CHARACTERIZING THE IMPACT OF POWER QUALITY ON PROGRAMMABLE LOGIC CONTROLLER WITH AND WITHOUT POWER-CONDITIONING DEVICES

CONSULTANT REPORT

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Characterizing the Impact of Power Quality on Programmable Logic Controllers With and Without Power-Conditioning Devices

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REPORT SUMMARY

This report presents information to help California's industrial sector increase productivity by minimizing process disruptions caused by programmable logic controller (PLC) upsets from power quality disturbances. The report documents the results of testing five PLCs against voltage sags, capacitor-switching transients, harmonics, and lighting-induced transients. It also includes two technical papers that provide practical guidelines to help PLC system integrators and industrial end users make their PLC systems more robust to voltage sags and electrical transients.

Background

Manufacturers throughout California are steadily increasing their use of programmable logic controllers (PLCs) as they adopt automated processes. However, power quality disturbances can upset PLCs, potentially causing unscheduled process interruptions and production losses in industrial facilities. The California Energy Commission (CEC) contracted EPRI to conduct research to determine the compatibility issues related to PLC systems and evaluate the effectiveness of commonly available power-conditioning devices.

Objective

To determine compatibility issues related to PLC systems and evaluate the effectiveness of commonly available power-conditioning devices. This report is intended to help the California industrial sector be more productive by mitigating power quality-related process disruptions caused by PLC upsets.

Approach

Investigators selected five PLCs for testing after determining which PLC brands and makes represent a significant portion of units used in California as well as the United States. A common power quality test algorithm was programmed into each unit and the equipment was installed on a test platform. Tests involving voltage sags, capacitor-switching transients, harmonics, and lightning-induced transient were conducted on the PLCs. During each test, the PLCs were evaluated with and without power-conditioning devices in place.

Results

Without power conditioning, the tested PLC systems were found to be vulnerable to voltage sags. Investigators ranked the tested PLCs from most to least susceptible based on depth, duration, and likelihood of voltage sags. Voltage-sag testing revealed that the common constant-voltage transformer (CVT) was very effective in improving voltage-sag ride-through of PLC systems. Uninterruptible Power Supplies (UPSs) that produce a square-wave output during voltage sags were not compatible with the 120-Vac input channels on three of the five tested

PLCs. However, a line-interactive UPS that produced a true sine-wave output effectively mitigated voltage sags.

The tests also revealed that capacitor-switching transient events did not upset the PLCs. Furthermore, the CVT and line-interactive UPSs with sine-wave output were able to completely block the transients from passing to the PLC system load. Even though the PLC could withstand the capacitor-switching transient without negatively affecting its operation, when powered by off-line UPSs with square-wave output, the PLC 120-Vac input channels once again caused the PLCs to malfunction and drop all output signals.

Added to the test protocol at the request of CEC after the start of the project, a test using adjustable speed drive (ASD)-induced harmonics was conducted on the Allen Bradley PLC. With an ASD used to induce harmonic current and line reactors used to represent long line lengths, voltage with harmonic content was applied to the PLC, which was subjected to voltage sag tests again. However, the "flat topping" effect of the harmonic voltage did not make the voltage-sag response of the PLC appreciably different. Additional tests with different impedance reactors and other PLCs should be conducted in the future to further verify the results.

Tests using lightning-induced transients were conducted first on all five PLCs with voltage-conditioning devices. The CVT mitigated the transients up to the 4-kV test level for line-to-neutral surges. Furthermore, the CVT mitigated line-to-ground transients up to 3.5 kV before flashover occurred on the primary of the transformer. Nonetheless, the output of the CVT continued to supply a mitigated voltage source to the PLC loads. The PLC reaction to the UPS tests with the APC UPS units was similar to the voltage sag and capacitor switching transient response – when the UPS transferred to battery, the PLCs could not resolve the 120-Vac discrete inputs and the PLC logic once again shut down the output signals.

Two of the five PLCs were tested without power conditioning to see how well they would survive surge events. One of the units survived the tests, while the power supply of the second unit was permanently damaged.

Perspective

Based on the results of this work, it is apparent that power conditioning should be used on both the PLC and its associated 120-Vac control power. End users will often provide voltage conditioning for the PLC power supply without making the control power source for the PLC and sensors robust as well. This approach can still lead to the failure of the control system during power quality events. Use of properly sized UPSs or CVTs on these circuits can greatly improve the overall robustness of PLC-based control systems. However, careful selection of power-conditioning devices is required to ensure that the entire system will not be made less compatible as a result. Power-conditioning devices that produce square-wave outputs are not compatible with all PLC systems. Square-wave outputs are not only available on many battery-based UPS systems but also on capacitor-based power conditioners.

EXECUTIVE SUMMARY

The programmable logic controller (PLC) is the automation backbone of the American manufacturing sector. Abandoning antiquated relay-based control systems in favor of new automated processes, manufacturers throughout California are steadily increasing their use of PLCs. However, the impacts of voltage disturbances, in the form of voltage sags, momentary interruptions, and transients, play a significant role in affecting PLC systems. Power quality disturbances can cause unscheduled process interruptions and production losses in industrial facilities. The California Energy Commission (CEC) contracted EPRI to conduct research to determine the compatibility issues related to PLC systems and evaluate the effectiveness of commonly available power-conditioning devices. The objective of this report is to help California's industrial sector be more productive by mitigating power quality-related process disruptions caused by PLC upsets.

Approach

This work began by determining which five PLC brands and makes represent a significant portion of units used in California as well as the United States. Based on EPRI PEAC experience in manufacturing facilities, as well as informal interviews with control-system experts and vendors, five PLCs were selected for testing. The selected units include hardware from Omron, Siemens, Schneider Electric (Modicon), and Rockwell Automation (Allen Bradley). Once the units were selected, hardware and software for the PLCs and power-conditioning devices were acquired from either existing EPRI PEAC inventory or by purchasing equipment from local vendors. In parallel with these efforts, a test protocol was developed to define the test methods and govern the flow of work. Once all PLCs were on-hand, a common power quality test algorithm was programmed into each unit and the equipment was installed on a test platform. Tests involving voltage sags, capacitor-switching transients, harmonics, and lightning-induced transient were conducted on the PLCs. During each test, the PLCs were evaluated with and without power-conditioning devices in place.

Findings

Without power conditioning, the tested PLC systems were found to be vulnerable to voltage sags. Table ES-1 shows the ranking of the tested PLCs from most to least susceptible based on depth, duration, and likelihood of voltage sags more severe.

Table ES-1
Voltage Sag Susceptibility Ranking of PLCs Tested

Voltage-Sag Susceptibility Ranking	PLC	First PLC Failure Point	Shutdown Mechanism
1	Allen Bradley PLC-5 (PLC D)	1 cycle, 78%Vnom	Firmware embedded decision based on AC input to P/S module.
2	Modicon Quantum (PLC C)	15 cycles, 65% Vnom	Believed to be based on DC power supply ride-through, load-dependent (number of modules).
3	Allen Bradley SLC 5/03 (PLC E)	20 cycles, 46% Vnom	DC power supply ride-through, load-dependent (number of modules).
4	Omron (PLC A)	45 cycles, 65% Vnom	DC power supply ride-through, load-dependent (number of modules).
5	Siemens TI 545 (PLC B)	47 cycles, 59% Vnom	DC power supply ride-through, load-dependent (number of modules).

The results of the voltage-sag tests revealed that the common constant-voltage transformer (CVT) was very effective in improving voltage-sag ride-through of PLC systems. The use of UPSs that produce a square-wave output during voltage sags was not compatible with the 120-Vac input channels on three of the five tested PLCs. In these cases, when the UPS switched to battery, the input channels on the PLCs could not resolve the square-wave input signals. Therefore, the PLC program acted on the change of the state of input channels and dropped the output signals. However, a line-interactive UPS that produced a true sine-wave output effectively mitigated voltage sags.

The tests also revealed that capacitor-switching transient events did not upset the PLCs. Furthermore, the CVT and line-interactive UPSs with sine-wave output were able to completely block the transients from passing to the PLC system load. Even though the PLC could withstand the capacitor-switching transient without negatively affecting its operation, when powered by off-line UPSs with square-wave output, the PLC 120-Vac input channels once again caused the PLCs to malfunction and drop all output signals.

Added to the test protocol at the request of CEC after the start of the project, a test using ASD-induced harmonics was conducted on the Allen Bradley PLC. With an ASD used to induce harmonic current and line reactors used to represent long line lengths, voltage with harmonic content was applied to the PLC, which was subjected to voltage sag tests again. However, the "flat topping" effect of the harmonic voltage did not make the voltage-sag response of the PLC appreciably different. Additional tests with different impedance reactors and other PLCs should be conducted in the future to further verify the results.

Tests using lightning-induced transients were conducted first on all five PLCs with voltage-conditioning devices. The CVT mitigated the transients up to the 4-kV test level for line-to-neutral surges. Furthermore, the CVT mitigated line-to-ground transients up to 3.5 kV before flashover occurred on the primary of the transformer. Nonetheless, the output of the CVT continued to supply a mitigated voltage source to the PLC loads. The PLC reaction to the UPS tests with the APC UPS units was similar to the voltage sag and capacitor switching transient response – when the UPS transferred to battery, the PLCs could not resolve the 120-Vac discrete inputs and the PLC logic once again shut down the output signals.

Two of the five PLCs were tested without power conditioning to see how well they would survive surge events. One of the units survived the tests, while the power supply of the second unit was permanently damaged.

Conclusion

Based on the results of this work, it is apparent that power conditioning should be used on both the PLC and its associated 120-Vac control power. End users will often provide voltage conditioning for the PLC power supply without making the control power source for the PLC and sensors robust as well. This approach can still lead to the failure of the control system during power quality events. Use of properly sized UPSs or CVTs on these circuits can greatly improve the overall robustness of PLC-based control systems. However, careful selection of power-conditioning devices is required to ensure that the entire system will not be made less compatible as a result. Power-conditioning devices that produce square-wave outputs are not compatible with all PLC systems. Square-wave outputs are not only available on many battery-based UPS systems but also on capacitor-based power conditioners.

This project involved testing PLCs with discrete (on/off) I/O in a limited test setup. Future tests should be conducted utilizing an array of I/O devices, including both discrete and analog (continuous) signals and control components.

ABSTRACT

This report contains three deliverables based on a collaborative project between the California Energy Commission (CEC) and EPRI. The purpose of the project is to develop technical guidelines and quantify the benefits of power conditioning with programmable logic controller (PLC) systems. This report documents the results of testing five PLCs against voltage sags, capacitor-switching transients, harmonics, and lighting-induced transients. The document includes results from tests conducted with and without power-conditioning devices installed. Furthermore, the report reveals that proper application of power-conditioning devices will lead to improved system compatibility.

As part of this project, two technical papers were produced that focus on guidelines for proper implementation of power conditioning on PLC systems. These papers are included in this report as Appendices F and G.

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1 INTRODUCTION

The programmable logic controller (PLC) is the automation backbone of the American manufacturing sector. Abandoning antiquated relay-based control systems in favor of new automated processes, manufacturers throughout California are steadily increasing their use of PLCs. However, the impacts of voltage disturbances, in the form of voltage sags, momentary interruptions, and transients, play a significant role in affecting PLC systems. Power quality disturbances can cause unscheduled process interruptions and production losses in industrial facilities. The California Energy Commission (CEC) contracted EPRI to conduct research to determine the compatibility issues related to PLC systems and evaluate the effectiveness of commonly available power-conditioning devices. The objective of this report is to help California's industrial sector be more productive by mitigating power quality-related process disruptions caused by PLC upsets.

1.1 Understanding PLC Systems

The PLC is basically a hardened computer that is used to control industrial equipment and processes. Unlike the popular desktop PC, the PLC is designed to withstand the effects of electrical noise, high humidity, and mechanical vibration.

In order to understand the power quality issues related to PLCs, one must first obtain a basic understanding of the various components that comprise a PLC-based control system. The PLC can monitor and control a process through field inputs and outputs (I/O) and a control program. A functional block diagram of the PLC is shown in Figure 1-1.

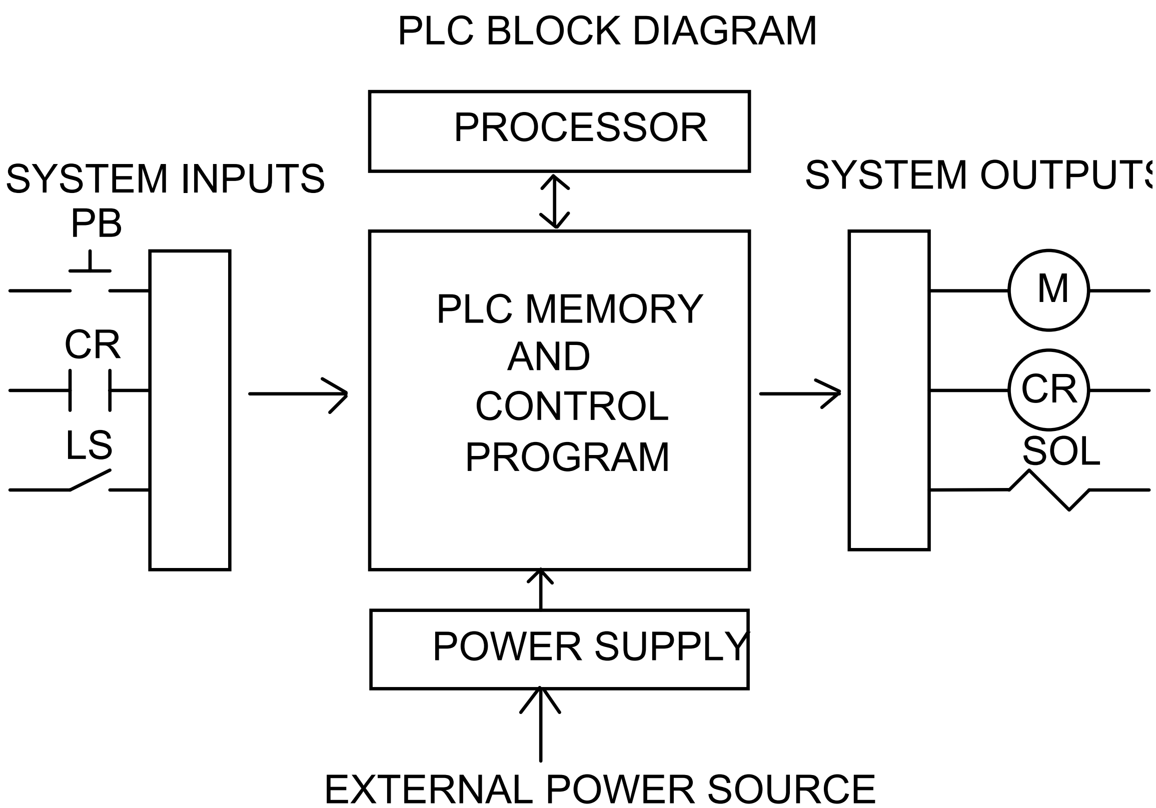


Figure 1-1
PLC Functional Block Diagram of a PLC System

The Central Processing Unit (CPU) Module. This device is the “brains” of the PLC. Usually occupying a single slot in a PLC rack, the CPU module (also referred to as the processor) holds the control program in random access memory (RAM). The CPU module receives operating power through the back plane of the I/O rack via the rack’s power supply. The back plane also contains a data bus for communication between the PLC and I/O rack. A Lithium battery and/or electrically erasable programmable read only memory (EEPROM) is typically used to maintain the PLC program in the event of a loss of power.

The CPU reads the input data table information, solves the control program, and updates the output data table. In addition, the PLC will perform “housekeeping” to check itself and other related PLC hardware components for faults and errors. A secondary microprocessor is typically used to transfer data from the system inputs into the data table and from the data table to the system outputs. The typical timing loop for a PLC processor is shown in Figure 1-2.

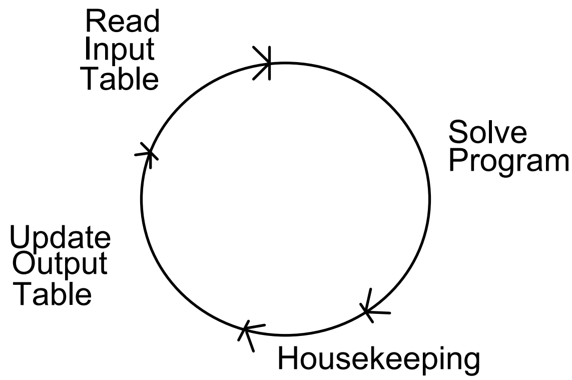


Figure 1-2
Typical PLC Task Timing Loop

The time required for the PLC to read the inputs, solve the control program, and update the output table is known as the scan rate. This time can vary greatly depending on the CPU model, the size of the control program, and the architecture of the system. A more definitive measurement of PLC response is known as "throughput." Throughput is defined as the amount of time required to detect an input from the field device, solve the control program, and manipulate an output field device. The throughput time includes the scan time plus the amount of time it takes for the electronics of the PLC module to detect an input and switch an output. Because a PLC input signal can be generated and an output state change can be detected on a scope, throughput time is easier to measure in a laboratory environment than scan rate.

The PLC Memory and Control Program. The memory required for a PLC to hold a control program and run a process is much less than that for a typical PC application because the PLC instruction set is simple. PLC memory sizes typically range from 1k for a small system up to 256k for very large applications. The PLC control program may take various forms. The most basic and common control program format is relay ladder logic (RLL). This control program format was created to model hardwired electrical relay logic and is subsequently very user-friendly for maintenance electricians. An RLL PLC program will utilize conventional "seal-in" techniques that have been used in relays in the past. Other program formats commonly used today include Sequential Function Chart (SFC), BASIC, and C. The method or technique that the PLC programmer uses to control process equipment is a potential cause for power quality immunity problems.

PLC Power Supply. The most commonly used PLC power supplies can typically accept 120 Vac and 240 Vac. Power supplies designed to accept 24 Vdc are also available for applications such as substation control. To further complicate matters, some PLC power supplies are physically built into the same card as the PLC processor to power the local I/O rack. The job of the PLC power supply is to supply DC power to all devices physically mounted in the PLC rack. These devices may include the CPU, communication modules, discrete I/O, and analog I/O. The PLC power supply typically does not supply power to field devices. The power required to operate field devices may pass through the PLC I/O. However, except for some analog output cards, power does not emanate from the PLC. PLC power supplies usually produce from 40 to 80 DC watts for use across the back plane.

PLC power supplies utilize switch-mode power supply technology to provide a well-regulated DC voltage to the various modules via the back plane edge connectors. Due to the rugged industrial environment, PLC power supplies are designed to maintain a regulated DC output throughout a 10% to 15% variation in line voltage and/or frequency.
Because of the potential danger that might result from a malfunctioning PLC system, most PLC power supplies also perform continuous diagnostics for line voltages that are outside of the tolerance envelope of the hardware. If a serious problem is detected, the power supply will notify the CPU to halt program execution in order to shut down process operations.

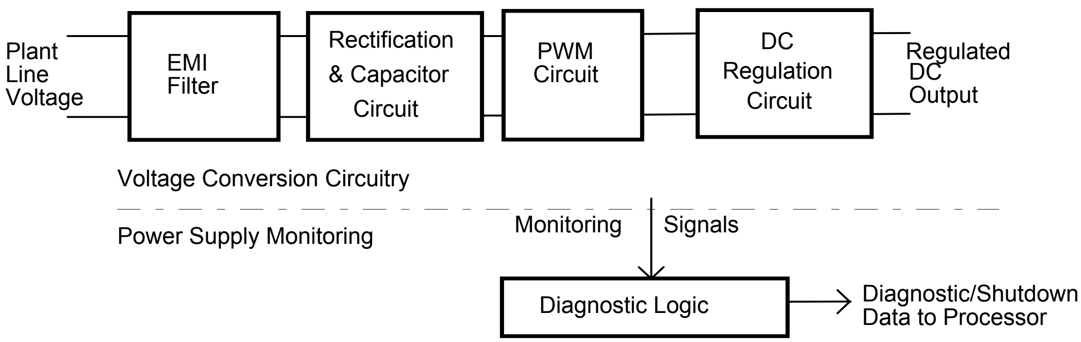


Figure 1-3
Typical PLC Power Supply Topology

Figure 1-3 shows the general topology of a PLC power supply. The incoming AC voltage is first filtered to remove electromagnetic interference (EMI). Next, a bridge rectifier along with several capacitors are used to convert the AC signal to DC. The use of a large amount of capacitance in this rectification stage (1350 micro-farads typical) is proportional to the amount of electrical energy stored by the power supply. The resulting pulse-width-modulation (PWM) signal is then regulated. The ability of the PLC power supply to ride through significant voltage sags theoretically depends on both the size of the capacitors used in the rectification stage and the number and type of modules in the I/O rack. However, some manufacturers may choose to shut the PLC down based on the monitoring signal rather than based on the available hold-up time of the power supply.

System Inputs and Outputs. PLC I/O modules (also referred to as “cards”) read process inputs and transfer the controller’s decisions to the process. These modules can be classified into two general categories: discrete and analog. For the purposes of the tests conducted in this project, only discrete I/O was investigated.
Discrete I/O modules control process operations through on/off control. PLC manufacturers provide I/O modules to accept and manipulate a wide range of voltages (5V TTL, 24 Vdc, 120 Vac, 240 Vac, and so on).
Discrete inputs (DIs) are used to sense the logical status of field devices. **Error! Reference source not found.** shows the typical circuit topology for a DI module input channel. The input signal from the field device is first rectified to a DC voltage. Next, a noise and debounce filter is employed to keep the card from detecting false input signals that may be caused by noise. Next, logic 1 and 0 is determined by a threshold-detector circuit. Finally, an optical coupler is employed to provide isolation between the field voltage and the input module’s logic circuitry.

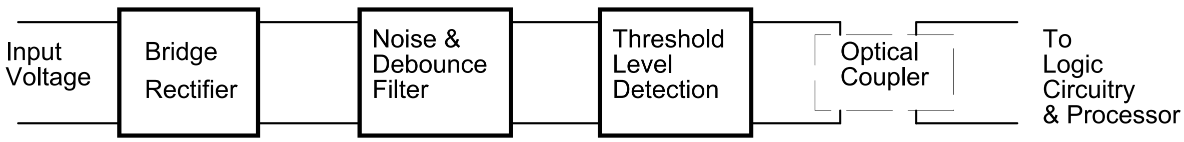


Figure 1-4
Typical AC/DC Discrete Input Circuit Topology

Typical discrete-input sensing devices are listed below:

- Proximity Switches
- Pushbuttons/Selector Switches
- Limit Switches
- Motor-Starter Auxiliary Contacts
- Relay Contacts
- Pressure Switches
- Zero-Speed Switches
- Flow Switches
- Dry-Contact Output Card of Another PLC

PLC discrete outputs (DOs) are used to start and stop field processes or equipment. Figure 1-5 shows a block diagram of a typical DO module output channel. The logic decision signal passes through the optical coupler and drives a switch. In the case of AC output modules, the switch will consist of either a relay and driver circuit or a triac. In the case of a DC output module, the switch is typically a transistor. The AC output module may also employ a filter and MOV to protect the output module against voltage transients induced by a switching load. The output channel will also employ a fuse (typically 2 to 5 amps) to further protect the I/O module from a field short circuit. PLC manufacturers provide DO modules with both individually fused output channels and grouped output channel fusing.

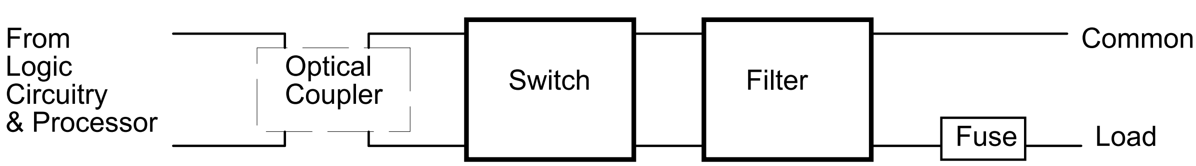


Figure 1-5
Typical Discrete Output Circuit Topology

Typical Discrete output devices include devices such as:

- Motor Starters
- Discrete On/Off Valves
- Solenoids

- Relays
- Pilot Lights
- Binary Coded Decimal (BCD) Displays
- Alarm Horns/Buzzers
- The input card of another PLC

1.2 PLCs Selected for CEC Research

In order to conduct testing on PLC systems, the five most common PLCs were selected based on prior experience and interviewing experts in the field of industrial controls:

- Rockwell Automation (Allen Bradley PLC-5 Line)
- Rockwell Automation (Allen Bradley SLC-500 Line)
- Schneider Electric (Modicon Quantum PLC Line)
- Siemens (SIMATIC line)
- Omron (SYSMAC Line)

Appendix D contains a detailed component list of each PLC.

Each of the PLC systems was assembled as shown in Figure 1-6.

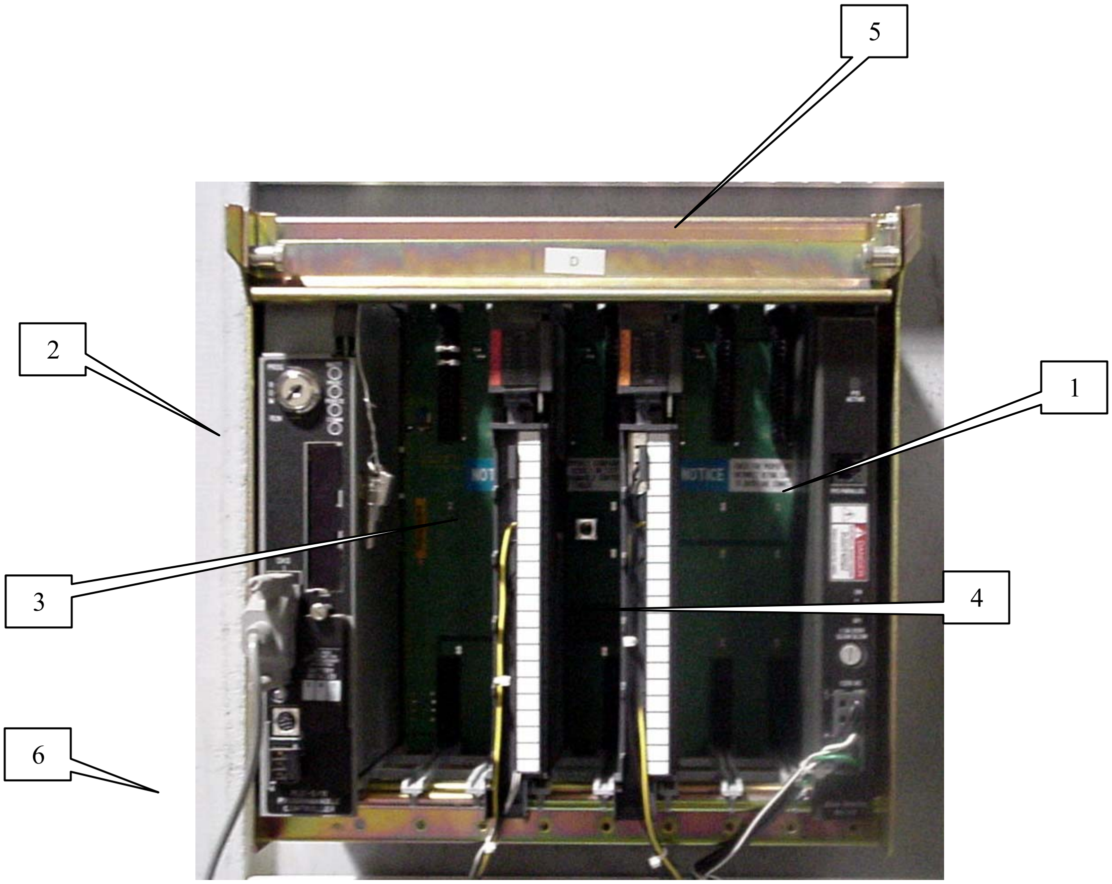


Figure 1-6
Allen Bradley PLC-5 Setup

Legend:

1. 120-Vac Input Power Supply Module
2. PLC Processor Module
3. 120-Vac Discrete Input Module
4. 120-Vac Discrete Output Module
5. Rack-to-House PLC Cards
6. Programming Cable

The PLCs were installed in the test fixture shown in Figure 1-7, and the test stand was assembled as shown in Appendix A. EPRI PEAC's Industrial Load Bank (ILB) was also used as additional loads for each PLC tested. The ILB, whose function is explained in detail in Appendix B, added loads such as contactors, motor starters, relays, and power supplies to the test setup. The target load of each PLC was 2 steady-state amps.

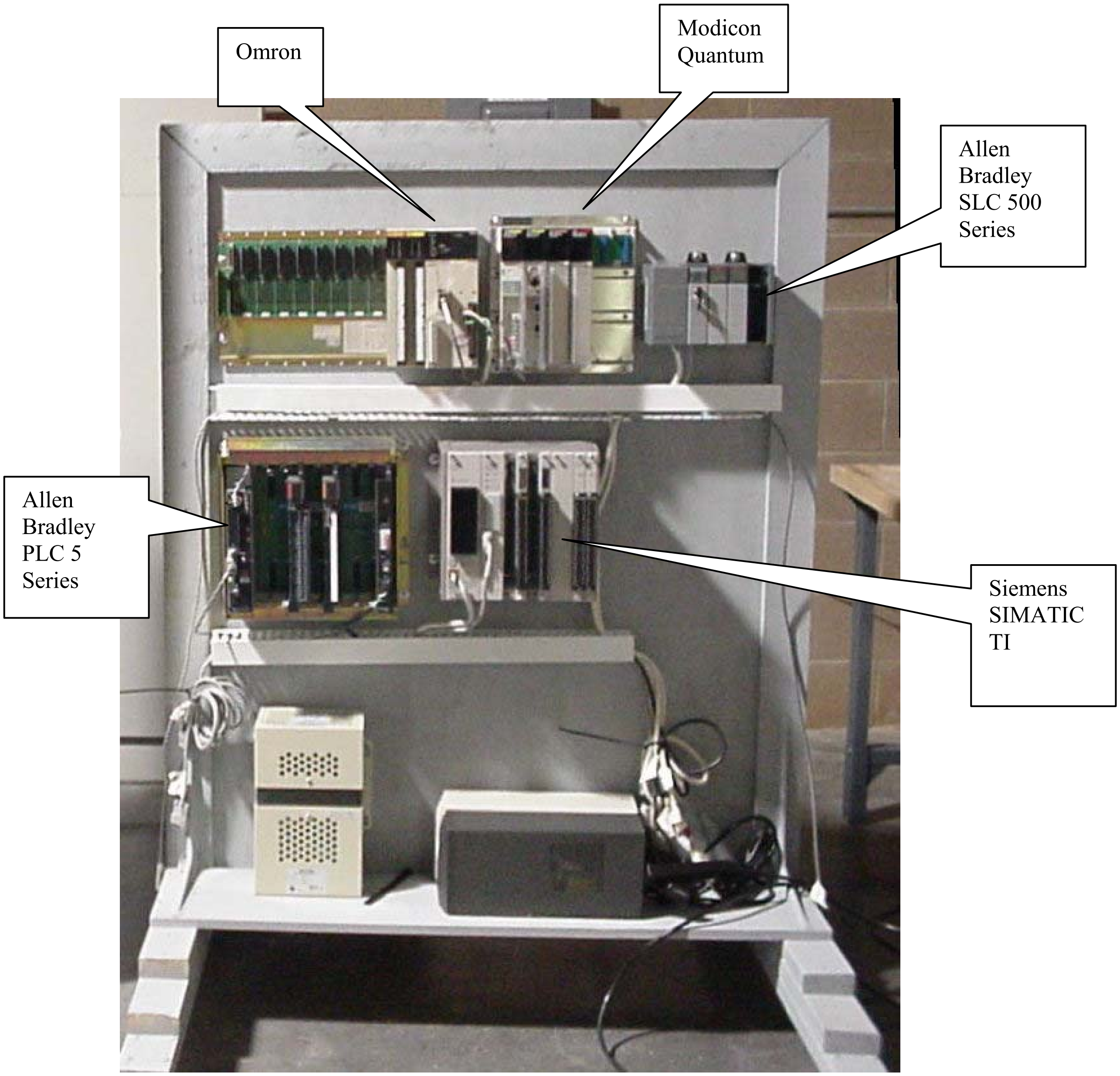


Figure 1-7
PLC Test Stand

2 TEST DESCRIPTION

The purpose of this section is to provide the test setup and protocol procedures for conducting power quality disturbance testing for the California Energy Commission project entitled "Characterizing the Impact of Power Quality on Programmable Logic Controllers with and without Power Conditioning Devices." This section contains excerpts from a previous protocol for PLC testing entitled *SC-630: Programmable Logic Controllers used in Industrial Power Systems.*

2.1 PLC Test Plan Matrix

Five PLCs will be tested for immunity to voltage sags, capacitor-switching transients, and lightning-induced transients. These tests will be conducted with and without power-conditioning equipment. The PLCs that will be tested and the tests that will be conducted on each unit are shown in Table 2-1.

Table 2-1
PLC Test Plan Matrix

PLC Designation/ Brand	Test 1: Baseline Test	Test 2: Voltage Sags & Momentary Outages	Test 3: Cap Switch Transients Test	Test 4: Harmonics Introduced by an Adjustable Speed Drive	Test 5-1: Lightning Induced Transients With Transient Protection	Test 5-2: Lightning Induced Transients Without Transient Protection
PLC A/ Omron	√	√	√		√	√
PLC B/TI 545	√	√	√		√	√
PLC C/Modicon Quantum	√	√	√		√	
PLC D/Allen Bradley PLC-5	√	√	√	√	√	
PLC E/Allen Bradley SLC-5/03	√	√	√		√	

All PLCs will be subjected to the baseline voltage, voltage sags, capacitor-switching transients, and lightning-induced transients for tests with power conditioners. However, only two selected PLCs (A and E) will be used for the tests with lightning-induced transients without protection or power conditioners (external MOV, CVT, or UPS). This approach is warranted because the test is destructive to the PLC equipment and EPRI PEAC already has data on lightning-induced transients for PLCs B and D.

Furthermore, PLC D was selected for a test of the effect of voltage harmonics on PLCs. This test was added per the request of Brian Laan of CEC based on the review of the original protocol.

2.2 Test Setup

The PLCs were arranged on a plywood stand for the duration of the testing as shown in Figure A-1 in Appendix A. This setup allowed for ease in testing by keeping all required hardware together for the duration of the test. A one-line diagram of the power wiring for the test setup is shown in Figure A-2. Each PLC was wired specifically to itself and a control relay as shown in Figures A-3 and A-4. Furthermore, to obtain the required 2.0 amp load for each system, EPRI PEAC's Industrial Load Bank (ILB) was utilized. This is a multipurpose load bank that allows the user to turn on and off various loads such as relays, contactors, and power supplies for testing of the components or power-conditioning devices. In this case, the ILB was used to help create a real-life loading environment for the PLCs and the power-conditioning devices that were used to demonstrate protection and immunity improvements. For more information about the ILB, see Appendix B.

2.3 Power Quality Test Algorithm

In order to characterize the operation of the stand-alone PLCs during a power quality disturbance, a PQ test algorithm was programmed into each PLC. A pseudo code listing of this program and the required electrical connections are explained in detail in Appendix C. Any reference to "program section" in the test protocols refer to specific parts of the algorithm. This program was loaded into each PLC prior to conducting the stand-alone PLC tests. In order to ensure comparable results between manufacturers, special emphasis was placed on writing duplicate code in each tested PLC.

2.4 Test Protocols

This section contains the protocols for the tests to be performed.

2.4.1 Test 1: Characterization of PLC Performance during Normal Operation

Rationale. The characteristics of a PLC during normal operation must be determined prior to beginning extensive testing so that its baseline performance can be established for future comparison to other test results. The PLC shall be characterized during start-up and steady-state operation.

Purpose. This test is designed to observe equipment in its normal operating mode during start-up and steady-state operation. Information obtained at this stage will be used as a reference to compare with behavior, waveforms, and performance data that will be recorded later during abnormal conditions. This test will also identify malfunctioning equipment prior to performing further testing.

Test Guidelines:

1. Select PLC system.

2. Load PLC processor with PQ test algorithm.

3. Install PLC in test circuit as shown in Appendix A, Figure A-2 and place processor in the run mode.

4. Press start/reset on test fixture.

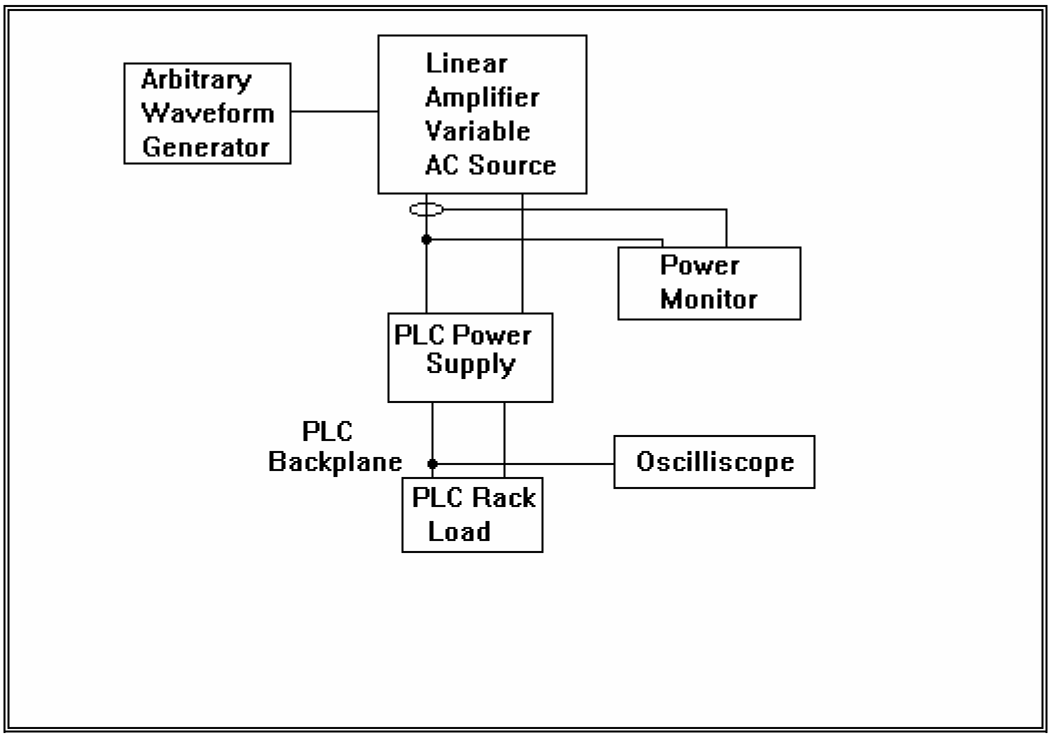


Figure 2-1
PLC Steady-State Test Circuit

Apply power to the PLC and immediately measure and record the input parameters (V, I, W, VA, pf, V_{thd}, I_{thd} and I_1, I_2,.....I_i [where i=20], voltage crest factor, current crest factor, and DC output voltage (V).

Immediately Monitor and record status of the following PLC conditions:

5. Processor status indicators (power, ready, run, and so on).

6. Discrete output "ON" status per test section DO-1.

7. PLC throughput per test program section TP-1.

Allow the system to warm-up and operate for at least 10 minutes. Repeat steps 5 and 6.

Expected Results. The PLC should operate in accordance with manufacturer specifications during start-up and steady-state operation. Results from this test should be considered baseline performance for comparison to other test results.

2.4.2 Test 2: PLC Susceptibility to Voltage Sags and Momentary Outages

Rationale: Sags in the line voltage lasting several cycles or longer may result during power system faults and when heavy loads are switched on. These disturbances produce unpredictable results for voltage-sensitive equipment and are common, direct causes of electronic-system upsets or failure.

Purpose: This test is designed to characterize PLC operation during and after a voltage sag or momentary outage.

Test Guidelines:

1. Select PLC system.

2. Load PLC processor with PQ test algorithm.

3. Install PLC in test circuit as shown in Appendix A, Figure A-2 and place processor in the run mode.

4. Press start/reset on test fixture.

5. Apply *rated voltage* and allow a 10-minute warm-up.

6. Using a line-voltage sag generator with incrementally adjustable sag duration and sag magnitude, apply a 95% sag voltage for 0.5 cycles. Measure and record the input voltage, input current waveforms, and output voltage during the voltage sag. Monitor and record status of the following PLC upset and failure conditions:

    a. **PLC Power Supply DC Output.** Upset Mode: DC output < 95% of nominal.

    b. **Processor Status Indicators (power, ready, run, and so on).** Upset Mode: Change in any Status Indicator.

    c. **Logic State Detected from Discrete Input Card, Changes during Disturbance per Test Section DI-3.** Upset Mode: Discrete Output 3 Turns on after Disturbance.

    d. **Discrete Output "ON" status per test section DO-1.** Upset Mode: PLC Output 1 Drops Out.

e. **PLC Throughput per Test Program Section TP-1.** Upset Mode: Throughput Varies during Disturbance.

f. **Output Relay Affected.** Upset Mode: Control Relay Turns off during/after Disturbance.

7. Repeat step 6 at 1, 2, 3, 4, 5, 8, 10, 20, 50, 100, and 120 cycles. If upset or failure occurs, record sag voltage, sag duration, and the nature of the upset.

8. Repeat step 6 and 7 at 95%, 90%, 85%, 80%, 75%, 70%, 65%, 60%, 55%, 50%, 45%, 40%, and 0% sag voltages.

9. Repeat steps 1 through 8 with a 500-VA CVT placed between the power disturbance generator and PLC power supply.

10. Repeat steps 1 through 8 with a UPS placed between the power disturbance generator and PLC power supply.

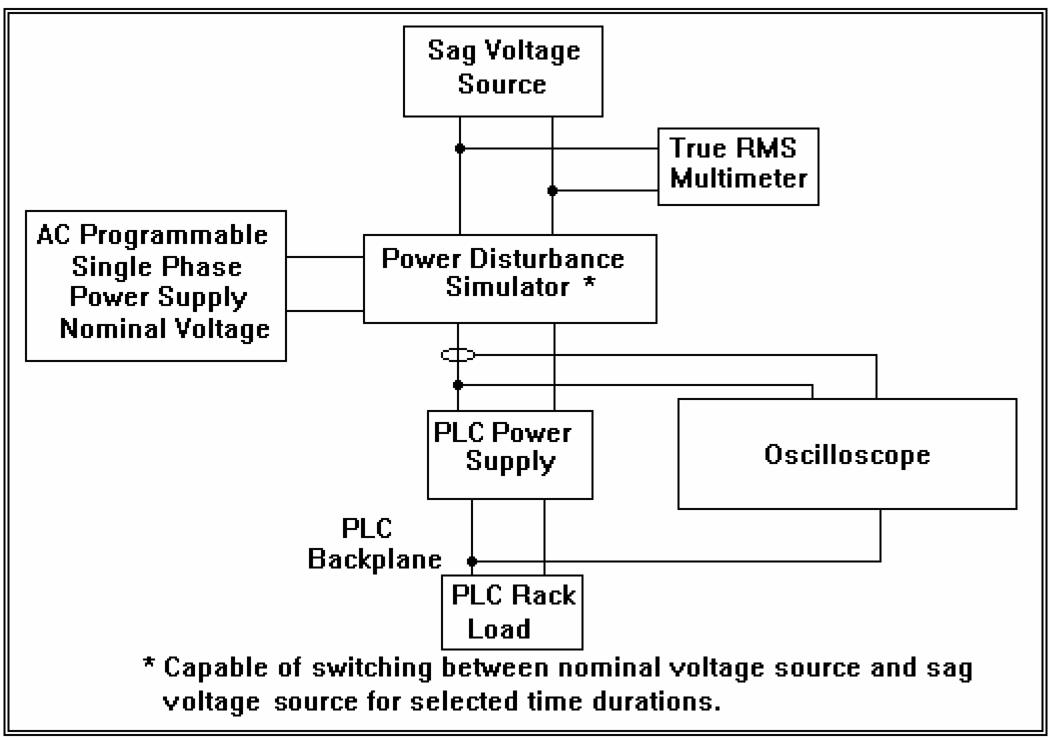


Figure 2-2
Test I3 setup

Note: The sag durations and sag voltage magnitudes specified in test guidelines 7 and 8 are designed to accurately create the lower portion of a voltage-tolerance envelope for each PLC tested. It may not be necessary to test at all specified levels to produce the voltage tolerance envelope. It may be necessary to test at more levels to ensure the envelope is as accurate as possible. The technician shall determine exactly which levels are required during testing.

Expected Results: The above test guidelines should characterize the undervoltage portion of the voltage-tolerance envelope for the subject PLC system. The PLC should resume operation without failure or be upset following the outage or sag.

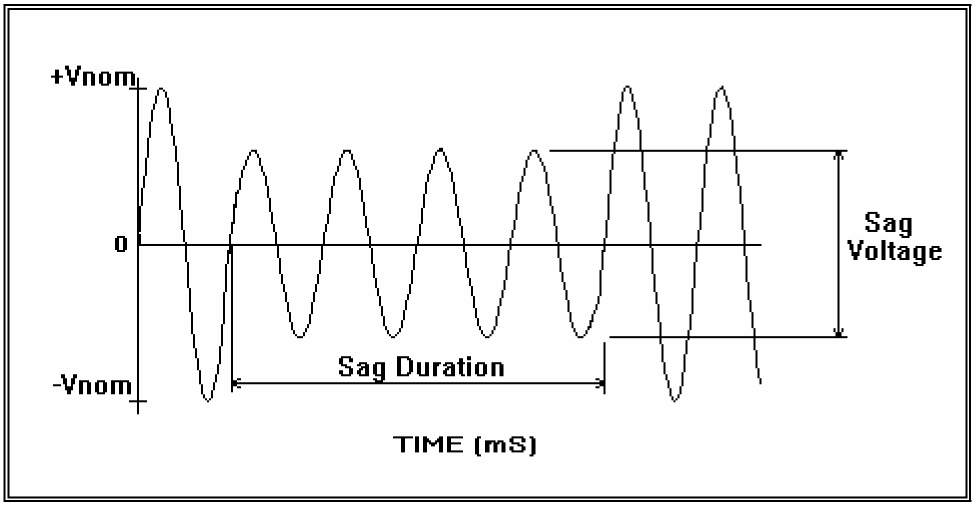


Figure 2-3
Graphical Definition of Sag Voltage

2.4.3 Test 3: Test Protocol for Capacitor-Switching Transients

Rationale: The switching of capacitor banks can cause an oscillatory transient on high-voltage systems, as represented by the 5-kHz Ring Wave defined in ANSI/IEEE C62.41-1991. This Ring Wave can also affect low-voltage distribution systems. The impedance of the power system diminishes the standard 5-kHz Ring Wave to a 500-Hz Ring Wave with a peak magnitude of approximately 160% of $V_{nominal}$. This waveform may deposit enough energy on the low-voltage system to cause failures on single-phase equipment with inadequate surge protection.

Purpose: This test is designed to determine the susceptibility of PLC systems to low-voltage surges caused by high-voltage capacitor switching.

Test Guidelines:

1. Select PLC system.
2. Load PLC processor with PQ test algorithm.
   Install PLC in test circuit and 500-Hz Ring Wave set as shown in Appendix A, Figure A-2 and
3. Figure 2-4 with a 650-VA UPS placed between power disturbance generator and PLC power supply. Place processor in the run mode.
4. Press start/reset on the test fixture.

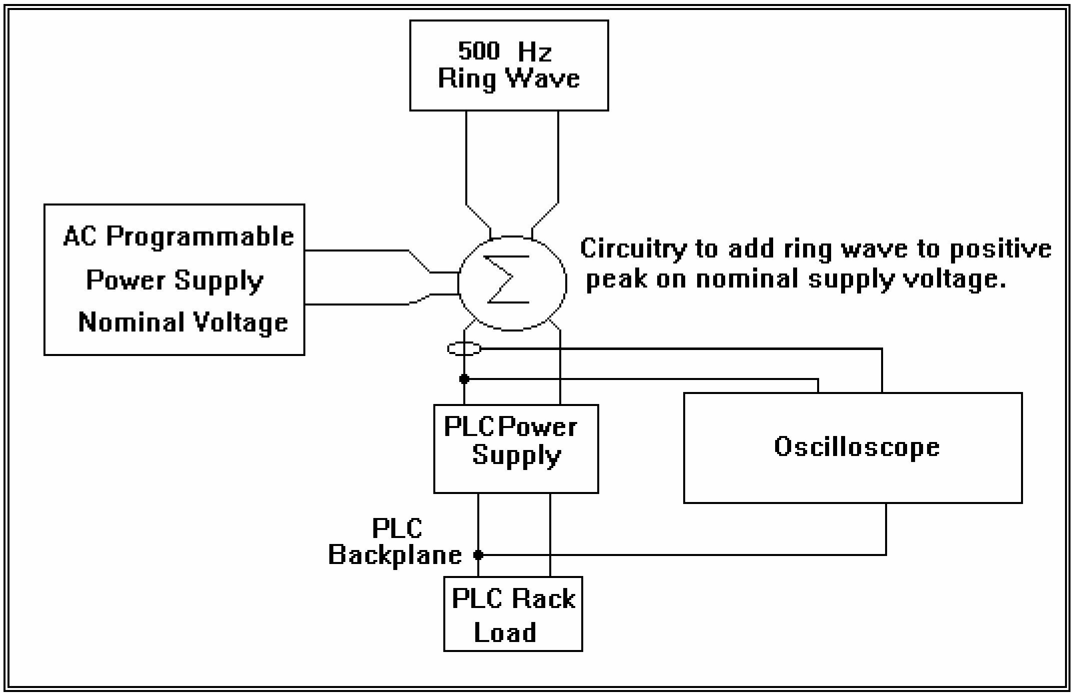


Figure 2-4
500-Hz Ring Wave Surge Test Setup

5. Apply rated voltage to test circuit and allow a 10-minute warm-up.

6. Determine the source—a single-phase, 60-Hz source operating at the rated voltage of the PLC, with an added 1.6 per unit 500-Hz Ring Wave.

7. Apply one surge, at the peak of the sine wave (additive) to the L-N conductors of the power cord while simultaneously measuring and recording the power supply input voltage, input current waveforms, and regulated DC output voltage (V). Monitor and record status of the following PLC upset and failure conditions:

    a. **PLC Power Supply DC Output.** Upset Mode: DC output < 95% of nominal.

    b. **Processor Status Indicators (power, ready, run, and so on).** Upset Mode: Change in any Status Indicator.

    c. **Logic State Detected from Discrete Input Card, Changes during Disturbance per Test Section DI-3.** Upset Mode: Discrete Output 3 Turns on after Disturbance.

    d. **Discrete Output "ON" status per test section DO-1.** Upset Mode: PLC Output 1 Drops Out.

    e. **PLC Throughput per Test Program Section TP-1.** Upset Mode: Throughput Varies during Disturbance.

f. **Output Relay Affected.** Upset Mode: Control Relay Turns off during/after Disturbance.

8. Repeat steps 1 through 7 with a 420-VA UPS placed between the power disturbance generator and PLC power supply.

9. Repeat steps 1 through 7 with 500-VA CVT placed between the power disturbance generator and PLC power supply.

10. Repeat steps 1 through 7 without any power conditioning between the disturbance and the PLC power supply.

Expected Results: This test might cause failure of PLC power supplies having a relatively low energy/current-handling capability. The peak voltages for this waveform are relatively low, compared to other types surges, but it is commonly seen by PLC power supplies. The 500-Hz Ring Wave can be detrimental because the input bridge rectifier of the PLC power supply can pump up the voltage of the DC bus, leading to upset or failure.

2.4.4 Test 4: Response to Voltage Harmonics

Rationale: Harmonics are sinusoidal voltages or currents having frequencies that are integer multiples of the fundamental power frequency. Harmonic distortion exists due to nonlinear devices and loads on the power system, such as adjustable-speed drives. Harmonic distortion levels can be characterized by the harmonic spectrum with magnitudes and phase angles of each individual harmonic component. *Total harmonic distortion* is a quantity commonly used to measure harmonic distortion.

Purpose: This test is designed to determine the immunity of selected PLCs to harmonic distortion and sag susceptibility while harmonic distortion is present.

Test Setup: Harmonics will be introduced into the system using the test setup **Error! Reference source not found.**. The nonlinear load, a 5-HP adjustable-speed drive (ASD) with 3%, 8-amp line reactors, will induce harmonics into the PLC input voltage.

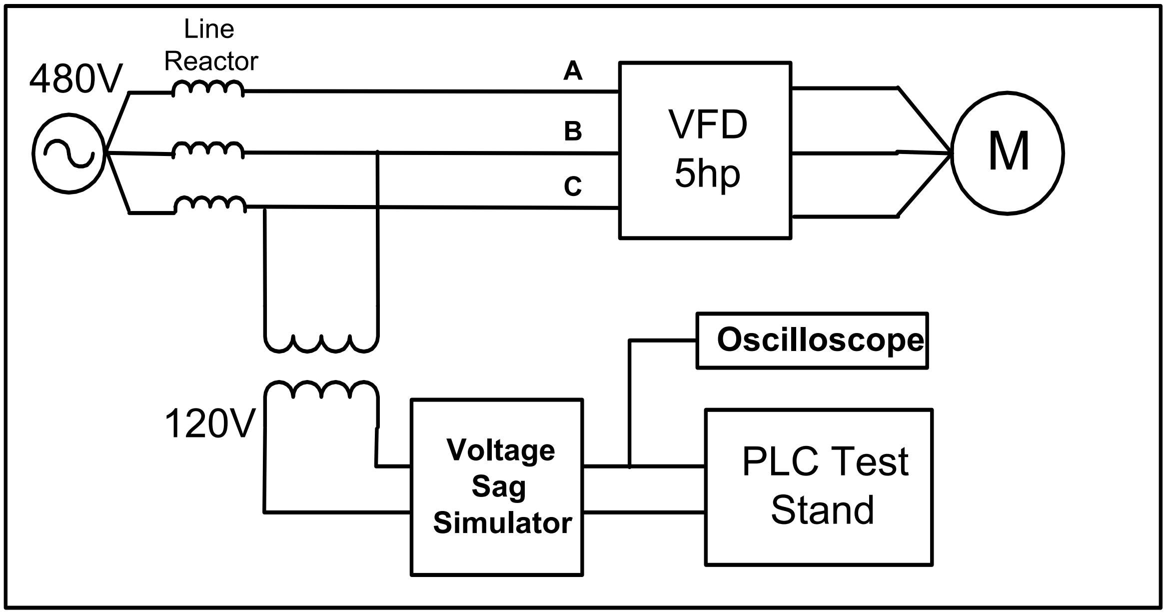


Figure 2-5
Test Setup for Harmonics Produced by an Adjustable-Speed Drive

Test Guidelines:

1. Select PLC system.

2. Load PLC processor with PQ test algorithm. Install PLC in test circuit shown in Appendix A. Place processor in the run mode.

3. Press start/reset on test fixture.

4. Apply rated voltage to test circuit and allow a 10-minute warm-up.

5. Using the test setup in Appendix A with no line reactors, set the ASD to 25% speed and 25% load (expected worst-case harmonic distortion). Measure and record the input voltage, total harmonic distortion (THD), current waveforms, and output voltage. Monitor and record the PLC failure upset conditions in step 6 to verify the PLC is working properly.

6. Using a line-voltage sag generator with incrementally adjustable sag duration and sag magnitude, apply a 95% sag voltage for 0.5 cycles. Measure and record the input voltage, input current waveforms, and output voltage during the voltage sag. Monitor and record the status of the following PLC upset and failure conditions:

   a. **PLC Power Supply DC Output.** Upset Mode: DC output < 95% of nominal.

   b. **Processor Status Indicators (power, ready, run, and so on).** Upset Mode: Change in any Status Indicator.

c. **Logic State Detected from Discrete Input Card, Changes during Disturbance per Test Section DI-3.** Upset Mode: Discrete Output 3 Turns on after Disturbance.

d. **Discrete Output "ON" status per test section DO-1.** Upset Mode: PLC Output 1 Drops Out.

e. **PLC Throughput per Test Program Section TP-1.** Upset Mode: Throughput Varies during Disturbance.

f. **Output Relay Affected.** Upset Mode: Control Relay Turns off during/after Disturbance.

7. Repeat step 6 at 1, 2, 3, 4, 5, 8, 10, 20, 50, 100, and 120 cycles. If upset or failure occurs, record sag voltage, sag duration, and the nature of the upset.

8. Repeat steps 6 and 7 at 95%, 90%, 85%, 80%, 75%, 70%, 65%, 60%, 55%, 50%, 45%, 40%, and 0% sag voltages.

9. Repeat steps 5 through 8 with a 3%, 35-amp line reactor.

10. Compare results from Test 2 (Voltage Sag Test) without harmonic distortion.

Expected Results: Most equipment is not impacted by harmonic distortion levels up to 8%. However, the harmonic voltage may lead to poor voltage ride-through performance.

2.4.5 Test 5: Test Protocol for a 1.2/50-µs, 8/20-µs Combination-Wave Surge Transient

Rationale: High-energy unidirectional transients caused by switching of capacitor banks, faults in the power network, and lightning strikes are known to exist in low-voltage systems and can cause failure of electronic devices.

Purpose: This test is designed to determine the improvement of PLC immunity to Combination Wave surges when transient suppression is used.

Waveform Definition: The combination Wave is delivered by a generator applying a 1.2/50-µs voltage wave across an open circuit and an 8/20-µs current wave into a short circuit. The exact waveform that is delivered is determined by the generator and impedance to which the surge is applied. Figure 2-6 depicts the voltage waveform with the front time (rise time) of 1.2 µs and a decay to 50% voltage at 50 µs. Figure2-7 is the graphical representation of the current surge waveform applied to a short circuit. The front time (rise time) is 8 µs, decaying to a magnitude of 50% in 20 µs. For these tests, IEEE C62.41 category B surge magnitudes will be used. Category B was chosen for this application because it is defined to pertain to electrical loads that are connected to bus and feeders in industrial plants. The maximum values of the Category B test waveforms for voltage and current are defined at 4kV and 2kA, respectively. These two waveforms have substantial energy-deposition capability and provide representative stresses to the surge protectors and commercial electronics connected to the power system.

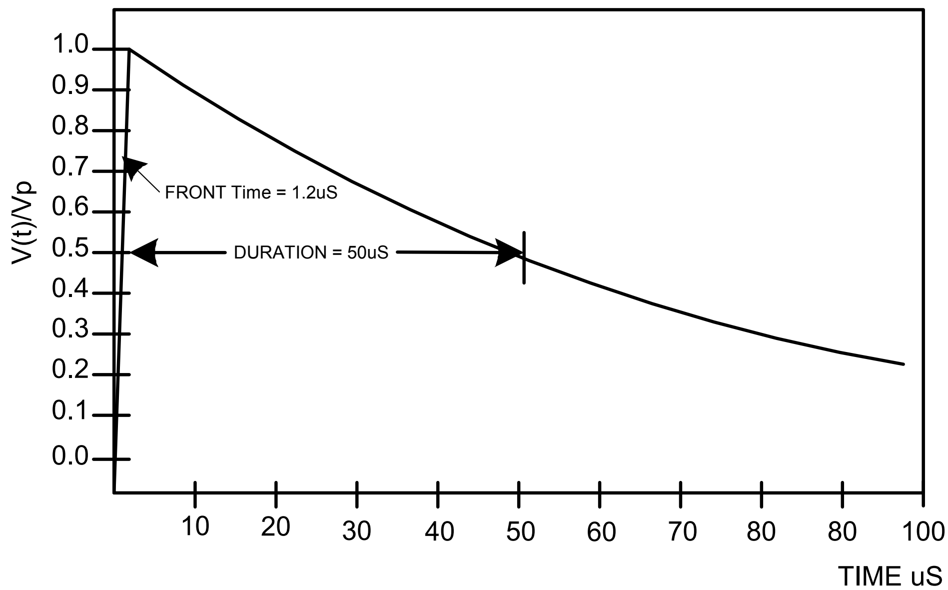


Figure 2-6
Graphical Definition of the ANSI/IEEE 1.2/50-µs Combination Wave Open-Circuit Voltage

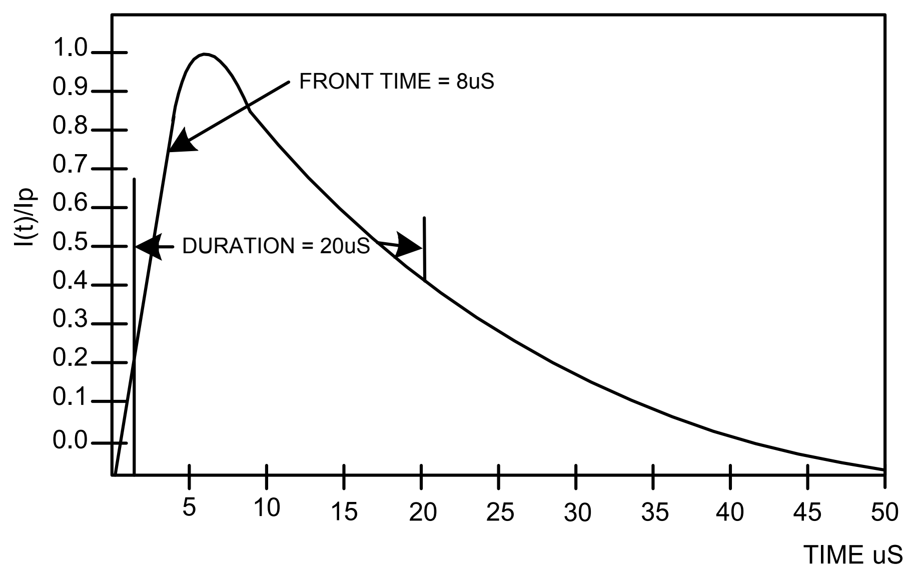


Figure 2-7
Graphical Definition of the ANSI/IEEE 8/20-µs Combination Wave Short-Circuit Current

Test Guidelines:

1. Select PLC system.

2. Install PLC in test circuit as shown in Figure A-2 with a 650-VA on-line UPS placed between the power surge generator and PLC power supply. Verify all electrical connections. This test will be done without the ILB as an auxiliary load.

3. Load PLC processor with PQ test algorithm.

4. Apply rated voltage to test circuit and allow a 10-minute warm-up.

5. Determine the source—a single-phase, 60-Hz source operating at the rated voltage of the PLC, with a Combination Wave as defined in C62.41-1991.

6. Connect the surge generator to the L-N input of the PLC.

7. Starting at 1000 Vac, apply a surge at the peak of the sine wave.

8. Record the surge-voltage response, the current waveform, and the corresponding energy deposition for each surge application. (Energy should be computed by integration over a 50-μs period after surge initiation.) Provide oscillograms for all tests.

9. Record peak current, peak voltage, and PLC response.

10. Increase peak voltage by 1000 Vac and repeat step 8 until 4 kV is reached. If unit is damaged prior to reaching 4 kV, stop the test.

11. Repeat test for L-G surge wave input.

12. Repeat steps 6 through 12 with a 420-VA on-line UPS placed between the power disturbance generator and PLC power supply.

13. Repeat steps 6 through 12 with 500-VA CVT placed between the power disturbance generator and PLC power supply.

14. Repeat steps 6 through 12 without any power-conditioning device between the surge generator and the PLC power supply.

Expected Results: The PLC system power supply and I/O cards should not be damaged by the disturbances due to the mitigation of the voltage conditioner and built-in transient suppressors.

3
TEST RESULTS

3.1 Base-Line Test Results

The characteristics of the five PLCs during normal operation was first determined prior to the beginning extensive testing so that their baseline performances can be established for future comparison to other test results. Each PLC was placed in the test setup in parallel to control components from the Industrial Load Bank (ILB) to represent the typical load of a PLC system. The overall desired load for each PLC was approximately 2.5 amps. Table 3-1 shows base-line characteristics of the overall loads for each system.

Table 3-1
Base-line Characteristics

Model	Power Required (Watts)	Volt-Amperes (VA)	PLC Throughput (msec)	Ithd (%)	1^{st},3^{rd},5^{th} Harmonics (mA/W)
PLC A: Omron	190	310	34	70.54	2.14,0.95,0.843
PLC B: Siemens TI545	190	320	16.7	72.13	2.14,0.94,0.87
PLC C: Modicon Quantum	180	290	17.4	63.4	2.08,0.91,0.74
PLC D: Allen Bradley PLC-5	190	320	74.8	72.99	2.04,0.95,0.86
PLC E: Allen Bradley SLC-5/03	180	300	25	72.5	2.04,0.93,0.83

3.2 Voltage-Sag and Momentary-Outage Test Results

Voltage sag tests were conducted on the five subject PLCs. For each PLC, tests were completed without power conditioning first to determine the base-line performance of each system. The Industrial Load Bank (ILB) was used as an adjacent load to increase the current to a typical level for a control system. The voltage sag ride-through of each PLC system as well as the I/O and control relay (defined as the system load) was then recorded for voltage sags lasting from 0.5 to 120 cycles. Next, tests were conducted with a 500-VA CVT, as well as two APC "on-line" UPS systems and a Best FerroUPS line-interactive UPS.

3.2.1 Summary of PLC Voltage-Sag Test Results

The voltage-sag tests of the five PLCs revealed the following:

- With the exception of PLC D (AB PLC-5), the overall system was less robust than the PLC itself. For the AB PLC-5, the PLC itself was more sensitive to voltage sags than the relay that it was controlling.
- In comparison to earlier EPRI PLC tests, the PLC DC power supplies evaluated in this project were loaded less. This is due to the fact that main loading on each PLC rack consists of one input card, one output card, and the PLC processor. Specifically, the Omron, TI-545, SLC-5/03, and AB PLC-5 series had been evaluated earlier with their power supplies more heavily loaded (two input cards, two output cards, and one analog input and one analog output.) With the exception of the AB PLC-5, the results of these tests indicate that although the magnitude of their ride-through curves is the same, the duration portion varies dependent on loading. To illustrate the difference in ride-through based on loading, the results of the Siemens TI 545 tests in 1995 are compared to the current results from this project in Figure 3-1.

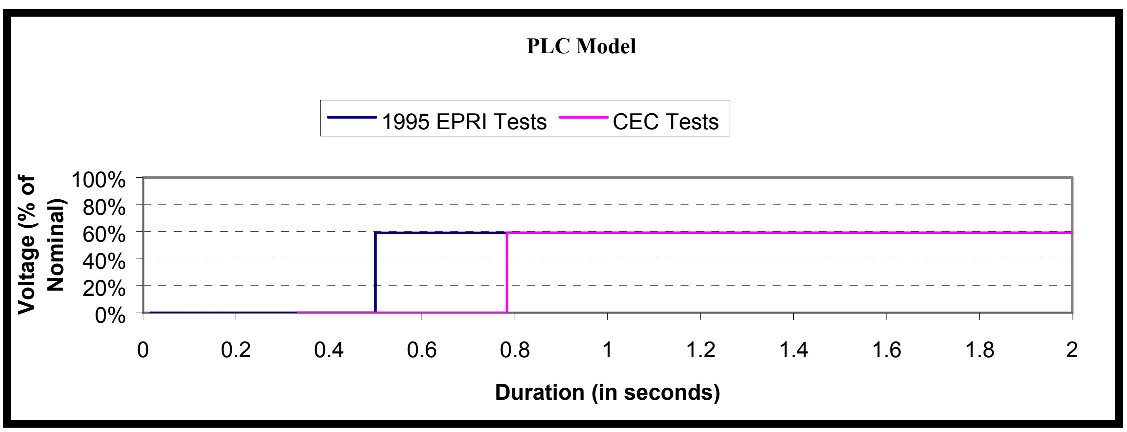


Figure 3-1
Voltage Sag Ride-Through of PLC-B with Respect to Loading *(1995 EPRI Tests Rack Fully Loaded, CEC Tests Rack Lightly Loaded)*

- The AB PLC-5 test results were identical to the results of the previous testing. This PLC shut down when a voltage sag was sensed rather than waiting on the power supply DC bus to drop and instigate the processor shutdown. This scheme of voltage sensing makes the PLC-5 very susceptible to voltage sags when 120-Vac power supplies are used. The following is an excerpt from AB literature about this issue:

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

- All PLCs exhibited better voltage-sag ride-through with the use of a 500-VA CVT on the control power. Furthermore, the current for the PLC and selected ILB loads was set to 2 amps nominally in order to allow proper operation of the CVT. The magnitude component of voltage sag ride-through of the five PLCs is shown in **Error! Reference source not found.** with and without the CVT in place.

Table 3-2
Test Results with and without CVT

PLC Model	Voltage Sag Magnitude Without CVT	Voltage Sag Magnitude With CVT
Omron (PLC A)	65 %	23%
TI 545 (PLC B)	59%	22%
Quantum (PLC C)	65%	22%
AB PLC-5 (PLC D)	78%	27%
AB SLC 5/03 (PLC E)	46%	22%

- The two APC UPS units produced surprising results. The two units used were an APC Smart UPS 420 (420 VA) and an APC Back UPS Pro 650 (650 VA). Unknown at the time of purchase, these two units produce a square-wave output when switching to battery power. Although the two UPS units kept the PLCs powered, some of the 120-Vac input cards could not resolve the square wave. This led to the PLC detecting logic level “0” instead of logic level “1.” As a result, the output relay was dropped when the UPS kicked on and the inputs could not be resolved. Table 3-3 below shows the results of the voltage-sag tests with the two UPS units.

Table 3-3
Test Results with UPS units

PLC Model	Compatible?	Outcome with APC Smart UPS 420	Outcome with APC Back UPS Pro 650
Omron (PLC A)	No	Toggling input could not be resolved.	Toggling input could not be resolved
TI 545 (PLC B)	No	All inputs dropped leading to the logical decision to drop the control relay.	All inputs dropped leading to the logical decision to drop the control relay.
Quantum (PLC C)	No	Same as TI 545	Same as TI 545
AB PLC-5 (PLC D)	Yes	System survived 120-cycle outage.	System survived 120-cycle outage.
AB SLC 5/03 (PLC E)	Yes	Same as AB PLC-5	Same as AB PLC-5

As a follow-up to the APC UPS tests, a true on-line UPS was procured and the PLCs were retested. The UPS selected was a Best FerroUPS Model FE500VA . With this unit in place, all PLCs and their associated I/O were able to survive voltage sags and outages over the voltage-sag test range of 0.5 cycles to two seconds.

3.2.2 Specific Results for Each PLC

In this section, the PLC results of the voltage-sag tests are shown with and without the use of the 500-VA CVT. In each case, the system failure curve and CPU failure curve are shown. **System Failure** denotes that the voltage sag was severe enough to cause the control relay on I/O that was driven and monitored by the PLC to drop out, which could potentially shutdown an industrial process. The **CPU Failure** denotes that the level at which the PLC processor decided to shutdown. In the case when a CPU failure occurred, all PLCs tested were found to reinitiate after the voltage sag.

3.2.2.1 Omron Test Results (PLC A)

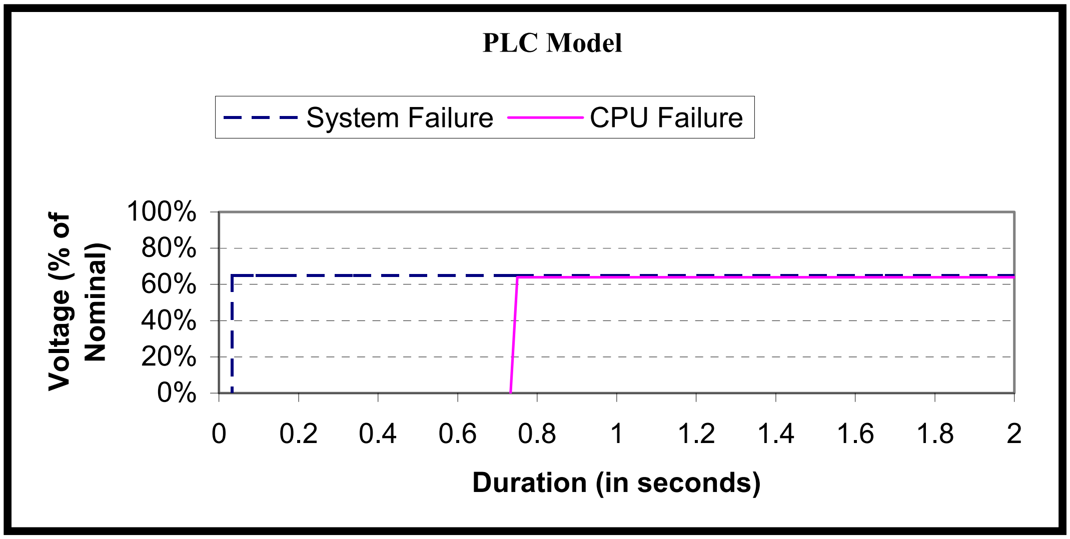


Figure 3-2
Omron Test Results without Power Conditioning

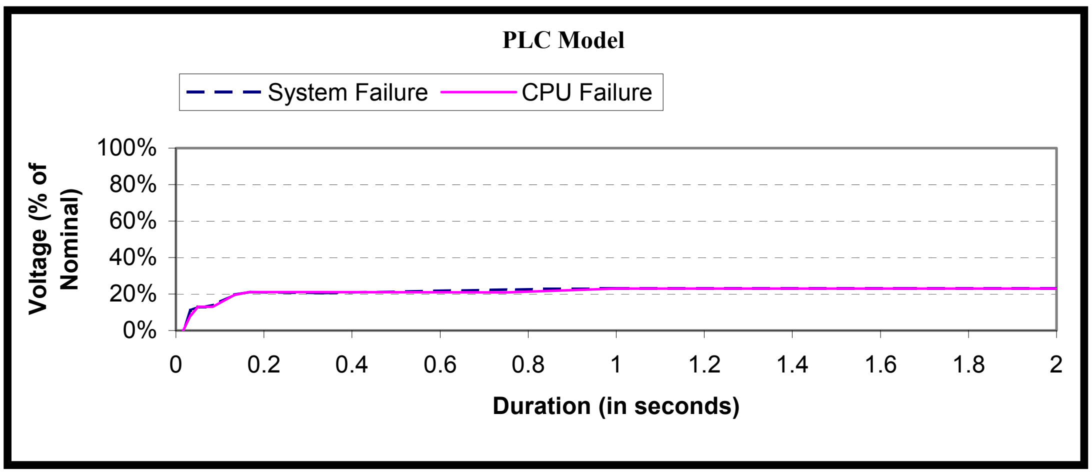


Figure 3-3
Omron Test Results with 500-VA CVT

3.2.2.2 Siemens TI-545 Test Results (PLC B)

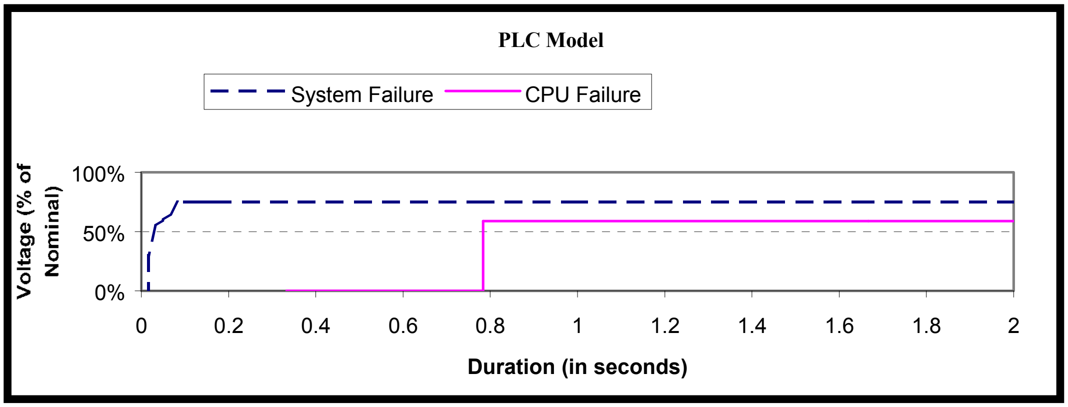


Figure 3-4
Siemens TI-545 Test Results with Power Conditioning

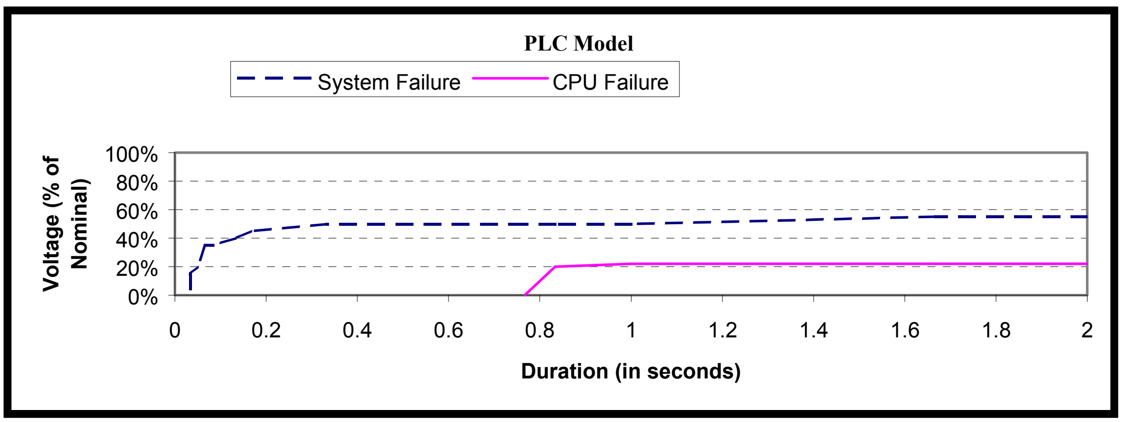


Figure 3-5
Siemens TI-545 Test Results with 500-VA CVT

3.2.2.3 Modicon Quantum Test Results (PLC C)

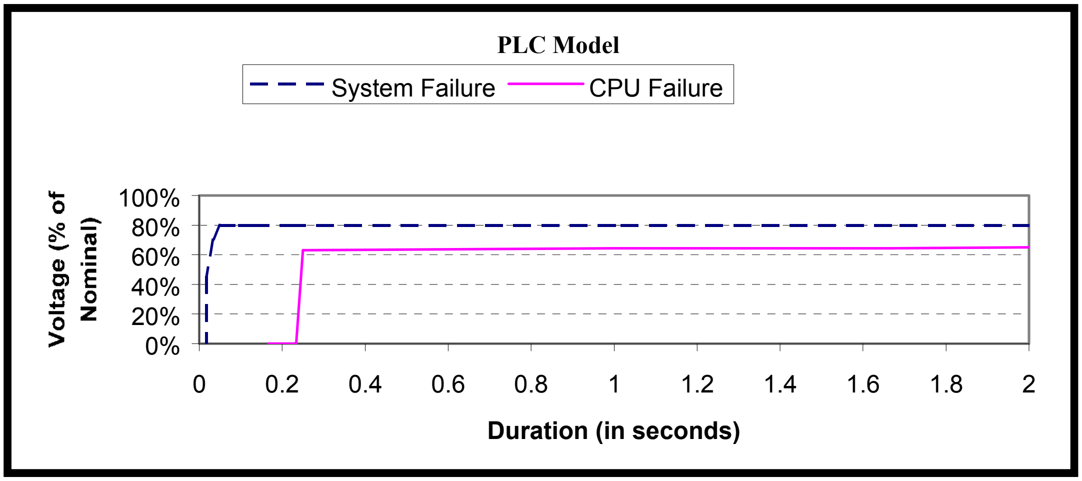


Figure 3-6
Modicon Quantum Test Results without Power Conditioning

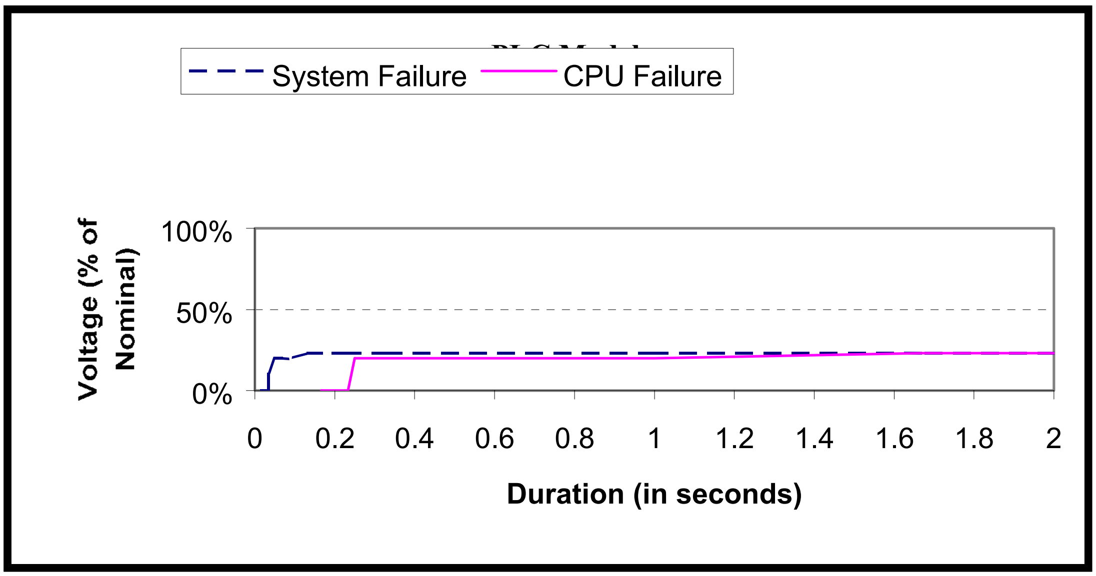


Figure 3-7
Modicon Quantum Test Results with 500-VA CVT

3.2.2.4 Allen Bradley PLC-5 Test Results (PLC D)

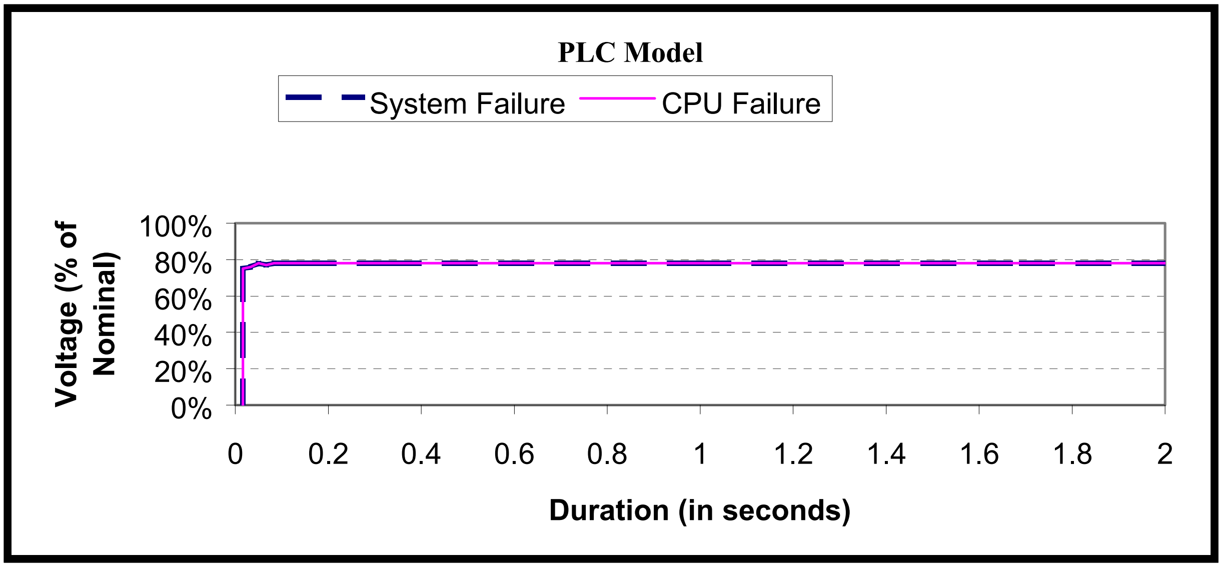


Figure 3-8
AB PLC-5 Test Results without Power Conditioning

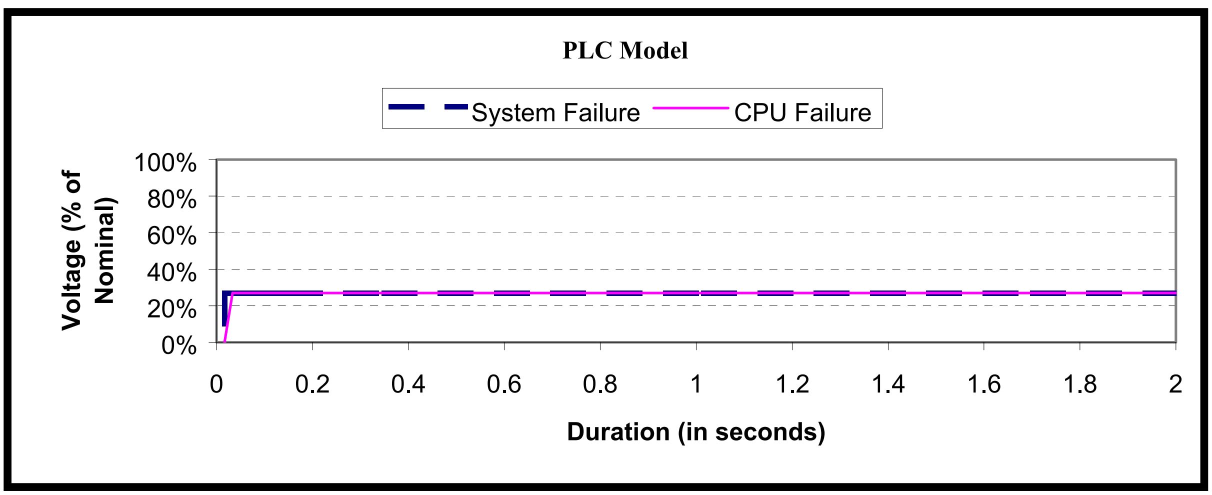


Figure 3-9
AB PLC-5 Test Results with 500VA CVT

3.2.2.5 Allen Bradley SLC 5/03 Test Results (PLC E)

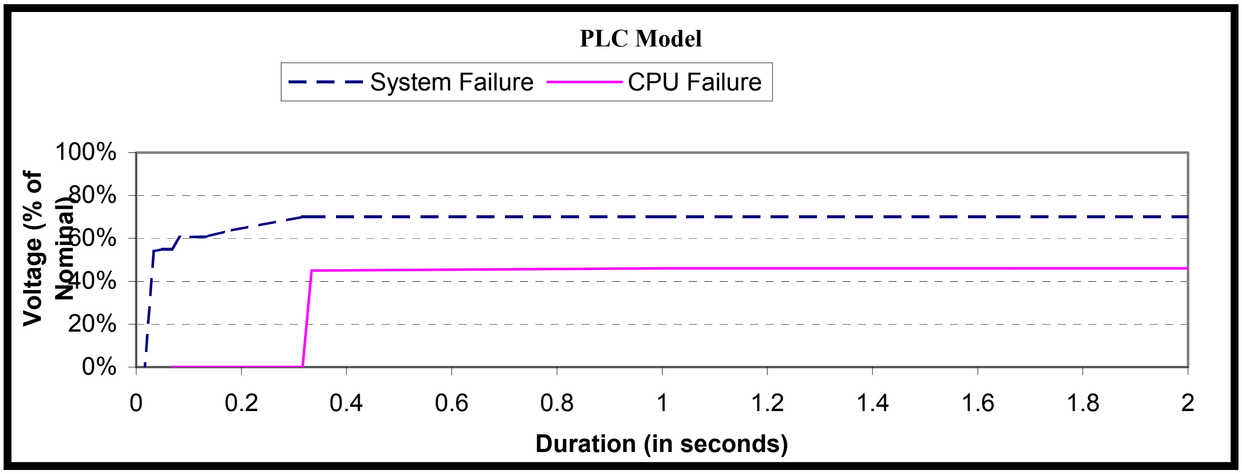


Figure 3-10
AB SLC 5/03 Test Results without Power Conditioning

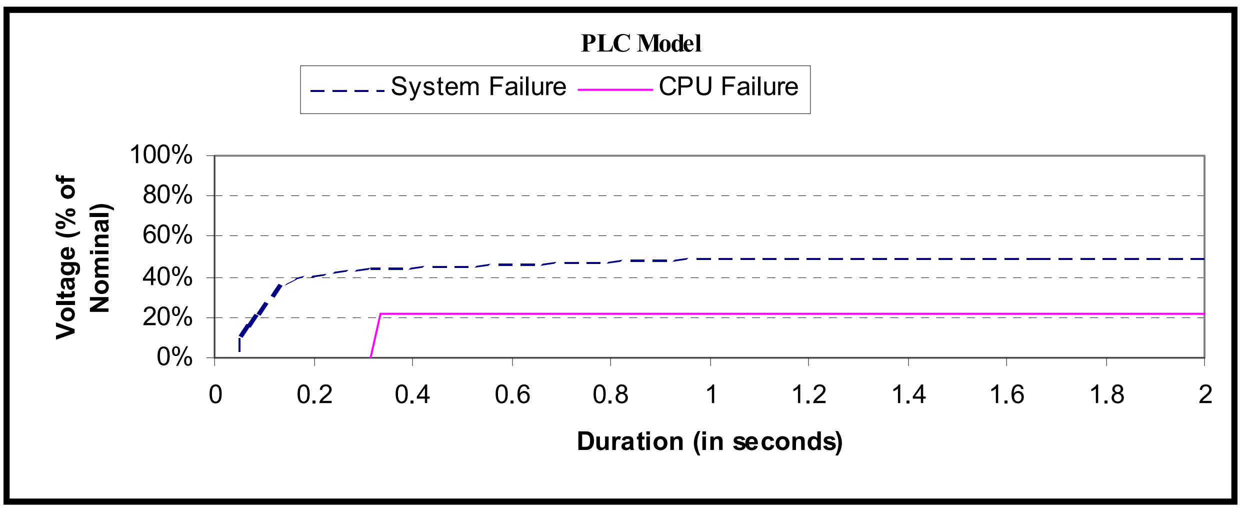


Figure 3-11
AB SLC 5/03 Test Results with 500-VA CVT

3.3 Test Results for Capacitor-Switching Transients

The five PLCs were subjected to capacitor-switching transients similar to the plot shown in **Error! Reference source not found.**. Tests were first conducted without power conditioning. Then, the tests were repeated with a 500-VA CVT between the PLC system and power source. Finally, three different UPS models were connected between the PLC and power source and the tests were repeated. Table 3-4 summarizes the results from the testing.

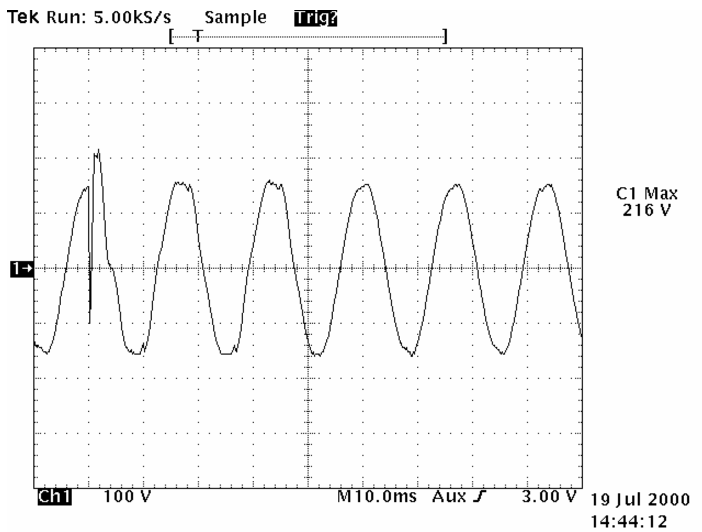


Figure 3-12
Typical Capacitor-Switching Transient

Table 3-4
Test Results for Capacitor-Switching Transients

PLC Model	Affected by Cap Switch w/o Power Conditioning?	Outcome with 500-VA CVT	Outcome with APC Smart UPS 420	Outcome with APC Back UPS Pro 650	Outcome with Best FerroUps
Transient Seen by PLC?	*Yes. Approximately 1.5 p.u.*	*No. See* ***Error! Reference source not found.**.*	*Yes, Approximately 1.5 p.u.- after ½ cycle switches to square wave output from UPS. See* ***Error! Reference source not found.**.*	*Yes, Approximately 1.3 p.u. - after ¼ cycle switches to square wave output from UPS. See* ***Error! Reference source not found.**.*	*No. See* ***Error! Reference source not found.**.*
Omron (PLC A)	No	Not affected. Transient mitigated.	Toggling input could not be resolved.	Toggling input could not be resolved.	Not affected. Transient mitigated.
TI 545 (PLC B)	No	Not affected. Transient mitigated.	All inputs dropped, leading to the logical decision to drop the control relay.	All inputs dropped, leading to the logical decision to drop the control relay.	Not affected. Transient mitigated.
Quantum (PLC C)	No	Not affected. Transient mitigated.	All inputs dropped, leading to the logical decision to drop the control relay.	All inputs dropped, leading to the logical decision to drop the control relay.	Not affected. Transient mitigated.
AB PLC-5 (PLC D)	No	Not affected. Transient mitigated.	**Not affected by transient or UPS square wave.**	**Not affected by transient or UPS square wave.**	Not affected. Transient mitigated.
AB SLC 5/03 (PLC E)	No	Not affected. Transient mitigated.	**Not affected by transient or UPS square wave.**	**Not affected by transient or UPS square wave.**	Not affected. Transient mitigated.

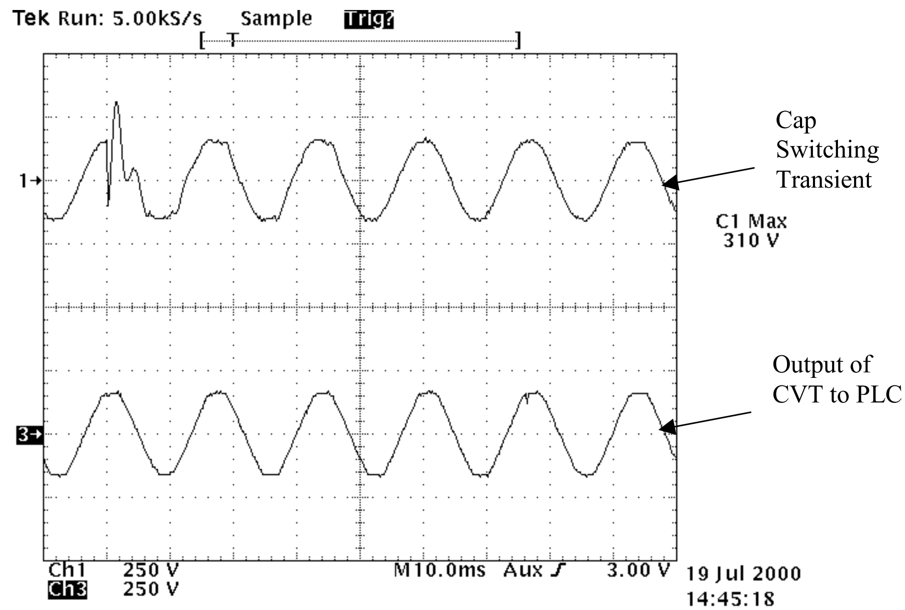


Figure 3-13
500-VA CVT Mitigates Capacitor-Switching Transient to PLC

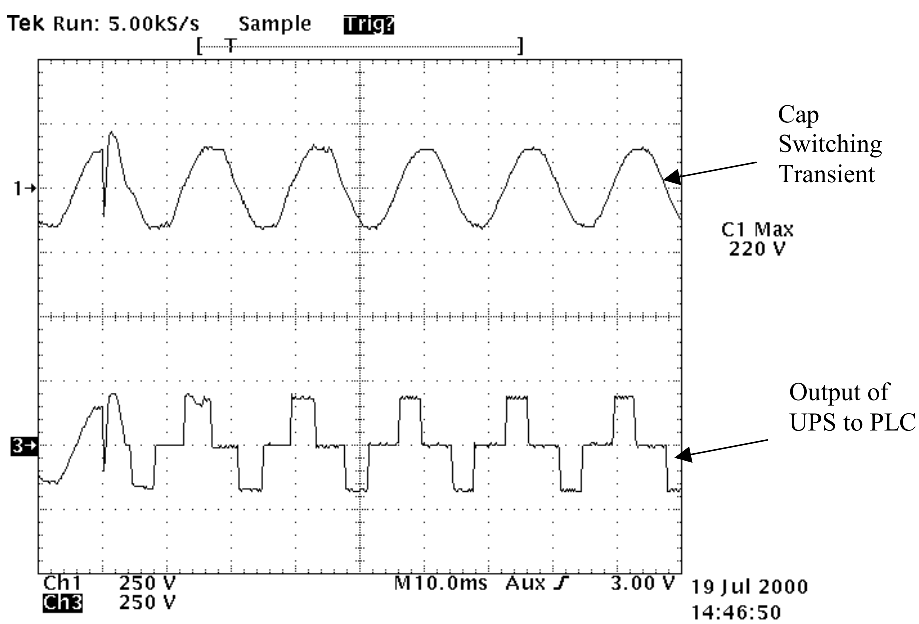


Figure 3-14
APC Smart UPS 420 Passes Transient for ½ Cycle, Then Switches to Battery to Supply a Square-Wave Output

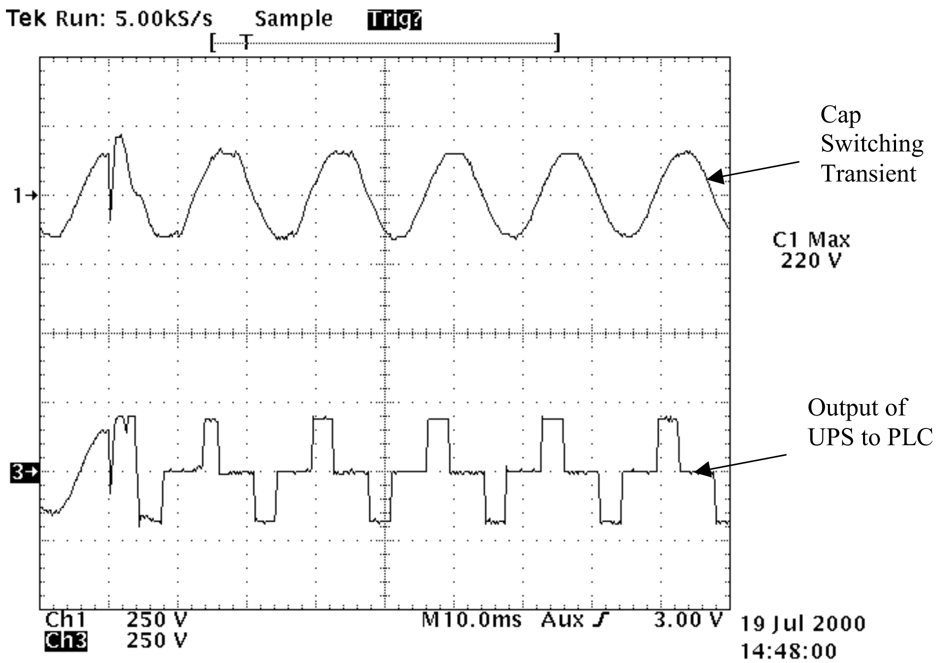


Figure 3-15
APC Back UPS Pro 650 Passes Initial Transient for ¼ Cycle, Then Switches to Battery to Supply a Square-Wave Output

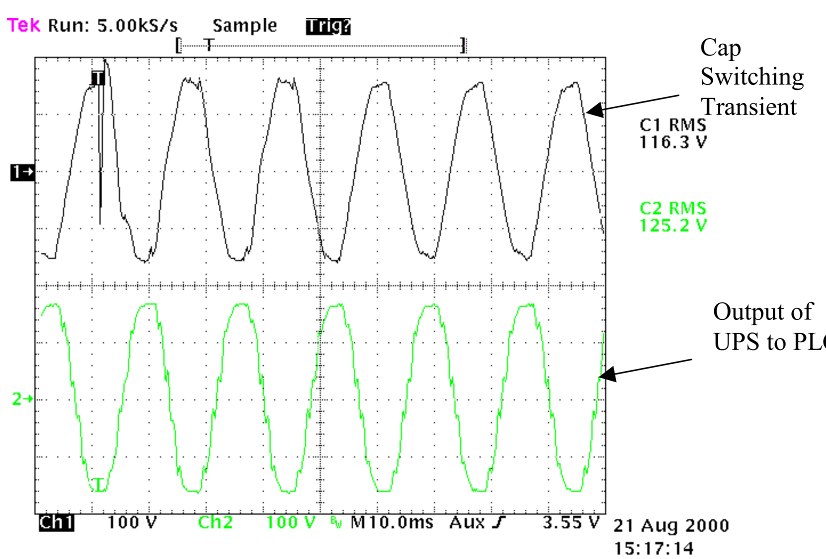


Figure 3-16
Best FerroUPS Mitigates Capacitor Switching Transient

Based on the test results, the following conclusions can be drawn about the PLC testing with capacitor-switching transients:

- PLC systems generally are not susceptible to these transients. (This result is consistent with the testing that was done in the 1995 EPRI System Compatibility Task 5 Project Entitled "PLC Systems used in the Industrial Power System."

- Square-wave output power conditioners are not universally compatible with PLCs, as shown when the two APC UPS systems switched to battery in order to try and mitigate the capacitor-switching transients. Although the two UPS units kept the PLCs powered, some of the 120-Vac input cards could not resolve the square wave. This led to the PLC detecting logic level “0” instead of logic level “1.” As a result, the output relay was dropped when the UPS kicked on, and the inputs could not be resolved.
- The CVT provides excellent mitigation of capacitor-switching transients as well as voltage sags.
- The Best FerroUPS, which utilizes a CVT in the design, provides excellent mitigation of capacitor-switching transients. Furthermore, this unit provides a sine-wave output that allows the PLC 120-Vac input cards to resolve input data.

3.4 Response to Voltage Harmonics Test Results

This test was added per the request of CEC to investigate the effect of harmonics on PLC performance and was not part of the original scope of work. PLC D, the Allen Bradley PLC 5/11, was used in this experiment as the test load. In order to create the most distortion possible, the 5-HP ASD was set to 100 percent speed and load.

The results of the test are summarized in Table 3-5. Representative voltage and current harmonic data from the experiment are shown in Figure 3-17, Figure 3-18 and Figure 3-19. The introduction of the reactors did change the RMS and peak voltages significantly. As expected, the PLC continued to operate normally during the steady-state tests. Furthermore, for a typical voltage sag of 5 cycles, the voltage sag ride-through performance was virtually unchanged for PLC D, which dropped out at 76 percent, 76 percent, and 75 percent for the three test cases. Based on the results of these tests, no appreciable difference in the PLC operation was noted as a result of the ASD-induced harmonics.

Table 3-5
ASD Harmonics Test Results with PLC D

	Outcome With no Reactors in Circuit	**Outcome With 3%, 8-A Reactors**	**Outcome With 3%, 35-A Reactors**
Baseline Performance	*PLC Operates Normally*	*PLC Operates Normally*	*PLC Operates Normally*
PLC Voltage-Sag Performance at 5 Cycles	Shutdown at 76% of Nominal	Shutdown at 76% of Nominal	Shutdown at 75% of Nominal
Vrms	124.5Vac	123.7Vac	123.19
Vpeak	178.1Vac	173.5Vac	174.8
Vthd RMS/Fund	1.48/1.48	2.46/2.46	1.68/1.68

Crest Factor	1.39	1.44	1.39

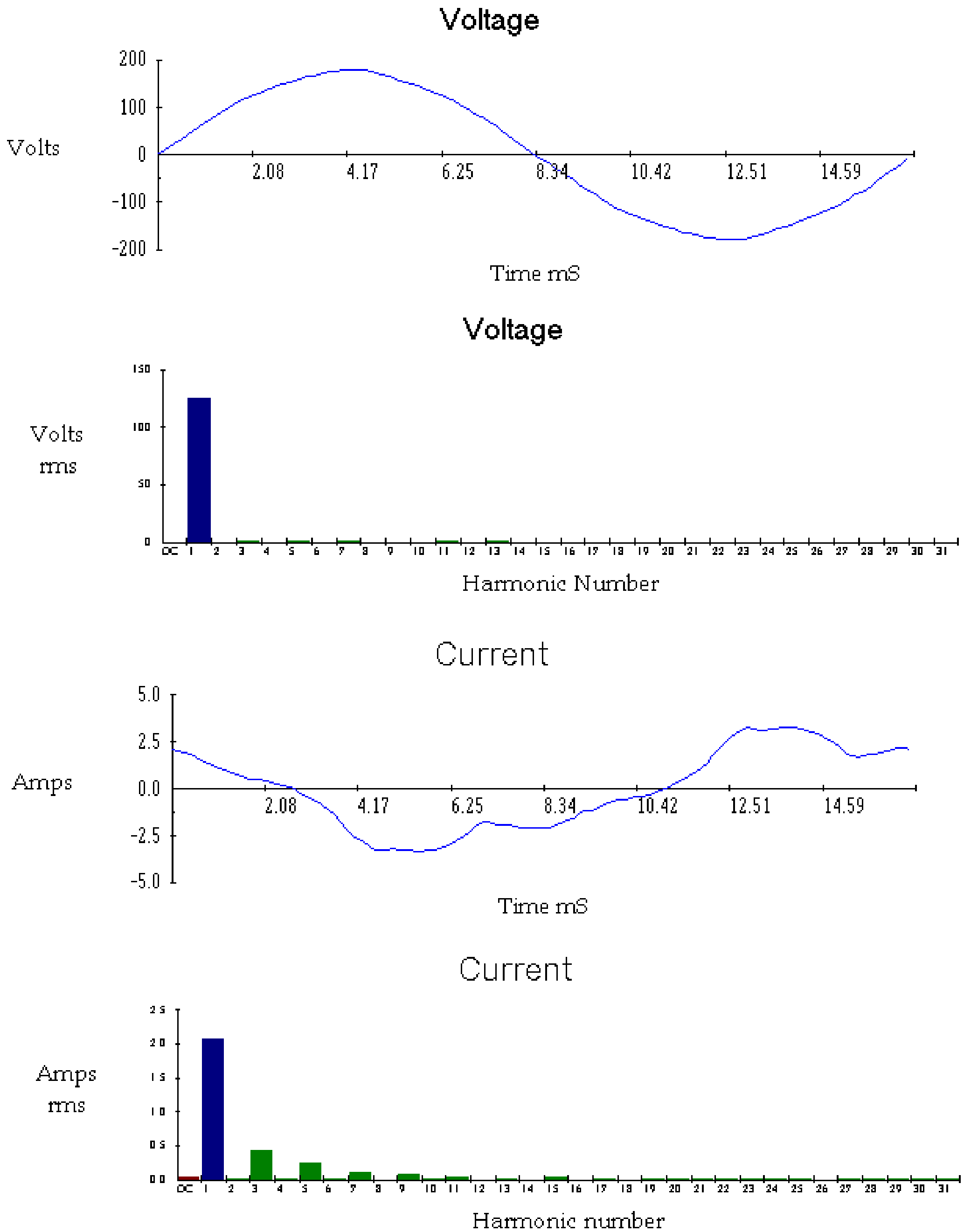


Figure 3-17
Voltage and Current Harmonics as Seen by PLC without any Line Reactors in Place

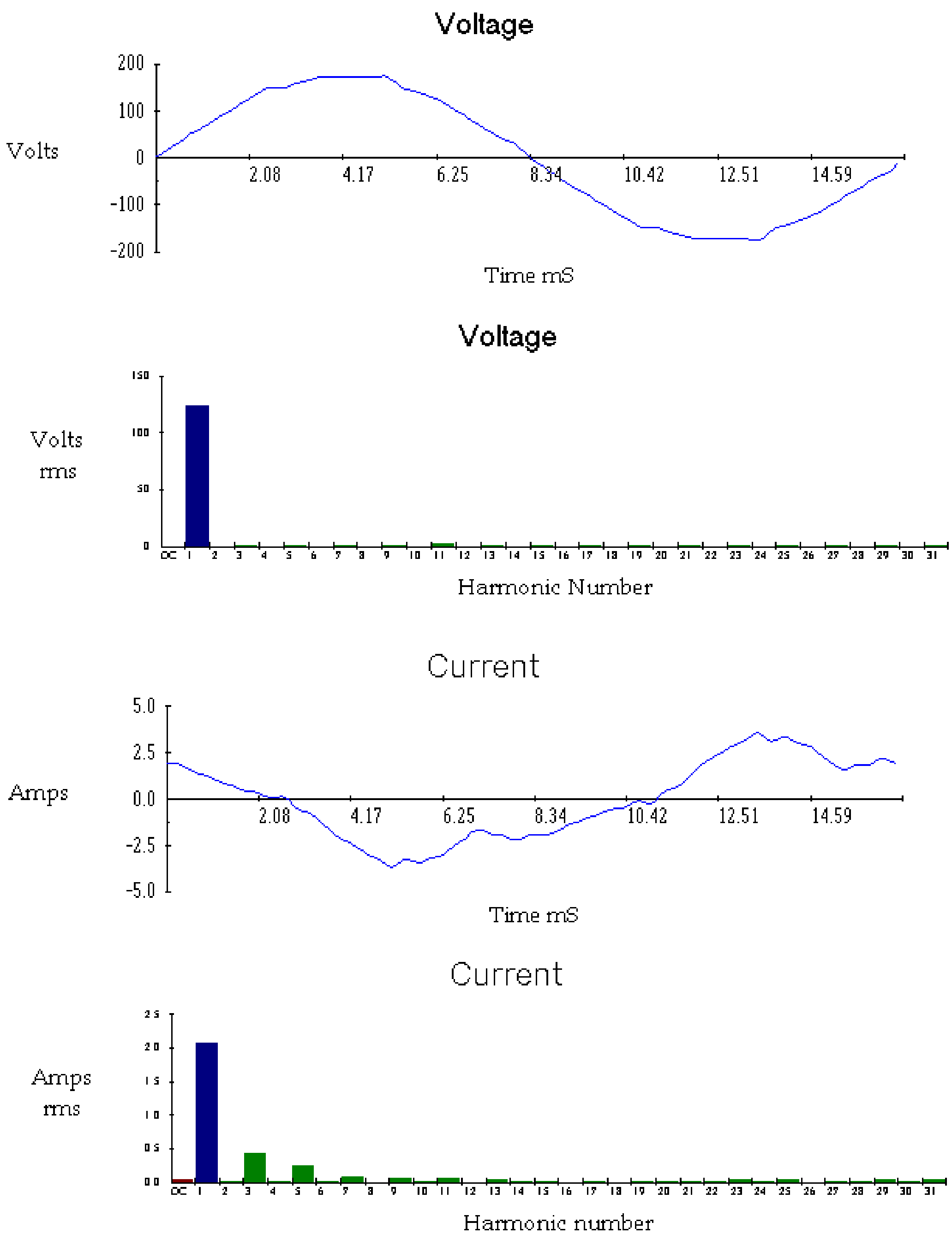


Figure 3-18
Voltage and Current Harmonics as Seen by PLC with 3%, 8-Amp Line Reactors in Place

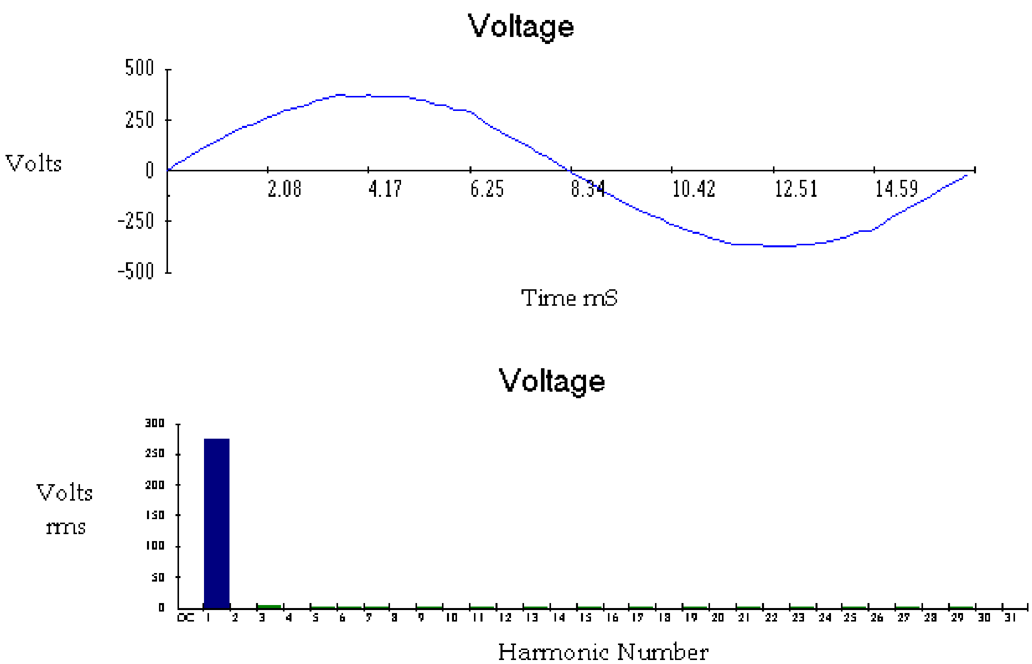


Figure 3-19
Harmonic Voltage as Seen by PLC with 3%, 35 Amp Line Reactors in Place

3.5 Test Results for Lightning-Induced Transients

3.5.1 Test Waveforms

Before devices under test were connected to the 801-S surge generator, baseline waveforms of the highest magnitude indicated in the test protocol were captured. Figure 3-20 shows a maximum open-circuit voltage of 4.19 kV measured at the output of the surge generator. Figure 3-21 shows the maximum short-circuit current of 1.92 kA measured at the output of the surge generator.

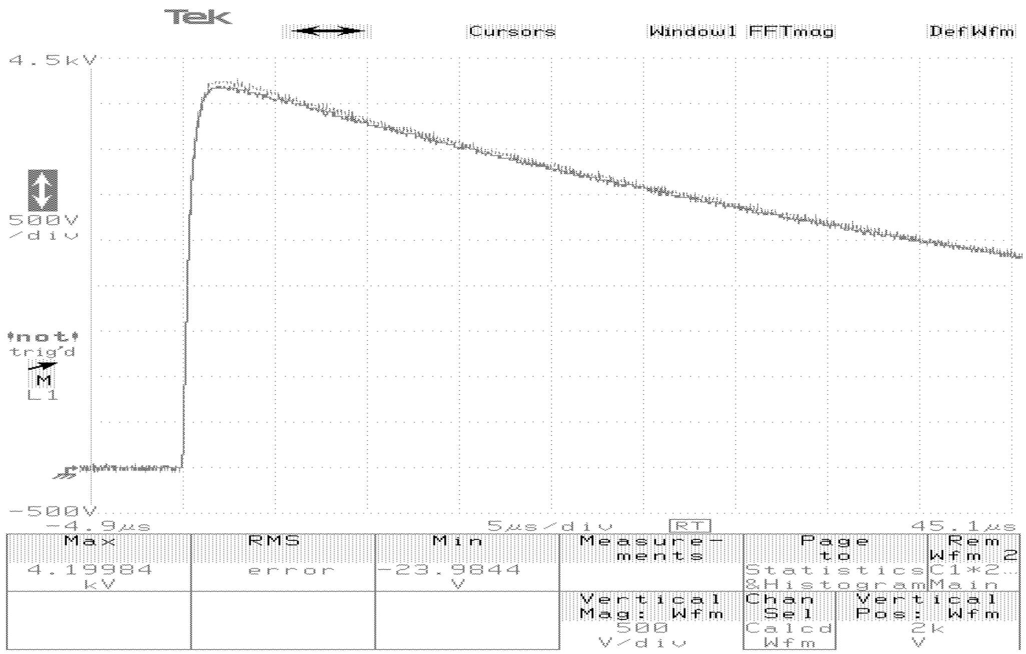


Figure 3-20
Baseline Open-Circuit Voltage

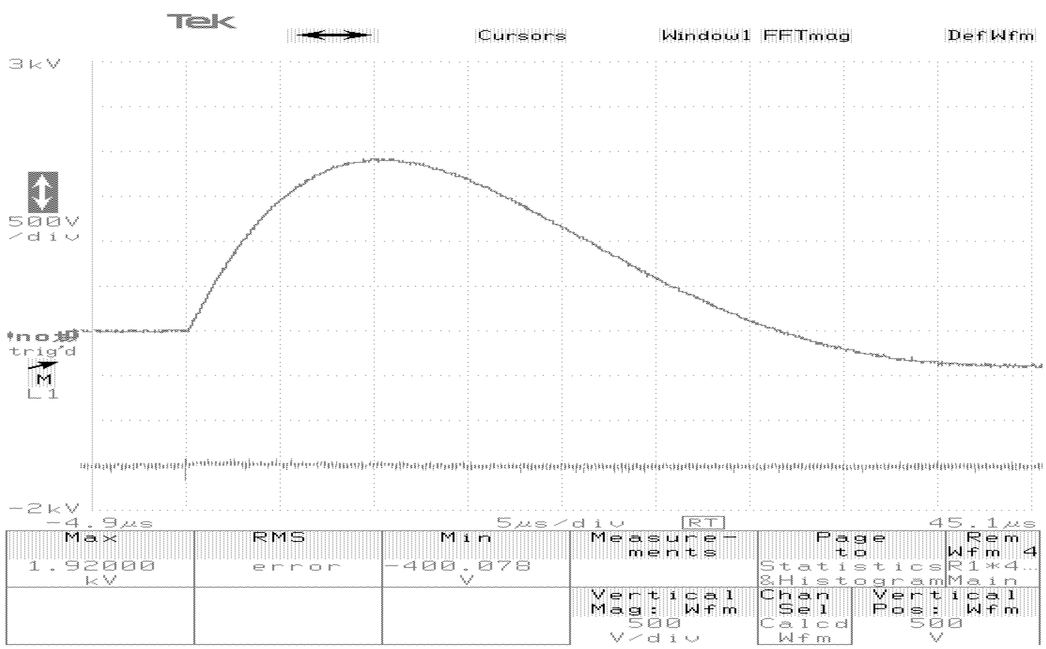


Figure 3-21
Baseline Short-Circuit Current

3.5.2 Test Results for Lightning-Induced Transients (With Power Conditioning)

Transient surge tests were performed with and without power conditioning. The first series of tests were done with power conditioning as illustrated in Figure 3-22.

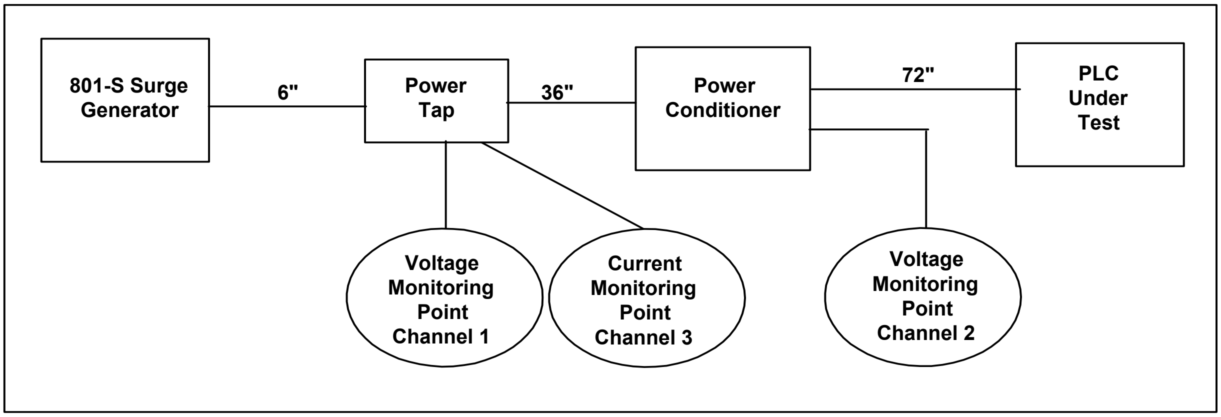


Figure 3-22
Test Set Up with power Conditioning

The first power-conditioning device connected to the test setup was a Sola MCR-series CVT, which was connected to the front of the PLC. A transient surge with a magnitude of 4.27 kV line-to-neutral had no effect on any of the five tested PLCs when the CVT was in place. An example of this surge waveform is shown in **Error! Reference source not found.**. Channel 2 is the output of the CVT. Notice that the surge transient, Channel 1, is not reflective in Channel 2. This indicates that the surge transient at this magnitude did not affect the output of the CVT or the PLC.

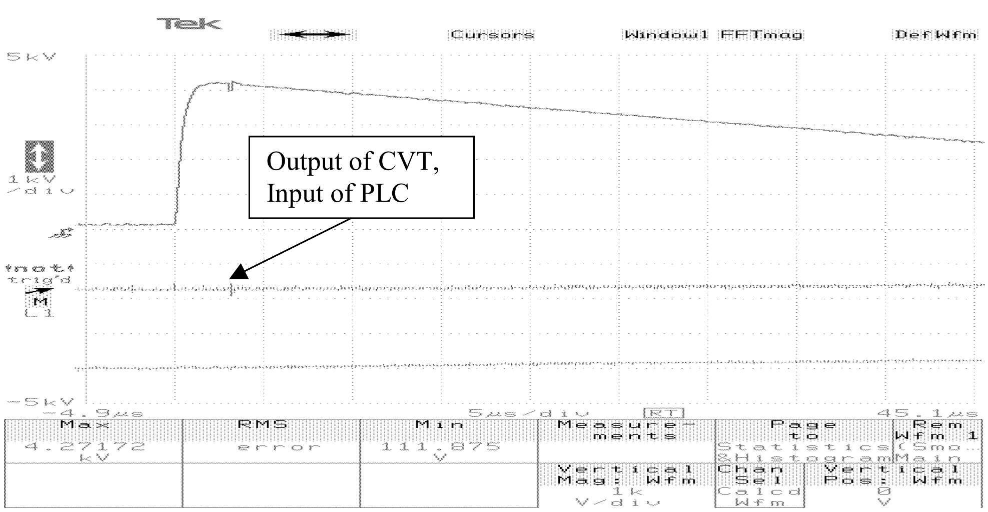


Figure 3-23
With 500-VA CVT Installed, Surge Transient of 4.27 kV (Line-to-Neutral) had No Effect on CVT Output or PLC Operation

A line-to-ground surge transient affected the primary side of the Sola MCR-series CVT. **Error! Reference source not found.** shows a 3-kV surge that caused a flash over on the primary side of the CVT, which caused the voltage to exceed the scope's measurement scale. The secondary of the CVT was unaffected by this flash over.

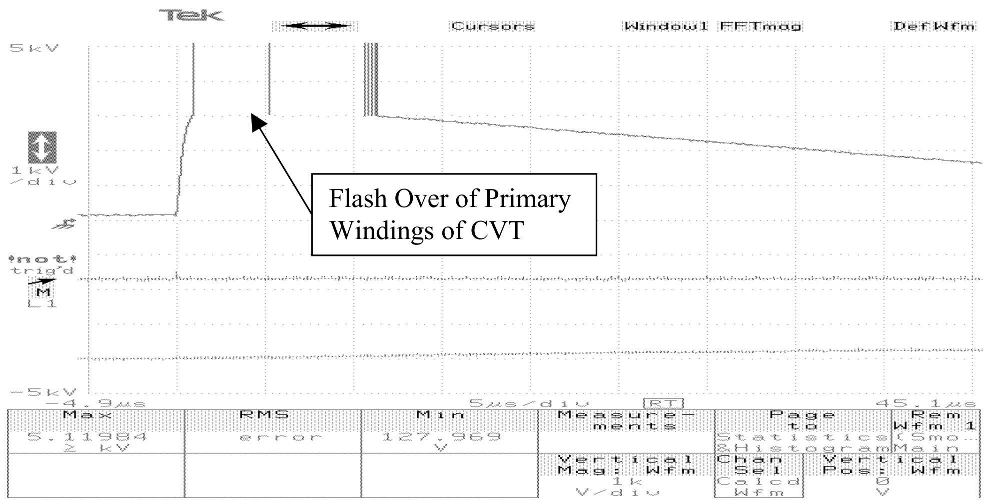


Figure 3-24
With 500-VA CVT Installed, a 3-kV Line-to-Ground Transient Led to Flashover on the Primary Side of the CVT

The second power-conditioning device installed was an APC 420 Smart-UPS. Line-to-neutral and line-to-ground transient surges up to 4 kV did not damage the UPS or PLC, but did cause a PLC system upset. The upset occurred when the UPS transferred to battery backup. As was shown for the voltage sags and capacitor-switching transients, when the UPS transferred to battery backup, the square-wave output of the APC 420 Smart-UPS led to erratic I/O operation on the TI545, Modicon Quantum, and Omron units. **Error! Reference source not found.** is representation of a 2-kV transient surge that caused these upsets.

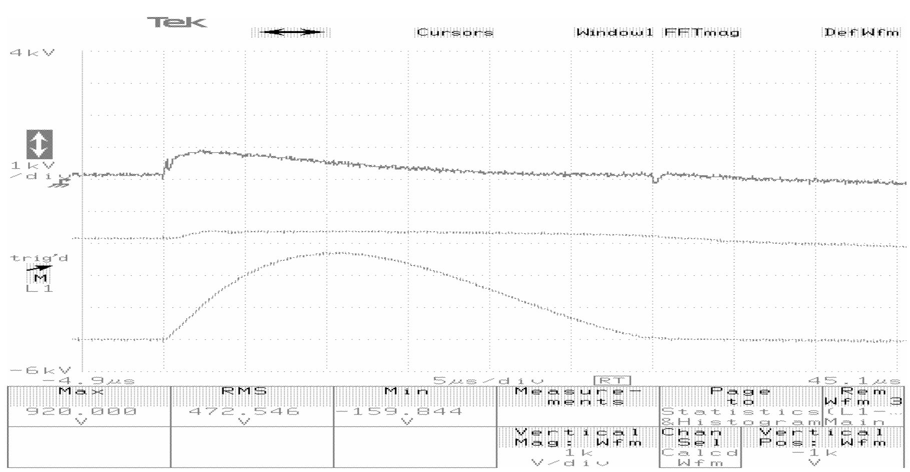


Figure 3-25
Line-to-Neutral 2-kV Transient Surge Caused a PLC System Upset

3.5.3 Test Results for Lightning-Induced Transients (Without Power Conditioning)

The second transient surge test was performed without power conditioning. The test setup is illustrated in Figure 3-26.

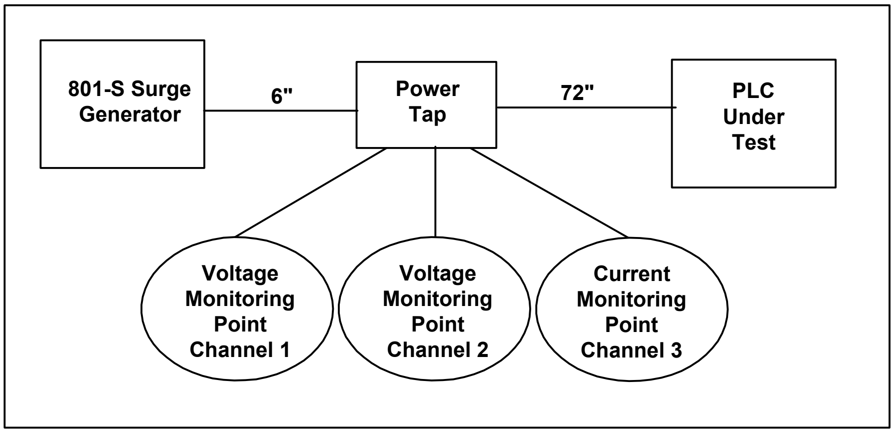


Figure 3-26
Surge Test Set Up Without Power Conditioning

The two PLCs tested were the Omron and TI545. The first one tested was the Omron. The Omron was able to survive surges up to 3 kV, but suffered critical damage from a 3.5-kV line-to-neutral transient surge (see the captured waveform in Figure 3-27).

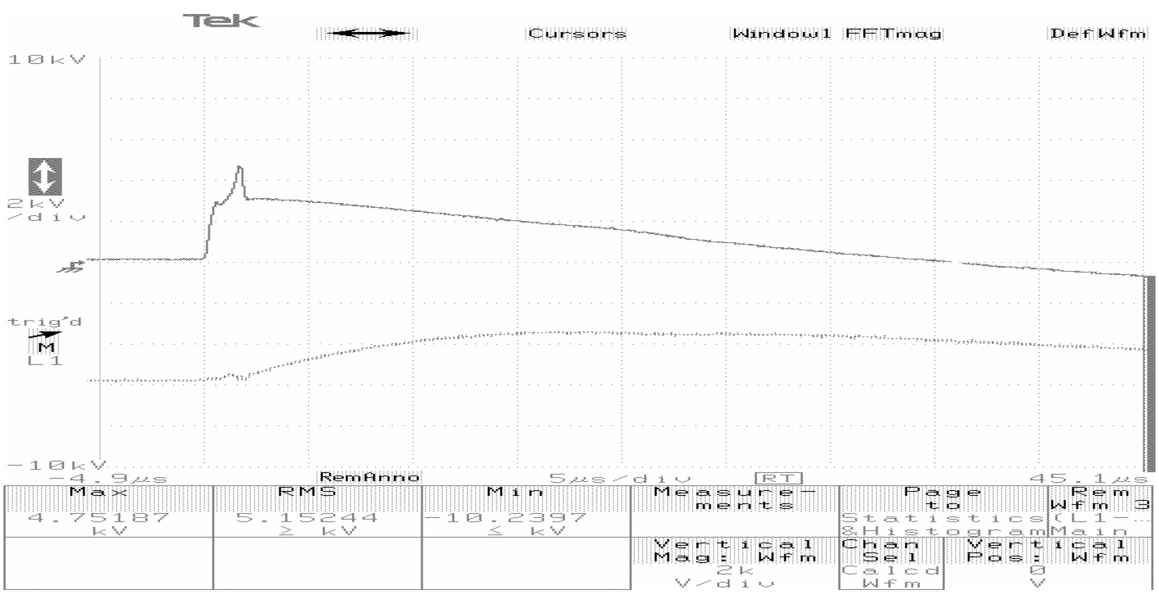


Figure 3-27
Without Power Conditioner, the Omron Was Critically Damaged during a 3.5-kV Line-to-Neutral Transient Surge

The second PLC tested without power conditioning was the Siemens TI545. This PLC was unaffected by transient surges up to 4 kV line-to-ground. **Error! Reference source not found.**

shows the 4-kV line-to-neutral transient surge that had no affect on the Siemens TI545. The maximum voltage measured during the 4-kV transient surge was 1.24 kV due to internal transient protection of the Siemens TI545.

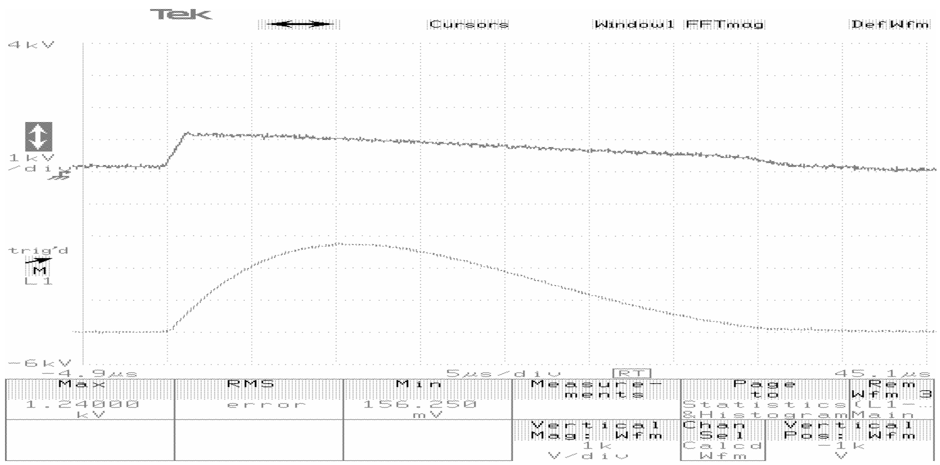


Figure 3-28
4-kV Line-to-Neutral Transient Surge Had No Effect on the Siemens TI545 PLC

3.5.4 Summary of Test Results for Lightning-Induced Transients

The test results for line-to-neutral and line-to-ground lightning-induced transients are summarized in Table 3-6.

Table 3-6
Summary of Test Results for Lightning-Induced Transients

PLC Model	Outcome with 500-VA CVT (Line-to-Neutral)	Outcome with 500-VA CVT (Line-to-Ground)	Outcome with APC Smart UPS 420 (L-N and L-G)	Affected by Surge Transient without Power Conditioning?
Omron (PLC A)	Not affected. Transient mitigated .	PLC not affected. Test stopped at 3 kV due to flashover of CVT.	After UPS transfer, toggling input could not be resolved .	Power supply suffered critical damage for 3.5-kV line-to-neutral transient surge.
TI 545 (PLC B)	Not affected. Transient mitigated.	PLC not affected. Test stopped at 3kV due to flashover of CVT	All inputs dropped, leading to the logical decision to drop the control relay.	PLC not affected. Internal MOV mitigated line-to-neutral surge to 1.24 kV.
Quantum (PLC C)	Not affected. Transient mitigated.	PLC not affected. Test stopped at 3 kV due to flashover of CVT	All inputs dropped, leading to the logical decision to drop the control relay,	Not tested per plan.
AB PLC-5 (PLC D)	Not affected. Transient mitigated.	PLC not affected. Test stopped at 3 kV due to flashover of CVT	Not affected by transient or UPS square wave.	Not tested per plan.
AB SLC 5/03 (PLC E)	Not affected. Transient mitigated.	PLC not affected. Test stopped at 3 kV due to flashover of CVT	Not affected by transient or UPS square wave	Not tested per plan.

4
CONCLUSIONS

Test results reveal that the tested PLC systems are susceptible to voltage sags. In the voltage-sag testing without power conditioning, it was found that the PLCs decided to shut themselves down when sag events ranging from 46 to 78 percent of nominal voltage occurred for one to 47 cycles. Furthermore, while at least one of the PLC systems purposely shut itself off during minor voltage sags, other units continued to operate until more significant voltage sags occurred. Table 4-1 shows the ranking of the tested PLCs from most to least susceptible based on depth, duration, and likelihood of voltage sags more severe.

Table 4-1
Voltage Sag Susceptibility Ranking of PLCs Tested

Voltage-Sag Susceptibility Ranking	PLC	First PLC Failure Point	Shutdown Mechanism
1	Allen Bradley PLC-5 (PLC D)	1 cycle, 78%Vnom	Firmware embedded decision based on AC input to P/S module.
2	Modicon Quantum (PLC C)	15 cycles, 65% Vnom	Believed to be based on DC power supply ride-through, load-dependent (number of modules).
3	Allen Bradley SLC 5/03 (PLC E)	20 cycles, 46% Vnom	DC power supply ride-through, load-dependent (number of modules).
4	Omron (PLC A)	45 cycles, 65% Vnom	DC power supply ride-through, load-dependent (number of modules).
5	Siemens TI 545 (PLC B)	47 cycles, 59% Vnom	DC power supply ride-through, load-dependent (number of modules).

Each of the PLCs were wired to monitor themselves and drive an external control relay as shown in appendix A. The shutdown levels of the PLC and I/O together were noted on the ride-through curves as the “System Failure” curves. A standard, general-purpose “Ice Cube” style relay was used because it is typically susceptible to voltage sags at 80 percent of nominal. Five individual but identical relays were used for each of the PLC systems. Because the relay was driven by the PLC and also “latched” by the PLC logic (see PQ Test Algorithm, Appendix C), the vulnerability of each device to voltage sags depended not only on the relay, but also the PLC system throughput. This suggests that PLCs that react slower due to longer program scan times or I/O speeds may be slightly less susceptible. Correlation of the individual system ride-through curves with the PLC throughput suggests that PLC response time does play a part in the system sensitivity.

The voltage-sag test results utilizing power-conditioning devices revealed that the common constant-voltage transformer (CVT) was very effective in improving voltage-sag ride-through of PLC systems. With a PLC and ILB load set at 2 amps, the 500-VA CVT enabled the PLCs to survive voltage sags from 22 to 27 percent of nominal, depending on the unit under test (see Appendix E for information on sizing CVTs).

Three UPSs were ultimately used to demonstrate power-conditioning options. In the beginning of the project, two APC UPSs were purchased and sold under the pretense that they were on-line UPS systems. After laboratory testing was conducted using the UPSs, it was noted that they were in fact “off-line” units that produced a square-wave output. This was actually a good turn of events in that the testing revealed incompatibilities between the square-wave output of UPS systems and three of the five PLCs. Although the two APC units were able to keep the PLC power supplies on-line during all voltage sags injected into the test fixture, the 120-Vac discrete inputs installed on the Omron, Siemens TI, and Quantum PLCs exhibited inability to detect logic “1” signals from the field wiring. Therefore, the program inside the PLCs made erroneous decisions, leading to system failure. A final test was conducted with a line-interactive Best FerroUPS system on all five PLCs. The Best unit, which incorporates a CVT in the unit and supplies a true sine-wave output, was able to hold up the PLC and I/O loads indefinitely.

As supported by this work and 1995 EPRI tests of a similar nature, PLC systems are generally not susceptible to capacitor-switching transients. However, because long-term exposure of PLCs to such events is not well known, power-conditioning devices may still be useful in mitigation of capacitor-switching transients. As shown in the test results, the CVT provides excellent mitigation of capacitor-switching transients, not allowing the event to pass the PLC load. Given that the two APC UPS systems were designed to detect overvoltages, both units transferred to battery as a result of the test, presenting the 120-Vac discrete inputs with a square wave. Once again, three of the five PLCs responded negatively, making erroneous program decisions and dropping the control relay. As expected, the Best UPS performed well in this test, not passing the transient to the connected load.

Added to the test protocol at the request of CEC after the start of the project, an ASD-induced harmonics tests was conducted using the Allen Bradley PLC 5/11 (PLC D.) With an ASD used to induce harmonic current and line reactors used to represent long line lengths, voltage with harmonic content was applied to the PLC, which was subjected to voltage sag tests again. However, the “flat topping” effect of the harmonic voltage did not make the voltage-sag response of the PLC appreciably different. Additional tests with different impedance reactors and other PLCs should be conducted in the future to further verify the results.

During the lightning-induced surge tests, the PLCs were evaluated without the ILB load bank. The tests were conducted first on all five PLCs with voltage-conditioning devices. From these tests, it was learned that the CVT mitigated the lightning-induced transients up to the 4 kV test level for line-to-neutral surge events. Furthermore, the CVT mitigated line-to-ground transients up to 3.5 kV before flashover occurred on the primary of the transformer. Nonetheless, the output of the CVT continued to supply a mitigated voltage source to the PLC loads. The PLC reaction to the UPS tests with the APC units was similar to the PLC response to voltage sags and capacitor-switching transients – when the UPS transferred to battery, the 120-Vac discrete inputs could not resolve the input signals and the PLC logic shutdown the output signals.

Without power conditioning, two of the five PLCs were tested to see how well they would survive surge events. Although the Siemens TI unit (PLC B) went unscathed during the line-to-neutral and line-to-ground tests up to 4 kV, the Omron (PLC A) power supply was critically damaged by a 3.5-kV line-to-neutral event. Based on the maximum magnitude of the recorded transient, the Siemens PLC has a good transient protection scheme design while the Omron does not. Based on the results of this work, it is apparent that power conditioning should be used on both the PLC and its associated 120-Vac control power. Use of properly sized UPSs or CVTs on these circuits can greatly improve the overall robustness of PLC-based control systems. However, careful selection of power-conditioning devices is required to ensure that the entire system will not be made less compatible as a result. Power-conditioning devices that produce square-wave outputs are not compatible with all PLC systems.

A
CEC PLC PROJECT TEST SETUP DRAWINGS

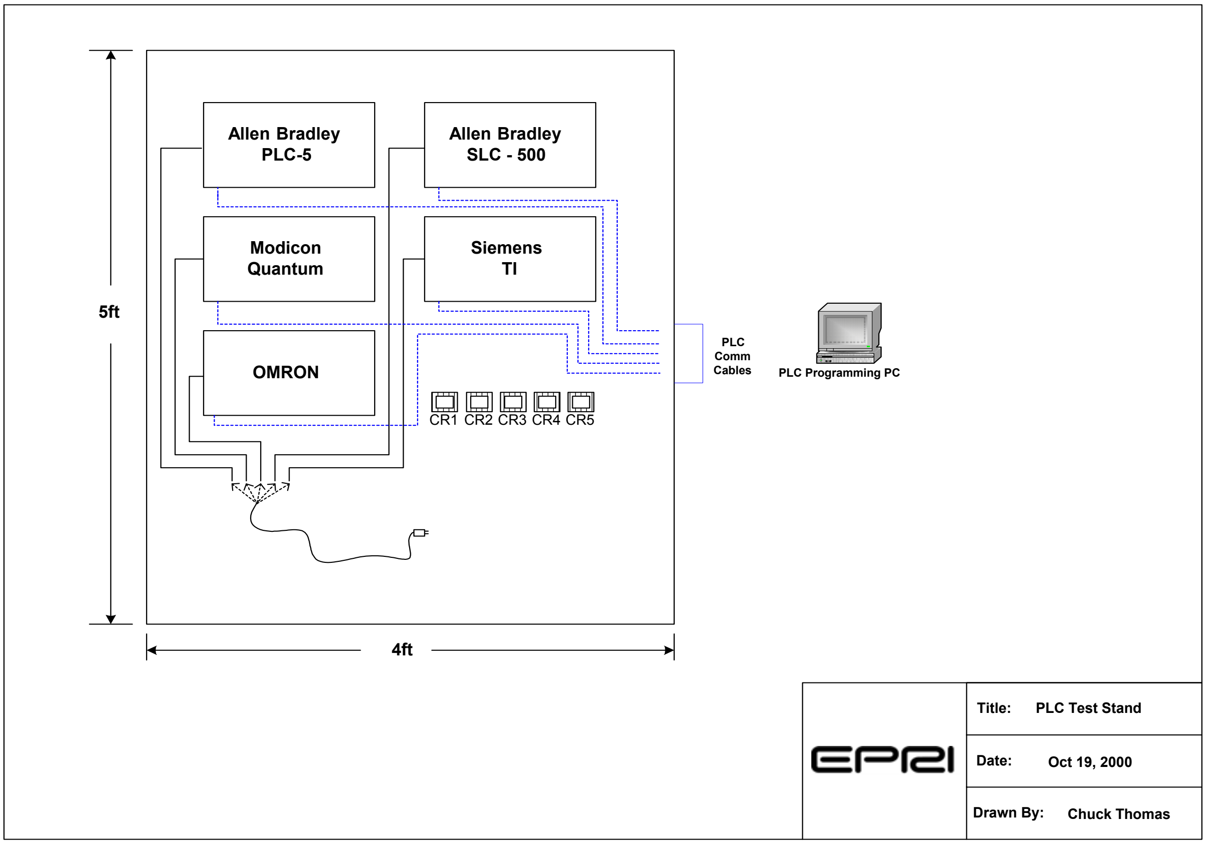


Figure A-1
PLC Test Stand Layout

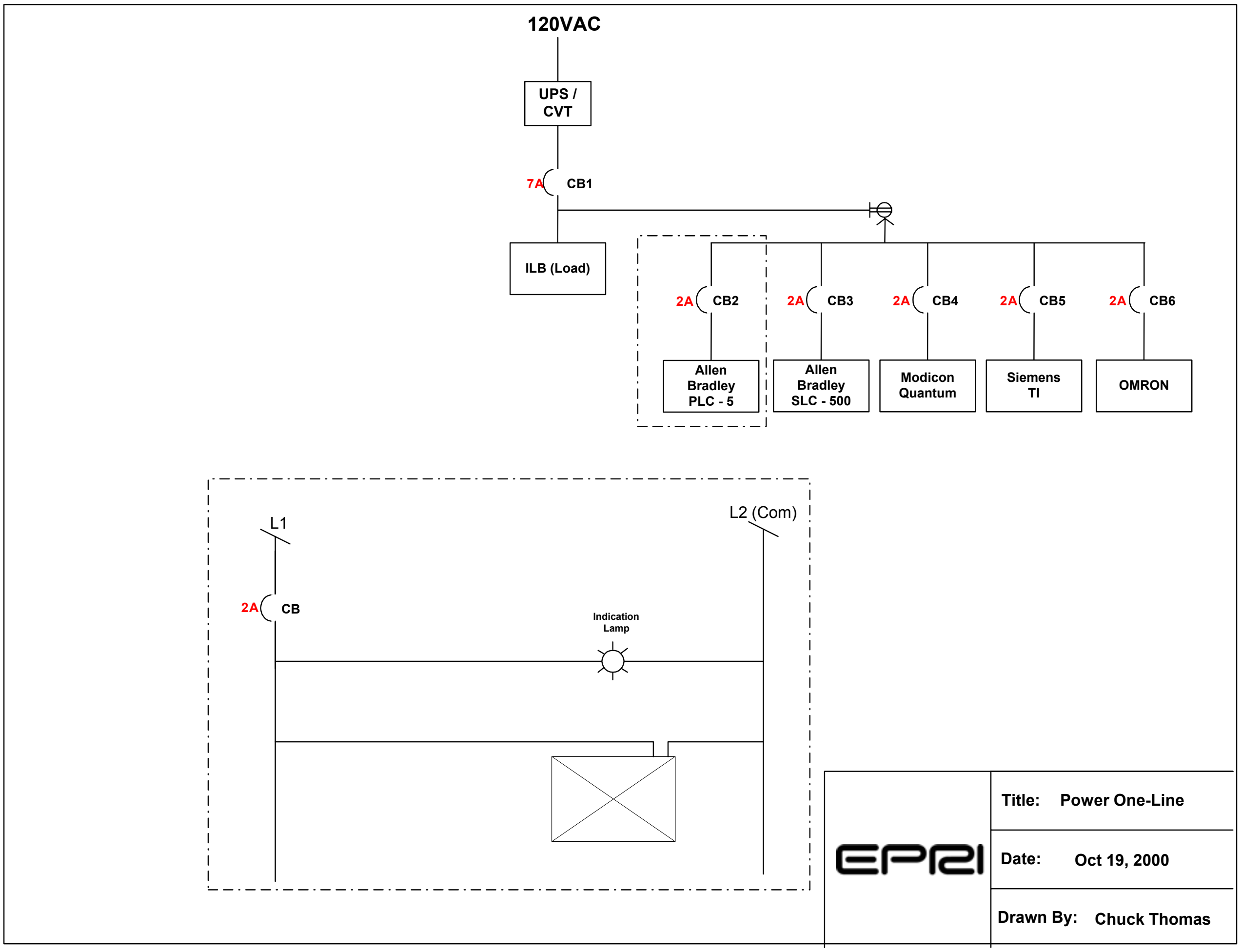


Figure A-2
PLC Test Stand Power One-Line Diagram

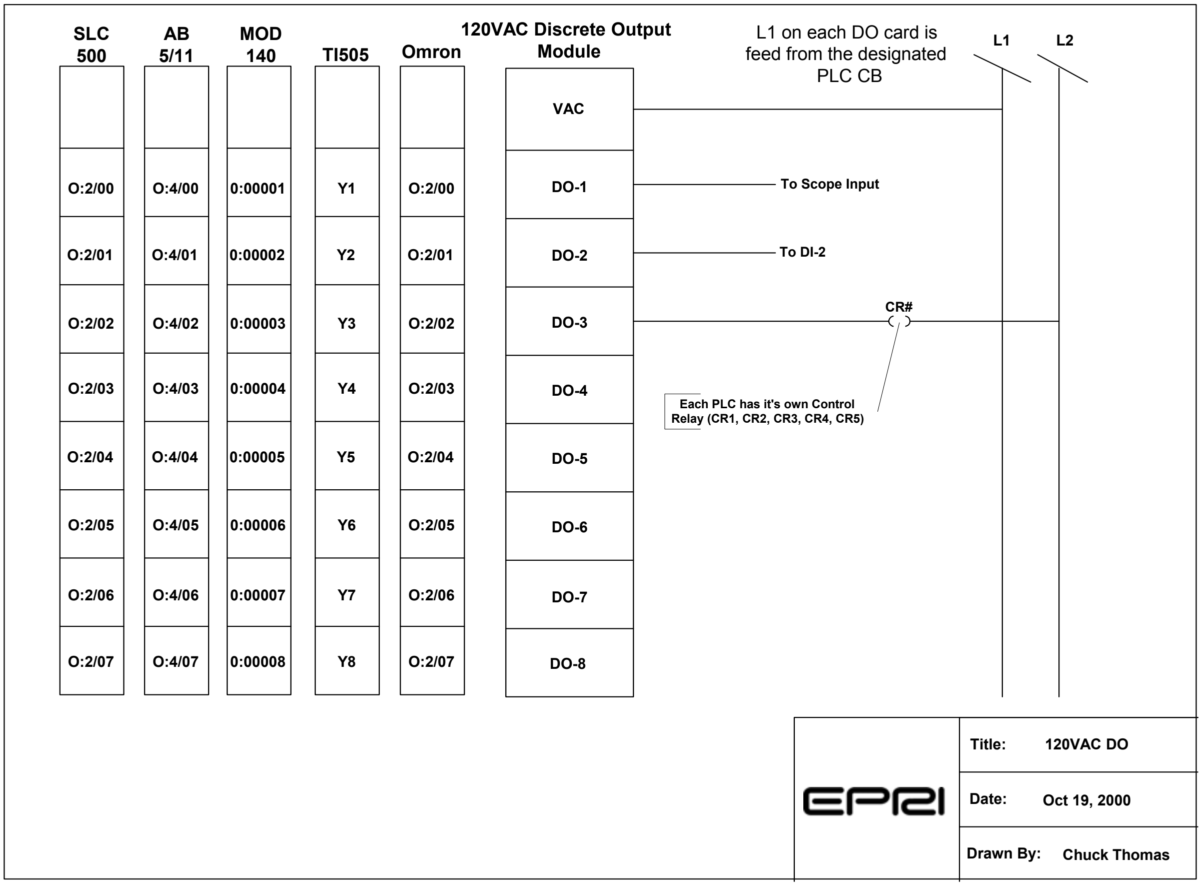


Figure A-3
PLC Test Stand 120Vac Digital Output Wiring

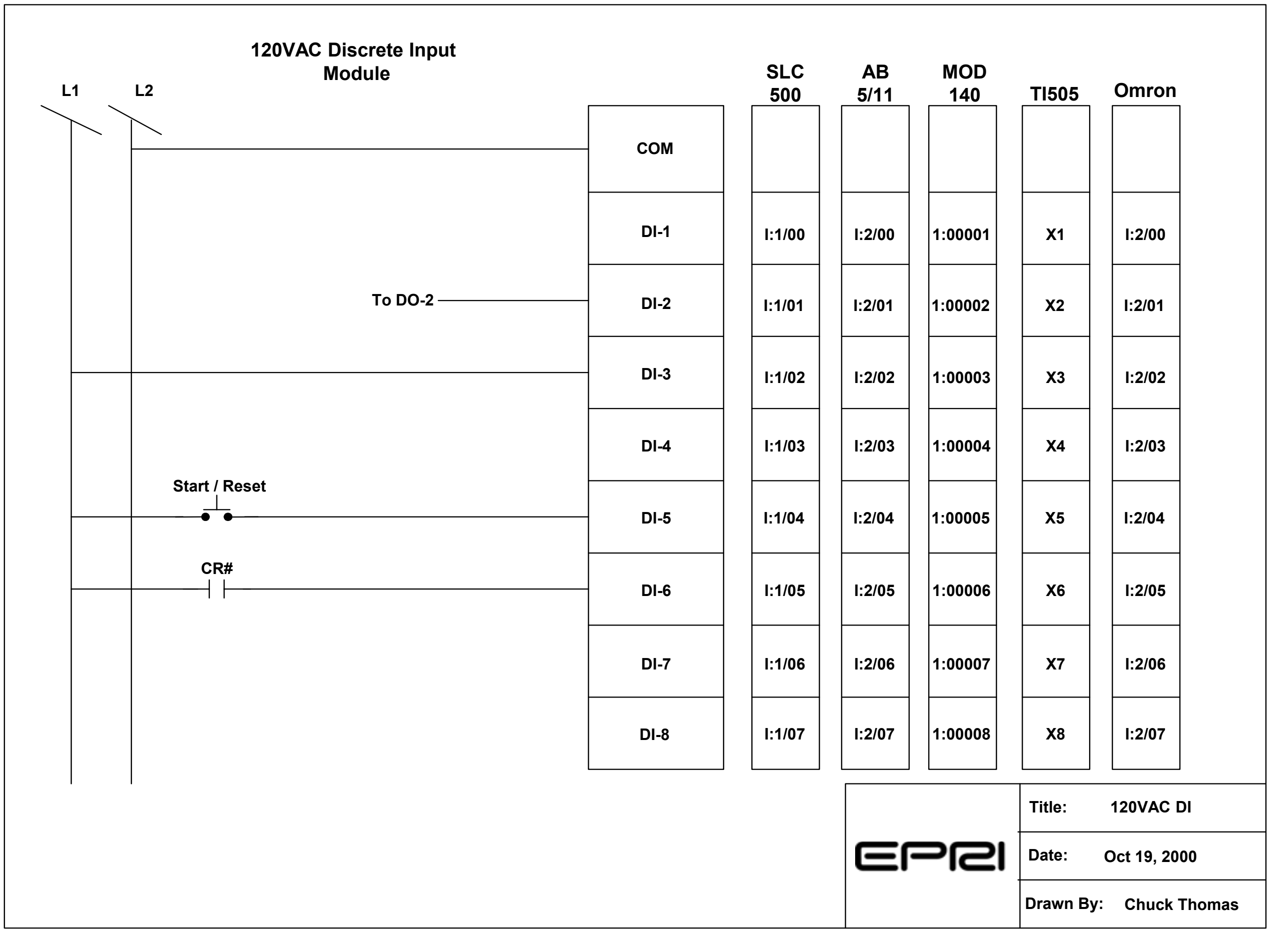


Figure A-4
PLC Test Stand 120Vac Digital Input Wiring

B
INDUSTRIAL LOAD BANK TEST FIXTURE

Industrial Load Bank (ILB) Test Fixture

The Industrial Load Bank (ILB) was originally created as a permanent fixture to demonstrate the voltage sag susceptibility of support typical control components such as Programmable Logic Controllers (PLCs), relays, contactors, and power supplies and to characterize the ability of single-phase power conditioners to improve immunity of these loads.

The ILB contains four general-purpose relays, five motor starters, seven contactors, and five DC power supplies (see Table B-1). As in many semiconductor circuits, two of the relays, and four of the contactors are powered by 24 Vac. The remaining power supplies, relays, and contactors are powered by 120 Vac. Power supply loads on the ILB includes those typically found in PCs, semiconductor tool controller I/O applications (power factor corrected, multiple ouput), and programmable logic controllers. Unregulated and regulated supplies were also included.

The 24 Vac source used in the ILB is derived by stepping down 120 Vac through a 250VA, 500VA, or 1KVA transformer. The transformer is selectable with a 3 position rotary switch on the control panel. The 1kva transformer was utilized for these tests since it exhibited a linear response.

Table B-1
ILB Load Components

Load	Name	Voltage (V)	Size	Description
1	CR1	120	10 A	DPDT Relay
2	CR2	120	10 A	DPDT Relay
3	CR3	24	10 A	DPDT Relay
4	CR4	24	5 A	DPDT Relay
5	MS1	120	2 HP @ 230 V	3-Pole Motor Starter
6	MS2	120	3 HP @ 230 V	3-Pole Motor Starter
7	MS3	120	3 HP @ 230 V	3-Pole Motor Starter
8	MS4	120	1.5 HP @ 230 V	3-Pole Motor Starter
9	MS5	120	30 HP @ 230 V	3-Pole Motor Starter
10	MC1	120	10 Amp	4-Pole Contactor
11	MC2	120	10 Amp	4-Pole Contactor
12	MC3	120	3 HP @ 230 V	3-Pole Contactor
13	MC4	24	7.5 HP @ 230 V	3-Pole Contactor
14	MC5	24	10 HP @ 230 V	3-Pole Contactor
15	MC6	24	7.5 HP @ 230 V	3-Pole Contactor
16	MC7	24	40 HP @ 230 V	3-Pole Contactor
17	PS1	120	60 W	PLC Power Supply
18	PS2	120	140 W	Instrument Power Supply
19	PS3	120	200 W	Computer Power Supply
20	PS4	120	500 W	Multi-Output Power Supply
21	PS5	120	40 W	Unregulated Power Supply

A simplified depiction of the ILB test setup is shown in Figure B-1. The ILB utilizes three small PLCs to perform data acquisition and monitoring of the status of the twenty-one test loads. Each test device has a dedicated input to the monitoring PLC that is connected across the contacts of each relay, contactor, and starter. If the device under test is energized, the PLC will see a 24 Vdc signal at the test devices dedicated input. If the contacts of the test device open during the sag event, the PLC will flash the corresponding indicator for the effected load, indicating that the device dropped out. There are two different methods of determining the state of the power supplies in the ILB. The output of each power supply is connected across the coil of a general-purpose relay and a potentiometer. The contacts of the relay are then connected to a dedicated input to the monitoring PLC. The potentiometer was adjusted so that the relay would drop out when the output of the DC power supply drops below 95% of its rated voltage. The second method of testing (the method used for this testing) is to connect the input of a PRTES or other metering device to the monitoring jacks on the outside of the panel corresponding the power supply in test as shown in Figure B-2. The monitoring jacks are connected across the output of the power supplies.

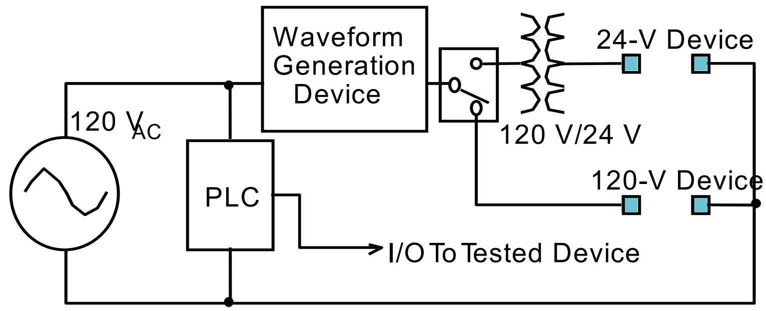


Figure B-1
Simplified ILB Test Setup

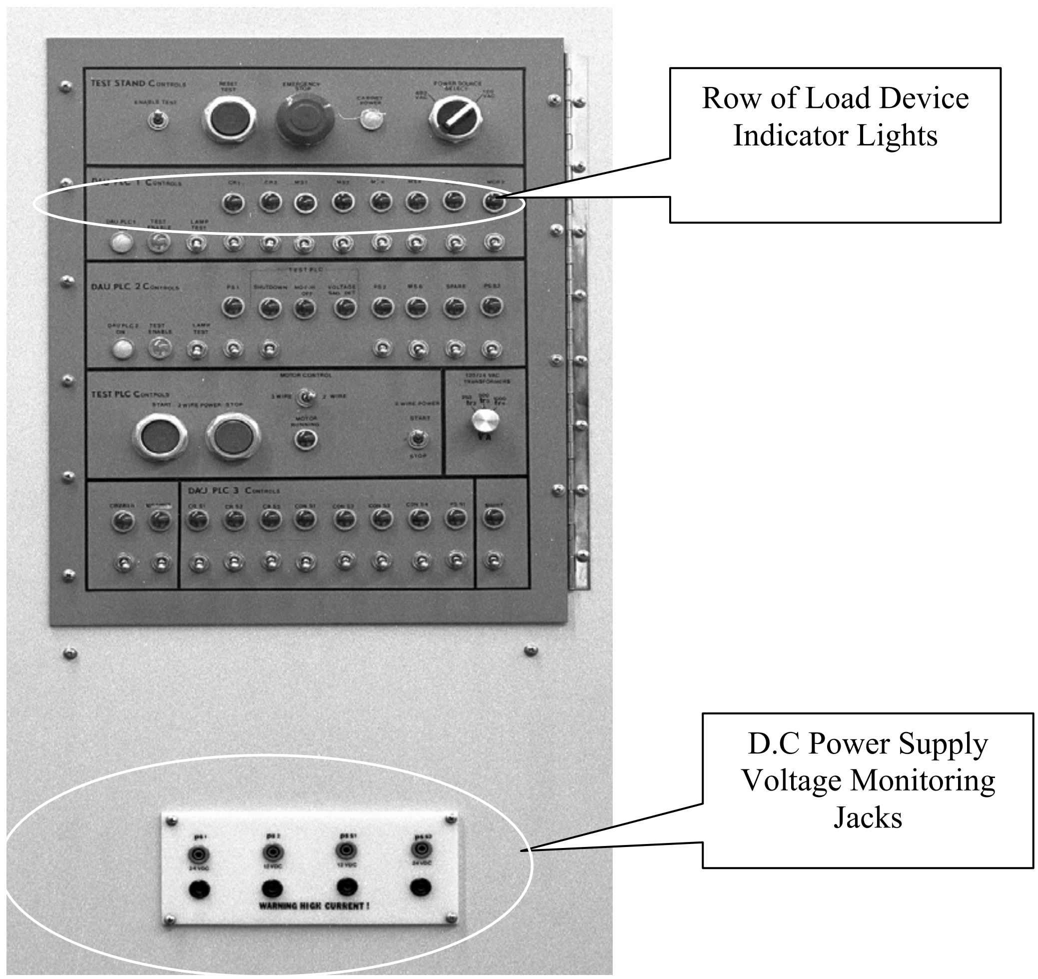


Figure B-2
ILB Control Panel

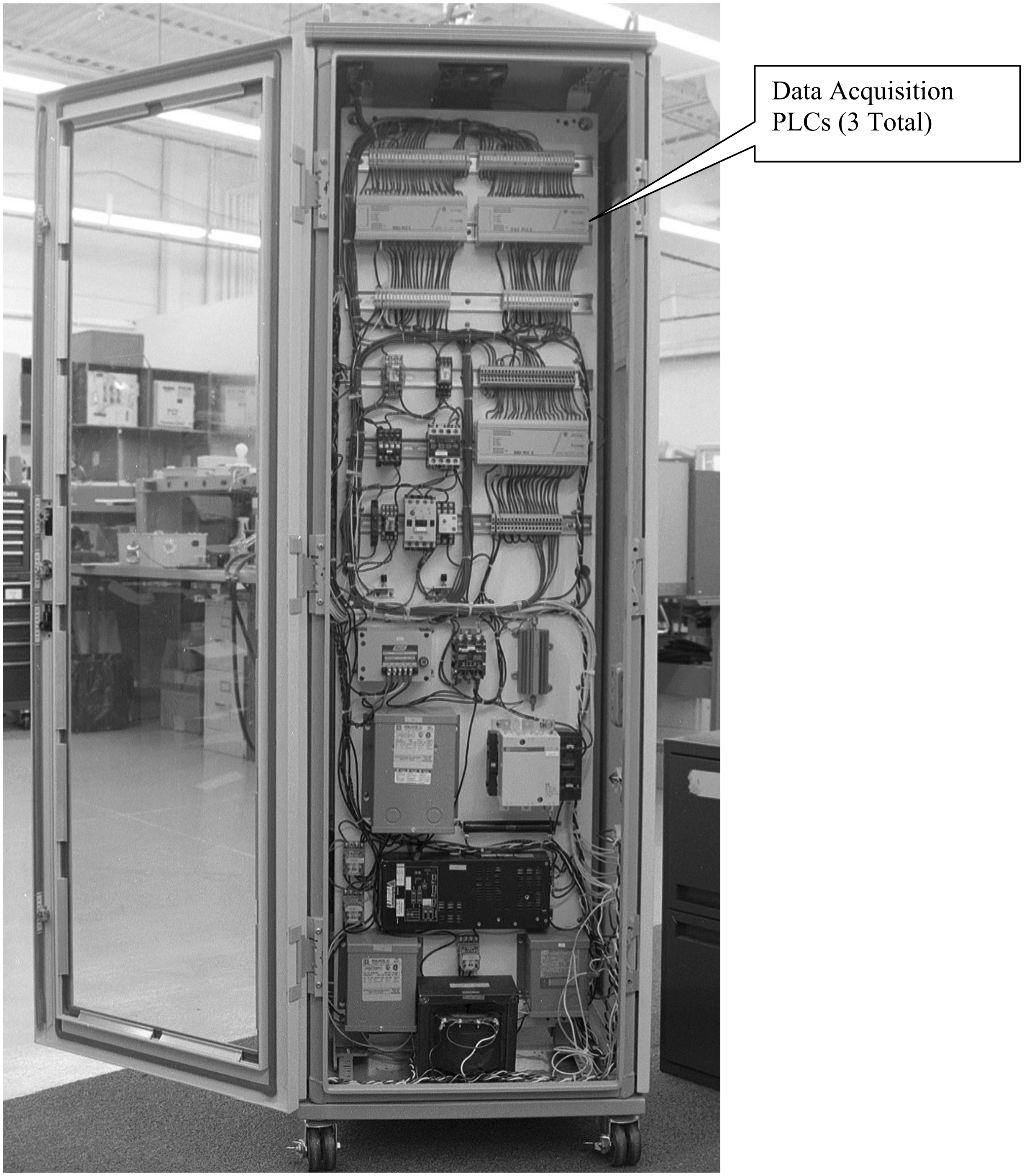


Figure B-3
ILB Component Side A

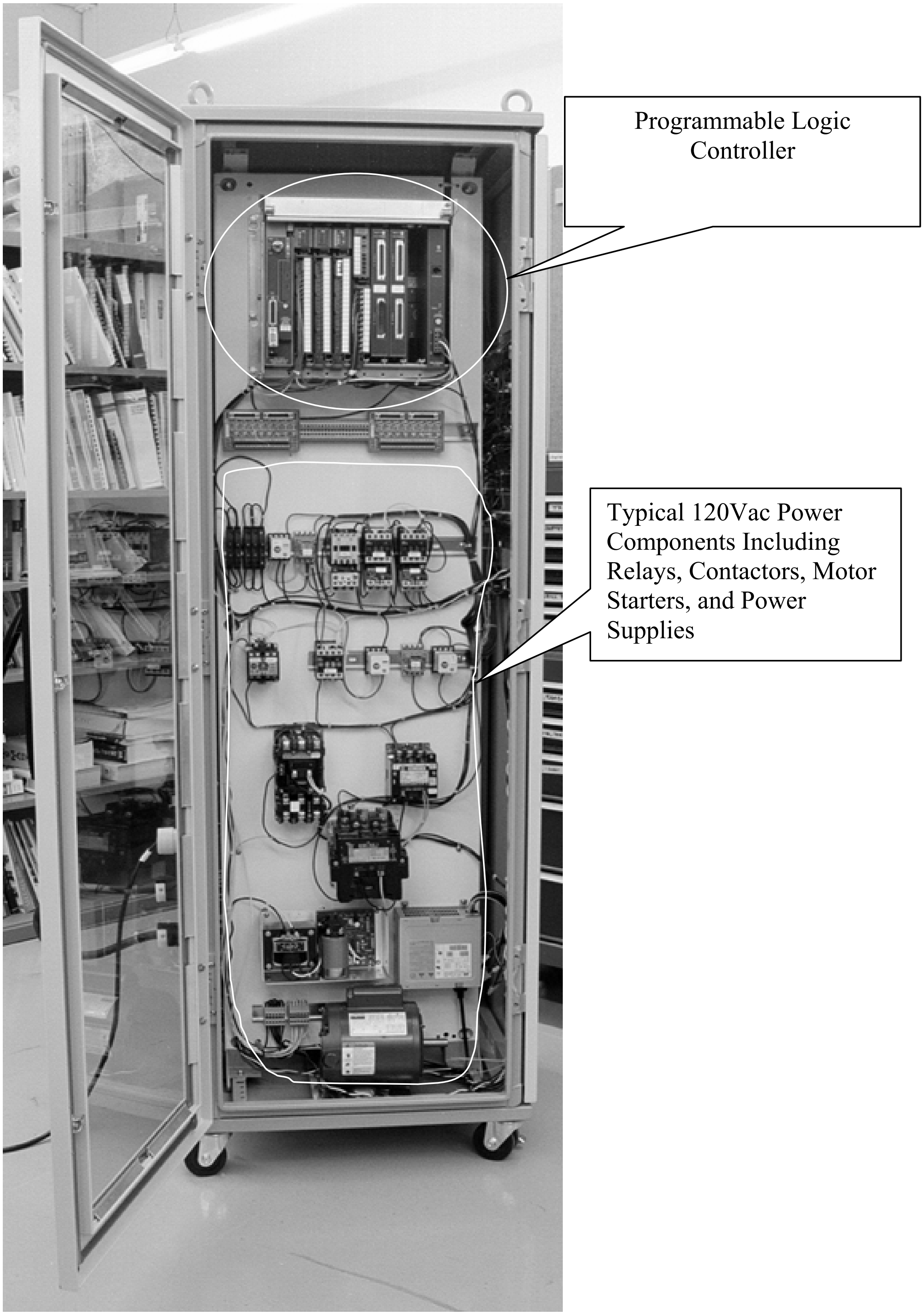


Figure B-4
ILB Component Side B

C
PQ TEST ALGORITHM

PQ Test Algorithm

General

This section describes the physical I/O wiring and algorithm that will be used to evaluate the performance of the PLC systems. The I/O wiring for the each part of the program is shown in Appendix A.

Connection Requirements

For proper operation of the PQ Test Algorithm, the PLC I/O must be properly connected. Because the actual connections required by each manufacturer may be slightly different, the wiring information presented in this section will be general in nature. The connection diagrams for the stand-alone PLC tests are shown in Appendix A.

Algorithm Description

The PQ test algorithm is described in a pseudo code format in the following section. A rudimentary knowledge of computer programming and PLCs will be helpful in understanding this section of logic.

Program Section DO-1

This part of the program will hold Output 1 on as long as the PLC is in the RUN mode. This signal will indicate if the Processor and I/O are still functioning during a PQ disturbance. Discrete Output 1 will be monitored by an oscilloscope input.

Pseudo Code:

```
IF Processor is in the RUN mode THEN
                    Discrete Output 1 = ON
ELSE
                    Discrete Output 1 = OFF
ENDIF
```

Program Section TP-1

This part of the program produces a square wave that can be measured with an oscilloscope as an indication of the PLC's throughput time. The resulting throughput consistency can be measured during a PQ disturbance as an indication of the PLC's response. This test requires that Discrete Output 2 be physically wired to drive Discrete Input 2.

Pseudo Code:

```
IF Processor is in the RUN mode THEN
        IF Discrete Input 2 is off, THEN
                Discrete Output 2 = ON
         ELSE
                Discrete Output 2= OFF
        ENDIF
ENDIF
```

Program Section DI-3

This section of the program is used to see if the PLC detects a Logic 0 from a field input that will be tied to a 120 VAC voltage that will undergo PQ disturbance. If a Logic 0 is detected, then the PLC will latch in an output to indicate the condition. The I/O wiring for this section of the program will require that Discrete Input 3 be tied to a 120 VAC voltage source that will undergo PQ disturbances. Since the status of Discrete Output 3 can be seen by viewing the output LED indicator, no external wiring to this point will be required.

Pseudo Code:

```
IF Processor is in the RUN mode THEN
        IF Discrete Input 3 = OFF THEN
                Latch Discrete Output 3 (turn ON)
        ENDIF
ELSE
        Unlatch Discrete Output 3 (turn OFF)
ENDIF
```

Program Section DO-4

The purpose of this section of the program is to latch in a control relay through the PLC logic once an external pushbutton is pressed. If the relay chatters or opens during a voltage disturbance, the PLC is expected to drop the relay depending on the scan rate, throughput time, and depth of the voltage sag event.

Pseudo Code:

```
IF Processor is in the RUN mode THEN
        IF Discrete Input 5 = ON (Pushbutton) or Discrete Input 6 = ON (Relay Contact) THEN
                Latch Discrete Output 4 (turn ON Control Relay)
ELSE
        Unlatch Discrete Output 3 (turn OFF)
ENDIF
```

D
PLC COMPONENTS LIST

Modifier (PLC-x)	Manufacturer	Series	Photo	Description	Part Number
A	**OMRON**	SYSMAC		PLC Processor Module	CVM1-CPU21-EV2
				10 Slot Rack	CV500-BC101
				PS 221, 120VAC Power Supply	CV500-PS221
				IA121, 120VAC 16 Channel Input Module	C500-IA121
				OA222, 120VAC 16 Channel Output Module	C500-OA222
B	**Siemens**	SIMATIC		TI545 PLC Processor Module	545-1101
				Power Supply Module	505-6660A
				110VAC 32 Channel Input Module	505-4232
				24-110VAC 32 Channel Output Module	505-4616
C	**Modicon**	Quantum		PLC Processor Module	CPU 113 02
				115/230VAC Power Supply	CPS 111 00
				115VAC 32 Channel Input Module	DAI 543 00
				115VAC 32 Channel Output Module	DAO 842 10
D	**Allen Bradley**	PLC 5 w/1771 I/O		PLC 5/11 PLC Processor Module	1785-L11B/E
				120VAC Power Supply	1771-P4S
				120V AC/DC 16 Channel Input Module	1771-IAD/D
				10-134 VAC 16 Channel Output Module	1771-OAD/C
E	**Allen Bradley**	SLC 500 w/ 1746 I/O		SLC 5/03 PLC Processor Module	1747-L532
				Power Supply Module	1746-P1
				4 Slot Chassis	1746-A4
				115VAC 16 Channel Input Module	1746-IA16
				115VAC 16 Channel TRIAC Output Module	1746-OA16

E
RELEVANT PQTN PUBLICATIONS

Application Note 5 “Sizing Single-Phase Uninterruptible Power Supplies”

Application Note 10 “Sizing Constant-Voltage Transformers to Maximize Voltage Regulation for Process Control Devices”

PQTN APPLICATION
Power Conditioning
Uninterruptible Power Supplies
Sizing Power Conditioners
Power Quality Testing Network
Published by the EPRI Power Electronics Applications Center Application No. 5 September 1995

Sizing Single-Phase Uninterruptible Power Supplies

Application

Traditionally, the uninterruptible power supply, or UPS, has been used to protect critical computing and data processing equipment. However, in recent years the UPS has been applied to everything from industrial process controllers to telephone switches to medical equipment. Because the loads supplied by a UPS can be either linear or nonlinear, be cycling or non-cycling, and have various levels of inrush current, sizing a UPS to match its load is not a simple task. This PQTN Application provides a method of sizing a single-phase UPS to match its intended loads.

What To Look For

Most loads have inrush currents that may be up to twenty times their steady-state currents. Therefore, the size of the UPS relative to its load is one of the most important considerations when specifying a UPS. Additionally, some loads such as laser printers and medical laboratory equipment can have intermittently operated heater elements or other internal devices that cycle on and off. If start-up and cycling effects are not addressed during the initial load analysis, an undersized UPS may be specified, resulting in load dropouts.

How To Size a UPS

The three main types of single-phase UPS are the standby, line-interactive, and rectifier/charger. Each type has a "normal ac line" operation mode and a "battery-power" operation mode. As discussed in the next section, the various features of the three types can complicate the sizing of a UPS. UPSs are often sized by adding the nameplate current of each load and then multiplying the total current by the UPS output voltage to yield a VA rating required to support the loads. However, this method is unreliable because nameplate current values can be inaccurate or missing and do not include inrush and cycling currents. To precisely determine the power demands of a load, its input current must be monitored during normal operation, including start-up and cycling. This *measurement method* for sizing a UPS considers steady-state, inrush, and cycling currents.

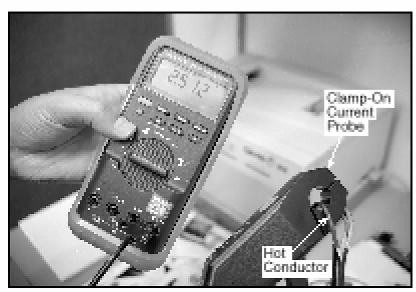
Sizing a UPS: The Measurement Method

Step 1 Get the proper measurement device (either an ammeter or a multimeter). For this procedure, use only a true RMS meter with "peak hold" detection circuitry. The use of "peak detection" RMS calibrated meters or "average responding" RMS calibrated meters will result in erroneous current and voltage readings if harmonics are present.

Step 2 Set the meter to measure the steady-state ac RMS current of each load to be connected to the UPS. Steady-state current is the current drawn by the load over a long period. For example, a computer draws steady-state current any time it is on. A laser printer draws steady-state current when it is on but idle. Steady-state current should not be measured when a load cycles (heater elements of a printer turn on) or when it is first turned on (inrush current). Enter all steady-state current measurements into the UPS Sizing Worksheet.

Step 3 Make sure the load is turned off. Then, set the meter to record maximum peak ac current (not RMS current). Turn the load on and let it operate for one hour. Be certain that the load has performed its main functions during that hour. For instance, make sure that a printer has printed several pages or control relays are all on. The meter will record the highest peak current drawn by the load. Enter all peak current measurements into the Worksheet.

Step 4 Fill out the rest of the Worksheet. Add all the steady-state currents together and then add the single highest peak current of the loads to get the total current requirement. The size of the UPS should be at least the total current times



To measure current, use a "cheater cord" with the three individually insulated conductors exposed. A clamp-on current probe attached to a true RMS meter can be used to measure the current flowing through the hot conductor (brown or black insulation).

PQTN APPLICATION No. 5

Inrush Issues

UPS Type	*Inrush Notes*	*Options*
Standby	Typically handles high inrush.	Consult dealer or manufacturer.
Line-Interactive with Ferro-Resonant Transformer	Output voltage may sag during high inrush.	Oversize this type or add inrush-limiting thermistors to the UPS output.
Line-Interactive without Ferro-Resonant Transformer	Typically handles high inrush.	Consult dealer or manufacturer.
Rectifier/Charger	Output voltage may sag during high inrush.	Oversize this type, get this type with an auto-bypass feature, or add inrush-limiting thermistors to the UPS output.

the UPS output voltage (VA). If the UPS is intended to support more than one cycling load or you anticipate that some or all of the loads will be turned on at the same time, then the size of the UPS may have to be increased, depending upon the type of UPS. For instance, line-interactive UPSs with ferro-resonant transformers must be sized properly to support high inrush current, as must rectifier/charger UPSs. However, nearly all standby and some line-interactive UPSs will support inrush currents beyond their rated capacity because they are normally connected to the utility power (see "Inrush Issues," above). In fact, you may be able to size those same UPSs by multiplying only the steady-state current total by the UPS output voltage. But ask the UPS dealer or manufacturer to verify that the UPS can handle high momentary inrush currents.

Once you have completed the UPS Sizing Worksheet, you may still need the advice of a UPS dealer or manufacturer. Although the Worksheet yields a good estimate for UPS size, it does not factor in UPS type and features. If you are sizing a UPS for unique loads, such as blood analyzers or mass spectrometers, consult the UPS manufacturer, who will have size recommendations for those particular loads. Additionally, line or source impedances vary and can affect inrush currents, so the measurement method of sizing a UPS may not apply if the measured loads and the UPS are going to be used in a different location.

BENEFITS

- Save time and money by installing the right size of UPS.
- Ensure UPS reliability by selecting the right type and features for the job.

WHERE TO FIND HELP

- UPS dealers and manufacturers
- Your local utility

ACKNOWLEDGMENTS

PEAC thanks the sponsors of Task 9 of the EPRI System Compatibility Research Project: Uninterruptible Power Supplies.

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UPS Sizing Worksheet

UPS Loads To Be Protected	*Measured Steady-State RMS Current*	*Measured Peak Current Over One Hour*

Sum of Steady-State RMS Current ________

Highest Peak Current of All Loads + ________ ← Bring down highest peak current.

Total Current ________

Output Voltage Required by Loads x ________

Required VA Rating of UPS ________

 TA-105721

PQTN
Power Quality Testing Network

APPLICATION

Power Conditioning
Constant-Voltage Transformers
Sizing Power Conditioners

Published by the EPRI Power Electronics Applications Center   Application No. 10   October 1997

Sizing Constant-Voltage Transformers to Maximize Voltage Regulation for Process Control Devices

Application

The constant-voltage transformer (CVT) is a popular power conditioner for mitigating the effects of voltage sags on industrial and commercial equipment (see Figure 1). A CVT can maintain a relatively constant output voltage despite harmonic distortion or brief variations in input voltage. In fact, if sized properly, a CVT can regulate its output voltage during a voltage sag to sixty percent of nominal voltage for virtually any duration, as shown in Figure 2. However, they are not effective during momentary voltage interruptions or extremely deep voltage sags (generally below fifty percent of nominal).

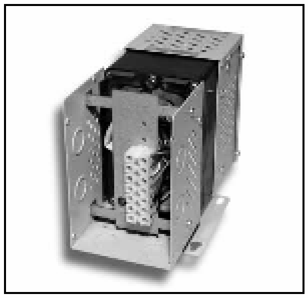

Figure 1. A constant-voltage transformer, also called a ferro-resonant transformer, regulates its output voltage without switching to an alternate power source, such as batteries.

CVTs are often favored over other sag-mitigation devices because they are relatively maintenance-free, with no batteries to replace or moving parts to maintain. They are particularly applicable to industrial-process control devices such as programmable logic controllers, motor starter coils, and the electronic control circuits of adjustable-speed drives—although loads with active power-factor correction must be connected to CVTs with caution (see PQTN Brief No. 15). CVTs are often used to sustain the logic voltage or critical "hold-up" functions of these loads during voltage sags. This PQTN Application provides a method for sizing a CVT to match its intended loads.

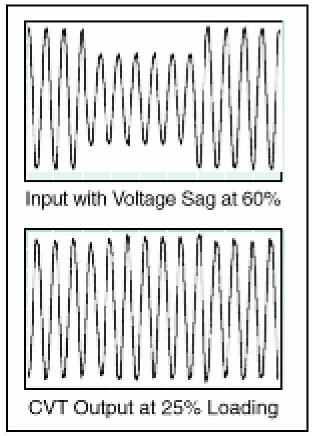

Figure 2. During a voltage sag to sixty percent of the nominal voltage, a properly sized CVT regulates its output voltage within the requirements of connected loads.

What To Look For

Because the type of loads connected to a single CVT may range widely, the startup and steady-state operational characteristics of each load must be well understood before deciding on the appropriate power rating of a CVT. Most industrial loads, whether a starter or contactor coil, a switch-mode power supply, or even a light bulb, will have an inrush current that may be up to twenty times the steady-state current normally drawn by that load. A load draws inrush current when it is first turned on or when it cycles on and off during normal process operation. If a CVT is sized without considering the inrush currents of all connected loads, the CVT may be inadequately sized for the inrush current. Thus, during the startup or cycling of a connected load, the CVT output voltage may sag, causing other sensitive loads on the output to shut down.

How To Size a CVT

The ability of a CVT to regulate its output voltage is generally based upon two characteristics of the connected loads, both of which are related to current and both of which must be determined to properly size a CVT. First, you must determine the amount of steady-state current drawn by all connected loads during their normal operation. As shown in Figure 3 (page 2), the lower the ratio between the actual current drawn by the connected loads and the rated current of the CVT, the better a CVT can regulate its output voltage. For example, a 1-kVA CVT loaded to 1 kVA will not mitigate voltage sags nearly as well as the same CVT loaded to 500 VA, and performance is even better if the same 1-kVA

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CVT is only loaded to 250 VA. Moreover, according to results of CVT testing at PEAC, a CVT rated at less than 500 VA may not be able to handle even moderate inrush current. Therefore, a minimum CVT rating of 500 VA is recommended.

The second characteristic of a CVT load is its inrush current. Values for inrush current and steady-state current of the connected loads will enable you to effectively size a CVT. Follow the procedure below to obtain the current characteristics of each circuit or load to be connected to the CVT.

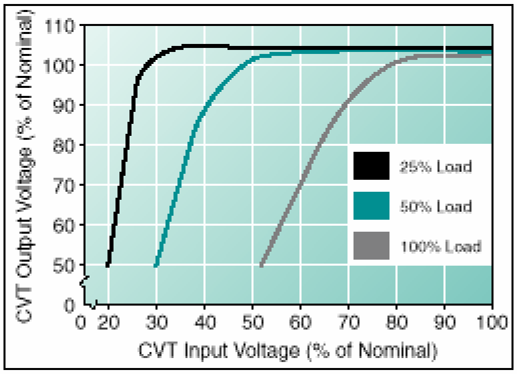


Figure 3. As the CVT load increases, the ability of the CVT to regulate its output voltage decreases.

Step 1: Identify the Loads Identify the circuit connections of each load to be connected to the CVT and locate an accessible point to measure load and circuit current.

Step 2: Select the Right Meter Because most of the equipment used in industrial control operations do not have easily obtainable nameplate data, a true RMS ammeter (or multimeter) is required to accurately estimate the current draw of loads to be connected to a CVT. Additionally, the meter must be able to capture transient peak current to measure inrush current (see "Tutorial: Inrush Current Measurement" on page 3). Powerline monitors and oscilloscopes with a waveform-capture function will also accurately estimate current draw. However, avoid using RMS calibrated meters or "average responding" RMS calibrated meters, which will result in erroneous current readings for a load that draws non-sinusoidal currents.

Step 3: Measure the Maximum Steady-State Current Set the meter to measure the maximum steady-state AC RMS current of each circuit to be connected to the CVT. Steady-state current is the current drawn by a load over a long period. For example, a programmable logic controller and a starter coil connected to the same circuit draw steady-state current any time they are on, but the starter coil may be on only a portion of the process cycle. Therefore, make sure that all loads in the circuit to be measured are in their normal operating state before measuring the circuit current. Steady-state current should not be measured when a load cycles (turns on or off automatically) or when it is first turned on and draws an inrush of current. If any loads on the circuit to be measured turn on and off automatically, then set the meter to record the maximum steady-state RMS current during a complete process cycle. Using either the current-probe method described in Figure 4 or by connecting your meter in series with the line conductor, measure the maximum steady-state current of each load and enter the values into the CVT Sizing Worksheet on the back of this PQTN Application. The sum of all steady-state currents you record should give you a clear indication of the worst case steady-state current demand on the CVT.

Figure 4. To eliminate the need to break a circuit during current measurements, measure current with a clamp-on current probe attached to a true RMS meter by clamping onto the hot conductor of a load or circuit.

Step 4: Measure the Inrush Current Make sure that all loads to be connected to the CVT are turned off and have been in the off position for at least one minute. This will ensure that any power-supply capacitors—which may hold energy for a short time after a load is turned off—have discharged. Set the meter to record maximum peak AC current over a one-millisecond period, not over a 100-millisecond period. With the meter set in a "record and hold" mode, manually turn on and off each load to be connected to the CVT at least eight times, leaving the load off for one minute in between each measurement. Such repeated measurements are necessary to increase the chances of capturing the highest inrush current of the load, which occurs close to the peak of the input-voltage sine wave. Turning on and off some loads may be difficult, but this step is critical to properly sizing a CVT. Enter the highest recorded peak current measurement for each load into the CVT Sizing Worksheet.

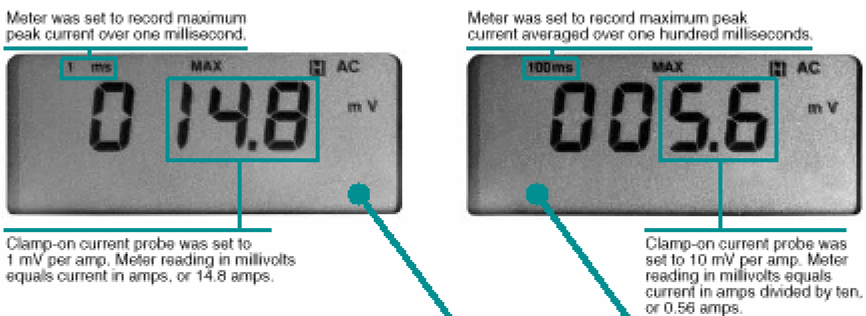
Step 5: Size the CVT Add together all the steady-state currents in the Worksheet and then multiply the resulting value by the circuit voltage to get the com-

Tutorial: Inrush Current Measurement

To accurately measure the inrush current of any equipment, an ammeter must be able to capture the maximum transient peak current over a period of less than one half cycle. However, many hand-held meters detect a series of current peaks and display the average over 100 milliseconds, or about six cycles, which will lead to a gross underestimate of inrush current for most industrial control devices. The 100-millisecond measurement of peak current is used specifically to determine the inrush current caused by starting a motor, which is not an instantaneous event. For loads that have energy-storage capacitors, such as a computer or a programmable logic controller, the inrush current can be as high as twenty times the steady-state current during the first half cycle of capacitor charging. Then, the current quickly decreases to steady-state levels. To accurately measure the inrush current of a process-control load, the meter must capture the peak of the inrush during the first cycle, not over a 100-millisecond period.

To determine the difference between the one-millisecond and 100-millisecond measurement methods, PEAC engineers took three types of measurements of the eight different loads shown in the table below: 1) steady-state current, 2) inrush current with the meter set at maximum current over one millisecond, and 3) inrush current with the meter set at maximum current averaged over 100 milliseconds. As shown in the table, the one-millisecond method yielded measurements about eleven times higher (on average) than the 100-millisecond measurements. For example, in the first measurement set, the meter recorded a peak inrush current of 14.8 amps for a programmable logic controller when the meter was set on one millisecond. However, when the meter was set on 100 milliseconds, the measurement was significantly lower—only 0.56 amps. If a CVT were sized for an inrush current of only 0.56 amps, it could not support the inrush current of the programmable logic controller.

The peak currents of all the process loads in the table were measured ten times for each load. The programmable logic controller, for example, had a range of peak-current measurements from 4.0 to 14.8 amps. Here's why: The amount of peak inrush current depends upon the angle of the input voltage at the moment the load is turned on. The closer the input voltage is to the zero crossing, the lower the inrush current. The maximum peak inrush current of the programmable logic controller occurred near the peak of the input-voltage sine wave, whereas the minimum peak inrush current (4.0 amps) occurred near the zero crossing. Therefore, taking many peak-current measurements of a single load is critical for predicting the maximum peak inrush current of that load.



Device	*Steady-State Current (Amps)*	***Peak Current (Amps, 1 ms)***	***Peak Current (Amps, 100 ms)***
Programmable Logic Controller	0.16	14.8	0.56
Programmable Logic Controller	0.36	10.8	0.72
±5-Volt, 12-Volt Power Supply	1.57	29.1	1.84
24-Volt Power Supply	1.29	14.4	1.84
NEMA Size 3 Motor Starter	0.43	9.9	1.52
NEMA Size 0 Motor Starter	0.13	3.1	0.30
Ice Cube Relay	0.05	0.2	0.10
Master Control Relay	0.09	1.8	0.10

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bined steady-state VA of all CVT loads. Then, select the highest peak inrush current measurement and multiply this value by the circuit voltage to get the worst-case inrush VA of all loads. For optimum regulation during input-voltage sags, the VA rating of the CVT should be at least 2.5 times the steady-state VA calculated in the Worksheet. For example, if the steady-state VA calculation is 200 VA, then the recommended size of the CVT would be 500 VA or more. For good sag regulation of the CVT output voltage during load starting or cycling, the VA rating of the CVT should be at least half of the maximum inrush VA calculated in the Worksheet. For example, if the maximum inrush VA is 2.4 kVA, then the optimum size of the CVT would be 1.2 kVA or more. Size the CVT based upon the larger of the two VA-rating calculations in the Worksheet (Steady-State Load VA or Inrush Load VA). A CVT can be specified and ordered by either a VA rating or a current rating.

Step 6: Verify CVT Performance After installing the CVT, verify its performance by powering all connected loads and running a complete process operation. If the CVT has been correctly sized for steady-state and inrush currents, the process will continuously operate.

The size of a CVT determined by using the CVT Sizing Worksheet may seem rather large compared to the VA rating of the connected loads. However, the enhanced sag tolerance of process control devices will likely pay for the cost of the CVT over time by reducing down-time, loss of production, and scrapped material otherwise caused by voltage sags.

BENEFITS

- Save time and money by reducing the number of process interruptions caused by voltage sags.
- Ensure the reliable operation of a CVT by considering both steady-state and inrush currents.

WHERE TO FIND HELP

- CVT dealers and manufacturers
- Your local electric utility

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For ordering information,
call PEAC (423) 974-8288.

CVT Sizing Worksheet (Recommended Minimum Size: 500 VA)

CVT Circuit or Load	*Measured Steady-State RMS Current*	*Measured Peak Inrush Current*

Sum of Steady-State RMS Currents		______		
Circuit Voltage	x	______		
Steady-State Load VA	=	______	x 2.5 =	☐
Highest Peak Inrush Current		______		Use the larger of these two values.
Circuit Voltage	x	______		
Inrush Load VA	=	______	x 0.5 =	☐

 TA-109233

F

GUIDELINES FOR IMPROVING THE VOLTAGE SAG PERFORMANCE OF PROGRAMMABLE LOGIC CONTROLLERS

Audience: PLC System Integrators and Industrial End-Users

Purpose: To help PLC System Integrators and Industrial End-Users make their PLC systems more robust to common voltage sag events.

Abstract: Originally invented in the late 1960's to replace relay logic in automotive manufacturing, today's Programmable Logic Controllers (PLCs) have evolved into sophisticated computers that are used in all manufacturing sectors and are capable of performing repetitive operations with a high degree of accuracy. In contrast to its infant counterpart, the PLC of today handles both analog (continuous) and discrete (on/off) control functions with ease. With these advances in mind, industrial manufacturers increasingly are using these systems to replace antiquated schemes to increase efficiency, productivity, and reliability. However, the susceptibility of PLC-based control systems to voltage sags is one of the main reasons that many industrial processes shut down and revenue is lost. This paper addresses the voltage sag issues related to PLC systems and proposes guidelines to both integrators and end-users that will make these industrial control systems more robust.

Introduction: The electrical upgrade of the green carbon facility at the aluminum plant was complete. A new state-of-the-art system utilizing a myriad of PLCs and PC-based Graphic User Interface (GUI) systems now replaced the hardwired system that had been installed in the 1960s. The plant manager proudly watched the GUI screens as the fully automated system performed batching, mixing, and conveying operations faster than ever, with little operator intervention. After $10 million had been spent on the cutover from hardwired relay control to the new PLC-based system, the change was finally complete. It was a new day for the plant. Then it happened. The lights blinked in the facility, an event that occurred at least twice a month. A minor voltage sag to 75 percent of nominal, lasting only 5 cycles, had occurred on the utility grid. Although it rarely affected the old hardwired system, the humming of the conveyors, crushers, mixers, and batching system stopped. As the operators began to scramble to restart the automatic operations, confusion rained as the batch-weighing system seemed no longer to know how much of each ingredient was in the hopper and how much more needed to be added. Stopping at different points in their respective mix sequences, the PLC no longer knew how long the 10 batch mixers needed to continue operations to complete their cycles. The plant manager's face reddened with anger as he contemplated the cost of the new system and the reliability of the old scheme. The operators' confusion turned to frustration as they realized that the batch in the weigh hopper would have to be scrapped because the automation system had lost track of the contents.

Events like this happen today in many facilities that employ PLC systems in their control schemes. Untold millions of dollars are lost when PLC-based control systems are upset by voltage sag events. However, these systems can be made much more robust to voltage sag phenomenon with proper electrical and software design techniques. This paper explores the problems that exist in PLC-based control systems and the solutions for making PLCs more robust to voltage sags.

The Voltage Sag

To begin to understand why PLCs are susceptible to voltage sags, it is important to understand the voltage sag. Industrial manufacturers almost always incorrectly assume all events that affect electrical equipment are “power surges” since the shutdown may have occurred during a lightning event. Although overvoltage conditions (known as voltage swells and surges) can occur, EPRI research has confirmed that short duration reductions in voltage (voltage sags) lead to the most frequent complaints from industrial customers. These events typically occur when a line-to-ground fault has occurred on the utility grid instigated by weather, trees, or animals. The depth of the event that is seen by the industrial customer is determined by the magnitude of the fault current, stiffness of the grid, and how close the customer’s facility is to the site of the fault. The duration of the event is related to the breaker-clearing time on the utility system. Typically described in terms of magnitude and duration (see Figure F-1), voltage sag events can affect the operation of sensitive production equipment leading to shutdown, malfunctions, lost product, and diminished revenue. When a voltage sag results in equipment shutdown or malfunction during normal power system operation, the equipment is said to be incompatible with its electrical environment, or to have poor system compatibility.

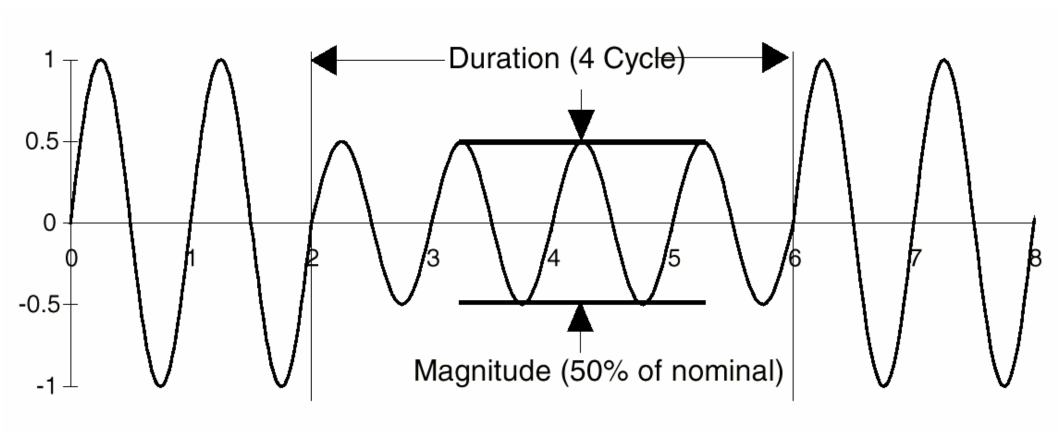


Figure F-1
Voltage Sags are Described by Magnitude and Duration

Typical voltage sag durations range from 4 to 30 cycles depending on whether the facility is fed from the transmission system (i.e., 69kV or161kV), which is somewhat stiff, or a distribution system (i.e., 13.8kV or 34.5kV), which typically cannot supply as much fault current. The EPRI Distribution Power Quality (DPQ) study found that voltage sags are 10 times more likely to occur than outages and the average depth of a voltage sag is 75 percent of nominal.

PLC Basics and Voltage Sag Susceptibilities

Figure F-2 shows a typical PLC I/O rack including a power supply, CPU, discrete input and output modules, and analog input and output modules. A discussion of each of these parts, as well as the power quality considerations, is warranted.

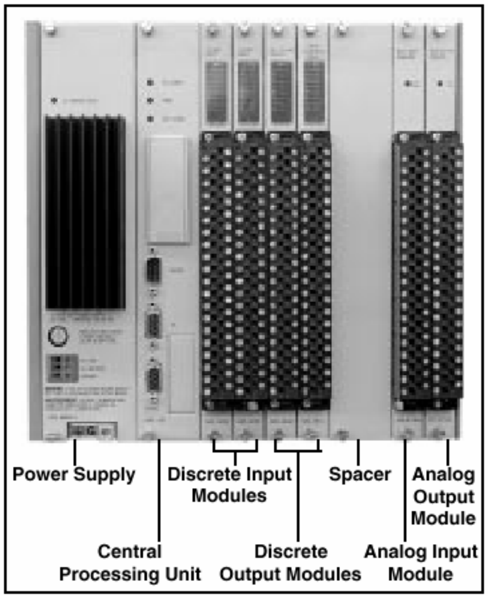


Figure F-2
Typical PLC System

PLC I/O Rack Power Supply. Utilizing the typical switch-mode power supply topology, the PLC power supply can be either a pillar of power quality robustness in these systems or the Achilles heel. Although available for both AC and DC input power sources, the most commonly procured units utilize an AC input source of 120/230Vac. Small in relative power output, the PLC power supply usually produces from 40 to 80 watts DC for use across the I/O rack back plane. The purpose of the unit is to supply DC power to all devices physically mounted in the PLC rack. These devices may include the PLC CPU and communications module(s), as well as discrete and analog I/O modules. It is important to note that, typically, the PLC power supply does not provide power to field devices such as sensors, transmitters, motor starters, and solenoids. Some PLC manufacturers may utilize the power supply to provide an analog output signal for control valve and drive interfacing. Others require an additional external power supply for these functions.

Because of the potential danger that might result from a malfunctioning PLC system, most PLC power supplies also perform continuous diagnostics for line voltages that are outside the tolerance envelope or hardware failure. If a serious problem is detected, the power supply will notify the CPU to halt program execution in order to shut down process operations. Figure F-3 displays the general topology of a PLC power supply.

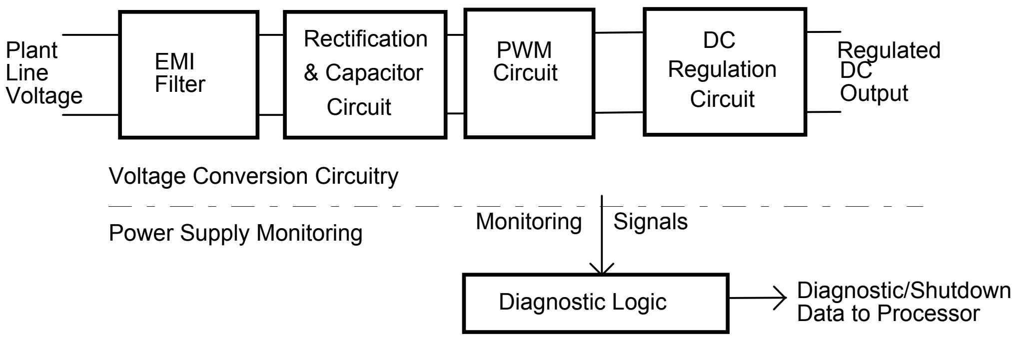


Figure F-3
Typical PLC Power Supply Topology

PLC manufacturers monitor either the level of the incoming AC plant line voltage or the level of the power supply DC output to decide when to shutdown during voltage sag events. The leading U.S. PLC manufacturer's power supply literature states the following about their voltage sag shutdown philosophy:

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

It is also interesting to note that other product lines from the same manufacturer base the shut down of the PLC on the DC output. Since a DC power supply can inherently store energy in the power supply capacitors, sensing the DC level rather than the incoming AC line voltage can lead to improved system compatibility.

PLC I/O Power Quality Issues. PLC Inputs and Outputs (I/O) can be grouped into four main categories. Namely, these are Discrete Inputs (DI), Discrete Outputs (DO), Analog Inputs (AI), and Analog Outputs (AO).

Discrete Inputs. Discrete Input Modules are available for AC or DC sensor types. Discrete Inputs include on/off status signals from pushbuttons, selector switches, motor starter auxiliary contacts, and relay contacts, as well as process sensor inputs such as pressure, flow, proximity, or zero speed. Typical wiring examples for AC and DC Discrete Input modules as well as typical field devices such as a proximity switch and pushbutton station are shown in Figure F-4.

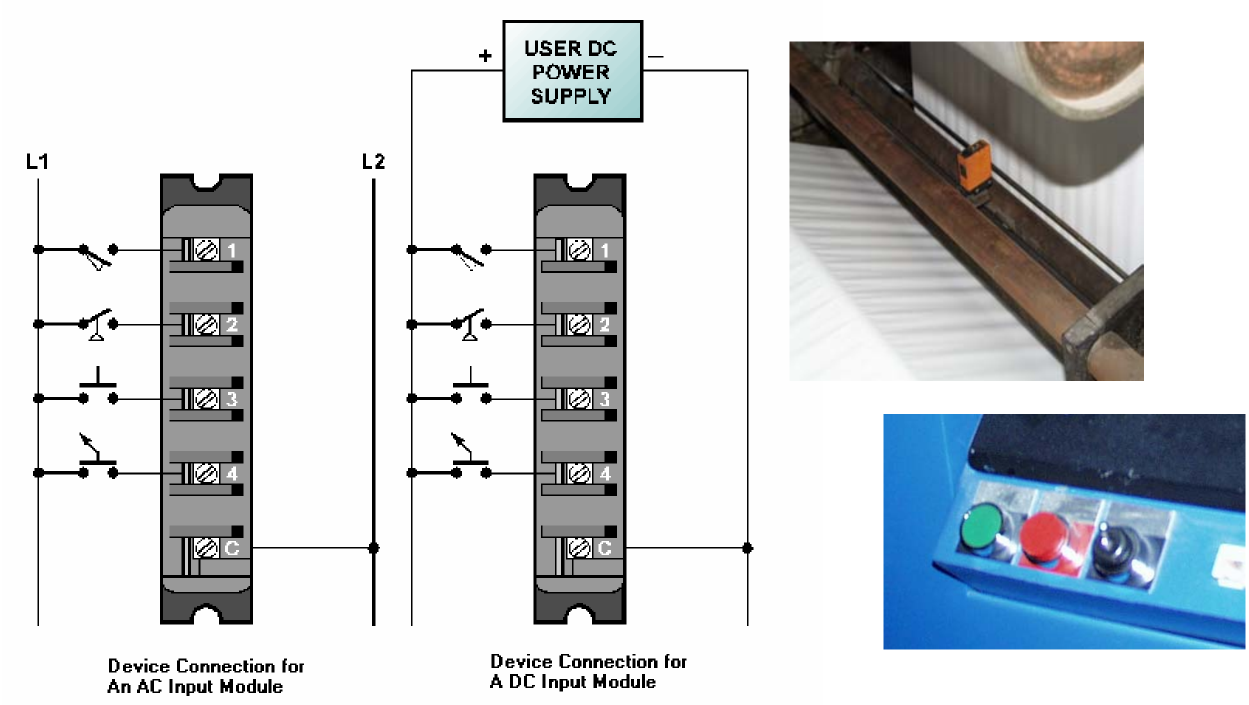


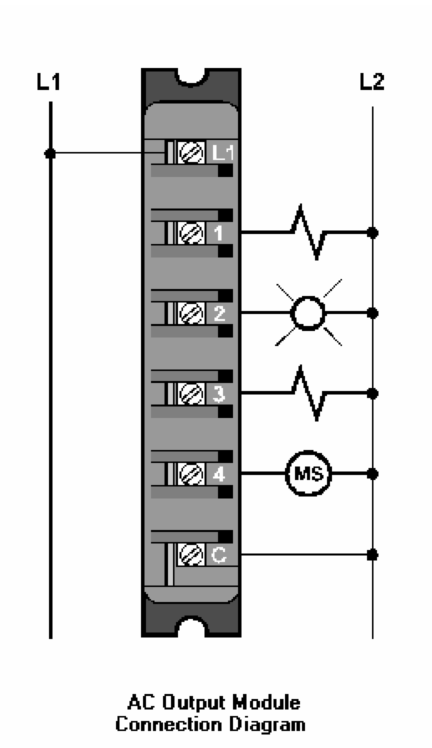
Figure F-4
Typical AC and DC Discrete Input Module Wiring and Field Devices

The susceptibility of the Discrete Input module to voltage sags is only relevant if the PLC power supply has not already led to a system shutdown. Since DI modules are designed to react quickly to detect an input status change, they can also react quickly when a voltage sag event occurs. The common response times for AC inputs to detect a transition from "on" to "off" can be as short as 11 milliseconds which is less than one cycle. For DC inputs, response to input status changes of as little as 4 milliseconds (1/4 cycle) is possible. Once the PLC DI module has sensed a real or perceived change in the status of the input, the PLC program will react. Since the effects of the voltage sag may translate directly to lower voltages at the input terminals of the module, the control system may misinterpret an "on" condition to actually be an "off" condition. Such **false negative** conditions from a process sensor can lead to the malfunction or immediate shutdown of the process.

In the case of AC input modules, the voltage sag immediately passes to the input terminals of the module. In the case of DC discrete input modules, the external DC power supply can act to filter a voltage sag such that the output power to the sensors may not be affected. The ability of the DC power supply to provide this "embedded" mitigation to voltage sags is dependent on the topology, sizing, load, and input voltage. If the DC power supply is unregulated, virtually no stored energy will be present to mitigate the voltage sag. However, if the power supply is robust, the input sensor signals will also be robust to voltage sags.

<u>Discrete Outputs</u>. Available in AC or DC types, Discrete Output modules act to switch the on/off voltage signal to field devices such as motor starters, relays, solenoids, and pilot lights. The susceptibility of the discrete output module is directly related to the PLC power supply shutdown signal as well as the susceptibility of the individual loads connected to the module. Since the

discrete output module simply acts as a switch to the individual loads, in itself it has little ability to affect the voltage sag response of the system. If the PLC decides to shut down as a result of a voltage sag, all discrete output signals typically will drop unless it is specially configured on the I/O rack. Most end users do not opt to allow the outputs to stay powered in this state since such a condition may lead to safety and machine damage issues. A typical AC discrete output module and motor starter are shown in Figure F-5.



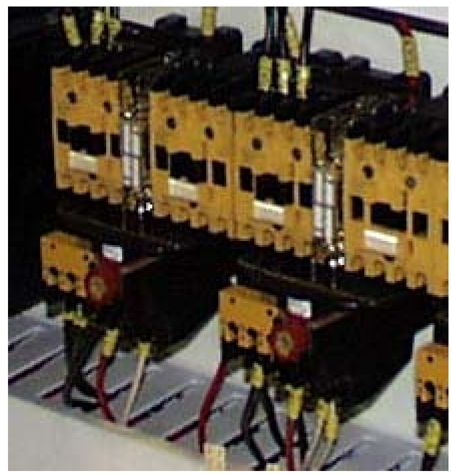


Figure F-5
AC Discrete Output Module and Typical Motor Starter Field Devices

In the case where the PLC power supply is robust to voltage sags, and the field devices, such as motor starters and relays, are susceptible to voltage sags, the process may still malfunction or shut down. To ensure that all outputs are robust, the most comprehensive approach is to ensure that the control power voltage source is robust. The system integrator can do this by conditioning the power source in an AC system or by using a robust DC power supply and DC output module, which in turn would require the use of DC-powered field devices such as motor starters, relays, and solenoids.

Analog Inputs. Utilizing DC signal ranges such as 4 to 20 milliamps, 1 to 5 volts, or 0 to 10 volts, analog input modules receive a continuous DC current or voltage signal from process transmitters. DC power supplies are required to source the voltage or current loops for the analog input signals. Therefore, the voltage sag susceptibility of the analog input module and the process transmitters is related to the ability of the external DC power supply to ride-through. Two basic configurations for process transmitters are known as “two-wire” and “four-wire,” each of which leads to power quality considerations. A “two-wire” process transmitter (see Figure F-6) is powered by an external DC power supply. This same supply may provide DC power for all transmitters in the system or control cabinet. With a single source of DC power, the analog input signals can be made robust to voltage sags if the DC supply is robust. With the "four-wire" transmitter topology (Figure F-7), an external AC voltage source is needed to power the transmitter. In this configuration, the transmitter provides the continuous DC signal to the individual channel on the analog input card. In this case, the required DC power supply is located within the transmitter itself. For these reasons, one must consider the voltage sag robustness of the AC power source for each of the "four-wire" transmitters in the process.

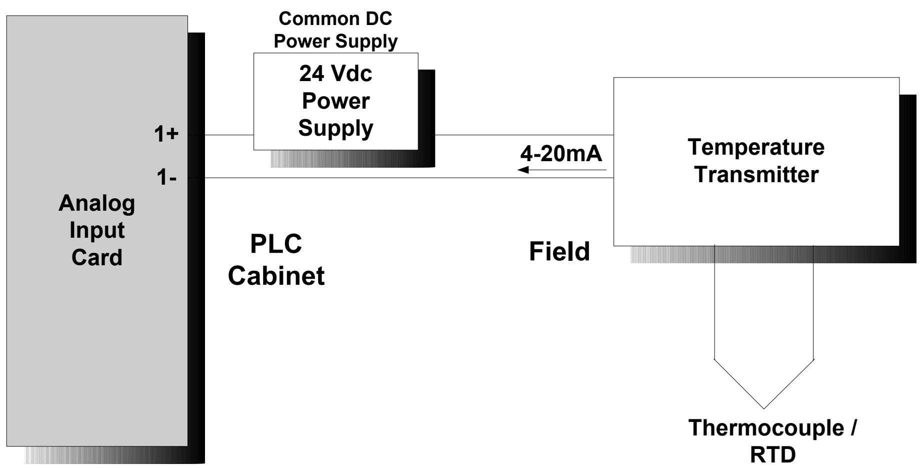


Figure F-6
A Two-Wire Transmitter is Powered by an External DC Power Supply

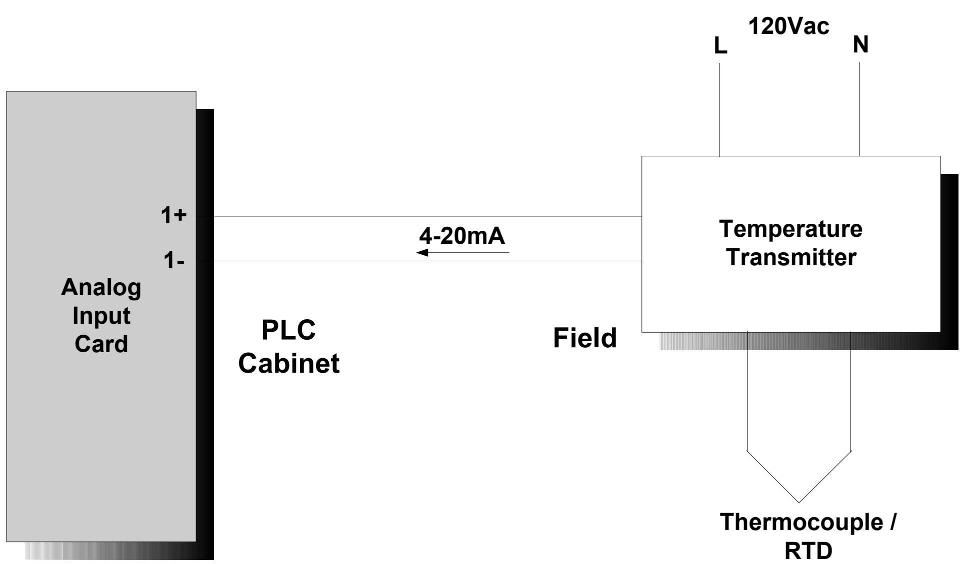


Figure F-7
A Four-Wire Transmitter Requires an External AC Source

Analog Outputs. Analog output modules provide a continuous DC voltage or current signal to field devices. Examples of analog output control loops include position control of a proportional valve or the speed control of a motor through an AC or DC adjustable speed drive (ASD).

Depending on the manufacturer and module type, analog output signals can be sourced by the PLC power supply through the I/O rack back plane or by an external DC supply. Therefore, the stability of the output signal to the field device is dependent on the robustness of the DC voltage source. Tests have indicated that, when sourced by the PLC power supply, the PLC will normally shut down before the DC output voltage and integrity of the control signal is affected. When the PLC shutdown occurs, the analog signal is removed from the field device, which will directly affect the position of a valve or the speed of a motor. In the case were an external DC power supply is required to source the analog output current loop, the robustness of the power supply to voltage sags may directly affect the control of the process.

PLC CPU Module and Programming Considerations

The Central Processing Unit (CPU) module. This device is the "brains" of the PLC. Usually occupying a single slot in the PLC rack, the CPU module (also referred to as the Processor) holds the control program in Random Access Memory (RAM). The CPU module receives operating power through the I/O rack back plane via the rack's power supply. The I/O Rack back plane also contains a data bus for communications between the PLC and rack I/O. A lithium battery and/or Electrically Erasable Programmable Read Only Memory (EEPROM) typically are used to maintain the PLC program in the event of loss of power.

The CPU reads the input data table information, solves the control program, and updates the output data table. In addition, the PLC will perform "housekeeping" to check itself and other related PLC hardware components for faults and errors. A secondary microprocessor may be used to transfer data from the system inputs into the data table and from the data table to the system outputs. The typical timing loop for a typical PLC processor is shown in Figure F-8.

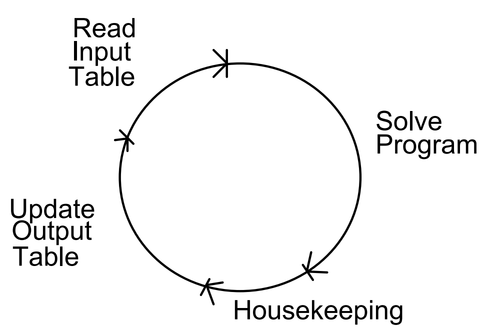


Figure F-8
Typical PLC Task Timing Loop

The time required for the PLC to read the inputs, solve the control program, and update the output table is known as the scan rate. This time can vary greatly depending on the CPU model, the size of the control program, and the architecture of the system. A more definitive measurement of PLC response is known as "throughput." Throughput is defined as the amount of time required to detect an input from the field device, solve the control program, and manipulate an output field device. The throughput time includes the scan time plus the amount of time it takes for the actual PLC module's electronics to detect, input, and switch the state of an output. Throughput measurements for PLCs can be as short as 17 milliseconds (approximately one 60Hz cycle) to several hundred milliseconds depending on the size of the control program and the number and speed of the I/O modules. With the ability to sense a state change and switch an output signal in such a short time, it is easy to understand why process upsets and shutdowns can occur as a result of voltage sags.

The Control Programming Techniques. The PLC control program may take various forms. The most basic and common control program format is Relay Ladder Logic (RLL). This control program format was created to model hardwired electrical relay logic and is subsequently very "user friendly" for maintenance electricians. An RLL PLC program will utilize conventional "seal-in" techniques that have been used in relays in the past. Other program formats commonly used today include Sequential Function Chart (SFC), BASIC, and C.

The method or technique that the PLC programmer uses to control process equipment is a potential cause for PLC system PQ immunity problems. For example, in process applications, the process step of a batch may be held in the PLC's memory by using a conventional "seal-in" technique in the ladder logic. If the PLC experiences a shutdown and restart as a result of a voltage sag, the process state of the batch likely will be cleared since the "seal-in" will be lost. As stated in the introduction, this may lead to the loss of the batch. A better technique is to write process step information into non-volatile memory areas that are not cleared when the PLC shuts down and restarts. By placing a process step number into a non-volatile memory location, the PLC can then, with proper coding, know where to resume process operations. This approach, which is known as the state-machine method, can be a powerful ally in helping to restart a control system when a voltage sag or outage-related upset occurs.

Voltage Sag Test Results

EPRI PEAC Corporation conducted voltage sag tests on five common PLCs in a laboratory environment. The tests were funded by the California Energy Commission (CEC) to establish PLC baseline performance and to help establish guidelines for improving system compatibility. These test results were complementary to similar PLC tests conducted in 1995 by EPRI. The five PLCs, referred to as PLC A, B, C, D, and E, were subjected to voltage sags in a test setup using a portable sag generator with and without power conditioning in place. The test setup included additional relays, power supplies, and motor starters to make the total load of the system reach a target of 2 amps.

To characterize the operation of the PLCs during a power quality disturbance, a PQ Test Algorithm was programmed into each PLC. The program in each PLC monitored the status of various AC input module channels and also controlled the status of various AC output channels. A general-purpose control relay was wired to an AC output module channel and the status of the relay was monitored by an AC input module channel. Furthermore, the PLC program was written to provide the latching logic to hold the output relay on once the appropriate input was received. Programmed in this manner, if the relay "chattered" or momentarily opened as a result of the voltage sag and the input channel detected the opening of the relay, the program latch was set to drop the output module signal to the relay. This condition was recorded as a **System Failure** since such an event could easily upset an automated process. On the other hand, if the PLC power supply was found to cause a shutdown as a result of a voltage sag, this was noted as a **CPU Failure** since all automatic sequences came to a halt.

Voltage Sag Test Results without Power Conditioning. The voltage sag test results without power conditioning for the five PLCs are shown in Figures F-9 through F-13.

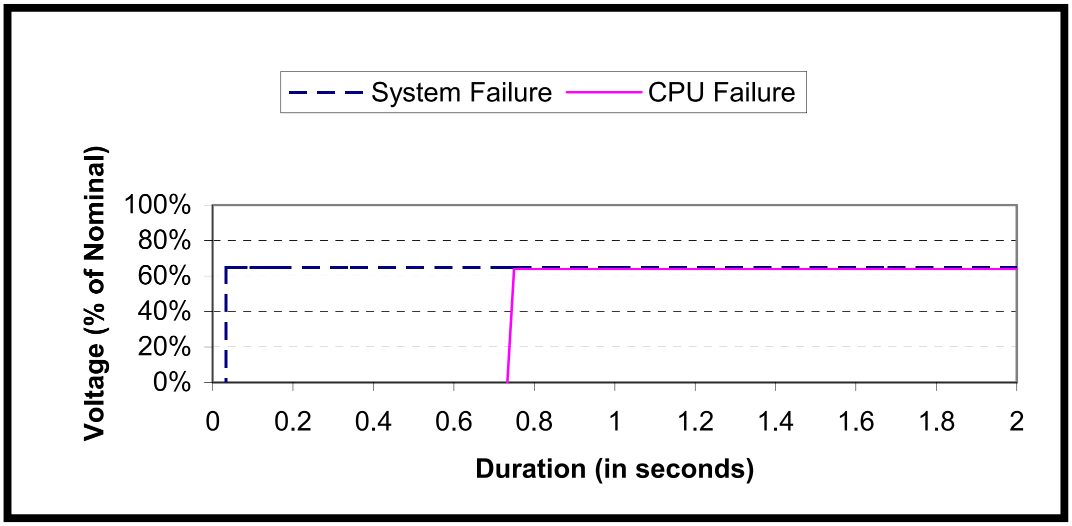


Figure F-9
PLC A VOLTAGE SAG RIDE-THROUGH

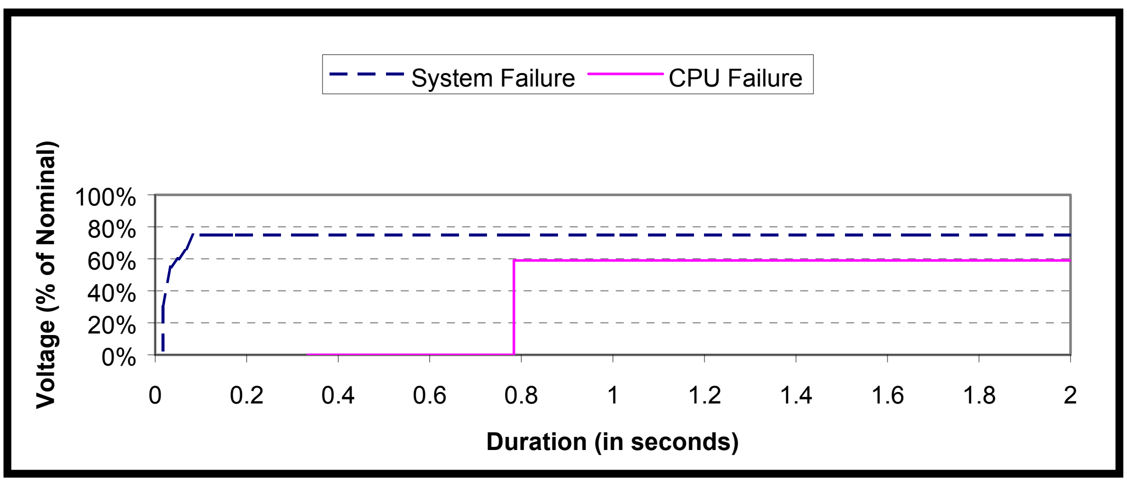


Figure F-10
PLC B Voltage Sag Ride-Through

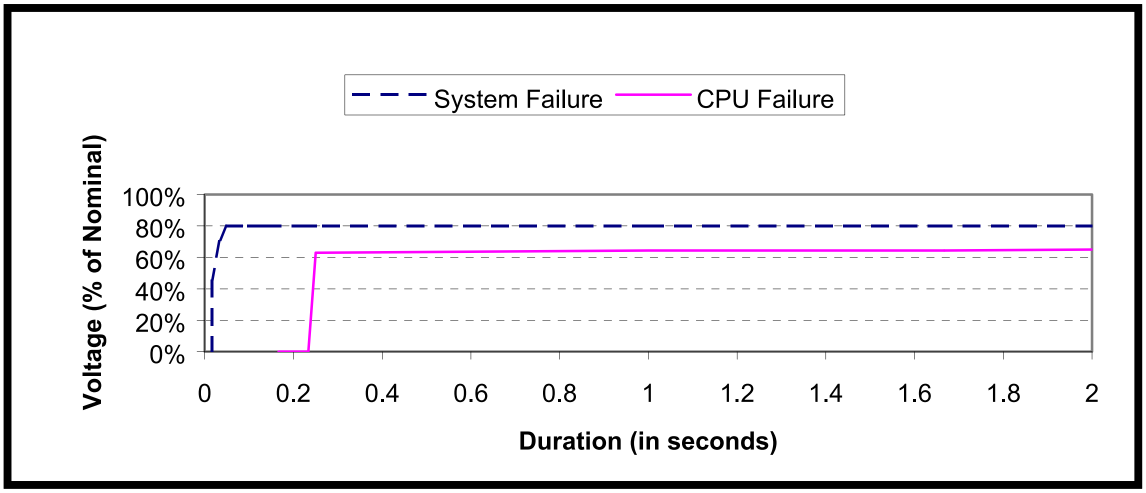


Figure F-11
PLC C Voltage Sag Ride-Through

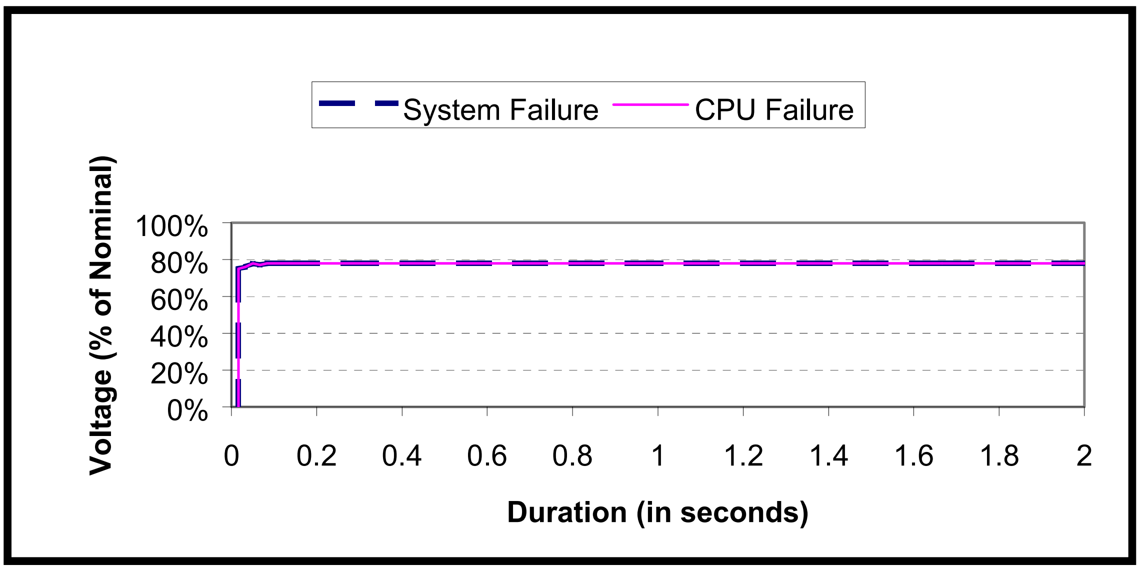


Figure F-12
PLC D Voltage Sag Ride-Through

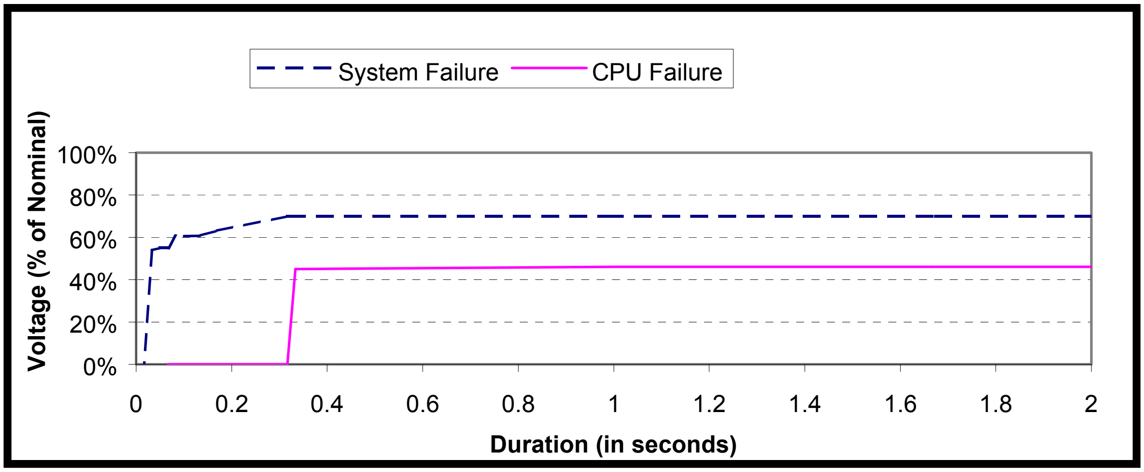


Figure F-13
PLC E Voltage Sag Ride-Through

Excluding PLC D, the responses of the remaining PLC power supplies were more robust than the overall system response (denoted as System Failure). These units appear to ride-through the voltage sag based on the output voltage of the DC power supply rather than the AC input voltage. This result means that the PLC CPU may continue to operate even if the voltage sag has disturbed the I/O and field devices. Such an event in a process control system can lead to a possible malfunction or process shutdown. Unlike the remaining units, PLC D was found to force a shutdown when a one cycle, 78 percent of nominal or less voltage sag occurred. As noted in the power supply discussion, this PLC decides to shut down based on the AC input voltage. Denoted as CPU Failure, this response insures that the PLC will shut down before possible malfunction of the control system may occur.

In comparison to earlier EPRI tests, the I/O racks in this series of tests contained fewer I/O modules (six I/O modules in earlier tests versus two modules in this series of tests). Therefore, the PLC DC power supply modules were more lightly loaded in these tests. Since PLC B was tested in earlier EPRI tests as well as in the CEC project, it is relevant to compare the results as shown in Figure F-14.

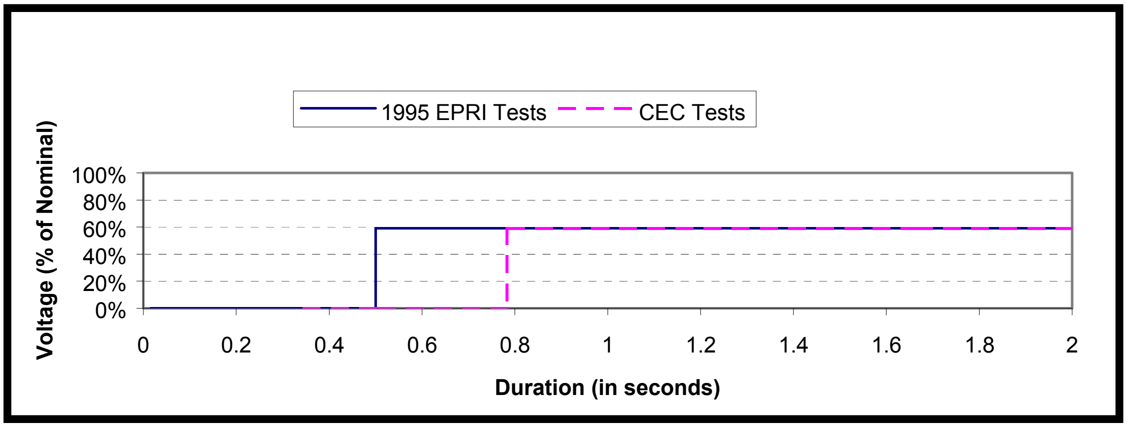


Figure F-14
Voltage Sag Ride-Through of PLC B with Respect to Loading
(1995 EPRI Tests Rack Heavily Loaded, CEC Tests Rack Lightly Loaded)

Voltage Sag Tests With Power Conditioning. Voltage sag tests were repeated on the five PLCs when the power source underwent conditioning. A constant voltage transformer (CVT), two off-line UPS units, and one on-line UPS were used to mitigate voltage sags. The power conditioning device was in the test setup as shown in Figure F-15. Loads for the test included a PLC power supply, control power, and other typical control component loads to reach the test target of 2 amps at 120Vac.

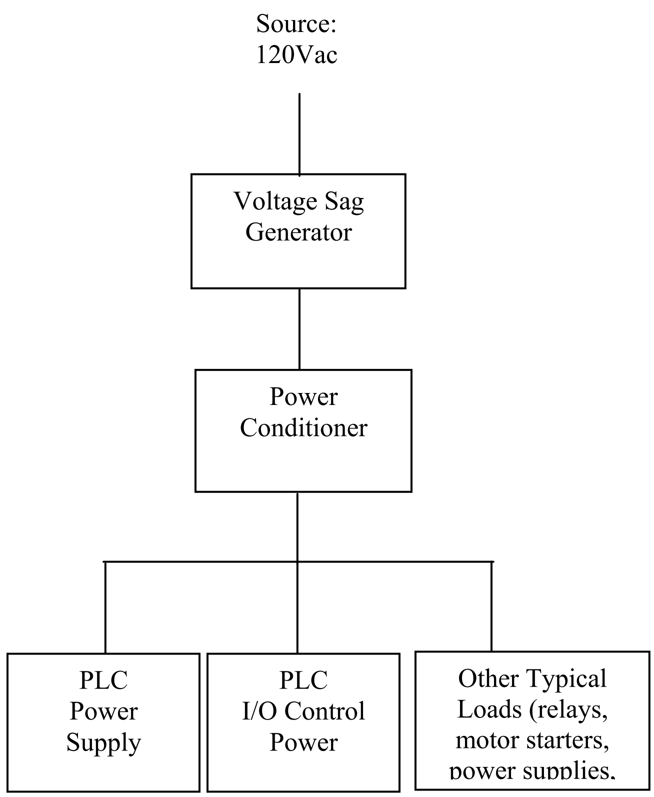


Figure F-15
Voltage Sag Test Setup with PLC and Power Conditioner

The Constant Voltage Transformer (CVT). The CVT (a.k.a. ferroresonant transformer) is a device that maintains two separate magnetic paths with limited coupling between them. The output contains a parallel resonant tank circuit and draws power from the primary to replace power delivered to the load. The transformer is designed so that the resonant path is in saturation while the other is not. As a result, a further change in the primary voltage will not translate into changes in the saturated secondary voltage, and voltage regulation occurs. The CVT is shown in Figure F-16. CVTs offer protection from voltage sags as well as voltage swells. Units that have multiple taps can be ordered from suppliers such as SOLA and ACME. For this reason, the existing step-down control power transformer can be replaced with a CVT. These devices will allow for much better voltage sag ride-through if they are sized to at least two and a half times the nominal VA requirement. Oversized in this manner, CVTs can supply a 100 percent output when the input voltage has dropped to as low as 40 percent of nominal. Figure F-17 displays the typical CVT performance characteristics at various loads.

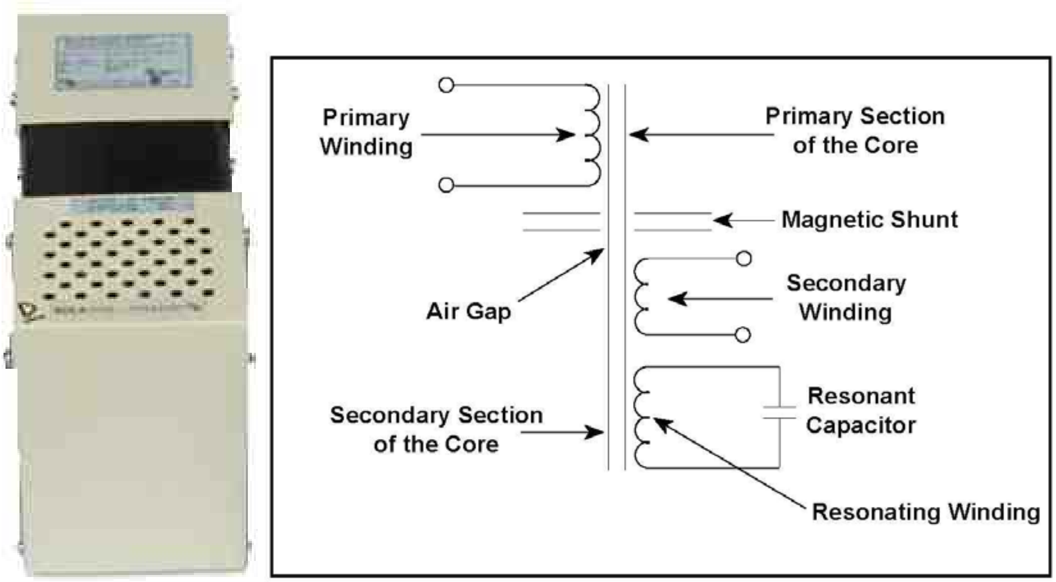


Figure F-16
The Constant Voltage Transformer (CVT)

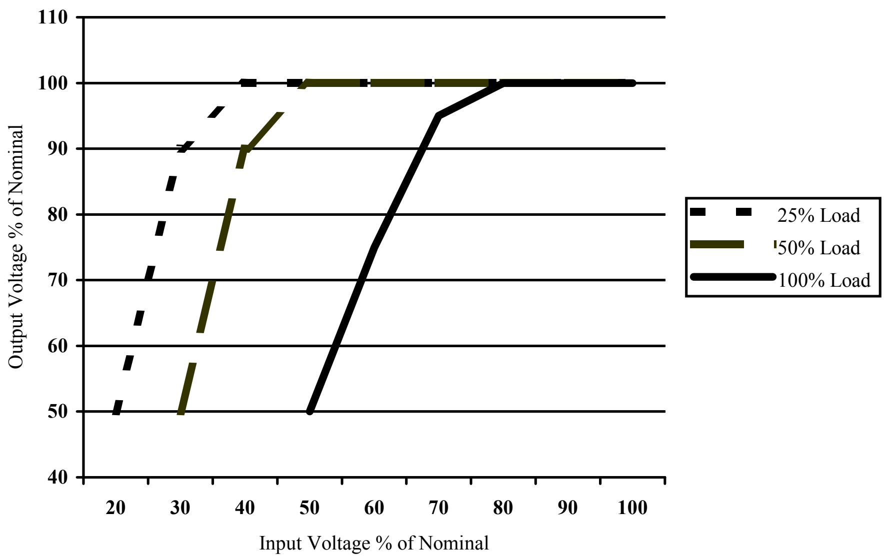


Figure F-17
Typical CVT Performance as a Function of Load

As indicated by Figure F-17, the CVT will not power the load circuit in the event of a momentary outage or a very severe voltage sag. The tricky part of applying the CVT is dealing with high inrush currents. For loads such as relays and contactors, the size requirement for a CVT is:

(1) CVT size = 2.5 X Nominal VA

or

(2) ½ Max Inrush VA

This rule-of-thumb may lead to oversizing the unit for some applications that have low nominal current, such as systems with large three-phase contactors. However, if the CVT is undersized for the load's inrush current, the output will collapse momentarily or possibly indefinitely. With a targeted load of 2 amps, the closest available standard CVT size of 500 VA was chosen.

<u>The Uninterruptible Power Supply (UPS)</u>. The UPS comes in three basic types: Standby, Line-Interactive, and Rectifier/Charger. The Standby UPS, which is also referred to as an off-line unit, normally passes the power straight through from the input of the unit to the output. When a voltage sag or outage is detected, the unit switches to a battery and provides an inverter output to the load. If the transfer is fast enough (<1 cycle) and is in phase with the incoming voltage, typical control components are not likely to be affected by the sag event. Since it is only switched into the circuit when a voltage sag or outage occurs, an off-line UPS can be sized to the nominal current required by the load. Two off-line UPS systems were evaluated in this test to determine their ability to mitigate voltage sags. These units were sized to 420VA and 650VA, respectively.

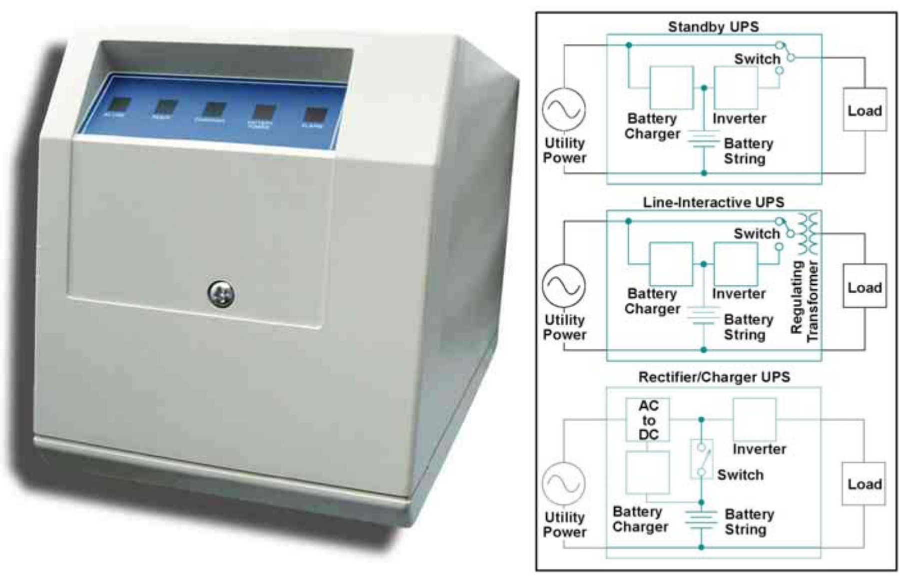


Figure F-18
The Uninterruptible Power Supply (UPS)

The *Line-Interactive UPS* is an on-line type that employs a regulating transformer (CVT) when the incoming voltage is nominal. When a voltage sag is sensed, the unit then switches to the inverter to power the load. High inrush loads must be taken into account when using this unit since the CVT output can collapse from overloading. One 500VA line-interactive UPS was utilized during this test to demonstrate its ability to mitigate voltage sags.

The Rectifier/Charger UPS is also an on-line unit. The unit constantly rectifies the incoming AC line voltage. The resulting DC voltage is then used to charge the batteries and to feed the inverter circuit for the unit's output section. In the event of a voltage sag or outage, the unit switches to the battery for the source of the inverter's power.

CVT Test Results. All PLCs exhibited superior voltage sag ride-through with the 500VA CVT power conditioner installed. On average, induced shutdown (CPU Failure) levels on the five PLC's power supplies were improved from an average of 62.6 percent of nominal without power conditioning down to 23.2 percent of nominal voltage with the CVT. Furthermore, the system failure shutdown level dropped from an average of 73.6 percent without power conditioning to an average of 33.4 percent of nominal with the CVT in place. The typical input and output voltage sag response of the CVT is shown in Figure F-19.

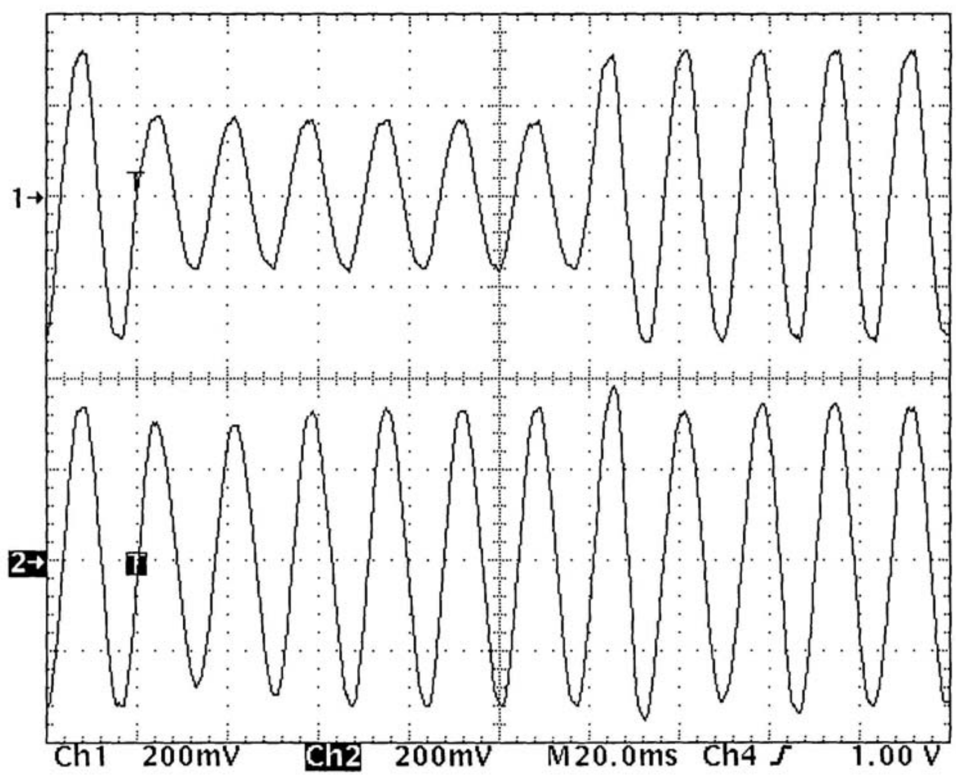


Figure F-19
Typical Response of CVT to a Voltage Sag

A representative example of the PLC ride-through with the 500VA CVT in place is shown in Figure F-20.

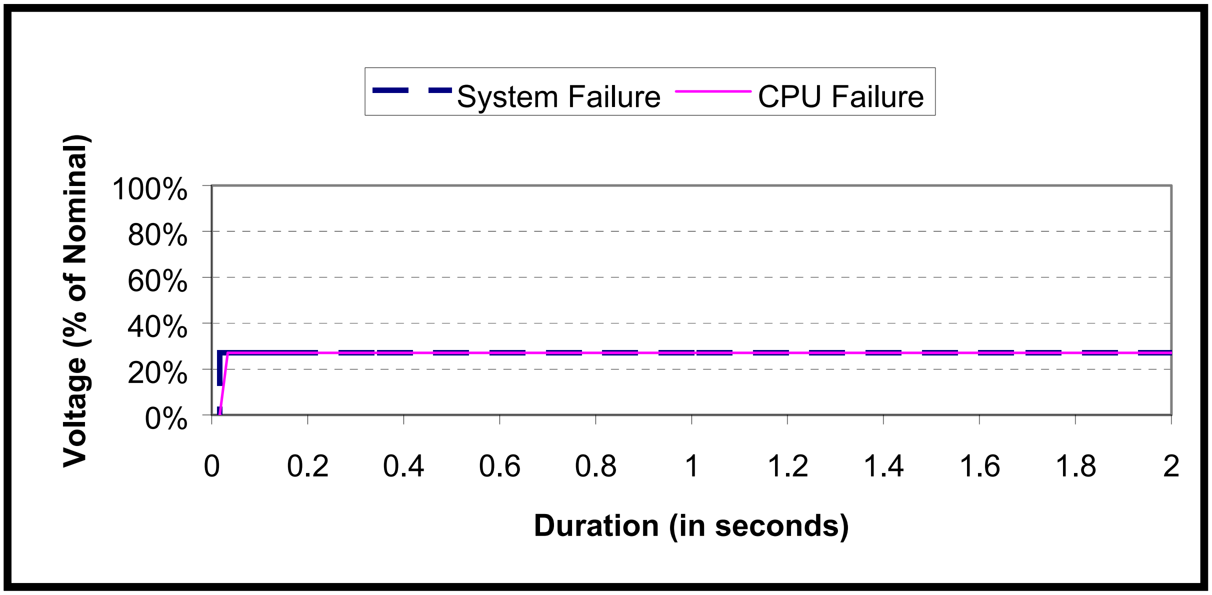


Figure F-20
PLC D Voltage Sag Response Drastically Improved with CVT

UPS Test Results. The results of the off-line and on-line UPS tests were very different. Figure F-21 shows the response of the off-line UPS versus the on-line, line-interactive UPS. During the voltage sag, the two off-line UPS units used in the project produced a "simulated" sine-wave output. Furthermore, the off-line units required about 4 milliseconds (1/4 cycle) to switch over to the battery source. This duration typically is not critical since most control equipment can withstand voltage sags of such short duration. Although the two square-wave output UPS units kept the PLCs powered and averted a CPU Failure, some of the PLC 120Vac input cards could not resolve the square wave. This led to the PLC detecting logic level "0" instead of logic level "1." As a result, the output relay was dropped when the UPS kicked on and the inputs could not be resolved. In all, three out of the five PLC systems tested could not resolve the square-wave on the AC input card and experienced System Failures as soon as the UPS transferred. On the other hand, the line-interactive UPS was found to be compatible with all PLCs tested allowing continued operation even in a complete power outage.

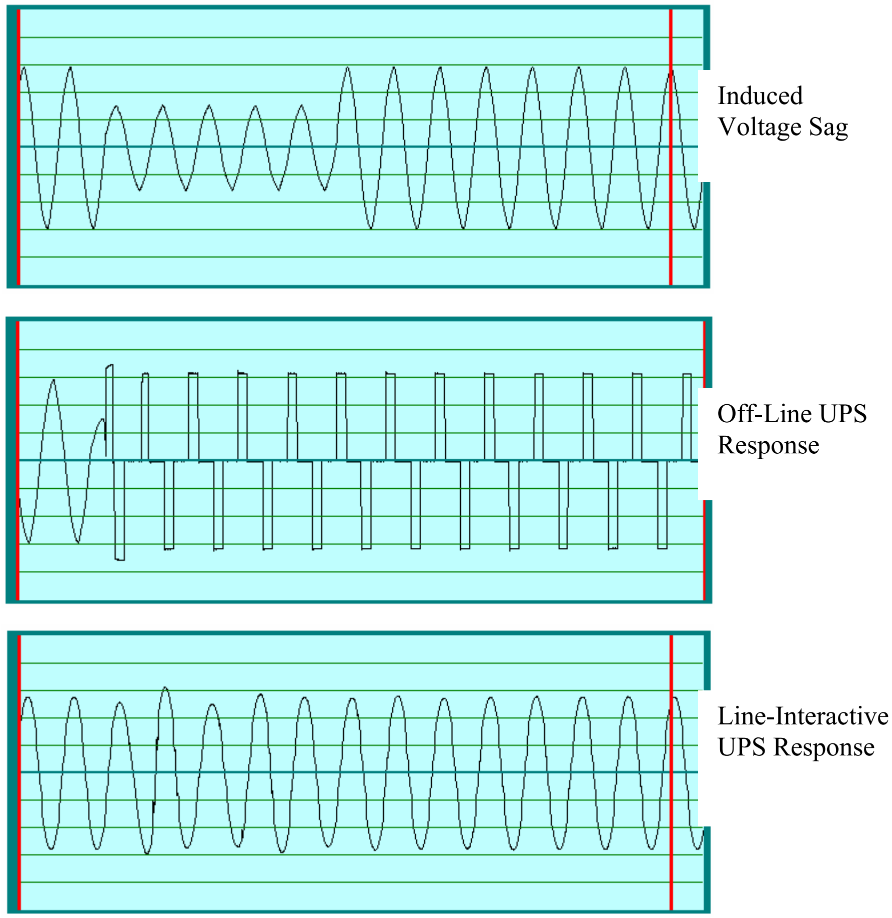


Figure F-21
Response of Off-Line, "Square-Wave" UPS and On-Line, Line-Interactive UPS to a 5 Cycle, 50 Percent of Nominal Voltage Sag

Ten Guidelines for Improving PLC Voltage Sag Performance

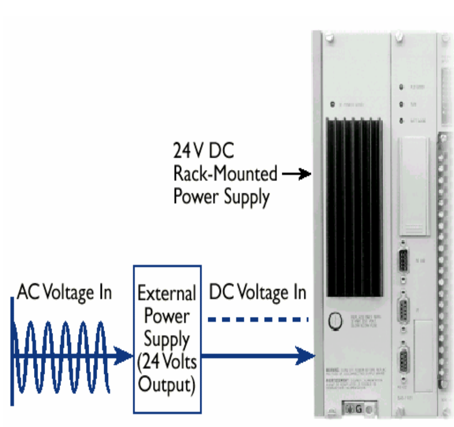
Based on the results of the PLC tests for CEC and previous EPRI tests, the following ten guidelines should be followed to make PLCs more robust to voltage sag events.

1. Avoid mismatched control power voltages. If the actual PLC system nominal voltage is lower than the expected nominal input voltage, the entire control system will be more susceptible to voltage sags. Such mismatches can occur when control power transformers are tapped low or a 230Vac input PLC power supply is connected to a 208Vac source. For relays and contactors, a mismatch of 10 percent of voltage equates to an increase in susceptibility by 10 percent. However, in DC power supplies, the energy stored in the internal capacitors can be as much as 18 percent lower when the input voltage is mismatched by a little as 10 percent--directly equating to a reduction in ride-through time.

2. Provide a robust power source for PLC power supply and I/O control power. Ensuring that the PLC Power Supply response to voltage sags will be robust without considering the I/O control power is only a partial fix. Although the PLC CPU may survive voltage sags, the system is still likely to suffer process upsets. Therefore, both the control power and I/O power must be considered.

3. Consider utilizing DC to power the PLC and I/O. EPRI tests have confirmed that utilizing a DC power scheme for the PLC power supply and I/O control power is an ideal embedded solution for solving voltage sag-related shutdowns. This approach is best designed into the system by the integrator since the PLC power supply must be specified as a DC input type, but the I/O modules, sensors, relays, solenoids, and motor starters must be specified for DC control voltages. In systems were the I/O control voltage is already DC, the solution is as easy as replacing the AC input power supply module with the comparable DC input power supply module. It is important to ensure that the DC power source, typically 24Vdc, is robust as well. The use of switch-mode or lightly loaded linear supplies is preferred. An example voltage sag response with a DC power scheme is shown in Figure F-22.

24V DC Input Rack Mounted Supply with External DC Power Supply



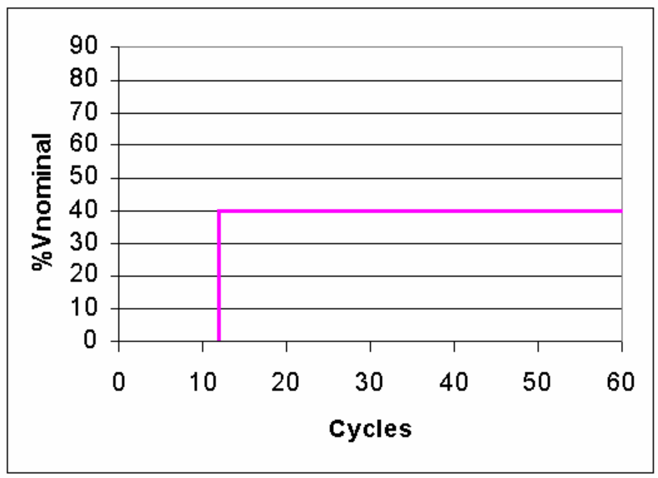


Figure F-22
Example Voltage Sag Ride-Through using DC Power Source Approach

4. Use universal input switching power supplies in every location possible, wired phase-to-phase. Typically, the universal input type power supply has a voltage range of 85 to 264Vac. When connected phase-to-phase in a 208Vac system, the power supply can continue to operate down to 41 percent of nominal. This type of supply should be specified for DC-powered instrumentation, I/O control voltage, and DC PLC power supplies.

5. Do not overload DC power supplies. Since the amount of voltage sag ride-through time available from a typical linear or switch-mode DC power supply is directly related to the loading, DC power supplies should not be running at their maximum capacity. Oversizing by at least two times the expected load will help the power supply to ride-through voltage sags. This is only critical for systems that do not use a universal input power supply wired in a phase-to-phase configuration.

6. Utilize a robust control relay for the Master Control Relay (MCR). The importance of selecting robust control components for the MCR circuit cannot be understated. The typical wiring for a PLC system that utilizes an MCR is shown in Figure F-23.

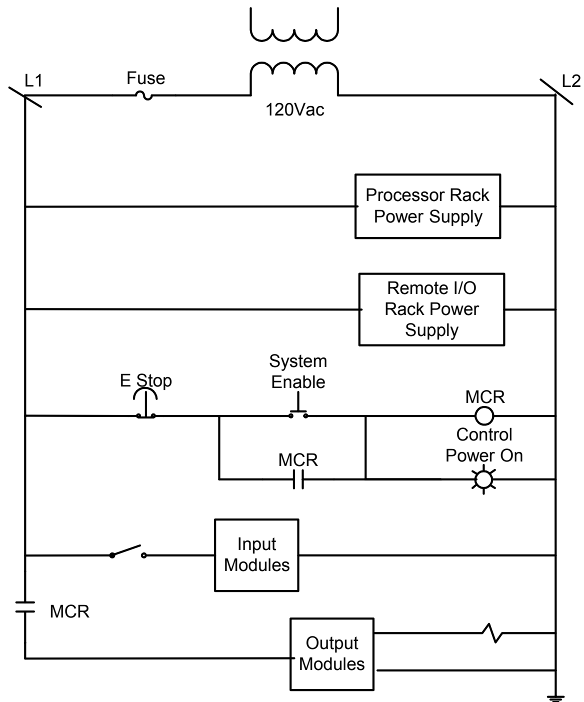


Figure F-23
Typical MCR Safety Circuit Wiring in a PLC System

When used in the safety circuits or as subsystem power contactors, the selection of the MCR can make a large difference in the control system's ability to survive voltage sags. Before installing a relay or contactor into the design scheme, the integrator should bench test the units for voltage sag immunity. One way to improve the MCR circuit is to avoid general-purpose "ice cube" relays as the MCR because they are too sensitive to voltage sags. A small four-pole contactor should be used instead. In general, a small contactor can survive voltage sags as low as 40 to 55 percent of nominal. A typical general-purpose "ice cube" relay and the recommended replacement contactor are shown in Figure F-24. The recommended contactor costs about $50 more than the relay and socket. It is important to note that if the PLC and I/O control power are made robust to voltage sags through proper placement of a power conditioner, the MCR circuit should be robust as well.

Figure F-24
Embedding the power quality solution is possible by utilizing a small contactor (right) instead of a general-purpose “ice cube” relay (left) to serve as the MCR

7. Properly maintain PLC battery. Many PLCs utilize lithium-ion batteries to maintain their control programs and non-volatile memory data in the event of a power loss or voltage sag-induced shutdown. Such a loss of the PLC program can cause extended down time due to the need to locate the latest back-up, reload, and restart the process. Since the active process data will be lost in this situation, scrapping of product may be inevitable. In addition to a battery status indicator on the PLC processor, many systems also map this information in the PLC’s memory, which can report as an alarm condition on upper-level GUI systems.

8. Utilize a state-machine programming method and/or non-volatile PLC memory. When properly coded, this type of programming technique ensures that the control system will not lose its place in the event of a voltage sag or outage and will result in quicker process restart times.

9. Consider the power source for analog input signals. For analog signals, ensure that the source is robust. If two-wire transmitters are used, the DC power supply should be lightly loaded or naturally robust as discussed in guidelines 4 and 5. If four-wire transmitters are used, consideration should be given to providing power conditioning for the AC voltage source.

10. Only utilize compatible power conditioners. As shown in this report, a properly sized CVT or Line-Interactive UPS can greatly enhance a PLC system’s ability to ride-through voltage sags. In general, power conditioners with square-wave outputs should be avoided since the AC input module channels on the PLC may not be able to resolve the square-wave signal. Only utilize square-wave output power conditioners with the PLC manufacturer’s assurance that the PLC power supply and I/O cards are compatible. Furthermore, when using an off-line power conditioner, the transfer time should be within ¼ cycle to ensure that the control system is not upset.

Conclusion

Programmable Logic Controllers can be affected by voltage sags as short as one cycle, leading to the shutdown of automated control systems and the loss of production time and money. However, proper hardware and software integration can lead to vast improvements in the response of these systems to power disturbances. When attacking voltage sag-related problems, it is important to ensure that the PLC and the I/O control power are robust. Techniques such as the utilization of power conditioners for the AC source voltage or employing a robust DC control power source can provide effective mitigation. Use of properly integrated and compatible UPS or CVT units on these circuits can greatly improve the overall robustness of PLC-based control systems to power quality disturbances. Careful selection of power conditioning devices is required to ensure that the entire system will not be made less compatible as a result. Power conditioning devices, which produce square-wave outputs, are not compatible with all PLC systems. Square-wave outputs are available on many battery-based UPS systems as well as on newer technology capacitor-based power conditioners.

G
MITIGATION OF TRANSIENTS ON PLC-BASED CONTROL SYSTEMS

Abstract

Originally invented in the late 1960s to replace relay logic in automotive manufacturing, today's Programmable Logic Controllers (PLCs) have evolved into sophisticated computers that are used in all manufacturing sectors and are capable of performing repetitive operations with a high degree of accuracy. In contrast to its infant counterpart, the PLC of today handles both analog (continuous) and discrete (on/off) control functions with ease. Because of these advances, industrial manufacturers are using these systems more and more to replace antiquated schemes to increase efficiency, productivity, and reliability. However, the susceptibility of PLC-based control systems to voltage transients can lead to damaged hardware and process upsets. This paper addresses transient issues related to PLC systems and proposes guidelines to both integrators and end-users to make these industrial control systems more robust.

Introduction

The afternoon summer sky turned to darkness as the rain intensified and the thunderstorm threatened. Near the water treatment plant, lightning danced through the sky as the thunderstorm raged. With some concern about the mass of run-off water that would soon enter the plant for processing, the operators at the wastewater treatment plant closely monitored their process instruments through the graphic user interface (GUI) screen. The PLC-based control system increased the speed set point to the influent and effluent pump variable frequency drives to keep pace with the onslaught of drainage water. If the plant could not keep up with the demand, a plant bypass would be required – dumping raw sewage into the area lake, an act that would result in fines for the local utility. As the powerful storm reached the plant, all system pumps were operating at full capacity and the control screen reported the influent tank level to be 90 percent full and rising. The shift supervisor recoiled as a brilliant flash of lightning hit in close proximity to the plant. The blaring of the alarms on the GUI made it apparent that something had gone wrong with the control system. With the dynamic updates from the PLC system now frozen, influent inverter drives quickly shut down because the controller was no longer functional. With the influent tank at maximum level, the water level quickly backed up to flood the bypass channel and sent untreated water directly into the lake.

Events like this can occur when PLCs are damaged or upset by lightning, causing the malfunction of process controls, lost process time, and money. This paper explores the issues related to the effect of transient events on PLC systems and proposes solutions for making PLCs more robust to such occurrences.

What are Transients?

Transient disturbances are caused by the injection of energy by switching or by lightning. The disturbance may be either *unidirectional* or *oscillatory*. Lightning, electrostatic discharge, load switching, or capacitor switching may cause a unidirectional transient, which is characterized by its peak value and rise time. An oscillatory transient is characterized by its frequency content and may be caused by a switching operation such as the energizing of a capacitor bank, distribution line, or cable, or the opening of an inductive current. Power system switching normally causes low- and medium-frequency oscillations, with principle frequencies less than 2 kHz. The switching of a load close in proximity may cause high-frequency oscillations with principle frequencies above 2 kHz. Common solutions to problems caused by transients include the application of surge arresters, passive and active filters, and isolation transformers.

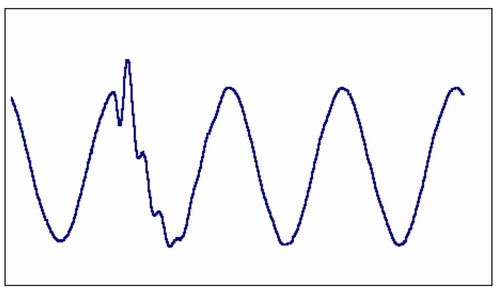


Figure G-1
Example Oscillatory Transient Waveform Caused by a Capacitor Energizing

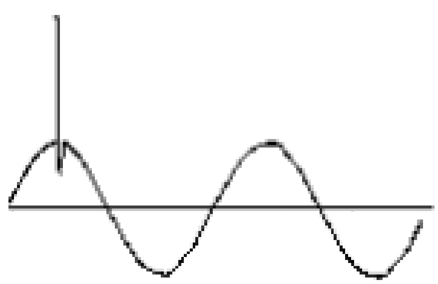


Figure G-2
Example Impulsive Transient Waveform Induced by Lightning

The proliferation in office use of electronic equipment and microprocessor-based controls, including PLC systems, has caused electric utilities to redefine power quality in terms of the quality of voltage supply rather than the availability of power. In this regard, *IEEE Std. 1159-1995, Recommended Practice for Monitoring Electric Power Quality,* has defined a set of terminologies and characteristics to describe the electrical environment in terms of voltage quality. Table G-1 shows the categories of power quality disturbances with spectral content, typical duration, and typical magnitude.

Table G-1
Categories of Power Quality Variation – IEEE 1159-1995

Categories	Spectral Content	Typical Duration	Typical Magnitudes
1.0 Transients			
1.1 Impulsive			
1.1.1 Voltage	> 5 kHz	< 200 µs	
1.1.2 Current	> 5 kHz	< 200 µs	
1.2 Oscillatory			
1.2.1 Low Frequency	< 500 kHz	< 30 cycles	
1.2.2 Medium Frequency	300–2 kHz	< 3 cycles	
1.2.3 High Frequency	> 2 kHz	< 0.5 cycle	
2.0 Short-Duration Variations			
2.1 Sags			
2.1.1 Instantaneous		0.5–30 cycles	0.1–1.0 pu
2.1.2 Momentary		30–120 cycles	0.1–1.0 pu
2.1.3 Temporary		2 sec–2 min	0.1–1.0 pu
2.2 Swells			
2.1.1 Instantaneous		0.5–30 cycles	0.1–1.8 pu
2.1.2 Momentary		30–120 cycles	0.1–1.8 pu
2.1.3 Temporary		2 sec–2 min	0.1–1.8 pu
3.0 Long-Duration Variations			
3.1 Overvoltages		> 2 min	0.1–1.2 pu
3.2 Undervoltages		> 2 min	0.8–1.0 pu
4.0 Interruptions			
4.1 Momentary		< 2 sec	0
4.2 Temporary		2 sec–2 min	0
4.3 Long-Term		> 2 min	0
5.0 Waveform Distortion			
5.2 Voltage	0–100th Harmonic	steady-state	0–20%
5.3 Current	0–100th Harmonic	steady-state	0–100%
6.0 Waveform Notching	0–200 kHz	steady-state	
7.0 Flicker	< 30 Hz	intermittent	0.1–7%
8.0 Noise	0–200 kHz	intermittent	

Transient Tests

To begin to understand a PLC's susceptibility to capacitor-switching and lightning-induced transients, laboratory tests were performed. The California Energy Commission (CEC) recently sponsored EPRI tests to evaluate the susceptibility of PLCs to electrical transients. To understand their response, five different PLC brands, generically labeled PLC A, B, C, D, and E, were subjected to transient conditions with and without power conditioning. Each of the PLC units was loaded with a common control algorithm; utilized 120Vac input, output, and power supply modules; and was wired in an identical scheme. These tests were conducted at EPRI PEAC Corporation in Knoxville, Tennessee.

Capacitor-Switching Transient Tests. To control power factor on the electric system, utilities dynamically switch in capacitive loads. The switching of these capacitor banks can cause 5kHz ring wave (defined in ANSI/IEEE C62.41-1991) to appear on high-voltage systems. This "ring wave" can also affect low-voltage distribution systems. The impedance of the power system diminishes the standard 5kHz ring wave to a 300-800Hz ring wave with a peak magnitude of approximately 160% of nominal voltage. This waveform may deposit enough energy on the low-voltage system to cause failures on single-phase equipment with inadequate surge protection. Figure G-3 displays a typical capacitor-switching transient that was injected into each PLC. Figure G-4 shows the test setup at EPRI PEAC. The test platform consists of a computer-controlled capacitor bank that is first charged by the technician. When ready to conduct the tests, the system closes a switch to bring the capacitor bank into the circuit with the PLC load, reproducing the effect that occurs on the utility system and triggering an external oscilloscope.

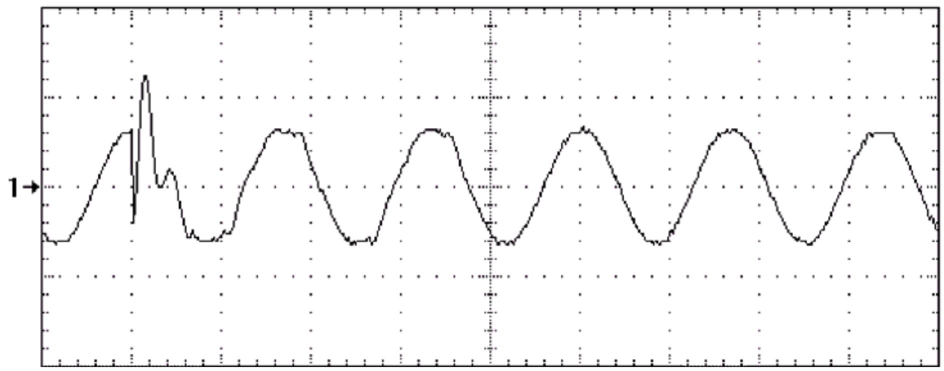


Figure G-3
Typical Capacitor-Switching Transient Injected into Each PLC

Figure G-4
Capacitor-Switching Transient Test Setup (PLC load not shown)

Capacitor-Switching Transient Test Results without Power Conditioning. The results from the capacitor-switching transient tests on the PLCs are shown in Table G-2. These results show that none of the PLCs were upset as a result of the tests. In each case, the PLC CPU and I/O continued to function normally without upset during the test. These results agree with earlier tests conducted by EPRI in 1995 in which six PLC models were tested and none were found to be affected by capacitor-switching transients. Although the PLCs were not affected by the capacitor-switching transients, the long-term effect on the PLC power supply is not known. Furthermore, other components of the control system, such as low-voltage DC power supplies, may pass the transient to their DC loads, possibly upsetting control loops. It has been well documented that adjustable speed drives, which are common elements in many PLC-based control systems, can experience "DC overvoltage" shutdowns as a result of the capacitor-switching transient passing to the DC link in the drive.

Table G-2
PLC Capacitor-Switching Transient Results

PLC Model	PLC Upset By Capacitor-Switching Transient?
PLC A	No
PLC B	No
PLC C	No
PLC D	No
PLC E	No

Capacitor-Switching Transient Tests Results with Power Conditioning. Even though none of the five PLCs were affected by the capacitor-switching transient test, it is possible that the long-term effect of these transients or other control system components powered by the same source might be affected. Therefore, tests were conducted using a 500VA constant voltage transformer, two off-line UPS units, and an on-line UPS.

The **Constant Voltage Transformer** (CVT) is a power conditioner that maintains two separate magnetic paths with limited coupling between them and, therefore, acts as an isolation transformer as well. The output contains a parallel resonant tank circuit and draws power from the primary to replace power delivered to the load. The transformer is designed so that the resonant path is in saturation while the other is not. As a result, a further change in the primary voltage will not translate into changes in the saturated secondary voltage, and voltage regulation results. Shown in Figure G-5, CVTs offer protection not only for voltage sags, but also for voltage swells and transients.

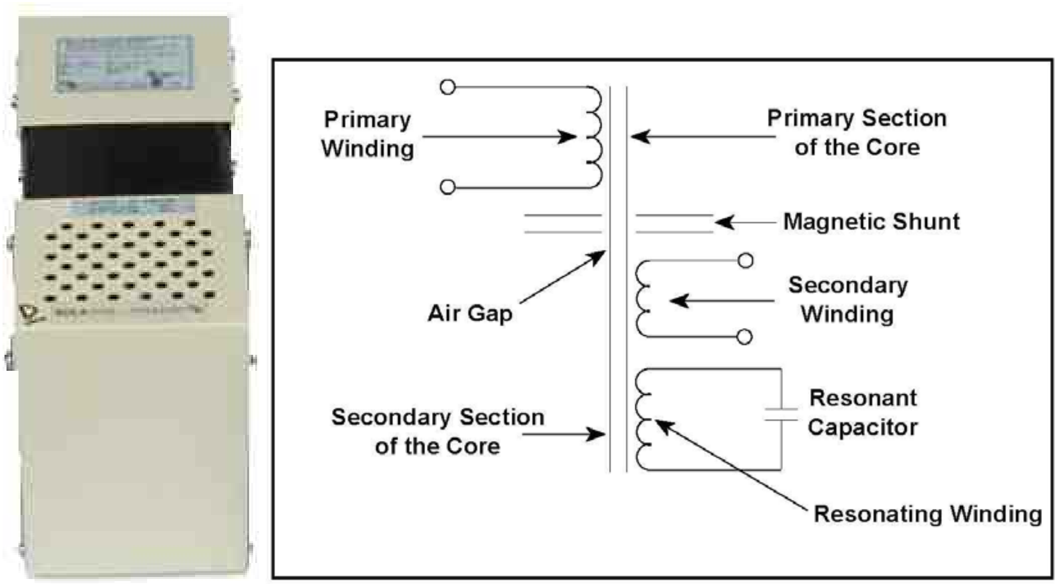


Figure G-5
The Constant Voltage Transformer (CVT)

The **UPS** can come in three basic types: standby, line-interactive, and rectifier/charger (see Figure G-6). The *standby UPS*, which is also referred to as an off-line unit, normally passes the power straight through from the input of the unit to the output. When an abnormal voltage is detected (voltage sag, outage, voltage swell, or transient), the unit switches to a battery and provides an inverter output to the load. If the transfer is fast enough (< 1/2 cycle) and is in phase with the incoming voltage, typical control components probably will not be affected by the sag event. Since it is only switched into the circuit when a voltage sag or outage occurs, an off-line UPS can be sized to the nominal current required by the load. Two off-line UPS systems were evaluated in this test to determine their ability to mitigate capacitor-switching transients. These units were sized to 420VA and 650VA, respectfully. Both of these units supplied a square-wave output to the PLC load.

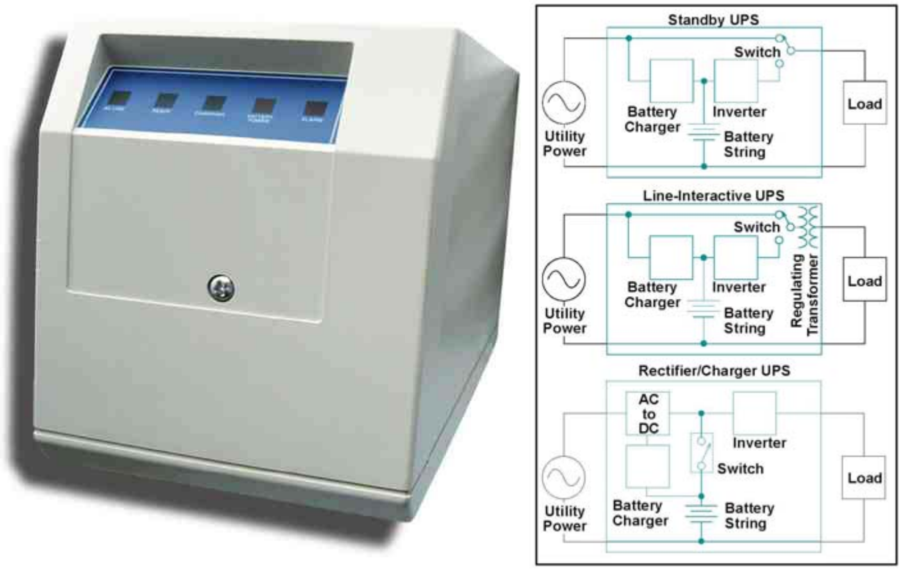


Figure G-6
The UPS Can Be Either a Standby, Line-Interactive, or Rectifier Charger Type

The *line-interactive UPS* is an on-line type that employs a regulating transformer (CVT) when the incoming voltage is nominal. When a voltage disturbance is sensed, the unit switches to the inverter to power the load. High inrush loads must be taken into account when using this unit since the CVT output can collapse from overloading. One 500VA line-interactive UPS was utilized during this test to demonstrate its ability to mitigate voltage sags.

The *rectifier/charger UPS* is also an on on-line unit. The unit constantly rectifies the incoming AC line voltage. The resulting DC voltage is then used to charge the batteries and to feed the inverter circuit for the unit's output section. In the event of a voltage fluctuation, the unit switches to the battery for the source of the inverter's power. The test results using the CVTs and UPS devices are shown in Table G-3.

Table G-3
Test Results Using Power Conditioners

	Outcome with 500 VA CVT	Outcome with Off-Line 420VA	Outcome with Off-Line 650VA	Outcome with Line-Interactive 500 VA UPS
Transient seen by PLCs?	*No. See FigureG-7.*	*Yes. Approximately 1.5 p.u. After ½ cycle, switches to square wave output from UPS. See Figure 8.*	*Yes. Approximately 1.3 p.u. After ¼ cycle, switches to square wave output from UPS. See Figure 9.*	*No. See Figure G-10.*

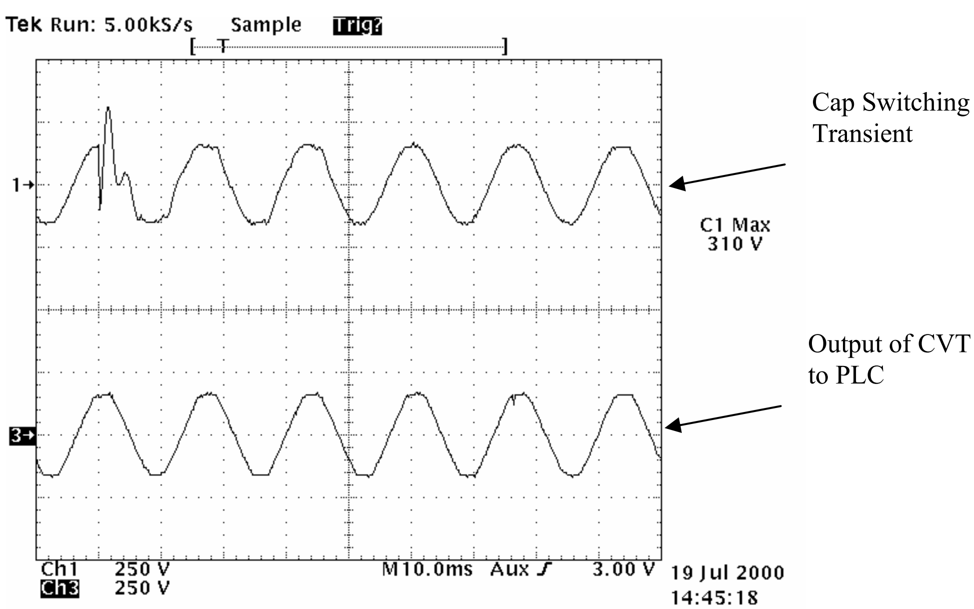


Figure G-7
500VA CVT Mitigates Capacitor-Switching Transient to PLC

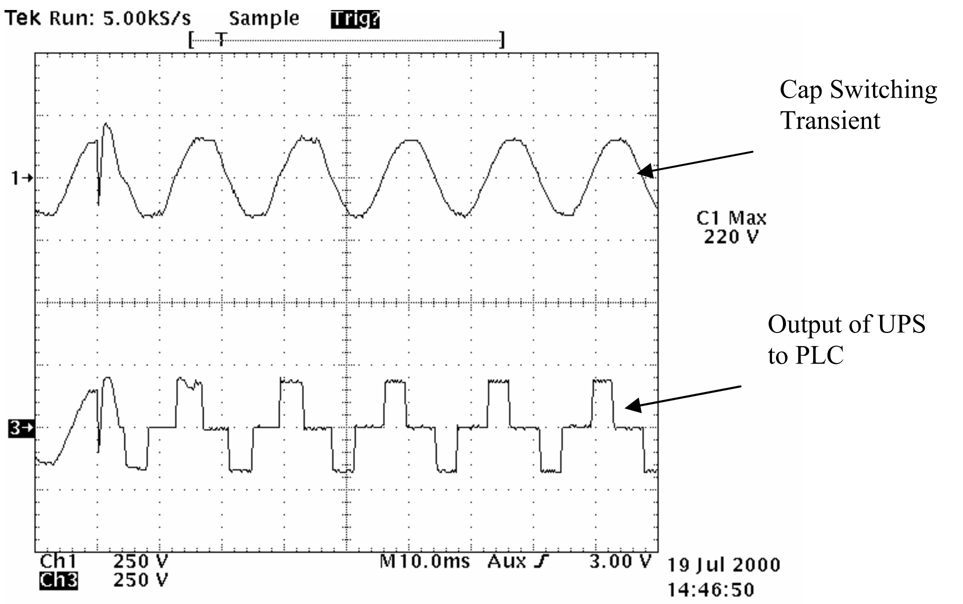


Figure G-8
420VA Off-Line UPS Passes Initial Transient for ½ Cycle then Switches to Battery to Supply a Square-Wave Output

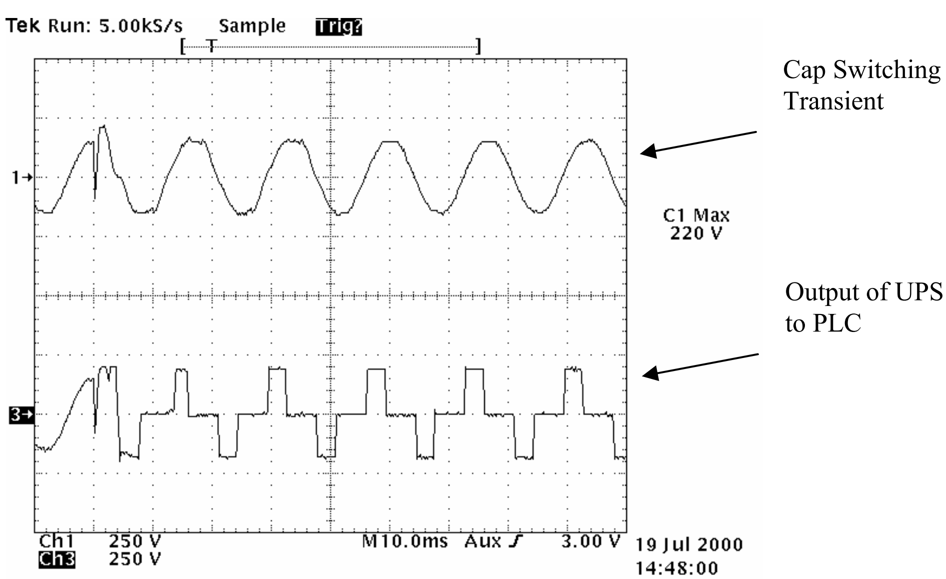


Figure G-9
650VA Off-Line UPS Passes Initial Transient for ¼ Cycle then Switches to Battery to Supply a Square-Wave Output

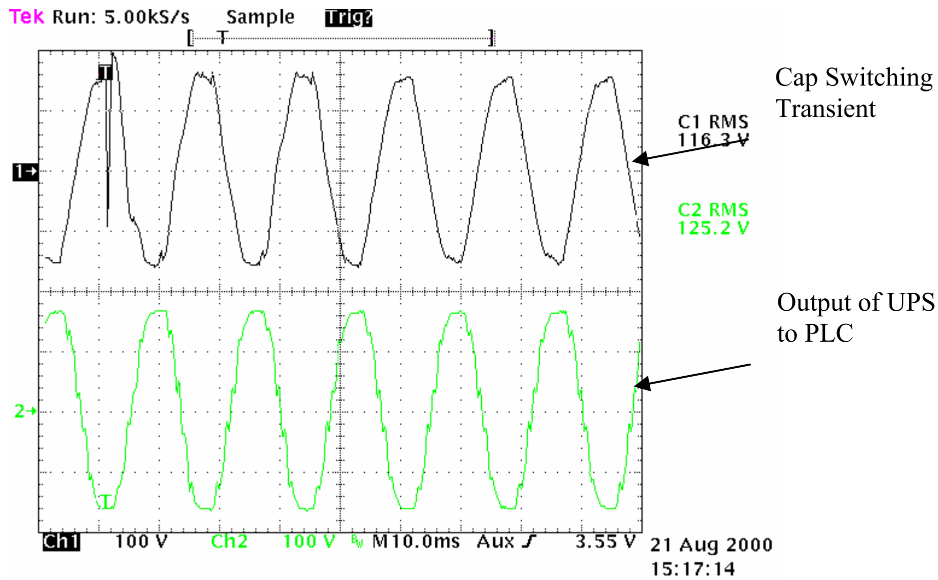


Figure G-10
500VA Line-Interactive UPS Mitigates Capacitor-Switching Transient

As shown by these test results, the CVT provides excellent mitigation of capacitor-switching transients as well as voltage sags. Furthermore, the line-interactive UPS, which contains a CVT in the design, mitigated the transients as well. However, the two off-line power conditioners did not mitigate the capacitor-switching transient well. Requiring ½ cycle for the 420VA units and ¼ cycle for the 650VA units to switch to the battery source, some of the transient event did pass the load. Furthermore, three of the five PLCs tested were upset by the square-wave output. Although the two UPS units kept the PLC power supplies powered, some of the 120Vac input cards could not resolve the square wave. This led to the PLC detecting logic level "0" instead of logic level "1." As a result, the PLC made erroneous decisions to turn off some output channels.

Lightning-Induced Transient Tests. To perform a lightning-induced transient test in a laboratory environment, a Keytek 801-S surge generator was utilized to create ANSI standard combination waveforms. The combination wave is delivered by a generator applying a 1.2/50µs voltage wave across an open circuit and an 8/20µs current wave into a short circuit. The exact waveform that is delivered is determined by the equipment impedance to which the surge is applied. Figure G-11 depicts the voltage waveform with the front time (rise time) of 1.2µs and decays to 50% voltage at 50µs. Figure G-12 is the graphical representation of the current surge waveform applied to a short circuit. The front time (rise time) is 8µs, decaying to a magnitude of 50% in 20µs. For these tests, IEEE C62.41, Category B, surge magnitudes will be used. Category B was chosen for this application since it is defined to pertain to electrical loads that are connected to bus and feeders in industrial plants. The maximum value of the Category B test waveforms for voltage and current are defined at 4kV and 2kA, respectfully. These two waveforms have substantial energy-deposition capability and provide representative stresses to the surge protectors and commercial electronics connected to the power system. These surge tests were conducted in line-to-neutral and line-to-ground configurations.

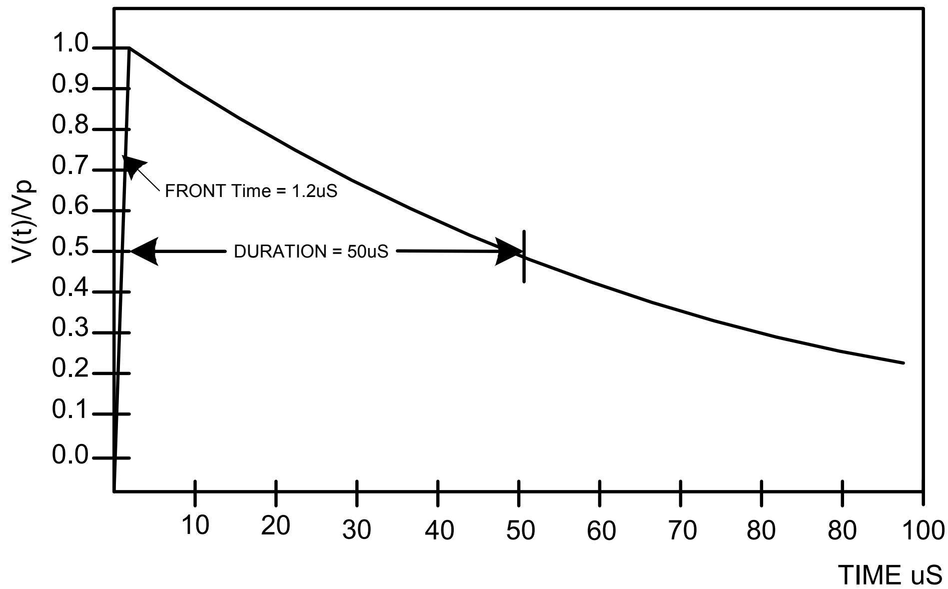


Figure G-11
Graphical Definition of the ANSI/IEEE 1.2/50-μs Combination Wave Open-Circuit Voltage

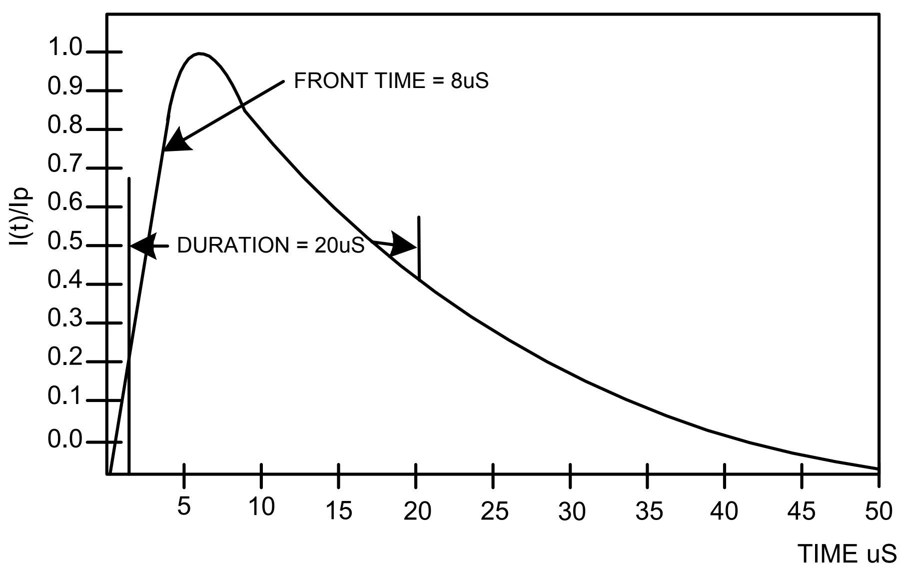


Figure G-12
Graphical Definition of the ANSI/IEEE 8/20-μs Combination Wave Short-Circuit Current

Lightning-Induced Transient Test Results with Power Conditioning. Transient surge tests were performed with and without power conditioning. The first series of tests was done with power conditioning as illustrated in Figure G-13.

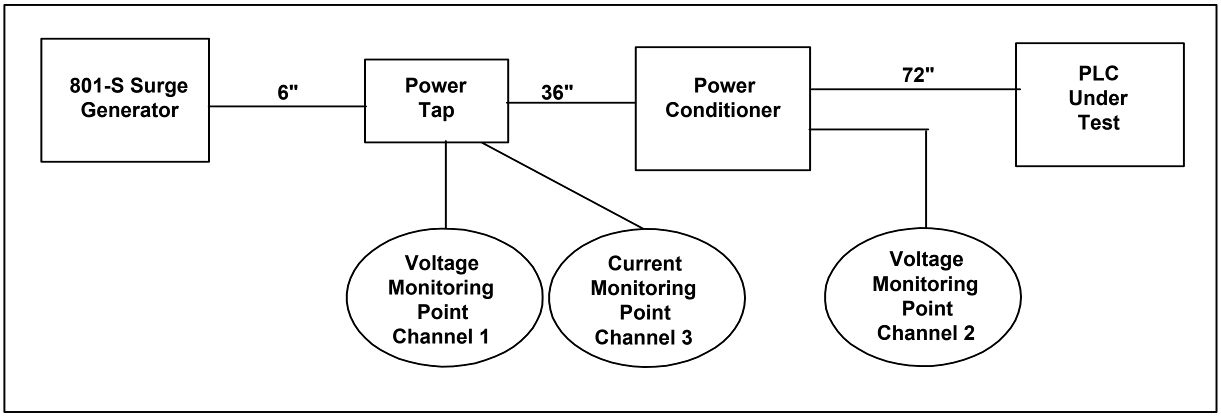


Figure G-13
Test Set Up with Power Conditioning

The first power conditioning device utilized was the 500 VA CVT. A transient surge with a magnitude of 4.27kV line-to-neutral had no effect on any of the five tested PLCs with the CVT in place. An example of this surge waveform is shown in Figure G-14. Channel 2 is the output of the CVT. Notice that the surge transient, Channel 1, is not reflective in Channel 2. This indicates that the surge transient at this magnitude does not affect the output of the CVT or the PLC.

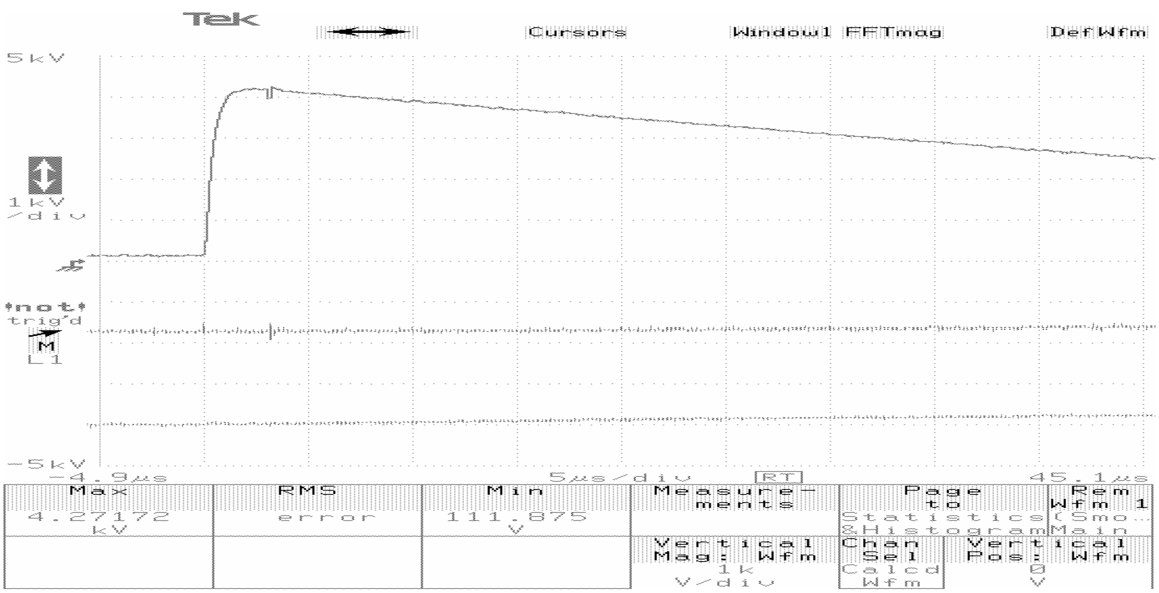


Figure G-14
With 500VA CVT Installed, a Surge Transient of 4.27kV (Line-to-Neutral) had no Effect on CVT Output or PLC Operation

A line-to-ground surge transient affected the primary side of the CVT. Figure G-15 displays a 3kV surge that caused a “flashover” on the primary side of the CVT (voltage exceeded the scope’s measurement scale.) The secondary of the CVT was unaffected by this flashover event.

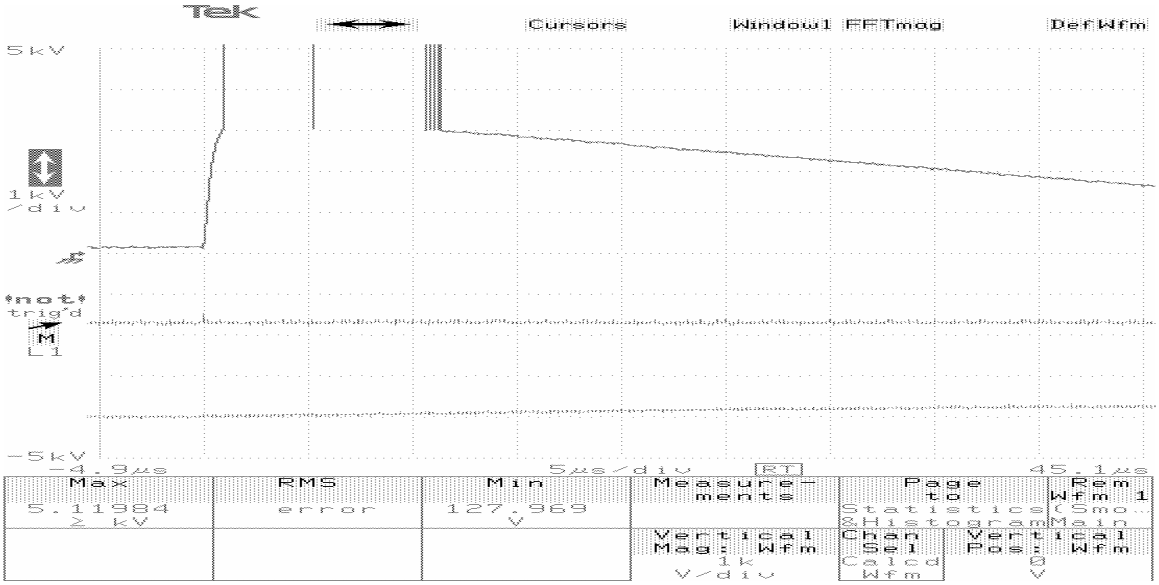


Figure G-15
With 500VA CVT Installed, a 3kV Line to Ground Surge Transient Led to Flashover on the Primary Side of the CVT

In addition to the CVT, the 420VA off-line UPS was subjected to tests. Line-to-neutral and line-to-ground transient surges up to 4kV did not damage the UPS or PLCs, but did cause some of the PLC systems to malfunction. The upset occurred when the UPS transferred to battery backup. As was shown in the capacitor-switching transient tests, when the UPS transferred to battery backup, the square-wave output of the off-line UPS led to erratic I/O operation on the three of the five PLC systems.

Lightning-induced Transient Test Results Without Power Conditioning. An additional round of transient surge tests was performed without power conditioning in front of the PLCs. The test setup is illustrated in Figure G-16.

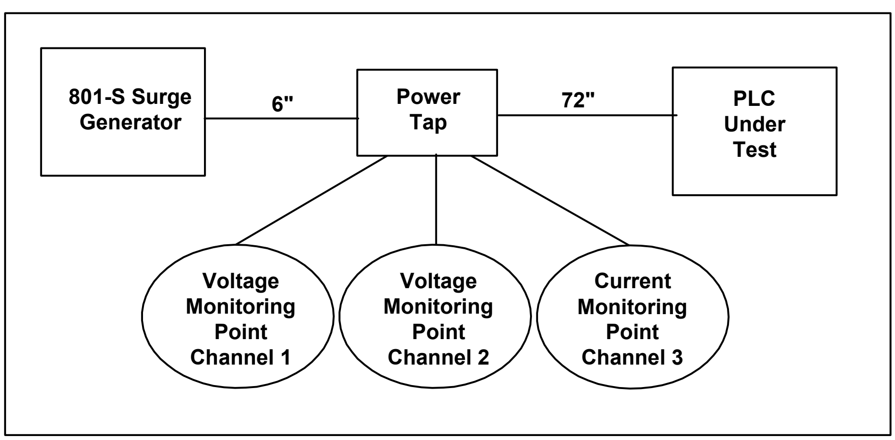


Figure G-16
Surge Test Set Up Without Power Conditioning

PLC Models A and B were subjected to lightning-strike transients without the benefit of external power conditioning. Tested in this mode, only internal surge suppressor protection from metal oxide varistors (MOVs) provided mitigation. PLC A was able to survive surges up to 3kV, but the power supply suffered critical damage from a 3.5kV line-to-neutral transient surge. The waveform is captured in Figure G-17.

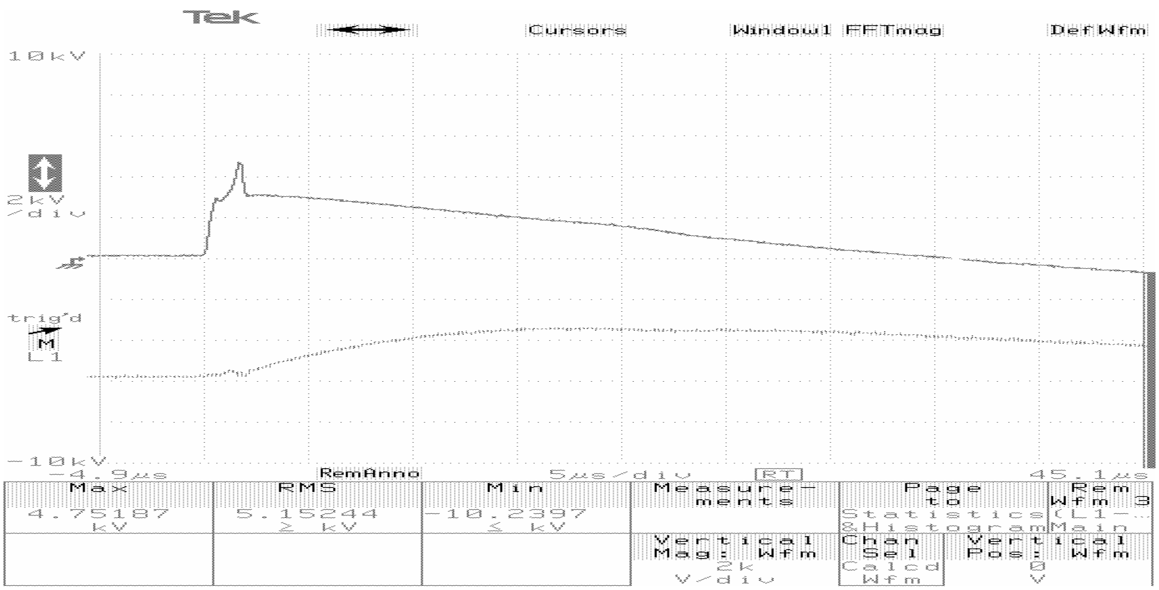


Figure G-17
Without an External Power Conditioner, PLC A's Power Supply Module was Critically Damaged at 3.5kV Line-to-Neutral Transient Surge

Unlike PLC A, PLC B was unaffected by transient surges up to 4kV line-to-ground. As shown in Figure G-18, the PLC power supply module clamped the 4Kv transient to 1.24kV.

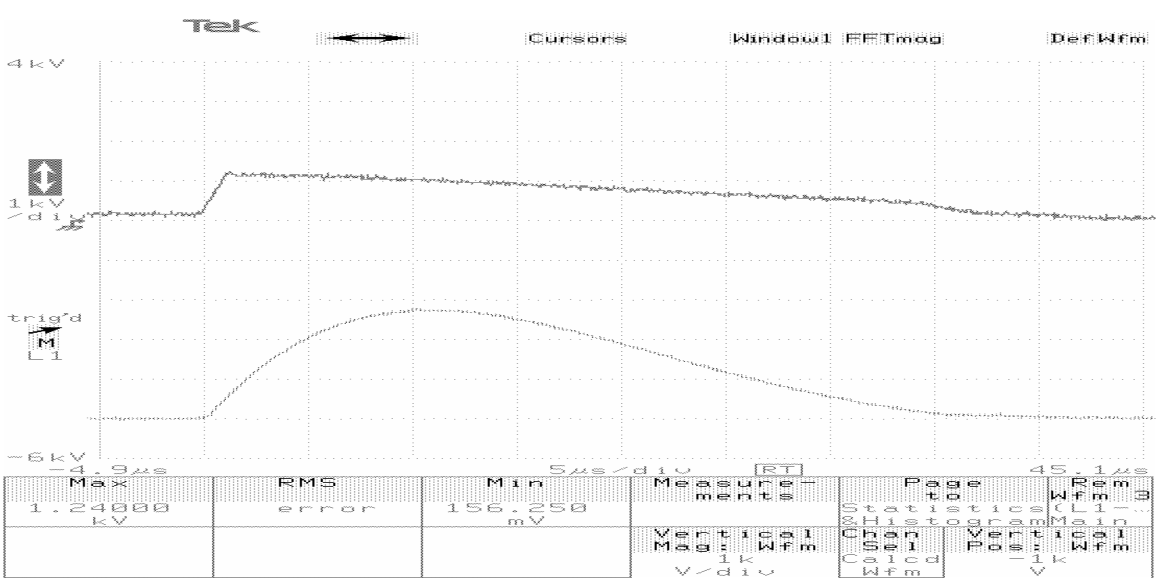


Figure G-18
4kV Line-to-Neutral Transient Surge had no Effect on PLC B

Further examination of the MOV surge suppression scheme in PLC A's and PLC B's power supplies was conducted following the test to determine why PLC A's power supply failed and PLC B's power supply did not. Figure G-19 shows the MOV placement in the two supplies. In PLC A, the designer chose to use two MOVs wired in a line-to-neutral and neutral-to-ground scheme. Furthermore, the incoming power is routed into the power supply solder trace past several electronic elements before it reaches the surge suppression devices. Inspection of the power supply after the unit failed revealed that the main switching transistor was damaged and a nearby resistor had opened. This probably occurred due to flashover of incoming surge voltage.

In contrast, PLC B's surge suppression design is more thorough. Three MOVs are utilized in the power supply to suppress line-to-neutral, neutral-to-ground, and line-to-ground surge events. Furthermore, the MOVs are in very close proximity to the incoming AC power source. Therefore, the MOV should provide surge mitigation with a lower risk of exposing other power supply components to the transient. The MOVs in this power supply were marked with known designations. Therefore, it was possible to determine that the devices were designed to clamp at around 800 volts at 2,000 amps.

PLC A Power Supply MOV Scheme:
2 MOVS: Line-to-Neutral and
Line-to-Ground

PLC B Power Supply MOV Scheme:
3 MOVS: Line-to-Neutral, Line-to-Ground,
Neutral-to-Ground

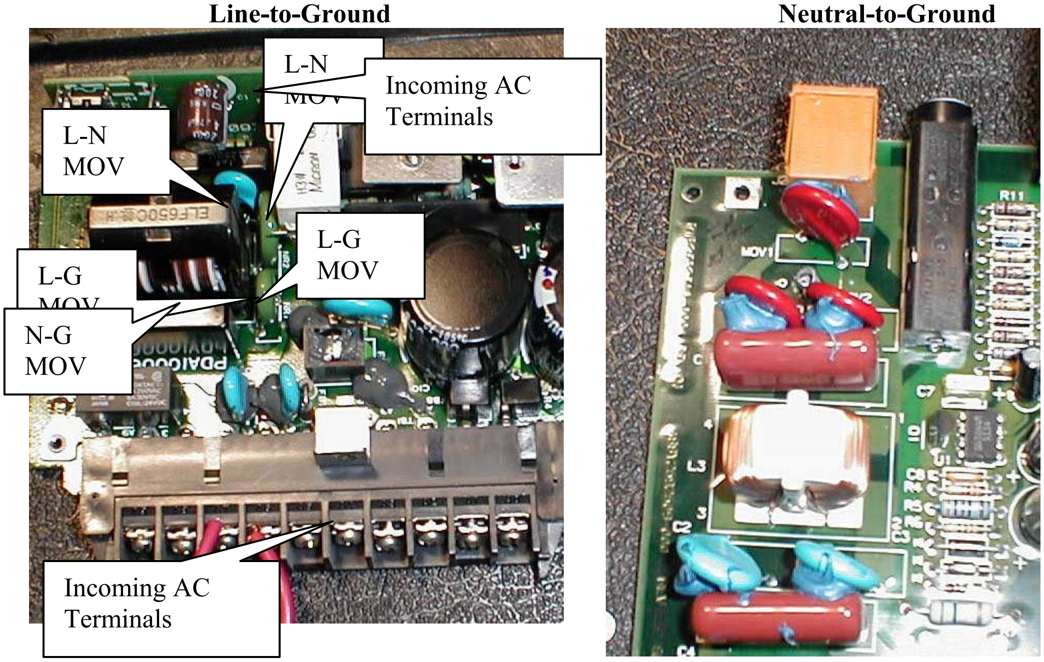


Figure G-19
Breakout of PLC A and PLC B Power Supply Surge Suppression Schemes

Conclusion

Laboratory tests conducted in 1995 and 2000 indicate that PLCs generally are not susceptible to capacitor-switching transients. However, the long-term effect of repeated capacitor switching transients on the PLC is not known. In addition, control devices, such as instrumentation and power supplies, may pass the transient event, possibly leading to erratic process operation. Therefore, mitigation of the transient is still desired.

The lightning-induced transient tests indicate that PLCs are susceptible to these surge events, possibly resulting in damage to the I/O rack power supply. The design of the PLC power supply, surge suppressor, and filter protection scheme can lead to increased survivability for the system. However, if the transient can be mitigated prior to reaching the PLC system, the odds for surviving such events increases dramatically.

A constant-voltage transformer acts as an isolation transformer and provides voltage sag, swell, and transient mitigation. Laboratory tests demonstrated the ability of an off-the-shelf CVT to suppress both capacitor-switching transients as well as lightning-induced transients up to 4kV line-to-neutral and 3.5kV line-to-ground. Although the surge event led to a flashover between the line and ground conductors at the 3.5kV level, the output of the CVT remained steady.

Many off-line UPS systems will still allow transients to pass before switching to the battery source. Furthermore, it is important to note that units that produce square-wave outputs are not always compatible with PLC I/O modules. These tests further demonstrated that line-interactive, on-line UPS units mitigate transients. This is due in part to the internal CVT that is designed into the UPS.

Based on the results of this work, it is apparent that PLCs with well-designed surge mitigation can survive transient events without damage to the PLC power supply. However, this does not ensure that the other control system components, such as power supplies, sensors, relays, and contactors, will not be damaged or lead to a process aberration. For this reason, a comprehensive strategy to provide mitigation to the PLC power supply and to the control power for the system is recommended. Utilizing a power conditioner such as a CVT in this manner will improve the ability of the control system to go unscathed when transient events occur.

Future testing should be performed to determine the effect of ground referencing and unregulated potentials between I/O card wiring and the power supply. Research also should be conducted to understand the different mode of transient coupling on data lines to verify the effectiveness of different data line surge protectors for control systems application.