# UTILIZING MICROPROCESSOR BASED RELAYS AS PREDICTIVE TOOLS TO MITIGATE VOLTAGE INSTABILITY PROBLEMS THAT STEM FROM THE FAST VOLTAGE COLLAPSE AND DELAYED VOLTAGE RECOVERY PHENOMENA

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THESIS ABSTRACT

UTILIZING MICROPROCESSOR BASED RELAYS AS PREDICTIVE TOOLS TO MITIGATE VOLTAGE INSTABILITY PROBLEMS THAT STEM FROM THE FAST VOLTAGE COLLAPSE AND DELAYED VOLTAGE RECOVERY PHENOMENA

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Fast voltage collapse and delayed voltage recovery are a growing concern in the power industry. Although there are several well-known methods to combat fast voltage collapse and delayed voltage recovery, additional methods can bring further stability to the power system. The powerful microprocessor based distribution relay, Schweitzer Engineering Laboratories-451 (SEL-451), is utilized here to counteract voltage instability that results from excessive induction motor loads on the power system. SEL-451 is used as a predictive tool to predict future voltage levels. These future voltage levels are then used by the relay to decide if undervoltage load shedding is needed.

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# CHAPTER 1

# INTRODUCTION

## 1.1 Delayed Voltage Recovery and Fast Voltage Collapse

Voltage instability can lead to a number of problems in any power system. The problems that may stem from voltage instability include load loss, equipment damage or blackouts. Therefore, power engineers strive for voltage stability within their power systems. Delayed voltage recovery and fast voltage collapse are two phenomena that have been leading to the voltage instability problem. Delayed voltage recovery refers to sustained low voltages that eventually recover to an appropriate level after some unknown period of time following power system faults [1]. Fast voltage collapse occurs when sustained low voltages fail to ever recover to an appropriate level. These two problems may affect the integrity of the power system; the transient stability of the transmission system may also become compromised [2]. Delayed voltage recovery and fast voltage collapse may cause protective relays to operate subsequently disconnecting electric loads and creating unwanted overvoltages [3]. These overvoltages can be very hazardous to the power system causing major equipment damage and major power outages. Hence, it is undesirable to shed load unless it is carefully planned or there is a potential disaster waiting to happen.

The problem with delayed voltage recovery and fast voltage collapse is well known and is generating a huge amount of attention in the power industry. The possible behavior of voltage recovery and fast voltage collapse during and after a fault are shown in Fig.1 and Fig. 2, respectively. In Fig.1, the voltage sag lasts for about 30 cycles; this voltage sag will cause unplanned system protective relay devices to trip if it sags for too long. The length of time that the voltage can sag depends on the sensitivity of the equipment [3]. For example, some equipment may trip if the voltage remains below 85% for more than 30 cycles. In Fig. 2, the voltage begins to sag after the fault is applied and the voltage never reaches the pre-fault level. The fast voltage collapse that is illustrated in Fig. 2 will also cause unplanned system protective relay devices to operate.

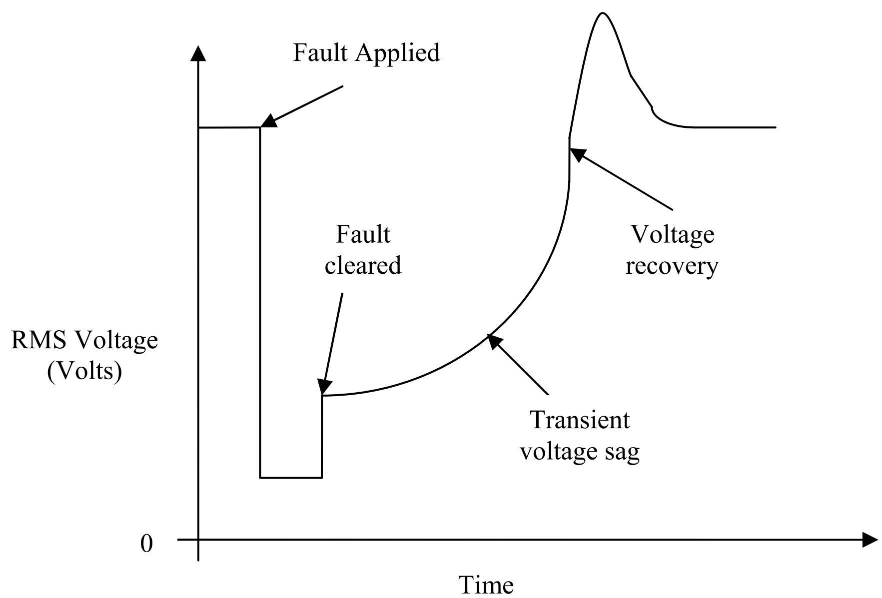



Fig. 1. Delayed Voltage Recovery Scenario Before and After a Fault

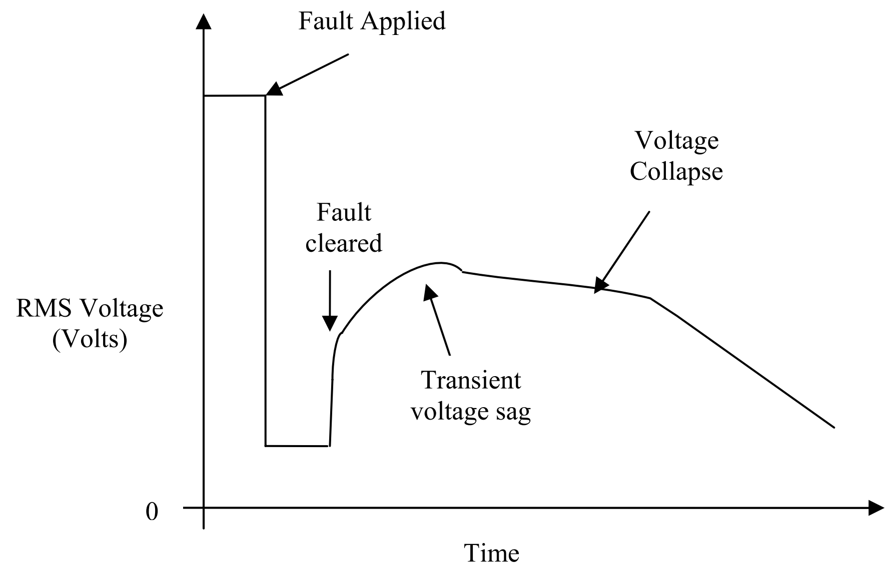



Fig. 2. Fast Voltage Collapse Scenario Before and After a Fault

### 1.2 Causes of Delayed Voltage Recovery and Fast Voltage Collapse

Following a fault on the power system, system overload, excessive induction motor loads and a lack of fast acting reactive power sources can all cause delayed voltage recovery and fast voltage collapse [4]. In most instances a combination of the three leads to the delayed voltage recovery or fast voltage collapse problems.

A. System overload

The voltage recovery problem is prominent in areas with excessive load. In high load seasons transmission lines and/or under ground cables and transformers can become overloaded [2]. Excessive load combined with a high percentage of motor loads and slow clearing faults appears to be a major cause of voltage recovery problems [1].

B. Induction motor loads

Excessive induction motor loads are a major contributor to the delayed voltage recovery phenomena. During the summer months or in hot regions, induction motor loads are in high demand because of the increased use of air conditioners. Following transmission faults, the air conditioners (induction motors) stall over huge geographic areas. These air conditioners remain connected to the utility system after they stall. This stall results in a sudden decrease in load impedance that prevents normal voltage recovery. At the same time, the elements in the transmission system that are disconnected to clear the fault may add additional impedance to the system, increasing the difficulty in reestablishing normal voltage levels [1].

"Prone to stall" motors are the type of induction motors that contribute to the voltage recovery and fast voltage collapse problems [1]. "Prone to stall" motors refers to light inertia motors that tend to lose speed quickly as a result of voltage dips [1]. Small refrigerators and air conditioners fall under the "prone to stall" motor category [1]. These motors tend to stall when the voltage is reduced below 60% for five cycles or longer [1]. The motors stall because the torque produced by the motor under low voltage levels cannot overcome the back pressure of the compressor. Under reduced-voltage conditions, the motor will continue to draw large amounts of current until the motor trips due to thermal overload [5].

C. Increased Reactive Power Demand

Power systems that are burdened with huge amounts of induction motor loads need additional reactive power to compensate for the increased reactive power demand of the stalled induction motor loads under reduced-voltage conditions. Most small induction motors used in small residential air conditioners and refrigerators will normally trip due to thermal overload after 3 to 30 seconds. Once these small induction motors begin to overload and slow down, prior to tripping, they will draw considerable amounts of active power and much larger amounts of reactive power from the system because the power factor of the motor is also reduced significantly. The continual increase of both active and reactive power demand tends to slow down voltage recovery and may also cause voltage collapse in certain instances [5].

### 1.3 Solutions

With the growing concern over delayed voltage recovery and fast voltage collapse, the power industry has adopted several solutions to try to negate their negative effects. The factors that contribute to the two problems are outlined in the previous section, but now some of the solutions that are prominent in the power industry will be revealed.

A. Dynamic Reactive Power Resources

Fast acting dynamic reactive power resources are used to alleviate the risk of delayed voltage recovery and fast voltage collapse on the power grid. The primary function of these dynamic reactive power resources is to replenish reactive power to the power system. Shunt support devices like mechanically switched capacitor banks, static var compensators (SVCs), and voltage-sourced converter based static compensators (STATCOMs) provide voltage support [6].

Mechanically switched capacitor banks must be properly sized and switched rapidly. The fact that fast on-off switching is difficult in these devices makes them an unsuitable choice for reacting to the rapid reactive power demands that are required to alleviate delayed voltage recovery and fast voltage collapse. There are electronically switched capacitor banks available that can provide the fast switching required, but these power electronic devices are more costly. [6]

An SVC is a much better alternative to direct mechanical switching of capacitor and reactor banks. SVCs provide fast and dynamic reactive power which in turn provides voltage stability. They offer the power system an efficient way to help prevent the motor stalling phenomenon and support the system following a fault disturbance [7]. Additionally, SVCs allow for the much needed fast voltage recovery following a fault [6]. In order to receive the best performance from SVCs, they must be properly sized and placed. The size and placement of the SVCs depends on the electrical characteristics of the transmission system [7].

STATCOMs or synchronous condensers provide better alternatives to SVCs. Both STATCOMs and SVCs regulate a bus voltage through the reactive current/power output [6]. STATCOMs and SVCs also use a slope characteristic of a few percent to avoid excessive control action and to coordinate with other voltage control equipment [6]. Moreover, STATCOMs and SVCs are cost-effective due to their power electronic components [6]. The difference in the two lies in the fact that STATCOMs provide superior performance for equal reactive power ratings. SVCs at their capacitive limit are basically very expensive ac capacitor banks. Whereas, STATCOMs intrinsically provide constant current output down to low voltage levels. As a result, STATCOMs can output greater amounts of current and reactive power than SVCs at the same voltage level. The difference between the reactive power outputs can be crucial when trying to maintain motor re-acceleration following a short circuit. Therefore, a smaller STATCOM will equal the performance of an SVC that is bigger [6].

## B. Planned Generation

Planned generation can help the voltage instability problems that stem from the delayed voltage recovery and fast voltage collapse phenomena but, not necessarily alleviative the problem. In cases where the reactive power demand is not very high and generation is adequately planned, the reactive power demands may be met during a contingency under steady state conditions. Since the delayed voltage recovery and fast voltage collapse phenomena are not steady state conditions, planned generation will not solve the voltage instability problems caused by delayed voltage recovery and fast voltage collapse. NERC Planning Standards only require that electric systems be planned to withstand a certain contingency level [7]. Therefore, if a contingency occurs that is more extreme than what was initially planned there may not be enough reactive power to prevent delayed voltage recovery and fast voltage collapse. To ensure that the delayed voltage recovery and fast voltage collapse problems are cured using planned generation, a huge amount of generation may have to be used. Using very large amounts of generation to alleviate the delayed voltage recovery and fast voltage collapse problems is impractical when dealing with normal load sizes.

## C. Faster Breaker Failure Clearing Times

Faster breaker failure clearing times will allow a fault to be removed from the system faster. This technique has been proven to help out the voltage recovery and fast voltage collapse problems. After an event in the metro Atlanta area, Southern Company Services analyzed the effectiveness of clearing a fault faster [7]. The company proved that a two cycle reduction in the breaker failure clearing time would have increased voltage recovery by a substantial amount. With this two cycle reduction in breaker failure clearing time, the voltage recovered to its nominal value about 8 seconds faster than it would recover using the original breaker failure clearing time [7].

D. Planned Load Shedding

Load shedding refers to disconnecting load from the power system by using protective relay applications. Shedding load to improve voltage recovery should only be used as a last resort. Once load is lost then the integrity of the power system is compromised; customers are left in the dark. Load should be disconnected from the system only if there is potential for widespread or cascading problems such as system separation.

Load shedding is a viable solution to the delayed voltage recovery and fast voltage collapse problems. Shedding the appropriate amount of load from the power system during delayed voltage recovery will relieve some of the reactive power demand on the system. As a result, the power system will have a sufficient amount of reactive power at the reduced load level to bring the voltage back to the appropriate level. The amount of load that needs to be shed depends on the system characteristics.

## 1.4 The Slope Approximation Method

The idea presented in this thesis involves using the slope of the voltage after a fault is cleared to determine whether protective relay devices should operate in order to mitigate system voltage instability problems caused by delayed voltage recovery and fast voltage collapse. The slope associated with the transient voltage sag related to delayed voltage recovery can be seen in Fig. 1. This slope, if used properly, can be beneficial in undervoltage load shedding applications. Because unwarranted load shedding is undesirable, using the slope in protective relay applications can help preserve the integrity of the power grid.  Protective relay devices that have the ability to approximate the slope of transient voltage sags will be able to properly estimate whether or not the voltage is going to reach a tolerable voltage level in enough time to prevent unacceptable conditions. Relays that possess the processing power and programming logic capabilities necessary to approximate the slope of the RMS voltage will be able to use both future, past and present voltage levels to determine whether or not undervoltage load shedding is necessary. The RMS voltages that will be used by the microprocessor based relay to approximate the slope are one cycle RMS magnitudes that will be calculated by the relay periodically.

A. Concept

Using the slope as a predictive tool for protective relay operations is based on simple mathematical principles. These principles can be illustrated by using a linear curve (Fig. 3) and the equation for the slope of a line (1). Figure 3 represents a linear curve with an unknown slope. This slope can be approximated using (1). Equation (1) has two important components: (1) position on the y-axis and (2) time on the x-axis. With these two vital pieces of information at two different points the slope for any linear curve can be calculated. Likewise, the slope of a transient sag can be approximated. It is important to understand that the slope of any curve that is not linear will change over time, thus the approximate nature of the slope also applies over time.

The slope approximation is only a portion of the underlying principle that will be used in this thesis. The most vital piece of information will be the recovery time that is approximated using the slope. The recovery time is approximated using (2). The recovery time will be representative of some future time. This future time will be used to trigger protective relay devices during delayed voltage recovery or fast voltage collapse. For example, if the relay is set to trip for voltages that do not recover to appropriate levels within 30 cycles, the relay can approximate the slope and use it to approximate how long it will take the voltage to reach an appropriate level. Therefore, if the relay approximates a future time 30 cycles or larger the relay will trip. The recovery voltage that is represented in (2) refers to the appropriate voltage level that the voltage is attempting to reach.

The illustration in Fig. 4 brings together the concepts presented in Fig. 3 and equations (1) and (2). The process that is used to approximate the slope and recovery time is clearly depicted in Fig. 4. The past time, past voltage, present time, and present voltage are values used to approximate the slope. The slope, recovery voltage level, present voltage, and present time are all used to approximate the recovery time. It is important to note that the target recovery time is longer than the actual recovery time. The recovery time approximation would be closer to the actual recovery time if the recovery time had been approximated using points at a later point in time on the voltage sag.

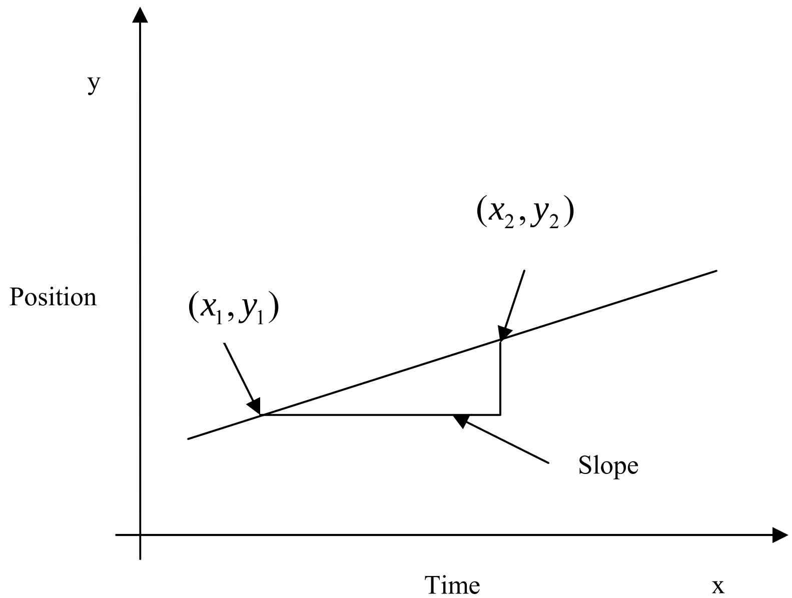



Fig. 3.  Slope Concept

$$Slope = \frac{y_2 - y_1}{x_2 - x_1} \qquad (1)$$

$$RecoveryTime = \frac{recoveryvoltage - presentvoltage}{slope} + presenttime \qquad (2)$$

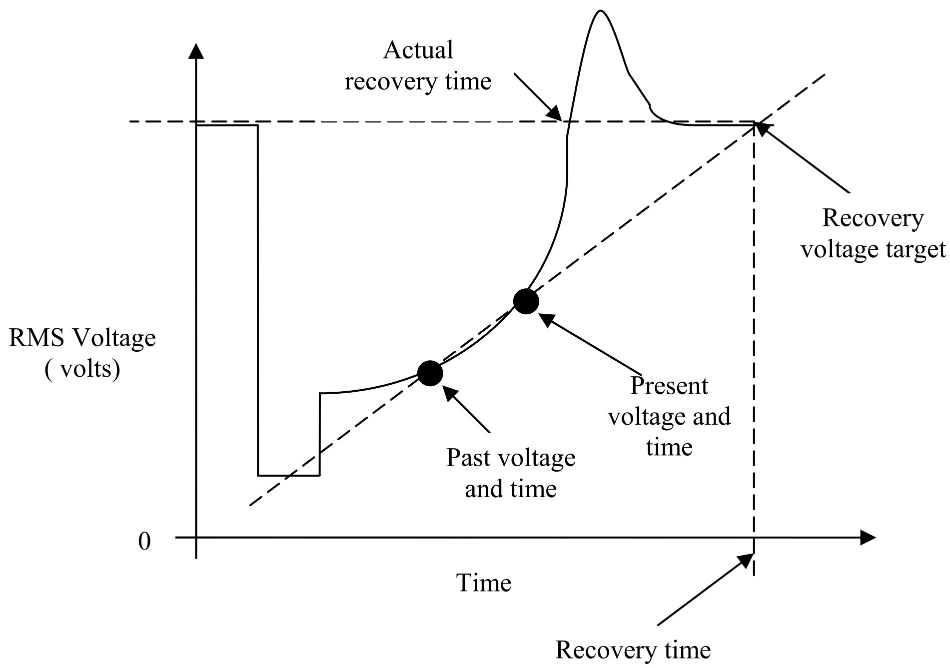



Fig. 4. Slope and Recovery Time Process Compilation

# CHAPTER 2

# THE SEL-451 DISTRIBUTION RELAY KEY FEATURES AND ACCESSORIES

## 2.1 The SEL-451 Distribution Relay Overview

The SEL-451 distribution relay is the relay that has been utililized to perform the slope approximations used to mitigate voltage instability problems that stem from the delayed voltage recovery and fast voltage collapse phenomena introduced in Chapter 1. The SEL-451 relay will serve as the device that will use the slope of a series of RMS voltages sampled over a specified time period to initiate the planned under-voltage load shedding that may be necessary to protect the power system. The SEL-451 relay is a microprocessor-based distribution relay that is produced by Schweitzer Engineering Laboratories. The relay offers several features including: auto-reclosing with synchronism check, circuit breaker monitoring and circuit breaker failure protection [8]. The SEL-451 relay also offers simple and flexible implementation of custom control schemes through expanded SELLOGIC® control equation programming [8]. Furthermore, the multifunctional distribution relay can have numerous communication interfaces ranging from SEL ASCII to ethernet connectivity with an optional ethernet card [8].

The SEL-451 distribution relay has several key features that will enable the approximation of the slope of the transient voltage sag associated with fault induced delayed voltage recovery. The relay is a powerful and flexible tool that allows power engineers to provide high caliber system protection and control. The wide range of applications and features that make up the SEL-451 relay make the implementation of a customized protection scheme manageable. The applications and features that are instrumental to effectively implementing the under-voltage protection scheme presented in this thesis are outlined in the following sections.

**2.2 ACSELERATOR® QuickSet SEL-5030 Software**

The SEL-5030 software provides users with a simple way to apply and use the SEL-451 relay. The software provides the distribution relay reliable analysis and measurement capabilities that can be applied to the power system. QuickSet makes it easier to create and manage relay settings, analyze events, monitor real-time and relay-stored power system data, control the relay and configure the serial port and passwords [8].

The user-friendliness of the SEL-5030 software enables users to easily create and manage relay settings. The settings structure of the relay makes setting the relay simple and efficient. The software displays all the relay settings categories in the settings tree view [8]. The tree view makes it easy to view, enable, disable and/or change relay settings. In the tree view, when settings are enabled and disabled, the tree view remains the same, but after using the tree view to access the settings in a disabled category these settings are dimmed. The tree view also allows for settings to be entered easily. Once the user clicks the '+' marks and buttons in the settings tree view the user is able to expand and select the settings, class, instance, and category that needs to be changed. The ACSELERATOR tree view is illustrated in Fig. 5.

The settings dialog box is a general heading chosen from the settings tree view that represents the particular group of settings or parameters being viewed by the user. For example, "General Global Settings" is the heading for the settings dialog box shown in Fig. 5. The text box is an area that the user can type in a specified amount of characters to identify or label relay parameters. The option buttons are buttons that give the user an option to choose to set a particular parameter within the settings dialog box. Lastly, the error text region is the area that is used by the relay to communicate errors that are made while trying to make settings changes within the settings dialog box.

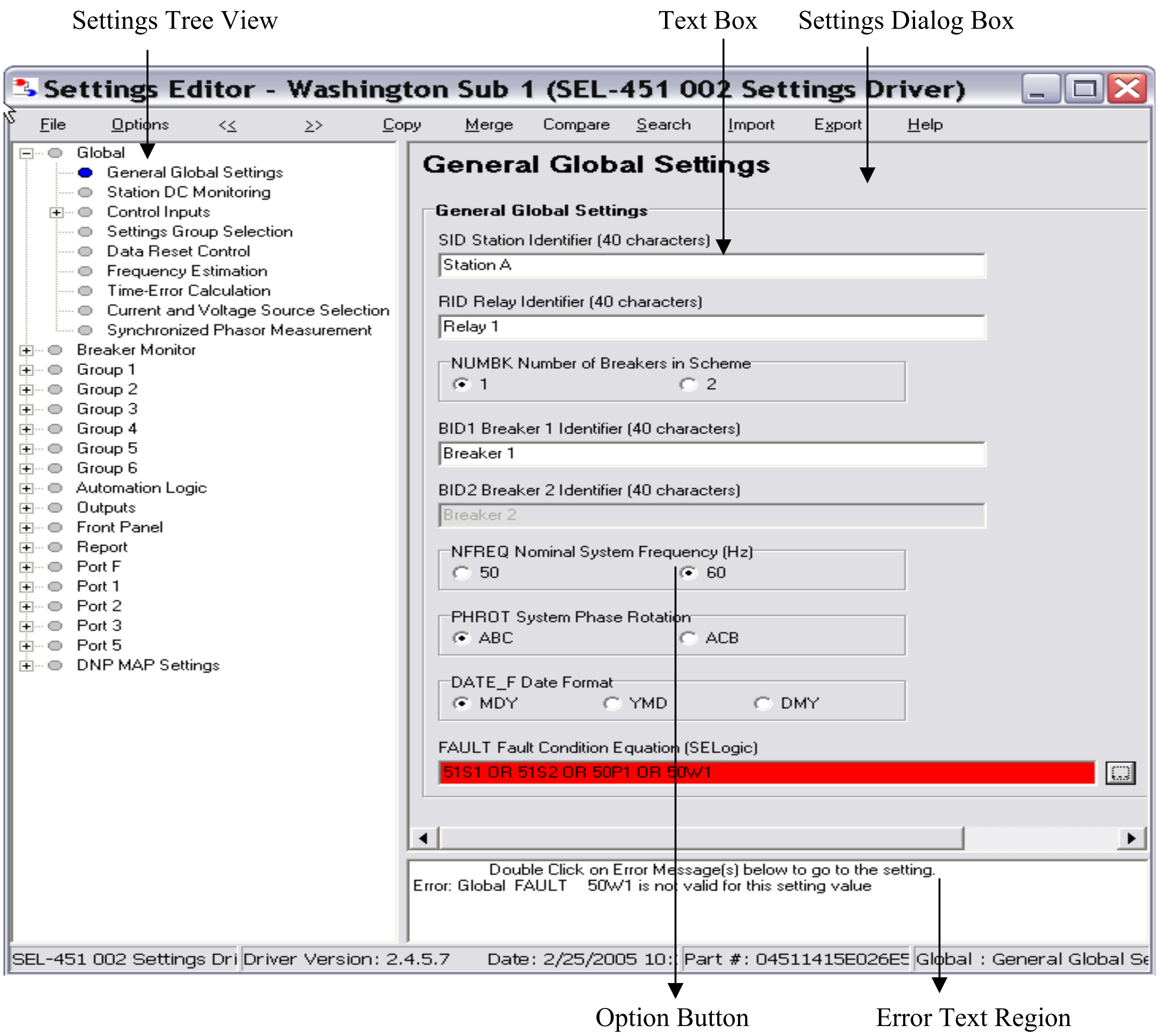



Fig. 5. ACSELERATOR Quickset Software Settings Tree View [8]

A. Free-Form SELOGIC Control Equations

Free-Form SELOGIC is a programming option available with the QuickSet software. The free-form SELOGIC control equation programming areas can be used for protection and automation [8]. The SELOGIC protection free-form option gives users the ability to program customized relay protection logic and execution order. There are 250 lines available for protection free-form SELOGIC. The settings execution order is important when programming with protection free-form SELOGIC. The relay processes the lines of logic in sequential order from 1 to 250 [8]. Therefore, the program steps that are entered will be performed in the order specified by the user. Additionally, entire storage locations within the software can be referred to several times in order to build up intermediate outputs in successive equations. Free-form also enables users to add entire lines of comments to aid in documentation of the program. Mathematical operations are available only through the protection or automation free-form SELOGIC control equation programming option. By accessing the protection free-form logic settings dialog box and clicking on the '…' button, users can create protection free-form logic through the QuickSet software's Expression Builder [8]. The ACSELERATOR QuickSet software protection free-form logic settings dialog box is shown in Fig. 6. The Expression Builder is discussed in greater detail in the next section.

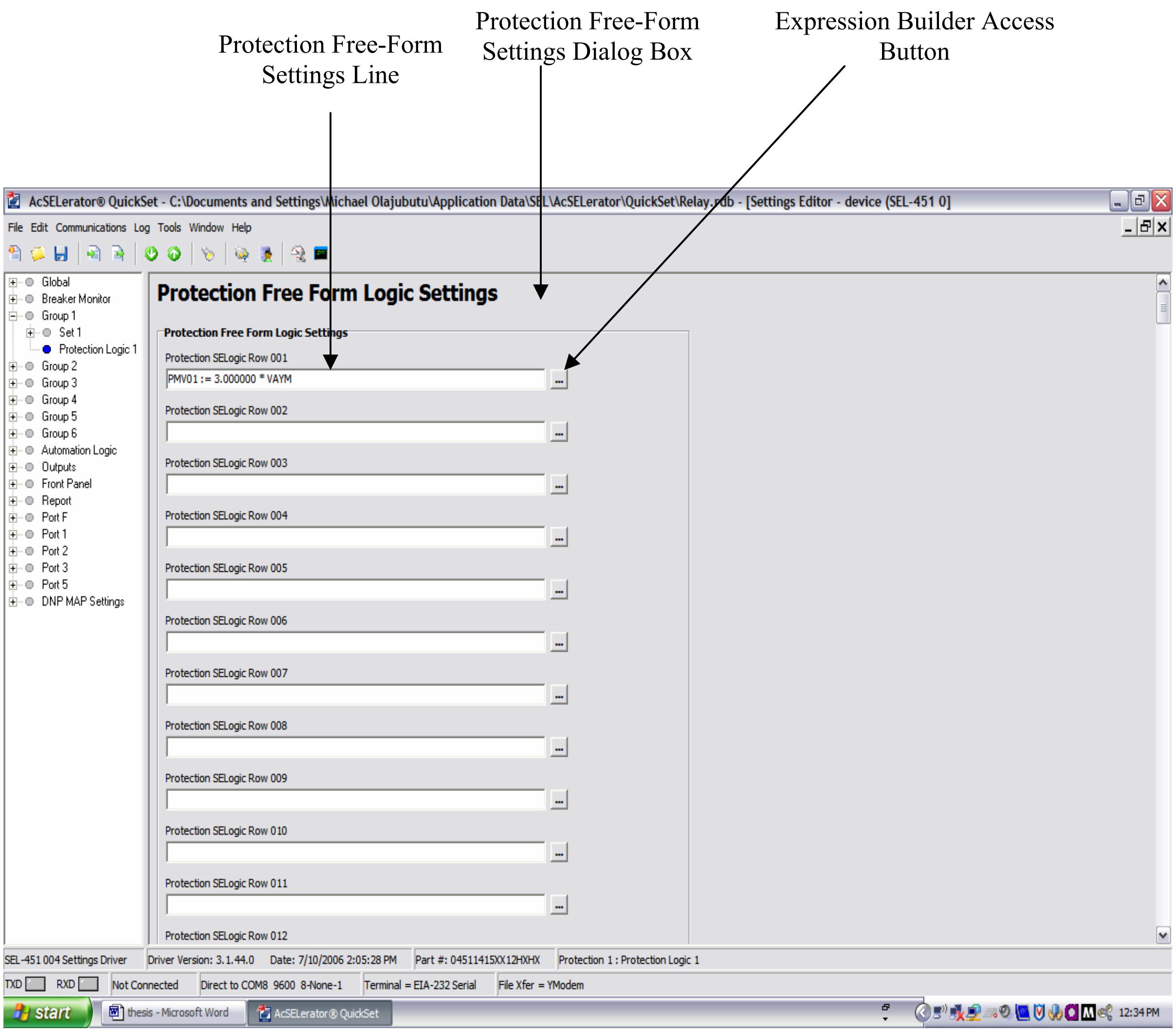



Fig. 6. ACSELERATOR Quickset Software Protection Free-Form Logic Settings Dialog Box

## B. Expression Builder

The Expression Builder is used within the protection free-form SELOGIC programming environment. The QuickSet software uses the Expression Builder to customize relay operations. The Expression Builder is a rules-based editor used to program SELOGIC control equations [8]. The software simplifies the creation of the SELOGIC control equations. The Expression Builder's dialog box is arranged into the left side (LValue) and right side (RValue) of the SELOGIC control equation [8].

Within the protection free-form SELOGIC settings the user has the flexibility to set both the LValue and RValue using the Expression Builder. The left and right side of the expression builder is separated by a long dark vertical line running through a colon and an equals sign (:=). The Expression Builder's dialog box is shown in Fig. 7. The LValue represents the location where the RValue will be stored. The LValue of any expression can be set to specific boolean variables, math variables, latches, conditioning timers, sequencing timers, or counters. The RValue within the Expression Builder can be set to an array of relay word bits, analog quantities, timers, latches, boolean variables, and math variables. Additionally, some boolean operations are available for the RValue. These operations include the following operators: and, or, not, rising and falling edge triggers, math functions, brackets and some expression comparators [8].

The Expression Builder can produce two basic types of expressions that form SELOGIC control equations. The first type is the boolean SELOGIC control equation. The boolean SELOGIC control equation evaluates the RValue to a logical 1 or a logical 0. The LValue must be a setting that requires a boolean value or some kind of boolean storage location [8]. For example, to set Protection Sequencing Timer 1 Input, PCT01IN, a logical 1 or 0 must be entered. The second type of expression produced by the Expression Builder is the math SELOGIC control equation. The math SELOGIC control equations are used to perform mathematical calculations using numerical data in the relay. For example, if PMV01 needs to be set to 3 times the a phase voltage magnitude, PMV01 := 3*VAYM will be entered in protection free-form logic. "PMV01" is one of 64 math variables that can be used to store numeric values using SELOGIC control equations. "VAYM" is the variable used by the SEL-451 relay to store the a phase voltage magnitude. The previous example that is used to illustrate how logic is created using the Expression Builder is shown in the protection free-form settings line in Fig. 6.

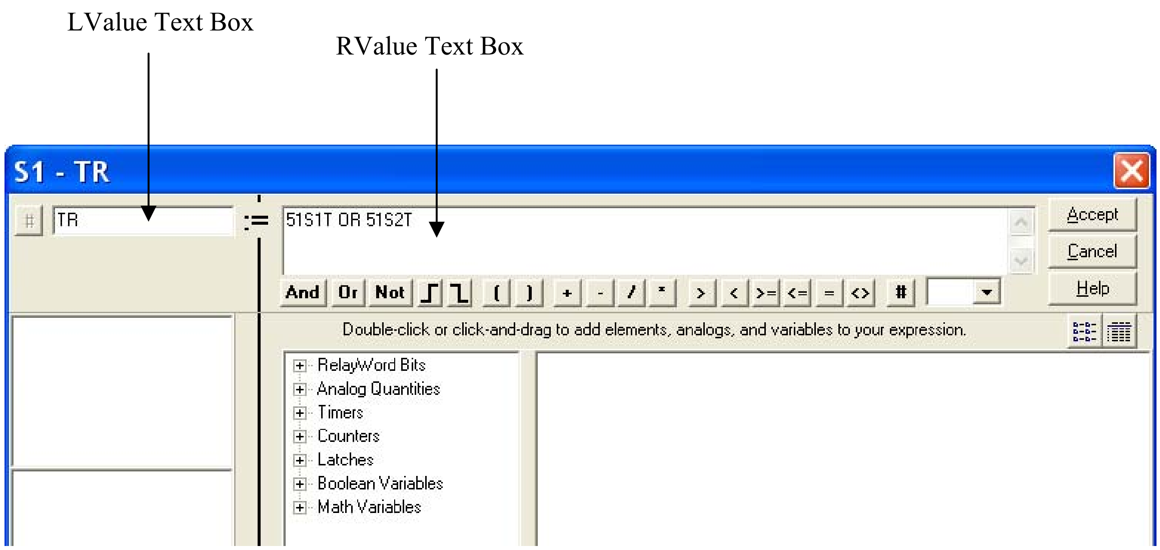



Fig. 7. ACSELERATOR QuickSet Expression Builder Dialog Box

C. Trip Logic

The SEL-451 relay trip logic can be used to program the relay to trip one or two circuit breakers. The relay can be set to trip with time overcurrent elements or with various directional schemes. The user sets the appropriate relay elements using the following commands:

- TR—Unconditional tripping
- TRSOTF—switch-onto-fault (SOTF tripping)
- TRCOMM—Communications-assisted tripping

The TR SELOGIC control equation is normally used to set all time-delayed tripping elements. The TRSOTF control equation identifies which elements trip only while SOTF protection is active. These elements will trip instantaneously if they are activated during the switch-onto-fault delay (SOFTD) time. TRCOMM SELOGIC is typically used to set the Level 2 directional overcurrent short delay element [8]. The SEL-451 relay also provides the minimum trip duration timer setting, which determines the minimum length of time that Relay Word bits assert, or stay high (logical 1). A Relay Word bit is a single relay element or logic result. Logical 1 represents a true logic condition, picked up element, or asserted control input or control output. Logical 0 represents a false logic condition, dropped out element, or deasserted control input or control output. Relay Word bits are used in SELOGIC control equations. The SEL-451 relay provides logic that allows manual tripping of the circuit breakers. The manual control of circuit breakers is controlled by setting SEL control equations BK1MTR and BK2MTR using the Expression Builder's logic [8].

D. Human Machine Interface (HMI)

The ACSELERATOR QuickSet software offers its users several types of relay information and relay controls through HMI features. The key functions offered through the HMI are as follows: Device Overview, Phasors, Instantaneous, Synchrophasor, Demand/Peak, Max/Min, Energy, Targets, Status, SER (Sequential Events Recorder), Breaker Monitor Data and Control Window. All of these functions have unique features, but only a few were used in connection with this thesis [8].

The HMI allows users to interactively access and utilize key meter and control features. The metering features played an important role in performing this thesis work because they allow users to view real-time relay information. The phasors function provides a graphical illustration of phase and sequence voltage and current phasors. Additionally, the phasor function allows the phase and sequence voltages and currents to be viewed in text format as well. The instantaneous function provides RMS magnitude values for the user. The function lists voltages, currents, powers, frequency and dc monitor voltages in a table format [8].

The SER is another important function of the HMI that is utilized in this thesis. The SER gives sequential information on relay states and relay element operation [8]. The SER records relay events and stamps a time to each state. These events include state changes of relay word bit elements and relay conditions. These relay conditions consist of relay power-up, relay enable and disable, group changes, settings changes, memory overflow, diagnostic restarts, and SER autoremoval/reinsertion. The SEL-451 relay records the most recent 1000 SER events into nonvolatile memory [8]. There are a number of special SER commands that give users the opportunity to customize the records viewed. One of these commands, SER *k,* allows the user to return a specified number *(k)* of records from the SER [8]. A second important SER command, SER C, clears all SER records on the present communication (serial) port. Lastly, SER *date 1,* allows users to recall events on a specific date [8].

The SER also contains an important point and alias feature. This unique feature allows users to program the relay to trigger an SER record. The triggers, or points, can be activated on control input and control output state changes, relay element pickups and dropouts, etc. The points allow users to view when a specific relay event occurs. These specific events can be given aliases that give distinct names to the instance or event [8].

E. Terminal

The terminal emulation program provided by the QuickSet software gives users the flexibility to set and operate the SEL-451 relay by using various SEL ASCII

(American National Standard Code for Information Interchange) commands [8]. These commands enable users to set, meter and control the SEL-451 relay. The terminal serves as an interface between the relay and the software. Users can view information in real time with the terminal emulation program.

The METER command allows users to view quantities that the relay measures in the power system. These quantities include: voltages, currents, frequency and remote analogs [8]. The “MET” command is one of the METER commands that is used to view fundamental metering quantities. These quantities do not include harmonics and dc components, but only displays measured quantities at the power system fundamental frequency [8]. Here in this thesis the “MET PMV” (protection math variables) command is issued to view the protection math variables used to store the slope values. The MET PMV command displays the last 16 protection math variables that are stored [8].

**2.3 SEL-451 Key Hardware Features**

The SEL-451 relay possesses several key hardware features that played a vital role in the successful completion of this thesis. The communication interfaces enable key external devices to adequately communicate with the relay. Additionally, the front panel provides much needed control and metering capabilities [8].

A. Communication Interfaces

The SEL-451 multiple communication interfaces allow users to communicate with various external devices. The communication interfaces represent the physical connections on the relay that allow users to set the relay, collect data from the relay and perform various diagnostic functions and relay tests [8]. The serial port and analog input interfaces were both actively used for this thesis.

The relay possesses four serial port connections. One of the serial ports is located on the front and the other three ports are located in the rear. These serial ports conform to the RS-232 or EIA/TIA-232 standard. These communication ports process data at a rate of 300-57600 bps [8]. The relay's serial ports are all standard female 9-pin connectors. The pin assignments for the 9-pin serial port are shown in Table I. After a physical connection has been made between the serial port and a device, a certain communications protocol must be used to adequately communicate with the relay [8]. A communications protocol is the arrangement of bytes/bits that must occur in order to properly communicate with a device. DNP3 is the protocol used to communicate via the serial ports [8]. The relay's serial ports act as an interface between a PC and the distribution relay. This interface enables the QuickSet software to communicate with SEL-451 relay's hardware.

Table I
9-Pin Serial Port Assignments [8]

| Pin | Signal Name | Description |
|---|---|---|
| 1 | 5 Vdc | Modem or EIA-232 to EIA-485 transceiver power |
| 2 | RXD | Receive data |
| 3 | TXD | Transmit data |
| 4 | +IRIG-B | Time code signal positive |
| 5 | GND | Signal Ground |
| 6 | -IRIG-B | Time code signal negative |
| 7 | RTS | Request to send |
| 8 | CTS | Clear to send (input) |
| 8 | TX/RX CLX (for SPEED := SYNC, only available when PROTO := MBA or MBB) | Transmit and receive clock (input) |
| 9 | GND | Chassis ground |

The relay also has a 34-pin low-level test interface located inside the front panel [8]. This interface serves as the link between the relay and test equipment. The SEL-

4000 adaptive multichannel source (AMS) is used for testing purposes in this thesis. The SEL-4000 AMS is capable of producing three phase and single phase voltages and currents. Signals are produced by the source and simulate power system conditions via the test interface. The voltages and currents produced are scaled based on specified PT and CT ratios [8]. The SEL-4000 AMS is controlled using the SEL-5401 software. This software is capable of producing numerous testing options and scenarios. The source can produce voltage and current sources that ramp up at a certain rate. Additionally, the source can simulate multiple states that last for specified amounts of time. Alternatively, each state can represent a new testing scenario.

B. SEL-451 Relay's Processing Power

The powerful microprocessor-based distribution relay effectively analyzes data and processes information. The relay has the capability of processing AC voltage and current inputs at a rate of 8000 samples per second. The relay also sequentially processes protection and control logic at a rate of 8 times per power system cycle or 8 times every one sixtieth of a second [8]. Therefore, for every power system cycle, protection and control logic will be sequentially processed 8 times.

C. SEL-451 Relay's Front-Panel Operations

The SEL-451 relay front-panel gives users the flexibility to control, view, and operate the relay without having to use the QuickSet software. The front-panel has an LCD (liquid crystal display) that shows relay operating data [8]. This data includes event summaries, settings, metering, and relay self-test information [8].

The front-panel gives users the flexibility to control or modify several settings. These settings include port, global, group, active group and date/time. The active group settings are where the logic used to produce the results needed for the completion of this thesis are stored.  The LCD displays RMS voltages and currents at the fundamental frequency.  SER reports are also accessible through the front-panel.

# CHAPTER 3

# MITIGATING VOLTAGE INSTABILITY PROBLEMS USING THE SEL-451 DISTRIBUTION RELAY

## 3.1 Introduction

In Chapter 1 of this thesis, some of the methods that are currently used in the power industry to counteract the voltage instability problems that stem from the delayed voltage recovery and fast voltage collapse phenomena are described. The sustained low voltages that are associated with the delayed voltage recovery and fast voltage collapse phenomena may lead to voltage instability causing the power system to be compromised. There were a number of solutions that can be used to mitigate the voltage instability problem that was also introduced in Chapter 1. These solutions include: additional dynamic reactive power sources, planned generation, faster breaker failure clearing times, and load shedding. A new potential solution that involves the use of the slope as a tool to predict future voltage levels at a certain point in time was introduced in Chapter 1. The time that is approximated from the slope of the voltage recovery or voltage sag is vital to solving the voltage instability problems that stem from delayed voltage recovery and fast voltage collapse problem. The time is a crucial piece of information that is needed in order for power engineers to properly set the trip logic on a relay. The relay will be set to trip if the time the relay approximates the voltage to recover to an appropriate level is above some predetermined threshold time. In this chapter, the means by which the SEL-

451 relay will be used as a predictive tool to mitigate voltage problems that stem from delayed voltage recovery and fast voltage collapse will be explained in detail.

Some of the relay's features will be utilized to accurately approximate the slope of the RMS voltage that is seen by the SEL-451 relay following a fault. This slope will in turn be used to predict the subsequent voltage levels following fault recovery. The SEL-4000 AMS is the test set that will be utilized to simulate the transient voltage sag. The SEL-4000 AMS has the ability to duplicate several slope scenarios that will give the SEL-451 relay the opportunity to verify that it is properly approximating the slope. The QuickSet software will be used to program the logic which the relay will use to approximate the slope of the simulated voltage collapse and/or the voltage recovery. The simulated voltage collapse or voltage recovery will be set to recover to some level by some predetermined time. The relay will then be set to trip if the voltage does not recover by this predetermined time.

A. The SEL-451 Relay Slope Approximation and Recovery Time Implementation Issues

The key to approximating the RMS voltage slope, as illustrated by (1), is to accurately identify position and time at two different points on a line or a curve (RMS voltage plot). Therefore, the SEL-451 relay has to have the ability to store and recollect position and time data of any transient sag in order to accurately approximate the slope. In the case of a curve, (1) can be used only to approximate where the curve will be at some future time. The fact that the SEL-451 relay automatically outputs RMS voltage makes the slope approximation process simpler. The issue with the SEL-451 distribution relay is that it does not have a systematic method for accessing and then utilizing previously stored data in its software's programming logic. The lack of any true recoverable memory options makes a trivial problem, slope approximation, a challenge for the SEL-451 relay.

The recovery time approximation process may seem to be a trivial matter once the slope approximation issue has been resolved, but the approximation of the recovery time presents its own dilemma. Recovering the present time component in (2) is the issue that needs to be resolved in order to adequately approximate the recovery time. The present time represents the point in time in which the present voltage is retrieved by the relay. The time begins to elapse once the relay begins the slope approximation process. Therefore, the present time in (2) should be updated every time the present voltage is updated in the slope approximation. The fact that the SEL-451 relay's software does not possess any logic that can readily recover elapsed time makes the recovery time approximation process complicated.

B. Solution

After exploring several options, the use of the SEL-451 relay's conditioning timer proves to be the best option for storing and recovering data for SELOGIC programming. The use of the conditioning timer in conjunction with some boolean operators and storage variables solves the memory problem presented in this section. Moreover, the combination of a conditioning timer and a counter can also resolve the time issues that the recovery time approximation process poses.

### 3.2 Implementation of the Conditioning Timer and Counter

A. Conditioning Timer

The conditioning timer is a tool used in the ACSELERATOR's protection free-form area to condition boolean values. There are sixteen conditioning timers available in the protection free-form area. The name ranges of the conditioning timers range from PCT01 to PCT16. Conditioning timers do one of two things: stretch incoming pulses or allow the user to require that an input take a state for a certain period before reacting to the new state. The conditioning timer input can take on a state of a logical 0 or 1. The conditioning timers have three input parameters and only one output [8]. The parameters of the conditioning timer can be found in Table II.

Table II
Conditioning Timer Parameters [8]

| **Type** | **Item** | **Description** | **Setting** | **Name Examples** |
| --- | --- | --- | --- | --- |
| Input | Timer Input | Value timed by the relay | Boolean SELOGIC control equation setting | PCT16IN |
| Input | Pickup Time | Amount of time that the input must be on before the output turns on | Time value in cycles | PCT16PU |
| Input | Dropout Time | Amount of time that the output stays on following the input being turned off | Time value in cycles | PCT16DO |
| Output | Timer Output | Output of the timer | Value for Boolean SELOGIC control equations | PCT16Q |

An overview of the three inputs and one output that make up the conditioning timer is given by the information in Table II. This timer is a powerful tool that can be customized to accomplish specific tasks. The timer's input serves as a catalyst for the timer; once the input's boolean SELOGIC control equation setting is satisfied, the timer's input is turned on. The timer output is turned on only after the input is on and the pickup time has expired. The dropout time gives users the flexibility to extend the length of time the timer output remains on. A value of 0 can be placed for the pickup time and dropout time if the user chooses not to utilize them. In this thesis, the dropout feature is not utilized. Using the conditioning timer to store data requires precise timing while implementing logic to complement its characteristics. A visual description of how a conditioning timer will operate under normal conditions is illustrated in Fig. 8.

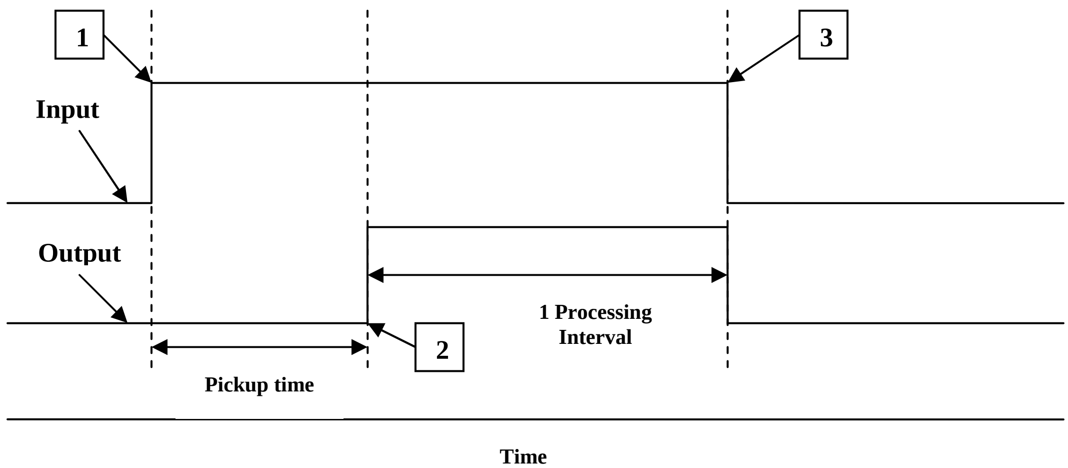



Fig. 8. Conditioning Timer Diagram without Dropout [8]

The input turns on or changes from a 0 to a 1 at position 1. After the pickup time elapses, the output is turned on. The pickup time expires at position 2 in the diagram. Due to the absence of a dropout time, the output remains on until the pickup time goes low (logical 0). The lack of a dropout time also results in the output remaining high (logical 1) for one processing interval (1/8 cycle). By properly choosing the settings for the inputs and output and using boolean operations, this conditioning timer can enable users to update a value until the timer times out and hold the value until it is updated. An example of how values can be held and updated using a conditioning timer is outlined in Table III.

Table III
Conditioning Timer Example

| Processing Interval | Elapsed Time (Cycles) | PMV02 = (VAYM x PSV02) + (PMV02 x Not PSV02) |
|---|---|---|
| 1 | 0.125 | (100 x 0) + (0 x 1) = 0 |
| 2 | 0.25 | (100 x 0) + (0 x 1) = 0 |
| 3 | 0.375 | (100 x 0) + (0 x 1) = 0 |
| 4 | 0.5 | (100 x 0) + (0 x 1) = 0 |
| 5 | 0.625 | (100 x 0) + (0 x 1) = 0 |
| 6 | 0.75 | (100 x 0) + (0 x 1) = 0 |
| 7 | 0.875 | (100 x 0) + (0 x 1) = 0 |
| 8 (Pickup Time Elapses) | 1 | (100 x 1) + (0 x 0) = 100 |
| 9 | 1.25 | (100 x 0) + (100 x 1) = 100 |
| … | … | … |

PMV02: Old Value
PSV02: Variable used to trigger update
VAYM: New Value (Assume VAYM = 100 V)
Pickup Time: 1 cycle

The example in Table III uses a conditioning timer to store a value and hold it for predetermined amount of time before updating that value. This is done by first setting the timer's pickup time to the amount of time the user wants a value to be stored. The timer's dropout time should be set to 0 cycles. Secondly, a Protection SELOGIC Variable (PSV) or some other variable must be set as the trigger for the timer's input in order for the SEL-451 relay to begin timing. Next, a PSV must be set to assert (change from a logical 0 to a logical 1) when the timer output turns on. The timer output will turn on (change from logical 0 to a logical 1) when the pickup time expires and the output will only be on for one processing interval (1/8 cycle). Lastly, the use of the boolean operators in the equation in column three of Table III provides the logic necessary to hold an old value and change that value after the pickup time expires. The logic is effective because once the pickup time expires the conditioning timer's output will turn on triggering the PSV to output a logical 1. At this point the old value will be updated and changed to a new value. The new value will be stored for the duration of the pickup time before being updated again. The storage and updating process goes on continually. In the above example, the old value that is picked up by the relay is assumed to be 0 Volts and the new value is assumed to be 100 Volts. The pickup time is set for 1 cycle or 8 processing intervals.

B. Counter

The counter is a tool used in the ACSELERATOR's protection free-form area to count changes or edges in boolean values [8]. There are 32 counters available in the protection free-form area. The name ranges of the counters range from PCN01 to PCN32. Counters have three input parameters and two output parameters. The parameters of the counter can be found in Table IV.

Table IV
Counter Parameters [8]

| Type | Item | Description | Setting | Name Examples |
|---|---|---|---|---|
| Input | Input | Value the relay counts | Boolean SELOGIC control equation setting | PCN16IN |
| Input | Preset Value | Number of counts before counter output is turned on | Constant or expression for the number of counts | PCN16PV |
| Input | Reset | Counter reset | Boolean SELOGIC control equation setting | PCN16R |
| Output | Current Value | Current accumulated count | Current accumulated count | PCN16CV |
| Output | Output | Counter output | Value for the SELOGIC control equations | PCN16Q |

All the counter inputs and outputs were utilized in the recovery time approximation process. As previously stated, the counter's purpose in the recovery time approximation process is to help provide the present time value that is needed in (2). This is done by using a conditioning timer in conjunction with a counter. Tables V and VI will be used to demonstrate how the recovery time approximation process works.

Table V
Recovery Time Approximation Logic

| SELOGIC Equations | Description |
|---|---|
| PCT02IN := NOT PCT02Q AND PSV03 | The conditioning timer's input is activated when the output is low and the voltage magnitude the relay measures is above 1 volt. |
| PCT02PU := 60 | Conditioning timer's pickup time is set to 60 cycles or 1 second. The timer's output, PCT02Q becomes a logical 1 when the pickup time expires. |
| PSV03 := VAYM >= 1 | PSV03 is a protection SELOGIC variable that outputs a logical 1 once the voltage magnitude is greater than or equal to one volt. |
| PCN01NPV := 75 | The counter's preset value is set to 75. |
| PCN01IN := PCT02Q | The counter counts the amount of time the timer's output change from logical 0 to 1. |
| PCN01R := NOT PSV03 | The counter resets and starts counting over once PSV03 becomes a logical 0. This will occur when the voltage magnitude is below or equal to 1 volt. |

Table VI
Counter Example

| **Elapsed Time (cycles)** | **Current Accumulated Count (PCN02CV)** |
|---|---|
| 60 | 1 |
| 120 | 2 |
| 180 | 3 |
| 240 | 4 |
| 300 | 5 |
| 360 | 6 |
| 420 | 7 |
| 480 | 8 |
| 540 | 9 |
| … | … |

As indicated by the SELOGIC equations used to approximate the recovery time in Table V, the counter counts the pulses of the conditioning timer's output, PCT02Q. The conditioning timer's pickup time used in the recovery time approximation process should be set to the same time as the pickup time for conditioning timer used in the slope approximation process. This will ensure that the present voltage and present time values used in (2) were taken at the same time. The conditioning timer's output turns on every 60 cycles. This is done by setting the pickup time to 60 cycles. Therefore, the counter's count increases every 60 cycles. The accumulated count output, PCN02CV, can be stored into a protection math variable (PMV) and then inserted in (2) as the present time value. The example in Table VI demonstrates how the counter count increases every 60 cycles or when the conditioning timer's output, PCT02Q, changes from logical 0 to logical 1. In this thesis, the approximations for the slope and recovery time are done every 60 cycles, but in reality the relay is capable of making the same approximations in any $1/8^{th}$ cycle increments.

C. Slope and Recovery Time Approximations with the SEL-451 Relay

The slope and recovery time approximation processes become less challenging once the memory and present time issues have been resolved. The only other challenge lies in understanding the characteristics of the relay's microprocessor and properly implementing logic accordingly for accurate results. As noted in chapter 2, it is important for users to know that the relay's microprocessor processes protection logic 8 times per cycle. The processing time comes into play when considering the value for the relay's pickup time. It is equally important to know that the relay's processor processes the logic sequentially one line at a time. Therefore, all the logic is processed sequentially

8 times per cycle. The steps involved in implementing the slope and recovery time approximations using the SEL-451 relay's QuickSet software SELOGIC applications are shown in Fig. 9. A detailed explanation of each step in the flowchart is outlined in Table VII.

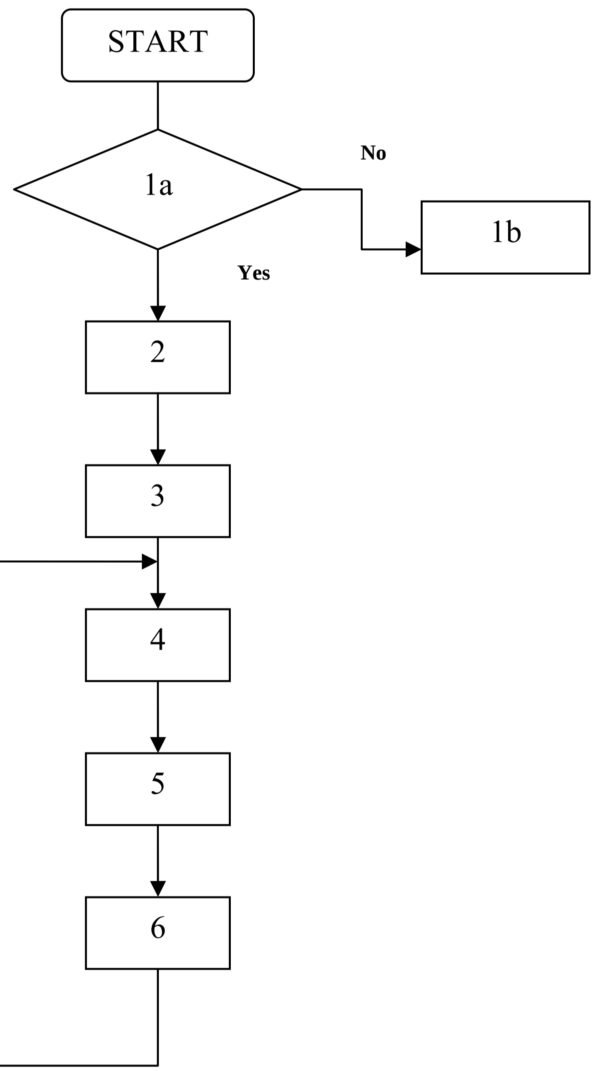



Fig. 9. Slope and Recovery Time Approximation Flowchart

Table VII
Slope and Recovery Time Approximation Process

| Step | Explanation |
|---|---|
| 1a | The relay checks to see if the input of the conditioning timer used in the slope approximation process is turned on or the input Boolean control equation* setting evaluates to a logical 0. The conditioning timer that controls the counter that tracks present time in the recovery time approximation is set to turn on at the same time the timer used in the slope approximation turns on.** (The timer's input is triggered by a Boolean SELOGIC control equation. Once the Boolean control equation evaluates to a logical 0 the timer will turn on.) |
| 1b | If the Boolean control equation does not evaluate to a logical 0 the timer will remain off and the relay will not begin timing. |
| 2 | The pickup time begins and the relay begins timing the input. The input remains on for the duration of the pickup time plus one processing interval (1/8 cycle). When the input is turned on the relay stores and holds initial or old voltage value using the Boolean logic outlined in Table III. During the first cycle of the conditioning timer the old value(initial value) will be 0. |
| 3 | The relay uses the old voltage and the present voltage which is metered by the relay at the instant the approximations are made to approximate the initial slope and recovery time. The time difference used in the slope approximation is set to 1 second because the relay approximates a new slope and recovery time every second. This time is set by setting the pickup time to 60 cycles or 1 second. The initial slope and recovery time is approximated and held until the pickup time expires. Equations (1) and (2) are used to approximate slope and recovery time, respectively. |
| 4 | Pickup time expires and conditioning timer output turns on or changes from logical 0 to 1. (timer output remains on for 1/8 cycle) |
| 5 | a. New slope and recovery time values are approximated.<br>b. Initial slope and recovery time values are updated to their new values. |
| 6 | a. Conditioning timer output and input turn off or changes from logical 1 to logical 0.<br>b. Pickup time begins and process restarts at step 4. |

*PCT01N = Not PSV02
PSV02 = R_TRIG PCT02Q
Variable PSV02 asserts when the (PCT02Q) timer output triggers on the rising edge. R_TRIG (Rising-edge trigger) is a Boolean SELOGIC control equation operator that triggers an operation upon logic detection of a rising edge [8].
** See Table V for more details on recovery time conditioning timer and counter

The slope and recovery time approximation processes begin when the timer's input boolean control equation setting output is evaluated as a logical 0 (PCT01N = Not PSV02). The Boolean control equation setting can be any equation that the user specifies to trigger the timer. The output of the equation can be either a logical 1 or logical 0. Once the timer is turned on, the pickup time begins. The relay approximates and holds the initial slope value constant for the duration of the pickup time. Therefore, if the pickup time is 60 cycles the slope value will be updated every 60 cycles. Once the pickup time expires, the timer output goes high and a new slope is approximated. The expiration of the pickup time also causes the conditioning timer's input boolean control equation setting output to change to a logical 0 or turn off. The conditioning timer's input will drop out or change to a logical 0 one processing interval after the pickup time expires. At this instant the conditioning timer's output will also dropout. The slope approximation process starts over once the timer input turns on again. The timer will turn on when the conditioning timer's input boolean control equation revaluates to a logical 1.

D. Testing the Slope Approximation Method

The voltage slope approximation was verified and tested using a PC, the SEL-451 relay, the SEL-4000 AMS, and an oscilloscope. Appendix 1 includes a diagram that shows how the test set is physically connected. A picture of the actual equipment in the test lab is also provided in Appendix I. Once the distribution relay is programmed to approximate the slope, the source can be used to administer some simulated voltages. The QuickSet software and the SEL-4000 AMS will be used to test and verify that the relay is approximating the slope correctly. The oscilloscope is used to verify that the source is producing the voltages that it is set to produce. The test procedure is as follows:

1. Set up test according to the description outlined in Appendix 1
2. Use the oscilloscope to verify that the SEL-4000 AMS is producing correct voltage values
3. Set the SEL-4000 AMS to produce a voltage scenario of the user's choice. The user can create multiple scenarios ranging from constant voltage, increasing voltage, decreasing voltage, or a combination of the three.
4. Use the QuickSet software's MET PMV ASCII command to display the slope and recovery time approximations.
5. Check the slope and recovery time approximations produced by the relay against the known slope and recovery time that the SEL-4000 AMS is supposed to produce.
6. Check to see if relay trip logic is working correctly. The relay should trip if recovery time exceeds some predetermined threshold value for the recovery time.

E. Test Results

The conditioning timer test was performed to verify that the slope approximation process works properly. The test scenario was conducted using the 6 steps outlined in the previous section. The approximation solution process was tested by using the SEL-4000 AMS to simulate two different scenarios. The first scenario involved two states. In state 1, the RMS voltage started off at zero and ramped up at a rate of 5 volts per second for 30 seconds. State 2 begins after 30 seconds elapses. During state 2, the voltage proceeds to ramp up at a ramp rate of 8 volts per second for 15 seconds The second scenario also involved two states. The first state in the second scenario was the same as state 1 in the first scenario. However, during state 2 the voltage no longer ramps up, but begins to produce a constant slope of 0 for 15 seconds. The two test scenario results are compiled in six graphs. Each test scenario contains three different graphs that capture the conditioning timer and the SEL-451 relay's test results. The recovery time is derived using (2) and the recovery voltage that is used by the relay to approximate the recovery time is 250 volts. The recovery voltage is the required threshold above which the voltage must recover. The recovery time is a relative approximation. The number depends on the present RMS voltage level and the present voltage recovery slope. Additionally, the relay is set to trip if the recovery time exceeds fifty seconds for longer than five seconds. A list of the parameters used in the relay trip process along with a description is located in Table VIII.

Table VIII
Relay Trip Process

| **Conditioning Timer Parameters** | **Description** | **Trip Logic Parameter** | **Description** |
|---|---|---|---|
| PCT03IN := *PMV64 >= 50 | PCT03IN represents the conditioning timer's input.<br>Timer turns on when the recovery time reaches 50 seconds or greater. | PCT03Q | PCT03Q represents the output for the conditioning timer. The output asserts (changes from logical 0 to logical 1) once the pickup time expires. When PCT03Q asserts the relay will trip. The TR (unconditional) trip logic is used to trip the relay. |
| PCT03PU := 300 | PCT03PU represents the input for the pickup time in cycles. The pickup time is set to 300 cycles or 5 seconds. This will cause the timer output to turn on only if the recovery time is greater than or equal to 50 seconds for longer than 5 seconds. The timer's output will turn on once the pickup time expires. | | |
| PCT03DO := 0 | PCT03DO represents the input for the dropout time.<br>The dropout time is set to 0. This will cause the input to turn off when the timer's output turns off. | | |

*PMV64: Math variable used to store the recovery time

The combination of the SEL-451 relay's unconditional trip logic and a conditioning timer is used to set the relay to trip properly. The conditioning timer's input does not turn on unless the recovery time is equal to or greater than fifty. The conditioning timer's pickup time is set to 300 cycles (5 seconds). Therefore, a recovery time of fifty seconds or greater that lasts for five seconds will cause the conditioning timer's output to assert (change from logical 0 to logical 1). The relay is set to trip based on the conditioning timer's output. When the output of the conditioning timer asserts or goes high the relay will trip. A trip output of 1 indicates that the relay tripped and a trip output of 0 indicates that the relay did not trip.

The RMS voltage results and the slope are captured in Fig. 10 for scenario 1. The curve on the graph illustrates the voltage scenario that the SEL-4000 AMS simulated. The slope starts off at 5 volts per second and then transitions to 8 volts per second at around 30 seconds. The recovery time for the voltage recovery simulated in scenario 1 is illustrated in Fig. 11. As indicated by Fig. 11, the recovery time starts off high, but almost instantly settles to around 50 seconds once the relay begins to get voltage input from the SEL-4000 AMS. Then at state transition the recovery time reduces to around 42 seconds for the duration of the test simulation. Lastly, the trip output for scenario 1 is shown in Fig. 12. The relay functioned properly and did not trip.

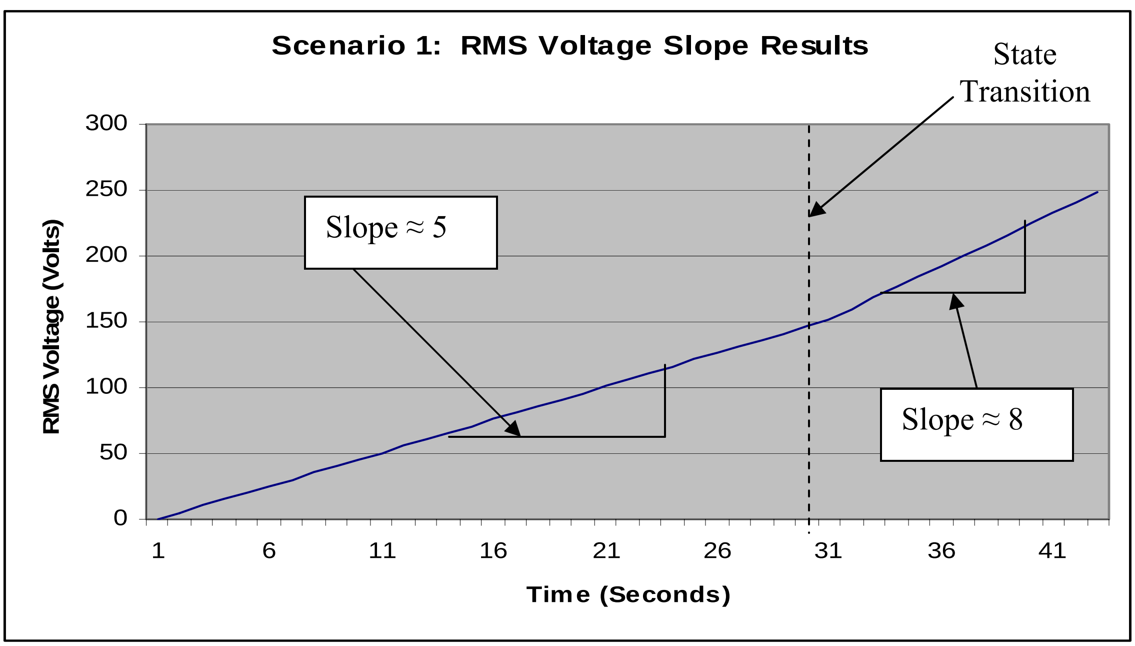



Fig. 10. Scenario 1: RMS Voltage Slope Results

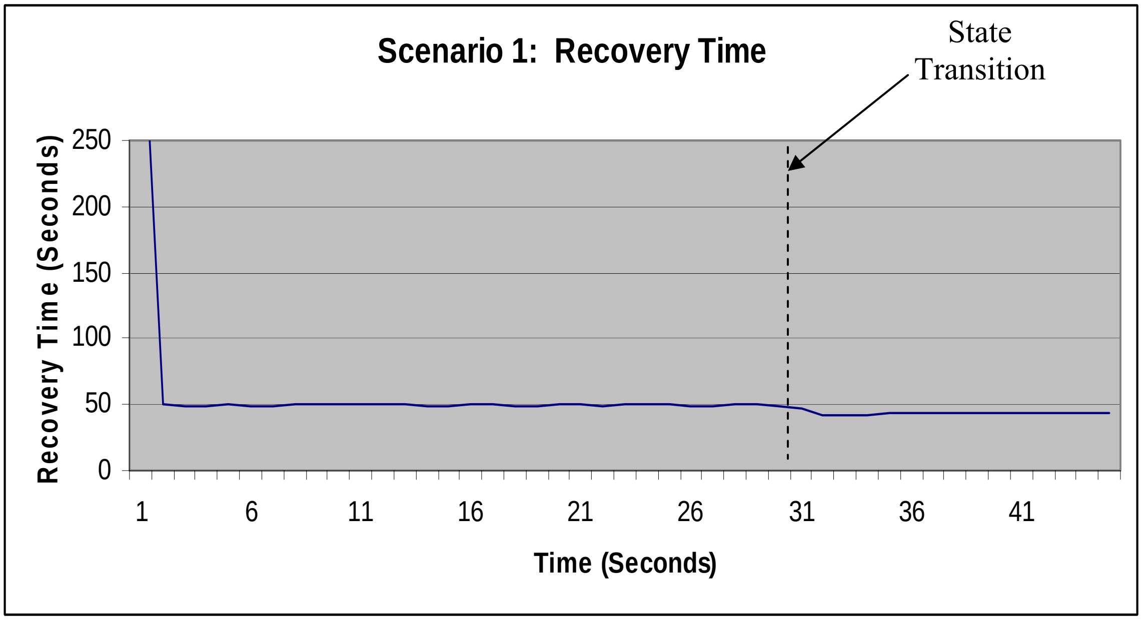



Fig. 11. Scenario 1: Recovery Time

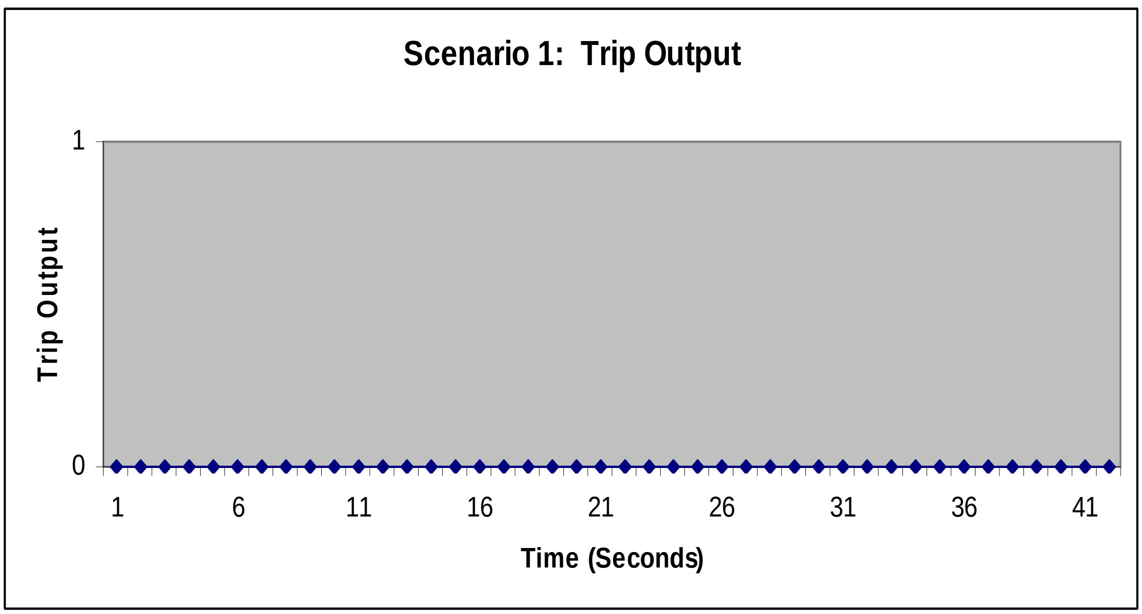



Fig. 12. Scenario 1: Trip Output

The RMS voltage results and the slope are captured in Fig. 13 for scenario 2. The graph illustrates the voltage scenario that the SEL-4000 AMS simulated. The slope starts off at 5 volts per second and then transitions to 0 volts per second at around 30 seconds.

The recovery time for the voltage recovery simulated in scenario 2 is illustrated in Fig. 14. As indicated by Fig. 14, the recovery time behaves exactly like the recovery time for scenario 1 when the slope is 5 volts per second, but the graphs vary drastically when the slope nears 0 volts per second at state transition. At 30 seconds the recovery time increases to infinity for the remaining 15 seconds of the test simulation. Lastly, the trip output for scenario 2 is shown in Fig. 15. The relay did not trip until the recovery time exceeded 50 seconds about 30 seconds into the test simulation. Again, the relay functioned properly.

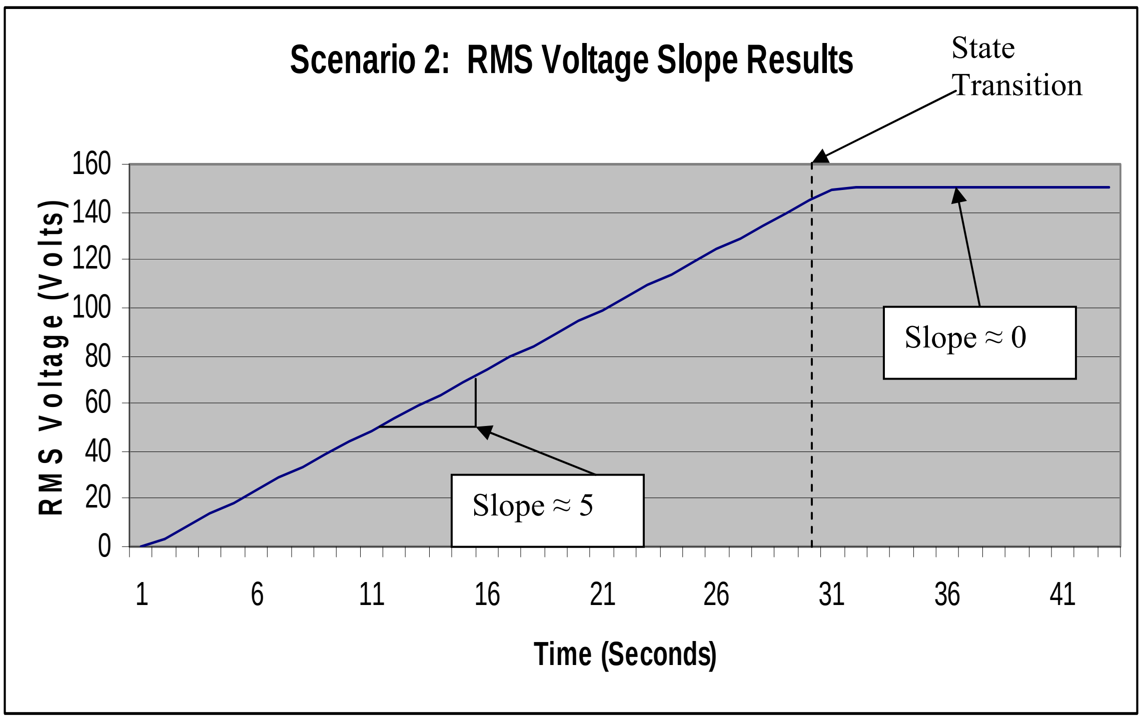



Fig. 13. Scenario 2: RMS Voltage Slope Results

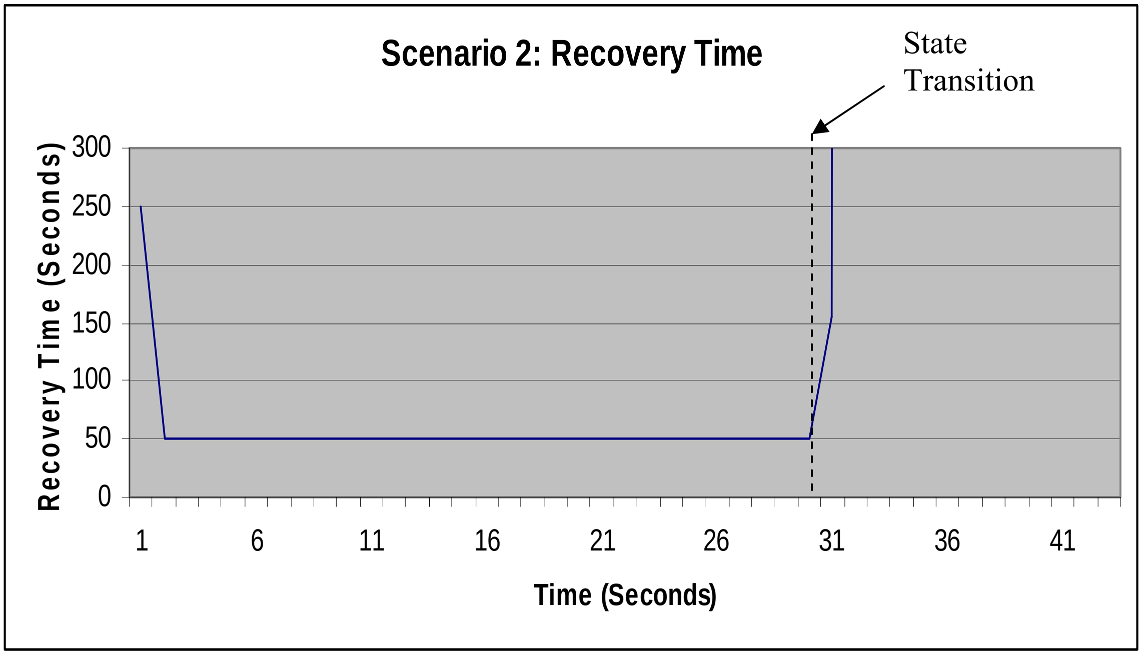



Fig. 14. Scenario 2:  Recovery Time

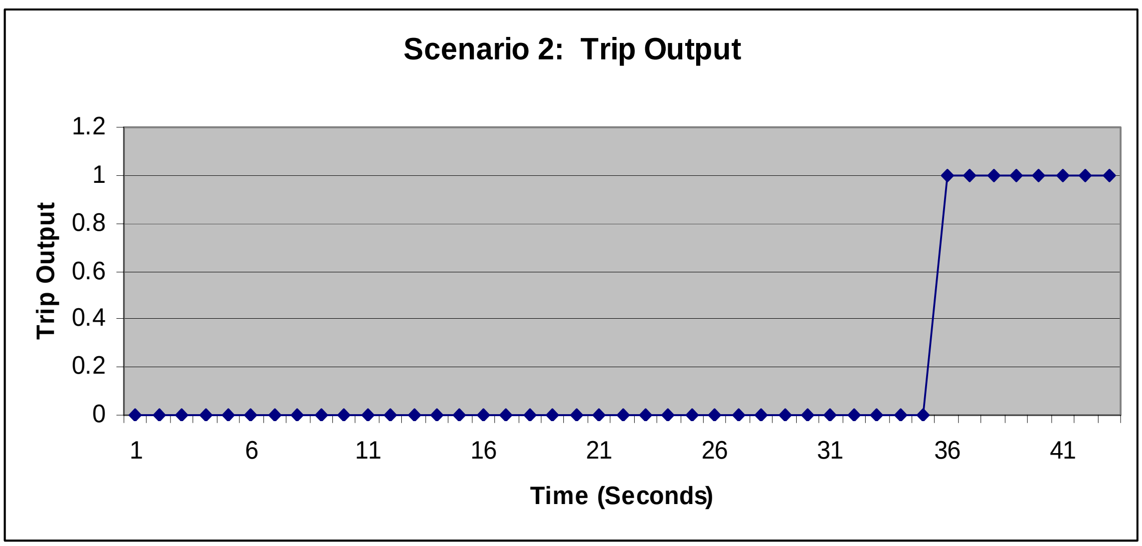



Fig. 15. Scenario 2:  Trip Output

### 3.3 Conclusion

Chapter 3 helped to bridge the information gap left between the first two chapters. The information in Chapter 3 describes in great detail how the SEL-451 distribution relay is used to mitigate voltage instability problems that stem from delayed voltage recovery and fast voltage collapse. The SEL-4000 AMS was used to simulate two scenarios that are similar to the voltage recovery process attributed to the delayed voltage recovery and fast voltage collapse phenomena. The SEL-451 relay's SELOGIC equations, conditioning timers, and a counter were used to verify that a microprocessor based relay can be used to approximate a slope and recovery time.

# CHAPTER 4

# CONCLUSION

The implementation of the recovery time approximation in protective relay applications gives power engineers another tool for combating voltage instability that stems from the delayed voltage recovery and fast voltage collapse phenomena. The slope of the voltage recovery or voltage collapse can be used in conjunction with some of the methods already used in the power engineering arena to combat fast voltage collapse and delayed voltage recovery. The combination of these methods will add additional protection to the power system while preserving its integrity.

The voltage slope approximation method can be easily implemented in a microprocessor based relay's trip logic. The relay will use the slope to predict future voltage levels. These voltage levels and recovery times will then determine whether or not the relay should operate. The appropriate voltage level and recovery time that the relay will use as the threshold for relay operation will be unique to the power system. The appropriate threshold voltage levels can be determined based on historical data of the power system. Equipment type and the amount of load on the system will also contribute to how long a certain voltage level can remain on the system before the relay needs to operate. Undervoltage load shedding is only appropriate if there is potential for widespread or cascading problems such as system separation.

In addition to the voltage slope approximation method being easy to implement, it is also cost effective. If power utilities already have the SEL-451 distribution relay or other capable microprocessor based relays in use, there will be virtually no equipment costs involved. Other microprocessor based relays can implement the logic discussed in this thesis if the relays have timers with the same capabilities as the conditioning timer in the SEL-451 relay. In the case where the relay already exists, the utility companies will only be responsible for the man hours involved in setting the appropriate trip logic for the relay. Alternatively, if the companies do not utilize microprocessor relays, the company will have to purchase them. The purchase of a microprocessor based relay is definitely justified because of the huge potential gains that additional protection will bring to the power system. The company will not have to replace expensive power system equipment that can be potentially damaged due to voltage instability issues that may stem from delayed voltage recovery and fast voltage collapse. Most importantly, the power company customers will benefit because the power system will be less susceptible to experiencing a major blackout due to fast voltage collapse or delayed voltage recovery.

## REFERENCES


[1] Bradley R. Williams, Wayne R. Schmus, and Douglas C. Dawson, "Transmission voltage recovery delayed by stalled air conditioner compressors*," IEEE Trans. Power Systems*, vol. 7, no 3, Aug. 1992, pp. 1173-1181.

[2] Ismail A. Hamzah and Jamal A. Yasin, " Static Var compensators (SVC) required to solve the problem of delayed voltage recovery following faults in the power system of the Saudi electricity company, western region (SEC-WR)," *Proceedings of the 2003 IEEE PowerTech Conference,* vol.4, Bologna, Italy, June 23-26, 2003.

[3] A. P. Sakis Meliopoulos, George Cokkinides, and George Stefopoulos, "Voltage stability and voltage recovery: load dynamics and dynamic VAR sources," *School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332-0250,* 2006 IEEE.

[4] George K, Stefopoulos and A.P. Meliopoulos, "Induction motor load dynamics: impact on voltage recovery phenomena," *School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332,* 2006 IEEE.

[5] Vince Stewart and Ernst H. Camm, "Modeling of stalled motor loads for power system short-term voltage stability analysis," *Power Engineering Society General Meeting,* 2005 IEEE.

[6] John A. Diaz de Leon II and Carson W. Taylor, "Understanding and solving short-term voltage stability problems," *Power Engineering Society Summer Meeting,* 2002 IEEE.

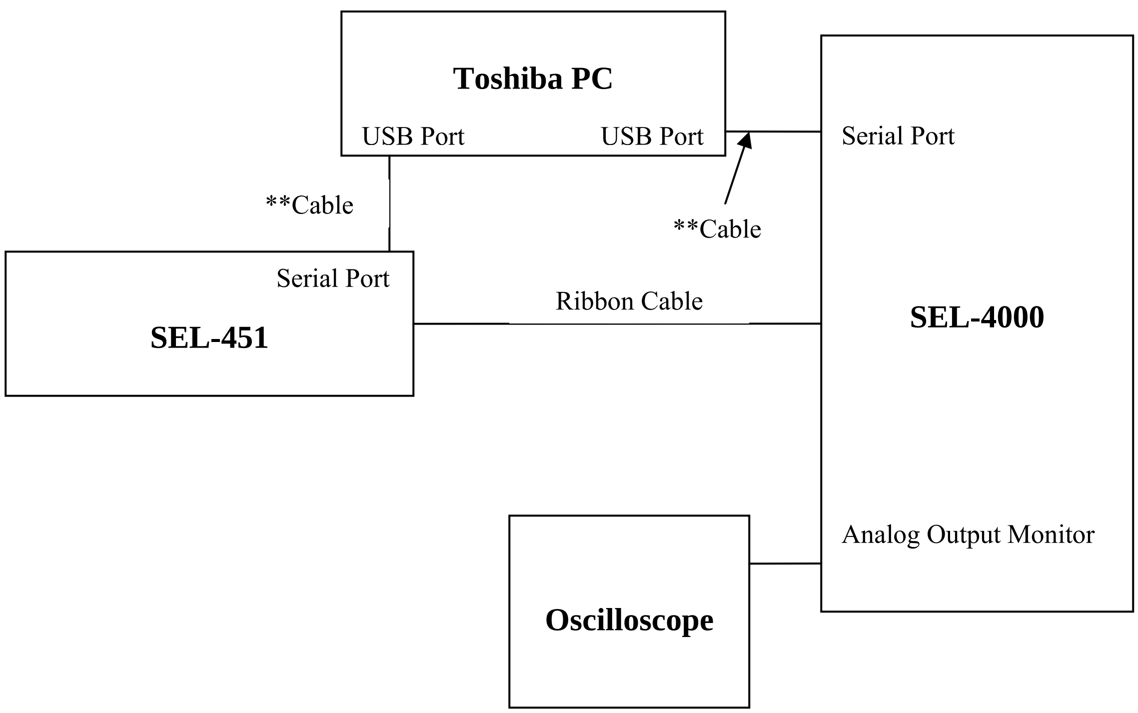
[7] Lee Y. Taylor and Shih-Min Hsu, "Transmission Voltage Recovery Following a Fault Event in the Metro Atlanta Area," *Power Engineering Society Summer Meeting,* 2000 IEEE.

[8] "SEL-451 relay protection, automation, and control system instruction manual," Washington: Schweitzer Engineering Laboratories, Inc., 2004-2006.

# APPENDIX A

## TEST SET DIAGRAMS

The diagram in Fig. A.1 represents a schematic of the test set used to perform the slope and recovery time approximations presented in Chapter 3 of this thesis. The actual test set used in represented in the photograph shown in Fig. A.2.




** 9-pin serial port connector described in Table I

Fig. A.1. Test Set Schematic

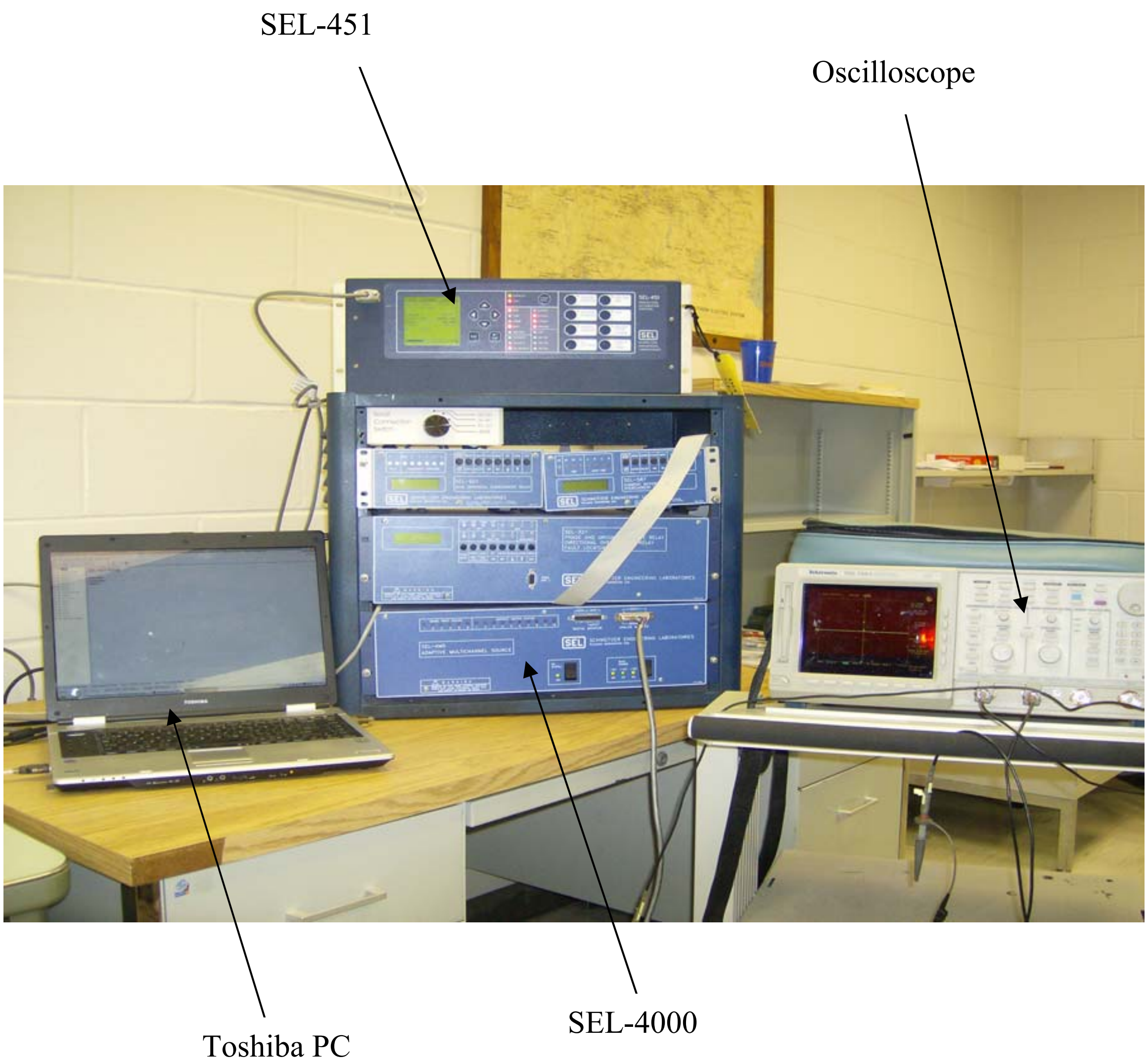



Fig. A.2. Actual Test Set