey	____________
Drawings	____________
Engineering Consultant	____________
Site Preparation	____________
Reconnection of Loads	____________
Vendor Visit	____________
Monitoring Equipment	____________
Equipment Cost	____________
Freight to Site	____________
Installation	____________
Cabling	____________
Startup	____________
Training	____________
Extended Warranty	____________
Data Accumulation	____________
Data Reduction	____________
Report Writing	____________
Total	$___________

Benefits

A comprehensive list of benefits that may accrue to the site once the PQ mitigation device has been installed.

Primary benefits are the avoidance of the annual cost associated with interrupted production however all other costs that may be avoided need to be collected.

Lost Production	____________
Wasted Material	____________[1]
Disposal Costs	____________
Maintenance Costs	____________
Replacement Parts	____________
Purchased Replacement Product	____________
Cost of Extra Staff	____________
Cost of Overline	____________
Total	$___________

In the course of applying the new mitigation device some other improvements may occur such as:

Improved Product Quality	____________
Reduced Maintenance	____________
Longer Run Lines	____________
Lower Utility Bills	____________
Faster Production Rates	____________
Total	$___________

The experience to date with demonstration projects has been that there have been unexpected additional benefits that have surfaced during the course of the project.

Finally the comparison of total cost $ to annual benefit $.

$$\text{Simple Payback Period} = \frac{\text{Total Cost}}{\text{Total Annual Benefit}}$$

Constructability Considerations

When power quality events have been isolated and a potential solution decided upon, it must be determined if it is feasible for the proposed equipment to be installed, operated and maintained. There are a number of items to be taken into consideration. A checklist of constructability issues for the project installation are listed in Table 6-1 below.

[1] Be careful to assess the cost of all the damaged product such as half filled bobbins that will be scrapped.

Table 6-1
Mitigation Equipment Construction Checklist

ITEM	VERIFIED
Footprint	
Additional Construction Required	
Equip. Suitable Indoor / Outdoor	
Structural Considerations	
Verify Building Floor Load	
Verify Building Roof Load	
Access	
Installation	
Cable Entry	
Maintenance	
Code Requirements	
Utilities	
Process / Inst. Air	
Water	
Equipment Power	
Ventilation Requirements	
Environmental Considerations	
Long-term Effects	
Battery Disposal (if applicable)	

7
PROJECT IMPLEMENTATION

Project Management

In order to carry out the demonstration project it is essential that a project management team is appointed. One of the team members shall be nominated project manager (PM) who will have the overall responsibilities for implementation of the project. The PM will be responsible for managing the scope, budget and schedule for the project. The PM will facilitate the following:

- Prepare a detailed statement of work (SOW)
- Prepare a project budget
- Prepare and update the project schedule
- Assemble the project team
- Negotiate all equipment specialized and installation services
- Coordinate project team activities
- Perform cost control and prepare progress reports

Project Budget

The project budget estimate is an essential part of the project management. It is important to be as detailed as possible in the estimating process, the more detail the lower the risk of the unexpected item. Every project has its special features and the budget should capture any associated cost.

For the installation of a power mitigation equipment the first stage in the budget preparation is to establish a statement of work (SOW). This will involve discussing the project with all the parties involved with the project. Once the SOW has been written send it to all the affected parties requesting their input in the “proposed” SOW. With the SOW identified each item of cost can be identified.

It will be necessary to obtain written quotations for the specialized equipment.

Typical Project Budget

	$
Cost of Preliminary Site Visit	___________
Preparation of Revised Single Line	___________
Labor to Reconnect Loads	___________
Material (ie Distribution Board, Cable, etc.) required to prepare site	___________
Costs of Monitoring Site Performance Prior to Installation of Mitigation Device	___________
Preparation of Project Schedule	___________
Mitigation Equipment (discuss with vendor to make sure that the Equipment price has sufficient options included)	___________
Ongoing Maintenance	___________
Startup Costs	___________
Extended Warranty	___________
Training	___________
Freight	___________
Cost of Project Manager Hours Developing and managing the project	___________
Installation Contractor will provide a price based on the scope of work	___________
Monitoring Equipment	___________
Testing the Product Against a Prepared List of Parameters	___________
Total	___________

Schedule

The purpose of the project schedule is to show when project tasks and activities must occur in order to meet the project objectives. The project schedule will be developed in sufficient detail to show the sequences and duration of project activities along with the resources responsible for these activities. The project schedule will show project concept development, installation budget development, project funding, design engineering, equipment procurement, construction, startup/commissioning, and testing.

Develop a project schedule by first creating a list of actions from the SOW. Make a careful note of any activities that are linked together and show this linking on the final schedule.

Once the key items have been identified estimated the start date and time to complete. All this information is best displayed on a gahnt chart (Appendix I) which shows the relative timing of each project “milestone”.

During the course of the project bring the schedule up to date by showing items completed or modifications required. A good plan is to reissue the project schedule every month to each member of the project team. Sometimes it is necessary to update the schedule at shorter intervals. Discuss the update procedures with the project team to discover the individual needs.

Request For Proposal (RFP)

An essential prerequisition of the RFP is a well defined specification for the product or service required. Make sure that the project team has reviewed and commented on the final specification document before it is released to the vendors. Use the guidelines in Section 7 to ensure that the specification contains a full range of information.

Once the product technical aspects have been thoroughly described these must be accompanied by a list of contractual requirements. The following is a list of information that the vendor shall provide with the proposal:

- Price
- Shipping terms, including carrier
- Payment terms
- Lead time, after award, for drawing submittal and product shipment
- Complete description of the product

The RFP shall contain a list of all the documents needed to be supplied with the purchased equipment. This information will include:

- Number of copies of drawing sets
- Number of reproducible drawings
- Number of instruction and operating manuals

To help with the generation of the proposal it is important to provide names and telephone numbers of contacts who can resolve technical and commercial queries.

Provided with the RFP shall be the purchasing company's terms and conditions of purchase. **DO NOT** use the sellers terms and conditions. Should any changes be required to the terms and conditions consult with your company attorney before making any changes.

An example of an actual RFP is included in Appendix I with a technical bid analysis form to assist with the evaluation of competitive proposals.

Project Team

The project team includes all personnel involved in the implementation of the project. It includes the following:

- Project Manager
- Equipment Supplier
- Construction Contractor

- Electric Utility
- Design Consultant (where applicable)

Memorandum of Understanding

Field demonstration of technology typically involves a number of separate entities which work together to achieve the full objectives of the project. To assist with the understanding of the roles and responsibilities of each team member it has been found very useful to generate a memorandum of understanding for the project. The document lays out definitions of the work and individuals who have responsibility for undertaking the activity. Most importantly the MOU provides a means of project management through the steering committee. In summary the memorandum of understanding should include the following elements.

- Definitions: Project management
System analysis
Steering committee
System integration
Project team
- Purpose of Project
- Understanding task definitions for each entity
- Agreement page with signatures

An example is included as Appendix I.

Specification Guidelines

This section presents an approach for the specification of Power Quality Mitigation equipment. The application of the following is considered:

- Energy Storage Systems
- Lighting and Surge Arrestors
- Static Switch
- Dynamic Voltage Regulators/Electronic Tap Changing Transformer
- Static VAR Compensator
- Harmonic Control
- Passive Harmonic Filters

Before the equipment is specified, front end engineering is required. Preliminary information needs to be obtained from the utility, from the proposed mitigation equipment suppliers, assuming that there is more than one and competitive bidding is anticipated. If partnering is expected, preliminary information is still needed.

It is recommended that a power quality survey be made of the facility. This may involve modeling the utility system, the industrial plant's electric supply system, and the new equipment using programs such as Electromagnetic Transients Program (EMTP) or SuperHarm. However these steps may often be avoided when the application screening process leads to clear solutions.

Information to be gathered, depending on which power quality problem is to be corrected, may include the following.

Historical data for each supply circuit from the utility:

- Interruption, averages annual number
- Momentary interruptions, average annual number
- Voltage sags, average annual number, and percent sag
- Voltage level range, maximum and minimum
- Ambient level of harmonics, total harmonic distortion value for each harmonic
- Minimum short-circuit kVA or MVA at the point of common coupling
- Identify any capacitors on the proposed supply circuit or circuits. Are the capacitors switched for voltage control?
- Single line diagram of the utility supply system showing power generation sources, transformers with impedances and capacitors

Information to be obtained from the industrial system:

- Single line diagram of plant electric system including transformers, circuit breakers, and capacitors
- Any harmonic producing equipment, such as rectifiers, adjustable speed drives, or other
- Any power quality mitigation equipment
- If the equipment is to be added to an existing plant, harmonic measurements on each supply bus and at the point of common coupling
- Identify any large motors that are started across-the-line, voltage and horsepower

Information obtained from the power quality survey and study:

- Voltage sag study, expected voltage sag level from line-to-line faults, from line-to-ground faults, and from motor starting
- Expected duration or any momentary interruptions, in cycles
- Level of voltage spikes to be expected from any capacitor switching or from circuit breaker operations on the utility system
- Expected harmonic levels from adding the new equipment
- Any potential electric harmonic resonances

Should the system be modeled, the process should be to model first without the mitigation equipment, to verify the accuracy of the model, by comparison with measurements, and with the mitigation equipment to demonstrate the effectiveness of the application.

Preparing the Power Quality Mitigation Equipment Specification

Based on information obtained from the power quality study, and what aberration is to be corrected, the specification should specify expected values for the following:

- Voltage sags, amplitude and duration
- Momentary interruptions, amplitude and duration
- Voltage spike amplitudes
- Ambient harmonic level
- Expected circuit resonant frequencies

The specification should include:

- Single-line diagrams of the utility power supply
- Single-line diagrams of the industrial plant point of common coupling identified
- Minimum available short circuit MVA from the utility at the point of common coupling to be specified

Developing the Power Quality Mitigation Equipment Specification

Once the type of mitigation equipment has been evaluated and selected, a detailed specification must be produced to convey to the prospective suppliers all information required for the purchase, installation and verification of the equipment. Historical information from the utility and data from the power quality survey and study of the facility needs to be collected before the equipment can be specified.

Information collected, depending on which power quality problem is to be corrected and the type of mitigating device selected, may include the following:

PQ Mitigation Equipment Design Basis

The Design Information Checklist (Table 7-1) will assist in the development of the equipment specification by determining each party's responsibilities for supplying information for the required design parameters of the mitigation equipment.

Table 7-1
Design Information Checklist

DESIGN INFORMATION CHECKLIST			
FROM UTILITY		**FROM FACILITY**	
Interruptions		**Harmonic Producing Equipment**	
Long Duration Annual Avg. Momentary Annual Avg.		Rectifiers ASD's Other	
Sags		**Single Line Diagrams**	
Annual Avg. % Sag		Facility	
Volatage Range		**Large Motors**	
Max. Min.		Quantity Voltage Horsepower	
Ambient Level of Harmonics		**Exist PQ Mitigation Equipment**	
THD Each		Type	
Min Short Circuit at PCC		**Sags**	
kVA mVA		Expected % Drop Line-Line Line-Ground Motor Starts	
Capacitors		**Momentary Interruptions**	
Voltage Control		Duration (Cycles)	
Single Line Diagrams		**Voltage Spikes**	
Utility Supply		Amplitude	
		Harmonics	
		Expected Levels Resonant Freq. At Bus At PCC	
		Modeling & Simulation	
		w/o PQ Equipment w/ PQ Equipment	

Guideline Specification

Based on information determined from the Design Checklist the Power Mitigation Equipment Specification may be completed. An additional Checklist for the PQ Equipment Specification (Table 7-2) will assist in making certain that all of the design and installation parameters have been addressed. Table 7-3 provides for the physical procurement and installation of the Power Mitigation Equipment.

Table 7-2
Power Quality Equipment Specification Checklist

ITEM	FOR QUOTES	FOR PURCHASE
1 SYSTEM REQUIREMENTS		
System Voltage Frequency Number of Phases Short Circuit. MVA at PCC Ambient Harmonics		
2 TYPE CONNECTION		
2-Wire 3-Wire 4-Wire		
3 GROUNDING RESTRICTIONS		
4 CONNECTION TO BY-PASS		
5 OTHER POWER SUPPLY INPUT		
6 AUXILLIARY REQUIREMENTS		
7 PERFORMANCE REQUIREMENTS		
Efficiency Voltage Distortion Current Distortion		
8 ENERGY STORAGE MEDIUM		
Full Charged Data End of Discharge Data Recharge Time		
9 RIDE-THROUGH CAPABILITY		
Time Power Levels		
10 LOAD TYPES		
Distorted Loads Critical Loads KVA Wave Form		
11 WILL CORRECT FOR:		
Sags Duration THV Distortion Interruptions Spikes Surges Harmonics		

Table 7-3
Power Quality Equipment Specification Checklist (continued)

ITEM	FOR QUOTES	FOR PURCHASE
12 PHYSICAL DATA REQUIREMENTS		

Location
Operating Temperature Range
Ambient Temperature Range
Dimensions
Weight
Center of Gravity
Accessibility
  Maintenance
  Cable Entry
Ventilation Requirements
Utility Requirements
  Air
  Water
Noise Level dBA
Other Special Considerations, size of doorway, etc		

13 OTHER INFORMATION		

Manufacturing Standards
Maintenance Requriements
Training
Warranty (extended?)
  Equipment
  Performance
  Testing
Installation Assistance
Start-Up Assistance
Spare Parts
Shipping		

14 DRAWINGS INCLUDED WITH THE SPECIFICATION		
Utility Single Line Diagram Plant Single Line Diagram		

Information to be Furnished by the Supplier with the Equipment Proposal

The equipment supplier should be informed of the necessity to fill in the customer provided specification in its entirety. This will facilitate the bid evaluation process. The equipment supplier may provide additional or back-up information but he must complete the initial specification.

The equipment supplier should furnish with his proposal; a statement of warranty to ensure equipment reliability of operation considering the specified expected system power quality characteristics. This warranty should include the duration, terms and conditions of additional on-site testing and monitoring for performance verification as well as the replacement installation of parts and major pieces of equipment.

The equipment supplier should furnish any training procedures or programs necessary for the proper operation and maintenance of the proposed equipment. Details of the training should include; any additional costs, the number of trainers to be involved, dates, number of training hours required and any special equipment or test instrumentation to be provided by the customer.

The equipment supplier should specify the tests to be performed during commissioning of his equipment to verify the reliability and proper operation of the equipment to the specified system power quality characteristics.

The equipment supplier should provide the method, terms and conditions for shipment of any and all equipment, software, test equipment, etc. included in the proposal. Pre-paid, FOB Destination is preferred.

The equipment supplier should provide with the proposal a complete spare parts list for all proposed equipment. This will include a list of recommended spare parts as well as price and availability

Mitigation Equipment Testing

The specification should designate the tests to be carried out by the Equipment Supplier (as in Table 7-4) to demonstrate compliance with the power quality corrective performance of the equipment specified per the system power quality requirements.

Table 7-4
Checklist for Power Quality Tests

ITEM	CUSTOMER	SUPPLIER
Test Procedure		
Test Technicians		
Test Equipment		
Test Schedule		
Equipment Availability		
Coordination		
Facility		
Utility		
Equipment Supplier		

Guidelines for the Evaluation of Bids Submitted

A bid tabulation sheet should be prepared from the proposals and specifications submitted by the equipment suppliers. Each supplier should provide his proposal in the same format as the specification issued with the "Request for Proposal". All items either technical or commercial can be addressed at the same time. Each supplier should be invited to provide additional or back-up information relating to his proposal but informed that if the format of the proposal deviates from the standard provided, it may be discarded. See Appendix I for an example of a checklist.

All of the issues regarding the proposed Power Quality solution, technical and commercial, needs to be addressed and included in the evaluation process. The customer will have to base his final decision on points such as the equipment and performance warranties, amount and type of training to be provided, the complexity of the proposed equipment and whether or not it can be properly operated and maintained. Remember that vendors have different levels of experience and expertise. Care should be exercised to choose the supplier on the basis of his/her technical capability as well as the price of the equipment.

The proposed suppliers have been provided with the results of the Power Quality Survey, Study and all of the back up information, including the Single Line Diagrams, Electrical Equipment List and any existing Power Quality Mitigating devices already installed. It is possible that each supplier won't propose similar types of mitigating devices for the same power quality problem or determine the cause and effect of a PQ anomaly to have the same origin. This is when the performance warranty and the on-site monitoring and testing provisions of the specification are most important. The supplier must warranty his solution as to the performance of the equipment to correct a problem as well its reliability.

A
IDENTIFYING AND QUANTIFYING POWER QUALITY ABERRATIONS

When the industrial process is performing without trouble, the focus is on “How much can we maximize profit”. Life is good. When the process is shut down because of trouble, and the cost is on the order of $25,000 per minute, life is not so good. The focus of management is on cause and effect. What is the cause of this abominable effect that is eating up profit? Subsequently, as analyses are made of the events leading up to the shutdown, the spotlight may end up on the electrical system, and the issue of power quality may come into sharp focus.

In this context, how do we quantify voltage aberrations indicative of power quality problems? These can be classified as follows:

- Transients
  - Impulsive
  - Oscillatory
- Interruptions
- Voltage Sags
- Voltage Fluctuations (Flicker)
- Voltage Regulation
- Voltage Imbalance
- Frequency Variations
- Interharmonics
- Noise
- Notching
- Harmonics

Accepted, defined value ranges for voltage aberrations are listed in Table A-1.

Table A-1
Categories and Characteristics of Voltage Aberrations

Categories	Typical Spectral Content	Typical Duration	Typical Voltage Magnitude
Impulsive Transients			
Nanosecond	5 ns rise	<50 ns	
Microsecond	1 us rise	50 ns- 1 ms	
Millisecond	0.1 ms rise	> 1 ms	
Oscillatory Transients			
Low Frequency	<5 kHz	0.3-50 ms	0-4 per unit
Medium Frequency	5-500 kHz	20 us	0-8 per unit
High Frequency	0.5-5 MHz	5 ms	0-4 per unit
Short-Duration Variations			
Instantaneous			
Interruption		0.5-30 cycles	<0.1 per unit
Sag		0.5-30 cycles	0.1-0.9 per unit
Swell		0.5-30 cycles	1.1-1.8 per unit
Momentary			
Interruption		30 cycles-3 s	<0.1 per unit
Sag		30 cycles-3 s	0.1-0.9 per unit
Swell		30 cycles-3 s	1.1-1.4 per unit
Temporary			
Interruption		3 s-1 min	<0.1 per unit
Sag		3 s-1 min	0.1-0.9 per unit
Swell		3 s-1 min	1.1-1.2 per unit
Long Duration			
Interruption, Sustained		>I min	0.00 per unit
Undervoltages		>1 min	0.8-0.9 per unit
Overvoltages		> I min	1.1-1.2 per unit
Voltage Unbalance			
		Steady-State	0.5-2%
Waveform Distortion			
DC Offset		Steady-state	0-0.1%
Harmonics	0-100th harmonic	Steady-state	0-20%
Interharmonics	0.6 kHz	Steady-state	0-2%
Notching		Steady-state	
Noise	Broadband	Steady-state	0-1%
Voltage Fluctuations			
	<25 Hz	Intermittent	0.1-7%
Power Frequency Variations			
		<10 s	

B
CHARACTERISTICS OF VOLTAGE ABERRATIONS

One must employ an accurate voltage-measuring device, such as an oscilloscope, to identify which of the voltage aberrations of Table A-1 is causing the problem. Several of these measuring devices are described later.

The pattern or trace characterizing each variation is shown in the following paragraphs.

Transients—Impulsive

These are commonly known as switching surges or voltage spikes. They can be caused by circuit breakers out of adjustment, by capacitor switching, by lightning, or by system faults. They are characterized by a sudden, non-power frequency change, by a high amplitude, by fast rise and decay times, and by high energy content.

Figure B-1
Impulsive Transient Voltage

Transients—Oscillatory

This is a sudden, bi-directional, non-power frequency change (a ringing). For high frequency ringing, >500 kHz of microsecond duration, and for 5 to 500 kHz ringing with tens of microseconds duration, it is likely the result of either the system response or the load response to an impulsive transient such as shown in Figure B-1. With a frequency of <5 kHz and 0.3–50ms duration, there could be one of a number of causes.

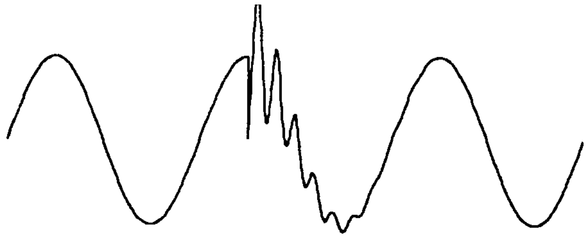

Figure B-2
Oscillatory Transient Voltage

Voltage Sag

This is a short-term, a few cycles duration, drop in voltage on the order of more than 10% to less than 90%. Typically, it lasts from 0.5 cycles to a minute. Voltage sags result from the voltage drop from starting big motors across the line, or from a fault on an adjacent power line.

IMPORTANT NOTE: The voltage sag represents the drop in percentage from the RMS value. As an example, a 30% voltage sag means a dip of 30% from the RMS voltage. The retained voltage is what is left, which would be 70% of the RMS voltage.

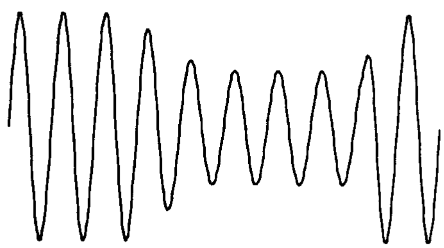

Figure B-3
Voltage Sag

Voltage Swell

This is a short-term increase in voltage of a few cycles duration. The magnitude of the increase is more than 10% and less than 80%. A swell can result from a single line to ground fault which raises the voltage on the other two phases. It can also result from dropping a large load or from energizing a capacitor bank.

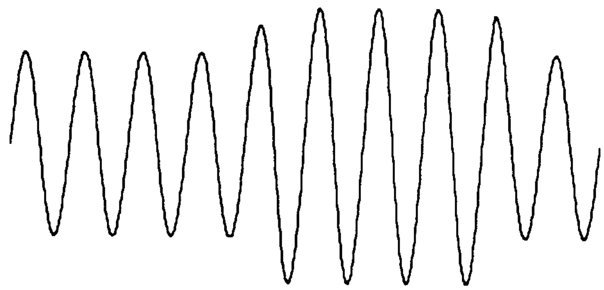

Figure B-4
Voltage Swell

Interruption

Ninety percent of the faults on overhead distribution lines are of a temporary nature. Typically, these faults result from lightning, tree limbs or animals causing grounds or shorts. Distribution lines are protected by a type of circuit breaker called a “Recloser”. Reclosers interrupt faults, then they automatically restore the circuit, or reclose, and if the fault has cleared, the Recloser stays closed. If the fault still persists, the recloser trips and again automatically closes back in. It usually recloses three times before locking out.

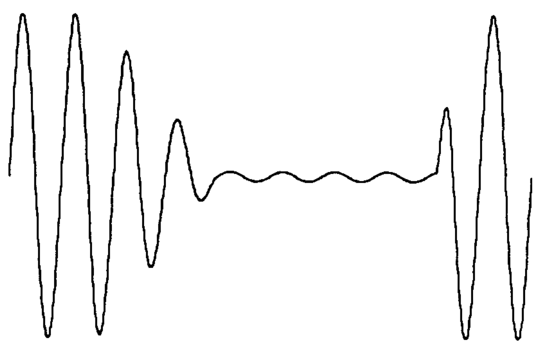

Figure B-5
Momentary Interruption

Voltage Flicker

Flicker comes from the aggravating, rapid on-off sensation of incandescent and fluorescent lamps as perceived by the human eye. It results from the rapid variation in voltage, within the normal allowable voltage range tolerance of 90 to 110%. Flicker can result from electric arc furnaces, welders, rapidly cycling loads, or it can result from a large ASD with inadequate dc link filtering on a weak distribution system. With inadequate dc link filtering, the inverter harmonics, which are a function of a non-60 Hz fundamental, flow into the power system, causing a pulsating of the 60 Hz fundamental.

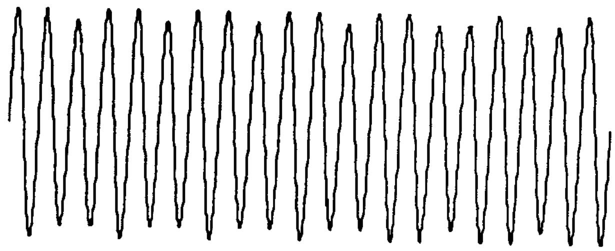

Figure B-6
Voltage Flicker

C
EQUIPMENT FAILURE CHECKLISTS

Failed Motor

Begin with the example of the failed motor checklist, Table C-1. The first ten items of possible cause can be investigated by dismantling the motor, e.g. removing the end bells and rotor, giving the windings standard electrical tests, inspecting the windings, and inspecting the bearings and the rotor.

Table C-1
Failed Motor—Checklist of Possible Causes

√	Possible Cause of Failure
	1 Manufacturing Defect
	2. High Ambient Temperature
	3. Foreign Material
	4. Water in Motor
	5. Inadequate Ventilation
	6. Winding Failure
	7. Locked Rotor
	8. Overload
	9. Over-Greasing
	10. Ground Fault
	11. Bearing Failure
	12. Transient Over-Voltage
	13. ASD Output Voltage-Related
	14. Voltage Phase Unbalance

Darkening of the color of the winding insulation enamel may corroborate overheating, lack of ventilation, overload, or locked rotor.

The last three possible causes of failure, Transient Over-Voltage, Adjustable Speed Drive Output Voltage-Related, and Voltage Phase Unbalance are power quality related. Evidence of each of these may possibly be supported by physical inspection (see Table C-2). Both the transient over-voltage and the Adjustable Speed Drive output voltage could cause a winding failure. The fact that the winding is failed can be determined either by the repetitive surge test or the megohmeter test, but the location of the failure in the winding will provide evidence if it is related to either of these causes. The failure would need to be located at a first or second coil from a line lead to qualify for either of these failure causes. Voltage phase unbalance would be evidenced by overheated windings. To find out if the failures are power quality related, a power quality study would have to be carried out.

Table C-2
Motor Tests and Inspections to Establish Cause of Failure

Procedure	Determines
Megohmeter Test	Motor winding is wet, dirty, or grounded.
Repetitive Surge Test	Motor winding is shorted or grounded.
Visual Inspection with Rotor Removed	
Windings	Motor windings are clean, dirty or wet. Winding insulation is burned or overheated. Evidence of over greasing,
Bearings	Evidence of bearing failure.
Rotor Surface	Evidence of bearing failure.
Shaft	Evidence of broken shaft.

Failed Dry-Type Transformer

The dry type transformer has failed in the warranty phase of a new project. There may be a difference of opinion between the project and the manufacturer as to the financial responsibility. To resolve this it is necessary to get to the root cause. As before, establish the checklist, Table C-3.

Table C-3
Failed Dry Type Transformer Checklist of Possible Causes

√	Possible Cause of Failure
	Manufacturing Defect
	High Ambient Temperature
	Water in Windings
	Overload
	Inadequate Ventilation
	Transient Over-Voltage
	Harmonic Current Heating

High cooling air temperature and lack of ventilation are possible causes of failure that need to be investigated. Temperature measurements in the vicinity of the transformer can be correlated with a review of temperature records. Studying temperatures in the immediate vicinity of the transformer can be made, noting the effect of sunlight on air and housing temperatures, and a check of cooling air inlet and discharge patterns with regard to any blockage or impediment to air flow.

An inspection of the windings with the covers removed may be worthwhile to locate the failure. Check for signs of overheating as evidenced by darkened color of varnish. Verify the presence or absence of water. Measurement of load amperes over a period of time can be made to check for overload as a possible cause of failure.

Condition of transformer over-voltage protection, such as metal oxide varistors (MOVs) should be checked for signs of transient over-voltage.

The investigation of Electromagnetic Interference (EMI), Transient Over-Voltage, or Harmonic Current Overheating as a cause of failure would include a Power Quality study to be described later.

Adjustable Speed Drive Trip

A critical process has shut down because a drive motor stopped when the adjustable speed drive controlling the motor tripped. Again, the checklist, Table C-4:

Table C-4
ASD Trip—Checklist of Possible Causes

√	**Possible Cause of Trip**
	Operator Action
	Process Computer Error
	High Ambient Temperature
	Ground Fault
	Restricted Ventilation
	Voltage Sag
	Electromagnetic Interference (EMI)
	Transient Over-voltage

The Adjustable Speed Drive's built-in self-diagnostics readout should be viewed to determine cause of failure. The self-diagnostics will tell if the shutdown was initiated by operator or control signal. Test equipment independent of the Drives self-diagnostics should be used to verify the cause of the shutdown. If the problem is related to high temperature, the ventilation of the Adjustable Speed Drive should be reviewed and ambient temperature checked. Adjustable Speed Drives are very sensitive to high temperature, and are self-protecting to limit major damage from diode and transistor overheating. If a high voltage trip is indicated, there is the possibility of a transient over-voltage.

Electromagnetic Interference (EMI) currents may be large enough to provide an erroneous trip signal. A low voltage trip may be indicative of a voltage sag. A power quality study may be warranted, if there is indication of high voltage, low voltage trip, or EMI.

Erratic Operation of Controls

Erratic operation of controls obviously can be caused by a number of things. Possible causes need to be put into a checklist, Table C-5:

Table C-5
Erratic Operation of Controls—Checklist of Possible Causes

√	Possible Cause of Problem
	Damaged Control Wire Insulation
	Damaged Critical Sensor
	Loose Connection
	Software Problem
	Voltage Sag
	Electromagnetic Interference (EMI)
	Current Harmonics

Before a power quality problem is assumed, other non-power quality related possible causes must be eliminated—damaged wire insulation, damaged instruments, loose connections, or software glitch.

A voltage sag may result in voltage so low that controls are not operating within their designed voltage-operating band, for example, plus or minus 10% of rated voltage. Electromagnetic Interference (EMI) produced currents may provide a stronger signal than the control signal and the controls are following EMI signals. Induced or conducted current harmonics may provide a stronger signal than the control signal, and the controls are following harmonic signals.

D
POSSIBLE EFFECTS OF POOR POWER QUALITY

Transient Overvoltage Effects—Nuisance Tripping and MOV Failures

In rural locations, it is not unusual for motors controlled by ASDs to trip off the line daily. These motors are often at remote irrigation pump sites fed from a distribution line. The owner likes the low cost of electricity associated with the ASD-controlled pump, but cannot tolerate the spurious trips. What is going on here?

Capacitor switching is a common event on most utility distribution systems. Shunt capacitors are applied on distribution feeders, at substations, and on transmission and distribution systems. They automatically switch on and off to adjust the line voltage for differences between daytime and nighttime loading and usually are switched on a daily basis: on during the day to boost voltage, and off at night to lower voltage.

The energizing of capacitors causes a transient voltage oscillation between the capacitor and the power system inductance. The result, illustrated in Figure D-1 for a 16 kV distribution system, is a transient overvoltage that can be as high as 2.0 per unit (pu) at the capacitor, where pu is the ratio of the voltage peak to the nominal voltage. The magnitude is usually less than this because of damping provided by system loads and losses.

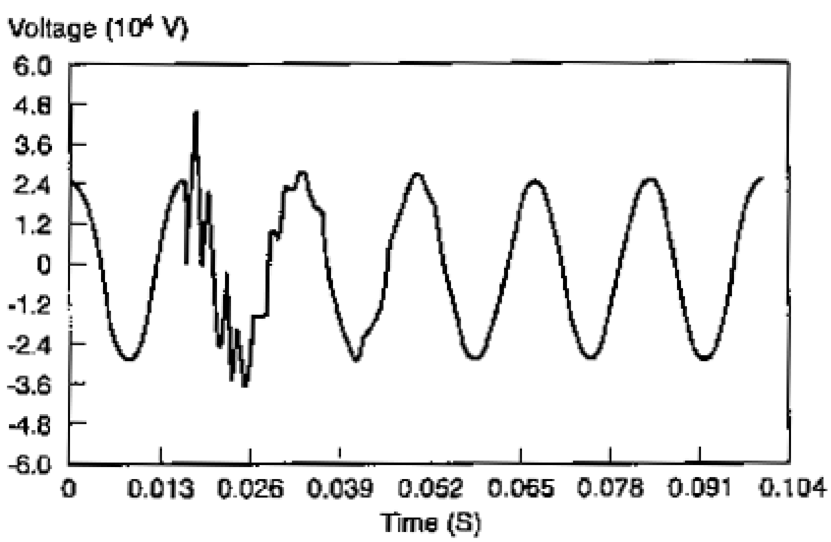

Figure D-1
Capacitor Bank Switching Transient

Transient overvoltages caused by energizing of capacitors are generally not a concern to the utility systems, other than for ASDs, because they are not high enough to operate surge protection and are well below the withstand levels of distribution transformers. Power factor correction capacitors located at the industrial facility may magnify these transients.

Figure D-2 illustrates the basic circuit of concern. The magnification of capacitor switching voltage transients is most severe when the following conditions exist:

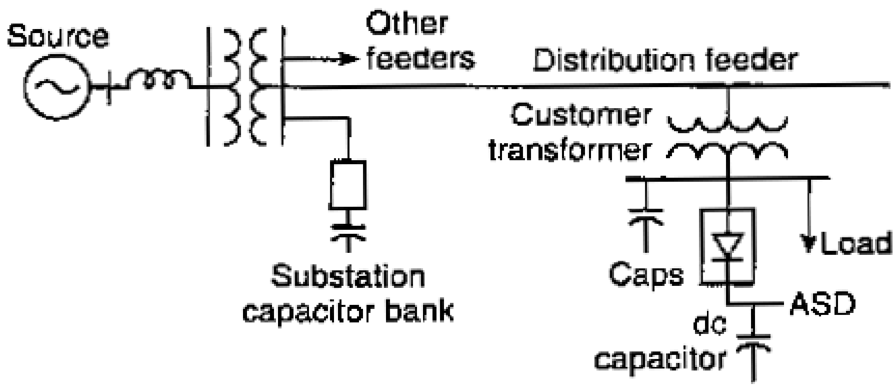

Figure D-2
Basic Circuit for Transient Voltage Magnification

The capacitor switched on the higher-voltage system has a much larger kVAR rating than the capacitor at the low-voltage bus.

The frequency of oscillation that occurs when the high-voltage capacitor is energized is close to the resonance frequency formed by the step-down transformer's reactance in series with the low voltage capacitor. This frequency occurs at minimum circuit impedance, where the resonant frequency f_r is as follows:

$$f_r = 1/2\pi(LC)^{1/2}$$

Where : L is the equivalent series inductance of the transformer.
C is the capacitance of the low voltage capacitor bank.

Resistive load present on the low-voltage system is not enough to provide damping of the transient. Lack of damping is also common for industrial power systems because motors do not provide significant damping.

Magnified transients at the low-voltage capacitors may be in the range of 3.0 to 4.0 pu. Figure D-3 shows an example of a magnified transient. These transients have significant energy levels and are likely to cause failure of metal oxide varistor, MOV, protective devices, electronic equipment, and capacitors. ASDs are particularly susceptible to these transients because of the relatively low Peak Inverse Voltage (PIV) ratings of the semiconductor switches and the low energy ratings of the MOVs used to protect the power electronics.

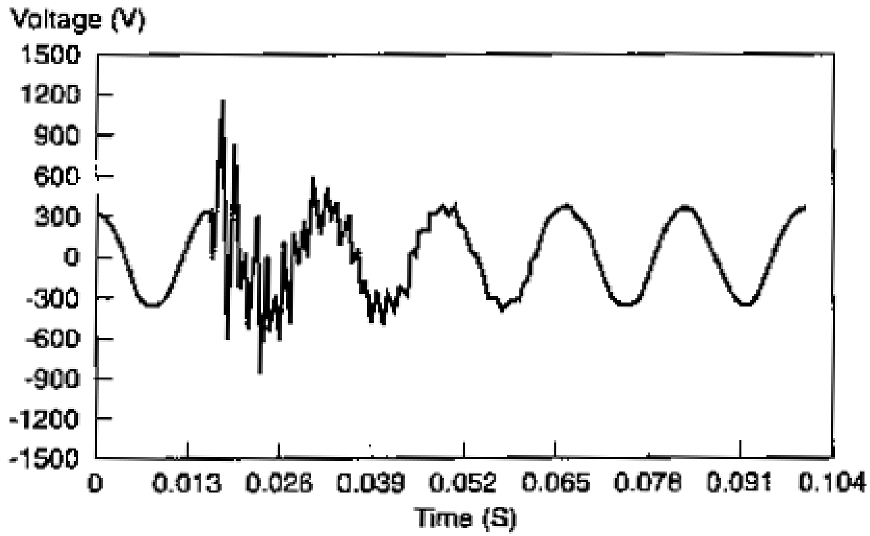

Figure D-3
Magnified Transient at 480-V Bus from Capacitor Switching

Low voltage ASD PWM inverters use a dc link capacitor. This type of ASD has protection for both dc overvoltage and undervoltage. It is not uncommon for the dc overvoltage control to trip the ASD whenever the dc voltage exceeds 1.17 per unit of its nominal 650 volt dc bus voltage (760 V for a nominal 480V system).

The dc link capacitor, Figure D-4, connected sequentially across each of the three motor phases, causes magnification of transient overvoltages that appear on the ac power side. Thus, utility capacitor switching results in a voltage surge at the dc link capacitor with a frequency in the 300- to 800-Hz range, tripping the ASD on overvoltage. Voltage and current wave forms at the ASD during a capacitor switching event are illustrated in Figure D-5.

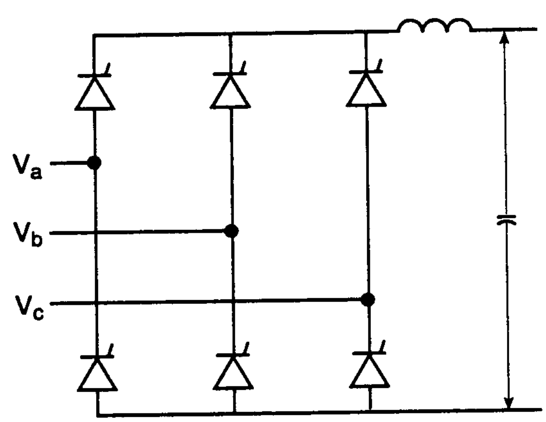

Figure D-4
Front End of Voltage-Source ASD

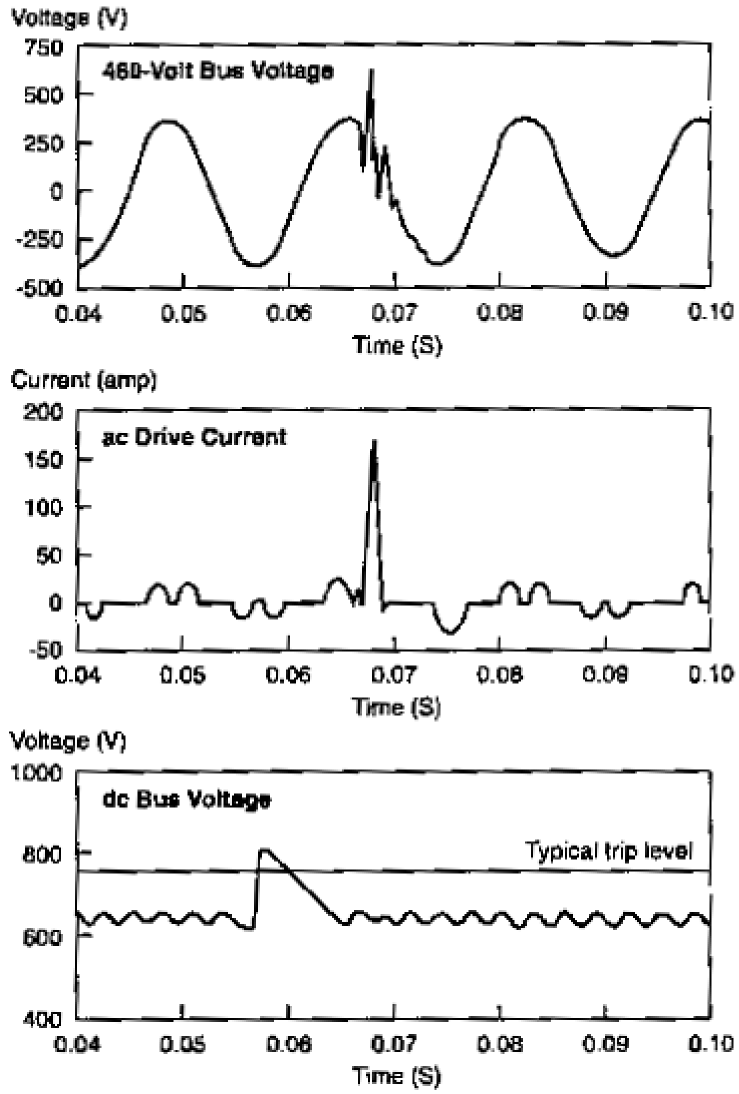

Figure D-5
Voltage and Current at the ASD

During Capacitor Switching ASDs are more susceptible to transient overvoltages than motors. The power semiconductor switches used in many ASDs have a peak inverse voltage (PIV) rating of 1200 V. This PIV rating equates to only 177% of nominal peak system voltage for a 480-V system. Most power semiconductor switch assemblies are equipped with MOVs for their protection. While the MOVs are effective for low-energy transients, they can be destroyed by magnified capacitor switching transients. These magnified transient overvoltages can be controlled in a number of different ways:

- The capacitor switching transient can be controlled on the utility system by using vacuum switches with synchronous closing control to energize the capacitor bank as close to the zero crossing as possible.

- High-energy MOV arresters can be used at the 480-V level. The energy capability of these arresters should be at least 1 kj. These can limit the magnified transient to approximately 1.8 per unit, which still may not be sufficient to protect sensitive electronics.
- Power factor correction at the 480-V level can be implemented as harmonic filters instead of shunt capacitor banks. The tuned filters change the response of the circuit and usually prevent magnification from being a problem. This is a good solution for a combination of power factor correction, harmonic control, and transient control.
- An effective way to eliminate the nuisance-tripping problem is to isolate the ASD from the power system with series inductance, either reactors or isolation transformers. The additional series inductance of the reactor or input transformer reduces the current surge into the ASD, thereby limiting the dc overvoltage. Determining the precise inductor size required for an ASD calls for a fairly detailed transient simulation, but a reactance value of 3% on the ASD's kVA rating is usually sufficient to solve the problem. Figure D-6 illustrates effects of various reactors on dc bus overvoltage.

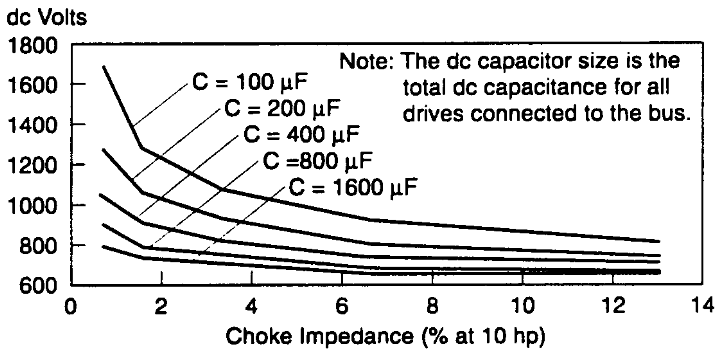

Figure D-6
Effect of Input Reactance on dc Link Voltage During Switching a 900 kVAR Capacitor Bank

The kVA rating of the reactor is determined as follows:

kW rating = hp rating x 0.746

kVA rating = kW rating / p. f.

To determine the impedance from the kVA rating, the kVA rating is called kVA_{base}. Using rated voltage, V, a base impedance, Z_{base} is calculated:

$Z_{base} = V^2 / kVA_{base}$ (ohms)

The 3% impedance is 3% of Z_{base}. To determine the inductance of the reactor, convert $.03 \times Z_{base}$ to inductance in Henries. The inductance of the reactor is considered to be equal to approximately the impedance. The inductance in Henries is given by the following:

$L = X_L / 2\pi \times 60$ henries

Sometimes even 5% reactance will not solve the problem, especially if the ASD is idling, drawing very little current. With the ASD idling, the reactors provide little voltage drop, and also, incoming excess energy is not transferred to the connected load. The difference in loading is the reason one ASD will trip on a voltage transient while another will not, and for voltage sags.

Motor Winding Failures from High dv/dt Switching Rates in Inverters

Advances in ASD technology have resulted in high switching rates in voltage-source PWM type ASDs. This has been done by ASD manufacturers (1) to reduce the current harmonics from the inverter to the motor and (2) to eliminate motor magnetic noise. The reduction of current harmonics has resulted in nearly negligible harmonic loss in the motor from inverter harmonics, so the motor does not have to be de-rated because of harmonic heating. It has also resulted in quiet motors, as the audible noise produced by high frequency harmonic resonance vibration of motor stator laminations has been eliminated. The audible noise reduction is good for motors driving air handler fans in air conditioning systems, but is not important for many industrial applications.

The downside to 12 kHz or higher switching frequencies has been cases of motor winding failures and motor bearing failures. In the 12 kHz range, high switching rates are accompanied by high rates-of-rise voltages. The rise time for inverter output voltage has gone from 0.5 to 2 used with bipolar voltage-source ASDs to as short as 0.05 used with IGBT voltage-source inverters. These new ASD output voltages are essentially of the same character as the switching surges from some circuit breakers that have been known to puncture motor winding insulation, except these from the inverter occur at a highly repetitive rate. Some manufacturers offer the choice of 3 kHz and 12 kHz carrier frequencies. The 3 kHz option eliminates the dv/dt issue. Others, marketing the ASD as a commodity, have their ASDs switch at 12 kHz to assure no noise problem.

Depending on the rate of rise of the voltage transient and the length of cable between the inverter and the motor, the classical transmission line reflected wave voltage doubling-effect can occur at the motor terminals.

Table D-1 shows that the faster the voltage rise time, or the higher the rate of change of voltage, dv/dt, the shorter the critical cable length in which the reflection occurs.

Table D-1
Voltage Doubling Reflection Occurs for Cable Lengths Longer Than

PWM Pulse Rise Time, us	Cable Length, Ft.
0.1	19
0.5	97
1.0	195
3.0	585
4.0	780
5.0	975

The surge impedance of the junction point determines if there is a reflection of an incident traveling voltage wave at the motor terminals. Consider the incident voltage reflections under the following three extreme conditions:

- Cable termination surge impedance is zero (e.g. a capacitor). The reflected wave will be equal in magnitude, but negative, compared to the incident wave resulting in zero net transient voltage.
- Cable is open at the end. The voltage reflection will be equal in magnitude to the incident wave and with the same sign, or, in other words, the voltage doubles.
- Cable is terminated in the characteristic impedance of the cable. There will be no reflection.

Since the characteristic impedance of a small motor is usually higher than the low surge impedance of the cables, the motor looks like an open connection to the cable. Voltage doubling is then possible, depending on the voltage rise time and the length of the cable.

Large machines have relatively low characteristic impedance since the winding capacitance increases and the equivalent inductance decreases. Table D-2 shows typical motor surge impedance values.

Table D-2
Typical Motor Surge Impedances

Motor HP	Surge Impedance, Ohms
25	1500
50	750
100	375
200	188
400	94

With cable characteristic impedance on the order of 50 ohms, it becomes clear that the voltage-doubling problem is one for small motors, generally considered to be 50 hp and less.

Controlling the Voltage Doubling Effect

To control the voltage doubling effect, there are several options:

- Use 230-volt motors. Although the voltage doubles, it is well within the capability of the motor insulation.
- Reduce the switching frequency to 2.5 to 3.0 kHz. With the lower rate-of-rise of voltage, there is no transmission line effect.
- Use only motors with sufficient insulation to withstand the voltage, even if it doubles. The ASD output voltage is the same as the dc link voltage. The dc link voltage can be 1.4 times the incoming ASD voltage times 1.1, since motors can operate at 10% above rated voltage, or 708 volts. Doubling this voltage is 1416 volts. Magnet wire manufacturers have developed a wire coating suitable for this duty. The new wire reportedly has 200 times more surge voltage withstand than conventional magnet wire used in motors, and apparently carries no extra cost. Assuming that this wire is as good as advertised, this solution is the simplest one, as far as the motor is concerned. It does not protect the cables, but there has been little published complaints about ASD reflected voltage waves affecting cables.
- Use appropriate filters.
- *Line reactor at ASD output* will solve many voltage doubling problems. The reactor slopes off the rise time and may increase the allowable cable length by a factor of ten. The reactor should be selected by the ASD manufacturer so that resonance problems do not occur, nullifying the benefit of the reactor.

Commercially available dv/dt filters consisting of reactors, capacitors and resistors can be used at the inverter output, Figure D-7. The unit shown in Figure D-7 is for a 5-hp motor with 100 feet of cable. R = 100 ohms,
L = 0.2 mH, C = 0.075 uf.

A Line termination network at the motor terminals closely matches the cable surge impedance to eliminate the reflection. Since the cable characteristic impedance changes only slightly from #14 wire to 500 kcmil wire, a single device can be used for any motor size.

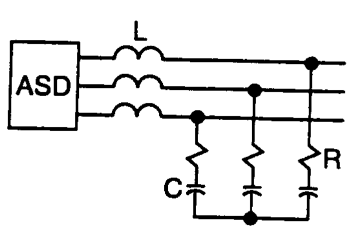

Figure D-7
ASD Output Filter for 5 hp Motor

Voltage Unbalance: ASD Overload Trip from Self-Generated High Third Harmonic Current

With a stiff system, e.g. a high short circuit current capability, a relatively small input voltage unbalance, say 2.6%, can result in an input current unbalance of 23% to 65%, depending on the amount of internal inductance or reactance in the ASD. The characteristic current wave shape, Figure D-8, shows a high third harmonic content as the internal series reactance saturates. This is not the normal current wave shape for balanced input voltages to the ASD.

An input reactor can be used to even-out the voltages to lessen this effect.

EMI: EMI Currents Overwhelm Control signal Current

Fast switching speed and high input impedance give IGBT inverters the potential to produce stray currents that can disrupt communications equipment, ASD control, programmable controllers, sensors, barcode scanners and position sensing equipment. These stray currents can lead to electromagnetic interference (EMI). EMI can lead to the impairment of low voltage control signals with adverse effects on sensitive process controls. EMI produced currents may provide a stronger signal than the control signal, and the controls start following EMI signals. Induced or conducted current harmonics may also provide a stronger signal than the control signal, and the controls start following harmonic signals.

EMI: ASD Overload Trip from Induced Voltage Unbalance

When multiple ASDs are installed, care must be taken in maintaining cable separation between the cables of the different ASDs so that voltage from one inverter is not induced into the cables of another inverter. It is possible to develop a voltage unbalance of up to 200 volts between phases from the effects of the cables of another inverter. This unbalance can result in extremely high motor temperatures, the cause of which can only be found by operating the motors individually, with the others shut down.

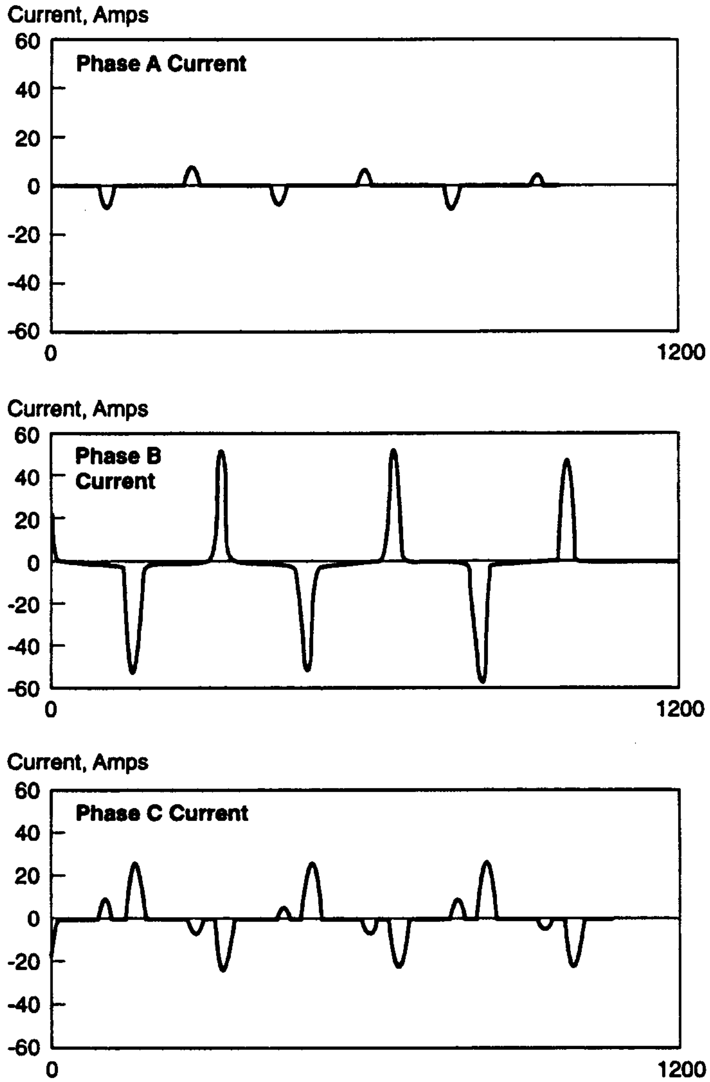

Figure D-8
Currents Resulting from Small Voltage Unbalance

Effects of Voltage Sags and Momentary Interruptions on ASDs

One ASD application concern is its sensitivity to short-duration voltage sags and momentary interruptions of the power supply.

Whenever there is a fault on the transmission or distribution system serving a commercial or industrial facility, there will be either a voltage sag or an interruption. Faults cannot be completely avoided regardless of the system design. The voltage sag will persist until the fault is cleared by a protective device, typically in 3 to 30 cycles depending on the fault location. If the fault is on the same feeder as the industrial facility, power is likely to be completely interrupted. With reclosing circuit breakers, power will be restored after a specified delay if the fault is temporary. Figure B-3 illustrated the voltage waveform that can occur at a facility remote from the fault location with the fault on a different feeder or on the transmission system.

The effect of remote system faults should be considered when ASDs are applied to critical processes. Nuisance tripping can cause an entire process to shut down.

Tests conducted by EPRI, on 5 hp ASDs of several manufacturers showed that all could tolerate 30 cycle voltage sags to 75% voltage. Some had problems with sags to 70% voltage, some could ride through sags down to 40 % of normal voltage, and the ASDs of two of the manufacturers could ride through 30 cycle sags down to zero volts.

This voltage sag ride through capability is obtained by energy storage in the dc link capacitor. While this capability is vital for critical loads, it may not be needed for a variety of applications such as irrigation pumps, parking garage ventilation fans, HVAC air handlers and pumps, and other non-critical applications, providing the ASD has a feature to automatically restart upon restoration of voltage. For most industrial applications, allowing the transient voltage sag to produce 50% speed and 50% torque allows margin for the ASD to respond to a voltage sag.

Voltage Flicker

Flicker comes from the aggravating, rapid on-off sensation of incandescent and fluorescent lamps as perceived by the human eye. It results from the rapid variation in voltage, within the normal allowable voltage range tolerance of 90 to 110%. Flicker can result from electric arc furnaces, welders, rapidly cycling loads, or it can result from a large ASD with inadequate dc link filtering on a weak distribution system. With inadequate dc link filtering, the inverter harmonics, which are a function of a non-60 Hz fundamental, flow into the power system, causing a pulsating of the 60 Hz fundamental. Powerful voltage flicker can cause vibration and heating problems in rotating electrical machinery.

Voltage Regulation

Low voltage during peak load periods can result from overloaded lines, improperly set transformer taps, or maladjusted automatic voltage regulators. The voltage is less than the normal 90% lower limit. Symptoms are light bulbs too dim, light bulbs burn out too often, electric motors not starting.

Harmonics

Harmonics can cause such problems as telephone interference, motor over heating, transformer overheating, capacitor fuse blowing, high neutral currents, and problems with electronic controls.

The utility system is the transmission or distribution system that serves multiple customers. The utility is responsible for the power quality at the point of common coupling with each of its customers. For most systems (below 69 kV), the Total Harmonic Voltage Distortion should be less than 5%. This means that the utility must work with the customers to make sure that system resonance conditions do not cause unacceptable voltage distortion levels, even if all customers are within the recommended guidelines for harmonic current generation.

IEEE Std 519 recommends limits for voltage and current distortion at the point of common coupling. These recommendations are summarized below. Total Harmonic Distortion (THD) is given by the following definition: the square root of the sum of the squares of amplitudes of individual voltage harmonics from 2 to 50, divided by the amplitude of the fundamental voltage, or expressed as follows:

$$THD = \frac{\sqrt{\text{sum of all squares of amplitude of all harmonic voltages}}}{\text{square of the amplitude of the fundamental voltage}} \bullet 100\%$$

$$THD = \frac{\sqrt{\sum_{h=2}^{50} V_h^2}}{V_1} \bullet 100\%$$

Table D-3
Recommended Limits for THD from (IEEE Std 519 Table 11.1)

Bus Voltage at PCC	Individual Voltage Distortion, %	Total Voltage Distortion, %
69 kV and below	3.0	5.0
69,001 through 161 kV	1.5	2.5
161,001 kV and above	1.0	1.5

Current distortion, in IEEE Std 519, is called Total Demand Distortion (TDD). It is defined as the square root of the sum of the squares of the individual current harmonics from 2 to 50, divided by the amplitude of the fundamental, or expressed as follows:

$$TDD = \frac{\sqrt{\text{sum of all squares of amplitude of all harmonic currents}}}{\text{square of the amplitude of the fundamental current}} \bullet 100\%$$

$$TDD = \frac{\sqrt{\sum_{h=2}^{50} I_h^2}}{I_1} \bullet 100\%$$

IEEE Std. 519 has three sets of recommended current distortion, each as a function of voltage level and short circuit ratio, I_{SC}/I_L, where I_{SC} and I_L are the short circuit current and the load current at the point of common coupling.

These recommendations are summarized in Tables D-4, D-5, and D-6. For each of the tables,

- Even harmonics are limited to 25% of the odd harmonic limits given.
- Current distortions that result in a dc offset, e.g. half-wave converters, are not allowed.
- I_{SC} = maximum short-circuit current at PCC.
- I_L = maximum demand load current (fundamental frequency component) at PCC.

Table D-4
Recommended Limits for Current Distortion (IEEE Std 519 Table 10.3)—120 Volts through 69,000 Volts

I_{sc}/I_L	<11	11<h<17	17<h<23	23<h<35	35<h	TDD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Table D-5
Recommended Limits for Current Distortion (IEEE Std 519 Table 10.4)—69,001 Volts through 161,000 Volts

I_{sc}/I_L	<11	11<h<17	17<h<23	23<h<35	35<h	TDD
<20	2.0	1.0	0.75	0.3	0.15	2.5
20<50	3.5	1.75	1.25	0.5	0.25	4.0
50<100	5.0	2.25	2.25	0.75	0.35	6.0
100<1000	6.0	2.75	2.75	1.0	0.5	7.5
>1000	7.5	3.5	3.5	1.25	0.7	10.0

Table D-6
Recommended Limits for Current Distortion for General Transmission Systems above 161 kV (IEEE Std 519 Table 10.5)

I_{sc}/I_L	<11	11<h<17	17<h<23	23<h<35	35<h	TDD
<50	2.0	1.0	0.75	0.3	0.15	2.5
>50	3.0	1.5	1.15	0.45	0.22	3.75

Interharmonics

Interharmonics are frequency components of distorted voltages that are not integer multiples of the fundamental 60 Hz frequency. Interharmonics can produce voltage flicker and control system misoperation.

Voltage Notching

Voltage notching is a periodic voltage disturbance results from the normal operation of power electronic devices, such as thyristors. It appears as a notch in a voltage sine wave. It is not normally a problem since it is controlled by circuit elements associated with the switching devices. It can be a significant problem on weak electric systems, where it can produce control system mis-operation.

E
MONITORING INSTRUMENTS AND EQUIPMENT—GENERAL

The following are instruments and equipment to be considered for the monitoring program:

- Oscilloscopes allow the technician to inspect voltage and current wave- forms for harmonic distortion or other steady state phenomena.
- Spectrum analyzers perform Fast Fourier Transforms (FFT) for calculation of the frequency components of a distorted waveform.
- Disturbance analyzers are designed specifically to record intermittent disturbances. Often thresholds are set to ignore normal voltage conditions and to record only events that exceed the thresholds
- Conventional analyzers summarize events with specific information on voltage, such as magnitude, surge/sag, and duration.
- Graphics-based disturbance analyzers save and print the actual waveform along with the descriptive information of conventional analyzers.
- Data acquisition systems collect waveforms at key sites for immediate and/or post collection processing.

The basic measuring tools for the power quality monitoring is the power quality monitor (Ref Appendix F for details). Other useful tools are the ground resistance meter, megohmmeter, circuit tester, multimeter, infrared scanner and clamp-on current probes.

F
MONITORING ANALYZERS—SPECIFIC

Following are industrial analyzers that have been used successfully in power quality studies to obtain a profile of power quality at sensitive equipment locations and at the service entrance:

- Steady State Phenomena
  BMI 3030A
  Dranetz 8000
- Disturbances
  BMI 4300, 8800, 8020, and 9020
  Dranetz 658
  Metrosonics (RMS only)
- Combined Steady State and Disturbance
  BMI 8010, 8020, and 9020 PQNodes
  NI Data Acquisition System
  Fluke VR101S Event Recorder

Selection of Power Quality Monitoring Equipment

There are a variety of power quality monitors available. The correct monitor for the job should be selected. As an example of the differences in available monitors, Table F-1 shows the capability of several power quality monitors offered by Dranetz-BMI. Monitors may be rented from firms such as: Industrial Test Equipment Rentals of Duluth, Georgia.

Table F-1
Capabilities of Power Quality Monitors

Capability	Hand-Held 4300	Portable PP1	Portable 8800	Portable 3030A	Portable 8020	Portable 9020
Circuit Type						
3-Phase	X	X	X	X	X	X
Power Quality						
Cycle-by-Cycle Analysis	X	X	X	X	X	X
Sags/Swells	X	X	X		X	X
Transients	X	X	X		X	X
Neutral-to-Ground	X	X	X	X	X	X
Flicker		X				
Power/Energy						
V,A,W,VA,VAR	X	X	X	X	X	X
Power Factor—True	X	X	X	X	X	X
Power Factor—Displacement	X	X	X	X	X	X
Demand, kW, kVA	X	X	X	X	X	X
Energy, kWH	X	X	X	X		X
Harmonics						
THD	X	X	X	X	X	X
TDD	X	X	X	X	X	X
Spectrum Analysis	X	X	X	X	X	X
Crest Factor	X	X		X		
Transformer K-Factor	X	X		X		
Transformer Derating		X		X		
Special Measurements						
Motor Inrush		X				
Transformer Inrush		X				
Voltage Unbalance	X	X		X		
DC Voltage	X	X				
Temperature And Humidity				X		
PC Software						
Report Writer	X	X				
Harmonic Analysis	X	X				
Communications						
Serial	X	X	X	X	X	X
Modem	X	X	X	X	X	X

Some of the key functions to consider in selecting a power quality monitor are as follows:

- Multiple channels to monitor phase, neutral and ground simultaneously
- Voltage and current measurements
- Waveform display
- Continuous monitoring
- Harmonic analysis
- Scope mode
- Simultaneous display of current and voltage wave forms
- Wide frequency response
- Event summaries to provide graphical plots of RMS and high frequency events
- Capability to access the monitor over the internet

G
SIMULATION MODELS

There are several computer programs available for the Power Quality study. Power flow programs such as PSS/E, PSLF and SIMPOW can be used for voltage sag and flicker depth calculations.

Harmonic analysis programs can be used for calculating harmonics, notching and noise. Examples are Electrotek Concepts' Superharm, and EPRI's Harmflo Plus.

The most widely used program for transient analysis is Bonneville Power's Electromagnetic Transients Program—EMTP. EMTP can be used for a variety of studies as listed in Table G-1.

Table G-1
Capabilities of EMTP

Switching surge studies	Other
Line energizing	Arrester duty
Single pole switching	Insulation coordination
High-speed reclosing	Static Var compensator operation
Capacitor switching	Ferroresonance
Fault clearing	Parallel resonance
Transformer switching	Motor starting
Reactor switching	Harmonic propagation analysis
	Power electronics harmonics analysis
Lightning surges	
Induced surges	
Incoming surge at station	

Another general purpose program for studying transient behavior of electrical networks is the Manitoba Hydro HVDC Research Centre's PSCAD/EMTDC program.

Power Quality Anomaly Simulation

Portable power quality test simulators are available for rent along with technicians from EPRI PEAC, Inc. (100 ampere, 480 volts) and Duke Power (200 ampere, 480 volts). The EPRI PEAC 100-ampere equipment is intended for component testing. The Duke Power 200-ampere equipment is intended for use at the motor control center. These devices can simulate the following anomalies:

- Voltage sag
- Voltage unbalance
- Voltage swell
- Low steady-state voltage

To simulate a voltage interruption, the supply breaker is opened and closed. If there is a utility capacitor bank in the region of test site, the effect of capacitor switching transient could be observed with the power quality monitor.

H
MITIGATION EQUIPMENT

Mitigation equipment exists for each of the power quality problem categories discussed: voltage transients, voltage sags, interruptions, regulation, harmonics, flicker and voltage unbalance. Some of this equipment is listed in Table H-1. Refer to Volume 2 of the guidebook for additional information on mitigating solutions and their applications.

Table H-1
Power Quality Mitigation Equipment

Problem	Mitigation Device
Voltage Transient	
Spike	Surge Arresters
Oscillation	Lightning Arresters
	Static Switch
	Controlled Switching
	Energy Storage Systems
Voltage Sag	
	Energy Storage Systems
	Static Switch
	Automatic Tap-Changing Transformer
	Dynamic Voltage Regulator
	Static Var Compensator
Voltage Interruption	
Momentary	Energy Storage Systems
Sustained	Static Switch
	Automatic Tap-Changing Transformer
	Dynamic Voltage Regulator
	Static Var Compensator
Regulation	
Overvoltage	Automatic Tap-Changing Transformer
Undervoltage	Dynamic Voltage Regulator
	Static Var Compensator
Harmonics, Notching, Noise	
	Passive Filter
	Dynamic Filter
	Static Var Compensator
Flicker	
	Static Var Compensator

I
PROJECT IMPLEMENTATION

Example I-1 Sample Memorandum of Understanding

MEMORANDUM OF UNDERSTANDING

Between

Utility
Manufacturer
Electric Power Research Institute
EPRI-ASD Demonstration Office

and

User

For

Product

Installed on Utility System for
Connected Customer

Date

MEMORANDUM OF UNDERSTANDING

1. DEFINITIONS

For the purpose of this memorandum, the following definitions are applicable:

Project Management defines the role of an individual or organization in coordinating overall work activities, combining and analyzing data and findings, and issuing monthly and final reports and minutes of all meetings.

System Analysis defines the process of reviewing the application of a product from the standpoint of its impact on connected and connecting elements, the process product, and the operating system as a whole.

Steering Committee—The purpose of the steering committee is to overview and provide direction and council to the project team. The committee will review and approve all major decisions. Any member of the steering committee will have the right of veto in regard to a decision. All decisions must have unanimous approval of the steering committee. The steering committee will consist of a representative from user, utility, manufacturer, EPRI.

System Integration defines the process of effectively applying the equipment as part of an overall cost/benefit, reliability and performance enhancement project goal. System integration considers interferor and interfere impact as well as process benefits.

Project Team defines the member organizations & individuals comprising the team. The team includes participation by the following individual organizations:

List

2. PURPOSE

The purpose of this memorandum is to describe the roles and responsibilities of the project team members. The team is charged with bringing together the required expertise and resources to provide and install product. The project will identify issues and benefits that occur from the equipment thereby promoting market transformation for the technology introduction.

The cooperation is to include non-confidential information exchange on equipment operation before and after the installation of the equipment. Measurements will be taken to determine the degree of effectiveness in avoiding production process impact due to PQ events.

EPRI and EPRI-ASDO have mutual interest in the successful application of energy storage to manufacturing processes. The energy storage will permit the process to continue operating through brief voltage sags and voltage interruptions.

Many industrial processes are vulnerable to the effects of voltage sags and momentary interruptions of supply voltage. The voltage sag is the most common power quality concern for industrial customers. These events cause significant process disruptions and downtime.

Energy storage in on equipment is a method of providing process ridethrough during voltage sag events. Recently this approach has become practical for large-scale applications due to the production of high capacity-flywheel ridethrough systems.

3. UNDERSTANDING

To accomplish the desired cooperation, each party will have a specific role in completing tasks as outlined by the defined Statement of Work. The objective of the work is to demonstrate the performance of the product under monitored field conditions. The roles defined for each team member are as follows:

Utility

Utility will provide project funding for equipment through an EPRI tailored collaboration ("TC") project agreement and will provide an individual to serve on the project team and steering committee. Details of the project activities to be completed by Utility are as follows:

Provide system information
Identify the host demonstration site
Install system
Install measurement equipment
Maintain measurement equipment
Collect data before and after the product installation
Participate in site coordination and timing issues
Provide coordination of all measurement activities
Act as "gate keeper" on all site information
Gather information on the application that may be used in conjunction with the electrical performance measures
Monitor the site and keep site information
Coordinate press releases
Contribute information for the utility/EPRI internal report
Establish a confidentiality agreement with supplier

Connected Customer

Connected customer will provide an individual to serve on the project steering committee meeting, provide a site for the installation of the new equipment. Detailed contribution to the project will be as follows:

Provide system information
Provide access to site for installation and service
Provide local assistance with data collection
Allow reasonable access to the installation for interested observers
Assist with the economic information
Contribute to the project report
Participate in the coordination and timing of the installation

Supplier

Supplier will provide information on the product, the detailed items are as follows:

- Provide detailed specification
- Supply to the customer site equipment that has been completely factory tested as per purchase order
- Arrange witness testing at _______

- Provide installation supervision. Startup and confirm performance on site and provide customer training concurrent with startup
- Assist with information collection
- Assist with data reduction
- Contribute specialized sections of the EPRI report covering the equipment design
- Participate in project coordination

EPRI Role

EPRI will act as overall project manager for the project and will maintain control of the project budget. EPRI will publish a report on the project.

The title for the equipment will be transferred by EPRI from EPRI to utility.

EPRI-ASDO

EPRI-ASDO will facilitate project review meetings, provide meeting agendas and histories. The ASDO will also be responsible for:

- Project budget tracking
- The data collection plan
- Order BMI 9010 instrument
- MOU preparation & write-up
- Contribute to project report
- Prepare report outline
- Coordinate the sections of the draft report
- Finalize the report for internal use

4. AGREEMENT

Based on the operational needs of each team member, the team will establish and define a mutually agreeable schedule for completion of the work. The Agreement set forth in this Memorandum of Understanding is not binding on the parties, but every reasonable means will be used to carry out the intent of the Memorandum of Understanding.

Accepted this _____________ day of __________________ , _____ by:

____________________________	____________________________
Name Title Utility	Name Title Manufacturer
____________________________	
Name Title Connected Customer	
____________________________	____________________________
Name Title Electric Power Research Institute	Name Title EPRI ASD Demonstration Office

Example I-2 Quotations/Proposals—Technical Bid Analysis

PAGE: 39 OF 7

QUOTATIONS/PROPOSALS—TECHNICAL BID ANALYSIS

Rev. No	Issue Date	Pages	Rev. Description	Prepared By	Check By	Approved By
				- -		

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5.0 RELATED DOCUMENTATION(REFERENCES)

Engineering Requisitions

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7.0 ATTACHMENTS/APPENDICES

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7.2 QUOTATIONS- TECHNICAL ANALYSIS SUMMARY (SHEET 1 OF 2)

- TECHNICAL ANALYSIS WORKSHEET (SHEET 2 OF 2)

1.0 PURPOSE

The purpose of this procedure is to define the activities associated with the technical analysis of quotations received in response to engineering requisitions.

2.0 SCOPE

This procedure covers engineering activities associated with the receipt of quotations and the subsequent review, reporting, approval and distribution of those quotations.

3.0 DEFINITIONS

None

4.0 METHOD (PROCEDURE)

4.1 INTRODUCTION

It is the responsibility of those engineering disciplines that generate requisitions to complete a Technical Analysis of the relevant Quotations. Preferably, this technical analysis should be carried out by either the originator or checker of the Inquiry Requisition and supporting specification/technical information.

4.2 APPRAISAL

The Technical Analysis shall include, but not be limited to, the following activities and their relevant criteria:

- Using the standard forms (Attachment 7.2, Sheet 1 of 2) list all criteria that will be used to evaluate the vendor's/subcontractor's technical quotations.
- Ensure that vendors/subcontractors comply completely with all technical requirements specified in the inquiry documentation.
- Compare the Company requirements with the vendor's/subcontractor's offer. Compliance/noncompliance shall be noted on standard form (Attachment 7.2 Sheet 2 of 2). Performance guarantee criteria must be confirmed. Where practicable, noncompliance should be rectified or noted and accepted.
- Ensure that testing requirements are confirmed.
- Ensure that the offered schedule commitments are acceptable.
- Ensure that the documents identified in the requisition, together with their delivery dates, are acceptable.
- Confirm the vendor's/subcontractor's capability to satisfy the requisition.
- Where vendors offer fully supported alternative options to specification or equipment, these must be fully evaluated and cross referenced to any price variations.

4.3 REPORTING

When Attachment 7.2 (Sheet 2 of 2) has been completed for all vendor/subcontractor quotations being considered the summary information is analyzed and the `Quotations—Technical Bid Analysis' report is finalized as follows:

- Technically compliant offers are identified and noted, with any variance from specification explained technically.
- Identify and note any technically superior offers, together with the basis of their superiority and an explanation of the technical benefits which they would provide.

- Technically compliant offers shall be ranked based on the perceived technical benefits.
- Engineering's recommended vendor/subcontractor shall be identified and noted together with the basis for recommendation.

4.4 APPROVAL

Where the technical analysis is completed by the originator or checker of the Inquiry Requisition no signature other than this individual is required.

Where the technical analysis is completed by a person who neither originated nor checked the inquiry requisition, the technical analysis must be signed by this person and the relevant Discipline Manager.

Approvals other than as specified will be identified within the Project Procedure; in particular, it is the responsibility of the person completing the technical analysis to review the analysis with the project process engineer and obtain his/her concurrence (by initialing the documents) that the technical offering complies with the process intent.

4.5 DISTRIBUTION

Using the agreed distribution method, the completed Quotation—Technical Bid Analysis will be issued to the project's purchasing function.

5.0 RELATED DOCUMENTATION (REFERENCES)

SOP-108 Engineering Requisitions

6.0 RECORDS

The Quotation—Technical Analysis (Attachment 7.2) is a Quality Record and a copy is to be retained in the purchase order file.

7.0 ATTACHMENTS/APPENDICES

7.1 FLOWCHART-QUOTATIONS—TECHNICAL BID ANALYSIS ACTIVITIES.

7.2 WORKSHEET-QUOTATIONS—TECHNICAL BID ANALYSIS.

Attachment 7.1
Flowchart of Quotation—Technical Bid Analysis Activities

RECEIVE
VENDOR QUOTATION/PROPOSAL

↓

APPRAISAL
- Compliance to Requisition?
- Compliance/non-compliance to Specification?
- Clarification Communications
- Evaluate alternative options

↓

REPORTING
- Establish Technical compliant offers
- Establish Technical superiority
- Rank Technically compliant
- Compliance/non-compliance to Specification?

→ Discipline Purchase Order File

↓

PURCHASING

Attachment 7.2
QUOTATIONS—TECHNICAL BID ANALYSIS—SHEET 1 OF 2

QUOTATIONS - TECHNICAL BID ANALYSIS
SUMMARY SHEET

Requisition No:	____________________	**Project No:**	____________
Specification No:	____________________	**Project Title:**	____________
Description:	____________________	**Client:**	____________
Service:	____________________	**Date:**	____________

Quotations were received from the following Vendors/Subcontractors:

Quotation #1 ____
Quotation #2 ____
Quotation #3 ____
Quotation #4 ____

Technically compliant Quotations:

Quotation # ____
Quotation # ____
Quotation # ____
Quotation # ____

Technical compliant alternatives:

Quotation # ____
Quotation # ____

Technical recommendation:

Quotation # ____

Basis for Technical recommendation:

Prepared By/Date: ____
Checked/Approved By/Date
(if appropriate) ____
Checked/Approved By/Date
(if appropriate) ____

Attachment 7.2
QUOTATIONS—TECHNICAL BID ANALYSIS—SHEET 2 OF 2

JACOBS ENGINEERING
QUOTATIONS - TECHNICAL BID ANALYSIS
WORKSHEET

Requisition No:		**Project No:**	
Specification No:		**Project Title:**	
Description:		**Client:**	
Service:		**Date:**	

	Description	Specification Requirements	Quotation #1 Reference	Quotation #2 Reference	Quotation #3 Reference	Quotation #4 Reference	Comments	Rev
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								
16								
17								
18								
19								
20								
21								
22								
23								
	Revision Number							
	Prep Number							
	Check/Approval/Date							

Example I-3 Request for Proposal

To:
Company:
Phone:
Fax:
Date:
Total Pages:

From:
Company:

References

Please provide a proposal by ________ for the equipment/material shown on attached Specification Sheet(s).

1. Proposal should include:

   a. Price

   b. Shipping Terms included carrier (i.e. UPS< motor freight etc.)

   c. Payment Terms

   d. Lead time after award for drawing/document submittal and shipment

   e. Manufacturer’s model number (with tag number shown)

2. Purchase Order Requirements:

   a. ______ prints and _______ reproducible are required per submittal

   b. ______ IOM Manuals per item

3. For Technical Questions Contact __________________________

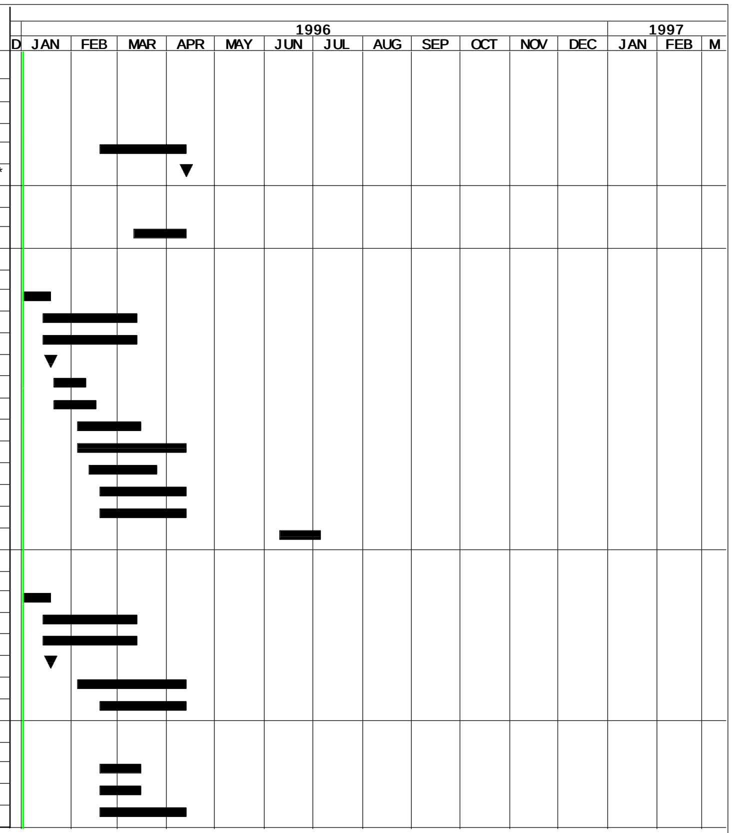
4: Buyer: _______________________

5. Fax proposal to _____________ at ______________ by date indicated above.

   Sincerely,

Example I-4 Sample Schedule

Activity ID	Activity Description	Early Start	Early Finish
DESIGN			
ARCHITECTURAL			
. .			
	Specifications	19FEB96	12APR96
	IFC Package Issue		12APR96*
EXTERNAL WORKS			
	Car Park,Paving	11MAR96*	12APR96
NEW OFFICE/LAB BUILDING			
	Floor plans	02JAN96	19JAN96
	Elevations	15JAN96	12MAR96
	Sections	15JAN96	12MAR96
	Floor Plans Frozen		19JAN96
	Reflected Ceiling Plans	22JAN96	09FEB96
	Develop Lab Layouts	22JAN96*	16FEB96
	Lift Design	05FEB96*	15MAR96
	Roofing/Cladding/Glazing -	05FEB96	12APR96
	Toilet layouts	12FEB96	25MAR96
	Entrance Lobby layouts/details	19FEB96	12APR96
	Finishes/schedules/details	19FEB96	12APR96
	Lab Layouts - Develop with	10JUN96	05JUL96
NEW WAREHOUSE			
	Floor plans	02JAN96	19JAN96
	Elevations	15JAN96	12MAR96
	Sections	15JAN96	12MAR96
	Floor Plans Frozen		19JAN96
	Roofing/Blockwork	05FEB96	12APR96
	Finishes/schedules/details	19FEB96	12APR96
EXISTING OFFICE , R&D BUILDINGS			
	Recladding package	19FEB96*	15MAR96
	Renovated offices - new layouts	19FEB96	15MAR96
	Finishes/details	19FEB96	12APR96



Project Start 01MAY95
Project Finish 12SEP97
Data Date 02JAN96
Plot Date 12FEB96

Primavera Systems, Inc.

Early Bar
Progress Bar
Critical Activity

LOC2

Sheet 1 of 6

LOCTITE (IRELAND) LIMITED
PROPOSED FACILITY EXPANSION
LEVEL III DESIGN SCHEDULE

REV 0 - 19 JAN 96

Date	Revision	Checked	Approved

F:\DEPT\COST\SCHEDULI\LEV3.PRN

J
REFERENCES

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