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Application Guidelines for Motor Control Circuits Protection and Control Circuits and Devices in the Voltage Sag Environment

System Compatibility Research

Technical Report

Application Guidelines for Motor Control Circuits Protection and Control Circuits and Devices in the Voltage Sag Environment

System Compatibility Research

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REPORT SUMMARY

Common electrical disturbances in the power system—such as voltage sags and brief interruptions—can disrupt the performance of electronic equipment. This project, part of EPRI's ongoing Power Quality Measurements and Testing program, focused on developing a system compatibility test protocol and conducting power quality performance testing for motor voltage controllers operating in a voltage sag environment.

Background
Over the past ten years, EPRI's System Compatibility Research Project (SCRP) has led to improved product voltage tolerance, better power quality-related standards, better power quality testing protocols, and an overall increase in the aggregate power quality knowledge base. The number of existing technologies improved by the SCRP is significant, yet the number of new products requiring testing continues to increase at an even greater rate. Because of the significant costs of downtime for today's electricity customer, the SCRP is now more important than ever throughout industry.

Objectives
- To develop a test protocol suitable for use in evaluating motor control circuitry (MCC) protection and control circuitry
- To conduct laboratory evaluations of five different manufacturer protection or control devices or circuits
- To develop solutions to power quality incompatibilities identified during the laboratory evaluations using the knowledge base of the EPRI Power Electronics Applications Center (PEAC) and EPRI-member utilities.

Approach
A team of experts with experience in system compatibility research developed a test protocol for evaluating motor controllers. Industry and utility experts then peer-review the protocol. Project sponsors selected five controllers to be tested. The project team tested the selected controllers with an eye to setup modifications that could improve power quality performance during voltage variations.

Results
Following are some of the relevant results presented in this report:

- Each controller has a different level of susceptibility to voltage deviations and none of the models tested comes factory-set for power-quality-friendly performance.

- There are substantial challenges when trying to program a controller to withstand voltage sags and voltage unbalance without compromising phase-loss protection.
- Combining voltage-unbalance protection with phase-loss protection in a single controller compromised the ability to program most units for voltage-sag compatibility.

EPRI Perspective

For years EPRI has been involved in helping utilities improve their level of service to their customers. With the deregulation of vertically integrated utilities well underway, EPRI is even more dedicated to helping their member utilities provide the best, most reliable service to their customers. Having detailed knowledge of customer processes and process equipment will greatly increase a utility's ability to respond to customer needs. Achieving electromagnetic compatibility between electrical equipment and the environment in which the equipment must operate has been an ongoing challenge in the evolution of our electric power system. Today, new digital-electronic technologies and power electronics devices are perhaps the most formidable challenges to the efforts of the utility industry, manufacturers, and end users to achieve compatibility. The System Compatibility Research Project identifies ways to enhance the design of appliances and equipment to be more compatible with their intended electrical environments. This applied research takes straight aim at results that directly benefit utilities. So far, more than a dozen manufacturers have altered the designs of their products—from computer power supplies to electronic ballasts—based upon the results of testing conducted under the System Compatibility Research Project.

Keywords

Power Quality
Motor Protection
System Compatibility Research

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INTRODUCTION

From adjustable-speed drives to personal computers, electronic appliances make electricity more valuable by using electricity more efficiently and in innovative ways that greatly reduce manual labor and increase productivity. But, as electric utilities know all too well, these beneficial technologies can and often do interfere with each other, and can even contribute to problems with facility transformers, wiring, and grounding. Furthermore, common electrical disturbances in the power system—such as voltage sags and brief interruptions—can disrupt the processes of many electronic appliances and equipment.

To accelerate the identification and resolution of compatibility problems, in 1993, EPRI created the comprehensive System Compatibility Research Project, a partnership between the electric power industry and individual equipment manufacturers. Sponsored by EPRI and its member utilities, and conducted by EPRI PEAC and members of the Power Quality Testing Network (PQTN), the project focuses on the development of performance criteria and test procedures, and compatibility testing of selected electronic equipment.

For the year 2000, the funders of EPRI's Retail and Power Market, Target 7, *Power Quality Measurements and Testing,* selected motor voltage controllers as the primary research task. The task involved developing a system compatibility test protocol, obtaining a selection of typical motor controllers, and conducting power quality performance testing. In addition, a website was created to help promote efficient and effective information exchange between the sponsors and the EPRI testing coordinators. This report details each aspect of the 2000 System Compatibility Research Project.

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SYSTEM COMPATIBILITY TEST PROTOCOL: ELECTRONIC MOTOR CONTROLS AND PROTECTIVE RELAYS USED IN THREE-PHASE AC INDUCTION MOTOR APPLICATIONS

Introduction

Scope

This document defines a test protocol for evaluation of motor protection relays and intelligent motor controllers for three-phase AC induction motors. The protocol, *SC-605,* includes definitions, reference standards, and performance criteria with test rationale, purpose, guidelines and instrumentation.

This protocol addresses motor protection relays and intelligent motor controllers for three-phase AC induction motors. However, some of the same tests may be applied to motor protection relays and intelligent motor controllers for three-phase AC synchronous motors with separately excited field controls. In addition, tests outside the scope of this document will be required to address the protection and control functions associated with the motor's field excitation. Although this protocol was specifically for three-phase AC induction motors, it may be applied to AC synchronous reluctance motors and permanent magnet AC synchronous motors, which do not have separate controls and protection for the motor's field excitation.

SC-605 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 electric utilities may be more stringent than the criteria defined in the present 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 Tests

Practically every residential, commercial, and industrial facility uses electric motors. Electric motors are used to convert electrical energy into mechanical energy for a vast array of machinery, from fans, pumps, and compressors to cranes, elevators, and extruders. Long-life, high reliability, and high efficiency are characteristics that make electric motors, particularly three-phase AC induction motors, a practical choice for a wide-range of applications.

The energy converted by electric motors is anywhere from one-half to two-thirds of all generated electric power, with industrial facilities being the largest users of electric motors and consumers of electric energy. Some industrial facilities use from 700 to 1000 motors or more.

The needs 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 several times 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 motor protection relays, intelligent motor controllers, and electric motors to electrical phenomena, coupled with the characteristics of their electrical environment, will largely determine the frequency and extent to which such shutdowns occur.

Many motor protection relays and intelligent motor controllers advertise sophisticated features. However, their susceptibility to electrical disturbances and their ability to protect electric motors from these phenomena are not well understood by end-users. , EPRI PEAC has developed three System Compatibility[1] tests, described in this protocol, to evaluate these devices.

The three tests are directed at understanding the following issues:

- How do motor protection relays and intelligent motor controllers react to voltage sags and momentary interruptions?
- Does the device setup and programming configuration make a difference in performance?
- Does the device protect the motor and load? Does it have protection for its own power supply?
- How do motor protection relays and intelligent motor controllers react to voltage unbalance conditions?
- Does the device setup and programming configuration make a difference in performance?
- Does the device experience nuisance trips during long duration voltage sags?
- How do motor protection relays and intelligent motor controllers react to single-phasing?

[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).

- Does the device protect the motor during single-phasing conditions?
- Does the device have protection for itself?
- The specific rationale for conducting each test will be briefly stated for each test listed in chapter 3; the specific purposes – what data is desired – will also be stated, followed by a guideline on the actual test procedure. Armed with the actual test results, the sponsor will be in a position to judge the degree of system compatibility and basic performance achieved by the device.

Required Standards

The documents listed below are Standards applicable to motor protection relays and intelligent motor controllers, according to current performance criteria. These include definitions, test procedures, and general considerations, as well as certain requirements specific to the agency which developed the Standard. At this time, the three tests described in this protocol do not necessarily cover all of the performance criteria addressed in these documents, but the tests will be expanded to support each of the relevant portions of these Standards:

ANSI/IEEE Standard 141-1993, *IEEE Recommended Practices for Electric Power Distribution for Industrial Plants.*

ANSI C84.1-1989, *Voltage Ratings for Power Systems and Equipment.*

NEMA MG-1 – 1998, *Section III – Large Machines: Part 20 – Induction Machines*.

IEC 61000-2-1, Part 2 – Environment*, Section 1: Electromagnetic Environment for Low-Frequency Conducted Disturbances and Signaling I Public Power Supply Systems.*

IEC 61000-2-2, Part 2 – Environment*, Section 2: Compatibility Levels for Low-Frequency Conducted Disturbances and Signaling I Public Power Supply Systems.*

IEC 61000-2-4, Part 2 – Environment*, Section 4: Compatibility Levels in Industrial Plants for Low-Frequency Conducted Disturbances.*

IEC 61000-4-1, Part 4 – Testing and Measurement Techniques*, Section 1: Overview of Immunity Tests.*

IEC 61000-4-11, Part 4 – Testing and Measurement Techniques*, Section 11: Voltage Dips, Short Interruptions, and Voltage Variations Immunity Tests.*

Motor Protection Relays, Intelligent Motor Controllers, and the Electrical Environment

What is a Motor Protection Relay?

Motor protection relays are microprocessor-based and/or electromechanical devices designed to monitor the input voltage and/or current of electric motors to protect the motors (and/or connected equipment) from damage caused by overloading, electrical disturbances, or fault conditions.

What is an Intelligent Motor Controller?

Intelligent motor controllers are microprocessor-based devices designed to monitor, control, and protect electric motors. Like motor protection relays, these devices monitor the input voltage and current of motors to protect them (and/or connected equipment) from damage caused by overloading, electrical disturbances, or fault conditions, but may also be used to control the start/stop functions of motors.

Testing of the Motor Protection Relays and Intelligent Motor Controllers

The motor protection relays and intelligent motor controllers may be tested in a laboratory environment or in the field. The typical laboratory test setup will include an AC induction motor and an eddy-current brake dynamometer, as shown in Appendix A. The motor protection relays and intelligent motor controllers will be configured as they would typically be found in an industrial application.

Significant Performance Criteria

Performance criteria for motor protection relays and intelligent motor controllers involve a number of concerns related to their response to steady-state and momentary power system variations, such as voltage sags, interruptions, voltage unbalance, and single-phasing conditions. In order to investigate these concerns, three tests designed to address these issues have been developed. The results of these tests will be tabulated and presented on data sheets for sponsor review.

Voltage Sags and Momentary Interruptions

Voltage sags and momentary interruptions are by far the most common electrical disturbances affecting electric power systems. They are inevitable events and can create a variety of problems for industries that use electric motors.

The operation of three-phase AC motors during voltage sags and momentary interruptions involves a number of issues related to product quality, safety, and protection. For example, undervoltage conditions can cause motors to become unstable: reduced source voltage decreases the torque available for operating coupled loads. Thus, the motor's pull-out torque may be exceeded, creating instability.

In momentary interruptions, reclosing of line-connected motors is another issue of concern. Out-of-phase reclosures can create current and torque transients that are significantly greater than across-the-line starts. The chances of damage to the motor and the coupled load are significantly increased.

In this protocol, motor protection relays and intelligent motor controllers will be evaluated for their ability to sense and appropriately respond to voltage sags and momentary interruptions.

Steady-State Voltage Unbalance

Voltage unbalance is a common condition that affects many end-users. Unbalanced single-phase loading and blown fuses in power-factor correction capacitor banks can create a significant amount of voltage unbalance in distribution systems. Voltage unbalance at the terminals of a motor will increase the levels of negative sequence currents within the machine. High levels of negative sequence currents create additional heating losses in the motor resulting in increased operating temperatures. Increased motor operating temperatures can significantly reduce the motor's life expectancy.

Also of concern, standard, current-activated thermal or magnetic overload protection devices respond to positive sequence currents (the currents created by mechanical overloading of a motor). As a result, these devices do not properly protect motors during voltage unbalance conditions.

The voltage unbalance tests in this protocol will analyze the voltage/current protection capabilities of motor protection relays and intelligent motor controllers during voltage unbalance.

Single-Phasing Tests

Single-phasing is an extreme case of voltage unbalance, created when one phase of a three-phase distribution feed to a load has opened. A typical cause of single-phasing is a blown fuse on one phase of a three-phase distribution transformer.

When single-phasing occurs, three-phase AC induction motors are forced to operate from single-phase power, which creates a severe case of current unbalance. As discussed previously, current unbalance will increase motor temperature, reducing the motor's life expectancy.

Because three-phase AC induction motors operating from a single-phase source induce a voltage on the open-phase conductor, motor protection schemes may not be able to detect a single-phasing condition. The single-phasing tests in this protocol will evaluate the single-phasing protection capabilities of motor protection relays and intelligent motor controllers.

General Guidelines

Requirements for Test Units

Procedure for Procurement

Devices to be tested will be ordered and purchased from local area suppliers and/or supplied by the manufacturers.

Manufacturer's Information Intended for the User

To assure correct application of the device under test, the following should be recorded on the data sheets labeled **Test 0: Manufacturer Name Plate Information**. (Except for the assigned cross-reference code, this information should be available on the device housing or package):

- Manufacturer's name or trademark
- Product name, model number, and serial number
- Reference to listing or certification as applicable (UL, FCC, etc.)
- Ratings: kVA, horsepower, voltage, current, and frequency
- Assign and record the test specimen cross-reference code, i.e., Model A1, A2, A3; Model B1, B2, B3, etc.

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.

Test Instrumentation and Equipment

The tests shall be performed using the devices supplied by the manufacturers. The required test equipment and instrumentation includes:

- Variable voltage source with programmable event duration capability.
- Data acquisition system capable of accurately monitoring the system voltages and currents. In some cases, monitoring of the motor's speed and torque may be necessary.
- AC induction motor and load. Specifically regarding the load, a dynamometer with variable steady-state loading capability is optimal.

Test Guidelines

TEST 0: Manufacturer Name Plate Information

Rationale

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

Purpose

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

Test Guidelines

Choose one device and record the following information:

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.
5. Assign and record the cross-reference code for identification purposes, i.e., Model A1, A2, A3; Model B1, B2, B3, etc.

TEST 1: Characterization of Performance – Voltage Sags and Momentary Interruptions

Rationale

Motor safety and stability are concerns for a number of motor applications during voltage sags and momentary interruptions.

Purpose

The test will identify the protection capabilities, susceptibilities, and application issues of each device during undervoltage events by assessing the performance of each device during single-phase, two-phase, and three-phase voltage sags and interruptions. "CBEMA-type" ride-through curves will be developed for each device during these tests. The ride-through curves will profile the voltage levels and durations of events for each of the following:

1. Events when the device responds to the applied voltage sag or momentary interruption.

2. Events when the device does not respond to the applied voltage sag or momentary interruption.

3. Events when the safety and operation of the motor and load could be compromised.

4. Events when the device does not respond as expected per the manufacturers specifications.

The sags and interruptions will be initiated at the zero crossing of the voltage sine wave with respect to Phase A-to-neutral (V_{AN}). The events will be initiated and referenced with respect to electrical neutral. Thus, a 90% single-phase voltage sag on Phase A corresponds to a voltage sag to 90% of nominal voltage referenced Phase A-to-neutral (V_{AN} = 90% during the sag). The corresponding phase-to-phase voltages will be 95% on Phase AB (V_{AB}), 100% on Phase BC (V_{BC}), and 95% on Phase CA (V_{CA}).

The data sheet provided in Appendix A may be used to facilitate the collection of data.

Test Guidelines

Choose one device and record the cross-reference code number of the device. Apply the following test sequence to each device.

1. Connect the device under test as shown in Figure 2-1, such that voltage sags and momentary interruptions may be applied to the input power supply of the motor and the device under test.

2. Set and record the programming settings and/or application configuration of the device under test.

3. Start the motor and adjust the dynamometer to create a load torque on the motor that corresponds to 75% full-load power (approximately 75% of full-load torque).

4. Begin applying single-phase voltage sags at 90% of nominal voltage for 3 cycles on Phase A. Record the response of the device and the effect on the motor system.

5. Repeat Step 2 with durations of 5, 10, 20, 30, 60, and 120 cycles.

6. Repeat Steps 4 and 5 with the voltage sag level at 80%, 70%, 60%, 50%, 40%, and 0% of nominal.

7. Repeat Steps 2, 3, 4, 5, and 6 for single-phase sags on Phase B and Phase C, two-phase sags on Phases A and B, Phase B and C, and Phases C and A, and three-phase sags.

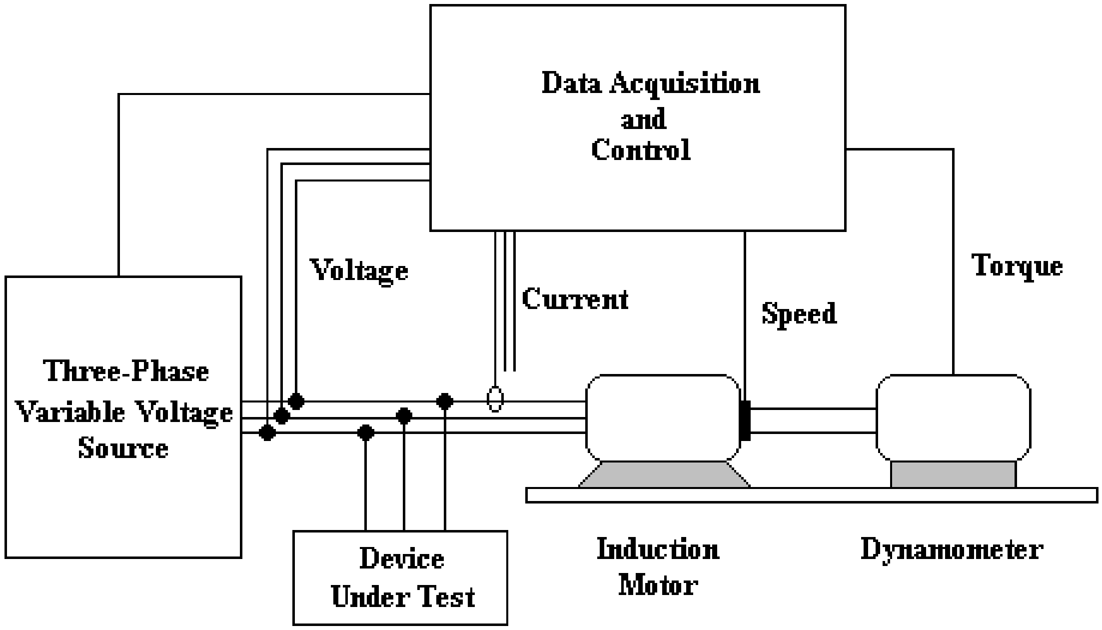


Figure 2-1
Motor-Protection Relay and Intelligent Motor Controller Test Setup

TEST 2: Characterization of Performance – Steady-State Voltage Unbalance

Rationale

A reduction in motor life due to overheating can be expected with significantly loaded motors operating from unbalanced voltage sources.

Purpose

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

Voltage unbalance conditions will be created by adjusting the phase-to-neutral voltages of the voltage source supplying the motor and device under test. The percent voltage unbalance will be measured with respect to the phase-to-phase voltages as shown in Equation 2-1.

$$V_{UB} = \frac{V_{DM}}{V_{ave}} \times 100\% \qquad (2\text{-}1)$$

where V_{UB} is the percent voltage unbalance, V_{DM} is the maximum deviation of the three-phase voltages from the average phase voltage, and V_{ave} is the average of the three-phase voltages.

The data sheet provided in Appendix B may be used to facilitate the collection of data.

Test Guidelines

Choose one device and record the cross-reference code number of the device. Apply the following test sequence to each device.

1. Connect the device under test as shown in Figure 2-1, such that steady-state voltage unbalance may be applied to the input power supply of the motor and the device.
2. Set and record the programming settings and/or application configuration of the device under test.
3. Start the motor and adjust the dynamometer to create a load torque on the motor that corresponds to 75% full-load power (approximately 75% of full-load torque).
4. Adjust the phase-to-neutral voltages to create a balanced steady-state input voltage condition. Record the motor's input voltages and currents.
5. Adjust the phase-to-neutral voltages to create the following phase-to-phase voltages:

1.5% Phase-to-Phase Voltage Unbalance:

Phase AB = 101.5%

Phase BC = 100%

Phase CA = 98.5%

6. Record the motor's input voltages and currents and the response of the device under test.
7. Repeat Steps 4, 5 and 6 for each of the following phase-to-phase voltage unbalance scenarios:

3% Phase-to-Phase Voltage Unbalance:

Phase AB = 103.0%

Phase BC = 100%

Phase CA = 97.0%

5% Phase-to-Phase Voltage Unbalance:

Phase AB = 105.0%

Phase BC = 100%

Phase CA = 95.0%

TEST 3: Characterization of Performance – Steady-State Single-Phasing

Rationale

Single-phasing represents the worst-case voltage unbalance conditions for operating electric motors. A significant increase of the motor's operating temperature and subsequent decrease in its life-span can be expected with prolonged operation during these conditions.

Purposes

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

Single-phasing conditions will be created by opening one of the phases that feeds the motor and the device under test.

The data sheet provided in Appendix B may be used to facilitate the collection of data.

Test Guidelines

Choose one device and record the cross-reference code number of the device. Apply the following test sequence to each device.

1. Connect the device under test as shown in Figure 2-1, such that steady-state single-phasing conditions may be applied to the input power supply of the motor and the device under test.

2. Set and record the programming settings and/or application configuration of the device under test.

3. Start the motor and adjust the dynamometer to create a load torque on the motor that corresponds to 75% full-load power (approximately 75% of full-load torque).

4. With nominal voltage applied to the motor and device under test, record the motor's input voltages and currents.

5. Open the Phase A connection to the device and motor. Record the motor's input voltages and currents and the response of the device under test.

3
TESTING OF MOTOR CONTROLLERS AND MOTOR PROTECTION RELAYS

Introduction

Practically every residential, commercial, and industrial facility uses electric motors. Electric motors are used to convert electrical energy into mechanical energy for a vast array of machinery—from fans, pumps, and compressors to cranes, elevators, and extruders. Long life, high reliability, and high efficiency are characteristics that make electric motors, particularly three-phase AC induction motors, a practical choice for a wide-range of applications.

The energy converted by electric motors is anywhere from one-half to two-thirds of all generated electric power, with industrial facilities being the largest users of electric motors and consumers of electric energy, some using 700 to 1000 motors or more.

The needs 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 several times 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 motor protection relays, intelligent motor controllers, and electric motors to electrical phenomena, coupled with the characteristics of their electrical environment, will largely determine the frequency and extent to which such shutdowns occur.

System Compatibility Tests

Many motor protection relays and intelligent motor controllers advertise sophisticated protection features. However, their susceptibility to electrical disturbances and their ability to protect electric motors from these phenomena are not well understood by end users. EPRI and EPRI

PEAC developed three system compatibility[2] tests to evaluate some of the protection features of these devices.

Each test is described below and includes the specific rationale and purpose for conducting each test. Armed with the actual test results, the sponsor will be in a position to judge the degree of system compatibility and basic performance achieved by the device.

The three tests are directed at understanding the following issues:

1. How do motor protection relays and intelligent motor controllers react to voltage sags and momentary interruptions? Does the device setup and programming configuration affect performance? Does the device provide adequate protection for the motor and load?

2. How do motor protection relays and intelligent motor controllers react to voltage unbalance conditions? Does the device setup and programming configuration affect performance?

3. How do motor protection relays and intelligent motor controllers react to single-phasing? Does the device protect the motor during single-phasing conditions?

Response to Voltage Sags and Momentary Interruptions

Voltage sags and momentary interruptions are by far the most common electrical disturbances affecting electric power systems. They are inevitable events and can create a variety of problems for industries that use electric motors.

The operation of three-phase AC motors during voltage sags and momentary interruptions involves a number of issues related to product quality, safety, and protection. For example, undervoltage conditions can cause motors to become unstable. A reduced source voltage decreases the motor torque available for operating a coupled load. Thus, a motor’s pullout torque may be exceeded, creating instability. However, the motor may be able to operate sufficiently without a significant decrease in speed or available torque.

During momentary interruptions, reclosure of two-wire-controlled motor contactors is another issue of concern. Out-of-phase reclosures can create current and torque transients that are significantly greater than across-the-line starts. The chances of damage to the motor and the coupled load are significantly increased.

With these issues in mind, the motor protection relays and intelligent motor controllers were evaluated for their ability to sense and appropriately respond to voltage sags and momentary interruptions. The devices were set up, programmed, and installed according to the specifications described in the documentation shipped with each unit.

To begin the tests, the motor was loaded to 75% of full-load with an eddy-current-brake dynamometer. Voltage sags were created with a contactor-based voltage-sag generator (see Appendix B for a complete description of the sag generator). Both the motor and the device

[2] 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).

under test were subjected to voltage sags. Starting with the sag magnitude at 90% of nominal voltage, single-phase voltage sags were created on Phase A at 3, 5, 10, 20, 30, 60, 120, and 130 electrical cycles. The subsequent response of the system was recorded for each test point. The sag magnitude was reduced in 5% increments, down to a minimum of 0% of nominal voltage. At the point where the device responded to a sag, a data point was added to an undervoltage-susceptibility plot for Phase A. The same characterization was performed for single-phase sags on Phases B and C. After the single-phase sag tests were completed, two-phase sag tests were performed on Phases A and B, Phases B and C, and Phases C and A. Finally, three-phase sag tests were performed on the system.

Response to Steady-State Voltage Unbalance

Voltage unbalance is a common condition that has the potential to affect end users from time to time. Unbalanced single-phase loading and blown fuses in power-factor-correction capacitor banks can create a significant amount of voltage unbalance in distribution systems. Voltage unbalance at the terminals of a motor will increase the levels of negative sequence-currents in the machine. High levels of negative-sequence currents create additional heating losses in the motor resulting in increased operating temperatures. Increased motor operating temperatures can significantly reduce the motor's life expectancy through premature aging of the stator insulation.

Standard, current-activated thermal or magnetic overload-protection devices respond to positive-sequence currents (the currents created by mechanical overloading of a motor). As a result, these devices do not properly protect motors during voltage unbalance conditions because they do not detect the increased levels of negative-sequence currents. It is unclear how the protective devices would respond to voltage unbalance conditions. Thus, voltage unbalance tests were conducted to analyze the protection capabilities of the motor protection relays and intelligent motor controllers. After completing the voltage sag tests, the devices were tested for their response to voltage unbalance.

The voltage unbalance test conditions were created by supplying power to the system under test through autotransformers. The output voltage of the autotransformers was adjusted to create 0%, 1.5%, 3%, and 5% voltage unbalance conditions. The responses of the devices under test were measured and recorded along with the current and voltage of each phase.

Response to Single-Phasing

Single-phasing is an extreme case of voltage unbalance. Single-phasing conditions occur when one phase feeding a three-phase load opens. A typical cause of single-phasing is a blown fuse on one phase of a three-phase distribution transformer.

When single-phasing occurs, three-phase AC induction motors are forced to operate from single-phase power. A severe case of voltage and current unbalance results. As discussed previously, current unbalance will increase motor temperature, reducing the motor's life expectancy.

Because three-phase AC induction motors operating from a single-phase source induce a voltage on the open-phase conductor, motor protection schemes may not be able to detect a single-phasing condition. Thus, the single-phasing tests were designed to evaluate the single-phasing protection capabilities of the motor protection relays and intelligent motor controllers.

After completion of the voltage unbalance test, the devices were tested to characterize their responses to single-phasing conditions. The single-phasing test conditions were created by opening the Phase-A power connection to the devices and the motor. The responses of the devices under test were measured and recorded.

Test Samples

The funders of EPRI's Retail and Power Market, *Target 7 – Power Quality Measurements and Testing,* were requested to vote for their top five choices of off-the-shelf motor protection relays and intelligent motor controllers for testing. The votes were tabulated, and the funders were notified about which devices received the most votes. The devices that received the most votes were purchased, and the three system compatibility tests were performed on each device. The following chapters describe the test results for each device.

The GE Motor Manager II

The GE Motor Manager II (MMII) is a multifunction, intelligent motor controller that combines motor protection features with motor control functions. It provides a compact means for motor control and protection without the need for discrete devices. Some of the specific product features are listed below:

- A programmable undervoltage restart of motors following an undervoltage condition (Option 1).
- Diagnostics, which includes pre-trip data and historical statistics (Option 1).
- Ground fault trips (50G/51G) (Option 2).
- Stalled rotor protection (48) (Option 2).
- Undercurrent/underpower protection (37) (Option 2).
- Overvoltage (59) and undervoltage (27) protection (Option 2).

Setup, Installation, and Programming of the GE MMII

The model number of the GE MMII purchased for these tests was MMII-PD-1-2-120. The unit had Options PD, 1, 2, and a 120-Vac control-power voltage. The relay was set up, programmed, and installed according to the instruction manual shipped with the unit. Because the MMII is a versatile device, there are a number of connection options for the control circuit that can be used. Figure 3-1 and Figure 3-2 show the two control-circuit configurations that were evaluated during these tests.

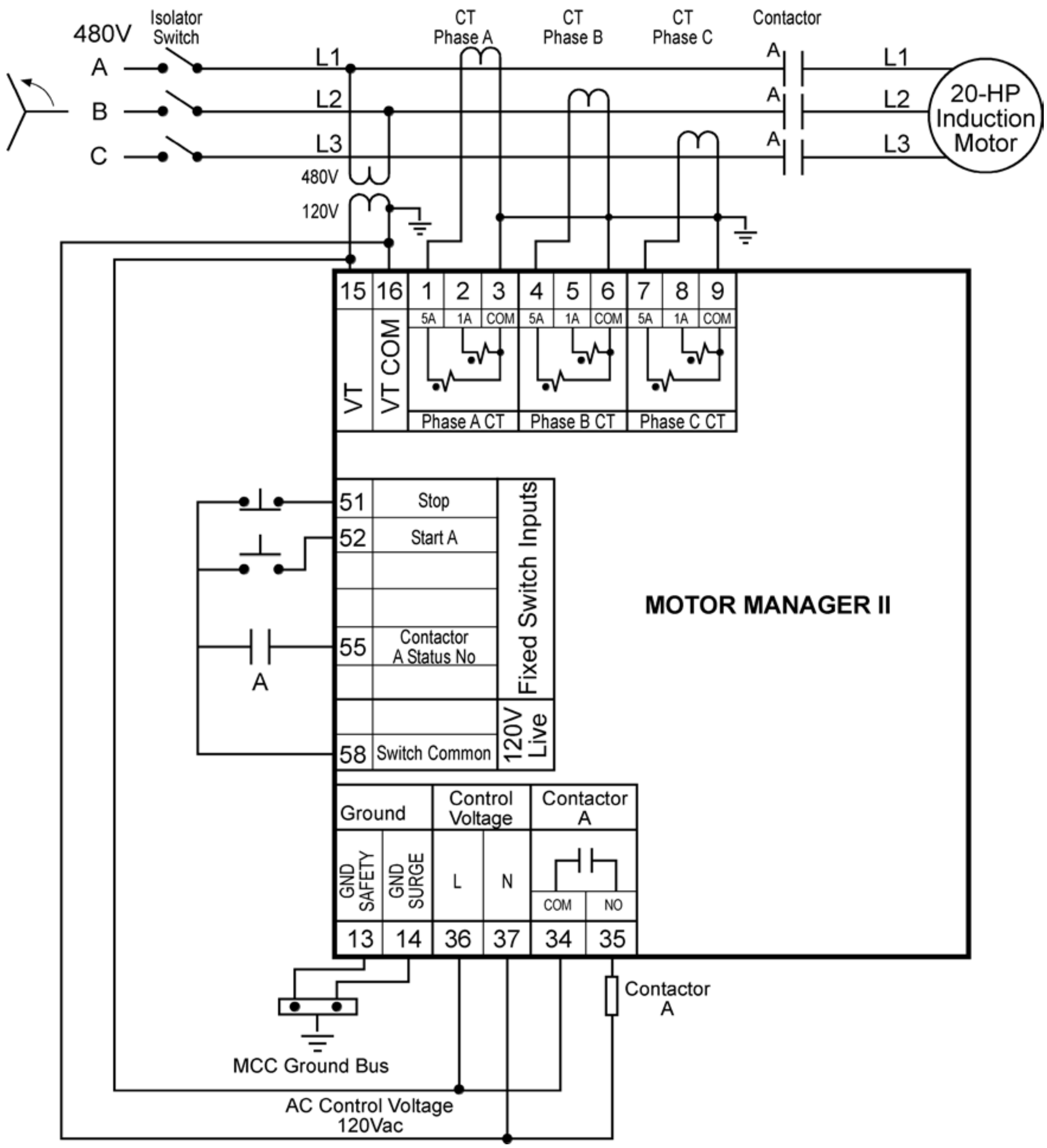


Figure 3-1
GE MMII Connection Configuration #1

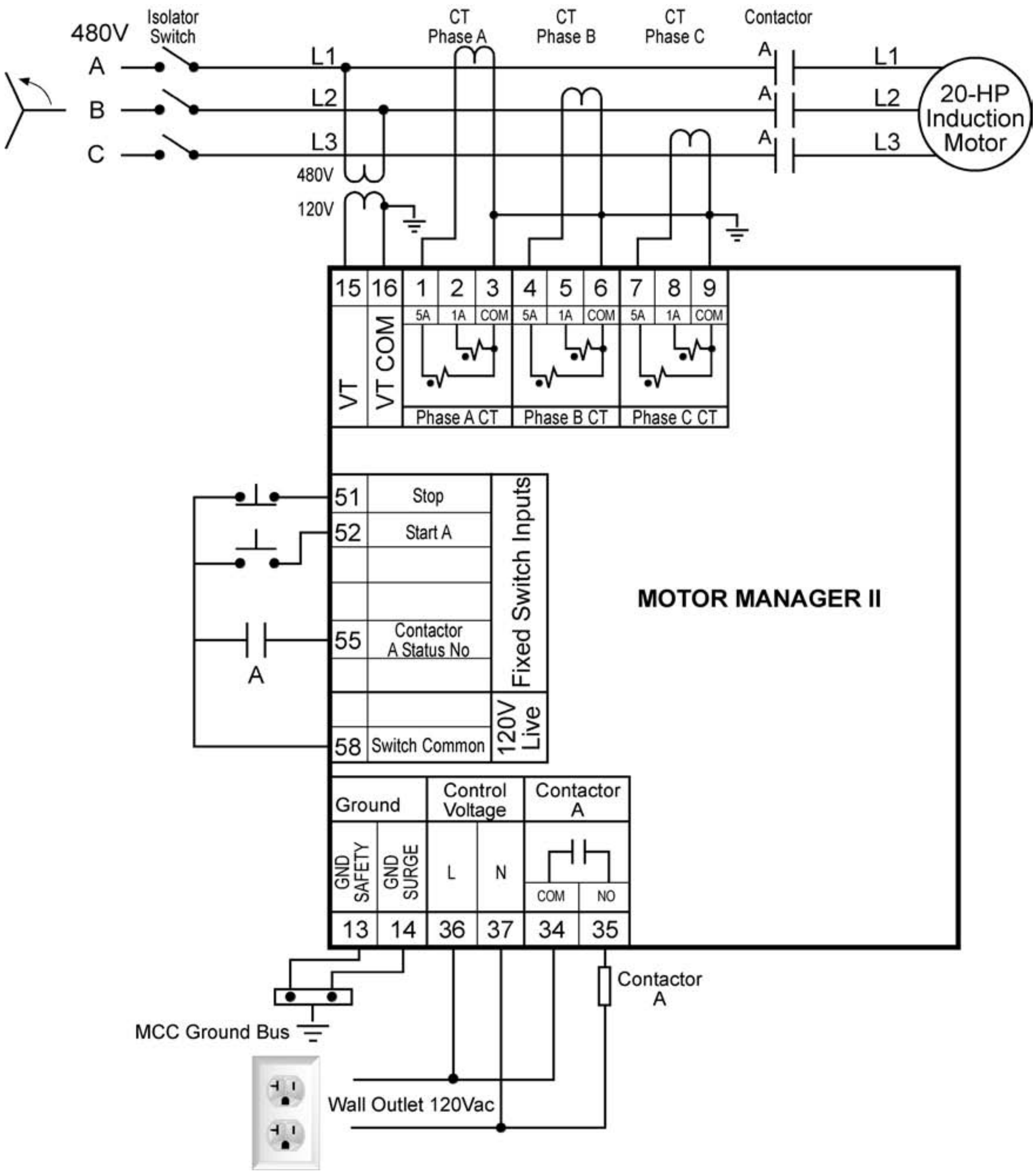


Figure 3-2
GE MMII Connection Configuration #2

The GE MMII has several programming parameters that will affect how the unit responds to voltage sags, momentary interruptions, and sustained undervoltage conditions. According to GE, the *Undervoltage Restart* feature is designed to automatically restart the motor after a momentary power loss when enabled. The MMII monitors its control power voltage (at terminals 36 and 37 in Figure 3-1 and Figure 3-2) to determine when a power loss occurs. According to the user's manual, the undervoltage trip threshold for the 120-Vac unit is 80 V (66.7% of nominal 120 V). The manual also specifies that the unit will ride through a power outage of less than 135 ms. Additional supporting programming parameters include the *Immediate Restart Power Loss*

Time, the *Delayed Restart Power Loss Time*, and the *Restart Time Delay*. If the input voltage recovers before the time set in the *Immediate Restart Power Loss Time*, the MMII restarts the motor immediately. If the input voltage recovers after the time set in the *Immediate Restart Power Loss Time* but before the time set in the *Delayed Restart Power Loss Time*, the motor is restarted after the time defined in the *Restart Time Delay*. The MMII can also be set to always execute a delayed restart. The user has the option to turn on or off these protection features.

The MMII also has programming parameters that can be used to protect the motor against sustained undervoltage conditions: *Undervoltage Alarm Level*, *Undervoltage Alarm Delay*, *Undervoltage Trip Level*, and *Undervoltage Trip Delay*. The *Undervoltage Alarm Level* allows the user to set an undervoltage level to alert an operator when undervoltage conditions are present. The *Undervoltage Alarm Delay* allows time for the undervoltage conditions to clear before execution of an *Undervoltage Alarm*. The *Undervoltage Trip Level* and *Undervoltage Trip Delay* function similarly. However, these parameters create a hard-trip condition. When the thresholds for these parameters are exceeded, the MMII will trip the motor. If the motor trips, the MMII must be reset and the motor must be restarted by an operator. The user has the option to turn off either or both of these protection features.

The current-unbalance protection feature is the *Phase Unbalance Alarm*. This feature has factory-defined levels. If a current unbalance between 15% and 30% exists for 5 seconds, a *Phase Unbalance Alarm* is initiated. This feature will only trip the motor if configured through one of the programmable output relays. The user has the option to turn off this protection feature.

The single-phasing protection feature is the *Single Phasing Trip* function. If a current unbalance greater than 30% exists for 5 seconds, a *Single-Phasing Trip* is executed, creating a hard-trip condition. The MMII will trip the motor. The MMII must be reset and the motor must be restarted by an operator. The user does *not* have the option of turning this protection feature on or off.

Connection Configuration #1

Connection Configuration #1 was chosen based on the suggested connection configurations shown in the MMII user's manual. The MMII was connected as shown in Figure 3-1. The pertinent programming features had the following values:

Undervoltage Alarm = Off

Undervoltage Trip Level = 432 V (90% of nominal 480 V)

Undervoltage Trip Delay = 5 s

Undervoltage Restart = ENABLE

Immediate Restart Power Loss Time = 0.5 s

Delayed Restart Power Loss Time = 2 s

Restart Time Delay = 2 s

It is interesting to note that the MMII only monitors one phase-to-phase voltage of the three-phase system at connection points 15 and 16 as shown in Figure 3-1.

Connection Configuration #2

Connection Configuration #2 (Figure 3-2) was chosen to determine the effect on the MMII's response characteristics when the control power voltage (connection points 36 and 37) was not subjected to the same voltage variations as the motor and the MMII's voltage monitoring points at connection points 15 and 16. The control power voltage was supplied from a 120-V wall outlet. This connection configuration represents a situation where a UPS or other power-conditioning device is used to support the MMII's control power and the rest of the motor control circuit. The pertinent programming features had the following values:

Undervoltage Alarm = Off

Undervoltage Trip Level = 432 V (90% of nominal 480 V)

Undervoltage Trip Delay = 2 s

Undervoltage Restart = ENABLE

Immediate Restart Power Loss Time = 0.5 s

Delayed Restart Power Loss Time = 2 s

Restart Time Delay = 2 s

Response to Voltage Sags

Characterization of Connection Configuration #1

Connection Configuration #1 was characterized first. The voltage-sag generator was connected to the utility power supply upstream of the MMII and the motor. The motor was loaded to approximately 75% of nominal with the eddy-current-brake dynamometer. Sags were initiated, and the MMII's responses were monitored and recorded. The results are shown in Figure 3-3, Figure 3-4, and Figure 3-5.

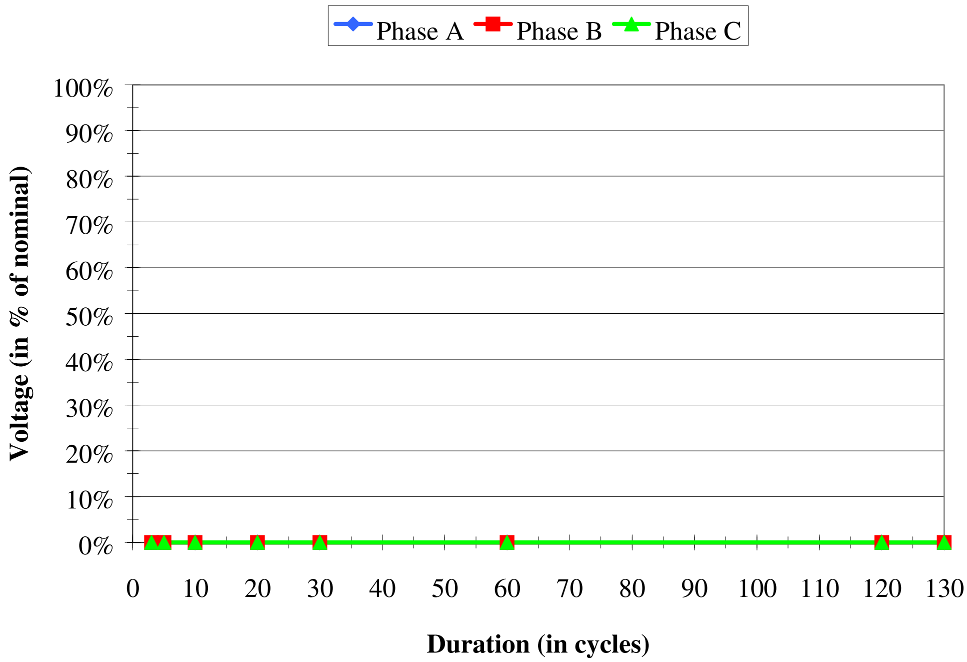


Figure 3-3
Single-Phase Sag Test Results for the GE MMII Connection Configuration #1

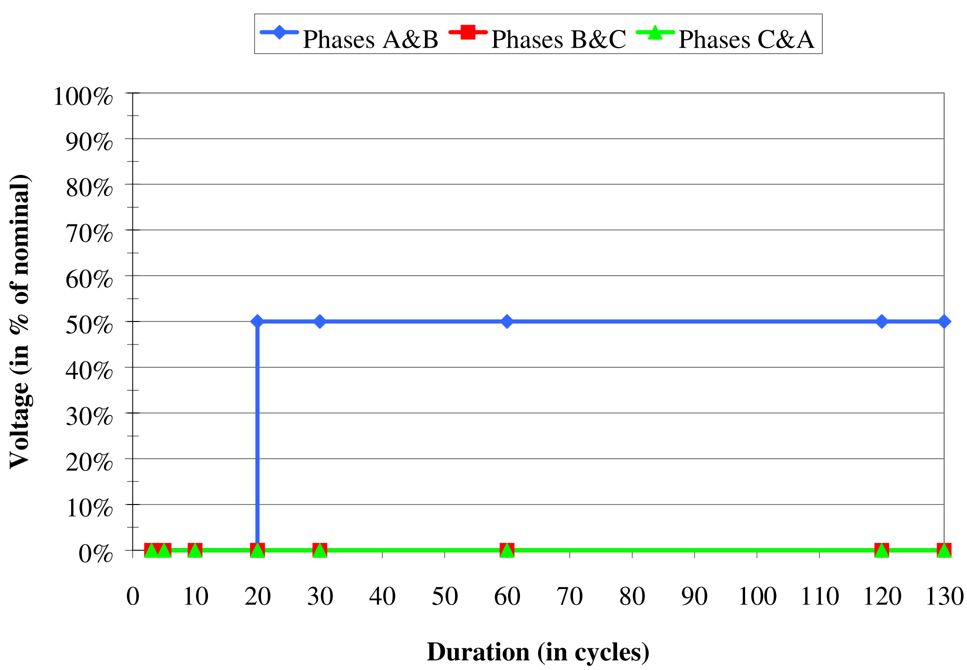


Figure 3-4
Two-Phase Sag Test Results for the GE MMII Connection Configuration #1

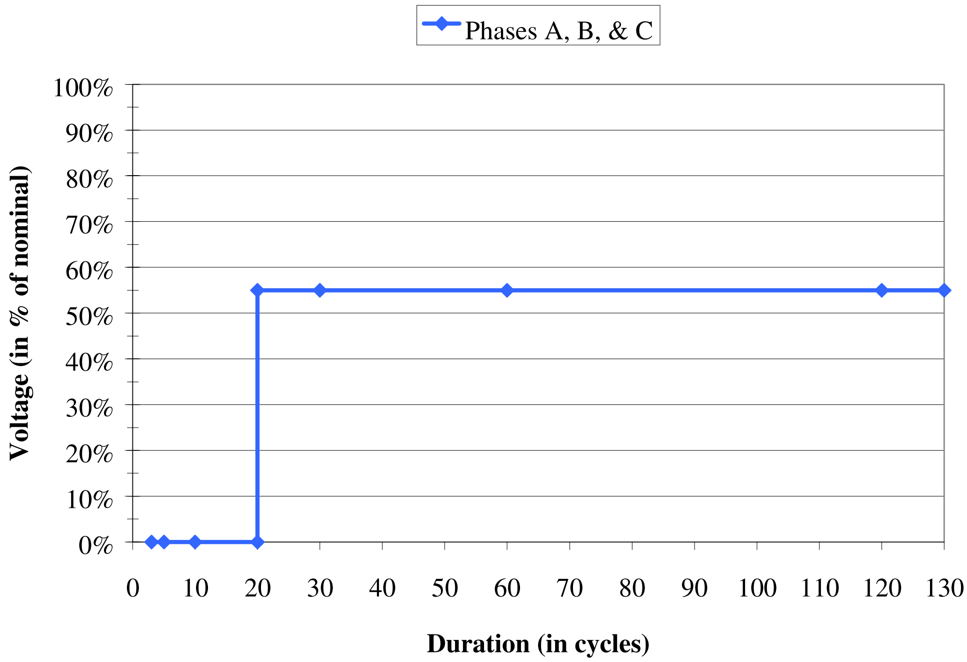


Figure 3-5
Three-Phase Sag Test Results for the GE MMII Connection Configuration #1

Characterization of Connection Configuration #2

The MMII was connected in Connection Configuration #2, and sags were initiated. The MMII's responses were monitored and recorded. The results are shown in Figure 3-6, Figure 3-7, and Figure 3-8.

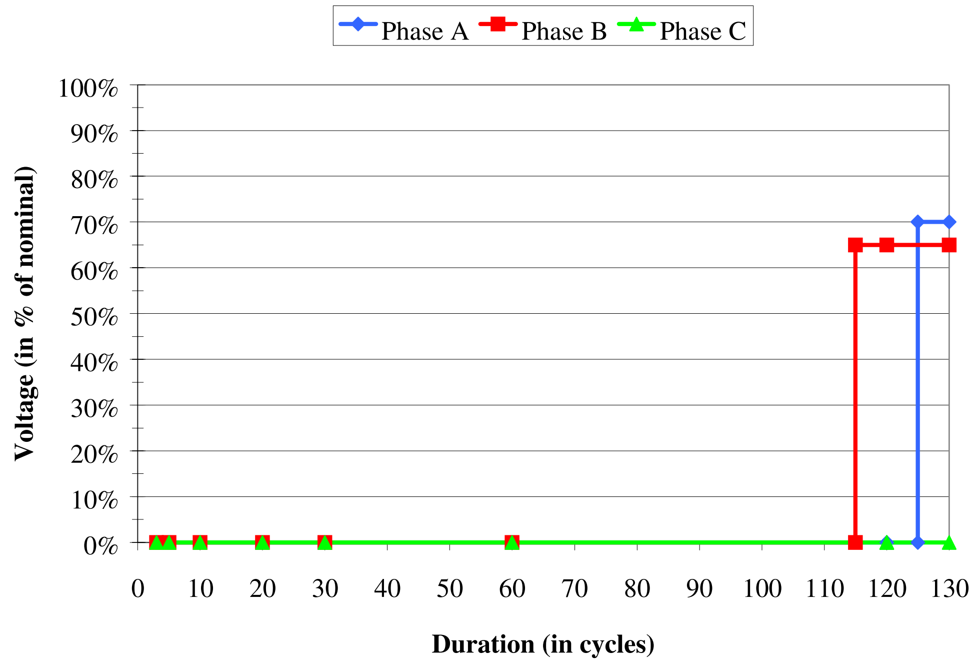


Figure 3-6
Single-Phase Sag Test Results for the GE MMII Connection Configuration #2

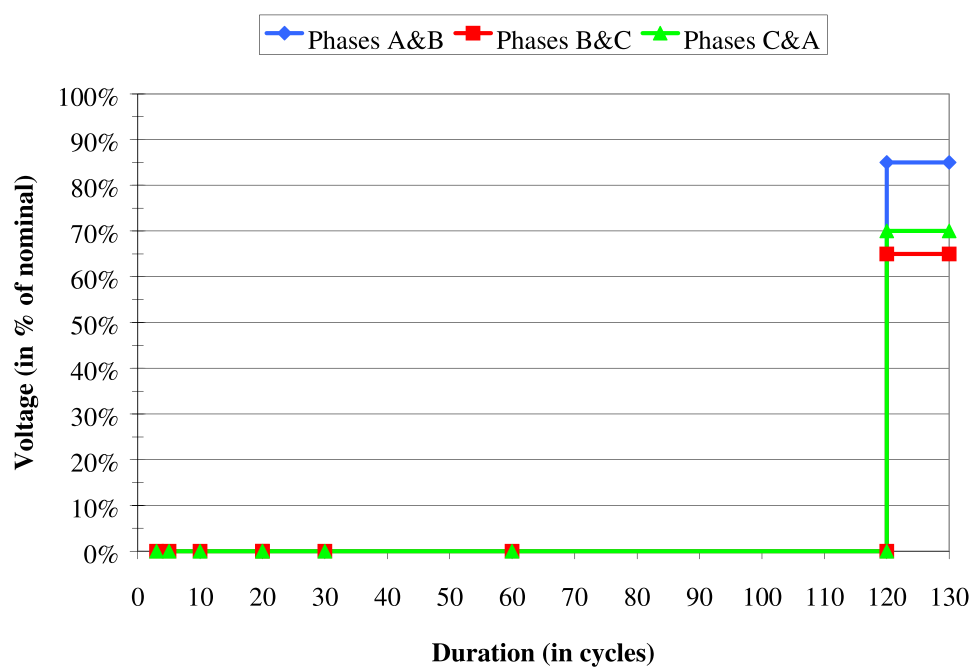


Figure 3-7
Two-Phase Sag Test Results for the GE MMII Connection Configuration #2

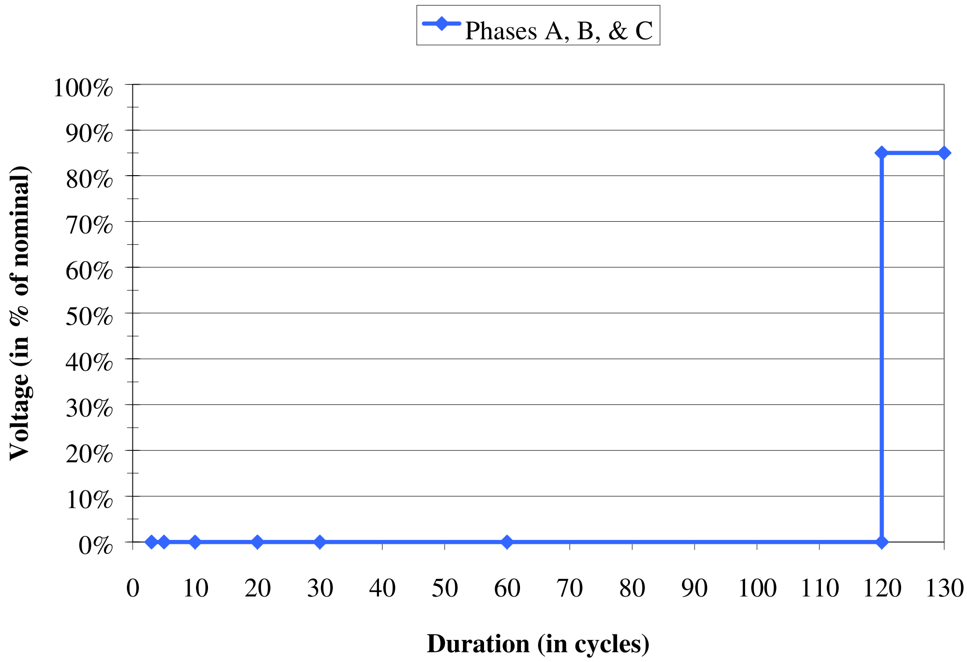


Figure 3-8
Three-Phase Sag Test Results for the GE MMII Connection Configuration #2

Discussion

During the sag tests of Connection Configuration #1, the MMII executed an automatic restart of the motor for all points where the MMII responded to the voltage sags. In the undervoltage-susceptibility plots, the area above the curve shows the voltage sags that had no effect on the MMII. The area below the curve shows the voltage sags that initiated an automatic restart. Notice that the results in Figure 3-3 show that the MMII does not react to single-phase sags when connected in Configuration #1.

With the control power voltage connected to the 120-V wall outlet and the *Undervoltage Trip Delay* parameter changed from 5 seconds to 2 seconds, the MMII responded quite differently, as shown in the undervoltage-susceptibility plots for Connection Configuration #2. The MMII responded according to the thresholds set for the *Undervoltage Trip Level* and the *Undervoltage Trip Delay*. During the sag tests of Connection Configuration #2, the MMII *did not* execute an automatic restart of the motor for the points where the MMII responded to the voltage sags. As shown in the undervoltage-susceptibility plots for Connection Configuration #2, the area above the curve shows the voltage sags that had no effect on the MMII. The area below the curve shows the voltage sags that initiated a hard trip of the motor. The MMII required a reset and a start command to restart the motor.

The results for both connection configurations show that the MMII does not respond favorably to voltage sags and momentary interruptions affecting the phase-to-phase voltages that it does not monitor at connection points 15 and 16 or 36 and 37. This could potentially lead to problems with motor stability and protection. There are a number of related factors that determine how a motor will be affected. The motor type, pullout torque, load torque, system inertia, and the depth and duration of the sag are all contributing factors. A stability study is recommended for systems where motor protection is a concern.

Response to Voltage Unbalance

Characterization of Connection Configuration #2

With the MMII connected in Control Configuration #2, the motor was loaded and voltage unbalances were initiated. The MMII's responses were monitored and recorded. The results are shown in Table 3-1.

Table 3-1
Voltage Unbalance Test Results for the GE MMII Connection Configuration #2

Test	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}	V_{ub}	I_a	I_b	I_c	I_{ub}	Result
0%	274	276	277	476	479	476	0.42%	18.2	20.2	19.6	5.86%	N/A
1.5%	266	276	277	470	481	470	1.55%	17.0	21.3	19.6	11.92%	1
3.0%	252	276	277	458	481	459	3.22%	14.6	24.2	20.4	26.01%	1
5.0%	238	276	277	445	479	447	4.81%	13.7	26.0	21.1	32.40%	2

1. No response by the MMII.
2. After approximately 5 seconds, a *Phase Unbalance Alarm* was visible on the LCD display. However, the MMII did not trip the motor.

Characterization of Connection Configuration #1

Voltage unbalances were initiated, and the MMII's responses were monitored and recorded with the MMII connected in Control Configuration #1. The results are shown in Table 3-2.

Table 3-2
Voltage Unbalance Test Results for the GE MMII Connection Configuration #1

Test	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}	V_{ub}	I_a	I_b	I_c	I_{ub}	Result
0%	273	275	276	475	478	475	0.42%	19	20.5	20.5	5.00%	N/A
1.5%	†	†	†	†	†	†	†	†	†	†	†	1
3.0%	†	†	†	†	†	†	†	†	†	†	†	2
5.0%	†	†	†	†	†	†	†	†	†	†	†	3

† No measurements recorded.

1. After approximately 5 seconds, a *Phase Voltage Alarm* was visible on the LCD display. However, the MMII did not trip the motor.
2. After approximately 5 seconds, a *Phase Voltage Alarm* was visible on the LCD display. After approximately 10 seconds, the MMII tripped with a Single-Phasing message on the LCD display.

Discussion

The results for each connection configuration show that there were differences at 3% and 5% voltage unbalance. With a 3% voltage unbalance and a current unbalance of 26%, it was expected that the MMII would display a *Phase Balance Alarm*. However, with the MMII in Connection Configuration #2, there was no response.

Under identical voltage unbalance conditions with the MMII in Connection Configuration #1, the MMII displayed a *Phase Voltage Alarm*. The *Phase Voltage Alarm* may have been caused by the reduction in Voltage V_{ab} to produce the voltage unbalance. A reduction in Voltage V_{ab} also causes a reduction in the MMII's control power voltage in Connection Configuration #1.

With a 5% voltage unbalance, the MMII in Connection Configuration #1 tripped due to a *Single-Phasing Fault.* This was expected because the current unbalance was greater than 30% (which is the criteria for a single-phasing fault according to the MMII user's manual). However, with the MMII in Connection Configuration #2, the MMII only responded with a *Phase Unbalance Alarm*.

The fact that the MMII faulted with one configuration but did not with the other should not be a real concern at this point. The current unbalance was very close to the 30% criterion for a *Single-Phasing Fault*. A slightly higher current unbalance for Connection Configuration #2 would have likely caused a *Single-Phasing Fault*. The current unbalance was most likely a little higher during the unbalance tests for Connection Configuration #1.

Response to Single-Phasing

Characterization of Connection Configuration #1

With the MMII connected in Control Configuration #1, the motor was loaded and Phase A of the power connection was opened. The MMII's response was monitored and recorded. The same steps were repeated for Phases B and C. The results are shown in Table 3-3.

Table 3-3
Single-Phasing Test Results for the GE MMII Connection Configuration #1

Test	Result
Phase A Opened	After approximately 2 seconds, the MMII lost power and tripped the motor.
Phase B Opened	After approximately 2 seconds, the MMII lost power and tripped the motor.
Phase C Opened	After approximately 5 seconds, the MMII tripped the motor with a *Single-Phasing Fault*.

Characterization of Connection Configuration #2

With the MMII connected in Control Configuration #2, the single-phasing tests were performed on each power phase. The MMII's response was monitored and recorded. The results are shown in Table 3-4.

Table 3-4
Single-Phasing Test Results for the GE MMII Connection Configuration #2

Test	Result
Phase A Opened	After approximately 2 seconds, the MMII tripped the motor due to *Undervoltage*.
Phase B Opened	After approximately 2 seconds, the MMII tripped the motor due to *Undervoltage*.
Phase C Opened	After approximately 5 seconds, the MMII tripped the motor with a *Single-Phasing Fault*.

Discussion

The results of the single-phasing tests were exactly in line with what was expected. The MMII was expected to lose power during single-phasing tests on Phases A and B with Connection Configuration #1 because the MMII's control power voltage is derived from those two phases.

The *Undervoltage* faults were also expected with Connection Configuration #2 during single-phasing conditions on Phases A and B because the MMII monitors voltage V_{ab}. The *Undervoltage Trip Delay* time (2 seconds) was less than the *Single-Phasing* trip delay time (5 seconds).

The Schweitzer Engineering Laboratories 701 Motor Protection Relay

The Schweitzer Engineering Laboratories 701 Motor Protection Relay (SEL 701) is a multifunction, intelligent motor protection relay that combines motor protection with motor control functions. It provides a compact means for motor control and protection without the need for discrete devices. Some of the specific features are listed below:

- Motor thermal protection.
- Short circuit tripping.
- Load loss, load jam, and frequent starting protection.
- Unbalance current and phase-reversal protection.
- Over/undervoltage, over/underfrequency, underpower protection.
- Reactive-power and power-factor metering.
- Motor start reports and trends.
- Internal or external RTD modules.
- Load profiling.
- Front-panel targets and messages.
- Event summaries.
- Sequential events recorder.

Setup, Installation, and Programming of the SEL 701

The model number of the SEL 701 purchased for these tests was 0701001XXX. The unit had optional voltage inputs and a 95-to-250-Vac control-power voltage. The relay was set up, programmed, and installed according to the instruction manual shipped with the unit. Because the SEL 701 is a versatile device, there are a number of connection options for the control circuit. Figure 3-9 shows the control circuit configuration that was evaluated during these tests.

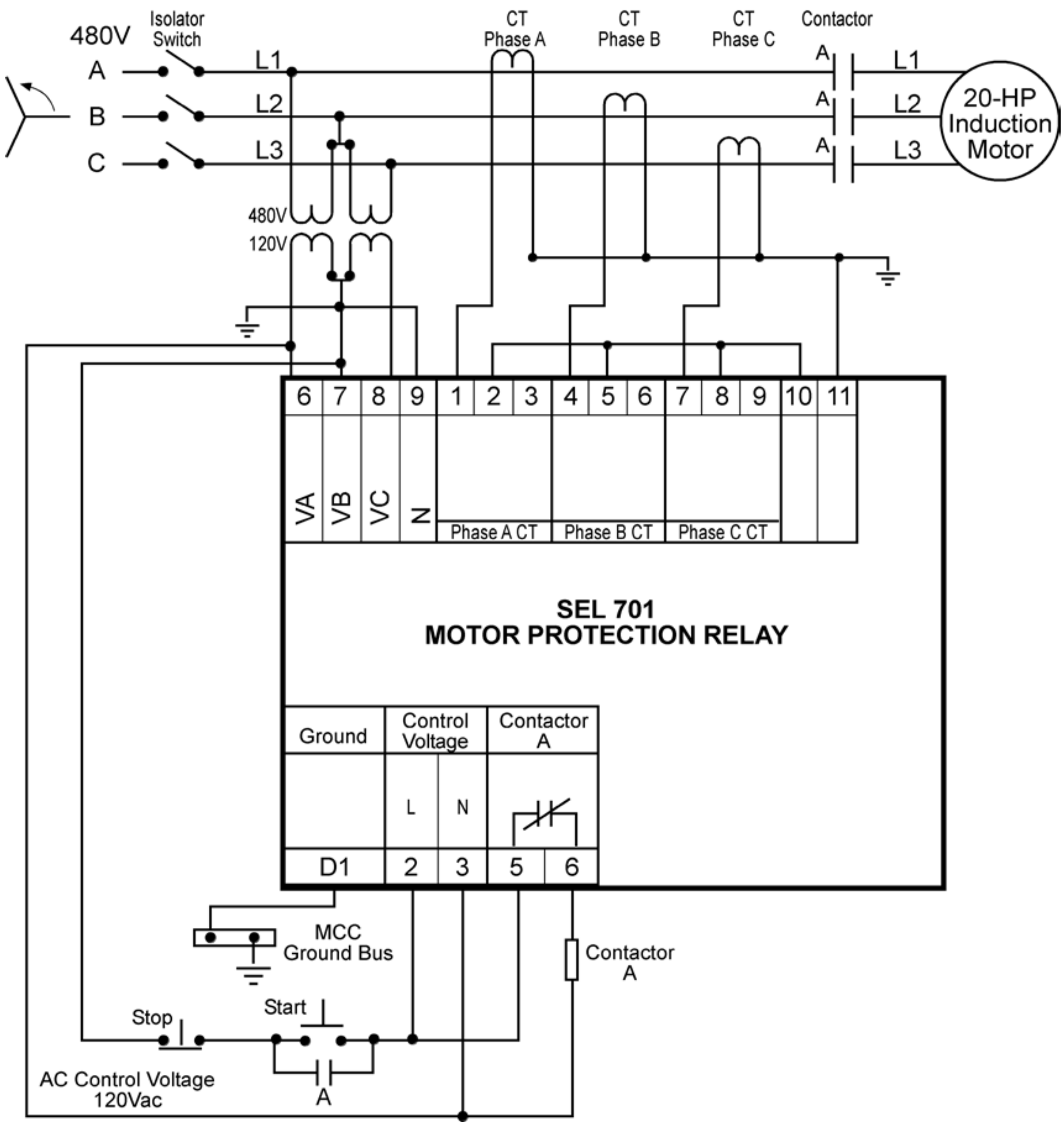


Figure 3-9
SEL 701 Connection Configuration

The SEL 701 has two specific programming parameters that will affect how the unit responds to undervoltage conditions, such as voltage sags, momentary interruptions, and sustained undervoltage conditions. The SEL 701 has two *Undervoltage Pickup* levels (27P1P and 27P2P) that are user-selectable from 0 to 300 V. The pickup levels are chosen based on the secondary voltages of the transformers that feed the voltage monitoring points VA, VB, and VC. One might set one pickup as an alarm, while the other might be used to trip the motor. They can be set at the same or different voltage levels. The user has the option to turn off either or both pickups. There is no user-selectable time-delay setting for these pickups.

The SEL 701 also has programming parameters that can be used to protect the motor against current unbalance, negative-sequence current, and phase reversal. For current-unbalance protection, the user can select a *Current Unbalance Alarm Pickup level (46UBA)*, a *Current*

Unbalance Alarm Delay (46UBAD), a *Current Unbalance Trip Pickup level (46UBT)*, and a *Current Unbalance Trip Delay (46UBTD)*. The user has the option to turn off these pickups and time delays.

For detecting excessive negative-sequence current levels, the user can select the *Negative Sequence O/C Pickup level (50QP)* and the *Negative Sequence O/C Time Delay (50QD)*. The user can set the levels or turn these protective features off.

For phase-reversal protection, the user can either enable or disable the *Enable Phase Reversal Tripping (E47T)*.

Connection Configuration of the SEL 701

The SEL 701 was connected based on the suggested connection configurations shown in the SEL 701 instruction manual. The SEL 701 was connected as shown in Figure 3-9. The pertinent programming features had the following values:

Undervoltage Pickup Level 1 = 85 V (70% of nominal 480 V)

Undervoltage Pickup Level 2 = OFF

Current Unbalance Alarm Pickup = OFF

Current Unbalance Trip Pickup = 25%

Current Unbalance Trip Delay = 5 seconds

Negative Sequence O/C Pickup = 0.5

Negative Sequence O/C Time Delay = 5 seconds

Enable Phase Reversal Tripping = ENABLE

It is interesting to note that the SEL 701 monitors two phase-to-phase voltages of the three-phase system at connection points VA, VB, and VC with the connection configuration shown in Figure 3-9.

Response to Voltage Sags

The voltage-sag generator was connected to the utility power supply upstream of the SEL 701 and the motor. The motor was loaded to approximately 75% of nominal with the eddy-current-brake dynamometer. Sags were initiated, and the SEL 701's responses were monitored and recorded. The results are shown in Figure 3-10, Figure 3-11, and Figure 3-12.

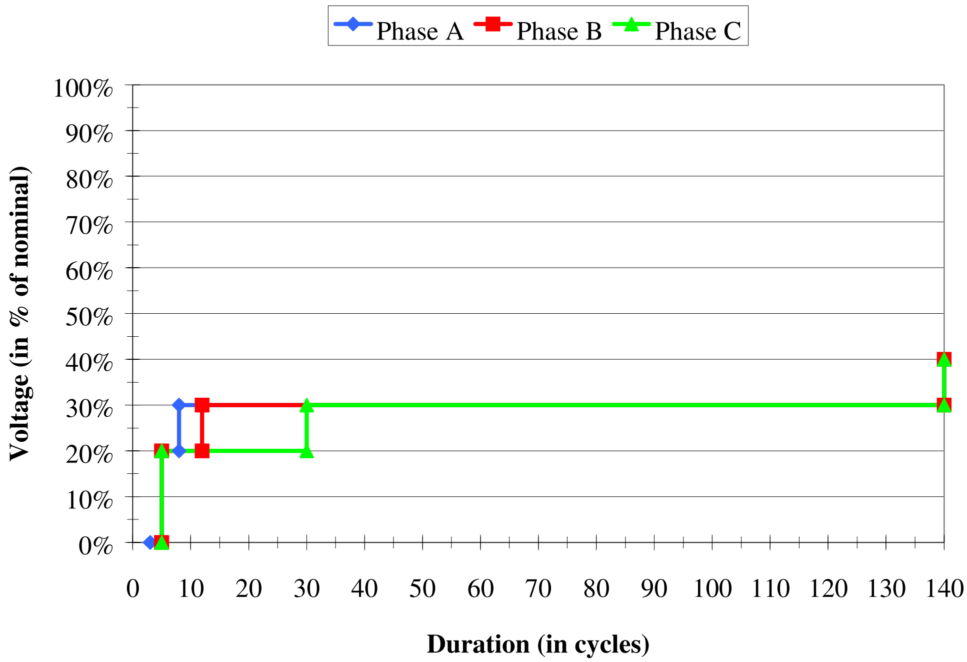


Figure 3-10
Single-Phase Sag Test Results for the SEL 701

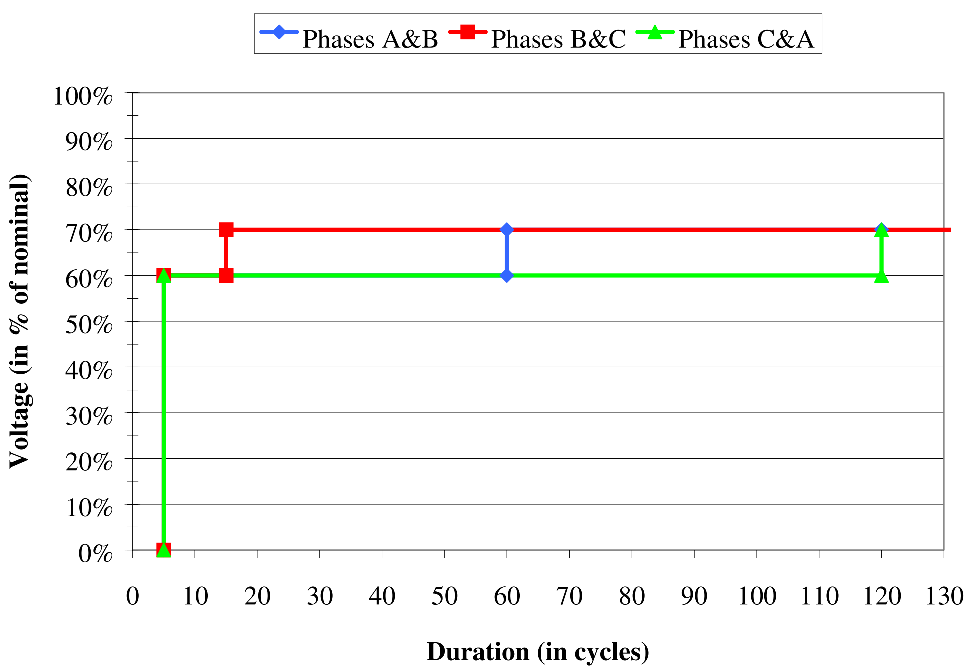


Figure 3-11
Two-Phase Sag Test Results for the SEL 701

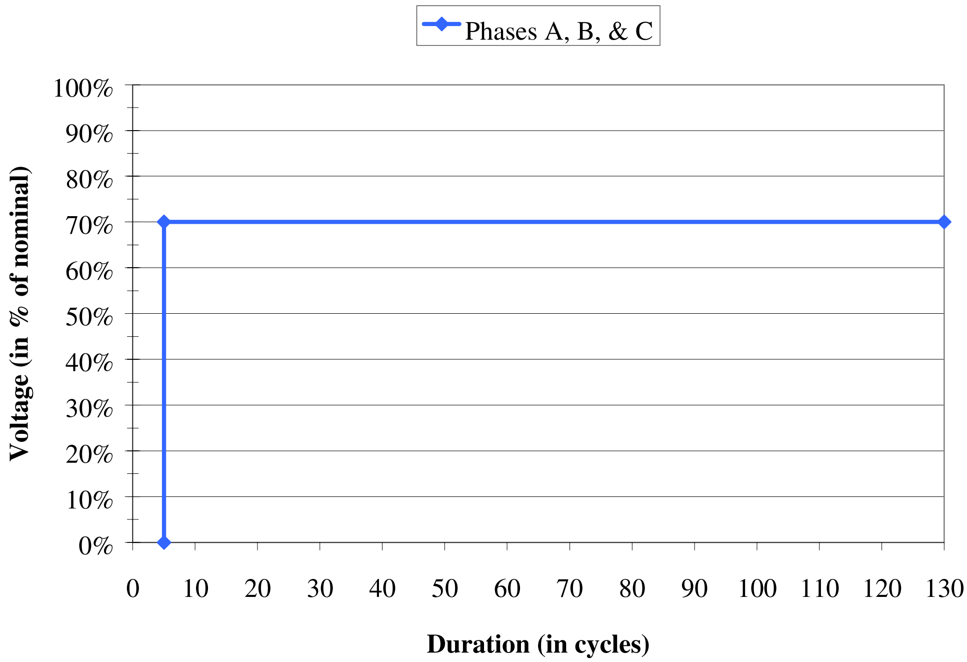


Figure 3-12
Three-Phase Sag Test Results for the SEL 701

Discussion

With the *Undervoltage Pickup* level set a 70% of nominal, the SEL 701 was able to accurately detect single-phase, two-phase, and three-phase voltage sags that resulted in line-to-line voltages of 70% of nominal and below. The SEL 701 was able to detect the sags regardless of which phases were sagged.

However, due to the fact that the SEL 701 does not provide the means for delaying the undervoltage trip, motor applications run the risk of being tripped off during short-duration voltage sags that most likely would not be a concern for stability or protection if the motors were allowed to remain connected to the source. When the SEL 701 detects an undervoltage condition, it trips the motor offline. The SEL 701 must be reset before the motor can be restarted. The design of the SEL 701 could be improved with the addition of automatic restart and time-delay trip functions. An auto-restart would help mitigate nuisance trips by automatically restarting the motor without requiring a human operator to reset the SEL 701 and restart the motor. A time-delay trip would help eliminate nuisance trips during benign voltage-sag conditions.

Response to Voltage Unbalance

With the SEL 701 connected, the motor was loaded and voltage unbalances were initiated. The SEL 701's responses were monitored and recorded. The results are shown in Table 3-5.

Table 3-5
Voltage Unbalance Test Results for the SEL 701

Test	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}	V_{ub}	I_a	I_b	I_c	I_{ub}	Result
0%	276	279	280	483	487	485	0.41%	18.1	19.5	19.9	5.57%	N/A
1.5%	265	278	278	471	483	473	1.54%	17.0	21.5	20.4	13.41%	1
3.0%	295	277	279	460	483	463	3.06%	15.4	23.6	21.0	23.00%	2
5.0%	240	277	279	448	483	451	4.85%	13.3	26.1	22.0	35.02%	2

1. After approximately 10 seconds, the SEL 701 tripped the motor with an *Undervoltage Trip* that was visible on the LCD display.
2. After approximately 6 seconds, the SEL 701 tripped the motor with an *Undervoltage Trip* that was visible on the LCD display.

Discussion

The results of the voltage unbalance tests were not expected. With as little as 1.5% voltage unbalance, the SEL 701 tripped the motor due to perceived undervoltage conditions. To produce the unbalance voltages, the nominal voltage of Phase A was slightly reduced. However, the voltages at 1.5%, 3%, and 5% voltage unbalance were 97%, 95%, and 92% of nominal, respectively. The *Undervoltage Pickup Level 1* was set to 70% of nominal. It is unclear why the SEL 701 was detecting undervoltage conditions and tripping the motor.

Response to Single-Phasing

With the SEL 701 connected and the motor running under load, the Phase-A power connection was opened. The SEL 701's response was monitored and recorded. The same steps were repeated for Phases B and C. The results are shown in Table 3-6.

Table 3-6
Single-Phasing Test Results for the SEL 701

Test	Result
Phase A Opened	The SEL 701 immediately lost power and tripped the motor.
Phase B Opened	After a few seconds, the SEL 701 displayed an *Overcurrent Alarm* on the LCD. A few seconds after that, the SEL 701 tripped the motor with an *Underfrequency Trip*.
Phase C Opened	The SEL 701 immediately lost power and tripped the motor.

Discussion

Some of the results of the single-phasing tests were expected; some were not. The SEL 701 was expected to lose power and trip the motor during the single-phasing tests on Phases A and B because the device's control-power voltage was derived from those phases. The device performed as expected when Phase A was removed. However, when Phase B was removed, the device tripped the motor with an *Underfrequency* fault and did not lose control power. A more surprising result occurred when Phase C was removed. The SEL 701 tripped in the same manner as it did for the test on Phase A. This, too, was not an expected result and theoretically should not have occurred because the SEL 701's control power was not referenced from Phase C.

The SymCom Motor Saver

The SymCom MotorSaver model 601 (SymCom 601) is a three-phase voltage monitor relay. Some of the specific features are listed below:

- Low/high-voltage protection.
- Voltage unbalance protection.
- Low/high-frequency protection.
- Trip-delay timer.
- Start-delay timer.
- Automatic or manual reset.
- Automatic reset delay timer.

Setup, Installation, and Programming of the SymCom 601

The SymCom 601 purchased for these tests could be used from 200 to 480 Vac. The relay was set up, programmed, and installed according to the instruction manual shipped with the unit. Figure 3-13 shows the control-circuit configuration that was evaluated during these tests.

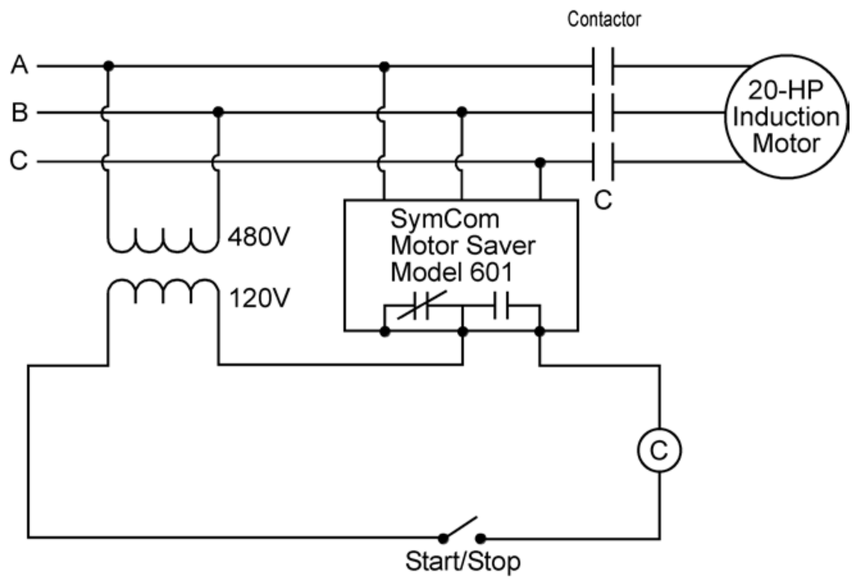


Figure 3-13
SymCom 601 Connection Configuration

The SymCom 601 has several programming parameters that will affect how the unit responds to undervoltage conditions, such as voltage sags, momentary interruptions, and sustained undervoltage conditions. The SymCom 601 has a *Low Voltage Trip Level*, a *Low-frequency Trip Threshold*, a *Trip Delay* for voltage and frequency faults, a *Trip Delay* for single-phasing faults, a *Rapid-cycle Timer* for repeated, successive motor starts, and a *Reset Delay Timer* for automatic resetting of its internal output relay contacts when fault conditions end. The user has access to set the trip thresholds and timers.

The SymCom 601 also has programming parameters that can be used to protect the motor against voltage unbalance conditions. The user has access to set the *Voltage Unbalance Trip Point*.

Connection Configuration of the SymCom 601

The SymCom 601 was connected based on the suggested connection configuration shown in the instruction sheets that were shipped with the unit. The SymCom 601 was connected as shown in Figure 3-13. The pertinent programming features had the following values:

Low-Voltage Trip Level = 432 V (90% of nominal 480 V)

Voltage Unbalance Trip Point = 3%

Low-Frequency Trip Threshold = 57 Hz

Trip Delay (TD1) for voltage and frequency faults = 2 seconds

Trip Delay (TD2) for single-phasing faults = 5 seconds

Rapid-Cycle Timer = 0 (to allow for immediate restarts)

Reset Delay Timer = 2 seconds

Reset (after fault) = A (automatic)

It is interesting to note that the SymCom 601 monitors all three phase-to-phase voltages of the three-phase system at connection points L1, L2, and L3 with the connection configuration shown in Figure 3-13.

Response to Voltage Sags

The voltage-sag generator was connected to the utility power supply upstream of the SymCom 601 and the motor. The motor was loaded to approximately 75% of nominal with the eddy-current-brake dynamometer. Sags were initiated, and the SymCom 601's responses were monitored and recorded. The results are shown in Figure 3-14, Figure 3-15, and Figure 3-16.

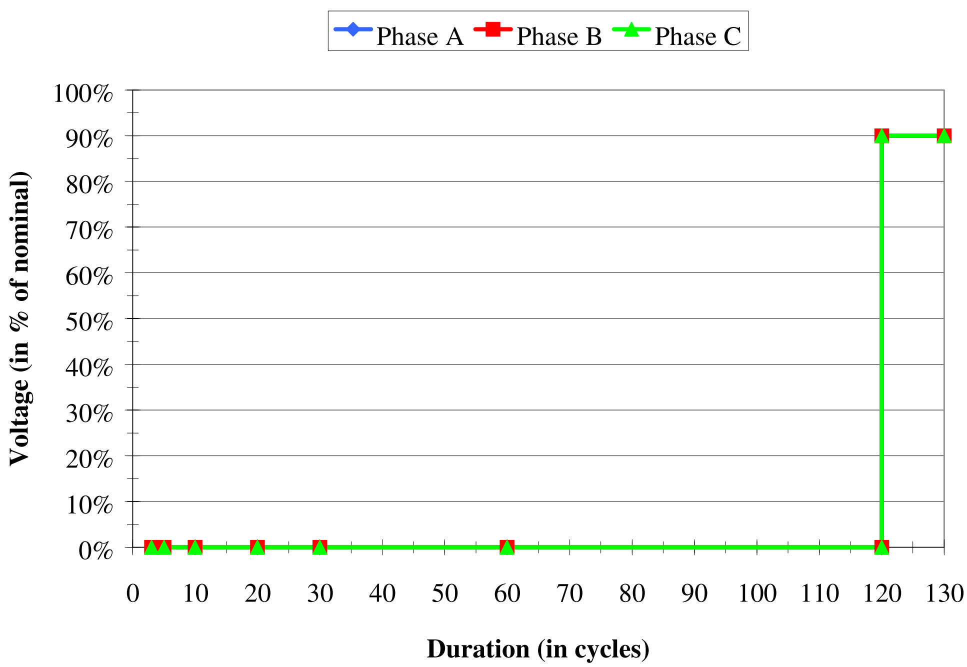


Figure 3-14
Single-Phase Sag Test Results for the SymCom 601

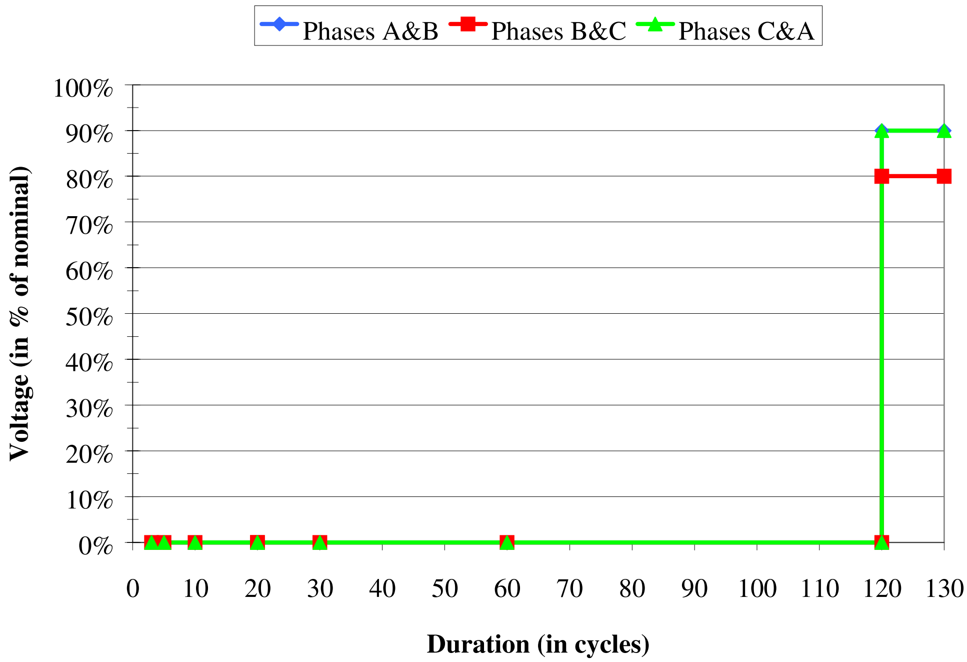


Figure 3-15
Two-Phase Sag Test Results for the SymCom 601

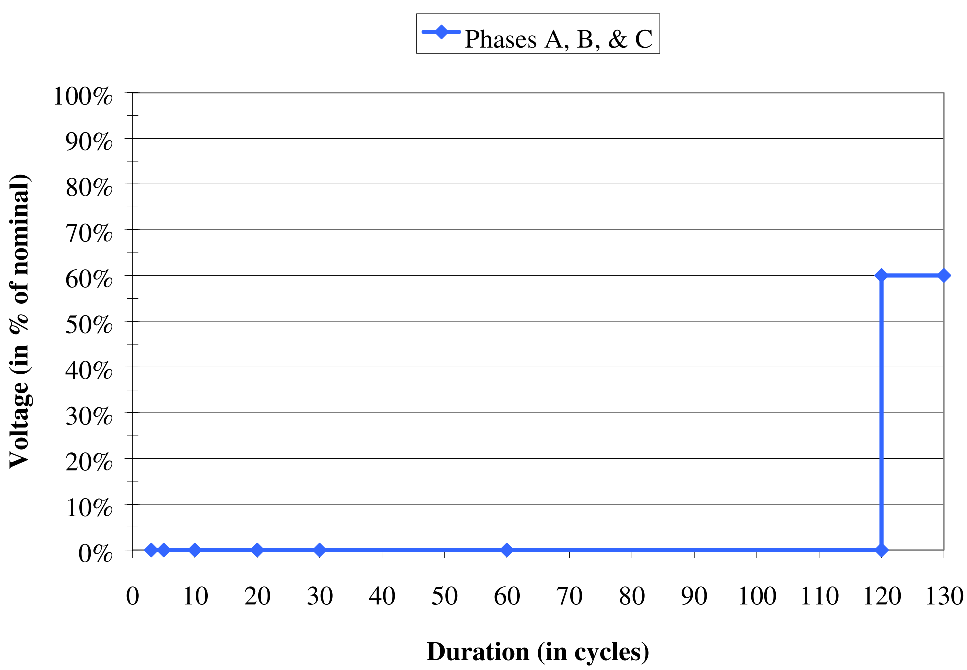


Figure 3-16
Three-Phase Sag Test Results for the SymCom 601

Discussion

With the *Low-Voltage Trip Level* set a 90% of nominal and the *Trip Delay* set to two seconds, the SymCom 601 was able to accurately detect single-phase and two-phase sags that resulted in line-to-line voltages of 90% of nominal and below for durations of two seconds and longer. In addition, the combination of the two-wire control circuit (see Figure 3-13) and the *Reset* and *Reset Delay* functions, the SymCom automatically reset its output relay contacts and the motor automatically restarted. The restart occurred two seconds after the voltage-sag conditions ended for all test points where the SymCom 601 responded to sag events. The SymCom 601 was able to detect single-phase and two-phase voltage sags regardless of which phases were affected.

However, the SymCom 601 did not perform as expected during the three-phase sag tests. Rather than responding to three-phase sags at 90% of nominal, the device did not respond until the voltage had fallen to 60% of nominal. The results tend to show that this device may not respond accurately to symmetrical three-phase voltage sags or sustained undervoltage conditions. NEMA-rated motors are designed to operate under rated load conditions successfully when their nominal voltage is between 110% and 90% of nominal. These results raise questions with regard to this device's ability to protect motors from sustained undervoltage conditions. However, further testing would be required before any concrete conclusions can be made with regard to the device's susceptibilities.

Response to Voltage Unbalance

With the SymCom 601 connected, the motor was loaded and voltage unbalances were initiated. The SymCom 601's responses were monitored and recorded. The results are shown in Table 3-7.

Table 3-7
Voltage Unbalance Test Results for the SymCom 601

Test	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}	V_{ub}	I_a	I_b	I_c	I_{ub}	Result
0%	276	278	278	479	483	480	0.49%	18.2	20.1	20.3	6.83%	N/A
1.5%	266	278	278	471	482	471	1.54%	17.0	21.3	20.3	12.97%	1
3.0%	254	278	277	460	481	461	2.92%	15.2	23.4	21.1	23.62%	2
5.0%	241	278	277	448	481	451	4.57%	13.3	25.8	21.8	34.48%	2

1. No response by the SymCom 601.
2. The SymCom 601 tripped the motor. When the voltage was returned to normal, the SymCom automatically reset its relay contacts and the motor automatically restarted.

Discussion

The results of all voltage unbalance tests were expected. With the *Voltage Unbalance Trip Point* set to 3%, the SymCom 601 tripped the motor at 3% and 5% voltage unbalance. It is interesting to note that the motor automatically restarted when the voltages returned to normal. This feature could reduce downtime. However, it could also potentially create a safety hazard for the process or process operators. With the SymCom 601's *Reset* feature set to A (for automatic reset), the SymCom will automatically reset its output contacts and the motor will restart without warning when the fault conditions end (assuming a two-wire motor control circuit topology). Therefore, it is important to address the safety implications before enabling this type of feature with any type of relay or motor controller.

Response to Single-Phasing

With the SymCom 601 connected and the motor running under load, the Phase-A power connection was opened. The SymCom 601's response was monitored and recorded. The same steps were repeated for Phases B and C. The results are shown in Table 3-8.

Table 3-8
Single-Phasing Test Results for the SymCom 601

Test	Result
Phase A Opened	The SymCom 601 tripped the motor during the event and automatically reset its output relay contacts when the event ended. The motor automatically restarted.
Phase B Opened	The SymCom 601 tripped the motor during the event and automatically reset its output relay contacts when the event ended. The motor automatically restarted.
Phase C Opened	The SymCom 601 tripped the motor during the event and automatically reset its output relay contacts when the event ended. The motor automatically restarted.

Discussion

All of the single-phasing test results were expected. The SymCom 601 detected single-phasing conditions regardless of which phase was opened. In addition, the SymCom 601 did not lose power during any of the tests. At each test point, the SymCom automatically reset its output relay contacts and the motor restarted. However, the same safety hazards apply here as were addressed in the previous section on voltage unbalance with regard to the automatic restarting of motors after fault conditions end. The use of two-wire control circuits and relays with auto-reset capabilities should be reviewed thoroughly before implementation.

The Amprobe Instrument Motor Guard

The Amprobe Instrument Motor Guard model MGX1A-400 is a three-phase voltage monitor relay. Some of the specific features are listed below:

- Low-voltage protection.
- Voltage-unbalance protection.
- Trip-delay timer.
- Automatic reset delay timer.

Setup, Installation, and Programming of the Motor Guard MGX1A-400

The Motor Guard purchased for these tests could be used for 400-Vac applications. The relay was set up, tuned, and installed according to the instruction sheets shipped with the unit. Figure 3-17 shows the control circuit configuration that was evaluated during these tests.

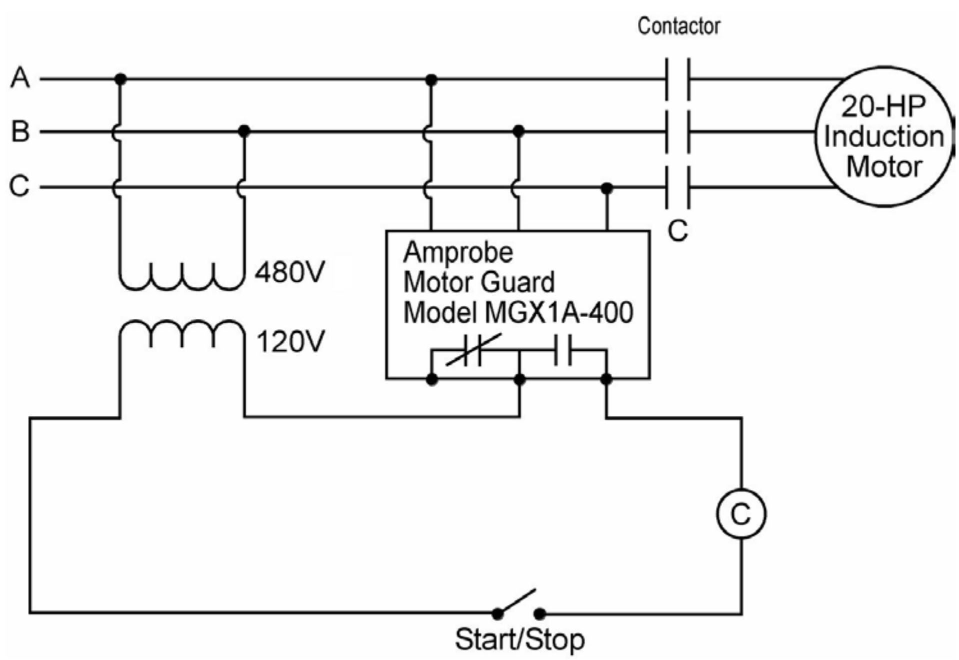


Figure 3-17
Motor Guard MGX1A-400 Connection Configuration

The Motor Guard has protection features that will affect how the unit responds to undervoltage conditions, such as voltage sags, momentary interruptions, and sustained undervoltage conditions. The Motor Guard has a *Low Voltage Trip Level*, a *Low Voltage Reset Level*, a *Trip Delay Timer*, and a *Reset Delay Timer*. The Motor Guard automatically resets its output relay contacts when fault conditions end. This is a non-changeable function with the tested unit. The trip thresholds and timers are factory-set, and the user does *not* have access to alter them.

The Motor Guard also has protection features that can be used to protect the motor against voltage unbalance conditions: the *Voltage Unbalance Trip Level* and the *Voltage Unbalance Reset Level*. The thresholds are factory-set, and the user does *not* have access to alter them.

Connection Configuration of the Motor Guard MGX1A-400

The Motor Guard was connected based on the suggested connection configuration shown in the instruction sheets. The Motor Guard was connected as shown in Figure 3-17. According to the instruction sheet shipped with the unit, the pertinent protection features had the following values:

Line Voltage Adjust = 480 V (the only user-selectable feature)

Low-Voltage Trip Level = 90% (of nominal *Line Voltage Adjust*)

Low-Voltage Reset Level = 93% (of nominal *Line Voltage Adjust*)

Voltage Unbalance Trip Level = 6%

Voltage Unbalance Reset Level = 4.5%

Trip Delay Timer (low voltage) = 4 seconds

Trip Delay Timer (unbalance and phasing faults) = 2 seconds

Reset Delay Timer (after a fault) = 2 seconds

Reset Delay Timer (after a complete power loss) = 5 seconds

It is interesting to note that the Motor Guard monitors all three phase-to-phase voltages of the three-phase system at connection points L1, L2, and L3 with the connection configuration shown in Figure 3-17.

Response to Voltage Sags

The voltage-sag generator was connected to the utility power supply upstream of the Motor Guard and the motor. The motor was loaded to approximately 75% of nominal with the eddy-current-brake dynamometer. Sags were initiated, and the Motor Guard's responses were monitored and recorded. The results are shown in Figure 3-18, Figure 3-19, and Figure 3-20.

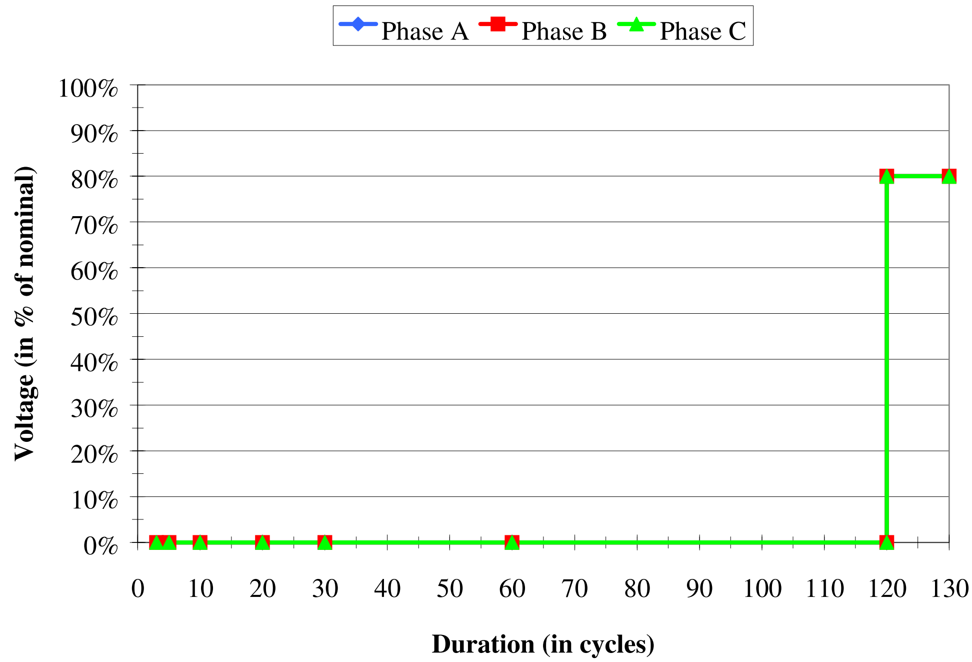


Figure 3-18
Single-Phase Sag Test Results for the Motor Guard MGX1A-400

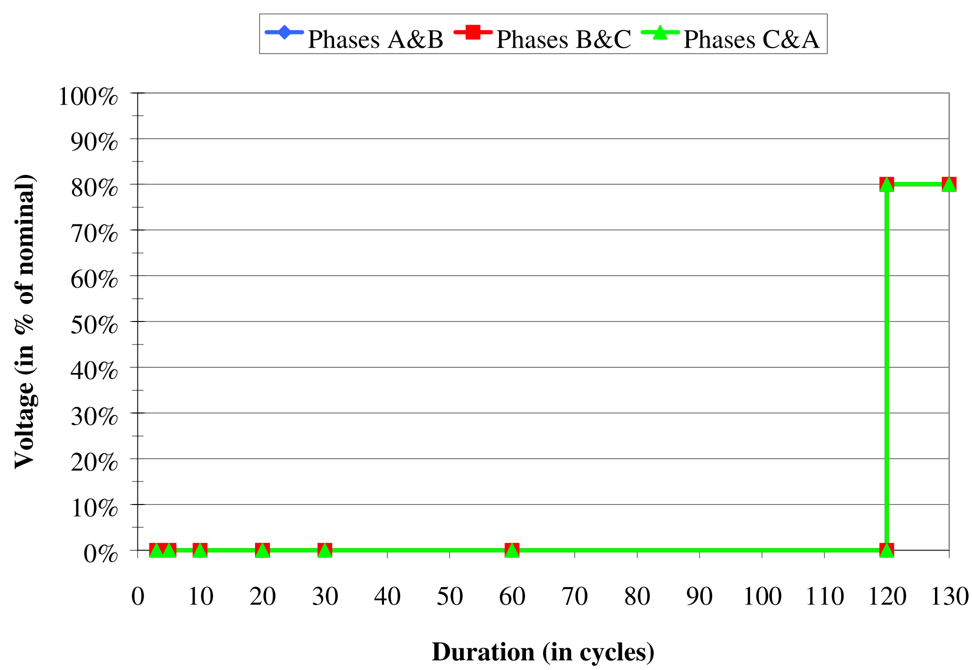


Figure 3-19
Two-Phase Sag Test Results for the Motor Guard MGX1A-400

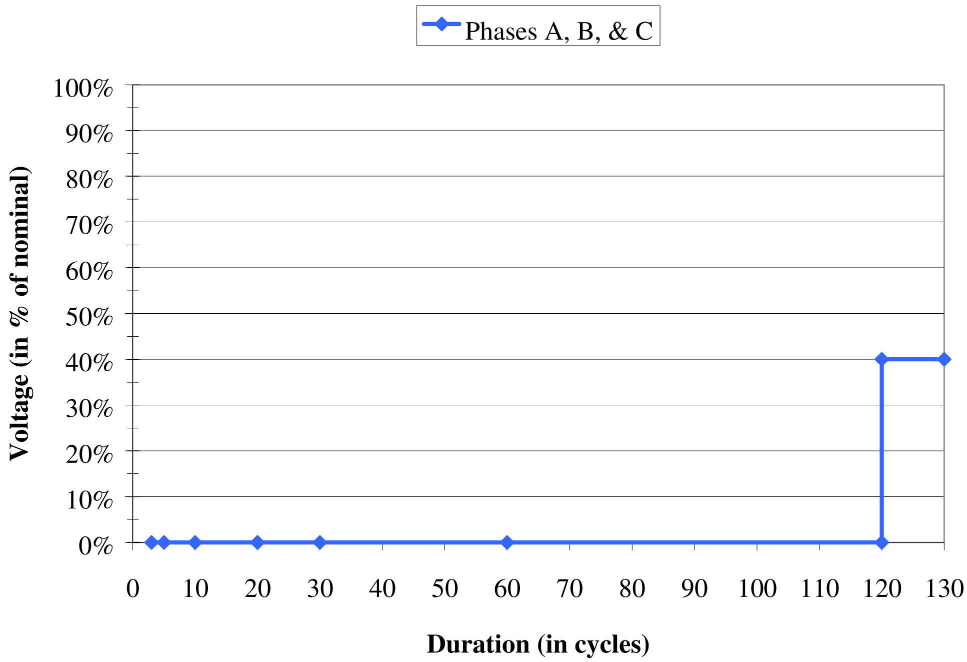


Figure 3-20
Three-Phase Sag Test Results for the Motor Guard MGX1A-400

Discussion

The single-phase and two-phase sag test results show that the Motor Guard detected the voltage sags at 80% of nominal, regardless of which phases were affected. However, the Motor Guard's specifications sheet defined the detection level as 90% of nominal voltage. These results do not raise any serious questions with regard to the device's ability to protect induction motors, because the voltage-unbalance protection should protect the device during sustained single-phase or two-phase voltage variations. With a combination of the two-wire control circuit (see Figure 3-17) and *Reset Delay Timer* function, the Motor Guard automatically reset its output relay contacts and the motor automatically restarted two seconds after the voltage-sag conditions ended for all test points where the Motor Guard responded to voltage sags. Similar safety hazards apply here as were discussed in the previous chapter when considering the use of the two-wire motor control circuits and auto-reset protection relays.

The Motor Guard did not perform as expected during the three-phase sag tests. Rather than responding to three-phase sags at 90% of nominal, the device did not respond until the voltage had fallen to 40% of nominal. The results tend to show that this device does not respond accurately to symmetrical three-phase voltage sags or sustained undervoltage conditions. NEMA-rated motors are designed to operate under rated load conditions successfully when their nominal voltage is between 110% and 90% of nominal. These results raise questions with regard to this device's ability to protect motors from sustained undervoltage conditions, when the source voltage is between 90% and 80% of nominal. However, further testing would be required before any concrete conclusions can be made with regard to the device's susceptibilities.

Response to Voltage Unbalance

With the Motor Guard connected, the motor was loaded and voltage unbalances were initiated. The Motor Guard's responses were monitored and recorded. The results are shown in Table 3-9.

Table 3-9
Voltage Unbalance Test Results for the Motor Guard

Test	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}	V_{ub}	I_a	I_b	I_c	I_{ub}	Result
0%	276	278	279	480	484	481	0.48%	18.6	19.9	20.2	4.94%	N/A
1.5%	267	278	279	471	483	472	1.61%	17.7	22.2	21	12.81%	1
3.0%	254	278	279	460	483	463	3.06%	15.6	24.5	22.1	24.76%	1
5.0%	241	278	279	448	483	452	4.77%	13.9	26.7	23.1	24.76%	1
7.0%	†	†	†	433	482	438	6.87%	†	†	†	†	1

† Indicates no measurements recorded.

1. No response by the Motor Guard.

Discussion

The results of all voltage-unbalance tests were not expected. With the *Voltage Unbalance Trip Level* factory-set at 6%, the Motor Guard did not trip the motor when the voltage unbalance was nearly 7%. An equally troubling fact is the factory-set value of 6% voltage unbalance. This value is too high for most motor-protection applications. High values of negative-sequence currents are possible with voltage unbalance levels as low as 3%. High values of negative-sequence currents lead to motor overheating and shorten the motor's life expectancy.

Response to Single-Phasing

With the Motor Guard connected and the motor running under load, the Phase-A power connection was opened. The Motor Guard's response was monitored and recorded. The same steps were repeated for Phases B and C. The results are shown in Table 3-10.

Table 3-10
Single-Phasing Test Results for the Motor Guard MGX1A-400

Test	Result
Phase A Opened	The Motor Guard tripped the motor approximately two seconds after event initiation and automatically reset its output relay contacts two seconds after the event ended. The motor automatically restarted.
Phase B Opened	The Motor Guard tripped the motor approximately two seconds after event initiation and automatically reset its output relay contacts two seconds after the event ended. The motor automatically restarted.
Phase C Opened	The Motor Guard tripped the motor approximately two seconds after event initiation and automatically reset its output relay contacts two seconds after the event ended. The motor automatically restarted.

Discussion

All of the single-phasing test results were expected. The Motor Guard detected single-phasing conditions regardless of which phase was opened two seconds after the event initiation. In addition, the Motor Guard did not lose power during any of the tests. At each test point, the Motor Guard automatically reset its output relay contacts two seconds after the event ended and the motor restarted. The same safety hazards apply here as were addressed in previous sections with regard to automatic restarting motors after fault conditions. The use of two-wire control circuits and relays with auto-reset capabilities should be reviewed thoroughly before implementation.

The Time Mark 3-Phase Monitor Micro-controller

The Time Mark model 2550 is a three-phase voltage monitor and micro-controller. Some of the specific features are listed below:

- Contact failure protection.
- Phase-loss protection.
- High/low-voltage protection.
- Voltage-unbalance protection.
- Phase-sequence protection.
- Trip-delay timer.
- Automatic or manual reset.
- Automatic reset delay timer.

Setup, Installation, and Programming of the Time Mark 2550

The Time Mark 2550 purchased for these tests could be used for applications rated at 200 to 240 Vac or 400 to 480 Vac. The relay was set up, tuned, and installed according to the instruction sheets shipped with the unit. Figure 3-21 shows the control circuit configuration that was evaluated during these tests.

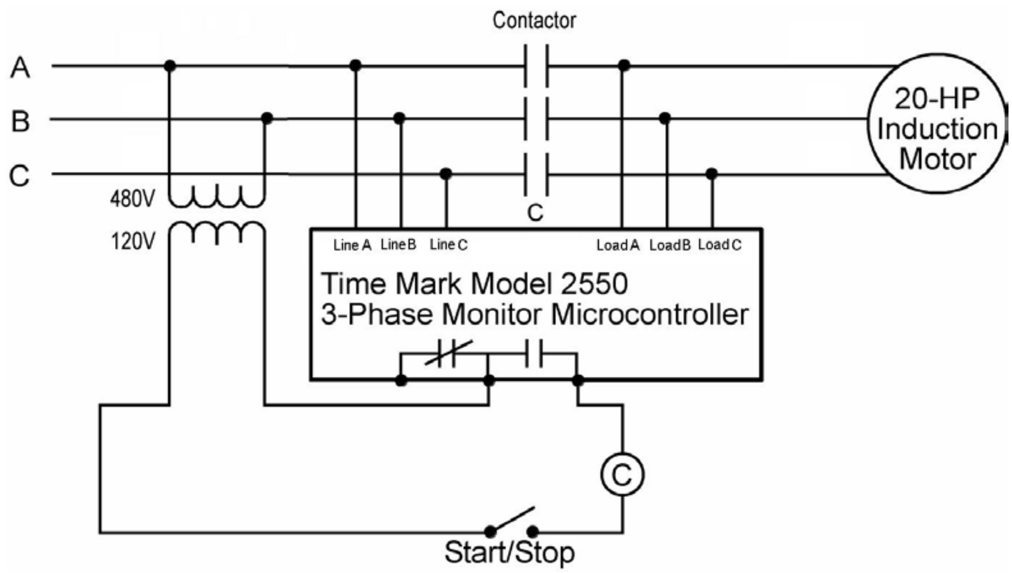


Figure 3-21
Time Mark 2550 Connection Configuration

The Time Mark 2550 has protection features that will affect how the unit responds to undervoltage conditions, such as voltage sags, momentary interruptions, and sustained undervoltage conditions. The Motor Guard has a *Low-Voltage Trip Level*, a *Low Voltage Reset Level*, a *Trip Delay Timer*, and a *Reset Delay Timer*. The Time Mark 2550 automatically resets its output relay contacts when fault conditions end. This function can be set to manual or automatic through the *Restart Delay Timer*. Most of the trip thresholds and timers are user-selectable.

The Time Mark 2550 also has one protection feature that can be used to protect the motor against voltage unbalance conditions: the *Voltage Unbalance Trip Level*. This threshold is user-selectable.

Connection Configuration of the Time Mark 2550

The Time Mark 2550 was connected based on the suggested connection configuration shown in the instruction sheets. The Time Mark 2550 was connected as shown in Figure 3-21. The pertinent protection features had the following values:

Line Voltage Adjust = 480 V (DIP switch)

Low-Voltage Trip Level = 90% (of nominal *Line Voltage Adjust*)

Low-Voltage Reset Level = 92% (of nominal *Line Voltage Adjust*)

Voltage Unbalance Trip Level = 3%

Trip Delay Timer = 2 seconds

Trip Delay Timer (single-phasing) = 2 seconds

Reset Delay Timer (after a fault) = 2 seconds

It is interesting to note that the Time Mark 2550 monitors all three phase-to-phase voltages on the line side of the contactor at connection points Line 1, Line 2, and Line 3 and on the load side of the contactor at connection points Load 1, Load 2, and Load 3 (see Figure 3-21).

Testing of the Time Mark 2550

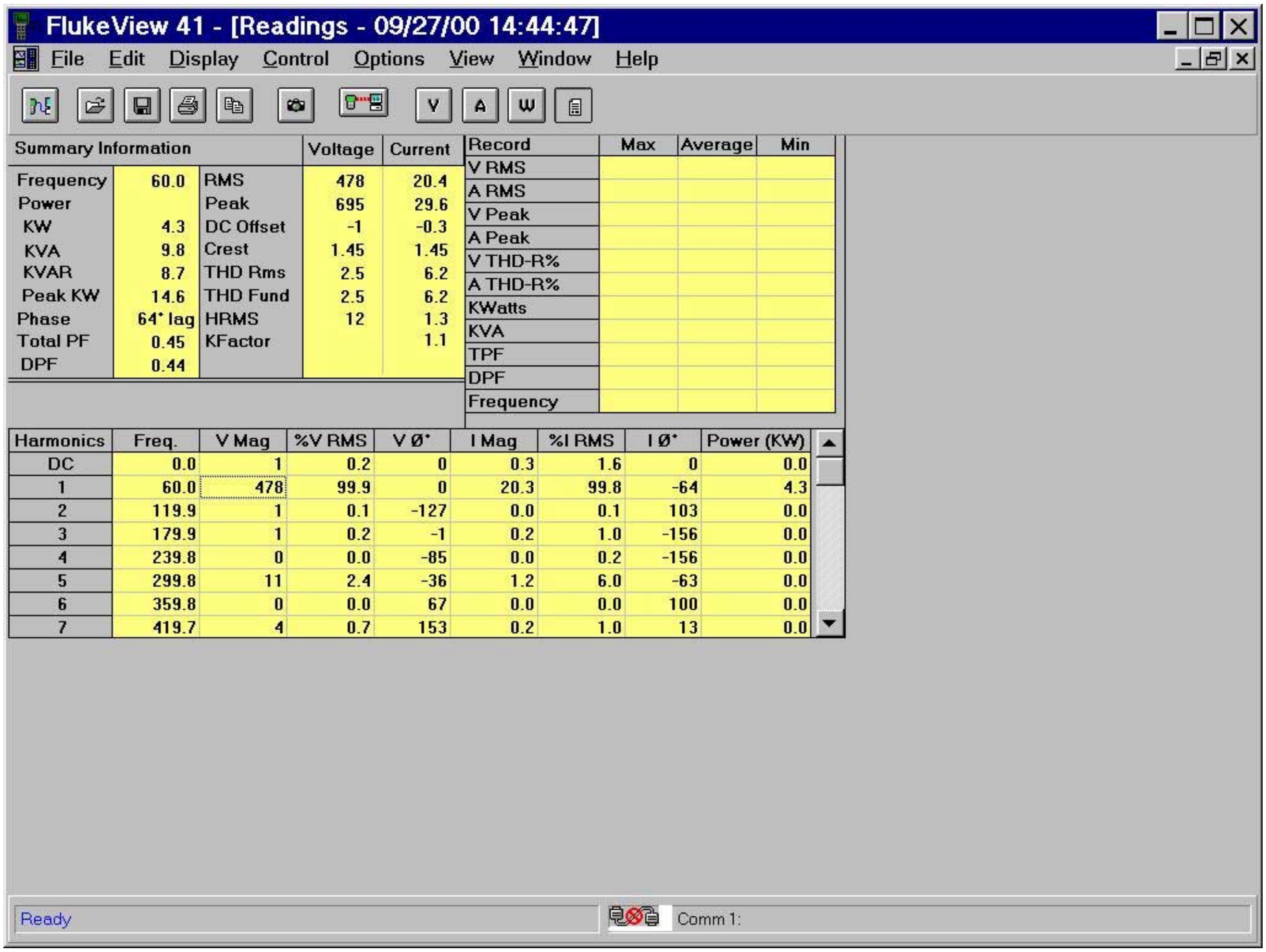
The voltage-sag generator was connected to the utility power supply upstream of the Time Mark 2550 and the motor. The motor was loaded to approximately 75% of nominal with the eddy-current-brake dynamometer.

During the voltage-sag testing, the Time Mark 2550 randomly tripped at times when no voltage sags were being introduced to the system. The device has LED fault-indication lamps on the front panel to help troubleshoot and identify faults. The phase unbalance lamp was illuminated during every nuisance trip. The nominal voltage at the terminals of the unit were 478 V, 482 V, and 479 V, resulting in a voltage unbalance of 0.5%. With the *Voltage Unbalance Trip Level* set to 3%, the device should not have been randomly tripping the motor.

The manufacturer was consulted regarding the setup and nuisance tripping of the device. The manufacturer recommended removing the load-side voltage connections (Load 1, Load 2, and Load 3). The recommendations were followed. However, the device continued to randomly trip.

The manufacturer was again consulted. A service technician explained that there are some applications where the Time Mark 2550 does not operate as designed. The technician explained that the device sometimes does not function properly in a harmonic-rich electrical environment. It was explained to the manufacturer that the voltage THD readings indicated the voltage distortion where the unit was located was at a low value (2.5% of fundamental). However, the manufacturer could not explain the behavior of the device and has not developed a fix for the problem. Due to the device's lack of compatibility and the continuous nuisance trips, it was decided to end the voltage-sag testing and forego further testing of the Time Mark 2550 due to the fact that none of the results could be accepted with any confidence.

Measurements of the line-to-line voltages and line current while the motor was running under load were obtained with a Fluke 41 Power Harmonic Analyzer. Screen captures from the FlukeView software are shown in Figure 3-22, Figure 3-23, and Figure 3-24.

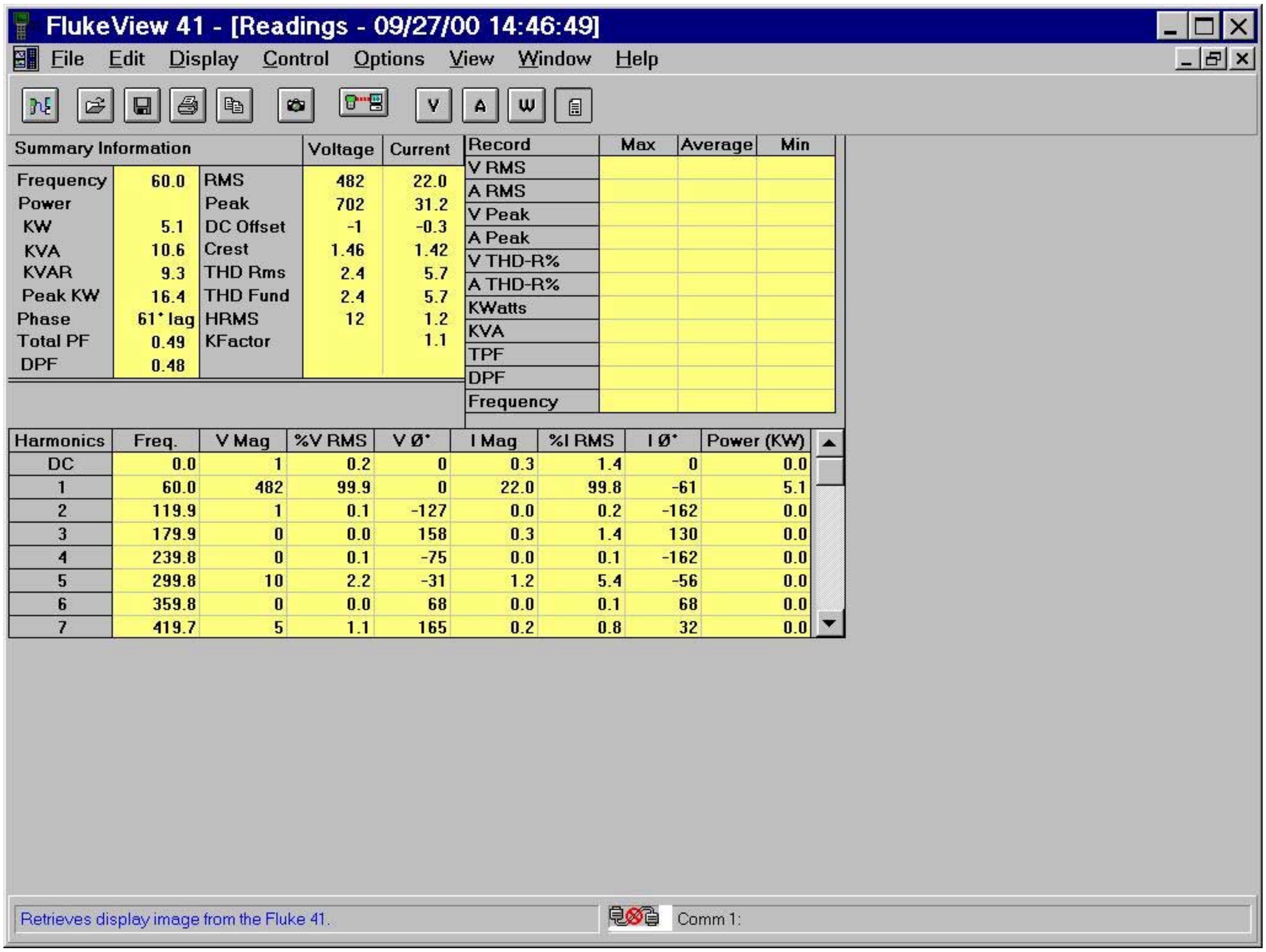


Summary Information			Voltage	Current
Frequency	60.0	RMS	478	20.4
Power		Peak	695	29.6
KW	4.3	DC Offset	-1	-0.3
KVA	9.8	Crest	1.45	1.45
KVAR	8.7	THD Rms	2.5	6.2
Peak KW	14.6	THD Fund	2.5	6.2
Phase	64° lag	HRMS	12	1.3
Total PF	0.45	KFactor		1.1
DPF	0.44			

Record	Max	Average	Min
V RMS			
A RMS			
V Peak			
A Peak			
V THD-R%			
A THD-R%			
KWatts			
KVA			
TPF			
DPF			
Frequency			

Harmonics	Freq.	V Mag	%V RMS	V Ø°	I Mag	%I RMS	I Ø°	Power (KW)
DC	0.0	1	0.2	0	0.3	1.6	0	0.0
1	60.0	478	99.9	0	20.3	99.8	-64	4.3
2	119.9	1	0.1	-127	0.0	0.1	103	0.0
3	179.9	1	0.2	-1	0.2	1.0	-156	0.0
4	239.8	0	0.0	-85	0.0	0.2	-156	0.0
5	299.8	11	2.4	-36	1.2	6.0	-63	0.0
6	359.8	0	0.0	67	0.0	0.0	100	0.0
7	419.7	4	0.7	153	0.2	1.0	13	0.0

Figure 3-22
Voltage and Current Harmonic Analysis for the Time Mark 2550 (Voltage V_{AB} and Current I_A)

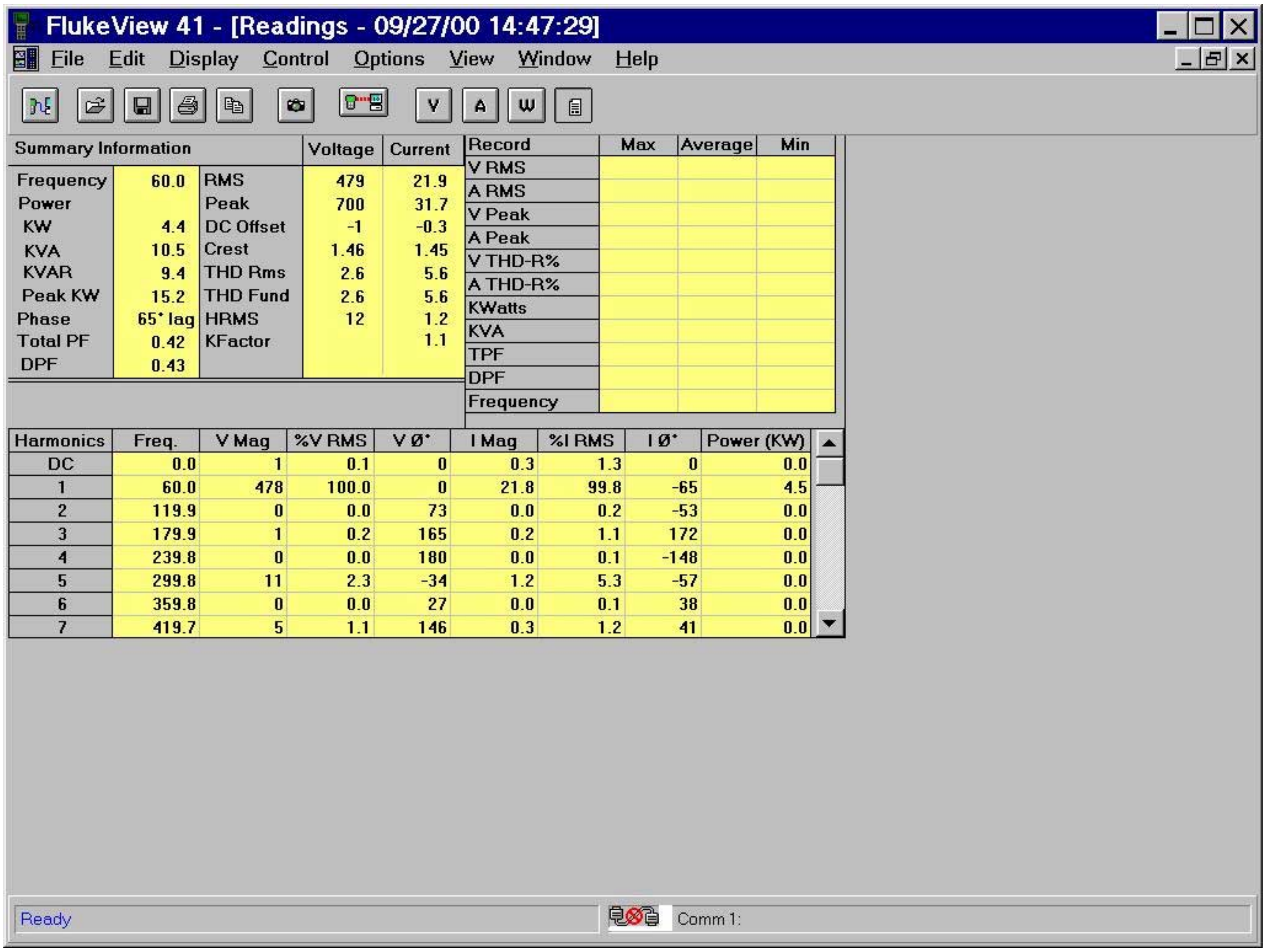


Summary Information			Voltage	Current
Frequency	60.0	RMS	482	22.0
Power		Peak	702	31.2
KW	5.1	DC Offset	-1	-0.3
KVA	10.6	Crest	1.46	1.42
KVAR	9.3	THD Rms	2.4	5.7
Peak KW	16.4	THD Fund	2.4	5.7
Phase	61° lag	HRMS	12	1.2
Total PF	0.49	KFactor		1.1
DPF	0.48			

Record	Max	Average	Min
V RMS			
A RMS			
V Peak			
A Peak			
V THD-R%			
A THD-R%			
KWatts			
KVA			
TPF			
DPF			
Frequency			

Harmonics	Freq.	V Mag	%V RMS	V Ø°	I Mag	%I RMS	I Ø°	Power (KW)
DC	0.0	1	0.2	0	0.3	1.4	0	0.0
1	60.0	482	99.9	0	22.0	99.8	-61	5.1
2	119.9	1	0.1	-127	0.0	0.2	-162	0.0
3	179.9	0	0.0	158	0.3	1.4	130	0.0
4	239.8	0	0.1	-75	0.0	0.1	-162	0.0
5	299.8	10	2.2	-31	1.2	5.4	-56	0.0
6	359.8	0	0.0	68	0.0	0.1	68	0.0
7	419.7	5	1.1	165	0.2	0.8	32	0.0

Figure 3-23
Voltage and Current Harmonic Analysis for the Time Mark 2550 (Voltage V_{BC} and Current I_B)



Summary Information			Voltage	Current
Frequency	60.0	RMS	479	21.9
Power		Peak	700	31.7
KW	4.4	DC Offset	-1	-0.3
KVA	10.5	Crest	1.46	1.45
KVAR	9.4	THD Rms	2.6	5.6
Peak KW	15.2	THD Fund	2.6	5.6
Phase	65° lag	HRMS	12	1.2
Total PF	0.42	KFactor		1.1
DPF	0.43			

Record	Max	Average	Min
V RMS			
A RMS			
V Peak			
A Peak			
V THD-R%			
A THD-R%			
KWatts			
KVA			
TPF			
DPF			
Frequency			

Harmonics	Freq.	V Mag	%V RMS	V Ø°	I Mag	%I RMS	I Ø°	Power (KW)
DC	0.0	1	0.1	0	0.3	1.3	0	0.0
1	60.0	478	100.0	0	21.8	99.8	-65	4.5
2	119.9	0	0.0	73	0.0	0.2	-53	0.0
3	179.9	1	0.2	165	0.2	1.1	172	0.0
4	239.8	0	0.0	180	0.0	0.1	-148	0.0
5	299.8	11	2.3	-34	1.2	5.3	-57	0.0
6	359.8	0	0.0	27	0.0	0.1	38	0.0
7	419.7	5	1.1	146	0.3	1.2	41	0.0

Figure 3-24
Voltage and Current Harmonic Analysis for the Time Mark 2550 (Voltage V_{CA} and Current I_c)

4

GUIDELINES FOR PROTECTING THREE-PHASE AC INDUCTION MOTORS FROM VOLTAGE SAGS, MOMENTARY INTERRUPTIONS, OUT-OF-PHASE RECLOSURES, AND SOURCE TRANSFERS

It is a well-known fact that electrical disturbances cause electrical appliances to trip, malfunction, or adversely affect production in some way—computers crash, production lines stop, and lights go out—all of which can spell disaster. Industrial and commercial facilities are usually hardest hit. Many companies produce materials with low profit margins. As a result, repeated trips can translate into significant monetary losses, which can often lead to friction between the customer and the utility. Because of industry's dependency on electrical process equipment, in particular electric motors, their susceptibility and protection is a concern for many. Some of the more common questions about motor protection include:

- When should motors be allowed to operate during voltage sags and momentary interruptions?
- What are the concerns?
- What are the factors that determine how motors will be affected?
- When and how should they be protected?

The voltage supply of a line-connected induction motor may vary from time to time. Fluctuations in the power demand on the power system may cause the system voltage to vary as much as ±10% of nominal. These types of variations will not be a concern for motor stability. However, they can affect the motor if the conditions are sustained for long periods of time. According to NEMA MG1-1998, induction motors are designed to operate without derating when the terminal voltage is between ±10% of the machine's nameplate rating. Table 4-1 shows the effects on motor performance when operated from a voltage source with nominal voltages of 90% and 110% of the nameplate voltage rating.

Table 4-1
Voltage Effects on Motor Performance

Motor Characteristic	*Voltage Range (% of Nameplate)*	
	90%	*110%*
Starting and Maximum Running Torque	–19%	+21%
Percent Slip	+23%	–19%
Full-Load Speed	–0.2 to –1.0%	+2.0 to 1.0%
Starting Current	–10%	+10%
Full-Load Current	+5 to +10%	–5 to –10%
No-Load Current	–10 to –30%	+10 to +10%
Temperature Rise	+10 to +15%	–10 to –15%
Full-Load Efficiency	–1 to –3%	+1 to +3%
Full-Load Power Factor	+3 to +7%	–1 to –7%
Magnetic Noise	Slight Decrease	Slight Increase

In addition to steady-state fluctuations of the motor's supply voltage, across-the-line starts will also create temporary reductions in the motor's terminal voltage. With the starting current of a typical induction motor at 6 to 7 times the rated full-load current, the terminal voltage may temporarily drop by 15% or more, depending on the stiffness of the source. As the motor gets closer to rated speed, the line current reduces and the terminal voltage increases. In most cases, voltage variations due to across-the-line starts will not affect motor stability.

Long-duration undervoltages, voltage sags, momentary interruptions, and source transfers are another story. There are a number of factors that determine how and when motors should be protected. This chapter will address a number of these motor-protection issues and is designed to be a reference for induction motor protection from the nuisance, perhaps damaging, side-effects of voltage sags, momentary interruptions, out-of-phase reclosures, and source transfers.

Analyzing the Need for Motor Protection

Motor protection should be categorized and coordinated with the requirements of the process. This is especially true for industries with large numbers of induction motors such as the petroleum and chemical industries. Heavy industrials like the petroleum and chemical industries have a number of electric motor-driven loads such as pumps, fans, and compressors that comprise the bulk of a system's energy demand. When many motors are used in a process, it is important to categorize each motor according to its priority in the process. Here is an example of three motor-protection categories:

1. **Category I**: Motors essential to production that should remain running at all times (highest priority).

2. **Category II**: Motors that can be stopped temporarily, but should be restarted as soon as possible following system voltage recovery.

3. **Category III**: Motors that are not essential to production. Motors that can be stopped and restarted when conditions are acceptable (lowest priority).

Once the process motors have been categorized according to their priority, motor protection and control schemes should be considered to obtain the required performance. However, there are electrical operating conditions and application considerations that must be addressed before applying certain types of protection devices.

According to ANSI C37.96-1998, when choosing undervoltage protection for large induction or synchronous motors, the protection should differentiate between long-duration undervoltage conditions, which could overheat the motor, and short-duration undervoltage conditions (up to 15 cycles), which could cause mechanical problems and instability. Operating induction motors outside of their rated voltages will subject them to possible damage. Therefore, special forms of protection may be required to ensure motor safety. The specific areas of concern are undervoltage, overvoltage, phase unbalance, and phase failure (single-phasing). However, to maintain the scope of this document, only the undervoltage concerns will be addressed here.

Long-Duration Undervoltage Conditions

When the power system voltage is too low during motor starting, the motor may not reach full operating speed. Excessive heating of the stator and rotor are possible. A low-voltage condition while the motor is running also creates additional heating of the stator and rotor. The concern is focused on the deterioration of the physical and dielectric properties of the stator insulation. Deterioration of insulation systems is accelerated in the presence of increased temperature levels. From testing and experience, the life expectancy of an insulation system is halved for every 10°C above the rated operating temperature. Conversely, the life expectancy is doubled every 10°C below the rated operating temperature.[3]

Elevated temperatures reduce the ability of an insulation system to withstand electrical and mechanical abuse. The choice of protection for an insulation system will depend on engineering judgment and applicable standards. When the cost of shutting down a motor to protect it from thermal damage outweighs the cost of lost production, it may be necessary to operate essential-service motors (Category I) during long-duration undervoltages even though the thermal stress may significantly reduce the life expectancy of the motor.

Permitting the motor to operate during sustained reduced voltages may allow system operators sufficient time to correct the low-voltage problem without shutting down the essential-service motors and losing valuable production time. Power plants are excellent examples of applications where essential-service motors should be allowed to operate for extended periods during low-voltage conditions. If essential-service motors, such as fans and pumps, in the generating units

[3] The ANSI/NFPA 70 standard or National Electric Code (NEC) was written to provide the practical safeguarding of persons, buildings, and content from hazards arising from the use of electricity and contains the provisions considered necessary for safety. The scope applies to electrical conductors and electric equipment for residential, industrial, and commercial applications. Electric utilities, mines, and other specific applications are not included. The standard specifies overload devices intended to protect electric motors, motor-control apparatus, and motor branch-circuit conductors from excessive heating due to overloading and failure to start and overcurrents due to short-circuits and faults.

shut down during undervoltage events, the system will lose generating capacity, which can result in total system collapse. Therefore, the use of long-duration undervoltage protection should be analyzed for the impact on the system.

Short-Duration Undervoltage Conditions (Voltage Sags)

It's no mystery that power system faults cause voltage sags. Factors such as the distance from the fault, the power system configuration, and the power system protection scheme affect the depth and duration of sags.

During a voltage sag, an induction motor may stall and may not be able to reaccelerate the load upon recovery of the system voltage. However, the motor may simply lose speed and reaccelerate normally. There are a number of related factors that determine how a motor will be affected. The motor type, pullout torque, load torque, system inertia, and the depth and duration of the sag are all contributing factors.

On a sudden lowering of the motor's source voltage (caused by a system fault), an induction motor will temporarily feed the fault due to trapped magnetic flux within the motor. From a stability standpoint, three-phase bolted faults on the motor power feeders are the worst case. Under these conditions, a negative torque transient approaching five times the rated torque and a current transient approaching ten times rated current are possible. On restoration of the power system voltage, additional current and torque transients will be produced. Figure 4-1 shows the effect of a 5-cycle, three-phase bolted fault at the terminals of a fully loaded, 460-V, 5-HP induction motor [1]. Two-phase-to-ground, phase-to-phase, and phase-to-ground faults are less severe on the motor and load in the order just listed.

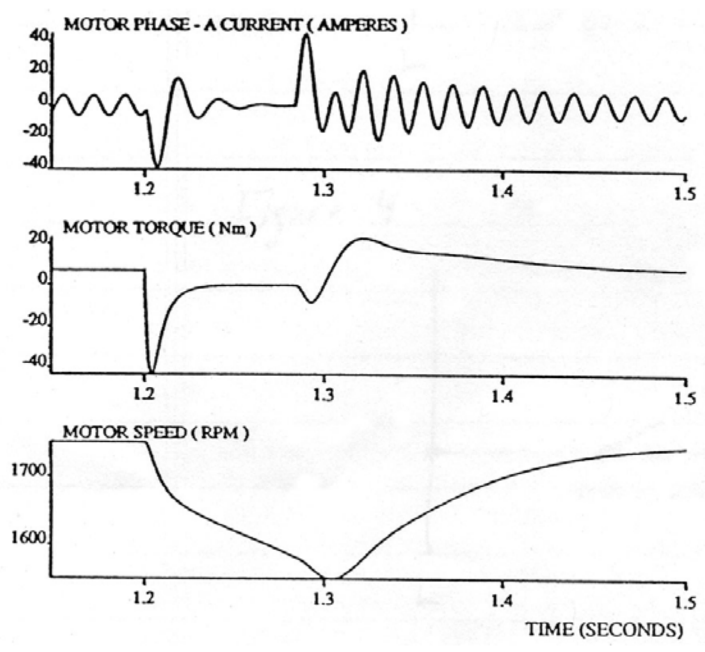


Figure 4-1
Effect of Three-Phase Fault on Fully Loaded Induction Motor

It is true that the electrical and mechanical transients will stress the motor and load. However, it can be said that so long as the motor remains connected to the utility power supply during a voltage sag, the torque and current transients will be no more severe than those associated with across-the-line starts [2]. Figure 4-2 shows the effects of a two-phase, 5-cycle voltage sag with phase-to-phase voltage magnitudes of 58%, 58%, and 100% of nominal voltage [1].

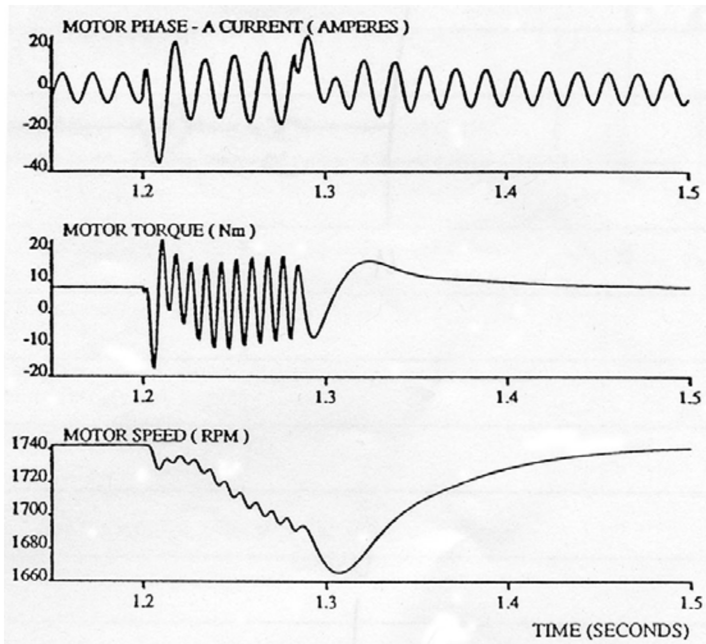


Figure 4-2
Effect of Two-Phase Voltage Sag on Induction Motor

It is important to keep in mind that the speed and torque of the motor may be significantly affected during voltage sags. Some processes or sub-processes cannot tolerate speed and torque deviations without adversely affecting product quality. Even though the motor may not be adversely affected, the product quality may suffer. Therefore, it may be necessary to trip some motors offline during deep voltage sags. As mentioned previously, the requirements of the process will determine the type and sensitivity of the protection scheme.

High-Speed Breaker Reclosing and Momentary Interruptions

Reclosing practices vary from utility to utility and, perhaps, from circuit to circuit. To reduce the impact on customer loads, some utilities are experimenting with faster reclosing times (0.3 to 0.5 seconds) for the first reclosing operation in order to solve customer problems with momentary interruptions. Electronic equipment such as clock radios, VCRs, microwaves, and televisions can often ride through a 0.5-second interruption but cannot ride through longer-duration interruptions. Although less likely than voltage sags, momentary interruptions will affect almost all power systems from time to time. Protecting induction motors from momentary interruptions focuses on the potential for damaging current and torque transients created when the switch reconnects motors to the source.

During nominal operating conditions, magnetic flux within an AC induction motor induces an internal voltage within the motor. Upon initiation of a momentary interruption, the magnetic flux trapped inside the motor does not decay instantaneously. Thus, the motor's internal voltage does not decay instantaneously and the motor will continue to produce an internal voltage until the magnetic flux decays. The rate of decay is exponential, with several influencing factors. The motor's open-circuit time constant, the system inertia, and the load level all affect the decay rate. The concern is that the motor's internal voltage and source voltage will be out-of-phase when the source voltage returns. Theoretically, the worst-case peak asymmetrical current approaches 30 to 40 times the motor's full-load current. The worst-case peak electromagnetic torque approaches 10 to 20 times the full-load torque of the motor.

Worst-Case Peak Asymmetrical Stator Current

The symmetrical stator current immediately following a momentary interruption, out-of-phase reclosure, or source transfer is given by Equation 4-1. The worst-case condition will occur when the motor's internal voltage is 180° out-of-phase with the source voltage. To calculate an absolute maximum current value, the source voltage and the motor's internal voltage are assumed to be equal in magnitude. These assumptions lead to the worst-case symmetrical stator current shown in Equation 4-2

$$I_{sym_{\max}} \approx \left| \frac{\tilde{E}_s - \tilde{E}_m}{X_s + X_m} \right| \tag{4-1}$$

where E_s is the source voltage, E_m is the motor's internal voltage, X_s is the Thevenin equivalent power system reactance at the terminals of the motor, and X_m is the motor's locked-rotor reactance (I_{rated}/I_{locked}).

$$I_{sym_{\max}} \approx \frac{2 \cdot E_s}{X_s + X_m} \tag{4-2}$$

In addition to the symmetrical current, a DC offset will be present. The combination of the worst-case symmetrical component and the DC offset gives the worst-case asymmetrical stator current shown in Equation 4-3. Typical values for the X_m and X_s yield values of 30 to 40 times the rated full-load current of the motor.

$$I_{aym_{\max}} \approx \frac{4\sqrt{2} \cdot E_s}{X_s + X_m} \tag{4-3}$$

Worst-Case Peak Electromagnetic Torque

The electromagnetic torque immediately following a momentary interruption, out-of-phase reclosure, or source transfer is the sum of an exponentially decaying unidirectional component and an oscillatory component at the power frequency [3]. When the motor's internal voltage is 0.8 per unit or higher, the worst-case reclosing angle between the motor's internal voltage and the source voltage is 120°. Again, the absolute worst-case maximum value occurs when the source voltage and the motor's internal voltage are assumed to be equal in magnitude. Equation 4-4 shows the worst-case peak electromagnetic torque. Typical values for the X_m and X_s yield values of 10 to 20 times the rated full-load torque of the motor.

$$T_{e_{\max}} \approx \frac{2.6 \cdot E_s^2}{X_s + X_m} \tag{4-4}$$

The magnetic forces within and between the windings in the stator of the motor are proportional to the square of the current. Therefore, it is obvious that the windings will be subjected to severe mechanical stress. However, moderately sized, integral horsepower squirrel-cage induction motors are designed to withstand the forces associated with full-voltage plug reversal. This condition also creates worst-case peak asymmetrical currents 30 to 40 times the motor's full-load current. Thus, the smaller squirrel-cage motors should rarely experience winding damage due to out-of-phase reclosures resulting from momentary interruptions.

Larger horsepower squirrel-cage induction motors (> 100 hp) are not designed (in general) for full-voltage plug reversal. Therefore, the possibility of winding damage exists. Wound-rotor induction motors are even more susceptible to damage. They are not designed to withstand the forces associated with normal startup conditions with their secondary slip rings shorted. Thus, they are the most susceptible to damage.

The critical timing issues between the initiation of the interruption and the reconnection of the power source will be described in detail in the section called *Source Transfers.*

Voltage-Sag-Induced Out-of-Phase Reclosures

Momentary interruptions, out-of-phase reclosures, and source transfers are completely different scenarios. However, they are related by the potential dangers they pose for induction motors. Out-of-phase reclosures and source transfers are similar to momentary interruptions because there exists the possibility for significantly high current and torque transients for induction motors caused by the phase and magnitude differences between the motor's internal voltage and the source voltage.

Out-of-phase reclosures occur when an induction motor is momentarily disconnected from the source. This situation can occur for any number of reasons. Human error and voltage sags are two of the more common reasons. Voltage sags are a concern for motors controlled with two-wire control circuits. Out-of-phase reclosures occur with two-wire control circuits when contactors and motor starters de-energize during voltage sags and re-energize when the sag ends. During the time that the contactor is de-energized, the motor will be disconnected from the source. When the sag ends, the contactor will re-energize and reconnect the motor to the source, possibly creating extremely high current and torque transients if the motor's internally induced voltage is significantly out-of-phase with the source.

However, with three-wire control circuits, there is no concern for out-of-phase reclosures. When the starter drops out, the starter will not automatically re-energize when the sag ends. Auxiliary contacts of the starter (or of a pilot relay) are used to "latch-in" the starter. The "latch" is broken when the starter drops out during the voltage sag. A new start command must be given to restart (reconnect) the motor. In most cases, an operator must press the start button to restart the motor.

Two-Wire and Three-Wire Control Circuits

Figure 4-3 shows an example of a three-wire control circuit used to control the start/stop functions of an AC induction motor. In this circuit, auxiliary contacts from the motor contactor are used to maintain or "latch-in" power to the contactor. When the contactor drops out, such as when the momentary stop button is pressed, the auxiliary contacts change states and power is lost to the starter. An operator must press the momentary start button to re-energize the contactor and latch-in the starter.

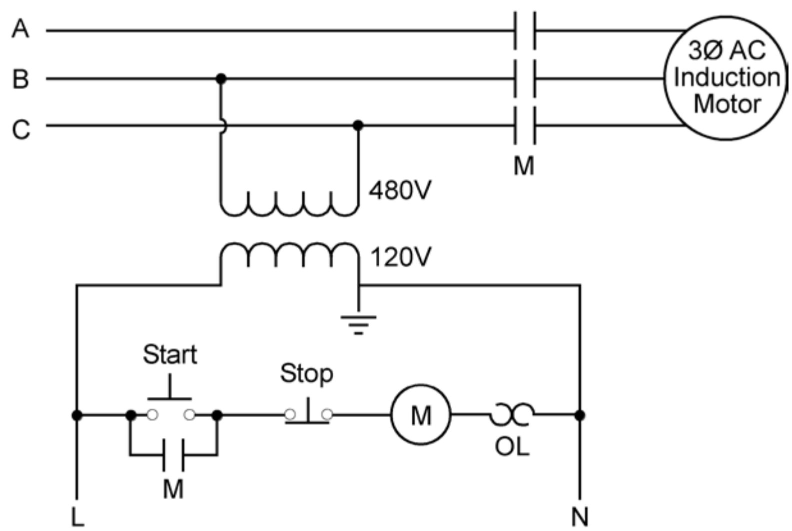


Figure 4-3
Three-Wire Control Circuit for Start/Stop Functions of an AC Motor

Three-wire control circuits are inherently susceptible to undervoltage events, such as voltage sags and momentary interruptions. The susceptibility of the contactor determines when the motor is disconnected from the source. In some cases, the susceptibility of the contactor is counted on to provide undervoltage protection for the motor. The advantages and disadvantages of this type of control circuit for undervoltage protection are discussed in detail in other sections of this document.

An example of a two-wire motor control circuit is also shown in Figure 4-4. The circuit provides the start/stop functions of an AC induction motor. In this circuit, a process two-position switch provides the start/stop functionality. When the switch is in the on position, the motor contactor is energized and the motor is connected to the source. When the switch is in the OFF position, the motor contactor is de-energized and the motor is not connected to the source. Two-wire control circuits are also susceptible to undervoltage events. However, unlike three-wire control circuits, the motor contactor will re-energize automatically once power is restored to the circuit. This situation can produce damaging transients for the motor and load if the reclosure takes place when the motor's internal voltage is significantly out-of-phase with the source voltage. Out-of-phase reclosures are discussed in detail in other sections of this document.

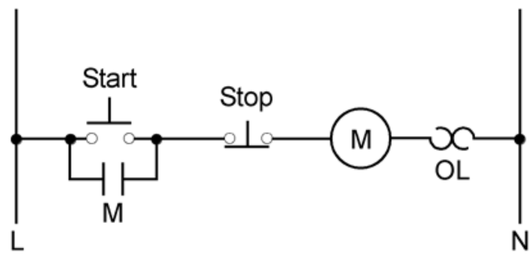


Figure 4-4
Two-Wire Control Circuit for Start/Stop Functions of an AC Motor

Source Transfers

Competitive markets around the world have forced many industries to seek high levels of power system reliability and availability. Redundant power sources are sometimes used as means of achieving these goals. When one source fails—as during a voltage sag, an interruption, or transformer failure—facility loads can be switched to an alternate source to minimize the negative impacts on production and reduce downtime.

When motors are switched from one source to another, the same concerns apply as those for momentary interruptions and out-of-phase reclosures. The motor will be temporarily disconnected from a power source. Upon connection to the alternate source, the motor's internal voltage and the alternate source may be significantly out-of-phase. The length of time between the disconnection from the failed source and the reconnection to the new source will determine the level of concern for damaging transients. The same timing issues apply to high-speed reclosures and momentary interruptions as they do for source transfers.

There are two types of source transfers: a slow transfer and a fast transfer. According to NEMA MG1-1998, a slow transfer or reclosing occurs when the time between disconnection and reclosure is equal to or greater than one and a half time constants of the motor's open-circuit alternating current. The open circuit time constant for an AC induction motor is given in Equation 4-5.

$$T''_{do} = \frac{X_m + X_2}{2\pi f r_2} \qquad (4\text{-}5)$$

where T''_{do} is the time constant of the open-circuit alternating for an AC induction motor, X_m is the per-phase magnetizing reactance, X_2 is the per-phase rotor leakage reactance at rated speed and rated current referred to the stator, f is the rated frequency of the AC induction motor, and r_2 is the per-phase rotor resistance at rated speed and operating temperature referred to the stator. The induction motor's open-circuit AC time constant and the parameters listed above should be readily available from the motor manufacturer.

NEMA MG1 recommends that a slow transfer method be used to limit the possibility of damage to the motor, motor drive, or both. A slow transfer allows the motor's internal voltage to decay to a point where current and torque transients are within tolerable limits. When multiple motors connected to the same bus are transferred at the same time, the transfer time should be equal to or greater than one and a half times the longest open-circuit time constant of all motors being transferred.

The NEMA standard defines a fast transfer or reclosure as one that occurs when the time between disconnection and reclosure is less than one and a half time constants of the motor's open-circuit alternating current. It further states that the transfer should take place when the difference between the motor residual voltage and frequency and the power supply voltage and frequency will not result in damaging transients.

During a fast transfer, there exists the possibility of severe damage to the mechanical system should the abrupt changes in electromagnetic torque excite one of the mechanical resonant frequencies. Extremely high torque transients (> 20 per unit) and severe equipment damage are possible. Therefore, NEMA MG1 recommends a complete system study before a fast-transfer method is attempted. The detail of the study will determine the amount of information required to complete the study. The typical information required includes the equivalent power system model, the equivalent motor model (saturated and unsaturated), the spring constants of the various components in the mechanical system, and the inertia of motor and load.

The effects of momentary interruptions, out-of-phase reclosures, and inappropriately timed source transfers can create subtle, immediate damage to motors. This type of damage tends to compound after a number of such events. The effects include:

- Loosening of winding braces and abrasion of stator-winding insulation. The eventual result is the electrical failure of the winding. This situation is often hidden and is mistaken to be a thermal degradation of the insulation.
- Loosening of rotor bars, which leads to vibration, fatigue, and failure of rotor.
- Fatigue failure of the motor shaft, coupling, or machinery shaft.

However, there are relatively few cases where motor failures have been directly attributed to momentary interruptions, out-of-phase reclosures, and inappropriately timed source transfers. The main reason stems from the fact that most of the failures occur as the result of the cumulative effects of several out-of-phase events and are seen as simply premature service failures. Thus, most often the failures are not attributed to the three types of out-of-phase events. Some additional reasons suggested by [3] are described below:

- The combination of events required to affect the theoretical extreme torque transients is not likely to occur frequently (system inertia, load torque, reclosure timing, and so on).
- The system inertia tends to dampen or attenuate the shock torque affecting the mechanical system components.
- The motor's internal voltage tends to decay rather quickly due the decay of the motor flux and the decrease in rotational speed of the rotor.

- When a large number of motors that are reconnected at the same time, the system voltage will depress according to the stiffness of the power system. A decrease in the system voltage will result in a corresponding decrease in the current and torque transients.

Protecting Motors from Voltage Sags, Momentary Interruptions, Out-Of-Phase Reclosures, and Source Transfers

Although very few voltage sags, momentary interruptions, or out-of-phase events cause immediate failures of motors and connected equipment, protection is recommended. There are a number of motor protection relays and intelligent motor controllers that are capable of providing protection as well meeting all process-performance requirements to keep the negative impacts on production to a minimum. However, motors should be neither under-protected nor over-protected. The consequences of either can lead to reduced motor life, damaged machinery, or nuisance trips, all of which can result in unnecessary production downtime.

ANSI C37.96 suggests that the selection of a complete motor-protection scheme should be based on the following factors:

- Motor horsepower rating and type.
- Supply characteristics—voltage, phases, method of grounding, and available short-circuit current.
- Type of motor controller employed.
- Operating characteristic and setting of protective devices between the motor starter and the source supply.
- Protective devices monitoring the driven machinery or load-process vibration, torque, and other mechanical limits.
- Function and nature of the process that determines the importance of the drive.
- Environment of the motor, associated switching device, and protective devices.
- Cost of protection scheme relative to that of the associated equipment.
- Hot and cold permissible locked-rotor time and permissible accelerating time.
- Time versus current curve during starting.

Protecting motors can be a daunting task, particularly when there are so many factors that affect the motor's performance. However, there are a number of different motor control and protection schemes that are capable of providing appropriate protection. Several motor-control circuits are depicted and described below. Each has its own advantages and disadvantages.

The circuit shown in Figure 4-3 is an example of a three-wire control circuit. The circuit does not use any relays designed specifically for undervoltage protection. The undervoltage protection is based on the undervoltage susceptibility of the motor's contactor or starter. When the contactor drops out, it will not automatically re-energize and reconnect the motor to the source. The start button must be pressed to restart the motor.

This circuit may not provide the necessary protection during momentary interruptions and source transfers. The transfer time may not be long enough for the contactor to drop out. The motor may generate enough power to sustain the contactor through the event, subjecting the motor to potentially high transient currents and torque.

In addition, this circuit will probably not provide the necessary protection during long-duration undervoltage conditions when the motor voltage is above the trip threshold of the contactor and below the recommended 90% of nameplate rating as specified by NEMA. It is interesting to note that this circuit is powered between two phases that also power the motor. Undervoltage events that affect the line-side voltage of the control power transformer will be the only events that will potentially affect the contactor. There will be no protection for events that occur on the other two phase-to-phase voltages.

The two-wire control circuit shown in Figure 4-4 uses several types of protection relays. Each relay serves a specific purpose in the overall undervoltage protection of the motor. A time-delay undervoltage relay is used to provide the protection from voltage sags, momentary interruptions, and source transfers. The relay (Device 27[4] or UV[5]) has voltage and time settings. The voltage setting is used to determine the voltage level where the relay operates, and a time setting is used to initiate a time delay. The time delay allows the undervoltage event to clear before the relay activates. With induction-type relays, the time delay is proportional to the degree of undervoltage. An example setting would trip the motor after five-seconds when the motor's terminal voltage falls below 90% of nominal (long-duration undervoltage conditions). However, the same relay would trip the motor instantaneously when power to the motor is interrupted (momentary interruptions and source transfers). However, every motor application will differ from the next. The settings for one motor may over-protect or under-protect another. The settings will depend on the characteristics of the power system, motor, and load. Therefore, the voltage and time settings should be based on stability studies for critical motors. The following section describes a method for estimating the time of stable operation.

In Figure 4-5, the time-delay relay (Device 2[1] or TR[2]) is used to provide a time-delay start/restart feature for the control circuit. This relay provides a settable time delay before the motor contactor or starter is energized. This relay is used in conjunction with the time-delay undervoltage relay to prevent out-of-phase reclosure of the motor contactor when the undervoltage relay resets at the end of the undervoltage event or when the source transfer is complete. The time-delay setting should be based on one and a half times the open-circuit AC time constant for the motor being protected. When multiple motors are protected with one set of protection relays, the motors should be studied and analyzed as a group to coordinate appropriate protection settings.

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[4] ANSI/IEEE C37.2

[5] ANSI/NEMA ICS 1

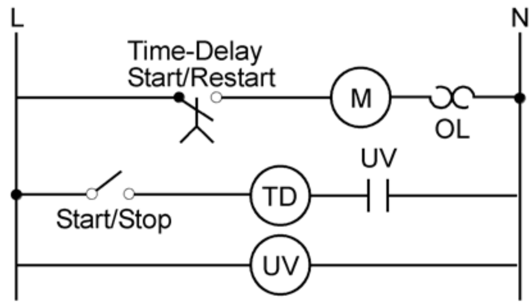


Figure 4-5
Two-Wire Control Circuit with Time-Delay Relay

Another important thing to consider is the fact that power-factor-correction capacitors that are switched with the motor tend to lengthen the time it takes for the motor's internal voltage to decay to acceptable values for reconnection. In some cases, the motor's terminal voltage may actually increase for a period of time due to self-excitation. This situation only applies to control circuits where motors and capacitors are switched together. These applications require careful selection of the time-delay start/restart settings.

It is interesting to note that this circuit is powered between two phases that also power the motor. Undervoltage events that affect the voltage of the transformer will be the only events that will be detected by the undervoltage relay. Events that occur on the other phase-to-phase voltages will not be detected. However, additional transformers and undervoltage relays may be added to the control circuit to provide sensing of the other phases.

During high-speed reclosing and source transfer operations, undervoltage relays may not accurately detect when the motor has been disconnected from the source. As mentioned previously, the motor's internally generated voltage may fool the relay into thinking that the motor is still connected to the utility power source. As a result, the relay may not disconnect the motor as it should, and the risk of a damaging out-of-phase reclosure is a real.

In situations such as these, there are a number of solutions to the problem. A trip signal from the utility relaying system sent to trip the motors offline would be a highly effective solution. However, this method is usually not practical from a logistical and economic standpoint. One of the most popular methods of sensing when motors are disconnected from the source is the use of high-speed static under-frequency relays. These relays detect the frequency decay of the motor's internally generated voltage to disconnect the motor.

However, there may be some applications where the frequency decay is slower than the high-speed reclosure time. Applications with high load inertia or lightly loaded motors and facilities with local generation are examples where even under-frequency relays may be insufficient. Under these circumstances, a complete system study is recommended to determine the most effective means of protection. A combination of under-frequency, undervoltage, reverse current, and reverse power relays may prove to be the only effective means of protection. Once the motor has been safely disconnected form the source, a time-delay start/restart relay can be used to automatically re-energize the motor as described above.

How to Determine the Time of Stable Operation

The time of stable operation is the length of time a motor can operate at a reduced voltage level before the load torque exceeds the pullout torque of the motor. At this point, the motor may stall because the load torque exceeds the maximum torque capability of the motor. High currents in the stator and rotor are likely.

For AC induction motors, the time of stable operation during voltage sags can be determined through an approximation, as shown in Equation 4-6 [2]. The equation will help motor user's determine how long a motor will remain stable during a voltage sag of a given voltage magnitude.

$$t = 2 s_p H \tau \text{ (in seconds)} \tag{4-6}$$

where t is the time of stable operation, s_p is the critical slip, H is defined in Equation 4-7, and τ is defined in Equation 4-8.

$$H = Wr^2 \cdot rpm^2 \cdot 0.231 \times 10^{-6} \tag{4-7}$$

where Wr^2 is the inertia of the rotating system (motor + load + coupling + …) and rpm is the motor's rated speed.

$$T = \left\{ \frac{s}{s_p} + k \cdot \ln\left[\frac{s}{s_p}\left(\frac{s}{s_p} + \frac{s_p}{s} - 2k \right)\right] + \frac{2k^2}{1-k^2} \cdot \tan^{-1}\left(\frac{\frac{s}{s_p} - k}{\sqrt{1-k^2}} \right) \right\}_{s_o}^{s_u} \tag{4-8}$$

where s_u and s_o are the corresponding slips and k is defined in Equation 4-9.

$$k = \frac{T_p}{T_l}\left(\frac{V}{V_o} \right)^2 \tag{4-9}$$

where T_p is the pullout torque of the induction motor, T_l is the load torque, V is the sag voltage, and V_o is the rated voltage of the induction motor.

The equations assume a three-phase, symmetrical voltage sag, step-changes of the sag voltage (initiation and recovery), a constant load torque on the motor, and no transients. If more accurate analysis is required, a system model can be developed and computer simulations performed.

The motor-control circuit shown in Figure 4-6 uses an intelligent motor controller (or multi-purpose motor-protection relay) than integrates several motor-protection functions into one package. There are a number of these types of controllers available on the market. Most of these devices provide some level undervoltage protection. However, most do not provide an undervoltage-protection scheme that is as complete as the one shown in Figure 4-5. Some only provide a time-delay undervoltage functionality, while others provide a time-delay undervoltage (non-induction type of relay) with time-delay restart. A complete understanding of the motor controller's functionality should be reviewed before making a purchase and installing the device.

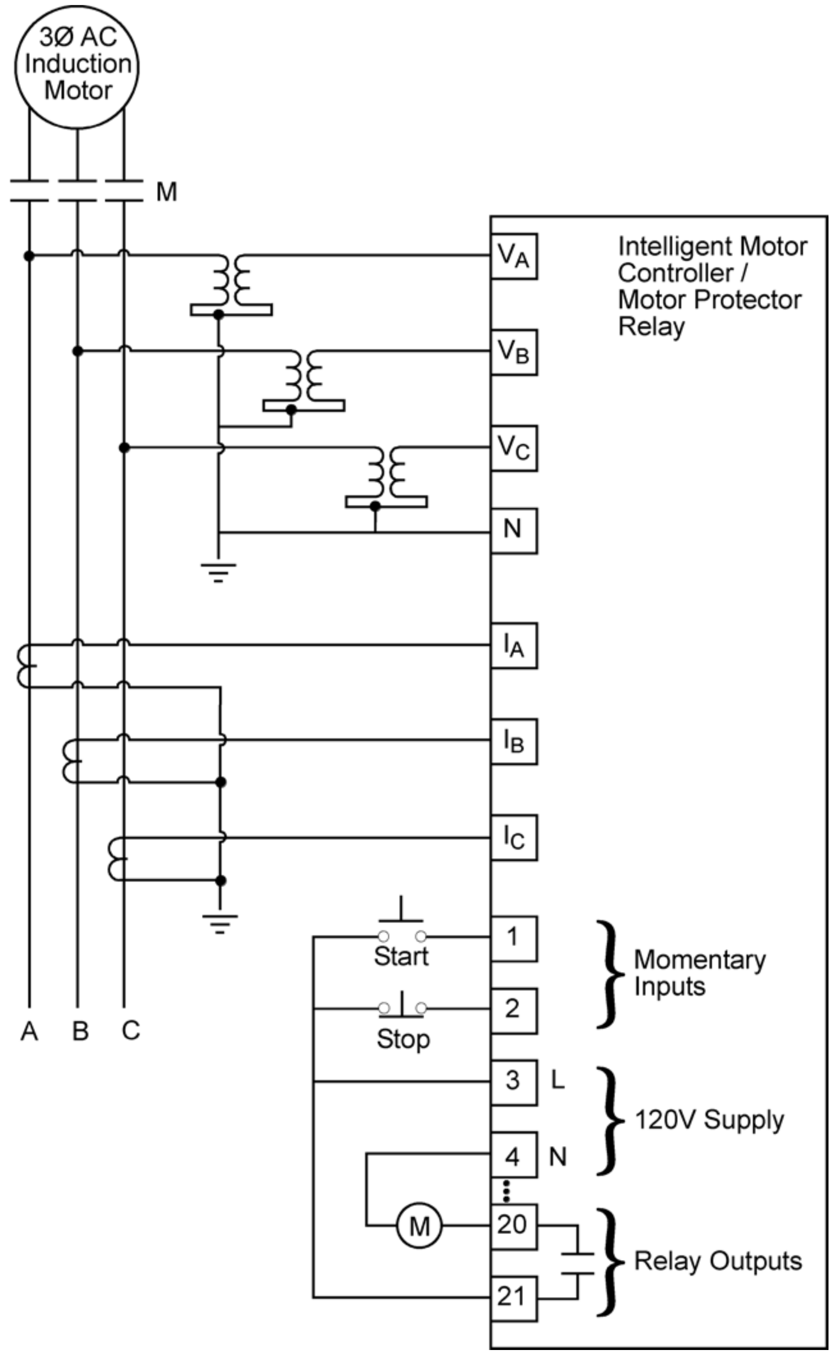


Figure 4-6
Intelligent Motor Controller

References

[1] Chattopadhyay, Subhomoy, and Key, Thomas S., "Predicting Behavior of Induction Motors During Electrical Service Faults and Momentary Interruptions," *Proceedings of the Industrial and Commercial Power Systems Conference,* St. Petersburg, Fla., May 1993.

[2] Das, J. C., "Effects of Momentary Voltage Dips on the Operation of Induction and Synchronous Motors," IEEE, 1989.

[3] IEEE, "Source Transfer and Reclosing Transients in Motors: A Preliminary Working Group Report," Working Group on Fast Transfer of Motors of the IEEE Industry Applications Society Power System Protection Committee, 1982.

5 WEB-BASED FORUM FOR INFORMATION EXCHANGE

Power quality is an increasingly critical issue in today's competitive energy services market. Major commercial and industrial customers rate power quality second only to price in their criteria for choosing an energy provider. They are actively seeking out energy providers with the highest-quality service and the best knowledge base of power quality solutions. The System Compatibility Research Project seeks to assist energy providers in obtaining this knowledge.

The challenge in this research project, as with all annual projects, is how to proliferate the exchange of information more effectively and efficiently so that the project sponsors don't have to wait a full year for the results. The solution in this case was the creation of a power quality web-based forum for information exchange with immediate access to activities, updates, and results.

Information Modules

The power quality web-based forum can be accessed at http://www.pqac.com/pqforums. The forum contains a selection of information targeted at keeping the project sponsors active and updated as the work progresses. There are six basic areas under the main page. These include clickable buttons labeled and described as follows:

Discover the features of the forum for Target 7.1a.

Vote on the types of devices you want to test.

View the latest news about motor monitor and protective devices.

Learn about testing and research opportunities.

Discussion Group

Read threads about subjects related to motor monitor and protective devices, reply to questions and comments, or post your own question or comment.

Frequently Asked Questions

Don't know much about Web forums or discussion groups? Go to the FAQ (Frequently Asked Questions) page to learn the basics.

Documents

Papers, presentations, standards documents—just about anything the project engineer can lay his hands on resides here.

List the Members

Here, you will find a list of Target 7.1 sponsors and, if available, their contact information.

Email the project Manager

A hyperlink to send comments directly to the project manager.

Major Area Details

Most of the above mentioned areas contain useful tools or information to promote project understanding, awareness, and communications. Some of the proprietary areas are password-protected, and each project sponsor has been assigned a username and password or can request one by clicking on the password key. The following sections will describe the type of information contained in each major area of the web-based forum for Target 7.1.

About this Forum

This area contains a list of project-team members and contains the following project description:

EPRI PEAC is pleased to present a new means for Target 7 funders to access information about the projects they fund. Via the World Wide Web, funders get access to the project test results in a fraction of the time it takes for the final report to be reviewed, finalized, and published. Funders also have a means for providing timely feedback about the current and future direction of the project, as well as having an opportunity to discuss their needs and the needs of their customers.

Please send us your comments and suggestions for improving and refining this information resource. EPRI PEAC looks forward to hearing from you. Check back from time to time to get up-to-date information about System Compatibility!

For the year 2000, the System Compatibility Research Task will investigate and attempt to characterize the response of motor monitor and protection devices during various electromagnetic phenomena, such as voltage sags, interruptions, single-phasing, and voltage unbalance.

The objectives of this forum are to:

- Provide an information resource for sponsors to get up-to-date information on the status of Target 7.1.
- Provide a channel of communication between project sponsors and the project manager to give the sponsors a means to express their needs and thoughts concerning the project and influence the direction of future work.
- Inform sponsors of Target 7.1 about local, regional, and world events that affect system compatibility research.

News

The news button contains three subsections. The first describes testing opportunities for devices not tested during this round or research. The second contains an update on the actual test results. The third button contains the manager's ongoing research report.

Discussion Group

This area was established to promote interactive exchanges between the project team and the project sponsors. Anyone can begin a threaded discussion for the rest of the group to comment on or continue the thread.

Documents

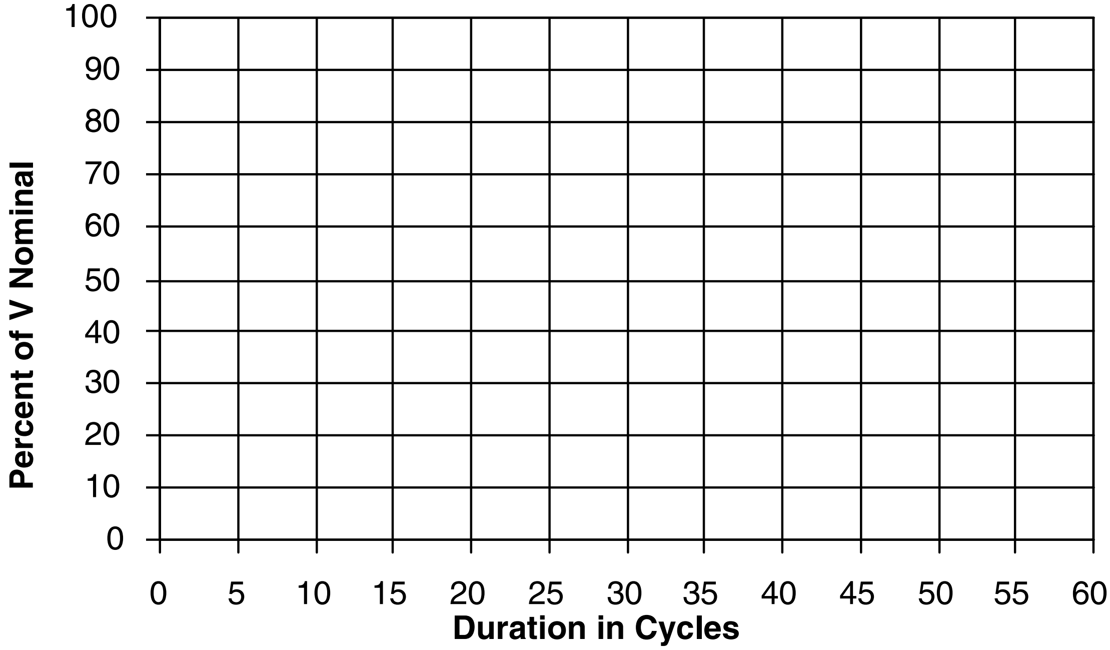
The documents area contains a wealth of password-protected information proprietary to the project sponsors (available in a PDF format). There are presentations applicable to the project. There are publications such as papers, application notes, and test briefs. The system compatibility test protocol developed for the project resides here. Aditionally, this area contains useful hyperlinks to the manufacturers of MCC protective devices.

Conclusions and Future Direction for this Website

Based upon input received from project sponsors, there is a sincere appreciation for this new method of sharing project information. Sponsors are finding the online project updates useful in their day-to-day business activities. The website is intended to present a new means of accessing up-to-date information. Via the World Wide Web, sponsors get access to the project results in a more timely manner. Funders also have a means for providing feedback about the current and future direction of the project, as well as having an opportunity to discuss their needs and the needs of their customers. This is a major change in the way power quality information may be accessed through the use of the web and is a valuable component of any power quality engineer's power quality toolbox.

A
DATA SHEETS

Sag Voltage (% of Nom.)	*Sag Duration (cycles)*	*Response*


100
90
80
70
60
50
40
30
20
10
0
Percent of V Nominal
0
5
10
15
20
25
30
35
40
45
50
55
60
Duration in Cycles

Test 1: Characterization of Performance –Voltage Sags and Momentary Interruptions

Device Description: ____Test Date:____________________

Device ID:__________________________________ Tested By:____

Phase Angle:___________Device Configuration:____

Comments: ____

Test 2: Characterization of Performance – Steady-State Voltage Unbalance

Device Description: ______________________________________Test Date:________________

Device ID:___________________________ Tested By:_________________________________

Phase Angle:__________Device Configuration:_____________________________________

Comments: ____

Test	V_{AN}	V_{BN}	V_{CN}	V_{AB}	V_{BC}	V_{CA}	V_{UB}	I_A	I_B	I_C	*Response*
V_{UB} = 0%											
V_{UB} = 1.5%											
V_{UB} = 3.0%											
V_{UB} = 5.0%											

Test 3: Characterization of Performance – Steady-State Single-Phasing

Device Description: ____ Test Date: ____________________

Device ID: ________________________________ Tested By: ______________________________________

Phase Angle: __________ Device Configuration: ____

Comments: ____

Response: ____

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B
EPRI PEAC'S PROCESS RIDE-THROUGH EVALUATION SYSTEM

EPRI PEAC's Process Ride-Through Evaluation System (PRTES) is a sag generator system that allows investigators to assess the undervoltage susceptibility of electrical equipment.

Voltage sags from the PRTES are created by switching momentarily from nominal voltage, to a lower voltage, and then back to nominal. The nominal and low voltage sources are created with autotransformers. The wipers on the autotransformers are adjusted to create a specific voltage sag magnitude. The switch between nominal voltage and sag voltage is created with contactors and was synchronized by precise timing controls from a laptop computer.

Figure B-1 is a block diagram showing a typical test setup for a three-phase load. Voltage sags are created with a phase-to-neutral reference point. Thus, a 50% sag on Phase A (with Phase B and C at nominal voltage) creates phase-to-phase voltages of 76%, 76%, and 100%.

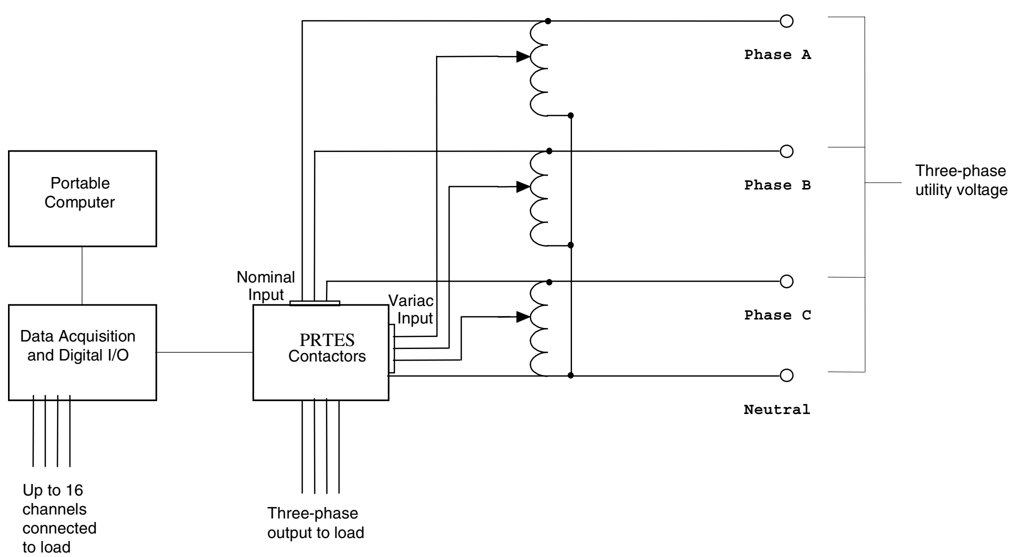

Figure B-1
PRTES Connection Diagram

Target:

Power Quality Measurements and Testing

About EPRI

EPRI creates science and technology solutions for the global energy and energy services industry. U.S. electric utilities established the Electric Power Research Institute in 1973 as a nonprofit research consortium for the benefit of utility members, their customers, and society. Now known simply as EPRI, the company provides a wide range of innovative products and services to more than 1000 energy-related organizations in 40 countries. EPRI's multidisciplinary team of scientists and engineers draws on a worldwide network of technical and business expertise to help solve today's toughest energy and environmental problems.

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