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Technology Assessment and Application Guide for the Utility Systems Technologies Voltage Sag Fighter

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ABSTRACT

Voltage sag, a disturbance in a power system defined as a decrease in root mean square (RMS) voltage magnitude lasting from 0.5 to 30 cycles, has been identified as the most prevalent power disturbance experienced by industrial customers. The higher frequency of voltage sages makes them inherently more costly than interruptions since fault-induced, short-duration voltage variations can result in costly loss of production, damaged materials, repair and cleaning of equipment, and lost business opportunities. Devices that can provide ride-through for critical processes without the use of batteries for energy storage are beginning to enjoy widespread application in industry as a way of preventing these problems. One such technology is the Sag Fighter by Utility Systems Technologies (UST), a firm based in Latham, New York.

This report describes and documents the operation and the performance evaluation of a three-phase 150-kVA UST Sag Fighter unit designed for 480-volt applications. All testing occurred in the laboratory of an EPRI-member utility and was conducted either by utility personnel or by EPRI engineers using sag-generation equipment manufactured by EPRI. EPRI engineers used a test protocol included in this report for their series of tests along with the SEMI F47 standard for sag testing.

The results of testing did not show that the device would protect loads consistent with the SEMI F47 standard. However, due to abnormalities discovered with the equipment under test during EPRI's series of tests and later analysis of collected data, the results of testing may be considered inconclusive; and further testing of this device will be necessary once it is repaired and again becomes available for testing.

Keywords

Power quality
Voltage sag

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1
INTRODUCTION

Background

As utility industrial customers enhance their productivity with modern electronic automation equipment, the sensitivity of such equipment to disturbances in the power system becomes increasingly important. While interruptions in power still occur, they are not the most common event. Instead, the *voltage sag* has been identified as the most prevalent power disturbance experienced by industrial customers. Their higher frequency of occurrence makes them inherently more costly than interruptions.

A *voltage sag* is defined as a decrease in RMS voltage magnitude lasting from 0.5 to 30 cycles. Voltage sags are usually caused by a fault in the utility transmission or distribution system. Such power-line faults can be caused by animals on lines, a car striking a utility pole, or lightning strikes to power lines. Although proper maintenance, grounding, and arresters can minimize the number of faults, faults can never be eliminated completely.

Fault-induced, short-duration voltage variations can result in costly loss of production, damaged materials, repair and cleaning of equipment, and lost business opportunities. Recognizing these trends and seeking to reduce or prevent such losses by customers, EPRI, in conjunction with several utilities, has undertaken numerous power quality projects for customers in many sectors, addressing problems related to voltage sags and implementing innovative technologies such as ride-through and energy-storage devices.

Devices that can provide ride-through for critical processes without the use of batteries for energy storage are beginning to enjoy widespread application in industry. One such technology is the Sag Fighter by Utility Systems Technologies (UST), shown in Figure 1-1. The Sag Fighter comes in various sizes for application to sensitive loads with a wide range of power ratings. The particular model tested may not represent the performance of UST's current machines because various upgrades have occurred since the tested unit was purchased. As shown in Figure 1-2, the model tested by EPRI is a three-phase, 150-kVA unit designed for 480-volt applications.

Figure 1-1
UST Sag Fighter with LCD Screen Panel

Figure 1-2
Nameplate for the UST Sag Fighter

Company Overview

Utility Systems Technologies, Inc. (UST) was founded 1991 by Dr. Robert Degeneff—its focus being the design and manufacture of electronic voltage-regulation products and performing analyses of electrical systems and transients. By 2001, the business produced a line of power-conditioning products, one of which is the subject of this report, the Sag Fighter.

Sag Fighter Operation

The three-phase Sag Fighter employs a method to correct voltage sags called "series injection," where the existing input voltage waveform is monitored by the device and corrective action is taken when required. In case of voltage sag, the missing voltage in the input voltage waveform is calculated and is replaced by the sag-correction device. Figure 1-3 shows a simple schematic of the operation of such a device.

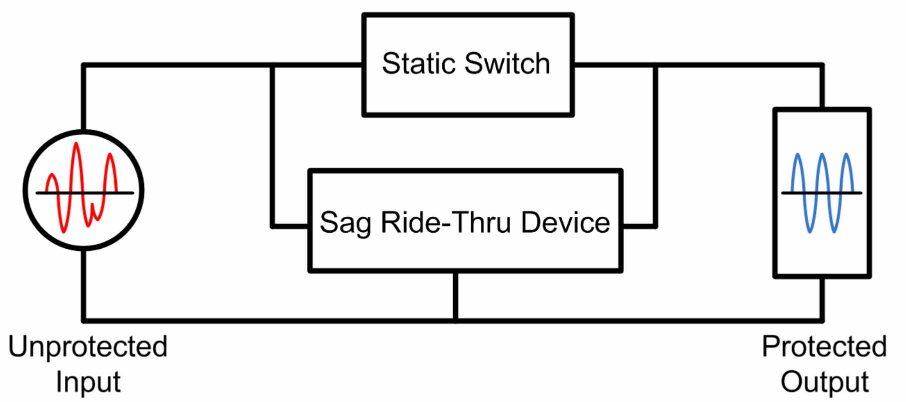


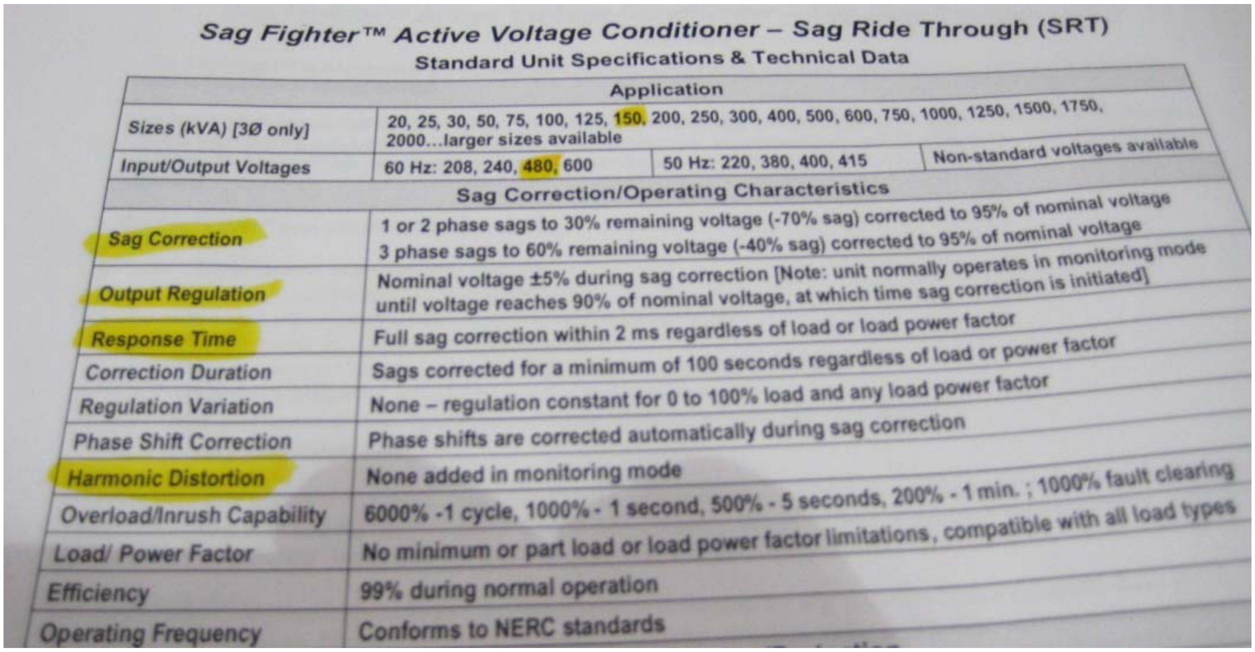
Figure 1-3
Schematic of Sag Fighter Operation

The Sag Fighter operates without batteries or energy storage. According to the manufacturer, the unit may sustain several levels of inrush current for specified periods of time as may be seen in Figure 1-4. Other advertised features in the manufacturer's literature include:

- Full sag correction within 2 milliseconds.
- Sag protection compliant with SEMI F47.
- Sag correction up to 100 seconds.
- Bypass operation is not required for high inrush or overload currents.
- Continuous protection without the need to recharge or reset.

The unit uses a three-phase transformer with the secondary windings connected in series between the incoming line and the load. The primary windings are series-connected and will provide corrective power when activated. During normal operation, the unit monitors the condition of the incoming power, allowing load current to flow through the secondary windings only. Should a deviation be sensed, the unit activates an inverter circuit to apply an injection voltage to the transformer's primary windings sufficient to correct the deviation at the transformer output for up to 100 seconds. When normal voltage conditions resume, the unit resumes monitoring line conditions.

A display on the front of the unit provides information on the unit's status as well as timestamps for sag-correction events. Alarm contacts are provided to allow indication of unit status remotely. Having no batteries, the unit should require no regularly scheduled maintenance.



Sag Fighter™ Active Voltage Conditioner – Sag Ride Through (SRT)
Standard Unit Specifications & Technical Data

Application			
Sizes (kVA) [3Ø only]	20, 25, 30, 50, 75, 100, 125, 150, 200, 250, 300, 400, 500, 600, 750, 1000, 1250, 1500, 1750, 2000…larger sizes available		
Input/Output Voltages	60 Hz: 208, 240, 480, 600	50 Hz: 220, 380, 400, 415	Non-standard voltages available
Sag Correction/Operating Characteristics			
Sag Correction	1 or 2 phase sags to 30% remaining voltage (-70% sag) corrected to 95% of nominal voltage 3 phase sags to 60% remaining voltage (-40% sag) corrected to 95% of nominal voltage		
Output Regulation	Nominal voltage ±5% during sag correction [Note: unit normally operates in monitoring mode until voltage reaches 90% of nominal voltage, at which time sag correction is initiated]		
Response Time	Full sag correction within 2 ms regardless of load or load power factor		
Correction Duration	Sags corrected for a minimum of 100 seconds regardless of load or power factor		
Regulation Variation	None – regulation constant for 0 to 100% load and any load power factor		
Phase Shift Correction	Phase shifts are corrected automatically during sag correction		
Harmonic Distortion	None added in monitoring mode		
Overload/Inrush Capability	6000% -1 cycle, 1000% - 1 second, 500% - 5 seconds, 200% - 1 min. ; 1000% fault clearing		
Load/ Power Factor	No minimum or part load or load power factor limitations, compatible with all load types		
Efficiency	99% during normal operation		
Operating Frequency	Conforms to NERC standards		

Figure 1-4
Manufacturer's Literature – Standard Unit Specifications and Technical Data

Report Organization

This report describes in detail the operation of the Sag Fighter observed during testing, its performance characteristics, and its applications and limitations. The second chapter provides an in-depth analysis of the various characterization tests performed and the results of the tests. The third chapter provides the applications and potential application issues of the device. The last chapter summarizes the tests and the results of the tests.

2
CHARACTERIZATION TESTS

Significance of Characterization Tests

The characterization tests highlight most of the common and in some cases the extreme conditions that may occur in typical manufacturing plants such as semiconductor fabrication, glass manufacturing, and plastics manufacturing, to name a few. The characterization tests thus bring out the ability of the device to handle various sensitive and severe conditions in a plant. Additionally, the characterization tests provide information that may help the customer to evaluate the suitability of this device in a particular facility.

Objective of the Tests

The objectives of the characterization tests are:

1. To characterize the performance of the device and verify that it meets the manufacturer's specifications.
2. To find the response time of the device to correct sag voltages.
3. To determine whether the device can handle large inrush currents caused by induction-motor loads.
4. To determine the sag-protection envelope of the device with industrial load types like ice-cube relays and magnetic contactors.
5. To uncover any application issues that will be valuable to the end user.

Test Setup

All testing occurred at the member utility's lab facility. The equipment under test (EUT) was a three-phase, four-wire, 480-V device with a current rating of 200 amps. The model number of the EUT was SRT-0150-480. Figure 2-1 shows the schematics of the test setup and Figure 2-2 shows the actual laboratory test setup. The 480-V_{AC} source was derived from the utility. EPRI's portable sag generator, which has a 200-A capacity, was connected in series between the EUT and the AC source. The load consisted of a three-phase 250-kW resistive load from the utility and a set of sensitive loads (a programmable logic controller (PLC) and an AC relay). It should be noted that the sensitive relay and PLC loads were connected to phase A-B only. The input and output measurements were recorded on a Nicolet Vision data-acquisition system, which is capable of storing transient as well as steady-state voltage and current waveforms at the rate of 1-kHz to 100-kHz sampling frequency.

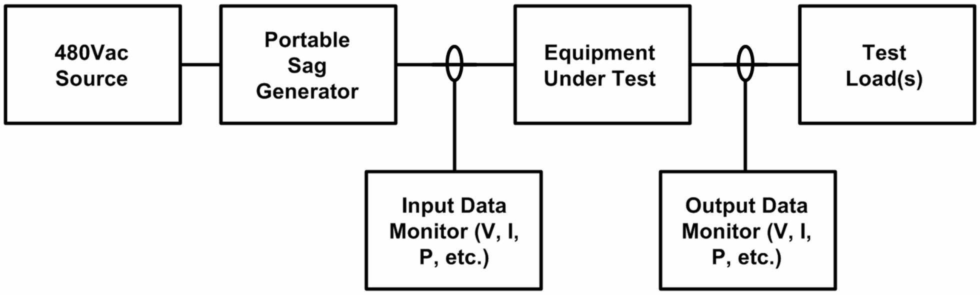


Figure 2-1
Schematic of the Test Setup

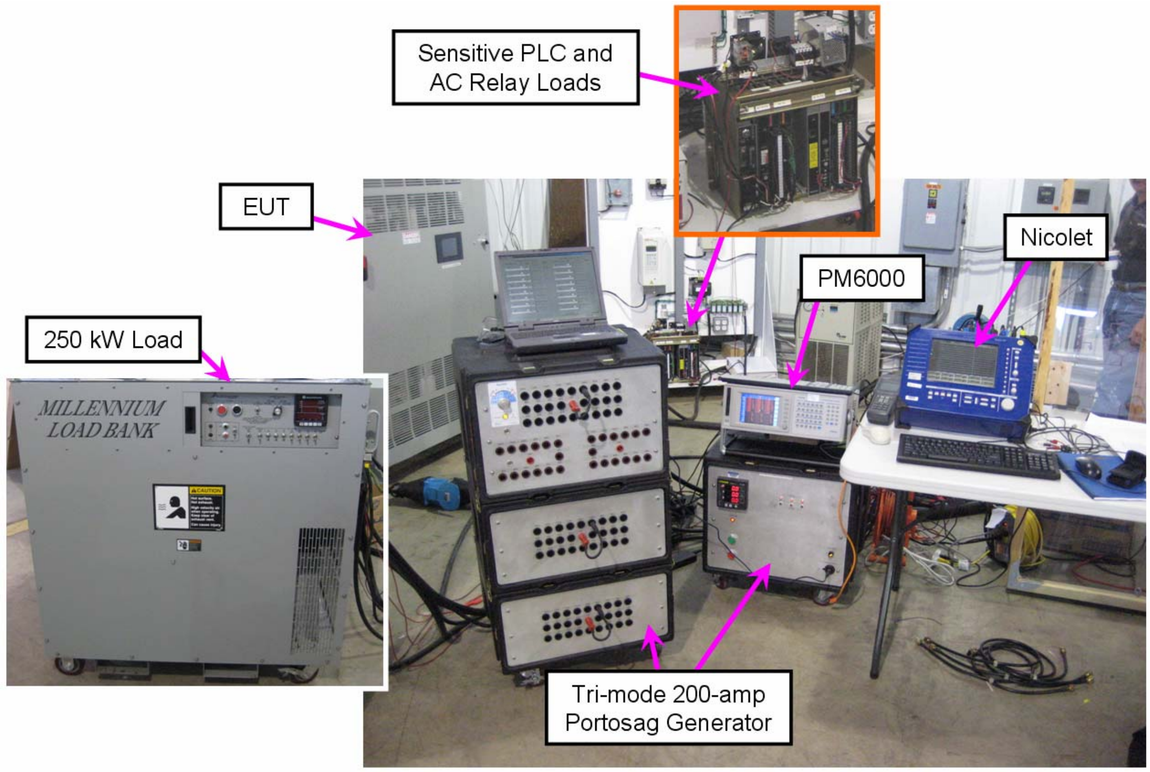


Figure 2-2
Actual Test Setup in the Field

Voltage-Sag and Interruption Tests

Automatic reclosers installed on distribution circuits protect the utility's equipment while providing the convenience of automatically restoring power after a fault. If a fault causes the circuit protection to open, a recloser will attempt to reapply power. In some cases, a fault will clear itself and power can be restored. If not, the recloser will typically make three to four attempts before "locking out" and requiring manual intervention. These repeated operations are often seen as successive voltage sags by customers on adjacent feeders.

Momentary reductions in line voltage lasting several cycles or longer may also occur when large loads are switched on. Voltage sags are one of the most common and most costly power quality issues in manufacturing environments. *Voltage sag* is defined as a decrease in the RMS voltage magnitude lasting from 0.5 to 30 cycles. When voltage sags are severe enough to interrupt a manufacturing process, the common results are downtime, product waste, and a lengthy cleanup. A momentary decrease in line voltage lasting several cycles can cause electronically-controlled equipment to respond by shutting down. In the case of sensitive relays, a normally-closed relay or contactor may open momentarily or "chatter" due to the sag. A PLC or motor drive may interpret this brief opening as a loss of voltage and stop the process. The PLC itself may shut down should its own input voltage be determined to be too low even briefly. For the purposes of testing, a trip occurred when the PLC was observed to reset in response to the voltage sag.

During the voltage-sag and interruption tests, the EUT was subjected to voltage sags of various magnitudes and durations. The voltage sags were of three different modes: phase-to-neutral, phase-to-phase, and three-phase.

SEMI F47 Tests

SEMI F47 is a stringent standard required by semiconductor industries to protect sensitive equipment in their facilities from voltage sags. Figure 2-3 shows the SEMI F47 standard curve used by the industry. According to this curve, a power quality mitigation device is said to have passed the SEMI F47 standard if it can protect the load from voltage sags on or above this curve. Any event below this curve may not be protected.

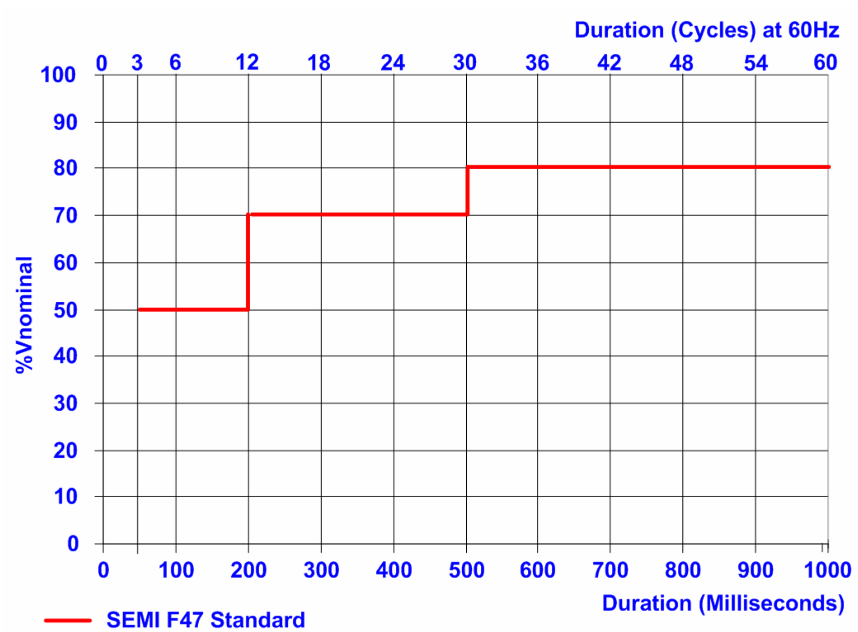


Figure 2-3
SEMI F47 Curve

Results of Sag Testing

Types of Voltage Sags

The phase-to-neutral voltage sags used in testing are illustrated in Figure 2-4.

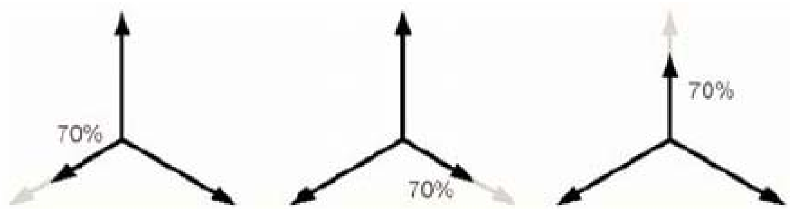


Figure 2-4
Phase-to-Neutral Voltage Sags

Two types of phase-to-phase voltage sags were considered for voltage sag testing: IEC-1 and IEC-2. The IEC-2 variety of voltage sag corresponds more closely to conditions experienced in the field. Figure 2-5 illustrates the two types of sags. EPRI engineers subjected the EUT to both types of sags.

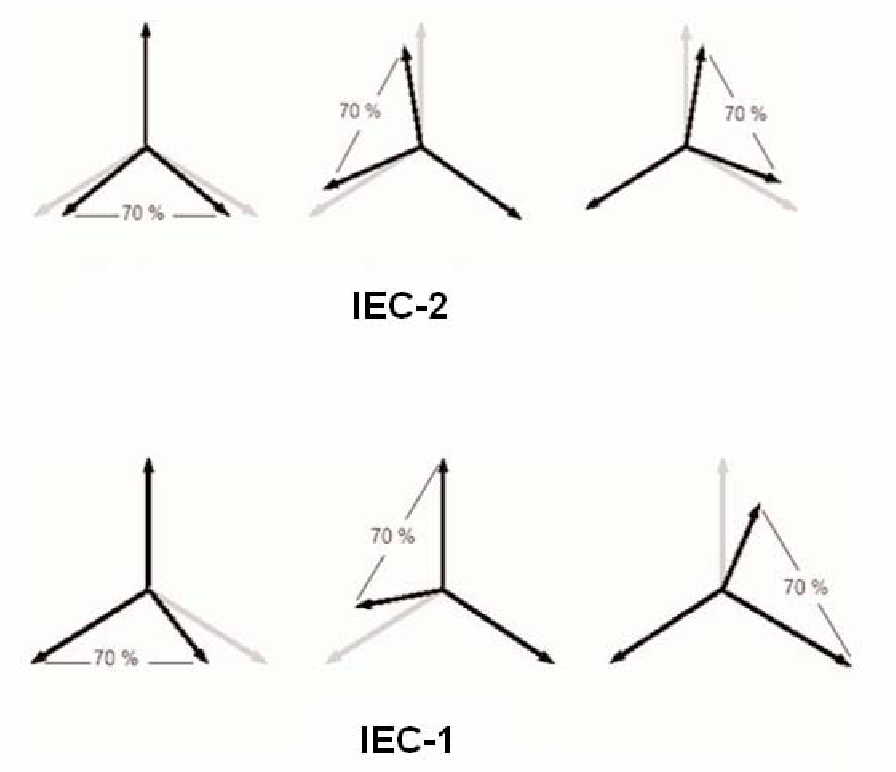


Figure 2-5
IEC-1 and IEC-2 Sag Types

Two phase-to-neutral voltage sags are illustrated in Figure 2-6.

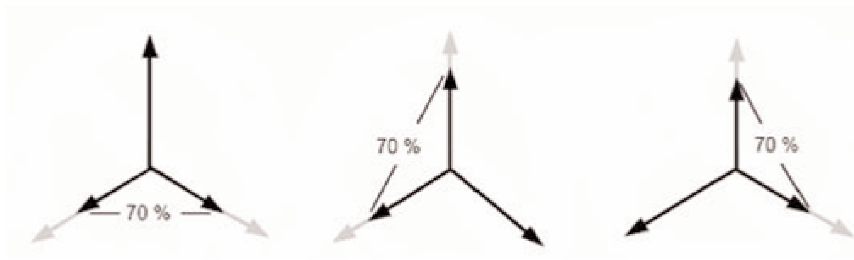


Figure 2-6
Two-Phase-to-Neutral Voltage Sag Type

While the rated load for the EUT should be around 200 amps, initial testing of the device by the utility using their own sag generator resulted in current inrush levels that caused damage to their sag generator. Therefore, it was determined that the load level for tests performed by EPRI would be less in order to prevent similar damage to EPRI's sag generator; two levels would be examined—approximately 50 amps and 100 amps.

As per the test protocol, the EUT was subjected to voltage sags of 3, 5, 10, 12, 30, and 60 cycles of the following magnitudes: 80%, 70%, 60%, 50%, 40%, and 0% of nominal voltage.

Test 1: Phase-to-Neutral Sags

Results of the single-phase-to-neutral voltage-sag testing for the EUT are illustrated in Figure 2-7 and Figure 2-8. As shown, the sensitive control load tripped on the SEMI F47 curve for single-phase sags at the 50-amp level, and above the curve for phases A and B at 5 cycles and 60% of $V_{NOMINAL}$ for the 100-amp level.

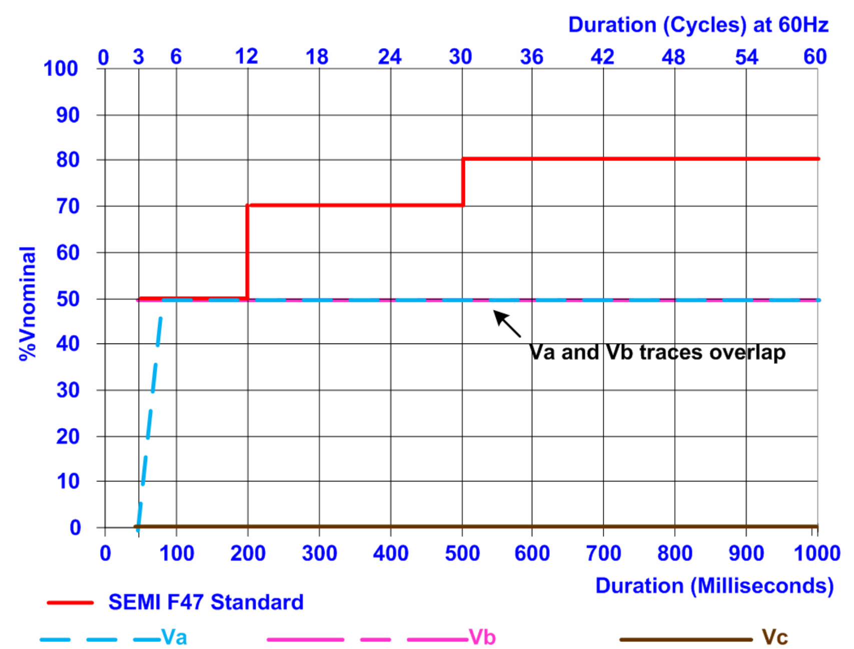


Figure 2-7
Voltage-Sag Curves for 50-Amp Load, Single-Phase-to-Neutral

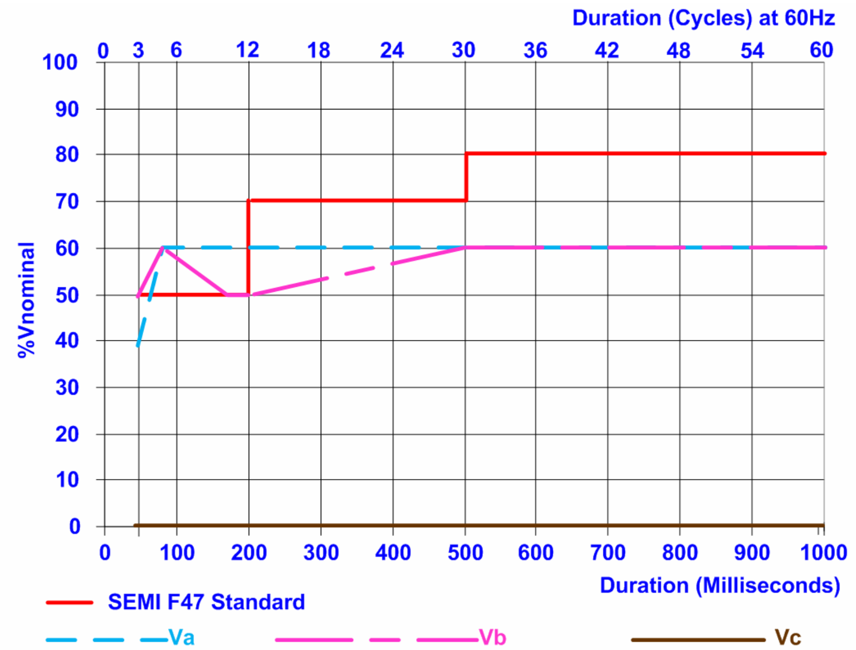


Figure 2-8
Voltage-Sag Curves for 100-Amp Load, Single-Phase-to-Neutral

Test 2: IEC-2 Phase-to-Phase Sags

Two-phase-to-neutral testing, shown in Figure 2-9, produced identical results for the 50- and 100-amp load levels: The sensitive load tripped for phase A-to-B sags just below 80% of $V_{NOMINAL}$, while no tripping occurred for either phase B-to-C or C-to-A even for 0% of $V_{NOMINAL}$ (shown at the bottom of the graph).

Therefore, the UST Sag Fighter device did not comply with SEMI F47 certification during this test.

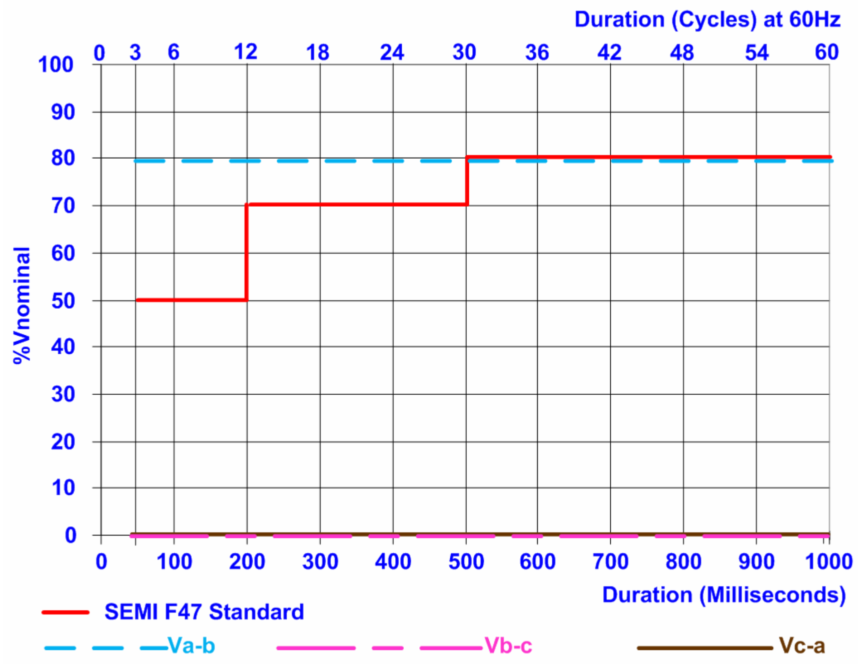


Figure 2-9
Voltage Sag Curves: IEC-2 Tests for 50-Amp and 100-Amp Loads

Test 3: IEC-1 Phase-to-Phase Sags

During EPRI's testing, the observed behavior of the EUT to IEC-1 sags was similar to that observed for the IEC-2 voltage sags. Figure 2-10 illustrates the EUT's response. The apparent lack of voltage-sag mitigation illustrated in the figure will be discussed later. The manufacturer advertises phase correction; however, the figure shows little or no sag or phase correction for the IEC-1 sag.

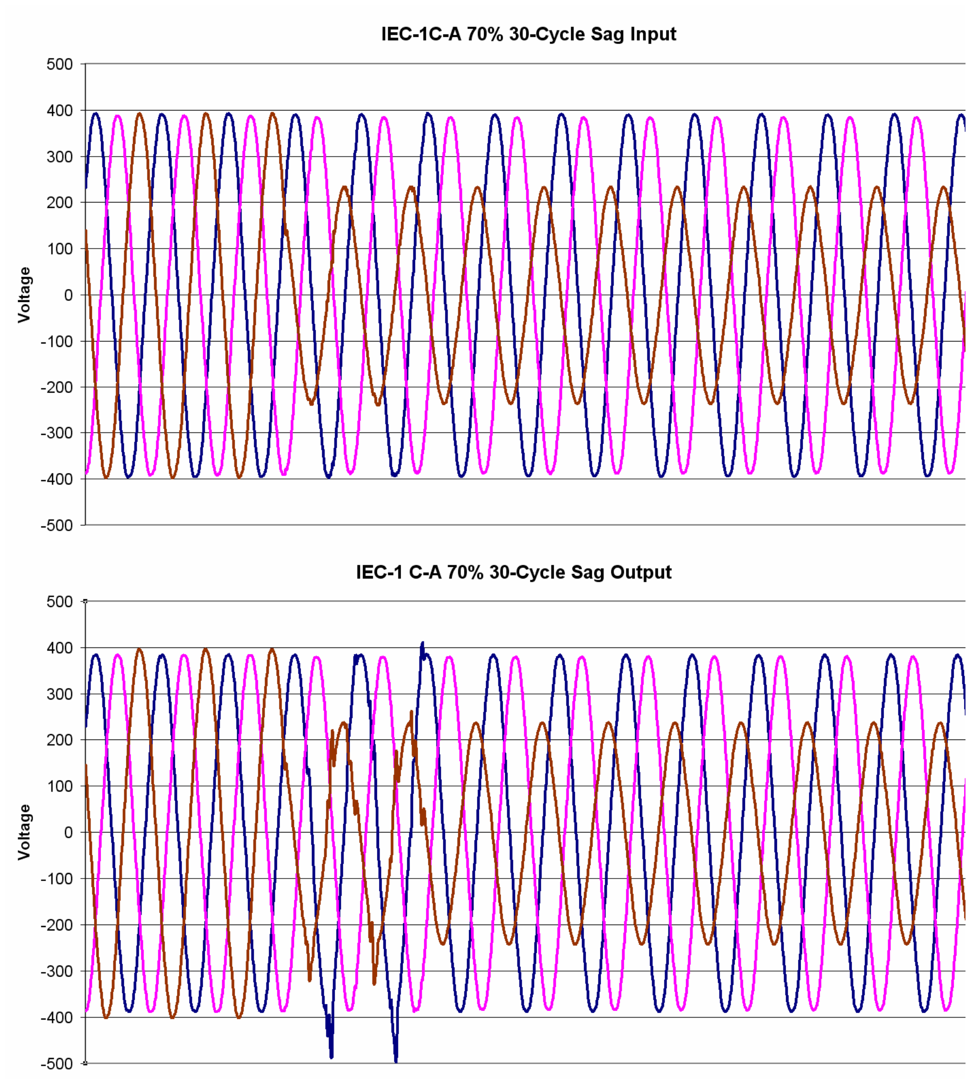


Figure 2-10
Voltage Sag Curves: Representative IEC-1 Test

Test 4: Two-Phase-to-Neutral Sags

50-Amp Load

Testing indicated that when loaded at 50 amps, the EUT mitigated voltage sags down to 80% $V_{NOMINAL}$ for 3 to 60 cycles in duration with the sensitive load connected only from phase A to B. In this same configuration, the EUT mitigated voltage sags down to 40% of nominal for phases B to C and C to A, as shown in Figure 2-11.

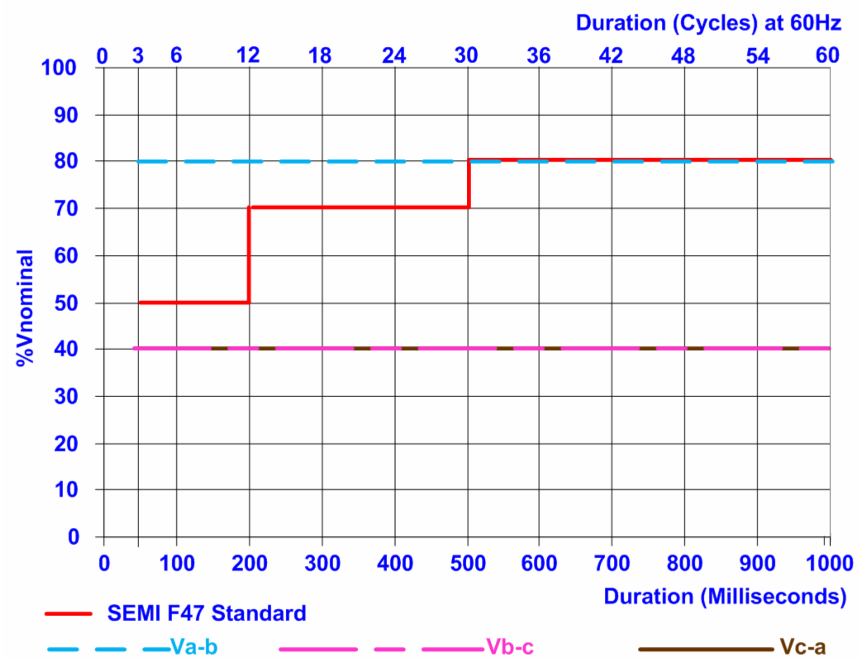


Figure 2-11
Two-Phase-to-Neutral Tests: 50-Amp Load

100-Amp Load

As with the previous testing, the EUT (this time loaded to 100 amps) mitigated voltage sags down to 80% $V_{NOMINAL}$ for 3 to 60 cycles in duration with the sensitive load connected from phase A to B. The EUT mitigated voltage sags down to 60% of nominal for phases B to C and from C to A for the same configuration, as shown in Figure 2-12. Although the Sag Fighter was completely compliant with the F47 standard during the 50-amp testing for phases B to C and from C to A, it was not fully compliant for the 100-amp testing on those two phase configurations, falling out of compliance under 12 cycles.

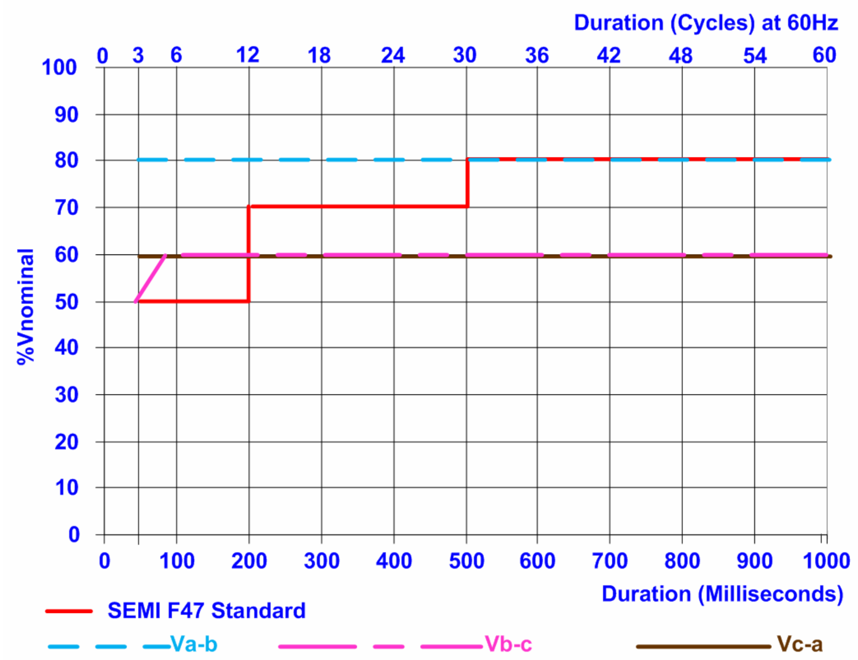


Figure 2-12
Two-Phase-to-Neutral Tests: 100-Amp Load

Again, test results indicate that the EUT did not perform in compliance with the SEMI F47 standard.

Three-Phase Sags

The SEMI F47 standard does not have any requirements for three-phase voltage sags.

Analysis of Sag Testing

Manufacturer literature for the Sag Fighter indicates that it should support a voltage sag down to 30% of nominal voltage. However, for both the 50-amp and 100-amp loads, the sensitive load tripped for several sags at or above the SEMI F47 curve.

A closer examination of test data, however, may indicate that the EUT may not have functioned properly at the time of testing. Figure 2-13 illustrates porto sag waveforms taken from earlier testing performed by the utility with a load current of around 92 amps. In this case, the EUT's response shows what should have been a reasonably successful attempt at mitigating a five-cycle voltage sag within about one-quarter cycle (4 milliseconds) from the start of the sag, which is close to the 2 milliseconds advertised by the manufacturer. Figure 2-13 also reveals two characteristics of the EUT's apparent response to the single-phase voltage sag: voltage swells on the other two unsagged phases and mitigation not quite achieving 100% on the sagged phase. This condition is examined further later in the report. By comparison, in Figure 2-14, a Nicolet recording of a voltage sag of similar magnitude and duration during EPRI's testing shows a faltering response and ultimately little if any mitigation as the waveform magnitudes of phase A input and output (Δain and Δaout) seem to be identical toward the end of the voltage sag. Further testing indicated a similar response to voltage sags at other magnitudes and durations for all phases for both IEC-1 and IEC-2 types of sags; that is, little or no mitigation being evident at the output. Because the sensitive PLC and relay loads were connected to only phase A-B, the voltage sags on the other phases, while as severe, might not be expected to affect these sensitive loads as significantly as voltage sags to phase A during this round of testing.

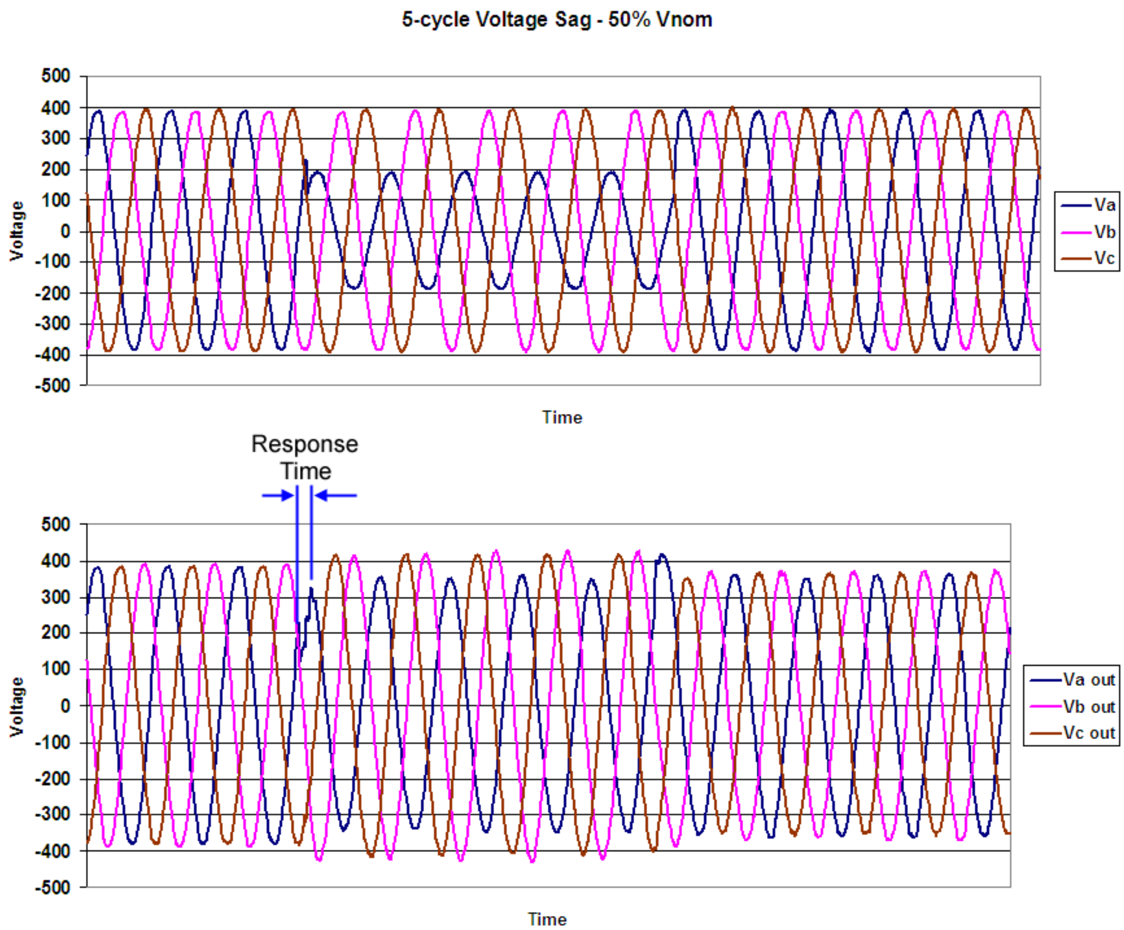


Figure 2-13
Voltage-Sag Waveforms from Utility Testing: Voltage Input (Top) and Voltage Output (Bottom)

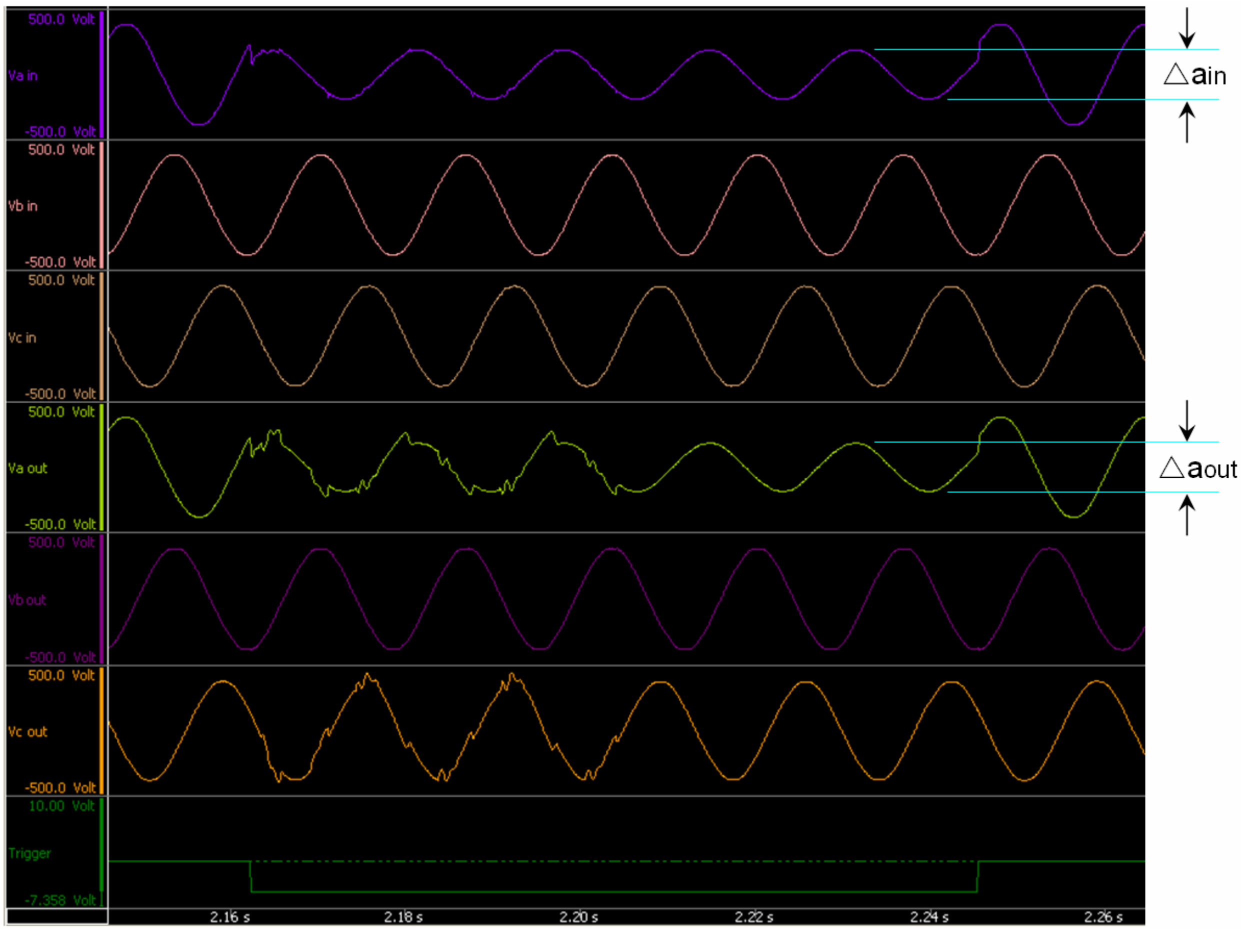


Figure 2-14
Voltage-Sag Waveforms from EPRI Testing

The difference in the two response characteristics shown in Figure 2-13 and Figure 2-14, taken at different times with the same EUT, suggests a problem existed with the EUT at the time of EPRI's tests that may not have been apparent during earlier testing by the utility. Indeed, not long after the field test, EPRI engineers learned that the EUT had been sent to the manufacturer for repairs to a faulty silicon-controlled rectifier (SCR). It should be noted that during EPRI's testing, no indication of faulty performance seemed to appear on the EUT's LCD screen.

Inrush Current

Inrush current is a critical factor when buying any power conditioner. Typically, motor loads have a large inrush current, and the power conditioner should be able to handle such current transients. Earlier testing by the utility resulted in inrush currents of over 1,000 amps. This inrush current may have caused damage to their sag generator which required repairs following their tests. It is possible that those same inrush currents damaged the aforementioned SCR. EPRI testing saw a current inrush peak of around 600 amps at one point during testing. However, in response to the high inrush current, the utility team had re-wired the power connections for a cooling fan motor on their 250-kW resistive industrial load bank to an entirely different power panel than that which powered the load bank during EPRI's testing; therefore, the measured inrush current levels from the two testing periods (before and after this change) may not not be comparable. At any rate, EPRI's tests did not reproduce the inrush current levels experienced by the utility.

Response Time

Response time is the time taken by the mitigation device to switch from the input supply voltage to the corrected voltage during a voltage sag. This is an important issue for power conditioners because some sensitive loads can trip before the transfer is complete (less than one cycle). The EUT has an advertised response time of 2 milliseconds. While impossible to confirm with EPRI's testing, closer examination of Figure 2-15 (a waveform from the utility's initial testing) suggests that the response time was very close to 2 milliseconds, or around an eighth of a cycle.

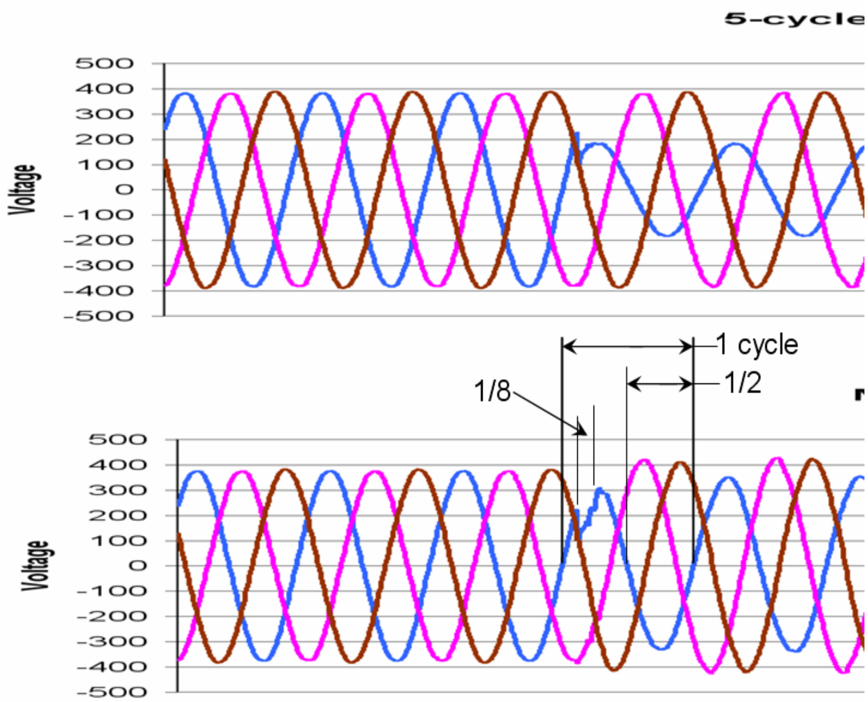


Figure 2-15
Graph of Response Time

Voltage Swell Tests

The EUT was subjected to voltage swells of up to a maximum of 115% of the rated nominal voltage. The voltage-swell testing did not produce any response from the EUT. This implies that during momentary voltage swells, the load sees the input voltage without correction. Electrical loads typically react more to voltage sags than momentary swells, so this condition may not cause problems to the majority of loads protected by the Sag Fighter.

Summary of Test Results

Due to an apparent malfunction of the EUT, the test results may not be considered conclusive. Certainly after the expected repairs (and perhaps upgrades) to this specific Sag Fighter have been accomplished by the manufacturer, SEMI F47 testing should be performed again. However, even with an apparently diminished capacity, the Sag Fighter almost passed the single-phase tests.

3
APPLICATION ISSUES

Due to the inconclusive nature of this round of testing, the suitability of the Sag Fighter for most loads is not clear. The transfer/response time is a critical issue because the device must respond within a fraction of a cycle in order to prevent the sensitive loads such as ice-cube relays or programmable logic controllers (PLCs) from dropping. An earlier round of testing seemed to support the specified response rate of 2 milliseconds.

Application issues include:

- *Input frequency.* The three-phase Sag Fighter is available for 50-Hz or 60-Hz application.
- *Neutral requirement*. The Sag Fighter is available in either three-wire (no neutral) or four-wire (neutral required) versions.
- *Response time.* Because control circuits often use small relays and very sensitive PLCs, care must be taken to ensure that the response time of the mitigation device is fast enough to prevent device dropout. Desensitizing control circuits may require reaction times as fast as ½ cycle, or about 8 milliseconds. Some PLCs and auxiliary relays can drop out as fast as 1 cycle; the Sag Fighter specification states that the device's detection and response time is 2 ms; therefore, most devices should not experience any problems.
- *Overload/inrush current.* The manufacturer's specifications for the Sag Fighter indicate that it may sustain 6,000% of rated current for one cycle, 1,000% for one second, and 200% for one minute. This specification was not tested. The onboard transformer and motor loads appeared to interact during tests performed by the utility during sag testing, as the utility reported a peak inrush current of over 1,000 amps.

Voltage Imbalance

Figure 2-13, shown earlier, indicates a possible source of problems for adjustable-speed drives (ASDs). The combination of the sag on phase A and the swells on phases B and C could be interpreted as a voltage imbalance of around 15%, which may cause the drive to trip. Certain parameters on most modern drives may be adjusted to avoid this problem.

System Reset

The EUT was observed to reset for 0% $V_{NOMINAL}$ voltage sags of 12 cycles and longer. No other activity or effect was observed due to the system reset.

System Maintenance

The manufacturer's specifications do not list any required maintenance.

4
SUMMARY

The evaluation of the UST Sag Fighter revealed a possible malfunction of the device perhaps due to damage sustained from high inrush currents. The EUT was subjected to extensive tests in the field. The results show that the tested Sag Fighter did not meet all of the specifications given by the manufacturer and did not meet the requirements of the SEMI F47 standard.

The display on the front of the EUT did not give any indication of the apparent malfunction of the unit being tested, neither for the utility during their tests nor for EPRI engineers.

After the round of testing that was the subject of this report, this Sag Fighter was sent back to the manufacturer for repairs and upgrades. The device had not been returned to the utility as of the writing of this report. Therefore, once repairs have been effected and the unit returned, this Sag Fighter should be tested again to better characterize its capabilities.

A

STANDARDS REQUIRED BY THE SYSTEM COMPATIBILITY TEST PROCEDURE

The documents listed below are standards applicable to testing industrial equipment, including intelligent motor controllers, programmable logic controllers, and other electronic equipment. These include definitions, test procedures, and general considerations, as well as certain requirements specific to the agency that developed the standard.

1. ANSI/IEEE Standard 141-1993, IEEE Recommended Practices for Electric Power Distribution for Industrial Plants.
2. ANSI C84.1-1989, Voltage Ratings for Power Systems and Equipment.
3. IEC 61000-2-1, Part 2 – Environment, Section 1: Electromagnetic Environment for Low-Frequency Conducted Disturbances and Signaling I Public Power Supply Systems.
4. IEC 61000-2-2, Part 2 – Environment, Section 2: Compatibility Levels for Low-Frequency Conducted Disturbances and Signaling I Public Power Supply Systems.
5. IEC 61000-2-4, Part 2 – Environment, Section 4: Compatibility Levels in Industrial Plants for Low-Frequency Conducted Disturbances.
6. IEC 61000-4-1, Part 4 – Testing and Measurement Techniques, Section 1: Overview of Immunity Tests.
7. IEC 61000-4-11, Part 4 – Testing and Measurement Techniques, Section 11: Voltage Dips, Short Interruptions, and Voltage Variations Immunity Tests.

B
TEST PROTOCOL

Introduction

Scope

This document defines a test protocol for the evaluation of the functionality of three-phase voltage restoration devices that are designed to support loads up to 100kVA during voltage sags. Each test is designed to help the investigator assess a particular aspect of compatibility between the electrical environment and the device under test. The protocol includes definitions and reference standards where applicable. For each test described in the document, a rationale, purpose, test procedure, and required instrumentation is listed.

Although this protocol was specifically written to evaluate the functionality of three-phase voltage restoration devices, it may be applied to other large power electronic devices such as adjustable speed drives, dynamic voltage restorers, and static VAR compensators to name a few.

This test protocol is intended to be compatible with industry Standards, in particular the safety requirements set forth by Underwriter Laboratories (UL), the Institute of Electrical and Electronics Engineers (IEEE) and the American National Standards Institute (ANSI). Applicable standards, test procedures and other requirements specified by the respective agencies or organizations may be more stringent than the criteria defined in this document. Therefore, meeting the criteria defined herein should not be construed as a waiver of any other relevant performance or safety requirements.

Rationale and Purpose of the Test Protocol

The need for higher production rates, lower production costs, and increased reliability in today's highly competitive world markets are fueling the need for increased automation and control of industrial processes. As a result, electrical equipment such as motor protection relays, intelligent motor controllers, programmable logic controllers (PLCs), adjustable-speed drives (ASDs), and computers are becoming more and more widely used to optimize performance in the manufacturing environment. Most industrial equipment is designed to operate when the electrical supply is "clean," that is, when voltage sags, momentary interruptions, voltage unbalance, single-phasing and other electrical disturbances are not part of the power supply. However, some variations in power quality are normal to power system operation. Most electrical disturbances are likely to occur repeatedly over the lifetime of an electric appliance.

Unscheduled shutdowns in production lines can be very costly. Electrical disturbances can cause both electronic and electromechanical devices to trip and shut down. Because of industry's dependency on automation, the susceptibility of these types of devices will largely determine the frequency and extent to which such shutdowns occur.

As new types of power conditioning equipment makes its way into the market, many users find that they understand little about the equipment's vulnerabilities and capacity to protect their loads. EPRI has developed this System Compatibility[1] Test Protocol to evaluate three-phase voltage restoration devices that are designed to support loads up to 100kVA.

Required Standards

The documents listed below are Standards applicable to industrial equipment including intelligent motor controllers, programmable logic controllers, and other electronic equipment. These include definitions, test procedures, and general considerations, as well as certain requirements specific to the agency that developed the Standard. At this time, the tests described in this protocol do not necessarily cover all of the performance criteria addressed in these documents, but cover specific portions of these documents:

8. ANSI/IEEE Standard 141-1993, *IEEE Recommended Practices for Electric Power Distribution for Industrial Plants.*
9. ANSI C84.1-1989, *Voltage Ratings for Power Systems and Equipment.*
10. IEC 61000-2-1, Part 2 – Environment*, Section 1: Electromagnetic Environment for Low-Frequency Conducted Disturbances and Signaling I Public Power Supply Systems.*
11. IEC 61000-2-2, Part 2 – Environment*, Section 2: Compatibility Levels for Low-Frequency Conducted Disturbances and Signaling I Public Power Supply Systems.*
12. IEC 61000-2-4, Part 2 – Environment*, Section 4: Compatibility Levels in Industrial Plants for Low-Frequency Conducted Disturbances.*
13. IEC 61000-4-1, Part 4 – Testing and Measurement Techniques*, Section 1: Overview of Immunity Tests.*
14. IEC 61000-4-11, Part 4 – Testing and Measurement Techniques*, Section 11: Voltage Dips, Short Interruptions, and Voltage Variations Immunity Tests.*

Three-Phase Voltage Restoration Equipment and the Electrical Environment

The Equipment under test (EUT) is a three-phase voltage restoration equipment designed to support and to protect its sensitive loads during voltage sags and/or other power quality-related phenomena. This type of equipment can be installed directly at the sensitive equipment, at the branch circuit, or even at the electrical service entrance.

Significant Performance Criteria

Performance criteria for a three-phase voltage restoration device involves a number of concerns related to its response to steady-state and momentary power system variations, such as temporary undervoltage, overvoltage, voltage sags, interruptions, voltage unbalance, and single-phasing conditions. In order to investigate these concerns, they are addressed individually by creating the particular disturbance under controlled conditions. As a minimum, the equipment under test (EUT) is expected to protect its load without causing harm to itself.

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[1] System Compatibility is the ability of equipment to work as designed in its intended electrical environment (called equipment immunity) without adversely affecting the operation of other equipment (called equipment emissions).

General Guidelines

Requirements for Test Samples

This section describes a procedure for procurement and documentation of test samples used for testing. These guidelines are written to help ensure consistency and accuracy during evaluation of the equipment.

Procedure for Procurement

It is a tenet of this protocol that test specimens should be obtained with the cooperation of the manufacturer to ensure that the units being tested correspond to the well-identified design of the device. Therefore, in addition to the information listed in the following section, which is intended to assist the user in selecting the device appropriate for the needs of the particular application, the manufacturer of the device will be requested to provide to the test laboratory relevant information such as date of manufacture, recent significant electrical design changes, and otherwise unpublished information that will place the tested specimens in the correct context. To ensure integrity of the data and to promote a relationship of trust, it is imperative that this information be considered confidential and be recorded only in the laboratory notebooks.

While procuring test samples, it is also important to request copies of all installation and operation instructions. The test facilitator(s) should become familiar with all documentation before testing begins.

When the equipment arrives at the test location, assign and record cross-reference codes for each specimen; i.e., Model A1, A2, A3; Model B1, B2, B3, etc. Apply these generic identification labels to the outer case and store the cross reference table in a safe place.

Nameplate Information

To assure correct application of the device under test, the following should be recorded on the data sheets labeled "Test 0: Manufacturer Nameplate Information". This information should be available on the device housing or package:

1. Manufacturer's name or trademark
2. Product name, model number, and serial number
3. Reference to listing or certification as applicable (UL, FCC, etc.)
4. Ratings: kVA, horsepower, voltage, current, and frequency

Test Plan and Number of Units Required

This test protocol contains data sheets and test guidelines which provide the guidance necessary to complete the testing. The test plan should optimize the test sequence so that all the devices are tested using each test setup. In this way, each test setup will only require a single construction. The number of devices shall be sufficient to allow for unexpected failures resulting from cumulative stresses of testing, test equipment malfunction, or test operator error. Potentially destructive tests should be performed last.

Test Instrumentation and Equipment

The required test equipment and instrumentation includes:

- Data acquisition system capable of accurately measuring true RMS voltages and currents. All tests require a monitor capable of measuring and recording all three phases of voltage (line to ground or line to neutral) and three phases of current on a cycle-by-cycle basis. This equipment should have a sampling rate of at least 64 samples per cycle. Accuracy of any measurement should be within +/- 1% of full scale. In addition to steady-state measurements, the data acquisition system is required to capture waveforms upon receipt of a trigger signal.
- Transducers having the range of voltages and currents that will allow measurements without signal distortion due to transducer saturation.
- A variable load bank having the capability to load the EUT at 25%, 50%, 75%, and 100% of its rated load (±5%).

Standard Test Conditions

The comparison of the tests results between two or more power conditioners will be valid only if the tests have been performed under identical test conditions. The following test conditions are based on the ANSI/IEEE Standards 100-1988 and 112-1984.

Temperature: 25ºC ±5ºC

Relative humidity: <85%

Altitude: < 2000m

RMS voltage tolerance: ±1%

Frequency 50 or 60Hz ±0.5%

Test 0: Manufacturer Nameplate Information

Rationale

Proper information records are necessary to ensure test equity and accurate, consistent reporting of the test results.

Purpose

To identify and maintain the pertinent information for the device tested.

Test Guidelines

Record the following information using the data sheet for Test 0:

1. Manufacturer’s name or trademark
2. Product name, model number, and serial number
3. Reference to listing or certification as applicable (UL, FCC etc.)
4. Ratings: kVA, horsepower, voltage, current, and frequency

Assign and record the cross-reference code for identification purposes, i.e., Model A1, A2, A3; Model B1, B2, B3, etc. Begin using these identification codes on all subsequent data sheets.

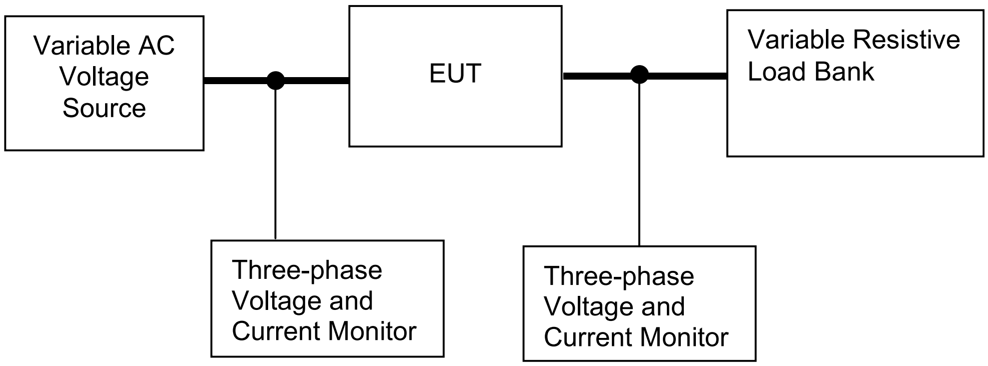


Figure B-1
Test Setup using Variable Resistive Load Bank

Test 1: Single-Phasing

Rationale

In cases where fuses are not coordinated or applied correctly, a single phase-to-ground fault in a facility can leave the other two phases in operation. Three-phase motors can overheat very quickly in this condition.

Purpose

These tests will identify the protection capabilities, susceptibilities, and application issues of the device during steady-state single-phasing conditions.

Test Set-up & Guidelines

1. Connect the EUT as shown in Figure 1.
2. Configure the resistive load bank for 50% of the EUT's rated load. Optionally, add any sensitive loads such as relays or contactors as load.
3. Reduce Phase A of the supply to zero volts.
4. Use the data sheet for Test 4 to record input and output voltages and currents. Indicate any alarm conditions of the EUT. Optionally, note whether the sensitive loads were upset by the conditions.
5. Return Phase A to nominal input voltage for the EUT.
6. Reduce Phase B to zero volts.
7. Record input and output voltages and currents. Indicate any alarm conditions of the EUT. Optionally, note whether the sensitive loads were upset by the conditions.
8. Return Phase B to nominal input voltage for the EUT.

9. Reduce Phase C to zero volts.
10. Record input and output voltages and currents. Indicate any alarm conditions of the EUT. Optionally, note whether the sensitive loads were upset by the conditions.

Test 2: Response to Voltage Sags and Interruptions

Rationale

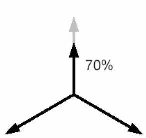
Momentary reductions in line voltage lasting several cycles or longer may result during power system faults and when large loads are switched on. Voltage sags are one of the most common and most costly power quality issues in manufacturing environments. When voltage sags are severe enough to interrupt a manufacturing process, the common results are downtime, product waste, and a lengthy cleanup. Because these events are so costly and so common, there are numerous voltage sag mitigation products on the market.

Purpose

This test will identify the protection capabilities, susceptibilities, and application issues of the three-phase power conditioner during voltage sags and interruptions. By connecting sensitive loads to its output, its effectiveness at providing load protection can be evaluated directly. The testing will be compared against standards such as SEMI F47 and ITIC, including testing the specific SEMI F47 test points.

There will be three types of sag test performed. Type I, Type II (of which there is three variations) and Type III.

Type I: Single Phase Sags

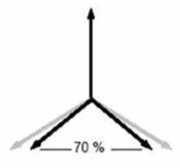


The first type of sag test will be single phase sags. These sags will be referenced from phase to neutral. Many controls are wired line to neutral in facilities, and at some point, will encounter sags that are line to neutral, single phase, usually off the secondary of a control transformer. This method of testing is most relevant to single phase equipment, or three phase equipment with a neutral.

Type II: Phase to Phase Sags

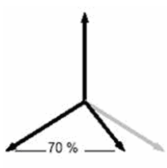
There are three types, or methods for testing with phase to phase sags. All three methods will be tested, to ensure that the device encounters the various configurations of sags.

Type II: IEC Type 3c



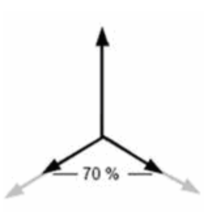
This is the most typical type of sag that would be seen on the secondary of a delta-wye configured transformer. The fault is caused when there is a single phase line to ground fault on the primary. This is one of the most common types of faults seen in the industry. It has medium phase shift and medium vector magnitudes.

Type II.A1: IEC Type 3b



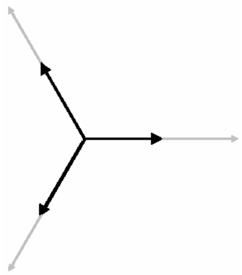
This type of fault is rarely seen because of the large phase shift that occurs with it. This is maximum phase shift with maximum vector magnitudes. The strength of this type of induced sag is it will reveal any susceptibilities to phase shift the loads or devices may have. Depending on the device though, it is possible it will not trip some types of adjustable speed drives or power supplies since one phase to phase vector will stay at 100% magnitude, regardless of the depth of the voltage sag.

Type II.A2: IEC Type 3d



While not as common as IEC Type 3, this is sometimes seen when two phases are shorted to ground at the same time. It does happen, just not often. This method has the lowest phase shift, and lowest vector magnitudes of the three types, and is the most stringent Type II method of testing with respect to sag magnitudes. The downside to this method is it may not trip devices that are susceptible to phase shifts.

Type III: Three Phase Sags



The final type of sag testing is Type III, or three phase sags. This is the most stringent type of sag with respect to sag magnitudes. While rare, they do occur around 11% of the time.

Test Setup & Guidelines

1. Connect the EUT as shown in Figure 1.
2. Adjust the load bank for 50% of the EUT's rated load.
3. Configure the voltage and current monitors for waveform capture during induced events.
4. Optionally, add sensitive loads such as control relays and contactors. Make sure that the coil voltages are compatible with the output of the EUT. Add a transformer if necessary.
5. Create single-phase voltage sags by reducing Phase A-N for 3, 5, 10, 12, 30, and 60 cycles to the following magnitudes: 80%, 70%, 60%, 50%, 40% and 0% of nominal voltage. Begin all sag events at zero degrees measured phase-to-neutral on the phase being reduced. Allow no less then 30 seconds between sags.
6. Record the voltage waveforms measured at the output of the EUT and indicate whether any of the sensitive loads were affected by the sag events.
7. Repeat steps 5 and 6 using Phase B-N
8. Repeat steps 5 and 6 using Phase C-N
9. Repeat single-phase sag tests, steps 5 through 8, at a phase angle of 90 degrees measured phase-neutral on the phase being reduced.
10. Adjust the load bank to 100% Of the EUT's rated load, repeat steps 5 though 9.
11. Put the Porto-Sag in IEC 2 configuration
12. Adjust the load bank for 50% Of EUT's rated load.
13. Configure the taps for Vab
14. Create sags for 3, 5, 10, 12, 30, and 60 cycles to each of the following magnitudes: 80%, 70%, 60%, 50%, 40%, and 0% of nominal voltage. Begin all sag events at zero degrees measured Phase A-B. Allow no less then 30 seconds between sags.
15. Configure the taps for Vbc
16. Create sags for 3, 5, 10, 12, 30, and 60 cycles to each of the following magnitudes: 80%, 70%, 60%, 50%, 40%, and 0% of nominal voltage. Begin all sag events at zero degrees measured Phase B-C. Allow no less then 30 seconds between sags.

17. Configure the taps for Vca
18. Create sags for 3, 5, 10, 12, 30, and 60 cycles to each of the following magnitudes: 80%, 70%, 60%, 50%, 40%, and 0% of nominal voltage. Begin all sag events at zero degrees measured Phase C-A. Allow no less then 30 seconds between sags.
19. Repeat steps 14 through 19 with the sag event starting at 90 degrees, with reference to the phase being sagged
20. Increase load to 100% of EUT's rated load. Repeat steps 13 through 20.
21. Put the Porto-Sag in IEC 1 configuration
22. Adjust the load bank for 50% Of EUT's rated load.
23. Configure the taps for Vab
24. Create sags for 3, 5, 10, 12, 30, and 60 cycles to each of the following magnitudes: 80%, 70%, 60%, 50%, 40%, and 0% of nominal voltage. Begin all sag events at zero degrees measured Phase A-B. Allow no less then 30 seconds between sags.
25. Configure the taps for Vbc
26. Create sags for 3, 5, 10, 12, 30, and 60 cycles to each of the following magnitudes: 80%, 70%, 60%, 50%, 40%, and 0% of nominal voltage. Begin all sag events at zero degrees measured Phase B-C. Allow no less then 30 seconds between sags.
27. Configure the taps for Vca
28. Create sags for 3, 5, 10, 12, 30, and 60 cycles to each of the following magnitudes: 80%, 70%, 60%, 50%, 40%, and 0% of nominal voltage. Begin all sag events at zero degrees measured Phase C-A. Allow no less then 30 seconds between sags.
29. Repeat steps 25 through 31 with the sag event starting at 90 degrees, with reference to the phase being sagged
30. Increase load to 100% of EUT's rated load. Repeat steps 23 through 29.
31. Configure the porto sag with three transformers to allow phase to neutral referenced sags
32. Adjust the load for 50% of the EUT's rated load.
33. Configure the taps for Vab
34. Create sags for Create two-phase sags by reducing Phases A-N and B-N for 3, 5, 10, 12, 30, and 60 cycles to each of the following magnitudes: 80%, 70%, 60%, 50%, 40%, and 0% of nominal voltage. Begin all sag events at zero degrees measured Phase A-N. Allow no less then 30 seconds between sags.
35. Create two-phase sags by reducing Phases B-N and C-N for 3, 5, 10, 12, 30, and 60 cycles to each of the following magnitudes: 80%, 70%, 60%, 50%, 40%, and 0% of nominal voltage. Begin all sag events at zero degrees measured Phase B-N. Allow no less then 30 seconds between sags.
36. Create two-phase sags by reducing Phases C-N and A-N for 3, 5, 10, 12, 30, and 60 cycles to each of the following magnitudes: 80%, 70%, 60%, 50%, 40%, and 0% of nominal voltage. Begin all sag events at zero degrees measured Phase C-N. Allow no less then 30 seconds between sags.

37. Repeat steps 32 through 37 with the sag event starting at 90 degrees, with reference to the phase being sagged
38. Increase load to 100% of EUT's rated load. Repeat steps 32 through 37.
39. Adjust the load bank for 50% of the EUT's rated load.
40. Create balanced three-phase sags by reducing each phase (with respect to neutral) for 3, 5, 10, 12, 30, and 60 cycles to each of the following magnitudes: 80%, 70%, 60%, 50%, 40%, and 0% of nominal voltage. Begin all sag events at zero degrees measured Phase A-N. Allow no less then 30 seconds between sags.
41. Repeat step 43 with all sag events beginning at 90 degrees with reference to A-N.
42. Adjust the load bank for 100% of the EUT's rated load. Repeat steps 40 and 41.

Test 3: Response to Voltage Swells

Rationale

A momentary increase in line voltage lasting several cycles can cause certain electronic equipment to respond by shutting down. Voltage swells can occur during power system faults or on secondary circuits in ungrounded systems. It is also possible for power lines to cross momentarily, causing a voltage swell.

Purpose

This test will identify the protection capabilities, susceptibilities, and application issues of the three-phase power conditioner during voltage swells.

Test Setup & Guidelines

1. Connect the EUT as shown in Figure 1.
2. Adjust the resitive load bank for 25% of the EUT's rated load.
3. Optionally, add various sizes of control relays and contactors as loads. Make sure that the coil voltages are compatible with the output of the EUT. Add a transformer if necessary.
4. Configure the voltage and current monitors for wavefrom capture during induced events.
5. Using the data sheet for Test 8 as a guide, create balanced, three-phase voltage swells of 5, 10, and 20 cycles each at the following magnitudes: 105%, 110% and 115% of nominal voltage. Begin all swell events at zero degrees with respect to Phase A-N
6. Record waveforms and comments describing the ability of the EUT to protect its load.
7. Adjust the resistive load bank for 100% of the EUT's rated load
8. Repeat steps 4 through 6.

Test 4: Response to Step Loads

Rationale

In many automated industrial processes, motors need to be supported by power conditioning equipment in order to produce consistent product during voltage variations. However, not all types of power conditioners can support the large inrush current needed to start the motor.

Purpose

This test will help to determine whether or not the EUT can support large motor loads during startup.

Test Setup & Guidelines

1. Select a single induction motor having the proper operating voltage and horsepower rating that does not exceed the steady-state load capacity of the EUT.
2. Connect the EUT as shown in Figure 3.
3. Prepare the motor load using an adjustable brake such that the EUT (not necessarily the motor) is loaded to 25% of its capacity
4. Configure the voltage and current monitors for wavefrom capture during induced events.
5. Optionally, add various sizes of control relays and contactors as loads. Make sure that the coil voltages are compatible with the output of the EUT. Add a transformer if necessary.
6. Start the EUT and energize its sensitive loads.
7. Start the motor.
8. Record waveforms and comments describing the ability of the EUT to protect its sensitive loads during the motor start.
9. Adjust the brake such that the EUT is loaded to 50% of its capacity.
10. Stop the motor and let it come to a complete stop
11. Repeat steps 7 and 8.
12. Adjust the brake such that the EUT is loaded to 75% of its capacity.
13. Stop the motor and let it come to a complete stop
14. Repeat steps 7 and 8.
15. Adjust the brake such that the EUT is loaded to 100% of its capacity.
16. Stop the motor and let it come to a complete stop
17. Repeat steps 7 and 8.

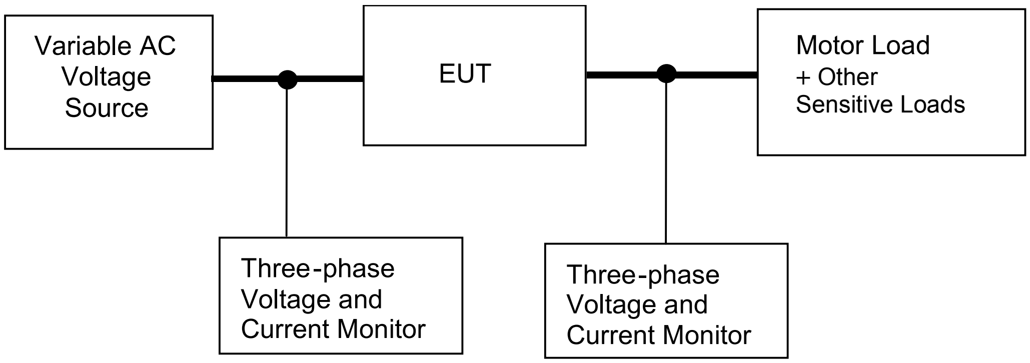


Figure B-2
Test Setup for Step Loads (Like Motor Loads)

Test 5: Power Quality Testing: 25% Load

The first test will be performed with the UST bypassed and the load bank set for 25% of the UST's rated load.

1. Verify connections are correct and input voltage is set for 480Vac
2. Set the PQ meter to record the following every second
    a. Volts
    b. Current
    c. Watts
    d. VA
    e. VAR
    f. PF
    g. Vthd, Athd, and harmonics
3. Start the data recorder.
4. Record data for 15 minutes.
5. Power Down the system and stop the recorder
6. Turn on or re-wire the UST into the circuit.
7. Leave the loading at 25%
8. Turn the power to the system back on
9. Turn on the recorder and record for 15 minutes
10. Remove power from the system.

Test 6: Power Quality Testing: 50% Load

The first test will be performed with the UST bypassed and the load bank set for 50% of the UST's rated load.

1. Verify connections are correct and input voltage is set for 480Vac
2. Set the PQ meter to record the following every second
    a. Volts
    b. Current
    c. Watts
    d. VA
    e. VAR
    f. PF
    g. Vthd, Athd, and harmonics
3. Start the data recorder.
4. Record data for 15 minutes.
5. Power Down the system and stop the recorder
6. Turn on or re-wire the UST into the circuit.
7. Leave the loading at 50%
8. Turn the power to the system back on
9. Turn on the recorder and record for 15 minutes
10. Remove power from the system.

Test 7: Power Quality Testing: 100% Load

The first test will be performed with the UST bypassed and the load bank set for 100% of the UST's rated load.

1. Verify connections are correct and input voltage is set for 480Vac
2. Set the PQ meter to record the following every second
    a. Volts
    b. Current
    c. Watts
    d. VA
    e. VAR
    f. PF
    g. Vthd, Athd, and harmonics
3. Start the data recorder.

4. Record data for 15 minutes.
5. Power Down the system and stop the recorder
6. Turn on or re-wire the UST into the circuit.
7. Leave the loading at 100%
8. Turn the power to the system back on
9. Turn on the recorder and record for 15 minutes
10. Remove power from the system.

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