Implementation of the Security-Dependability Adaptive Voting Scheme

Michael Kyle Thomas

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Committee Members

Virgilio A. Centeno (Chairman)

R. Matthew Gardner

Jaime De La Ree Lopez

Arun G. Phadke

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Abstract

As the world moves further into the 21st century, the electricity demand worldwide continues to rapidly grow. The power systems that supply this growing demand continue to be pushed closer to their limits. When those limits are exceeded, system blackouts occur that have massive societal and economical impact.

Power system protection relays make up a piece of these limits and can be important factors in preventing or causing a system blackout. The purpose of this thesis is to present a working implementation of an adaptive protection scheme known as the adaptive voting scheme, used to alter the security/dependability balance of protection schemes. It is argued that as power system conditions change, the ability of protection relays to adjust the security/dependability balance based on those conditions can allow relays to play a part in preventing power system catastrophes.

It is shown that the adaptive voting scheme can be implemented on existing protection technology given Wide Area Measurements (WAMs) provided by Phasor Measurement Units (PMUs). The proposed implementation characteristics allow numerous existing protection practices to be used without changing the basic operation of the practices.

To My Parents: Michael Thomas and Rachel Williamson

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Chapter 1 – Introduction

Today the world is using more electricity than ever before. Consumer electronics are in the hands of millions, if not billions, of people; more manufacturers are creating electric vehicles as the market continues to grow; and parts of the world that have never had electricity are beginning to come online. These are just a few of the factors causing the rise in electricity demand around the world. And this demand is growing ever year, and it is growing fast. Unfortunately, the aging power systems in the United States and the other parts of the world are fighting to keep up with the growing demand. Investments are being made in equipment, transmission lines, generating stations, and the works. But in the power system world, these investments have long lead times – it can take at least 5 years for the completion of a new extra high voltage transmission line. With all of these factors adding up, a serious problem arises. That problem is the physical stress that is forced onto the power system and its equipment. As more and more electricity is generated and transmitted through the system, the power system equipment is pushed closer to its limit. On August 14, 2003, a significant event occurred showing what happens when that limit is exceeded. On that day, the Northeastern United States and nearby parts of Canada lost power when a sustained system blackout occurred. The result was 50 million people without power and billions of dollars lost [1].

One of the major contributors to the blackout was the lack of situational awareness among system operators [2]. With a better understanding of the current conditions of the power system, operators may have been able to take corrective or preventive control actions to stop/prevent the cascading blackout. One specific action that could have halted the cascading blackout is the prevention of relays protecting the most heavily loaded transmission lines from misoperating due to the increased electric load flowing through the lines. The focus of this thesis is the implementation of a protection scheme designed to help prevent these misoperations by automating the scheme with the use of Wide Area Measurements that provide situational awareness.

1.1 Power System Relaying Security and Dependability

With the focus of this thesis being a power system protection scheme, it is important to introduce two terms related to the reliability of power system protection. The first is dependability, which is defined as "the degree of certainty that a relay or relay system will operate correctly." The second is security, which is defined as "the degree of certainty that a relay or relay system will not operate incorrectly" [3]. These two concepts perfectly contrast one another. An increase in dependability of a protection scheme creates a decrease in security of the scheme, and vice versa.

Power system protection has been traditionally biased towards dependability, where protective schemes are designed so that any fault will be cleared by some relay in the system [4]. This increase in dependability results in a decrease of security. Traditionally this disparity has been acceptable due to the network structure of power systems that allow for many alternate power flows in the system. But the systems have evolved. Transmission lines in power systems today are more heavily loaded along paths, and while the systems are designed to withstand a single or double contingency, additional contingencies caused by relay misoperations could lead to a cascading blackout of the system, such as the August 2003 blackout mentioned earlier.

1.2 Adaptive Protection Schemes with Wide Area Measurements

Adaptive protection schemes are just as their name describes. These protection schemes adapt to the state of the power system by updating their control and protective actions based on the state of the system. For the purposes of this thesis, the state of the power system is determined by Wide Area Measurements (WAMs) provided by Phasor Measurement Units (PMUs). Wide Area Measurements are just as their name describes – measurements taken throughout a wide geographic area of the power system. PMUs are devices with the ability to provide synchronized phasor measurements, called Synchrophasors.

To accurately determine the state of a large power system, measurements must be taken throughout the entire system – these are the WAMs. However, an inherent problem arises with taking Wide Area Measurements. The measurements must be taken at the same exact time, but a number of different devices provide these measurements. All of the devices must therefore have the same time reference when measurements are taken. PMUs accomplish this requirement, as each PMU uses a common signal from the Global Positioning System (GPS) to provide synchronized measurements. PMUs from any point in the system will be synchronized with each other, that is, the measurements from all the PMUs will be time-stamped based on the GPS signal. Therefore, with Wide Area Measurements from PMUs an accurate power system state can be determined and sent to an adaptive protection scheme, whose control actions may be updated based on the system state.

1.3 The Adaptive Voting Scheme

The adaptive protection scheme that is the focus of this thesis, called the adaptive voting scheme, is an adaptive protection scheme that will adjust the protection scheme of a critical transmission line to be more secure or more dependable based on the state of the power system. For the voting scheme, the state of the power system is classified into two states – safe or stressed. A power system is classified as safe when it is determined from WAMs that the voting scheme's critical transmission line could be tripped offline (due to a relay misoperation) without causing detrimental effects to the power system. A power system is classified as stressed when just the opposite is determined, where the critical transmission line tripping offline has very detrimental effects to the system, such as a cascading blackout.

If the system is classified as safe, the adaptive voting scheme will take no action and will leave the protection scheme as it was originally designed; with a bias towards dependability. This bias is desired during safe, normal operating conditions – the consequence of not tripping quickly due to a fault is severe equipment damage. If the system is classified as stressed, the voting scheme will bias a protection scheme towards security by requiring multiple relays to vote on tripping the line. By allowing a trip only if the majority of the relays agree to trip, the potential for a misoperation – caused by a hidden failure, lack of security, or other failure of the protection system – is removed [5]. Security is desired during stressed system conditions – the consequence of a relay operating incorrectly (defined as a misoperation) induces more stress on the system; potentially leading to a cascading blackout.

The term hidden failure, in relation to power system protection systems, is defined as "a permanent defect that will cause a relay or a relay system to incorrectly and inappropriately remove a circuit element(s) as a direct consequence of another switching event" [6]. A hidden failure is exactly what the adaptive voting scheme aims to protect against. If one relay or relay system is used to protect a critical transmission line and a hidden failure occurs in that protection system causing a misoperation of the line, two events have now occurred – the original event that caused the hidden failure and the critical transmission line misoperation. At any time, this is a significant event in a power system. But if this same event were to occur when the system is already stressed, the unnecessary outage of the critical line could lead to a cascading blackout of the system. The goal of the Wide Area Measurements and adaptive protection schemes, such as the adaptive voting scheme, is to fight catastrophic failures in power systems caused by protection system misoperations [7].

1.4 Outline of this Thesis

This thesis documents the laboratory implementation and testing of an adaptive voting scheme. Chapter 2 provides the architecture of the adaptive voting scheme, the necessary equipment needed to fully implement the scheme, and the algorithms and logic equations that were developed for the voting scheme devices. Chapter 3 details the various adaptive voting scheme implementations that were tested, along with the test procedure and results of all the implementations. The results of all the implementations will prove that the developments in Chapter 2 produce adaptive voting schemes that operate correctly for all relay misoperations. In addition to this, it is shown that the original protection schemes are not affected by the adaptive voting scheme in any way. The only change is the decision to trip the circuit breaker based on the trip signals of the original protection schemes. Chapter 4 provides a summary of the thesis, with conclusions and future work also presented. Last is a list of references, followed by a set of appendices providing actual information and settings of all the devices used in the adaptive voting scheme implementations.

Chapter 2 – The Voting Scheme

The protection scheme that is the focus of this thesis, called the voting scheme, is an adaptive protection scheme that will adjust protection to be more secure or more dependable based on the state of the power system. As introduced in Chapter 1, if the power system is in a safe operating condition, the voting scheme will take no action and will leave the protection scheme as it was originally designed; with a bias towards dependability. This bias is desired during safe, normal operating conditions – the consequence of not tripping quickly due to a fault is severe equipment damage. If the power system is in stressed operating condition, the voting scheme will bias the protection scheme towards security by having multiple relays vote on tripping the line. By allowing a trip only if the majority of the relays agree to trip, the potential for a misoperation caused by one relay is removed. Security is desired during stressed system conditions – the consequence of a relay operating incorrectly induces more stress on the system; potentially leading to a cascading blackout.

The following sections of Chapter 2 provide the architecture of the adaptive voting scheme, the necessary equipment needed to fully implement the scheme, and the algorithms and logic equations that were developed for the voting scheme devices.

2.1 Architecture of the Voting Scheme

The voting scheme is an adaptive protection scheme that will determine whether dependability or security is desired for power system protection. The voting scheme uses a phasor data concentrator (PDC) to collect system data (WAMs) from phasor measurement units (PMUs) that are strategically placed throughout a power system to determine the state of the system as being safe or stressed. Section 2.7 explains the PMU measurements, the state classification by the PDC, and the critical transmission line determination.

By design, the voting scheme PMUs transmit synchronized measurements at rates of up to 60 frames per second. The PDC continually collects this data and processes it for a program to determine the state of the system and therefore if the voting scheme should be enabled or not. This program may be performed by the PDC itself or by a computer attached to the PDC. Section 2.8 provides more details on the PDC and state determination program. As the system is continually classified, the classification is continually transmitted as a digital signal to the voting scheme devices. This digital signal, called the arming signal, informs the devices to arm or disarm the voting scheme to adjust the security/dependability balance of the protection scheme.

When the arming signal indicates a safe system, the transmission line protection scheme remains unaltered from normal conditions. This safe identification causes the voting scheme to be "disarmed," and the protection scheme returns to using its original control and protection functions. Alternatively, if the arming signal indicates that the system is stressed, the voting scheme is armed. With the voting scheme armed, the protection scheme is biased towards security by having any tripping decisions performed through a voting of the three digital relays. Instead of having each relay act only on what it sees alone, the voting scheme will use all three digital relays to determine whether the transmission line will trip by performing a majority vote of the relays' trip signals. The decision to trip the transmission line will be decided by a tallying of the "trip" or "do not trip" signals coming from all of the relays. If the majority, two or more of the three relays, indicate asserted trip signals (i.e. "trip" signals) the circuit breaker(s) will be opened and the transmission line will be de-energized. However, if the majority of the relays have deasserted trip signals (i.e. "do not trip" signals), the circuit breaker(s) will stay closed and the transmission line will stay in service. The voting scheme removes the possibility of one relay incorrectly operating the circuit breaker(s) for a variety of erroneous reasons: incorrect relay settings (human error), a hidden failure, etc. Whatever the reason may be, the voting scheme will not be influenced by one single relay's operation (or misoperation) and, therefore, biases the critical line's protection towards security. A bias towards security is desired for conditions when the power system is stressed, as an incorrect removal of a critical, heavily loaded transmission line could start a chain of events leading to a cascading blackout of the system.

There are two possible architectures of the adaptive voting scheme. Figure 2-1 shows Architecture-1 of the adaptive voting scheme. In this architecture, a new device is installed at the critical location and is defined as the Master device. This device receives the arming signal and is responsible for determining if a majority of the three relay trip signals are asserted and then tripping the circuit breaker, when the voting scheme is armed. The benefit of this architecture is that the original three relay protection systems are not altered from existing practices in any way. All that is required is that the protection system's trip signals be sent to the Master device [5]. The downside of Architecture-1, however, is that the Master device is the only device that can trip the breaker – even when the voting scheme is disarmed. This will introduce a time delay dependent on the trip signal communication channels used. Chapter 3 will discuss this time delay topic in detail.

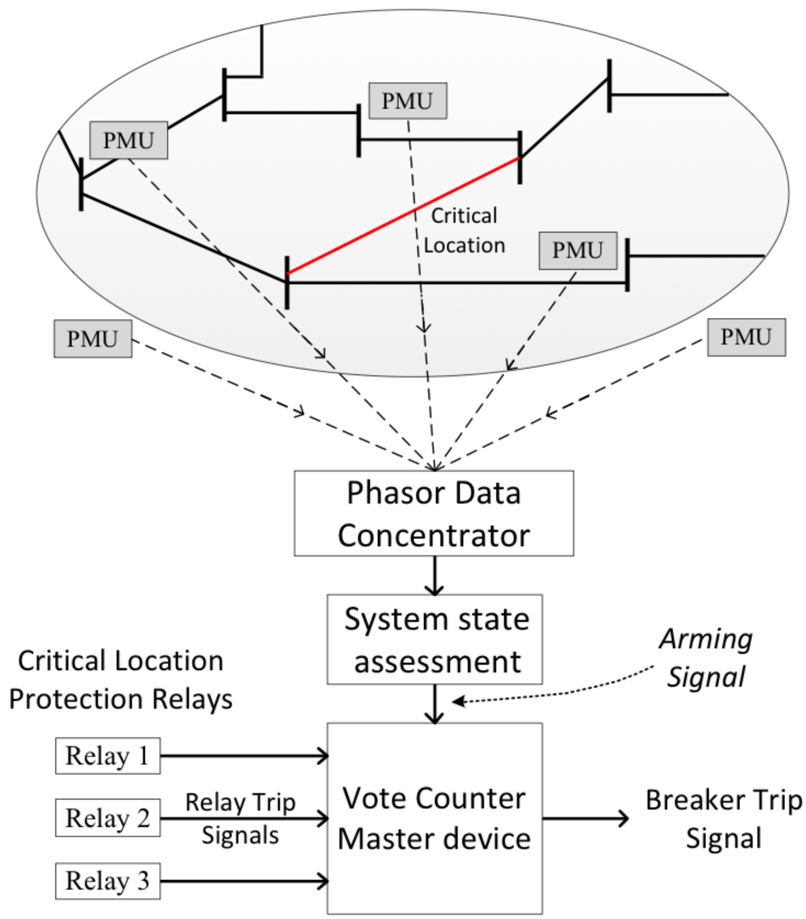

Figure 2-1. Architecture-1 of the adaptive voting scheme.

The second architecture of the adaptive voting scheme is shown in Figure 2-2. In this architecture, Architecture-2, the arming signal is sent to the three protection systems at the critical transmission line. One of the relays is set as the Master relay, while the remaining two relays are defined as the Slave relays. The Master relay is responsible for determining if a majority of the three relay trip signals are asserted and then tripping the circuit breaker, when the voting scheme is armed. The benefit of this architecture is that when the voting scheme is disarmed, the original protection schemes return to normal operation, where the relays trip the circuit breaker directly. The downside of Architecture-2, however, is that the internal logic of the three protection systems must be updated to operate as a voting scheme. It is important to note that these logic updates only alter the decision to trip the circuit breaker, not the original protection algorithms and schemes. The work presented in this thesis focuses on Architecture-2 of the adaptive voting scheme; however, the logic and equations developed in this thesis are the same for Architecture-1.

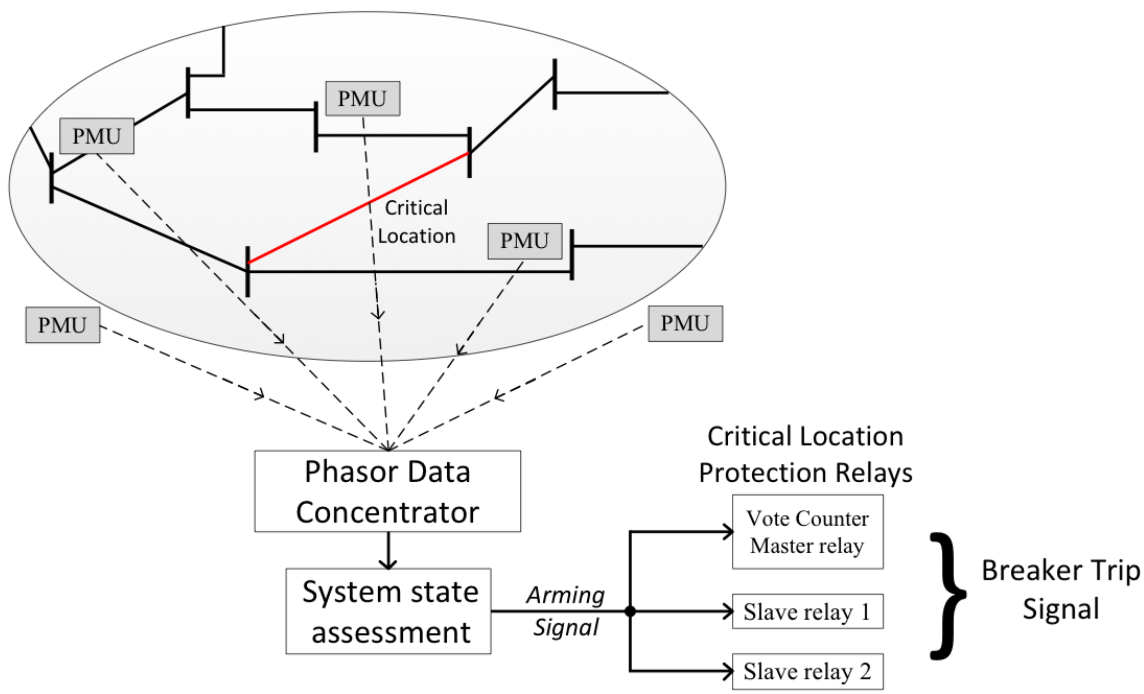

Figure 2-2. Architecture-2 of the adaptive voting scheme.

A significant advantage of the adaptive voting scheme is the ability to use existing protection practices in the voting scheme because the existing protection settings are not altered in any way. The only change is the decision to trip the circuit breaker based on the trip signals of the original protection schemes. What the voting scheme does require, however, is that three primary digital protection systems are installed at the critical location [5]. One of these primary digital protection systems can be implemented using the existing protection scheme at the critical location. With two other protection systems to implement, decisions must be made on a case-by-case basis.

There are various implementations to consider with the three digital protection systems of the voting scheme. One voting scheme implementation, relevant to times when the voting scheme is armed, could be implemented with three identical protection systems, such as using three distance protection systems. The benefits of this type of voting scheme setup are that only one protection study to be performed and applied to the relays; and having identical purchasing orders and construction for all three systems saves time and lowers costs. The downside of this type of voting scheme setup is there is no protection against a common mode of failure in the specific type of protection system used. The assumption here is that the failure in protection system used, such as an incorrect control circuit, exists in all three voting scheme systems. Therefore all three systems would fail together under this assumption. However, what the voting scheme does provide protection against in this setup (and all other setups) is if one relay system were to misoperate due to an isolated failure in that single system. During that event, the voting scheme would prevent that single system from operating a circuit breaker during stressed system conditions.

The next voting scheme implementation, again relevant to times when the voting scheme is armed, aims at protecting against a common mode of failure in a specific type of protection system. In this type of voting scheme, three different protection systems are used. For example, using a distance protection system, a Directional Comparison Blocking (DCB) system, and a Permissive Overreaching Transfer Trip (POTT) system. In this type of setup if one protection system had a protection scheme failure, the voting scheme would protect against that system misoperating. The downside of this type of voting scheme implementation is increased complexity, time, and costs.

The previous two types of voting scheme implementations focused on a common mode of failure in a type of protection scheme. The voting scheme can be used to also protect against a common of failure in the hardware used in the protection systems. Again, this type of protection is relevant only when the voting scheme is armed and three relay systems are used for protection. To protect against a common mode of failure in hardware, protection relays from different manufacturers must be used. If all the voting scheme protection relays were the same device made from the same manufacturer, all the voting scheme devices would fail together if a hardware failure existed in that specific device. Using three relays, all from different manufacturers or a combination of manufacturers, would enable the voting scheme to protect against a common mode of failure in one manufacturer's hardware.

The last consideration of a voting scheme implementation is protection system operation during times when the voting scheme is disarmed. When voting is disarmed, the protection on the line returns to the original control design. Therefore, it is expected that the original primary protection system will activate and trip the circuit breaker directly during fault conditions. The remaining two protection systems have the potential to also be activated during the disarmed phase. During these times, if either or both of these systems were activated and allowed to trip the circuit breaker, redundant protection systems would exist at a critical location. Redundancy aims at protecting against the same types of failures mentioned above: common modes of failure in protection schemes and in hardware. However, with the various types of configurations possible with the voting scheme, redundancy may or may not be desired. If three identical protection systems are used in the voting scheme, redundancy could be acceptable when voting is disarmed because all three schemes have identical protection settings. If three different protection systems are used in the voting scheme, redundancy may want to be avoided because the different protection margins between the three systems may lead to an increased likelihood of misoperating from overreaching protection zones. For this implementation, having only the original primary protection scheme activated would be desired.

All these considerations for voting scheme implementations need to be taken into consideration for each individual critical location. All parties involved should decide these voting scheme implementation choices collectively.

The purpose of this thesis was to provide a working implementation of an adaptive voting scheme. All voting scheme implementations performed in this thesis used three identical protection systems and enabled redundancy when the voting scheme was disarmed. Two versions of this adaptive voting scheme implementation were setup: the first used relays from the same manufacturer, and the second used devices from multiple manufacturers. All implementations were setup and tested, with the results discussed at the end of Chapter 3.

2.2 Tripping Logic of the Voting Scheme

Implementation of the voting scheme is the focus of this thesis. This chapter covers the details of all the devices, settings, and wiring required for a voting scheme to function. This section begins the discussion with the fundamental tripping logic of the voting scheme.

The three voting scheme digital relays must have their settings updated to perform as an adaptive voting scheme. To build the logic equations that these relays must use, the first step is to list the possible tripping events for the three relays. It is already known that the voting scheme, when armed, will only trip the circuit breaker if two or more relays have positive trip signals. Table 2-1 contains all of the possible tripping outcomes for the three voting scheme relays, and has a fourth column that represents the majority vote decision on tripping the circuit breaker or not.

Table 2-1. The tripping decisions of the voting scheme.

Relay 1 Trip	**Relay 2 Trip**	**Relay 3 Trip**	**Trip Circuit Breaker**
No	No	No	No
No	No	Yes	No
No	Yes	No	No
Yes	No	No	No
No	Yes	Yes	**Yes**
Yes	No	Yes	**Yes**
Yes	Yes	No	**Yes**
Yes	Yes	Yes	**Yes**

In a voting scheme, one relay is classified as the Master relay, and the other two are classified as slave relays. For the remaining of this chapter, Relay 1 will be set as Slave 1, Relay 2 will be set as Slave 2, and Relay 3 will be set as the Master relay. The Master relay is responsible for implementing the actual "voting" of the voting scheme, and can also be referred to as the "vote counter."

The master relay must have the trip signals of the slave relays, Slave 1 and Slave 2, input to it. Sending the slave relay trip signals to the Master relay can be performed using many different methods, but the method chosen will largely depend on the location of the voting scheme and the existing practices of the transmission line owner. Section 2.6 further discusses the available methods for communicating the slave relay trip signals to the Master relay.

The Master relay will implement the majority voting through a digital logic equation that uses its own trip signal and the two trip signals from the slaves. This logic equation will be part of the master relay's voting scheme trip equation, which will be discussed in more detail in Section 2.4. In order to build the logic equation for the majority vote, Table 2-1 is rewritten as a truth table where a "No" will equal zero, and a "Yes" will equal a one.

Table 2-2. Truth table of the voting scheme's tripping logic.

Slave 1 Trip	**Slave 2 Trip**	**Master Trip**	**Trip Circuit Breaker**
0	0	0	0
0	0	1	0
0	1	0	0
1	0	0	0
0	1	1	**1**
1	0	1	**1**
1	1	0	**1**
1	1	1	**1**

In Table 2-2**,** a zero represents a digital relay not tripping (does not have a positive trip signal), while a one represents a digital relay wanting to trip (does have a positive trip signal). In a real implementation, these digits represent the tripping bits to be sent from the slave relays to the Master relay. A slave's tripping signal equal to one represents the slave relay has tripped based on its settings and the voltage/current signals measured by the relay. A tripping bit equal to zero means the slave has not tripped. With the truth table for the voting scheme known, the logic equation for the Master relay can be constructed with the knowledge of logic gates and their operations. The logic diagram for the voting scheme's trip signal is shown in Figure 2-2.

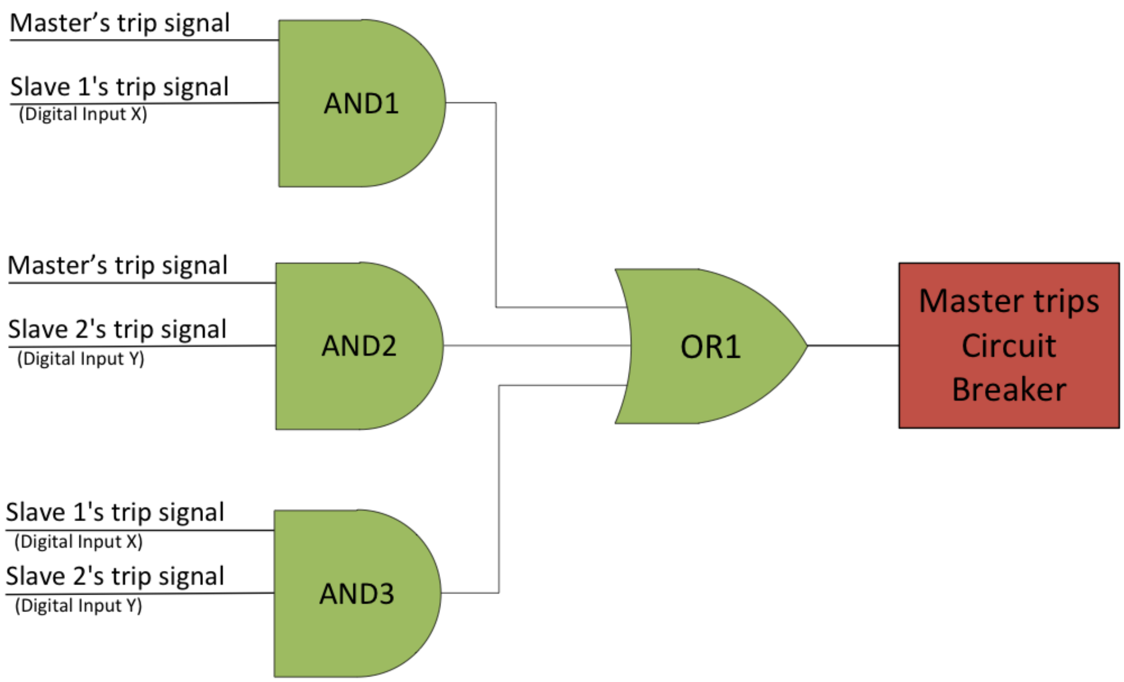

Figure 2-3. Logic diagram for the voting scheme tripping logic.

To implement the voting scheme, the trip signals from the two slave relays will be sent to the Master relay. The trip signals will be sent as digital inputs, and therefore the Master relay must be able to accept and process those digital inputs. In Figure 2-3, Digital Input X and Digital Input Y are the trip signals sent from Slave 1 and Slave 2, respectively. Slave 1 is configured so that its trip signal is masked to one of its own digital outputs. That digital output is sent to one of the Master relay’s digital input terminals. Slave 2 is configured just as Slave 1 was, but this slave will send its trip signal to a different digital input terminal on the Master relay. The third signal for the voting scheme is the Master relay’s trip signal. This signal is the Master relay’s original protection trip equation before the implementation of the voting scheme.

Installation of a working voting scheme requires that the Master relay implement the tripping logic in Figure 2-3. This will be possible by translating the logic diagram into a logic equation for the Master relay’s voting scheme trip setting.

$$
\begin{aligned}
Voting\ scheme\ trip = \ & (Master\ trip\ AND\ Slave\ 1\ trip) \\
& OR \\
& (Master\ trip\ AND\ Slave\ 2\ trip) \\
& OR \\
& (Slave\ 1\ trip\ AND\ Slave\ 2\ trip)
\end{aligned} \tag{2.1}
$$

Equation (2.1) can be simplified using standard logic equation notation for gates.[1] The input names can also be given acronyms to shorten the equation: Mt = master trip, $S1t$ = Slave 1 trip, and $S2t$ = Slave 2 trip. Equation (2.2) is the simplified voting scheme trip equation.

$$Voting\ scheme\ trip = (Mt * S1t) + (Mt * S2t) + (S1t * S2t) \tag{2.2}$$

Because the voting scheme is implemented with logic equations that only require contact digital inputs and outputs, most digital relays that are used in the field today can be used in the voting scheme. In the laboratory implementation discussed in Chapter 3, a digital relay manufactured in 2004 was used as the Master relay in the voting scheme.

As all three relays of the voting scheme are identically set, the original trip equations for all three relays will be exactly the same. It is necessary to alter these original trip equations to create the voting scheme among the three digital relays. The next three sections of this chapter provide the setting change details.

2.3 The Arming Signal

The logic equation of Section 2.2 depicts a voting scheme that is always turned on, or always armed. For the voting scheme to be an adaptive protection scheme, the voting scheme must be turned on (armed) and off (disarmed) based on the existing state of the system. The system state will be determined by the previously mentioned PDC

[1] * is an AND gate; + is an OR gate; and ! is a NOT gate.

and PMUs. Section 2.7 and 2.8 will cover the details of the voting scheme PMUs and PDC. The voting scheme will be armed when the system is found to be in a stressful situation, and will be disarmed during safe system conditions. The beginning of this chapter gives reasoning for this operation of the voting scheme. To transform the voting scheme into an adaptive scheme, a signal called the "arming signal" will be implemented. The arming signal will tell the voting scheme relays the real-time state of the system, with the system being classified as either stressed or safe. In an actual implementation, the arming signal will be a single digital bit. If the system is classified as safe, the arming signal will be a `0`. Alternatively, the arming signal will be a `1` if the system is classified as stressed. The arming signal will need to be sent over some communication protocol to the voting scheme relays. The communication protocol options for the arming signal will be discussed in more detail in Section 2.8.

The Master relay is the only device implementing the majority vote when the voting scheme is armed, therefore is the only relay that can actually trip the circuit breaker(s) of the transmission line. Clearly, the Master relay must receive the arming signal so that the relay knows when to implement the vote counting task.

For the implementations performed in this thesis, when the voting scheme is disarmed the protection scheme will have three redundant relays. During the disarmed stage, each redundant relay is an exact replica of the primary relay, which is the Master relay of the voting scheme. To ensure that the redundant relays (the Slave 1 and Slave 2 relays) completely mimic the primary relay during disarmed times, these slave relays must also have the arming signal sent to them. This will allow the slave relays to have all the same control actions as the Master relay, including tripping the circuit breaker, when the voting scheme is disarmed.

The arming signal operation for the implementations in this thesis can be summarized as follows. When the arming signal is `0`, the voting scheme is disarmed. The Master and slave relays will then all operate as identical, redundant protection relays. Tripping the circuit breaker will be possible with any of the redundant relays, and no voting will be performed before tripping. When the arming signal is `1`, the voting scheme is armed. The Master relay is then the only relay that can trip the circuit breaker, and tripping can only happen when the majority of the voting scheme relays have positive trip signals.

It should be mentioned that if redundant relaying is not desired for normal operation (voting scheme is disarmed), the voting scheme slave relays can be set to perform no protective actions during that disarm time. The benefit of the adaptive voting scheme is that any customization can be made to match the voting scheme to existing protection practices, as discussed in Section 2.1.

2.4 Master Relay Logic

Implementing a voting scheme requires the Master relay's logic equation (equation 2.2) to include the arming signal. With redundant slave relays, they will also receive the arming signal and therefore the settings of those relays must be updated accordingly. To create the new logic equations for the Master and slave relays, new truth tables are created that include the arming signal. This section describes the Master relay logic only; Section 2.5 provides the slave relay logic.

Table 2-3 is the truth table for the Master relay with the arming signal included. This table is only for the Master relay, and represents all the possible events the Master could encounter with the arming signal on (equal to one) and off (equal to zero). If the arming signal is a zero, the voting scheme is disarmed. If the arming signal is a one, the voting scheme is armed.

Table 2-3. Truth table for Master relay with arming signal.

Voting Scheme Status	Arming Signal	Slave 1 Trip	Slave 2 Trip	Master relay Trip	Breaker Trip Signal*
Disarmed	0	Master not influenced	Master not influenced	0	0
	0	Master not influenced	Master not influenced	1	**1**
Armed	1	0	0	0	0
	1	0	0	1	0
	1	0	1	0	0
	1	1	0	0	0
	1	0	1	1	**1**
	1	1	0	1	**1**
	1	1	1	0	**1**
	1	1	1	1	**1**

***0 = No Trip**

***1 = Trip**

The design of the voting scheme can be seen in the Master relay's truth table. With the voting scheme disarmed, the Master and slave relationship among the voting scheme relays no longer applies; the original protection scheme becomes active and will consist of three redundant relays. When the scheme is disarmed, the Master relay's trip functionality will not be influenced by the input trip signals from the slave relays. Therefore, if any of the three relays have a positive trip signal, it will send the trip signal directly to the circuit breaker telling it to open. This is shown in the first two rows of Table 2-3. The Master relay will trip the circuit breaker only if it has a positive trip signal itself; the Master is blinded from the actions of the slave relays.

The truth table of Table 2-3 is used to construct the trip logic diagram and equation for the Master relay. Figure 2-4 shows the Master relay's logic diagram with the arming signal included.

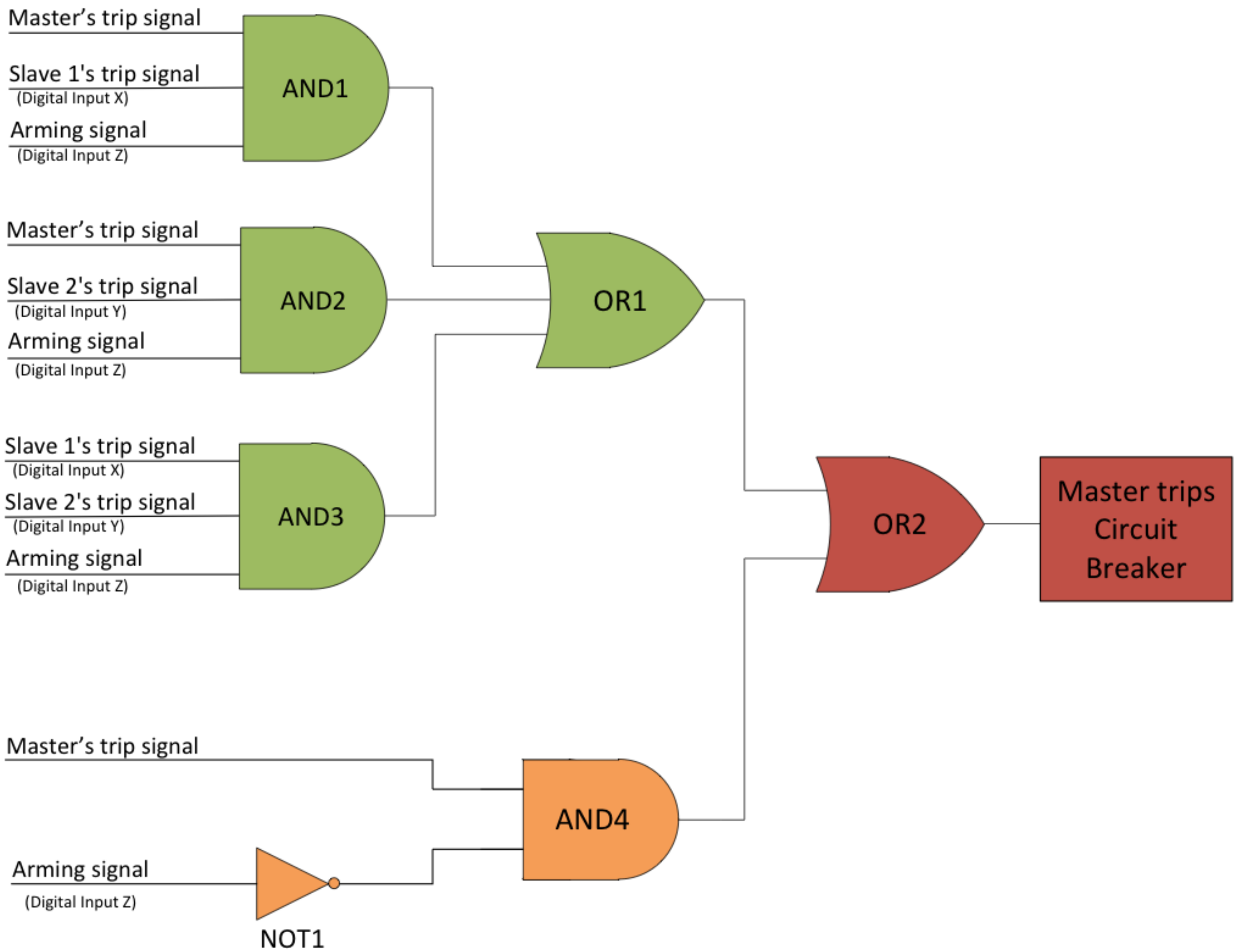

Figure 2-4. Logic diagram for the Master relay's tripping logic.

The logic going into the OR1 gate is the same logic from Figure 2-3 with the addition of the arming signal. This logic section, highlighted in green, represents the actual voting performed by the Master relay when the voting scheme is armed. The arming signal is the third digital input to the Master relay, and can be set to any available input on the Master relay. When the arming signal is 1, that digital input wired as the arming signal in the Master relay will be 1. In order for any trip to occur with the voting scheme armed, the arming signal must be a one and at least two relay trip signals must be one. The two slave relays will have their digital trip signals sent to the Master relay, digital inputs X and Y in Figure 2-4. Again, these digital inputs can be wired to the Master relay at any available input terminals. Whichever input terminals are chosen for the voting scheme, those are the input signals that must be used in the Master relay's trip equation. The third trip signal for the armed voting scheme logic is the Master relay's trip signal. This signal is the Master relay's original protection trip equation before implementation of the voting scheme. Just as in Figure 2-3, the three AND gates AND1, AND2, AND3 are the elements that will cause a trip only if a true majority vote has occurred. Each of those AND gates will only output a positive signal if all three inputs to the gate are positive, or equal to one. If any AND gate has three positive inputs, then the arming signal is asserted and two of the voting scheme relays have asserted trip signals. Therefore the Master relay should trip the circuit breaker.

The three AND gates are then sent to the OR1 gate, which will output a positive signal if any positive signals are input to the gate. This operation is correct for the voting scheme because any combination of two relays tripping will need to trip the circuit breaker. The OR2 gate is the final gate, and it will output a positive signal if any positive signals are input to the gate. If the OR2 gate outputs a positive signal, the Master relay will trip the circuit breaker.

The logic going into the AND4 gate represents conditions when the voting scheme is disarmed. Sending the arming signal, digital input Z in Figure 2-4, through a NOT gate will send the opposite signal of the arming signal to the AND4 gate. This NOT gate is responsible for ensuring that the Master relay function as a single relay when the voting scheme is disarmed. If the arming signal is a zero, NOT1 will send a one to the AND4 gate. At this same time, the arming signal inputs going to AND1, AND2, AND3 for the voting logic will all be zero, and therefore none of those AND gates could output a positive signal. Therefore, when the arming signal is zero, no voting can take place among the relays. The last piece of the disarm logic is to take the original trip equation of the Master relay and send the trip signal to AND4. With the voting scheme disarmed, the Master relay will therefore protect the transmission line as a single relay, using the original trip logic of the Master relay before the voting scheme was implemented.

The Master relay's logic diagram in Figure 2-4 must be translated into an equation, which will then be the actual setting for the element of the Master relay that will tell the circuit breaker to open. For the purposes of this thesis, this setting will be defined as "Master relay CB TRIP".

$$
\begin{aligned}
Master\ relay\ CB\ TRIP = {} & (Master\ trip\ AND\ Slave\ 1\ trip\ AND\ Arming\ signal) \\
& OR \\
& (Master\ trip\ AND\ Slave\ 2\ trip\ AND\ Arming\ signal) \\
& OR \\
& (Slave\ 1\ trip\ AND\ Slave\ 2\ trip\ AND\ Arming\ signal) \\
& OR \\
& (Master\ trip\ AND\ NOT(Arming\ signal)) \qquad (2.3)
\end{aligned}
$$

Equation (2.3) can be simplified using standard logic equation notation for gates. Equation (2.4) is the Master relay's simplified voting scheme trip equation, with the same acronyms from Section 2.2.

$$
\begin{aligned}
& Master\ relay\ CB\ TRIP = \\
& [(Mt * S1t * ARM) + (Mt * S2t * ARM) + (S1t * S2t * ARM)] + [Mt * !ARM] \qquad (2.4)
\end{aligned}
$$

The Master relay's trip logic here is not complete. The **Mt** element represents the Master relay's original trip equation before the voting scheme was implemented. Therefore, the **Mt** element could potentially be a long equation itself. That entire equation must be placed in equation (2.4) at every **Mt** location. For example, if the master relay's original trip equation was:

$$Mt = 50P1 + 50G1 + 51P1 + 51G1 + IN204 + IN205 \qquad (2.5)$$

Placing equation (2.5) into the equation (2.4) would create the following Master relay CB TRIP equation:

$$Master\ relay\ CB\ TRIP =$$
$$[(\{\mathbf{50P1+50G1+51P1+51G1+IN204+IN205}\} * S1t * ARM)$$
$$+ (\{\mathbf{50P1+50G1+51P1+51G1+IN204+IN205}\} * S2t * ARM)$$
$$+ (S1t * S2t * ARM)]$$
$$+[\{\mathbf{50P1+50G1+51P1+51G1+IN204+IN205}\} * !ARM] \quad (2.6)$$

If an aliasing feature is available in the Master relay, it will make it easier to set the Master relay's voting scheme trip equation. Extending on the previous example, assume the Master relay's original trip equation is still equation (2.5):

$$Mt = 50P1 + 50G1 + 51P1 + 51G1 + IN204 + IN205 \quad (2.5)$$

Instead of placing this entire original trip equation into Master relay CB TRIP equation, as done in equation (2.6), equation (2.5) would now be aliased to a custom setting element defined by a user. For example, assume the Master relay allows 50 custom setting elements, ranging from "CS1" to "CS49". Now, assuming that element CS49 is not used in the Master relay, CS49 would be set to equation (2.5):

$$CS49 = 50P1 + 50G1 + 51P1 + 51G1 + IN204 + IN205 \quad (2.7)$$

This would allow equation (2.6) to simplify down to equation (2.8):

$$Master\ relay\ CB\ TRIP =$$
$$[(CS49 * S1t * ARM) + (CS49 * S2t * ARM) + (S1t * S2t * ARM)] + [CS49 * !ARM] \quad (2.8)$$

The custom setting element allows for a simple, easy to read trip setting for the Master relay that may also help reduce typing in the wrong trip equation into the relay. Equation (2.8) represents the final version of the Master relay's voting scheme trip equation. This setting ultimately decides if the Master relay will trip the circuit breaker (or not) when the voting scheme is armed or disarmed.

2.5 Slave Relay Logic

The inclusion of the voting scheme may require alterations to the slave relays' original trip equations. The slave relays must be sent the arming signal if the slaves are to operate as redundant relays when the voting scheme is disarmed. Acting as redundant relays would mean the slave relays can trip the circuit breaker when the voting scheme is disarmed. However, if the Master relay should be the only relay to trip the circuit breaker, whether the voting scheme is armed or disarmed, then the slave relays will require no alterations to their original trip equations and will not need to receive the arming signal. In this case, the only requirement for the slave relays is that their digital trip signals be sent to the Master relay.

For the purposes of this thesis, it is assumed that the slave relays are to act as redundant relays when the voting scheme is disarmed. Therefore, the slave relays will be sent the arming signal and the settings of the two relays must be updated accordingly. These setting updates are the focus of this section.

To create the new logic equations for the voting scheme relays, a new truth table is created that includes the arming signal, similar to Table 2-3 for the Master relay's truth table. Table 2-4 is the truth table for the each slave relay with the arming signal included. This table is only for the slave relays, and represents all the possible events that would cause a slave relay to trip the circuit breaker of the line. If the arming signal is a zero, the voting scheme is disarmed. If the arming signal is a one, the voting scheme is armed.

Table 2-4. Truth table for the slave relays with arming signal.

Voting Scheme Status	**Arming Signal**	**Slave 1 (or Slave 2) Trip**	**Will Slave relay trip circuit breaker?***
Disarmed	0	0	0
	0	1	**1**
Armed	1	0	0
	1	1	0

***0 = No** ***1 = Yes**

It is important to note that the truth table for both slave relays, Slave 1 and Slave 2, are the same. The logic for both slave relays will be identical, and therefore Table 2-4 can be used for each slave relay.

The design of the voting scheme can be seen in the slave relay truth table. With the voting scheme disarmed, the Master and slave relationship among the voting scheme relays no longer applies; the original protection scheme become active and will consist of three redundant relays. When the scheme is disarmed, a slave relay will only trip the circuit breaker if it has a positive trip signal itself; a slave relay is blinded from the actions of the other slave relay and the Master relay.

The truth table of Table 2-4 is used to construct the trip logic diagram and equation for a slave relay. Figure 2-5 shows the logic diagram for Slave 1 and Slave 2 with the arming signal included for both.

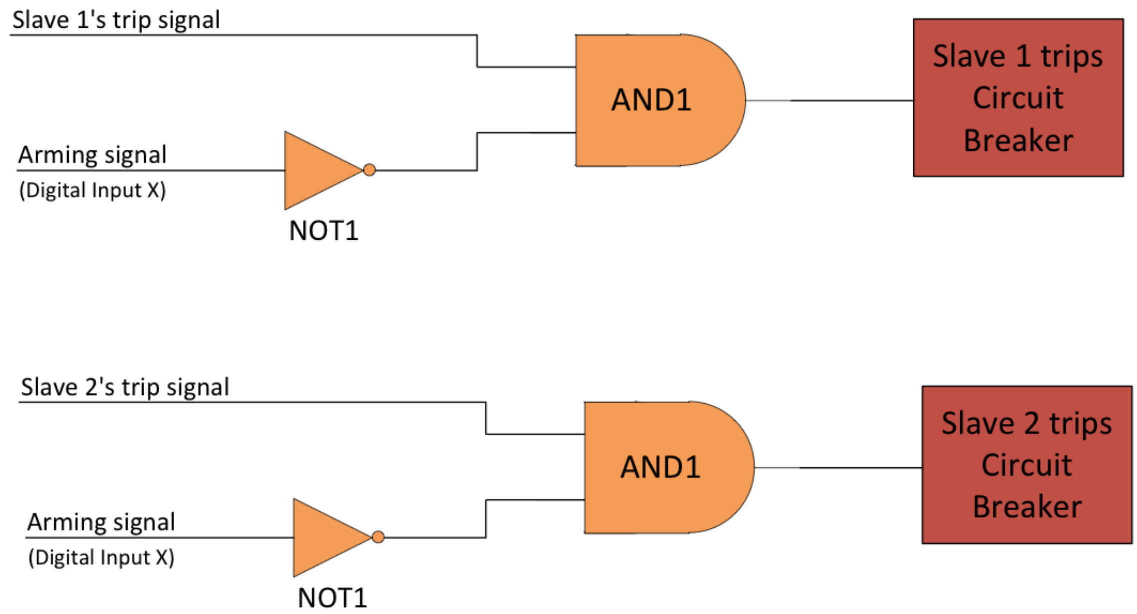

Figure 2-5. Logic diagram for tripping logic of the slave relays.

The logic diagram for the slave relays is less complex than the Master relay's logic because the slaves do not have to implementing the vote counting logic. Only the Master relay is responsible for implementing the vote counting logic. With the arming signal equal to zero, the Digital Input X going to each slave relay will be zero. Sending the arming signal through a NOT gate will create the opposite signal of the arming status. This NOT gate is responsible for ensuring how the slave relays operate when the scheme is armed or disarmed. If Digital Input X is a one, NOT1 will send a zero to the AND1 gate. With a zero sent to one input of the AND1 gate, the gate can never output a positive signal and therefore the slave relays will never send trip signals to the circuit breaker. Slave relays should operate in this exact way when the voting scheme is armed. That is, when the scheme is armed the slave relays will not be able to trip the circuit breaker. Only the Master relay can trip the circuit breaker when the voting scheme is armed. If Digital Input X is a zero, NOT1 will send a one to the AND1 gate. With this disarm logic, the slave relays will trip the circuit breaker whenever the arming signal is zero and their original trip logic equation goes positive. The original trip logic equations are represented by "Slave 1's trip signal" and "Slave 2's trip signal" in Figure 2-5.

The slave relay’s logic diagram in Figure 2-5 must be translated into an equation, which will then be the actual setting for the element of each slave relay that will tell the circuit breaker to open. For the purposes of this thesis, these settings will be defined as “Slave 1 CB TRIP” and “Slave 2 CB TRIP”.

$$Slave\ 1\ CB\ TRIP = Slave\ 1\ trip\ AND\ NOT\ Arming\ signal \tag{2.9}$$

$$Slave\ 2\ CB\ TRIP = Slave\ 2\ trip\ AND\ NOT\ Arming\ signal \tag{2.10}$$

Equation (2.9) can be simplified using standard logic equation notation for gates. Equation (2.11) and (2.12) are the simplified voting scheme trip equations for the slave relays.

$$Slave\ 1\ CB\ TRIP = S1t * !ARM \tag{2.11}$$

$$Slave\ 2\ CB\ TRIP = S2t * !ARM \tag{2.12}$$

The slave relay’s trip logic here is not complete. The **S1t** and **S2t** elements represent the slave relay’s original trip equations before the voting scheme was implemented. Therefore, these elements could potentially be long equations. The entire equations must be placed in equation (2.11) and (2.12) at every **S1t** and **S2t** location. Because all of the voting scheme relays are redundant relays, the equations for **Mt**, **S1t**, and **S2t** will all be the same. Using the same example in Section 2.4, the slave relay trip equations would be the same as the **M1t** example:

$$S1t = 50P1 + 50G1 + 51P1 + 51G1 + IN204 + IN205 \tag{2.13}$$

$$S2t = 50P1 + 50G1 + 51P1 + 51G1 + IN204 + IN205 \tag{2.14}$$

Placing equation (2.13) and (2.14) into equations (2.11) and (2.12), respectively, would create the following slave relay CB TRIP equations:

$$Slave\ 1\ CB\ TRIP = (\{\mathbf{50P1 + 50G1 + 51P1 + 51G1 + IN204 + IN205}\} * !ARM) \tag{2.15}$$

$$Slave\ 2\ CB\ TRIP = (\{\mathbf{50P1 + 50G1 + 51P1 + 51G1 + IN204 + IN205}\} * !ARM) \tag{2.16}$$

As mentioned in Section 2.4, it is recommended to use the aliasing feature if it is available on the slave relays. Extending on that same example, assume the slave relays also allow 50 custom setting elements, ranging from "CS1" to "CS49". Now, assuming that element CS49 is not used in either slave, CS49 in each relay would be set as:

$Slave$ 1:

$$CS49 = 50P1 + 50G1 + 51P1 + 51G1 + IN204 + IN205 \tag{2.17}$$

$Slave$ 2:

$$CS49 = 50P1 + 50G1 + 51P1 + 51G1 + IN204 + IN205 \tag{2.18}$$

This would allow equations (2.15) and (2.16) to simplify down to equations (2.19) and (2.20) respectively:

$$Slave\ 1\ CB\ TRIP = CS49 * !ARM \tag{2.19}$$

$$Slave\ 2\ CB\ TRIP = CS49 * !ARM \tag{2.20}$$

The custom setting elements allow for a simple, easy to read trip setting for the slave relays that may also help reduce typing the wrong trip equations into the relays.

Equations (2.19) and (2.20) represent the final versions of the voting scheme trip equations for Slave 1 and Slave 2. These settings ultimately decide if a slave relay will trip the circuit breaker (or not) when the voting scheme is disarmed, and will also prevent the slave relays from tripping the circuit breaker when the voting scheme is armed.

The only alterations to the slave relays for the voting scheme are the new settings of equation (2.19) and (2.20), and the original trip signals being sent to the Master relay. The original slave relay trip signals are the equations (2.17) and (2.18). The results of these equations must be sent to the Master relay. The next section will cover the possible communication methods that could be used to send these trip signals to the Master relay.

2.6 Trip Signal Communications

The digital trip signals from the slave relays can be sent to the Master relay in variety of ways because all of the voting scheme relays will be in the same control house, and likely will be on the same equipment rack. The chosen communication method will be based on the devices used in the voting scheme and the existing practices of the transmission owner.

Perhaps one of the easiest and quickest ways to send these digital signals to the Master relay is to hard-wire the signals into the relay's terminal blocks. This method would require little additional wire, and would only require that the signals be sent to available digital inputs on the Master relay.

Digital relays have a variety of ways to communicate with one another, and many relay vendors have their own proprietary protocols as well. Some examples that could be used include: serial cables, Ethernet cables, and fiber optics. Any of these communication methods could be used provided the voting scheme devices can use the protocols.

In the implementation of Chapter 4, a voting scheme was implemented with hard-wiring digital signals and with serial cable communications.

2.7 Offline Analysis

The arming signal plays an important role in the voting scheme. This signal is responsible for the voting scheme's qualification as an adaptive protection scheme. Using the arming signal to identify whether the system is stressed or safe, the relays will operate as a triple redundant protection scheme or operate as a voting scheme. The arming signal and digital relays that make up the voting scheme will adjust the protection of a critical transmission line to be biased towards security or dependability based on the state of the power system. The transmission line protection is biased towards security when the voting scheme is armed, while it is biased towards dependability when the voting scheme is disarmed.

The arming signal is the product of the PDC and PMUs that were discussed at the beginning of this chapter. The voting scheme is based on an idea to use data mining on a collection of power system phasor measurements to determine a small, specific set of phasor measurements that can solely describe the state of the power system. These specific phasor measurements could be voltage and current phasor magnitudes, angles, real values, and reactive values at locations throughout the power system. Phasor measurement units (PMUs) are the devices of choice to measure the specific set of phasors, given their ability to provide synchronized phasor measurements, called Synchrophasors. The specific set of measurements needed for the voting scheme will be measured throughout the system, possibly hundreds of miles apart. To compare these phasor measurements with each other and obtain a true state of the system, the measurements must be taken at the exact same moment in time. PMUs accomplish this requirement, as each PMU uses a common signal from the Global Positioning System (GPS) to provide synchronized measurements. PMUs from any point in the system will be synchronized with each other, that is, the measurements from all the PMUs will be time-stamped based on the GPS signal. For the voting scheme, a PMU will need to be placed at any system substation where any of the specific phasor measurements can be obtained. Because of the use of PMUs, a phasor data concentrator (PDC) must therefore be used to collect and process the PMU data. PMUs follow a standard protocol, IEEE C37.118, that defines how Synchrophasors are measured and communicated [9]. PDCs follow this same protocol to collect PMU measurements and distribute the data. The voting scheme PDC will collect the measurements that are streamed from the PMUs in real-time. Next, the PDC will continually process, in real-time, the PMU data to determine the state of the power system as either safe or stressed. It is important to restate that this safe or stressed classification of the power system is done with respect to a single critical transmission line. This classification is not representative of the entire power system, and is not to be used for any other elements in the power system [10].

Three questions are likely to arise from this description of the voting scheme's PDC:

- What process does the PDC use to determine the state of the system?
- How is the specific set of phasor measurements determined through data mining?
- How is a critical transmission line determined?

It must be acknowledged that there are some transmission lines in power systems that are critical to the operation of the grid. These lines are often referred to as the "backbone" of the system, and have heavy power flows through them to deliver electricity to large load centers [11]. These lines are where adaptive relaying could be very useful. The critical lines are determined through "an exhaustive set of simulations that include faults and hidden failures in protection relays" [10]. A disturbance severity ranking list is created from the simulation data and "hidden failures at the top of the list are potential location candidates for placing the adaptive [voting] scheme," as they are the transmission lines in a power system that most severely impact the grid if they are incorrectly tripped offline due to a protection hidden failure [10].

To determine the specific set of phasor measurements needed to determine the system state, a second round of computer simulations are performed using a modeled fault and hidden failure occurring at the chosen critical transmission line under various system operating conditions, followed by system load flow calculations. If the load flow converges for the operating conditions, fault, and hidden failure, the system is classified as "safe". If the load flow does not converge for any condition, the system is classified as "stressed". The last step is to take all of the system operating conditions (voltages, currents, etc.) for those contingencies where the system is classified as "stressed" and run the data through the data mining Decision Trees (DTs). This process will comb through all the data and determine patterns among the data. When a DT is trimmed down to an acceptable level, it will provide those phasor measurements that are needed to determine the state of the system. For further details on the offline analysis supporting the science of adaptive relay voting schemes, consult [10].

2.8 The Voting Scheme PDC

2.8.1 Decision Tree Program

As it turns out, not only will the final Decision Tree (DT) provide the specific phasor measurements needed (and thus the locations to place PMUs), it also provides the analysis that the PDC must perform on the PMU data to determine, in real-time, the state of the system. A Decision Tree example is shown in Figure 2-6.

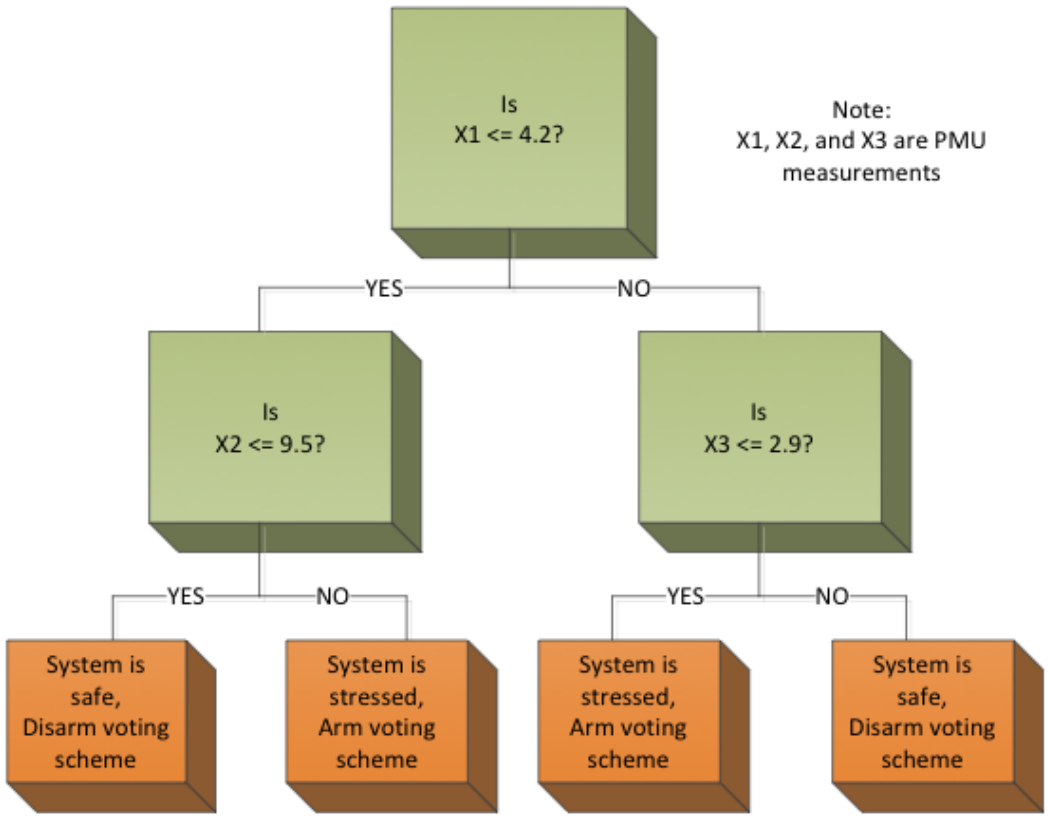

Figure 2-6. Decision Tree example for the voting scheme.

This example shows the required voting scheme phasor measurements listed in each large green box; these boxes are called splitting nodes. The values X1, X2, and X3 are the PMU measurements needed. It is important to note that this tree serves only as an example, and trees created for real systems may be of different sizes and configurations. But for any voting scheme DT, the splitting nodes will always contain the PMU measurements needed for the voting scheme. A PMU will need to be placed at any system substation where any of the specific phasor measurements can be measured.

The voting scheme's PDC must be programmed to process the PMU data through a DT like the example above. The PDC will collect all the PMU measurements for the tree, and will work down the tree comparing the specified measurement to its threshold at any node it comes to. When the PDC's program reaches a node at the last level, defined as a terminal node, the state of the system will be known. The PDC will then update a pre-defined bit to a zero if the system is safe or a one if the system is stressed. Once that bit is updated, the PDC will perform its last task by wrapping that bit into the arming signal and sending it to the voting scheme relays.

Referring back to the DT example in Figure 2-6, it is possible to rewrite the tree in programming terms for implementation into a PDC.

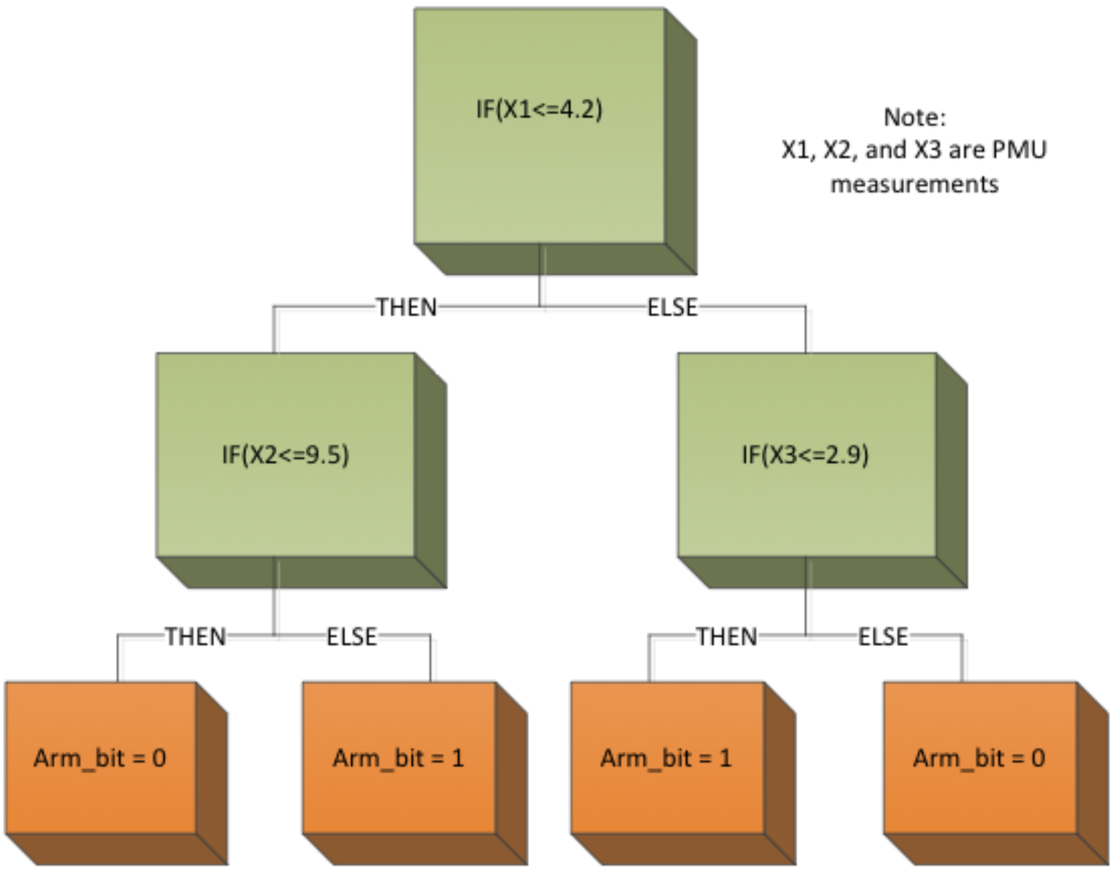

Figure 2-7. Decision Tree example with programming terms.

The Decision Tree in Figure 2-7 can be translated into an if-else programming code statement:

```
IF(X1 <= 4.2)
{       IF(X2 <= 9.5)
        {       Arm_bit = 0;
        }
        ELSE
        {       Arm_bit = 1;
        }
        }
ELSE
{       IF(X3 <= 2.9)
        {       Arm_bit = 1;
        }
        ELSE
        {       Arm_bit = 0;
        }
}
END
```

The PDC program above is a custom program for the voting scheme. A problem arises from this in that some PDC vendors do not support custom applications. In the event that a PDC used in a voting scheme does not support this custom program, one solution would be to use a system control center computer to perform the program. In this setup, it is possible for the voting scheme PDC to be part of the computer itself by using a software based PDC. If the PDC is software-based or a physical device PDC, the PDC must send the PMU data to the voting scheme program on the computer. This solution, however, may require more latency in arming or disarming the voting scheme as the arming signal will have to be sent from the control center computer to the voting scheme relays.

An optimal solution for the voting scheme is to use a PDC that can collect PMU data and process the data in real-time using custom applications. A PDC with this ability could be located at the same critical location that the voting scheme is implemented at, which would significantly minimize the latency in arming of disarming the voting scheme.

An additional section of code must come before this decision tree program in the PDC. Because the PMUs are sending phasor angles, the angles must be compared to a reference angle. As part of the offline analysis, one substation in the system will be defined as the reference bus. Therefore, a PMU must be placed at this substation to measure the bus angle at the substation. In order to use any of the other PMU angles in the PDC program, all the angles must be referenced to this reference bus angle. This is completed by subtracting the reference angle from each PMU measured angle. The PDC program must first perform these subtractions so that any PMU angle can be used in the Decision Tree, if an angle is required at a splitting node. As an example, assume there are six PMUs for the voting scheme, all measuring a total of six phasor angles with one of the six being the reference angle. The PDC program would start by subtracting the reference angle from all the other angles. The code statement below would begin the PDC program:

```
Angle_ref_substation = PMU1.angle – PMU1.angle;
Angle_substation_2 = PMU2.angle – PMU1.angle;
Angle_substation_3 = PMU3.angle – PMU1.angle;
Angle_substation_4 = PMU4.angle – PMU1.angle;
Angle_substation_5 = PMU5.angle – PMU1.angle;
Angle_substation_6 = PMU6.angle – PMU1.angle;
```

The new referenced PMU angles can now be used in the voting scheme's Decision Tree.

2.8.2 Arming Signal Communications

There are some additional details that should be addressed with the voting scheme's arming signal. There are many methods available to send the digital arming signal to the voting scheme relays. However, the choice of PDC, setup of the PDC program, and existing practices will determine which methods could be used for a voting scheme.

A PDC's primary role is to collect, align, and output PMU data. However, the voting scheme must process the PMU data and output the arming signal. An optimal PDC for the voting scheme would perform that processing directly and output the arming signal directly to the voting scheme relays as a digital signal. However, not all PDCs will be able to perform these tasks independently.

It has already been mentioned the need for a computer to perform the Decision Tree program if a voting scheme PDC cannot process PMU data directly. For this setup, the computer program will determine the status of the system, and therefore determines the appropriate arming signal to send to the digital relays. Once the computer program decides the appropriate arming signal, a process must start to actually send that arming signal to the relays. The location of this computer would then help narrow down the possible methods to use. If the computer is located at a system control center, the existing methods used by the control center to communicate with substation equipment could be used with the voting scheme computer. Examples of the existing methods to communicate with digital relays from a control center are: Telnet links, fiber optic networks, and Input/Output modules. The addition of the voting scheme arming signal to a control center's existing methods should not create any significant burden, as it is just a single bit being sent one-way to the digital relays continuously. If the computer is located at the same substation control house as the voting scheme relays, direct links between the PDC and relays may be possible. These direct links could be serial cable communications, hard wiring the arming signal with cable, Telnet communications, or vendor patented protocols. The method chosen here, again, depends on features that the PDC and digital relays have.

If a voting scheme PDC that can directly process the PMU data directly is used, all of the same possibilities apply to it as with the computer-PDC option. If the PDC is located in the same substation control house as the voting scheme relays, the same direct links mentioned earlier could be used: serial cables, hard-wiring with small gauge cable, Telnet communications, or vendor patented protocols. If the PDC is located in a control center, any of the existing methods used to communicate with substation equipment could be employed for the voting scheme.

The voting scheme's arming signal should always be sent to the digital relays, meaning the PDC/computer must be processing the PMU data, updating the arming signal, and sending the signal to the relays constantly. This is the adaptive feature of the voting scheme, in that the scheme will always be observing the prevailing conditions of the power system and then arming or disarming accordingly.

However, if arming signal communications are lost, the PDC fails, or some other event happens that causes the arming signal to stop being sent to the voting relays, the voting scheme relays will simply believe the arming signal to be zero. The relays will then operate as a triple redundant protection scheme, and therefore the critical transmission will continue to be protected as designed without the voting scheme. To prevent the arming signal from potentially arming and disarming the voting scheme at fast intervals, a timer may be added to the PDC. Once an arming signal decision is made, this timer could keep that decision active for a predefined amount of time. This would prevent the voting scheme from arming and disarming frequently. This timing feature would need to be explored further, and listed in the future work section in Chapter 4.

Another event that could take place is the incorrect arming or disarming of the voting scheme. This event could happen for a couple of reasons. Incorrect wirings or device settings could cause the arming signal bit to be viewed by the relays as opposite of the intended value. The digital relays would then arm the voting scheme when it should be disarmed, and disarm the scheme when it should be armed. This event could also happen at the PDC's Decision Tree program. The Decisions Tress in [10] had misclassification rates of approximately 1%. A misclassification means that the PDC program's Decision Tree incorrectly classified the system as being safe or stressed. The digital relays would then arm or disarm the voting scheme opposite of what is desired for the prevailing system conditions. It should be noted that this 1% misclassification rate does not apply to all DTs, and that this misclassification rate increases as the system departs from the assumptions in the model used for the simulations. To avoid the misclassification rate increasing, new Decision Trees must be made when the power system changes significantly, such as the seasonal loads or the addition of a new EHV transmission line [10].

For any arming signal problems, what are the consequences if the voting scheme is incorrectly armed or disarmed? There are two possible events that could occur:

1) The voting scheme is disarmed when it should be armed, as the true system state is "stressed" and a bias towards security is desired.

When the voting scheme is disarmed, the protection scheme at the critical line will return to its original design, as a triple redundant protection scheme. Therefore in this case, if the voting scheme is incorrectly disarmed, the protection scheme returns to the normal protection practices used on the system.

2) The voting scheme is armed when it should be disarmed, as the true system state is "safe" and a bias towards dependability is desired.

When the voting scheme is armed, the protection scheme at the critical line will be voting for a trip and be biased towards security. To increase security of system protection, a common practice is to set protection schemes for continuous trip voting, regardless of the state of the system. Therefore an incorrect arming of the voting scheme will cause the protection scheme to operate as this normal protection practice.

Chapter 3 – Laboratory Implementation of the Adaptive Voting Scheme

Every transmission owner and utility operates a unique power system, has their own existing engineering practices, and has their own unique blend of equipment in the field. Because of this, the adaptive voting scheme should have the ability to be implemented in a number of ways using various combinations of system equipment. In addition to this, widespread acceptance of the voting scheme would become more of a reality if the scheme could be implemented on today's digital relays that already exist in the grids throughout the world. These traits were the motivation of the various voting scheme implementations of this chapter. This chapter discusses the different implementations of the voting scheme that were setup and tested, detailing all of the devices, wiring, and settings used. The tests performed and the results for each implementation are also presented in this chapter. All voting scheme implementations and testing were performed at Virginia Tech's Center for Energy Engineering.

3.1 Single Manufacturer Implementation

The first voting scheme implementation was done with three identical relays all from the same manufacturer. The motivation for this setup was: proof of concept of the voting scheme; and the fact that some transmission owners only use one manufacturer for all of their digital relays and control equipment. Section 3.3 contains all the results for the single manufacturer implementation tests.

3.1.1 Digital Relays

The three digital relays used in this voting scheme setup were all SEL-421 Protection, Automation, and Control System digital relays from Schweitzer Engineering Laboratories (SEL). The SEL-421 digital relay is an all-in-one relay package for transmission line protection using distance, overcurrent, breaker failure, and many other protective functions [12]. The SEL-421 relay can be used for the Master and slave voting scheme relays as each SEL-421 can receive up to 7 digital input signals, can output 8 digital signals, and can have custom logic equations used for its setting elements.

3.1.2 Wiring the Slave Trip Signals

One of the SEL-421 relays is chosen as the Master relay. The other two SEL-421 relays are therefore the slave relays of the voting scheme. The slave relays must have their original trig signals sent to the Master relay. Chapter 2 discussed the possible methods for sending the slave trip signals to the Master relay. The single manufacturer implementation performed in this section tested two of the methods mentioned: hard-wiring the signals to the Master relay's digital input terminals; and serial cable communications between SEL relays using SEL's Mirrored Bits® Communications protocol. Testing was performed with the voting scheme using both of these methods, and the testing results will be detailed in Section 3.3.

Schweitzer's Mirrored Bits® Communications protocol is a custom protocol created by SEL that allows relay-to-relay logic communication among SEL digital relays. Because the voting scheme digital relays would most likely be implemented in the same substation control house in a real power system, a cable could directly connect the SEL relays together and then allow communications using the Mirrored Bits. This communications protocol was tested with the voting scheme because of its low cost, ease of setup, and its ability to send digital signals between SEL relays [14].

When using the hard-wired method, it is necessary to have a power source that can drive the digital trip signals from the slave relays to the Master relay. This source is usually a DC source, but some digital relays have the ability to send contact outputs using an AC power supply. For the implementations performed in this chapter, a DC power supply was used to drive the digital trip signals of the voting scheme. The primary motivation for this is the knowledge that most substation control houses have a DC battery bank used to drive other contacts between substation equipment.

3.1.3 The PDC

For all the voting scheme implementations of this thesis, the PDC used was the SEL-3378 Synchrophasor Vector Processor. The SEL-3378 is an ideal PDC for the voting scheme. The PDC is a physical device that is designed and hardened for installation at a power system substation. This PDC can collect data from up to 20 PMUs [15]. This is more than enough PMUs for the voting scheme, as reference [10] found that a total of seven PMUs would accurately determine the state of a particular system. It can be noted that the more PMUs used in a system, the more accurate the state determination process will be.

After the SEL-3378 collects PMU data, it can also process that data in real-time, with custom programs created by a user [15]. With this ability and the fact that the device is substation hardened, the SEL-3378 could be located in the same substation control house as the voting scheme digital relays. This minimizes the latency when sending the arming signal from the PDC to the relays.

The SEL-3378 is capable of two types of output signals. Since the 3378 is a PDC, it can output C37.118 synchrophasor messages containing the data from all the PMU inputs. The second type of output from the SEL-3378 is the SEL Fast Operate Command. SEL Fast Operate commands Commands are sent from the SEL-3378 to "set, clear, and pulse 32 remote bits per external device and generate up to eight open and close circuit breaker commands per external device" [15]. The Fast Operate Commands can be sent from the 3378 over a serial or Ethernet connected digital relay.

Because the voting scheme slave relays used in this thesis did not have PMU functionality enabled, the SEL Fast Operate Commands were used to send the arming signal from the 3378 to all three voting scheme relays. Each voting scheme implementation in Section 3.3 will provide more details about the implementation of the Fast Operate Commands using the SEL-3378.

3.1.4 The PMU

All of the voting scheme implementations of this chapter used a single PMU. A SEL-421 digital relay was used as the single PMU in all the voting scheme implementations of this chapter. The SEL-421 can be configured as a dual-use relay, meaning the relay will perform system protection function and/or phasor measurement functions. For the purpose of the voting scheme implementations, the SEL-421 used as the PMU was configured to perform only as a phasor measurement unit. The SEL-421 device has two three phase voltage inputs and two three phase current inputs [12]. Together, this allows an SEL-421 to output a total of 16 voltage and current phasors – phases A, B, C and positive sequence phasors for each input. This is an acceptable amount of phasors to test the voting scheme arming feature using the PDC.

The SEL-421 used as the voting scheme PMU is the same model as the SEL-421s used as voting scheme relays in the implementations. See Appendix A for the part number and firmware version of this device and all devices used in this thesis.

To provide the SEL-421 PMU with voltage and current signals, the SEL Relay Test System (SEL-RTS) was used. This system is comprised of the SEL Adaptive Multichannel Source (SEL-AMS) and the SEL-5401 Test System Software (SEL-5401). This system can be used as a three-phase power source for SEL digital relays. The system will send low-level analog and digital signals to SEL digital relays, allowing for quick and simple tests to be performed on the relays [16]. There is no difference between using the SEL-RTS or an actual three-phase variac to provide signals to the relays under test, other than the convenience when working with the SEL-RTS.

An Arbiter 1094B GPS Substation Clock was used to provide the GPS signal to the voting scheme PMU. The GPS signal sent to the PMU from the 1094B was in IRIG-B format.

Appendix A contains the part numbers and firmware versions of the substation clock and the PMU.

3.2 Multiple Manufacturer Implementation

The second voting scheme implementation was done with two digital relays from SEL and one digital relay from General Electric (GE). The motivation for this setup was: proof of concept of the voting scheme; and that using multiple manufacturers aids in protecting again a common mode of failure in a single manufacturer's equipment. Section 3.3 contains all the results for the multiple manufacturer implementation tests.

The two SEL digital relays used in this voting scheme setup were again SEL-421 digital relays. The SEL-421s used in this implementation were two of the SEL-421s used described in Section 3.1.

The third digital relay for this implementation was the F60 Feeder Management Relay from GE. The F60 digital relay is another all-in-one relay package for feeder protection using overcurrent, breaker failure, overvoltage/undervoltage and many other protective functions. The F60 relay can be used as the Master or as the slave in the voting scheme as each F60 relay can receive multiple digital input signals, can output multiple digital signals, and can have custom logic equations used for its setting elements [18].

For the multiple manufacturer implementation, the GE F60 relay was set as the Master relay. The two SEL-421 relays are therefore the slave relays of the voting scheme. The slave relays must have their original trig signals sent to the Master relay. Chapter 2 discussed the possible methods for sending the slave trip signals to the Master relay. The multiple manufacturer implementation performed in this section tested one of those methods, which was hard-wiring the signals to the Master relay's digital input terminals. Testing was performed with the voting scheme using this method, and the testing results will be detailed in Section 3.3.

As was done in the single manufacturer implementation of Section 3.1, a DC power supply was used to drive the digital trip signals of the voting scheme. The primary motivation for this is the knowledge that most substation control houses already have a DC battery bank used to drive other contacts between substation equipment.

With the use of digital relays from GE and SEL, the SEL Mirrored Bits Communication protocol could no longer be used to communicate the trip signals. That protocol is only for transferring data between two SEL digital relays. Communication between relays of different manufacturers is limited, as most communication protocols created by manufacturers work only with each manufacturers own relays. Hard-wiring digital signals is a low-cost and effective option for communicating digital contacts between relays of different manufacturers.

The PMU, PDC, and GPS substation clock were the same as those used in the single manufacturer voting scheme implementation.

3.3 Implementation Tests and Results

For all the voting scheme implementations in this chapter, the same laboratory setup was used with certain changes made between each implementation. Figure 3-1 shows the generic laboratory setup used throughout this chapter.

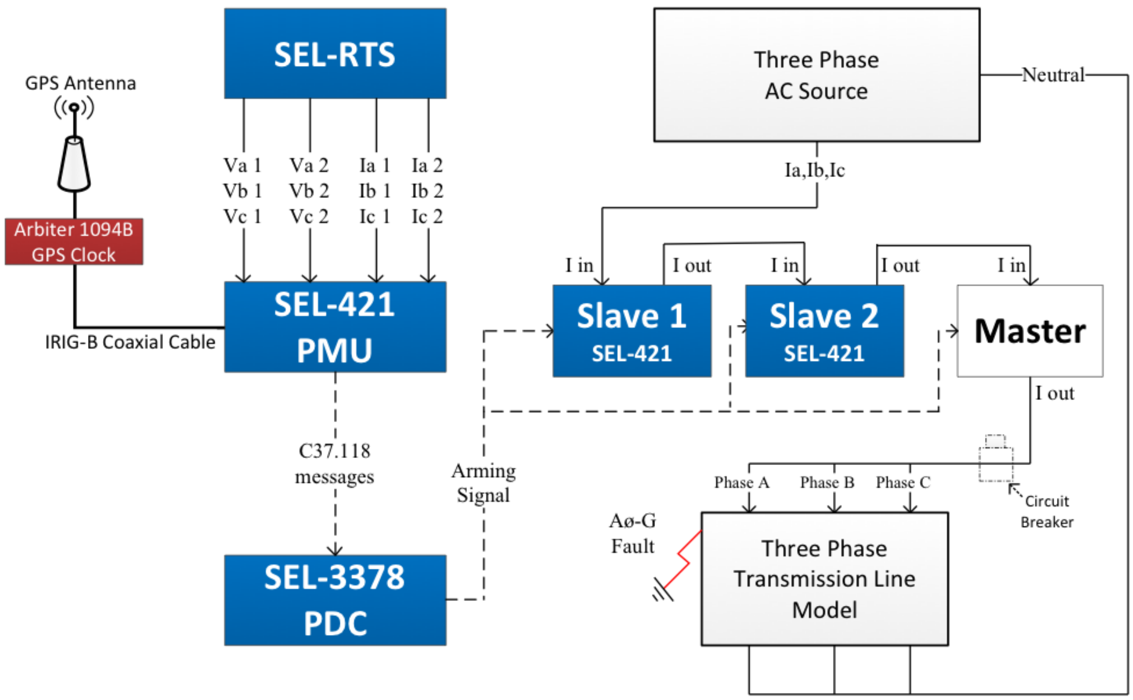

Figure 3-1. Laboratory setup for the voting scheme implementations.

Throughout this chapter, Figure 3-1 will reproduced with the changes made for each voting scheme implementation. The changes involve the variations discussed in the previous two sections of this chapter:

- Two voting scheme operations (redundant slaves, non-redundant slaves)
- Two Master relay devices (SEL-421, GE F60)
- Two trip signal communications (hard-wired, SEL Mirrored Bits)

Using the standard setup of Figure 3-1, the following procedure was performed to test each voting scheme implementation for correct operation:

1) The SEL-3378 was configured to perform the small Decision Tree in Figure 3-2.

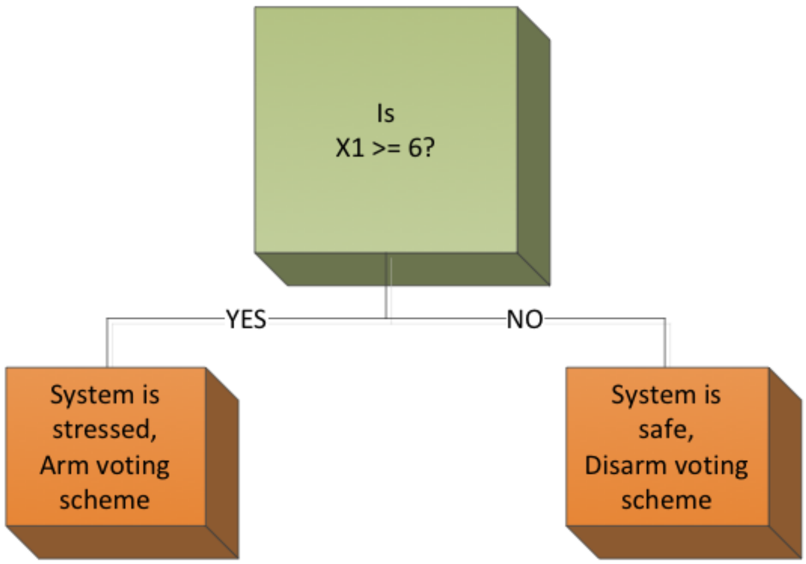

Figure 3-2. Decision Tree for the SEL-3378 during voting scheme testing.

The DT in Figure 3-2 was implemented in the SEL-3378 by creating an If-Else code statement based on the DT. That If-Else statement is shown below.

```
IF(X1 >= 6)
{       Arming_bit = 1;
}
ELSE
{       Arming_bit = 0;
}
END
```

This If-Else statement is a representation of the code used in the SEL-3378. Appendix B contains the actual SEL-3378 code and settings used for the voting scheme implementations.

The X1 phasor measurement was arbitrarily set as the phase B current magnitude going to the X terminal of the SEL-421 PMU. This phasor was randomly chosen from the available phasors from the SEL-421 PMU.

The SEL-3378 PDC continually processes the incoming PMU data (measurement X1) from the single SEL-421 PMU, runs the data through the simple DT (Figure 3-2) to determine the appropriate arming bit, and sends the arming bit to the voting scheme relays via the arming signal. Specifically, the PDC will process the PMU data into raw measurements, determine if the Terminal X phase B current magnitude is either less than or greater than/equal to 6 amps, set the arming bit to the appropriate value (0 or 1) based on the current magnitude, and output the arming signal to the voting scheme relays.

2) The SEL-421 device used as the PMU was set to measure voltage and current signals from the SEL-RTS. The SEL-RTS was used because of the ability of a user to set the level of the voltage and current signals as desired. This allows a user to manipulate the data seen by the PMU, and therefore the PDC because the PMU is set to send its Synchrophasors to the SEL-3378 via the IEEE C37.118 protocol.

By being able to manipulate the voltage and current signals seen by the PDC from the PMU, the arming and disarming of the voting scheme is easily controlled for the tests. With the SEL-3378 PDC using the DT in Figure 3-2, the SEL-RTS is set to send 5 or 7 Amps to the SEL-421 PMU's Terminal X phase B current input channel. When the SEL-RTS is set to send 5 Amps, the system is simulated to be safe and therefore causes the PDC to disarm the voting scheme by setting the arming bit equal to 0. When the SEL-RTS is set to send 7 Amps, the system is simulated to be stressed and therefore causes the PDC to arm the voting scheme by setting the arming bit equal to 1.

Appendix C contains the actual settings used for the SEL-421 PMU and the SEL-RTS.

3) The arming signal will be sent from the SEL-3378 using SEL Fast Operate Commands. In the Virginia Tech laboratory where the voting scheme implementations were setup, the SEL-3378 and voting scheme relays were on the same local area network. Therefore, the Fast Operate Commands were sent from the SEL-3378 PDC to the voting scheme relays over the Ethernet connection through the local area network. In future voting scheme implementations with the SEL-3378, these same Fast Operate Commands could be sent using serial cable connections between the PDC and voting scheme relays. Either of these arming signal communication methods can be used for the voting scheme with the SEL-3378.

With the arming signal communication chosen, the SEL-3378 was configured to send the arming bit in the DT as two SEL Fast Operate Commands to the voting scheme relays. THE *Fast Operate Remote Bit Set* command was used as the "arming" command. When issued, the SEL-3378 sends this arming command to the SEL voting scheme relays. This command then asserts one Remote Bit in the relays. For all voting scheme implementations, the Remote Bit in the SEL relays was set to bit **RB01.** Therefore, RB01 was used in the logic equations of all the voting scheme relays. When the RB01 element is asserted (i.e. RB01=1), the voting scheme is armed [15].

Appendix D contains the actual settings used for all the SEL-3378 and all voting scheme relays used in this thesis.

4) Tables 2-3 and 2-4 list all the possible events with the three voting scheme digital relays. The ability to arm or disarm the voting scheme at will allows for all the events in those two tables to be tested. Each voting scheme implementation in this chapter was tested for correct functionality during each of the events in the two tables. The two tables are combined into one table, Table 3-1, to list the 16 test events for each voting scheme implementation.

Table 3-1. Tripping events tested for each voting scheme implementation.

Voting Scheme Status	Arming Signal	Event	Circuit Breaker Status	Which relays tripped the breaker?
Disarmed	0	1. Trip Slave 1, Slave 2, Master	?	?
	0	3. Trip Slave 1, Slave 2	?	?
	0	5. Trip Slave 1, Master	?	?
	0	7. Trip Slave 2, Master	?	?
	0	9. Trip Slave 1	?	?
	0	11. Trip Slave 2	?	?
	0	13. Trip Master	?	?
	0	15. No relays trip	?	?
Armed	1	2. Trip Slave 1, Slave 2, Master	?	?
	1	4. Trip Slave 1, Slave 2	?	?
	1	6. Trip Slave 1, Master	?	?
	1	8. Trip Slave 2, Master	?	?
	1	10. Trip Slave 1	?	?
	1	12. Trip Slave 2	?	?
	1	14. Trip Master	?	?
	1	16. No relays trip	?	?

For every voting scheme implementation in this chapter, every event in Table 3-1 was tested for correct functionality, which is determining if the circuit breaker was tripped (or not) and which voting scheme relays sent trip signals to the circuit breaker.

To implement the events in Table 3-1, the three digital relays used in each implementation were configured with an instantaneous overcurrent protection setting. The relays in each event that were supposed to trip had the overcurrent setting at a low Ampere value (1.0 Amp). The relays in each event that were not supposed to trip had the overcurrent setting at a high Ampere setting (20.0 Amps). The three phase AC source in Figure 3-1 was then used to send three phase currents through all three voting scheme relays and then through a three phase transmission line model. The current in the voting scheme circuit was forced high by causing a Phase A to ground fault, which is a feature of the transmission line model used. Then those relays with the low Ampere setting detect the fault, causing the voting scheme to operate accordingly. This procedure creates events where the digital relays with the high Ampere setting are simulated as not operating correctly for the given event.

Sequential Event Records from each voting scheme relay were then downloaded and analyzed to determine the simulated circuit breaker's status (tripped or not tripped) and which of the voting scheme relays sent a trip signal to the simulated circuit breaker.

The remaining sections in this chapter document each voting scheme implementation and its results for the 16 test events performed.

3.3.1 Single Manufacturer with Hard-Wired Trip Signals

This voting scheme implementation uses three SEL-421 digital relays – two relays are slave relays and the third is the Master relay. The setup of this voting scheme implementation is shown in Figure 3-3.

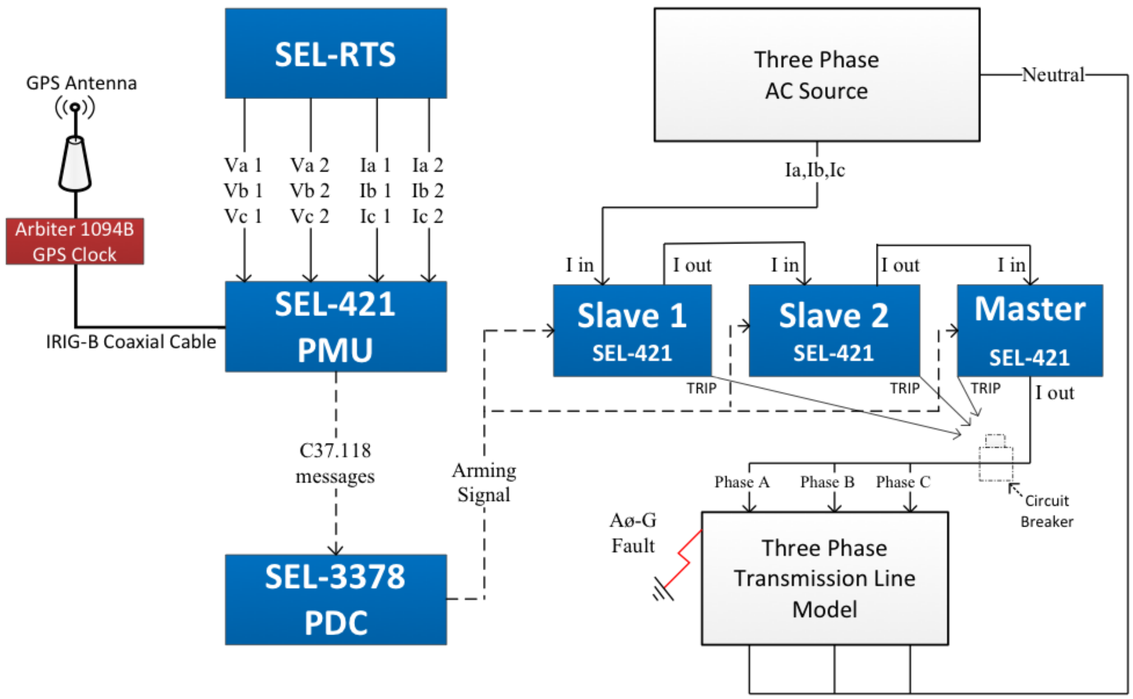

Figure 3-3. Voting scheme implementation w/ all SEL-421 digital relays & redundant slaves.

In this implementation, all three of the voting scheme relays are redundant relays when the voting scheme is disarmed. As discussed in Chapter 2, with a redundant relay voting scheme each digital relay must receive the arming signal to allow each relay to trip the circuit breaker if needed when the voting scheme is disarmed (see Sections 2.4 and 2.5). The last piece of this implementation is the trip signal communication. For this voting scheme, trip signal communication was performed over the hard-wired path. To implement hard-wired trip signal communications, the circuit in Figure 3-4 was implemented.

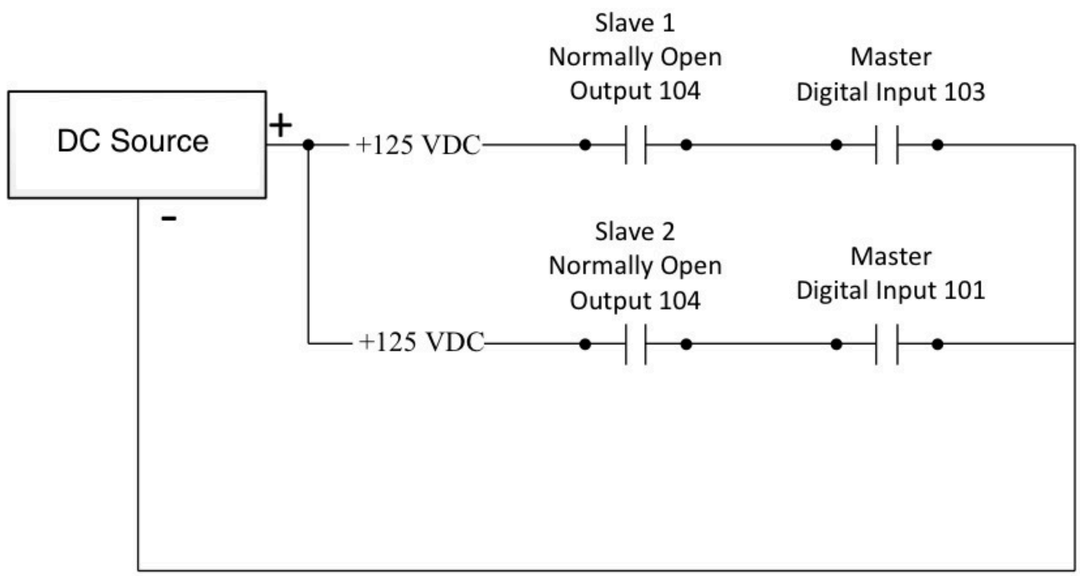

Figure 3-4. Circuit for the hard-wired trip signal communications.

As discussed earlier in this chapter, a DC source was used to send the trip signals from the slave relays to the SEL-421 Master relay using hard-wired connections. For all hard-wired voting scheme implementations in this chapter, each SEL-421 slave relay was configured to send its trip signal through the normally open output contact, OUT104. If a slave relay trips with this setup, its output contact OUT104 closes, providing DC voltage to a digital input on the SEL-421 Master relay. Slave 1 sends its trip signal to the Master's IN103 digital input, and Slave 2 sends its trip signal to the Master's IN101 digital input, as shown in Figure 3-4. When the DC voltage is applied to a digital input on the Master relay, the input contact will close and the digital bit corresponding to that input contact will assert to 1. The SEL-421 Master relay's voting scheme logic then uses the two digital bits corresponding to the two digital contact inputs.

The results for this voting scheme implementation are shown in Table 3-2. The table shows that the all SEL, redundant, hard-wired I/O voting scheme implementation correctly operated for all tested events.

Table 3-2. Results for the all SEL, redundant, hard-wired I/O voting scheme.

Voting Scheme Status	Arming Signal	Event	Circuit Breaker Status (Tripped = 1) (Not tripped = 0)	Which relays sent trip signals to the breaker?
Disarmed	0	**1**. Trip Slave 1, Slave 2, Master	**1**	Slave 1, Slave 2, Master
	0	**3**. Trip Slave 1, Slave 2	**1**	Slave 1, Slave 2
	0	**5**. Trip Slave 1, Master	**1**	Slave 1, Master
	0	**7**. Trip Slave 2, Master	**1**	Slave 2, Master
	0	**9**. Trip Slave 1	**1**	Slave 1
	0	**11**. Trip Slave 2	**1**	Slave 2
	0	**13**. Trip Master	**1**	Master
	0	**15**. No relays trip	0	None
Armed	1	**2**. Trip Slave 1, Slave 2, Master	**1**	Master
	1	**4**. Trip Slave 1, Slave 2	**1**	Master
	1	**6**. Trip Slave 1, Master	**1**	Master
	1	**8**. Trip Slave 2, Master	**1**	Master
	1	**10**. Trip Slave 1	0	None
	1	**12**. Trip Slave 2	0	None
	1	**14**. Trip Master	0	None
	1	**16**. No relays trip	0	None

The results in Table 3-2 were derived from the Sequential Event Records (SERs) from each SEL digital relay. In each SEL digital relay, "the SER captures and time-tags state changes of Relay Word bit elements and relay condition [12]." After each of the 16 events in Table 3-2 were run, the SER was downloaded from each voting scheme relay and then analyzed to verify correct operation. It is important to note that in each SER, the oldest Relay Word bit element captured is numbered the highest, while the most recent Relay Word bit element captured is numbered **1**.

The SERs for the single manufacturer, redundant slave, hard-wired I/O voting scheme implementation testing are listed and explained below. Note that each event is numbered according to Table 3-2.

To analyze the SERs for the SEL digital relays, the digital bits in the records must be explained. In each SEL-421 relay, the `50P1` element is the instantaneous overcurrent function. When the `50P1` element asserts, the SEL digital relay has measured a current input signal above the instantaneous overcurrent pickup setting in the relay. For all voting scheme implementations in this thesis, the instantaneous overcurrent pickup for all relays was set to 1.0 Amp. For each event tested, the current input to the relays was forced above 1.0 Amp to make the `50P1` element assert for the relays that are tripped in an event.

In each SEL-421 relay, the `TRIP` element is the digital trip signal sent to the circuit breaker. When the `TRIP` element asserts, the SEL digital relay is directly sending the signal that will cause the circuit breaker to open.

In the SEL-421 slave relays, the `OUT104` element is the trip signal of each slave relay sent to the Master relay via the hard-wired communications. When the `OUT104` element asserts, the SEL digital relay sends the Master relay its trip signal decision. The `OUT104` and the `TRIP` elements in the slave relay are not the same. An asserted `TRIP` element is when a slave relay is directly tripping the circuit breaker; however, an asserted `OUT104` element is indication that a slave relay would trip the circuit breaker under normal operating conditions (i.e. the voting scheme is disarmed). When the voting scheme is armed the `OUT104` element is a "vote" from the slave relay that is sent to the Master relay, as shown in Figure 3-4.

In the SEL-421 Master relay, the `IN101` and `IN103` elements are the digital trip signals from each slave relay input to the Master relay via hard-wired communications. The Master relay uses an asserted digital input as a tripping "vote" from the slave relay that sent the digital input. These digital inputs are used in the logic equation of the Master relay, as discussed in Chapter 2.

The last element in the SEL SERs is `RB01`. This element is the arming bit contained in the arming signal from the SEL-3378. The beginning of Section 3.3 provided the details of how the SEL digital relays receive this `RB01` arming bit.

All of these elements are used in the voting scheme devices in this implementation, and most are in the logic equations of the relays. Equation (3.1), (3.2), and (3.3) show the logic equations for the Master, Slave 1, and Slave 2 digital relays, respectively.

$$SEL - 421\ Master\ relay\ CB\ TRIP = [(50P1 * IN101 * RB01) + (50P1 * IN103 * RB01) + (IN101 * IN103 * RB01)] + [50P1 * !RB01] \tag{3.1}$$

$$SEL - 421\ Slave\ 1\ CB\ TRIP = 50P1 * !RB01 \tag{3.2}$$

$$SEL - 421\ Slave\ 2\ CB\ TRIP = 50P1 * !RB01 \tag{3.3}$$

Event 1: Trip Slave 1, Slave 2, and Master [Voting disarmed]

```
--------------------------------------------------------------------------------
SLAVE 1: SEL-421                  Date: 04/17/2011  Time: 17:08:22.910
VT Panel 4                               Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE        TIME            ELEMENT              STATE
3    04/17/2011  17:08:14.339   50P1                  Asserted
2    04/17/2011  17:08:14.339   TRIP                  Asserted
1    04/17/2011  17:08:14.339   OUT104                Asserted
--------------------------------------------------------------------------------
SLAVE 2: SEL-421                  Date: 04/17/2011  Time: 17:08:43.669
VT Panel 3                               Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE        TIME            ELEMENT              STATE
3    04/17/2011  17:08:14.339   50P1                  Asserted
2    04/17/2011  17:08:14.339   TRIP                  Asserted
1    04/17/2011  17:08:14.339   OUT104                Asserted
--------------------------------------------------------------------------------
Master: SEL-421                   Date: 04/17/2011  Time: 17:08:53.744
VT Panel 2                               Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE        TIME            ELEMENT              STATE
4    04/17/2011  17:08:14.338   50P1                  Asserted
3    04/17/2011  17:08:14.338   TRIP                  Asserted
2    04/17/2011  17:08:14.347   IN101                 Asserted
1    04/17/2011  17:08:14.347   IN103                 Asserted
--------------------------------------------------------------------------------
```

In Event 1, all three voting scheme relays tripped the circuit breaker (element TRIP asserted) immediately after their respective instantaneous overcurrent pickup values asserted. This is the desired operation for Event 1 because the voting scheme was disarmed (arming signal not asserted) and all three relays were set as redundant relays. Notice that even though the slave relay trip signals were still sent to the Master relay (IN101 and IN103), the Master relay ignored the signals because voting was disarmed.

Event 2: Trip Slave 1, Slave 2, and Master [Voting **armed**]

```
-----------------------------------------------------------------------------------------
SLAVE 1: SEL-421                 Date: 04/17/2011  Time: 17:10:10.076
VT Panel 4                                  Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT                STATE
3    04/17/2011  17:09:53.335   RB01                     Asserted
2    04/17/2011  17:10:02.724   50P1                     Asserted
1    04/17/2011  17:10:02.724   OUT104                   Asserted
-----------------------------------------------------------------------------------------
SLAVE 2: SEL-421                 Date: 04/17/2011  Time: 17:10:26.584
VT Panel 3                                  Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT                STATE
3    04/17/2011  17:09:53.320   RB01                     Asserted
2    04/17/2011  17:10:02.726   50P1                     Asserted
1    04/17/2011  17:10:02.726   OUT104                   Asserted
-----------------------------------------------------------------------------------------
Master: SEL-421                  Date: 04/17/2011  Time: 17:10:36.007
VT Panel 2                                  Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT                STATE
5    04/17/2011  17:09:53.349   RB01                     Asserted
4    04/17/2011  17:10:02.726   50P1                     Asserted
3    04/17/2011  17:10:02.732   IN103                    Asserted
2    04/17/2011  17:10:02.732   TRIP                     Asserted
1    04/17/2011  17:10:02.734   IN101                    Asserted
-----------------------------------------------------------------------------------------
```

Event 2 is the same case as Event 1, but with the voting scheme armed. In each SEL relay, the RB01 element is the arming signal sent from the SEL-3378 PDC. When RB01 asserts, the voting scheme is armed.

In this event, all three relays are set to trip for the phase A to ground fault. Each of the slave relays pickups for the fault (50P1 asserted), but they do not trip the circuit breaker. This is the design of the voting scheme, as only the Master relay can trip the breaker when the majority of relays vote to trip.

The Master relay received the arming signal and also picked up for the fault. However, the Master relay did not trip until it received the IN103 signal from Slave 1.

As soon as the `IN103` signal was detected, the Master relay issued the trip signal to the circuit breaker because two out of the three voting scheme relays had positive trip signals (`50P1 and IN103`). Two miliseconds after the Master issued the trip signal, the Master received the trip signal from Slave 2, `IN101`. This had no effect on the Master relay's logic as the majority of the voting scheme relays had already voted to trip.

Additional information regarding the time delays associated with hard-wired trip signal communications can be found from the SERs. Slave 1 issued its trip signal, `OUT104`, at time `17:10:02.724` . The Master relay received Slave 1's trip signal at time `17:10:02.732`. It therefore took 8 milliseconds for the trip signal to travel through the hard-wired path to the Master relay. For the Slave 2 relay, it took 8 milliseconds for its trip signal to reach the Master relay (`IN101`). Both of these signal communications took a half of a cycle or less in a 60 Hz power system. With these short delays, system stability and equipment damage should not be expected. However, appropriate studies should be performed on the implemented system to determine the effects of these communications delays.

Event 3: Trip Slave 1 and Slave 2 [Voting disarmed]

```
------------------------------------------------------------------------------------------------

SLAVE 1: SEL-421                Date: 04/17/2011  Time: 17:12:35.844
VT Panel 4                                 Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#     DATE         TIME            ELEMENT              STATE
3    04/17/2011  17:12:23.858   50P1                 Asserted
2    04/17/2011  17:12:23.858   TRIP                 Asserted
1    04/17/2011  17:12:23.858   OUT104               Asserted
------------------------------------------------------------------------------------------------

SLAVE 2: SEL-421                Date: 04/17/2011  Time: 17:12:48.044
VT Panel 3                                 Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#     DATE         TIME            ELEMENT              STATE
3    04/17/2011  17:12:23.857   50P1                 Asserted
2    04/17/2011  17:12:23.857   TRIP                 Asserted
1    04/17/2011  17:12:23.857   OUT104               Asserted
------------------------------------------------------------------------------------------------

Master: SEL-421                 Date: 04/17/2011  Time: 17:12:57.789
VT Panel 2                                 Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#     DATE         TIME            ELEMENT              STATE
2    04/17/2011  17:12:23.864   IN101                Asserted
1    04/17/2011  17:12:23.866   IN103                Asserted
------------------------------------------------------------------------------------------------
```

Only the slave relays are tripped in Event 3, with voting disarmed. The SERs show correct operation with only the slave relays tripping the circuit breaker directly.

Event 4: Trip Slave 1 and Slave 2 [Voting **armed**]

```
------------------------------------------------------------------------------------------------------
SLAVE 1: SEL-421                Date: 04/17/2011  Time: 17:13:53.280
VT Panel 4                                 Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT               STATE
3    04/17/2011  17:13:36.064   RB01                    Asserted
2    04/17/2011  17:13:47.414   50P1                    Asserted
1    04/17/2011  17:13:47.414   OUT104                  Asserted
------------------------------------------------------------------------------------------------------
SLAVE 2: SEL-421                Date: 04/17/2011  Time: 17:14:01.745
VT Panel 3                                 Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT               STATE
3    04/17/2011  17:13:36.103   RB01                    Asserted
2    04/17/2011  17:13:47.413   50P1                    Asserted
1    04/17/2011  17:13:47.413   OUT104                  Asserted
------------------------------------------------------------------------------------------------------
Master: SEL-421                 Date: 04/17/2011  Time: 17:14:12.409
VT Panel 2                                 Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT               STATE
4    04/17/2011  17:13:36.054   RB01                    Asserted
3    04/17/2011  17:13:47.420   IN101                   Asserted
2    04/17/2011  17:13:47.422   IN103                   Asserted
1    04/17/2011  17:13:47.422   TRIP                    Asserted
------------------------------------------------------------------------------------------------------
```

Only the Master relay tripped the circuit breaker after it received the asserted arming signal and the trip signals from both slave relays.

Slave 1’s trip signal took 8 milliseconds to reach the Master, while Slave 2’s trip signal took 7 milliseconds.

Event 5: Trip Slave 1 and Master [Voting disarmed]

```
------------------------------------------------------------------------------------------------------

SLAVE 1: SEL-421                Date: 04/17/2011  Time: 17:21:24.299
VT Panel 4                                 Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT                STATE
3    04/17/2011  17:21:12.379   50P1                    Asserted
2    04/17/2011  17:21:12.379   TRIP                    Asserted
1    04/17/2011  17:21:12.379   OUT104                  Asserted
------------------------------------------------------------------------------------------------------

SLAVE 2: SEL-421                Date: 04/17/2011  Time: 17:21:38.899
VT Panel 3                                 Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT                STATE
------------------------------------------------------------------------------------------------------

Master: SEL-421                 Date: 04/17/2011  Time: 17:21:38.899
VT Panel 2                                 Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT                STATE
3    04/17/2011  17:21:12.379   50P1                    Asserted
2    04/17/2011  17:21:12.379   TRIP                    Asserted
1    04/17/2011  17:21:12.385   IN103                   Asserted
------------------------------------------------------------------------------------------------------
```

The SERs show correct operation for Event 5 with the Slave 1 and Master relays tripping the circuit breaker directly. Notice that Slave 2 had no recordings for this event. This is a simulation of the Slave 2 relay having some malfunction that prevents the relay from seeing the fault.

Event 6: Trip Slave 1 and Master [Voting **armed**]

```
------------------------------------------------------------------------------------------------------------
SLAVE 1: SEL-421                Date: 04/17/2011  Time: 17:23:22.024
VT Panel 4                                 Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME           ELEMENT                STATE
3    04/17/2011  17:23:01.829   RB01                    Asserted
2    04/17/2011  17:23:16.152   50P1                    Asserted
1    04/17/2011  17:23:16.152   OUT104                  Asserted
------------------------------------------------------------------------------------------------------------
SLAVE 2: SEL-421                Date: 04/17/2011  Time: 17:23:33.845
VT Panel 3                                 Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME           ELEMENT                STATE
1    04/17/2011  17:23:01.856   RB01                    Asserted
------------------------------------------------------------------------------------------------------------
Master: SEL-421                 Date: 04/17/2011  Time: 17:23:43.395
VT Panel 2                                 Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME           ELEMENT                STATE
4    04/17/2011  17:23:01.852   RB01                    Asserted
3    04/17/2011  17:23:16.152   50P1                    Asserted
2    04/17/2011  17:23:16.160   IN103                   Asserted
1    04/17/2011  17:23:16.160   TRIP                    Asserted
------------------------------------------------------------------------------------------------------------
```

The SERs show correct operation for Event 6, with the Master relay tripping the circuit breaker directly due to the tripping votes from Slave 1 and the Master. Notice that Slave 2 did receive the asserted arming signal, but took no action as it did not observe the fault.

Slave 1’s trip signal took 8 milliseconds to reach the Master.

Event 7: Trip Slave 2 and Master [Voting disarmed]

```
------------------------------------------------------------------------
SLAVE 1: SEL-421                  Date: 04/17/2011  Time: 17:27:41.310
VT Panel 4                                   Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE          TIME           ELEMENT               STATE
------------------------------------------------------------------------
SLAVE 2: SEL-421                  Date: 04/17/2011  Time: 17:27:30.403
VT Panel 3                                   Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE          TIME           ELEMENT               STATE
3    04/17/2011  17:27:23.332   50P1                    Asserted
2    04/17/2011  17:27:23.332   TRIP                    Asserted
1    04/17/2011  17:27:23.332   OUT104                  Asserted
------------------------------------------------------------------------
Master: SEL-421                   Date: 04/17/2011  Time: 17:27:41.310
VT Panel 2                                   Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE          TIME           ELEMENT               STATE
3    04/17/2011  17:27:23.331   50P1                    Asserted
2    04/17/2011  17:27:23.331   TRIP                    Asserted
1    04/17/2011  17:27:23.339   IN101                   Asserted
------------------------------------------------------------------------
```

The SERs show correct operation for Event 7 with the Slave 2 and Master relays tripping the circuit breaker directly. Notice that Slave 1 had no recordings for this event. This is a simulation of the Slave 1 relay having some malfunction that prevents the relay from seeing the fault.

Event 8: Trip Slave 2 and Master [Voting **armed**]

```
-----------------------------------------------------------------------------------------------
SLAVE 1: SEL-421                    Date: 04/17/2011  Time: 17:29:15.216
VT Panel 4                                     Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME              ELEMENT                  STATE
1    04/17/2011  17:28:46.869   RB01                     Asserted
-----------------------------------------------------------------------------------------------
SLAVE 2: SEL-421                    Date: 04/17/2011  Time: 17:29:25.545
VT Panel 3                                     Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME              ELEMENT                  STATE
3    04/17/2011  17:28:46.826   RB01                     Asserted
2    04/17/2011  17:29:08.255   50P1                     Asserted
1    04/17/2011  17:29:08.255   OUT104                   Asserted
-----------------------------------------------------------------------------------------------
Master: SEL-421                     Date: 04/17/2011  Time: 17:29:34.376
VT Panel 2                                     Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME              ELEMENT                  STATE
4    04/17/2011  17:28:46.866   RB01                     Asserted
3    04/17/2011  17:29:08.256   50P1                     Asserted
2    04/17/2011  17:29:08.262   IN101                    Asserted
1    04/17/2011  17:29:08.262   TRIP                     Asserted
-----------------------------------------------------------------------------------------------
```

The SERs show correct operation for Event 8, with the Master relay tripping the circuit breaker due to the tripping votes from Slave 2 and the Master. Notice that Slave 1 did receive the asserted arming signal, but took no action as it did not observe the fault.

Slave 2’s trip signal took 7 milliseconds to reach the Master.

Event 9: Trip Slave 1 [Voting disarmed]

```
--------------------------------------------------------------------------------------------------------
SLAVE 1: SEL-421                Date: 04/17/2011  Time: 17:31:15.913
VT Panel 4                                Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT                STATE
3    04/17/2011  17:31:11.155   50P1                  Asserted
2    04/17/2011  17:31:11.155   TRIP                  Asserted
1    04/17/2011  17:31:11.155   OUT104                Asserted
--------------------------------------------------------------------------------------------------------
SLAVE 2: SEL-421                Date: 04/17/2011  Time: 17:31:29.213
VT Panel 3                                Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT                STATE
--------------------------------------------------------------------------------------------------------
Master: SEL-421                 Date: 04/17/2011  Time: 17:31:29.213
VT Panel 2                                Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT                STATE
1    04/17/2011  17:31:11.163   IN103                 Asserted
--------------------------------------------------------------------------------------------------------
```

The SERs show correct operation for Event 9 with only Slave 1 tripping the circuit breaker directly. The Master relay did receive the trip signal from Slave 1, but it did not effect the Master relay's disarmed logic.

Event 10: Trip Slave 1 [Voting **armed**]

```
--------------------------------------------------------------------------------------------------------

SLAVE 1: SEL-421                Date: 04/17/2011  Time: 17:33:03.729
VT Panel 4                                 Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT                 STATE
3    04/17/2011  17:32:48.326   RB01                     Asserted
2    04/17/2011  17:32:56.747   50P1                     Asserted
1    04/17/2011  17:32:56.747   OUT104                   Asserted
--------------------------------------------------------------------------------------------------------

SLAVE 2: SEL-421                Date: 04/17/2011  Time: 17:33:13.839
VT Panel 3                                 Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT                 STATE
1    04/17/2011  17:32:48.362   RB01                     Asserted
--------------------------------------------------------------------------------------------------------

Master: SEL-421                 Date: 04/17/2011  Time: 17:33:25.741
VT Panel 2                                 Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT                 STATE
2    04/17/2011  17:32:48.380   RB01                     Asserted
1    04/17/2011  17:32:56.755   IN103                    Asserted
--------------------------------------------------------------------------------------------------------
```

The SERs show correct operation for Event 10 – none of the voting scheme relays tripped the circuit breaker. With the voting scheme armed, all three relays received the asserted arming signal. However, the Master relay did not count a majority of the relays voting to trip. Only the trip signal from Slave 1 was counted by the Master relay. Therefore, no breaker trip signal was issued by the Master relay.

Slave 1's trip signal took 8 milliseconds to reach the Master.

Event 11: Trip Slave 2 [Voting disarmed]

```
-----------------------------------------------------------------------------------------
SLAVE 1: SEL-421                Date: 04/17/2011  Time: 17:34:37.340
VT Panel 4                                Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE        TIME           ELEMENT                STATE
-----------------------------------------------------------------------------------------
SLAVE 2: SEL-421                Date: 04/17/2011  Time: 17:34:37.340
VT Panel 3                                Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE        TIME           ELEMENT                STATE
3    04/17/2011  17:34:30.366   50P1                  Asserted
2    04/17/2011  17:34:30.366   TRIP                  Asserted
1    04/17/2011  17:34:30.366   OUT104                Asserted
-----------------------------------------------------------------------------------------
Master: SEL-421                 Date: 04/17/2011  Time: 17:35:02.614
VT Panel 2                                Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE        TIME           ELEMENT                STATE
1    04/17/2011  17:34:30.373   IN101                 Asserted
-----------------------------------------------------------------------------------------
```

The SERs show correct operation for Event 11 with only Slave 2 tripping the circuit breaker directly. The Master relay did receive the trip signal from Slave 2, but it did not effect the Master relay's disarmed logic.

Event 12: Trip Slave 2 [Voting **armed**]

```
--------------------------------------------------------------------------------
SLAVE 1: SEL-421                Date: 04/17/2011  Time: 17:36:51.056
VT Panel 4                                Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE          TIME            ELEMENT               STATE
1    04/17/2011  17:36:35.231   RB01                    Asserted
--------------------------------------------------------------------------------
SLAVE 2: SEL-421                Date: 04/17/2011  Time: 17:37:00.005
VT Panel 3                                Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE          TIME            ELEMENT               STATE
3    04/17/2011  17:36:35.200   RB01                    Asserted
2    04/17/2011  17:36:43.560   50P1                    Asserted
1    04/17/2011  17:36:43.560   OUT104                  Asserted
--------------------------------------------------------------------------------
Master: SEL-421                 Date: 04/17/2011  Time: 17:37:08.268
VT Panel 2                                Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE          TIME            ELEMENT               STATE
2    04/17/2011  17:36:35.235   RB01                    Asserted
1    04/17/2011  17:36:43.568   IN101                   Asserted
--------------------------------------------------------------------------------
```

The SERs show correct operation for Event 12 – none of the voting scheme relays tripped the circuit breaker. With the voting scheme armed, all three relays received the asserted arming signal. However, the Master relay did not count a majority of the relays voting to trip. Only the trip signal from Slave 2 was counted by the Master relay. Therefore, no breaker trip signal was issued by the Master relay.

Slave 2's trip signal took 8 milliseconds to reach the Master.

Event 13: Trip Master [Voting disarmed]

```
---------------------------------------------------------------------------------------------------
SLAVE 1: SEL-421                Date: 04/17/2011  Time: 17:38:23.396
VT Panel 4                                Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE        TIME           ELEMENT               STATE
---------------------------------------------------------------------------------------------------
SLAVE 2: SEL-421                Date: 04/17/2011  Time: 17:38:23.396
VT Panel 3                                 Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE        TIME           ELEMENT               STATE
---------------------------------------------------------------------------------------------------
Master: SEL-421                 Date: 04/17/2011  Time: 17:38:23.396
VT Panel 2                                 Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE        TIME           ELEMENT               STATE
2    04/17/2011  17:38:14.271   50P1                  Asserted
1    04/17/2011  17:38:14.271   TRIP                  Asserted
---------------------------------------------------------------------------------------------------
```

The SERs show correct operation for Event 13 with only the Master relay tripping the circuit breaker directly.

Event 14: Trip Master [Voting **armed**]

```
----------------------------------------------------------------------------------------------------
SLAVE 1: SEL-421                Date: 04/17/2011  Time: 17:40:50.604
VT Panel 4                                Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE          TIME            ELEMENT                STATE
1    04/17/2011  17:40:38.486   RB01                      Asserted
----------------------------------------------------------------------------------------------------
SLAVE 2: SEL-421                Date: 04/17/2011  Time: 17:41:00.938
VT Panel 3                                Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE          TIME            ELEMENT                STATE
1    04/17/2011  17:40:38.461   RB01                      Asserted
----------------------------------------------------------------------------------------------------
Master: SEL-421                 Date: 04/17/2011  Time: 17:41:10.711
VT Panel 2                                Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE          TIME            ELEMENT                STATE
2    04/17/2011  17:40:38.479   RB01                      Asserted
1    04/17/2011  17:40:45.067   50P1                      Asserted
----------------------------------------------------------------------------------------------------
```

The SERs show correct operation for Event 14 – none of the voting scheme relays tripped the circuit breaker. With the voting scheme armed, all three relays received the asserted arming signal. However, the Master relay did not count a majority of the relays voting to trip. Only the Master's own tripping vote was counted by the Master relay. Therefore, no breaker trip signal was issued by the Master relay.

Event 15: No relays trip [Voting disarmed]

```
------------------------------------------------------------------------------------------------------
SLAVE 1: SEL-421                 Date: 04/17/2011  Time: 17:41:45.586
VT Panel 4                                  Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE        TIME           ELEMENT                 STATE
------------------------------------------------------------------------------------------------------
SLAVE 2: SEL-421                 Date: 04/17/2011  Time: 17:42:12.476
VT Panel 3                                  Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE        TIME           ELEMENT                 STATE
------------------------------------------------------------------------------------------------------
Master: SEL-421                  Date: 04/17/2011  Time: 17:42:33.380
VT Panel 2                                  Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE        TIME           ELEMENT                 STATE
------------------------------------------------------------------------------------------------------
```

The SERs show correct operation for Event 15. No relays detected the fault, and therefore no actions were taken by any of the relays.

Event 16: No relays trip [Voting **armed**]

```
----------------------------------------------------------------------------------------------------
SLAVE 1: SEL-421                Date: 04/17/2011  Time: 17:41:45.586
VT Panel 4                                Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT              STATE
1    04/17/2011  17:41:43.619   RB01                   Asserted
----------------------------------------------------------------------------------------------
SLAVE 2: SEL-421                Date: 04/17/2011  Time: 17:42:12.476
VT Panel 3                                Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT              STATE
1    04/17/2011  17:41:43.630   RB01                   Asserted
----------------------------------------------------------------------------------------------------
Master: SEL-421                 Date: 04/17/2011  Time: 17:42:33.380
VT Panel 2                                Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT              STATE
1    04/17/2011  17:41:43.610   RB01                   Asserted
----------------------------------------------------------------------------------------------------
```

The SERs show correct operation for Event 16 – none of the voting scheme relays tripped the circuit breaker. With the voting scheme armed, all three relays received the asserted arming signal. However, the Master relay did not count any tripping votes. Therefore, no breaker trip signal was issued by the Master relay.

3.3.2 Single Manufacturer with SEL Mirrored Bits Trip Signals

This voting scheme implementation is the same as the previous implementation in Section 3.3.1, with one exception. For this voting scheme, trip signal communication was performed using SEL Mirrored Bits Communication. To implement SEL Mirrored Bits Communications for the trip signals, the configuration in Figure 3-5 was implemented.

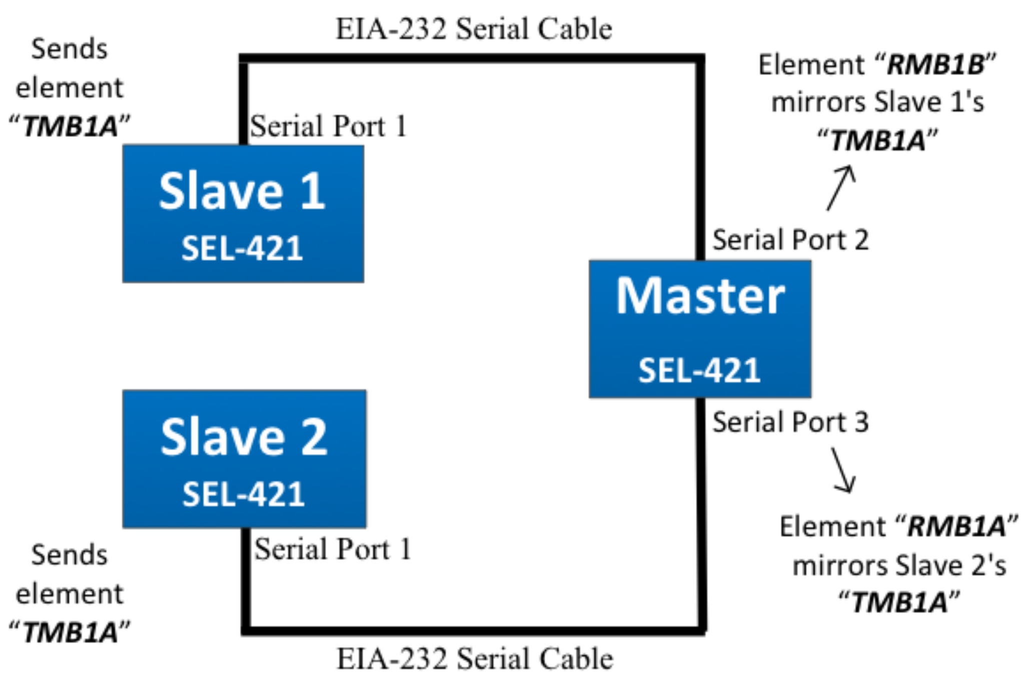

Figure 3-5. Circuit for trip signals sent using SEL Mirrored Bits Communications.

For trip signals using this communications protocol, each SEL-421 slave relay is configured to send its trip signal through one Transmit Mirrored Bit, or TMB. With Mirrored Bits communication, the slave relays send all of their TMBs to the Master relay through an EIA-232 Serial Cable. If a slave relay trips with Mirrored Bits enabled, the Transmit bit used will assert to 1. This bit is sent through the serial cable to the Master relay, where the corresponding Receive Mirrored Bit, RMB, will receive the TMB and mirror the value of that TMB. The SEL-421 Master relay's voting scheme logic then uses the two internal RMBs corresponding to the two TMBs from the SEL-421 slave relays.

As mentioned previously, this voting scheme implementation is the same as the previous setup in all other features. This implementation uses three SEL-421 digital relays – two relays are slave relays and the third is the Master relay – and all three voting scheme relays are redundant relays when the voting scheme is disarmed. The setup of this voting scheme implementation is the same as that in Figure 3-3.

The results for this voting scheme implementation are shown in Table 3-3. The table shows that the all SEL, redundant, Mirrored Bits voting scheme implementation correctly operated for all tested events.

Table 3-3. Results for the all SEL, redundant, SEL Mirrored Bits voting scheme.

Voting Scheme Status	Arming Signal	Event	Circuit Breaker Status (Tripped = 1) (Not tripped = 0)	Which relays sent trip signals to the breaker?
Disarmed	0	**1**. Trip Slave 1, Slave 2, Master	**1**	Slave 1, Slave 2, Master
	0	**3**. Trip Slave 1, Slave 2	**1**	Slave 1, Slave 2
	0	**5**. Trip Slave 1, Master	**1**	Slave 1, Master
	0	**7**. Trip Slave 2, Master	**1**	Slave 2, Master
	0	**9**. Trip Slave 1	**1**	Slave 1
	0	**11**. Trip Slave 2	**1**	Slave 2
	0	**13**. Trip Master	**1**	Master
	0	**15**. No relays trip	0	None
Armed	1	**2**. Trip Slave 1, Slave 2, Master	**1**	Master
	1	**4**. Trip Slave 1, Slave 2	**1**	Master
	1	**6**. Trip Slave 1, Master	**1**	Master
	1	**8**. Trip Slave 2, Master	**1**	Master
	1	**10**. Trip Slave 1	0	None
	1	**12**. Trip Slave 2	0	None
	1	**14**. Trip Master	0	None
	1	**16**. No relays trip	0	None

The results in Table 3-3 were derived from the Sequential Event Records (SERs) from each SEL digital relay. All of the digital bits in the SERs for this implementation are the same except for the addition of the Mirrored Bits elements. In the two SEL-421 slave relays, the `TMB1A` element is the Transmit Mirrored Bit used in each slave to send the arming signal to the Master relay. The `TMB1A` element is assigned the trip signal of the slave relay. When the `TMB1A` element asserts, the Master relay's associated Receive Mirrored Bit element will assert. As shown in Figure 3-5, the Master relay is set to use the `RMB1B` element for Slave 1's trip signal and the `RMB1A` element for Slave 2's trip signal. When Slave 1 votes to trip, the `RMB1B` element in the Master relay will assert; when Slave 2 votes to trip, the `RMB1A` element in the Master relay will assert.

The SERs for the single manufacturer, redundant slave, Mirrored Bits voting scheme implementation testing are listed and explained below. Note that each event is numbered according to Table 3-3.

All of these elements are used in the voting scheme devices in this implementation, and most are in the logic equations of the relays. Equation (3.4), (3.5), and (3.6) show the logic equations for the Master, Slave 1, and Slave 2 digital relays, respectively.

$$SEL-421\ Master\ relay\ CB\ TRIP = [(50P1*RMB1A*RB01)+(50P1*RMB1B*RB01)+(RMB1A*RMB1B*RB01)] + [50P1*!RB01] \tag{3.4}$$

$$SEL-421\ Slave\ 1\ CB\ TRIP = 50P1*!RB01 \tag{3.5}$$

$$SEL-421\ Slave\ 2\ CB\ TRIP = 50P1*!RB01 \tag{3.6}$$

Event 1: Trip Slave 1, Slave 2, and Master [Voting disarmed]

```
------------------------------------------------------------------------
SLAVE 1: SEL-421                Date: 04/15/2011  Time: 21:07:33.295
VT Panel 4                               Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#     DATE        TIME          ELEMENT              STATE
3    04/15/2011  21:07:26.041   50P1                Asserted
2    04/15/2011  21:07:26.041   TRIP                Asserted
1    04/15/2011  21:07:26.041   TMB1A               Asserted
------------------------------------------------------------------------
SLAVE 2: SEL-421                Date: 04/15/2011  Time: 21:07:55.009
VT Panel 3                               Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#     DATE        TIME          ELEMENT              STATE
3    04/15/2011  21:07:26.040   50P1                Asserted
2    04/15/2011  21:07:26.040   TRIP                Asserted
1    04/15/2011  21:07:26.040   TMB1A               Asserted
------------------------------------------------------------------------
Master: SEL-421                 Date: 04/15/2011  Time: 21:08:11.110
VT Panel 2                               Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#     DATE        TIME          ELEMENT              STATE
4    04/15/2011  21:07:26.040   50P1                Asserted
3    04/15/2011  21:07:26.040   TRIP                Asserted
2    04/15/2011  21:07:26.050   RMB1A               Asserted
1    04/15/2011  21:07:26.052   RMB1B               Asserted
------------------------------------------------------------------------
```

In Event 1, all three voting scheme relays tripped the circuit breaker (element TRIP asserted) immediately after their respective instantaneous overcurrent pickup values asserted. This is the desired operation for Event 1 because the voting scheme was disarmed (arming signal not asserted) and all three relays were set as redundant relays. Notice that even though the slave relay trip signals were still sent to the Master relay (RMB1A and RMB1B), the Master relay ignored the signals because voting was disarmed.

Event 2: Trip Slave 1, Slave 2, and Master [Voting **armed**]

```
----------------------------------------------------------------------------------------------------------------
SLAVE 1: SEL-421                Date: 04/15/2011  Time: 22:35:59.507
VT Panel 4                                 Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#     DATE         TIME           ELEMENT              STATE
3    04/15/2011  22:35:42.976   RB01                 Asserted
2    04/15/2011  22:35:52.099   50P1                 Asserted
1    04/15/2011  22:35:52.099   TMB1A                Asserted
----------------------------------------------------------------------------------------------------------------
SLAVE 2: SEL-421                Date: 04/15/2011  Time: 22:36:22.429
VT Panel 3                                 Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#     DATE         TIME           ELEMENT              STATE
3    04/15/2011  22:35:42.982   RB01                 Asserted
2    04/15/2011  22:35:52.099   50P1                 Asserted
1    04/15/2011  22:35:52.099   TMB1A                Asserted
----------------------------------------------------------------------------------------------------------------
Master: SEL-421                 Date: 04/15/2011  Time: 22:36:51.771
VT Panel 2                                 Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#     DATE         TIME           ELEMENT              STATE
5    04/15/2011  22:35:42.967   RB01                 Asserted
4    04/15/2011  22:35:52.100   50P1                 Asserted
3    04/15/2011  22:35:52.108   RMB1A                Asserted
2    04/15/2011  22:35:52.108   RMB1B                Asserted
1    04/15/2011  22:35:52.108   TRIP                 Asserted
----------------------------------------------------------------------------------------------------------------
```

The SERs show correct voting scheme operation for Event 2. All three relays received the asserted arming signal (RB01 asserted), all three relays voted to trip (50P1 asserted), and the Master relay tripped the circuit breaker when it received two votes to trip (TRIP asserted).

As done in Section 3.3.1 with the hard-wired I/O signals, the time delays associated with SEL Mirrored Bits Communication are calculated from the SER. For both slave relays, the trip signals took 9 milliseconds to reach the Master relay through the serial cable using Mirrored Bits. This delay is on the same magnitude as the communication delays with the hard-wired signals in the previous section.

Event 3: Trip Slave 1 and Slave 2 [Voting disarmed]

```
----------------------------------------------------------------------------------------------------
SLAVE 1: SEL-421                Date: 04/15/2011  Time: 23:14:52.806
VT Panel 4                                 Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE        TIME           ELEMENT                STATE
3    04/15/2011  23:14:38.821   50P1                   Asserted
2    04/15/2011  23:14:38.821   TRIP                   Asserted
1    04/15/2011  23:14:38.821   TMB1A                  Asserted
----------------------------------------------------------------------------------------------------
SLAVE 2: SEL-421                Date: 04/15/2011  Time: 23:15:14.575
VT Panel 3                                 Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE        TIME           ELEMENT                STATE
3    04/15/2011  23:14:38.821   50P1                   Asserted
2    04/15/2011  23:14:38.821   TRIP                   Asserted
1    04/15/2011  23:14:38.821   TMB1A                  Asserted
----------------------------------------------------------------------------------------------------
Master: SEL-421                 Date: 04/15/2011  Time: 23:15:32.410
VT Panel 2                                 Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE        TIME           ELEMENT                STATE
2    04/15/2011  23:14:38.830   RMB1A                  Asserted
1    04/15/2011  23:14:38.830   RMB1B                  Asserted
----------------------------------------------------------------------------------------------------
```

Only the slave relays are tripped in Event 3, with voting disarmed. The SERs show correct operation with only the slave relays tripping the circuit breaker directly.

Event 4: Trip Slave 1 and Slave 2 [Voting **armed**]

```
----------------------------------------------------------------------------------
SLAVE 1: SEL-421                Date: 04/15/2011  Time: 23:05:09.012
VT Panel 4                                 Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME          ELEMENT              STATE
3    04/15/2011  22:15:46.003   RB01                 Asserted
2    04/15/2011  23:04:23.031   50P1                 Asserted
1    04/15/2011  23:04:23.031   TMB1A                Asserted
----------------------------------------------------------------------------------
SLAVE 2: SEL-421                Date: 04/15/2011  Time: 23:06:52.060
VT Panel 3                                 Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME          ELEMENT              STATE
3    04/15/2011  22:15:46.005   RB01                 Asserted
2    04/15/2011  23:04:23.032   50P1                 Asserted
1    04/15/2011  23:04:23.032   TMB1A                Asserted
----------------------------------------------------------------------------------
Master: SEL-421                 Date: 04/15/2011  Time: 23:08:40.169
VT Panel 2                                 Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME          ELEMENT              STATE
4    04/15/2011  22:15:46.003   RB01                 Asserted
3    04/15/2011  23:04:23.039   RMB1B                Asserted
2    04/15/2011  23:04:23.041   RMB1A                Asserted
1    04/15/2011  23:04:23.041   TRIP                 Asserted
----------------------------------------------------------------------------------
```

Only the Master relay tripped the circuit breaker after it received the asserted arming signal and the trip signals from both slave relays.

Slave 1’s trip signal took 8 milliseconds to reach the Master, while Slave 2’s trip signal took 9 milliseconds.

Event 5: Trip Slave 1 and Master [Voting disarmed]

```
-----------------------------------------------------------------------------------------------------
SLAVE 1: SEL-421                Date: 04/15/2011  Time: 23:17:08.910
VT Panel 4                                Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT                 STATE
3    04/15/2011  23:17:00.050   50P1                    Asserted
2    04/15/2011  23:17:00.050   TRIP                    Asserted
1    04/15/2011  23:17:00.050   TMB1A                   Asserted
-----------------------------------------------------------------------------------------------------
SLAVE 2: SEL-421                Date: 04/15/2011  Time: 23:17:08.910
VT Panel 3                                Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT                 STATE
-----------------------------------------------------------------------------------------------------
Master: SEL-421                 Date: 04/15/2011  Time: 23:19:02.948
VT Panel 2                                Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT                 STATE
3    04/15/2011  23:17:00.050   50P1                    Asserted
2    04/15/2011  23:17:00.050   TRIP                    Asserted
1    04/15/2011  23:17:00.059   RMB1B                   Asserted
-----------------------------------------------------------------------------------------------------
```

The SERs show correct operation for Event 5 with the Slave 1 and Master relays tripping the circuit breaker directly.

Event 6: Trip Slave 1 and Master [Voting **armed**]

```
-------------------------------------------------------------------------------------------------------

SLAVE 1: SEL-421                Date: 04/15/2011  Time: 23:24:49.146
VT Panel 4                                 Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT                STATE
3    04/15/2011  23:24:16.432   RB01                     Asserted
2    04/15/2011  23:24:37.009   50P1                     Asserted
1    04/15/2011  23:24:37.009   TMB1A                    Asserted
-------------------------------------------------------------------------------------------------------

SLAVE 2: SEL-421                Date: 04/15/2011  Time: 23:25:05.867
VT Panel 3                                 Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT                STATE
1    04/15/2011  23:24:16.394   RB01                     Asserted
-------------------------------------------------------------------------------------------------------

Master: SEL-421                 Date: 04/15/2011  Time: 23:25:21.222
VT Panel 2                                 Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT                STATE
4    04/15/2011  23:24:16.431   RB01                     Asserted
3    04/15/2011  23:24:37.008   50P1                     Asserted
2    04/15/2011  23:24:37.012   RMB1B                    Asserted
1    04/15/2011  23:24:37.012   TRIP                     Asserted

-------------------------------------------------------------------------------------------------------
```

The SERs show correct operation for Event 6, with the Master relay tripping the circuit breaker directly due to the tripping votes from Slave 1 and the Master. Notice that Slave 2 did receive the asserted arming signal, but took no action as it did not observe the fault.

Slave 1's trip signal took 3 milliseconds to reach the Master.

Event 7: Trip Slave 2 and Master [Voting disarmed]

```
--------------------------------------------------------------------------------------------------------
SLAVE 1: SEL-421                Date: 04/15/2011  Time: 23:29:45.642
VT Panel 4                                 Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME           ELEMENT               STATE
--------------------------------------------------------------------------------------------------------
SLAVE 2: SEL-421                Date: 04/15/2011  Time: 23:29:45.642
VT Panel 3                                 Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME           ELEMENT               STATE
3    04/15/2011  23:29:25.067   50P1                    Asserted
2    04/15/2011  23:29:25.067   TRIP                    Asserted
1    04/15/2011  23:29:25.067   TMB1A                   Asserted
--------------------------------------------------------------------------------------------------------
Master: SEL-421                 Date: 04/15/2011  Time: 23:31:26.245
VT Panel 2                                 Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME           ELEMENT               STATE
3    04/15/2011  23:29:25.066   50P1                    Asserted
2    04/15/2011  23:29:25.066   TRIP                    Asserted
1    04/15/2011  23:29:25.075   RMB1A                   Asserted
--------------------------------------------------------------------------------------------------------
```

The SERs show correct operation for Event 7 with the Slave 2 and Master relays tripping the circuit breaker directly.

Event 8: Trip Slave 2 and Master [Voting **armed**]

```
----------------------------------------------------------------------------------------------------------
SLAVE 1: SEL-421                    Date: 04/15/2011  Time: 23:33:34.366
VT Panel 4                                     Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT                 STATE
1    04/15/2011  23:33:13.164   RB01                    Asserted
----------------------------------------------------------------------------------------------------------
SLAVE 2: SEL-421                    Date: 04/15/2011  Time: 23:33:45.206
VT Panel 3                                     Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT                 STATE
3    04/15/2011  23:33:13.184   RB01                    Asserted
2    04/15/2011  23:33:26.896   50P1                    Asserted
1    04/15/2011  23:33:26.896   TMB1A                   Asserted
----------------------------------------------------------------------------------------------------------
Master: SEL-421                     Date: 04/15/2011  Time: 23:33:59.084
VT Panel 2                                     Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT                 STATE
4    04/15/2011  23:33:13.206   RB01                    Asserted
3    04/15/2011  23:33:26.897   50P1                    Asserted
2    04/15/2011  23:33:26.904   RMB1A                   Asserted
1    04/15/2011  23:33:26.904   TRIP                    Asserted
----------------------------------------------------------------------------------------------------------
```

The SERs show correct operation for Event 8, with the Master relay tripping the circuit breaker due to the tripping votes from Slave 2 and the Master. Notice that Slave 1 did receive the asserted arming signal, but took no action as it did not observe the fault.

Slave 2's trip signal took 8 milliseconds to reach the Master.

Event 9: Trip Slave 1 [Voting disarmed]

```
------------------------------------------------------------------------------------------------------
SLAVE 1: SEL-421                Date: 04/15/2011  Time: 23:36:17.251
VT Panel 4                                Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT               STATE
3    04/15/2011  23:36:09.031   50P1                   Asserted
2    04/15/2011  23:36:09.031   TRIP                   Asserted
1    04/15/2011  23:36:09.031   TMB1A                  Asserted
------------------------------------------------------------------------------------------------------
SLAVE 2: SEL-421                Date: 04/15/2011  Time: 23:36:17.251
VT Panel 3                                Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT               STATE
------------------------------------------------------------------------------------------------------
Master: SEL-421                 Date: 04/15/2011  Time: 23:36:32.479
VT Panel 2                                Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT               STATE
1    04/15/2011  23:36:09.040   RMB1B                  Asserted
------------------------------------------------------------------------------------------------------
```

The SERs show correct operation for Event 9 with only Slave 1 tripping the circuit breaker directly. The Master relay did receive the trip signal from Slave 1, but it did not effect the Master relay's disarmed logic.

Event 10: Trip Slave 1 [Voting **armed**]

```
----------------------------------------------------------------------------------------------------------
SLAVE 1: SEL-421                Date: 04/15/2011  Time: 23:38:29.562
VT Panel 4                                Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME           ELEMENT               STATE
3    04/15/2011  23:38:11.217   RB01                  Asserted
2    04/15/2011  23:38:21.586   50P1                  Asserted
1    04/15/2011  23:38:21.586   TMB1A                 Asserted
----------------------------------------------------------------------------------------------------------
SLAVE 2: SEL-421                Date: 04/15/2011  Time: 23:38:50.225
VT Panel 3                                Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME           ELEMENT               STATE
1    04/15/2011  23:38:11.194   RB01                  Asserted
----------------------------------------------------------------------------------------------------------
Master: SEL-421                 Date: 04/15/2011  Time: 23:39:10.851
VT Panel 2                                Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME           ELEMENT               STATE
2    04/15/2011  23:38:11.171   RB01                  Asserted
1    04/15/2011  23:38:21.590   RMB1B                 Asserted
----------------------------------------------------------------------------------------------------------
```

The SERs show correct operation for Event 10 – none of the voting scheme relays tripped the circuit breaker. With the voting scheme armed, all three relays received the asserted arming signal. However, the Master relay did not count a majority of the relays voting to trip. Only the trip signal from Slave 1 was counted by the Master relay. Therefore, no breaker trip signal was issued by the Master relay.

Slave 1's trip signal took 4 milliseconds to reach the Master.

Event 11: Trip Slave 2 [Voting disarmed]

```
--------------------------------------------------------------------------------------------------------
SLAVE 1: SEL-421                Date: 04/15/2011  Time: 23:43:08.172
VT Panel 4                                 Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME           ELEMENT                STATE
--------------------------------------------------------------------------------------------------------
SLAVE 2: SEL-421                Date: 04/15/2011  Time: 23:42:55.103
VT Panel 3                                 Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME           ELEMENT                STATE
3    04/15/2011  23:42:46.785   50P1                    Asserted
2    04/15/2011  23:42:46.785   TRIP                    Asserted
1    04/15/2011  23:42:46.785   TMB1A                   Asserted
--------------------------------------------------------------------------------------------------------
Master: SEL-421                 Date: 04/15/2011  Time: 23:43:08.172
VT Panel 2                                 Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME           ELEMENT                STATE
1    04/15/2011  23:42:46.794   RMB1A                   Asserted
--------------------------------------------------------------------------------------------------------
```

The SERs show correct operation for Event 11 with only Slave 2 tripping the circuit breaker directly. The Master relay did receive the trip signal from Slave 2, but it did not effect the Master relay's disarmed logic.

Event 12: Trip Slave 2 [Voting **armed**]

```
-----------------------------------------------------------------------------
SLAVE 1: SEL-421                 Date: 04/15/2011  Time: 23:45:12.549
VT Panel 4                                 Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT              STATE
1    04/15/2011  23:44:54.545   RB01                   Asserted
-----------------------------------------------------------------------------
SLAVE 2: SEL-421                 Date: 04/15/2011  Time: 23:45:28.218
VT Panel 3                                 Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT              STATE
3    04/15/2011  23:44:54.543   RB01                   Asserted
2    04/15/2011  23:45:06.085   50P1                   Asserted
1    04/15/2011  23:45:06.085   TMB1A                  Asserted
-----------------------------------------------------------------------------
Master: SEL-421                  Date: 04/15/2011  Time: 23:45:39.111
VT Panel 2                                 Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT              STATE
2    04/15/2011  23:44:54.537   RB01                   Asserted
1    04/15/2011  23:45:06.091   RMB1A                  Asserted
-----------------------------------------------------------------------------
```

The SERs show correct operation for Event 12 – none of the voting scheme relays tripped the circuit breaker. With the voting scheme armed, all three relays received the asserted arming signal. However, the Master relay did not count a majority of the relays voting to trip. Only the trip signal from Slave 2 was counted by the Master relay. Therefore, no breaker trip signal was issued by the Master relay.

Slave 2's trip signal took 6 milliseconds to reach the Master.

Event 13: Trip Master [Voting disarmed]

```
----------------------------------------------------------------------------------------------------
SLAVE 1: SEL-421                Date: 04/15/2011  Time: 23:48:22.557
VT Panel 4                                  Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT              STATE
----------------------------------------------------------------------------------------------------
SLAVE 2: SEL-421                Date: 04/15/2011  Time: 23:48:24.046
VT Panel 3                                  Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT              STATE
----------------------------------------------------------------------------------------------------
Master: SEL-421                 Date: 04/15/2011  Time: 23:48:27.036
VT Panel 2                                  Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME            ELEMENT              STATE
2    04/15/2011  23:48:18.103   50P1                   Asserted
1    04/15/2011  23:48:18.103   TRIP                   Asserted
----------------------------------------------------------------------------------------------------
```

The SERs show correct operation for Event 13 with only the Master relay tripping the circuit breaker directly.

Event 14: Trip Master [Voting **armed**]

```
------------------------------------------------------------------------------------------
SLAVE 1: SEL-421                 Date: 04/15/2011  Time: 23:50:33.714
VT Panel 4                                 Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME           ELEMENT                STATE
1    04/15/2011  23:50:16.337   RB01                    Asserted
------------------------------------------------------------------------------------------
SLAVE 2: SEL-421                 Date: 04/15/2011  Time: 23:50:46.860
VT Panel 3                                 Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME           ELEMENT                STATE
1    04/15/2011  23:50:16.340   RB01                    Asserted
------------------------------------------------------------------------------------------
Master: SEL-421                  Date: 04/15/2011  Time: 23:51:00.398
VT Panel 2                                 Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME           ELEMENT                STATE
2    04/15/2011  23:50:16.325   RB01                    Asserted
1    04/15/2011  23:50:27.342   50P1                    Asserted
------------------------------------------------------------------------------------------
```

The SERs show correct operation for Event 14 – none of the voting scheme relays tripped the circuit breaker. With the voting scheme armed, all three relays received the asserted arming signal. However, the Master relay did not count a majority of the relays voting to trip. Only the Master's own tripping vote was counted by the Master relay. Therefore, no breaker trip signal was issued by the Master relay.

Event 15: No relays trip [Voting disarmed]

```
----------------------------------------------------------------------------------------------------
SLAVE 1: SEL-421                Date: 04/15/2011  Time: 23:53:19.477
VT Panel 4                                 Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE        TIME           ELEMENT                STATE
----------------------------------------------------------------------------------------------------
SLAVE 2: SEL-421                Date: 04/15/2011  Time: 23:53:41.408
VT Panel 3                                 Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE        TIME           ELEMENT                STATE
----------------------------------------------------------------------------------------------------
Master: SEL-421                 Date: 04/15/2011  Time: 23:53:52.177
VT Panel 2                                 Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE        TIME           ELEMENT                STATE
----------------------------------------------------------------------------------------------------
```

The SERs show correct operation for Event 15. No relays detected the fault, and therefore no actions were taken by any of the relays.

Event 16: No relays trip [Voting **armed**]

```
----------------------------------------------------------------------------------------------------
SLAVE 1: SEL-421                Date: 04/15/2011  Time: 23:52:19.477
VT Panel 4                                Serial Number: 2009124182

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME           ELEMENT                STATE
1    04/15/2011  23:52:14.577   RB01                    Asserted
----------------------------------------------------------------------------------------------------
SLAVE 2: SEL-421                Date: 04/15/2011  Time: 23:52:31.408
VT Panel 3                                Serial Number: 2009124183

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME           ELEMENT                STATE
1    04/15/2011  23:52:14.582   RB01                    Asserted
----------------------------------------------------------------------------------------------------
Master: SEL-421                 Date: 04/15/2011  Time: 23:52:42.177
VT Panel 2                                Serial Number: 2009124185

FID=SEL-421-3-R127-V0-Z012011-D20090218

#      DATE         TIME           ELEMENT                STATE
1    04/15/2011  23:52:14.556   RB01                    Asserted
----------------------------------------------------------------------------------------------------
```

The SERs show correct operation for Event 16 – none of the voting scheme relays tripped the circuit breaker. With the voting scheme armed, all three relays received the asserted arming signal. However, the Master relay did not count any tripping votes. Therefore, no breaker trip signal was issued by the Master relay.

3.3.3 Multiple Manufacturers with Hard-Wired Trip Signals

This voting scheme implementation uses two SEL-421 digital relays as the slave relays and a GE F60 digital relay as Master relay. The setup of this voting scheme implementation is shown in Figure 3-6.

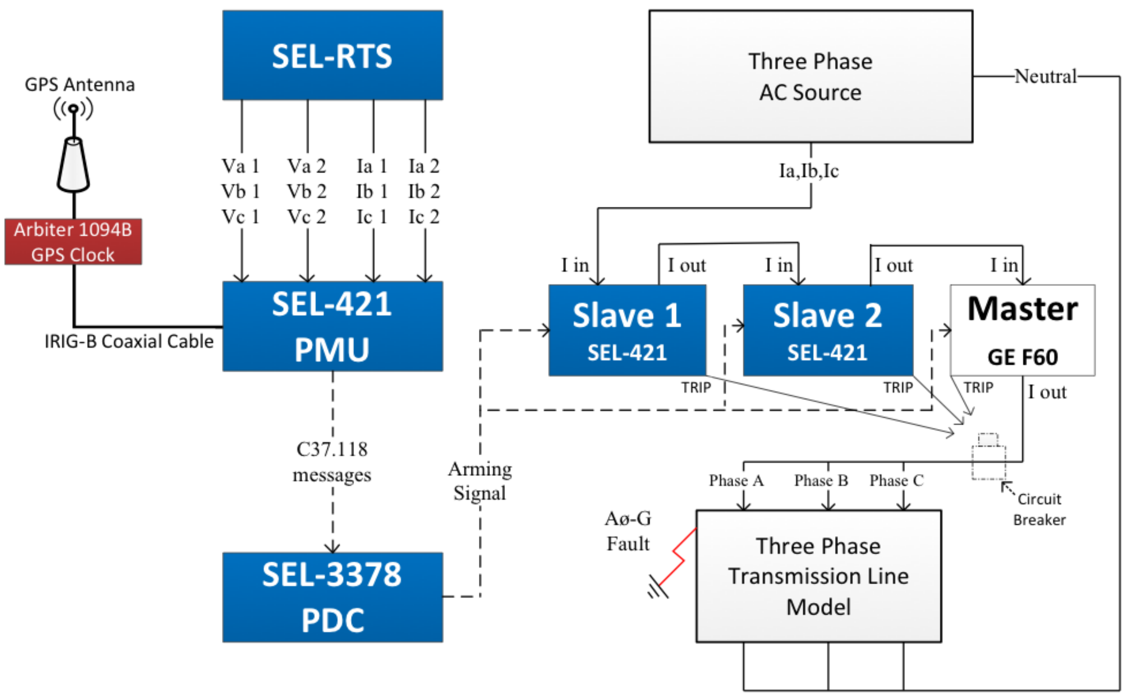

Figure 3-6. Voting scheme implementation w/ GE Master & redundant SEL-421 slaves.

In this implementation, all three of the voting scheme relays are redundant relays when the voting scheme is disarmed. As discussed in Chapter 2, with a redundant relay voting scheme each digital relay must receive the arming signal to allow each relay to trip the circuit breaker if needed when the voting scheme is disarmed (see Sections 2.4 and 2.5). To send the arming signal from the SEL-3378 to the SEL-421 slave relays in this implementation, the same SEL Fast Operate Commands were sent over Ethernet through the local area network (see the beginning of Section 3.3).

The SEL Fast Operate Commands only communicate with SEL digital relays; therefore, a new device was introduced into the voting scheme implementation that allows the GE F60 Master relay to receive the arming signal through SEL Fast Operate Commands. That device is the SEL-2515 Remote I/O Module. This SEL device accepts SEL Fast Operate Commands from the SEL-3378 over a fiber-optic cable and then translates those commands to hard-wired digital contact outputs. A digital contact input on the GE F60 Master relay can then be hard-wired to the appropriate SEL-2515 contact output to receive the arming signal. The circuit in Figure 3-7 shows this arming signal communication to the GE Master using the SEL-2515.

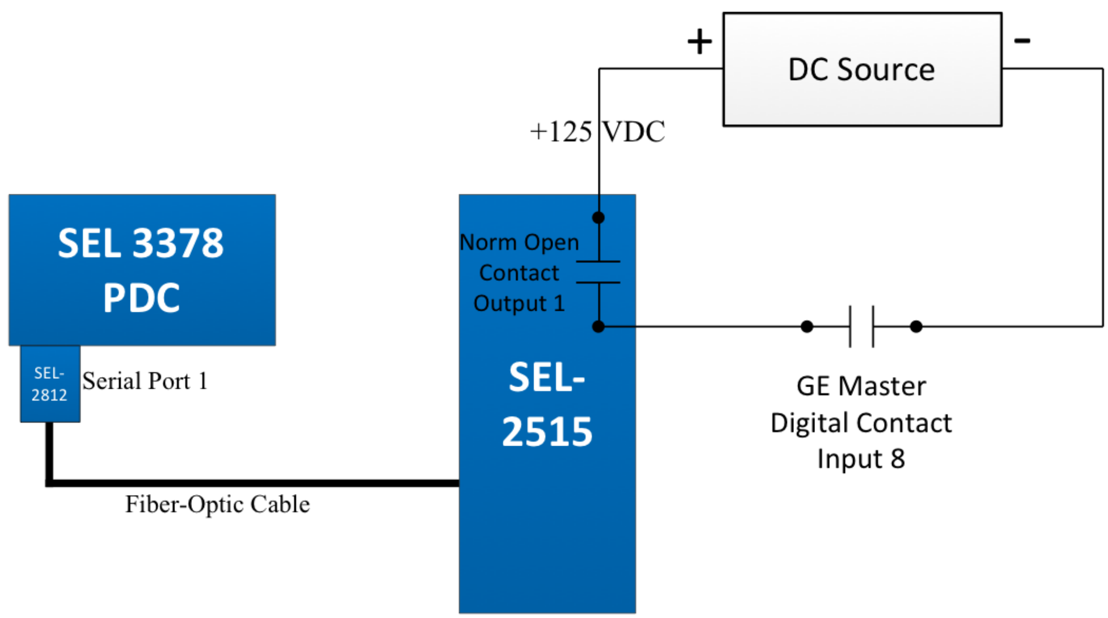

Figure 3-7. Circuit for arming signal communication using the SEL-2515.

In Figure 3-7, a fiber-optic cable is used to send the SEL Fast Operate Commands from the SEL-3378 to the SEL-2515. Notice the addition of the SEL-2812 device on the serial port of the SEL-3378. This device is a fiber-optic transceiver that is connected to a serial port on one side and a fiber-optic cable on the other. Because the SEL-3378 does not have any fiber-optic ports, the SEL-2812 had to be used to communicate with the SEL-2515. When the SEL-3378 issues the SEL Fast Operate Commands to arm or disarm the voting scheme, the SEL-2515 receives the commands and will open or close its normally open Contact Output 1. Contact Output 1 is open when the voting scheme is disarmed and closed when the scheme is armed. When the contact is closed, DC voltage is applied to the GE Master's digital Contact Input 8 causing the internal digital bit corresponding to that input to assert. The GE Master relay's voting scheme logic uses that Contact Input 8 digital bit as the arming signal element.

The last piece of this implementation is the trip signal communication. For all multiple manufacturer voting scheme implementations, trip signal communication was performed over the hard-wired path. To implement hard-wired trip signal communications, the circuit in Figure 3-8 was implemented.

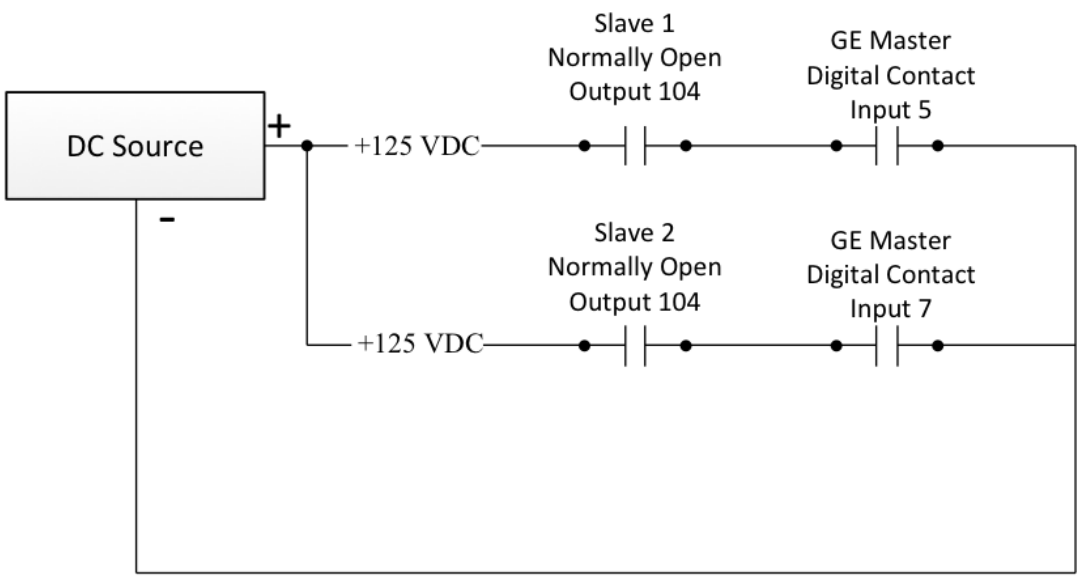

Figure 3-8. Circuit for the hard-wired trip signal communications w/ GE Master.

As discussed earlier in this chapter, a DC source was used to send the trip signals from the slave relays to the GE F60 Master relay using hard-wired connections. The SEL-421 slave relays are the same as the previous implementations, and therefore send their trip signals through OUT104. Slave 1 sends its trip signal to the GE F60 Master relay's digital Contact Input 5, and Slave 2 sends its trip signal to the GE Master's digital Contact Input 7, as shown in Figure 3-8. When the DC voltage is applied to a digital input on the Master relay, the input contact will close and the digital bit corresponding to that input contact will assert to 1. The GE F60 Master relay's voting scheme logic then uses the two digital bits corresponding to the two digital contact inputs.

The results for this voting scheme implementation are shown in Table 3-4. The table shows that the multiple manufacturer, redundant, hard-wired trip signal voting scheme implementation correctly operated for all tested events.

Table 3-4. Results for the multiple manufacturer, redundant slave voting scheme.

Voting Scheme Status	Arming Signal	Event	Circuit Breaker Status (Tripped = 1) (Not tripped = 0)	Which relays sent trip signals to the breaker?
Disarmed	0	**1**. Trip Slave 1, Slave 2, Master	**1**	Slave 1, Slave 2, Master
	0	**3**. Trip Slave 1, Slave 2	**1**	Slave 1, Slave 2
	0	**5**. Trip Slave 1, Master	**1**	Slave 1, Master
	0	**7**. Trip Slave 2, Master	**1**	Slave 2, Master
	0	**9**. Trip Slave 1	**1**	Slave 1
	0	**11**. Trip Slave 2	**1**	Slave 2
	0	**13**. Trip Master	**1**	Master
	0	**15**. No relays trip	0	None
Armed	1	**2**. Trip Slave 1, Slave 2, Master	**1**	Master
	1	**4**. Trip Slave 1, Slave 2	**1**	Master
	1	**6**. Trip Slave 1, Master	**1**	Master
	1	**8**. Trip Slave 2, Master	**1**	Master
	1	**10**. Trip Slave 1	0	None
	1	**12**. Trip Slave 2	0	None
	1	**14**. Trip Master	0	None
	1	**16**. No relays trip	0	None

The results in Table 3-4 were derived from the Sequential Event Records (SERs) from each voting scheme digital relay. This voting scheme implementation is the identical to the implementation in Section 3.3.1, except for the Master relay is now a GE F60 digital relay. Therefore, the SERs are not listed for the SEL-421 slave relays in this section's multiple manufacturer implementation because the SERs for the slave relays are exactly the same as the slave relay SERs in Section 3.3.1.

The SERs for the GE F60 Master relay are shown below. To analyze the SERs for the GE F60 digital relay, the digital bits in the records must be explained. In the GE F60 Master relay, the `PHASE IOC1 PKP A and PHASE IOC1 OP A` elements are the instantaneous overcurrent function elements. When the `PHASE IOC` element asserts, the GE digital relay has measured a current input signal above the instantaneous overcurrent pickup setting in the relay (set at 1.0 Amp).

The `Virt OP 1` element is the Master relay's trip element. When the `Virt OP 1` element asserts, the Master relay's voting scheme logic has decided to trip the circuit breaker. This element in GE Master relay represents the "Master trips Circuit breaker" box in Figure 2-4. To allow the GE Master relay to physically send the trip signal to the circuit breaker, the `Cont OP 1` element was used. This element provides the open or close command for the GE relay's digital Contact Output 1. When `Cont OP 1` asserts, the Contact Output 1 closes and sends the trip signal to the circuit breaker. Whenever `Cont OP 1` is deasserted, the Contact Output 1 remains open and therefore no trip signal is sent to the circuit breaker. The `Cont OP 1` element was set equal to the `Virt OP 1` element. Therefore, the GE Master's tripping decision is ultimately sent to Contact Output 1 (`Cont OP 1`) to directly trip the circuit breaker if the decision is made.

The `Cont IP 5` and `Cont IP 7` elements are the digital trip signals from each slave relay input to the Master relay via hard-wired communications. The Master relay uses an asserted digital input as a tripping "vote" from the slave relay that sent the digital input. These digital inputs are used in the logic equation of the Master relay, as discussed in Chapter 2. As shown in Figure 3-8, the `Cont IP 5` is the trip signal from Slave 1 and `Cont IP 7` is the trip signal from Slave 2.

The last element in the GE relay's SERs is `Cont IP 8`. This element is the arming bit contained in the arming signal from the SEL-3378. Figure 3-7 how the GE F60 Master relays receive this `Cont IP 8` arming bit.

Note that the SERs for the GE Master relay list the oldest element actions first, but label them with the smallest number. This numbering is opposite to the SERs for the SEL-421 digital relays.

All of these elements are used in the voting scheme devices in this implementation, and most are in the logic equations of the relays. Equation (3.7), (3.8), and (3.9) show the logic equations for the Master, Slave 1, and Slave 2 digital relays, respectively.

$$
\begin{aligned}
&GE\ F60\ Master\ relay\ CB\ TRIP = Cont\ Op\ 1 = Virt\ Op\ 1 = \\
&\quad [(PHASE\ IOC1\ PKP * Cont\ Ip\ 5\ ON * Cont\ Ip\ 8\ ON) \\
&\quad +(PHASE\ IOC1\ PKP * Cont\ Ip\ 7\ ON * Cont\ Ip\ 8\ ON) \\
&\quad +(Cont\ Ip\ 5\ ON * Cont\ Ip\ 7\ ON * Cont\ Ip\ 8\ ON)] \\
&\quad +[PHASE\ IOC1\ PKP * !Cont\ Ip\ 8\ ON]
\end{aligned} \tag{3.7}
$$

$$SEL - 421\ Slave\ 1\ CB\ TRIP = 50P1 * !RB01 \tag{3.8}$$

$$SEL - 421\ Slave\ 2\ CB\ TRIP = 50P1 * !RB01 \tag{3.9}$$

Event 1: Trip Slave 1, Slave 2, and Master [Voting disarmed]

```
MASTER: GE F60

FORMAT,SNAPSHOT_EVENT,Event Number,Date/Time,Cause (Hex),Cause

SHORT_EVENT,2,Apr 17 2011 14:51:12.183110,0407,Cont Ip 7    On
SHORT_EVENT,3,Apr 17 2011 14:51:12.184113,0405,Cont Ip 5    On
SHORT_EVENT,4,Apr 17 2011 14:51:12.186011,8800,PHASE IOC1 PKP A
SHORT_EVENT,5,Apr 17 2011 14:51:12.186011,9400,PHASE IOC1 OP A
SHORT_EVENT,6,Apr 17 2011 14:51:12.186011,0C01,Virt Op 1    On
SHORT_EVENT,7,Apr 17 2011 14:51:12.186011,1001,Cont Op 1    On
```

In Event 1, the GE Master tripped the circuit breaker immediately after its instantaneous overcurrent pickup values asserted (`Cont Op 1` asserted). Notice that the Master received both slave relay trip signals before the Master detected the fault. The Master ignored the signals because voting was disarmed.

Event 2: Trip Slave 1, Slave 2, and Master [Voting **armed**]

```
Master: GE F60

FORMAT,SNAPSHOT_EVENT,Event Number,Date/Time,Cause (Hex),Cause

SHORT_EVENT,2,Apr 17 2011 14:51:58.980783,0408,Cont Ip 8    On
SHORT_EVENT,3,Apr 17 2011 14:52:08.114339,8800,PHASE IOC1 PKP A
SHORT_EVENT,4,Apr 17 2011 14:52:08.114339,9400,PHASE IOC1 OP A
SHORT_EVENT,5,Apr 17 2011 14:52:08.121315,0407,Cont Ip 7    On
SHORT_EVENT,6,Apr 17 2011 14:52:08.121315,0405,Cont Ip 5    On
SHORT_EVENT,7,Apr 17 2011 14:52:08.124651,0C01,Virt Op 1    On
SHORT_EVENT,8,Apr 17 2011 14:52:08.124651,1001,Cont Op 1    On
```

Event 2 is the same case as Event 1, but with the voting scheme armed. The Master relay received the arming signal (`Cont Ip 8` asserted) and also picked up for the fault. However, the Master relay did not trip until it received the `Cont Ip 7` signal from Slave 2. As soon as the `Cont Ip 7` signal was detected, the Master relay issued the trip signal to the circuit breaker because two out of the three voting scheme relays had positive trip signals (`PHASE IOC1 OP A and Cont Ip 7`). The voting scheme operated correctly for Event 2.

Event 3: Trip Slave 1 and Slave 2 [Voting disarmed]

```
----------------------------------------------------------------------------------------------------
Master: GE F60

FORMAT,SNAPSHOT_EVENT,Event Number,Date/Time,Cause (Hex),Cause

SHORT_EVENT,2,Apr 17 2011 14:53:21.533975,0407,Cont Ip 7    On
SHORT_EVENT,3,Apr 17 2011 14:53:21.535976,0405,Cont Ip 5    On
----------------------------------------------------------------------------------------------------
```

The GE Master did not trip for Event 3. The GE relay did receive the trip signals from the two slave relays (`Cont Ip 5` and `Cont Ip 7 asserted`), but this did not effect the tripping decision of the GE Master. The SERs show correct operation for Event 3.

Event 4: Trip Slave 1 and Slave 2 [Voting **armed**]

```
----------------------------------------------------------------------------------------------------
MASTER: GE F60

FORMAT,SNAPSHOT_EVENT,Event Number,Date/Time,Cause (Hex),Cause

SHORT_EVENT,2,Apr 17 2011 14:54:16.360632,0408,Cont Ip 8    On
SHORT_EVENT,3,Apr 17 2011 14:54:27.467666,0405,Cont Ip 5    On
SHORT_EVENT,4,Apr 17 2011 14:54:27.468169,0407,Cont Ip 7    On
SHORT_EVENT,5,Apr 17 2011 14:54:27.471398,0C01,Virt Op 1    On
SHORT_EVENT,6,Apr 17 2011 14:54:27.471398,1001,Cont Op 1    On
----------------------------------------------------------------------------------------------------
```

The Master relay tripped the circuit breaker after it received the asserted arming signal and the trip signals from both slave relays. This is the correct operation for Event 4.

Event 5: Trip Slave 1 and Master [Voting disarmed]

```
-----------------------------------------------------------------------------------------------------------
MASTER: GE F60

FORMAT,SNAPSHOT_EVENT,Event Number,Date/Time,Cause (Hex),Cause

SHORT_EVENT,2,Apr 17 2011 14:55:54.745150,8800,PHASE IOC1 PKP A
SHORT_EVENT,3,Apr 17 2011 14:55:54.745150,9400,PHASE IOC1 OP A
SHORT_EVENT,4,Apr 17 2011 14:55:54.745150,0C01,Virt Op 1    On
SHORT_EVENT,5,Apr 17 2011 14:55:54.745150,1001,Cont Op 1    On
SHORT_EVENT,6,Apr 17 2011 14:55:54.748473,0405,Cont Ip 5    On

-----------------------------------------------------------------------------------------------------------
```

The SER shows correct operation for Event 5 with the Master relay tripping the circuit breaker directly and receiving the trip signal from Slave 1 three milliseconds later.

Event 6: Trip Slave 1 and Master [Voting **armed**]

```
-----------------------------------------------------------------------------------------------------------
MASTER: GE F60

FORMAT,SHORT_EVENT,Event Number,Date/Time,Cause (Hex),Cause

SHORT_EVENT,2,Apr 17 2011 14:56:33.741970,0408,Cont Ip 8    On
SHORT_EVENT,3,Apr 17 2011 14:56:41.514276,8800,PHASE IOC1 PKP A
SHORT_EVENT,4,Apr 17 2011 14:56:41.514276,9400,PHASE IOC1 OP A
SHORT_EVENT,5,Apr 17 2011 14:56:41.516867,0405,Cont Ip 5    On
SHORT_EVENT,6,Apr 17 2011 14:56:41.520530,0C01,Virt Op 1    On
SHORT_EVENT,7,Apr 17 2011 14:56:41.520530,1001,Cont Op 1    On
-----------------------------------------------------------------------------------------------------------
```

The SER shows correct operation for Event 6, with the Master relay receiving the arming bit and tripping the circuit breaker directly due to the tripping votes from Slave 1 and the Master.

Event 7: Trip Slave 2 and Master [Voting disarmed]

```
------------------------------------------------------------------------------------------------------
MASTER: GE F60

FORMAT,SHORT_EVENT,Event Number,Date/Time,Cause (Hex),Cause

SHORT_EVENT,2,Apr 17 2011 14:57:51.328280,8800,PHASE IOC1 PKP A
SHORT_EVENT,3,Apr 17 2011 14:57:51.328280,9400,PHASE IOC1 OP A
SHORT_EVENT,4,Apr 17 2011 14:57:51.328280,0C01,Virt Op 1    On
SHORT_EVENT,5,Apr 17 2011 14:57:51.328280,1001,Cont Op 1    On
SHORT_EVENT,6,Apr 17 2011 14:57:51.330579,0407,Cont Ip 7    On
------------------------------------------------------------------------------------------------------
```

The SER shows correct operation for Event 5 with the Master relay tripping the circuit breaker directly and receiving the trip signal from Slave 2 two milliseconds later.

Event 8: Trip Slave 2 and Master [Voting **armed**]

```
------------------------------------------------------------------------------------------------------
MASTER: GE F60

FORMAT,SHORT_EVENT,Event Number,Date/Time,Cause (Hex),Cause

SHORT_EVENT,2,Apr 17 2011 14:58:39.101954,0408,Cont Ip 8    On
SHORT_EVENT,3,Apr 17 2011 14:58:50.419031,0407,Cont Ip 7    On
SHORT_EVENT,4,Apr 17 2011 14:58:50.420098,8800,PHASE IOC1 PKP A
SHORT_EVENT,5,Apr 17 2011 14:58:50.420098,9400,PHASE IOC1 OP A
SHORT_EVENT,6,Apr 17 2011 14:58:50.422182,0C01,Virt Op 1    On
SHORT_EVENT,7,Apr 17 2011 14:58:50.422182,1001,Cont Op 1    On
------------------------------------------------------------------------------------------------------
```

The SER shows correct operation for Event 8, with the Master relay tripping the circuit breaker due to the tripping votes from Slave 2 and the Master.

Event 9: Trip Slave 1 [Voting disarmed]

```
--------------------------------------------------------------------------------------------------------
MASTER: GE F60

FORMAT,SHORT_EVENT,Event Number,Date/Time,Cause (Hex),Cause

SHORT_EVENT,2,Apr 17 2011 14:59:59.655871,0405,Cont Ip 5    On
--------------------------------------------------------------------------------------------------------
```

The SER shows correct operation for Event 9 with the Master relay receiving the trip signal from Slave 1. This did not cause the Master relay to trip the breaker, as designed.

Event 10: Trip Slave 1 [Voting **armed**]

```
--------------------------------------------------------------------------------------------------------
FORMAT,SHORT_EVENT,Event Number,Date/Time,Cause (Hex),Cause
FORMAT,SNAPSHOT_EVENT,Event Number,Date/Time,Cause (Hex),Cause
SHORT_EVENT,1,Apr 17 2011 15:00:27.836678,7C00,EVENTS CLEARED
SHORT_EVENT,2,Apr 17 2011 15:00:31.232176,0408,Cont Ip 8    On
SHORT_EVENT,3,Apr 17 2011 15:00:44.170985,0405,Cont Ip 5    On
--------------------------------------------------------------------------------------------------------
```

The SER shows correct operation for Event 10. The Master relay received the arming signal and the trip signal from Slave 1, but no breaker trip was issued by the Master.

Event 11: Trip Slave 2 [Voting disarmed]

```
-----------------------------------------------------------------------------------------------------------
MASTER: GE F60

FORMAT,SHORT_EVENT,Event Number,Date/Time,Cause (Hex),Cause

SHORT_EVENT,2,Apr 17 2011 15:02:02.997917,0407,Cont Ip 7    On
-----------------------------------------------------------------------------------------------------------
```

The SER shows correct operation for Event 11 with the Master relay receiving the trip signal from Slave 2. This did not cause the Master relay to trip the breaker, as designed.

Event 12: Trip Slave 2 [Voting **armed**]

```
-----------------------------------------------------------------------------------------------------------
FORMAT,SHORT_EVENT,Event Number,Date/Time,Cause (Hex),Cause
FORMAT,SNAPSHOT_EVENT,Event Number,Date/Time,Cause (Hex),Cause
SHORT_EVENT,1,Apr 17 2011 15:02:34.172926,7C00,EVENTS CLEARED
SHORT_EVENT,2,Apr 17 2011 15:02:40.363678,0408,Cont Ip 8    On
SHORT_EVENT,3,Apr 17 2011 15:02:47.783928,0407,Cont Ip 7    On
-----------------------------------------------------------------------------------------------------------
```

The SER shows correct operation for Event 12. The Master relay received the arming signal and the trip signal from Slave 2, but no breaker trip was issued by the Master.

Event 13: Trip Master [Voting disarmed]

```
------------------------------------------------------------------------------------------------------
MASTER: GE F60

FORMAT,SHORT_EVENT,Event Number,Date/Time,Cause (Hex),Cause

SHORT_EVENT,2,Apr 17 2011 15:03:56.247098,8800,PHASE IOC1 PKP A
SHORT_EVENT,3,Apr 17 2011 15:03:56.247098,9400,PHASE IOC1 OP A
SHORT_EVENT,4,Apr 17 2011 15:03:56.247098,0C01,Virt Op 1    On
SHORT_EVENT,5,Apr 17 2011 15:03:56.247098,1001,Cont Op 1    On
------------------------------------------------------------------------------------------------------
```

The SER shows correct operation for Event 13 with the Master relay tripping the circuit breaker directly.

Event 14: Trip Master [Voting **armed**]

```
------------------------------------------------------------------------------------------------------
MASTER: GE F60

FORMAT,SHORT_EVENT,Event Number,Date/Time,Cause (Hex),Cause

SHORT_EVENT,2,Apr 17 2011 15:04:31.111089,0408,Cont Ip 8    On
SHORT_EVENT,3,Apr 17 2011 15:04:38.587726,8800,PHASE IOC1 PKP A
SHORT_EVENT,4,Apr 17 2011 15:04:38.587726,9400,PHASE IOC1 OP A
------------------------------------------------------------------------------------------------------
```

The SER shows correct operation for Event 14. The Master relay received the arming signal and picked up for the fault, but no breaker trip was issued by the Master as it did not receive two (or more) tripping votes.

Event 15: No relays trip [Voting disarmed]

```
-----------------------------------------------------------------------------------------------------
MASTER: GE F60
FORMAT,SHORT_EVENT,Event Number,Date/Time,Cause (Hex),Cause

-----------------------------------------------------------------------------------------------------
```

The SERs show correct operation for Event 15. The Master relay performed no action as it did not detect the fault and did not receive the arming signal.

Event 16: No relays trip [Voting **armed**]

```
-----------------------------------------------------------------------------------------------------
MASTER: GE F60
FORMAT,SHORT_EVENT,Event Number,Date/Time,Cause (Hex),Cause
SHORT_EVENT,2,Apr 17 2011 15:05:46.226258,0408,Cont Ip 8    On
-----------------------------------------------------------------------------------------------------
```

The SER shows correct operation for Event 16. The Master relay received the arming signal, did not detect the fault, and did not issue a trip signal to the circuit breaker.

All the voting scheme implementations setup and tested in Chapter 3 performed correctly. The work presented in Chapter 2 and Chapter 3 produce fully operational adaptive voting schemes.

3.3.4 Trip Signal Communication Results

As mentioned earlier in Chapter 3, all the SERs were analyzed to determine the time delays associated with both trip signal communication methods: hard-wired and SEL Mirrored Bits. Table 3-5 lists all of the calculated trip signal time delays for the tested voting scheme implementations, in the order of implementations in Chapter 3.

Table 3-5. Observed trip signal communication time delays.

Hard-Wired Trip Signal Delays (msec)	SEL Mirrored Bits Trip Signal Delays (msec)
8	10
8	11
8	9
8	9
7	9
8	9
7	8
8	9
6	9
8	3
7	8
7	8
8	9
8	4
7	9
8	6

With any time delays in power system protection, it is critical to know the worst-case, or maximum, delay that could exist. The results in Table 3-5 can be summarized into Table 3-6.

Table 3-6. Summary of observed trip signal communication time delays.

Hard-Wired Trip Signal Delays	**SEL Mirrored Bits Trip Signal Delays**
Maximum delay observed: **8 msec** Minimum delay observed: **6 msec** Average of observed delays: **7.56 msec**	Maximum delay observed: **11 msec** Minimum delay observed: **3 msec** Average of observed delays: **8.125 msec**

From the tests performed on the various voting scheme implementations in this thesis, the hard-wired trip signals had a maximum time delay of 8 milliseconds, while the SEL Mirrored Bits trip signals had a maximum time delay of 11 milliseconds. Further testing of these communication channels needs to be performed to achieve a more accurate summary than that shown in Table 3-6. However, the results in Tables 3-5 and 3-6 can provide an estimate of the time delays to expect when implementing an adaptive voting scheme.

The trip signal communication time delays is a critical part of the adaptive voting scheme. When the voting scheme is armed, the Master relay's final trip signal sent to a circuit breaker will always depend on the trip signal communication channels from the slave relays. The Master relay has to wait for trip signal communication channel delays before a majority vote can ever be determined. Therefore, the adaptive voting scheme adds an existing time delay – which is dependent on the trip signal communication channels – to the existing time delay of the original protection schemes. This additional time delay needs to be evaluated for each separate voting scheme implementation. While this is a negative attribute of the adaptive voting scheme, improvements could be made to reduce the trip signal communication delays, such as: faster communication mediums, configuring relay processing priority to the trip signal inputs, and decreasing the physical distance between the Master and slave relays. These improvements need to be investigated further, but the work in this Chapter presents a procedure for determining the trip signal time delay for various adaptive voting schemes implementations.

Chapter 4 – Conclusions and Future Work

4.1 Conclusions

The primary topic of this thesis was the full implementation of the adaptive voting scheme, an adaptive protection scheme that optimally adjusts the security/dependability balance of a power system based on the existing state of the system. With just the addition a phasor data concentrator and strategically placed phasor measurement units providing Wide Area Measurements of a system, the adaptive voting scheme can be implemented at a power system's critical location using existing protection practices. The adaptive voting scheme acts as hidden protection at a critical location, activating to prevent misoperations only during times when the system is stressed. During all other times when the system is in a safe condition, the adaptive voting scheme will be deactivated, allowing the existing protection practices to operate as normal.

Because of the various existing protection practices of utilities around the world, the adaptive voting scheme may be implemented in a number of ways. Redundant digital relays, digital input/output communications, and type of protection schemes are some of the options that must be considered for each voting scheme implementation. However, the only requirement of the voting scheme relays is that they must have the ability to use custom trip equations and digital input/output signals. All other variations can be chosen based on existing practices. If three different protection systems with an armed voting scheme are used, the scheme will provide more security than using the same protection system for all three relays. If different manufacturers for all voting scheme relays are used, the scheme will provide protection against a common mode of failure in one manufacturer's devices. The voting scheme can provide additional security when it is disarmed if redundant slave relays are used. These voting scheme implementation considerations must be collectively decided upon on a case-by-case basis.

The research work in this thesis proves that the adaptive protection scheme can be implemented by adding a PDC and PMUs with existing digital relays and existing protection practices. The main conclusions obtained from this research are listed below.

1. The digital relays used in the adaptive protection scheme must have digital input/output modules and custom trip equation capabilities.
2. The adaptive voting scheme can be implemented in various ways to match the existing practices around the world and protect against common modes of failure in hardware and protection schemes.
3. The code to implement Decision Trees on a phasor data concentrator is simple enough to allow other commercial PDCs to be used with the voting scheme.
4. Hard-wired I/O and SEL Mirrored Bits communications are both acceptable to use for the adaptive voting scheme.
5. All the voting scheme implementations performed in this thesis operated correctly for all events.

4.2 Future Work

Implementing other variations of the adaptive voting scheme can extend the work presented in this thesis. One implementation that should be setup and tested is an adaptive voting scheme that uses three different types of power system protection. As an example, the voting scheme could use one distance protection relay and two different pilot protection schemes, such as Directional Comparison Blocking and Permissive Underreaching Transfer Trip. Architecture-1 of the adaptive voting scheme should also be setup and tested to determine its operational characteristics.

Other implementations that could be tested involve using other manufacturer's digital relays, other communication protocols and associated time delays, and different commercial phasor data concentrator's. If the adaptive voting scheme relays used have multiple protection group settings, the relays could also be configured to have two protection groups. One protection group would be active when the voting scheme is disarmed, while the other protection group would be active when the voting scheme is armed. The internal operations of the digital relays would be changed, but the operation of the overall voting scheme remains the same. The addition of an arming signal timer could also be implemented and tested on adaptive voting schemes. This timer would be used to prevent the voting scheme from being armed and disarmed frequently within a short period of time.

With any new protection scheme, the end goal is the installation of the scheme in a power system and then providing a benefit to system operators. The adaptive voting scheme is no different. Having the adaptive voting scheme installed in an actual system with its performance monitored is the ultimate extension of the work presented in this thesis.

4.3 Main Contribution

The main contribution of the research work presented in this thesis was the full implementation of an adaptive protection scheme. For that to main contribution to become a reality, other significant contributions were made. Those contributions are listed below.

1. Implemented and tested multiple voting scheme implementations matching various protection practices existing today.
2. Developed and tested the logic equations for the adaptive voting scheme Master and slave relays.
3. Developed a procedure for testing voting scheme implementations.
4. Developed and tested code for implementing Decision Trees in a phasor data concentrator.
5. Tested two communication protocols with voting scheme implementations and found both are acceptable to use for the adaptive voting scheme.

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15. Schweitzer Engineering Laboratories, *SEL-3378 Synchrophasor Vector Processor Instruction Manual*, 2010.
16. Schweitzer Engineering Laboratories, *SEL-RTS Relay Test System Instruction Manual*, 1997.
17. Arbiter Systems, http://www.arbiter.com/.
18. General Electric Industrial Systems, *F60 Feeder Management Relay: UR Series Instruction Manual*, 2009.

Appendix A – Devices in the Voting Scheme Implementations

1. SEL-421 Relay – Protection, Automation, Control

Model #	SEL-421-3
Part #	042134152C4AXH31XXX
Firmware version	SEL-421-3-R127-V0-Z012011-D20090218

2. GE F60 Feeder Management Relay

Version	GE F60 3.4X
Order Code	F60-C00-HCH-F8A-H6M-M6N-PXX-UXX-WXX

3. SEL-3378 Synchrophasor Vector Processor

Model #	SEL-3378
Part #	3378043X561XXHXX
Firmware version	SEL-3378-R102-V0-Z002002-D20100127

4. SEL-2515 Remote I/O Module

Part #	2515364XX
Firmware version	SEL-2515-R101-V0-Z0000000-D20060915

5. SEL Adaptive Multichannel Source (SEL-AMS)

Part #	400000110

6. SEL-2812MT Fiber-Optic Transceiver

Appendix B – SEL-3378 PDC Settings and Code

B.1 TCS Program

This program is responsible for setting input and output connections to the SEL-3378, as well as performing the time alignment function with the IEEE C37.118 synchrophasor data.

B.1.1 Voting Scheme with SEL-421 Master

```
(*Panel 1 PMU*)
PMCU_INPUT[1].EN := TRUE;
PMCU_INPUT[1].IDCODE:= 1;
PMCU_INPUT[1].C37_118_CLIENT:=TRUE;
PMCU_INPUT[1].FASTOP:=0;
PMCU_INPUT[1].CONNECTION := 'E';
PMCU_INPUT[1].EPORT.SERVER_IP := '192.168.1.113';
PMCU_INPUT[1].EPORT.SERVER_CMD_PORT := 4757;
PMCU_INPUT[1].EPORT.TRANSPORT_SCHEME := 'UDP_T';
PMCU_INPUT[1].EPORT.CLIENT_IP := '192.168.1.145';
PMCU_INPUT[1].EPORT.CLIENT_DATA_PORT := 51116;

(*Panel 2 SEL-421 Master Relay*)
PMCU_INPUT[2].EN := TRUE;
PMCU_INPUT[2].IDCODE:= 2;
PMCU_INPUT[2].C37_118_CLIENT:=FALSE;
PMCU_INPUT[2].FASTOP:=1;
PMCU_INPUT[2].CONNECTION := 'E';
PMCU_INPUT[2].EPORT.SERVER_IP := '192.168.1.114';
PMCU_INPUT[2].EPORT.FASTOP_PORT:=23; (* Sends FO commands to Port 23 on the SEL-421 *)
PMCU_INPUT[2].EPORT.FASTOP_PORT_TELNET_EN:=TRUE;

(*Panel 3 SEL-421 Slave Relay*)
PMCU_INPUT[3].EN := TRUE;
PMCU_INPUT[3].IDCODE:= 3;
PMCU_INPUT[3].C37_118_CLIENT:=FALSE;
PMCU_INPUT[3].FASTOP:=1;
PMCU_INPUT[3].CONNECTION := 'E';
PMCU_INPUT[3].EPORT.SERVER_IP := '192.168.1.115';
PMCU_INPUT[3].EPORT.FASTOP_PORT:=23; (* Sends FO commands to Port 23 on the SEL-421 *)
PMCU_INPUT[3].EPORT.FASTOP_PORT_TELNET_EN:=TRUE;

(*Panel 4 SEL-421 Slave Relay*)
PMCU_INPUT[4].EN := TRUE;
PMCU_INPUT[4].IDCODE:= 4;
PMCU_INPUT[4].C37_118_CLIENT:=FALSE;
PMCU_INPUT[4].FASTOP:=1;
PMCU_INPUT[4].CONNECTION := 'E';
PMCU_INPUT[4].EPORT.SERVER_IP := '192.168.1.116';
PMCU_INPUT[4].EPORT.FASTOP_PORT:=23; (* Sends FO commands to Port 23 on the SEL-421 *)
PMCU_INPUT[4].EPORT.FASTOP_PORT_TELNET_EN:=TRUE;
```

```
TCSconfigOK := TCS_CONFIG(EN := TRUE,
PDC_IDCODE := 1000,
pHID := ADR(HEADER_118),
NFREQ := 60,
MRATE := 60,
MISSING_MESSAGE_THRESHOLD := 30,
TIME_UNSYNC_BLOCK := TRUE,
pCMD_OUT_DATA_IN := ADR(PMCU_INPUT),
pCMD_IN_DATA_OUT := ADR(PMCU_OUTPUT),
pERROR := ADR(TCS_ERROR_OUT),
pSTATUS := ADR(TCS_STATUS_OUT));
```

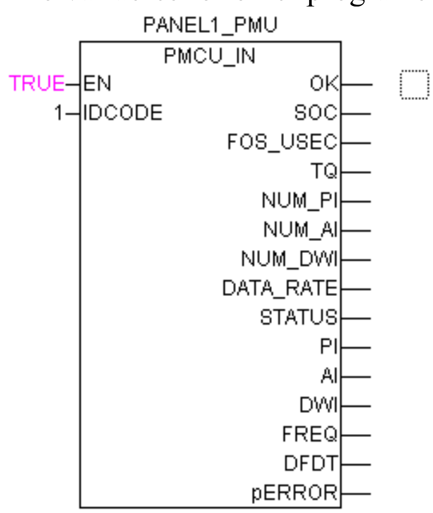
B.1.2 Voting Scheme with GE F60 Master

```
(*Panel 1 PMU*)
PMCU_INPUT[1].EN := TRUE;
PMCU_INPUT[1].IDCODE:= 1;
PMCU_INPUT[1].C37_118_CLIENT:=TRUE;
PMCU_INPUT[1].FASTOP:=0;
PMCU_INPUT[1].CONNECTION := 'E';
PMCU_INPUT[1].EPORT.SERVER_IP := '192.168.1.113';
PMCU_INPUT[1].EPORT.SERVER_CMD_PORT := 4757;
PMCU_INPUT[1].EPORT.TRANSPORT_SCHEME := 'UDP_T';
PMCU_INPUT[1].EPORT.CLIENT_IP := '192.168.1.145';
PMCU_INPUT[1].EPORT.CLIENT_DATA_PORT := 51116;

(*SEL-2515 for the GE Master relay*)
PMCU_INPUT[5].EN := TRUE;
PMCU_INPUT[5].IDCODE:= 5;
PMCU_INPUT[5].C37_118_CLIENT:=FALSE;
PMCU_INPUT[5].FASTOP:=1;
PMCU_INPUT[5].CONNECTION:='S';
PMCU_INPUT[5].SPORT.PORT_NUMBER:=1;
PMCU_INPUT[5].SPORT.CONNECTION_SPEED:=19200;
PMCU_INPUT[5].SPORT.RTS_CTS:=TRUE;

(*Panel 3 Slave Relay*)
PMCU_INPUT[3].EN := TRUE;
PMCU_INPUT[3].IDCODE:= 3;
PMCU_INPUT[3].C37_118_CLIENT:=FALSE;
PMCU_INPUT[3].FASTOP:=1;
PMCU_INPUT[3].CONNECTION := 'E';
PMCU_INPUT[3].EPORT.SERVER_IP := '192.168.1.115';
PMCU_INPUT[3].EPORT.FASTOP_PORT:=23; (* Sends FO commands to Port 23 on the SEL-421 *)
PMCU_INPUT[3].EPORT.FASTOP_PORT_TELNET_EN:=TRUE;

(*Panel 4 Slave Relay*)
PMCU_INPUT[4].EN := TRUE;
PMCU_INPUT[4].IDCODE:= 4;
PMCU_INPUT[4].C37_118_CLIENT:=FALSE;
PMCU_INPUT[4].FASTOP:=1;
PMCU_INPUT[4].CONNECTION := 'E';
PMCU_INPUT[4].EPORT.SERVER_IP := '192.168.1.116';
```

```
PMCU_INPUT[4].EPORT.FASTOP_PORT:=23; (* Sends FO commands to Port 23 on the SEL-421 *)
PMCU_INPUT[4].EPORT.FASTOP_PORT_TELNET_EN:=TRUE;

TCSconfigOK := TCS_CONFIG(EN := TRUE,
PDC_IDCODE := 1000,
pHID := ADR(HEADER_118),
NFREQ := 60,
MRATE := 60,
MISSING_MESSAGE_THRESHOLD := 30,
TIME_UNSYNC_BLOCK := TRUE,
pCMD_OUT_DATA_IN := ADR(PMCU_INPUT),
pCMD_IN_DATA_OUT := ADR(PMCU_OUTPUT),
pERROR := ADR(TCS_ERROR_OUT),
pSTATUS := ADR(TCS_STATUS_OUT));
```

B.2 PMCU_ASSIGN Program

This program is responsible for collecting the incoming PMU data and assigning it to variables for other programs to use.



B.3 ARMING_DT Program

This program runs the Decision Tree for the voting scheme using the incoming PMU data and then assigns the Arming Signal bit (TRUE = stressed, FALSE = safe).

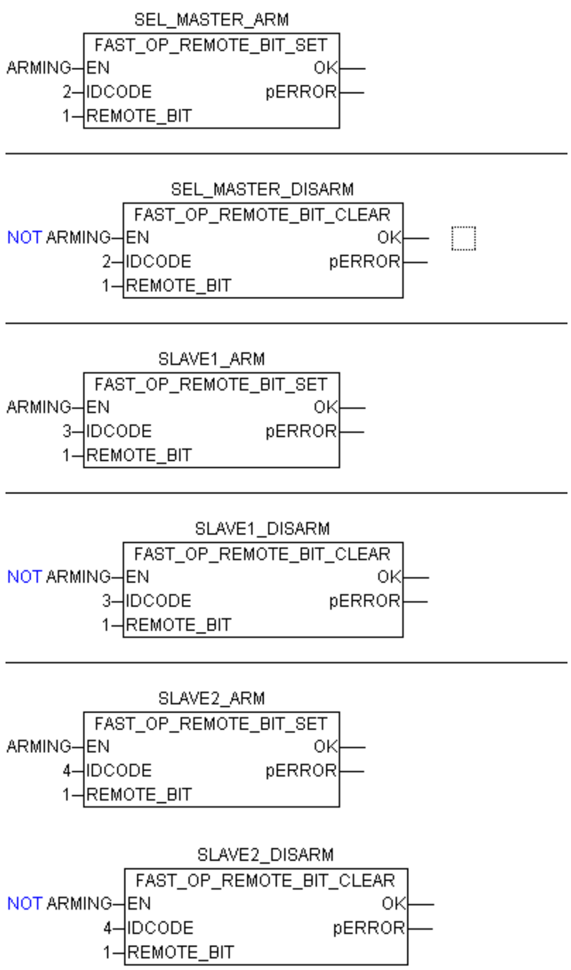
Code:

```
IF PANEL1_PMU.PI[10].MAG >= 6
THEN
        ARMING := TRUE;
ELSE
        ARMING := FALSE;
END_IF;
```

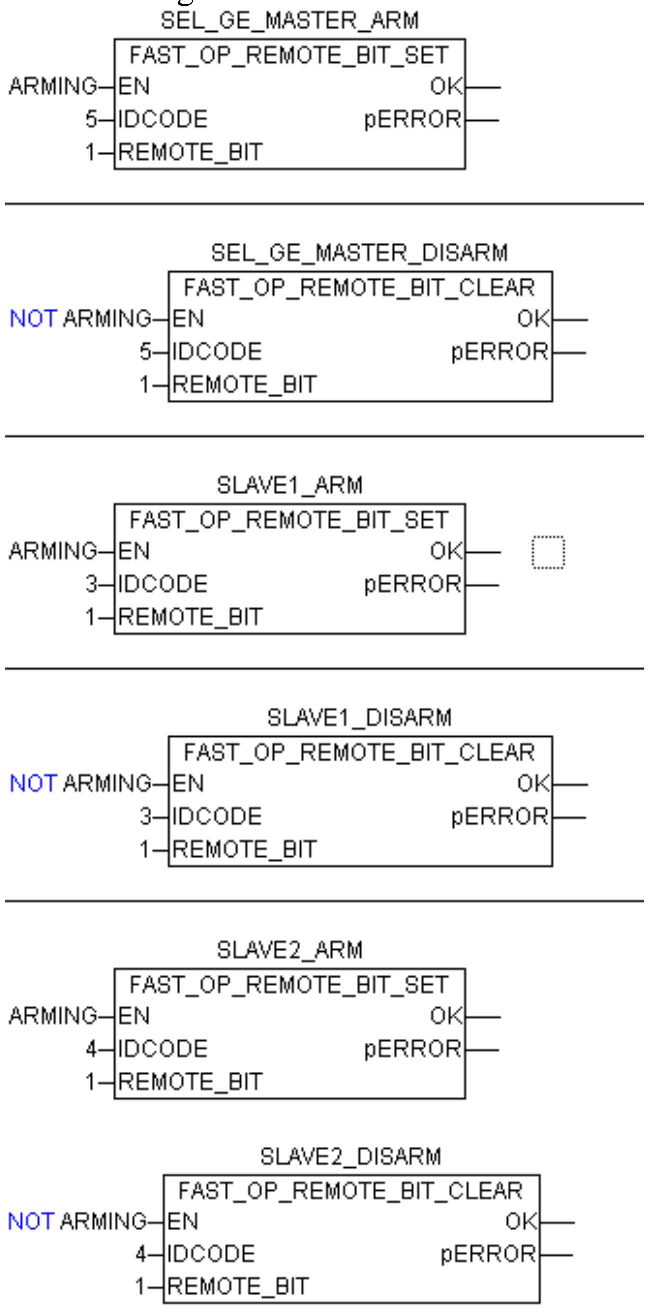
B.4 SEND_ARMING Program

This program is used to configure where to send the arming signal.

B.4.1 Voting Scheme with SEL-421 Master

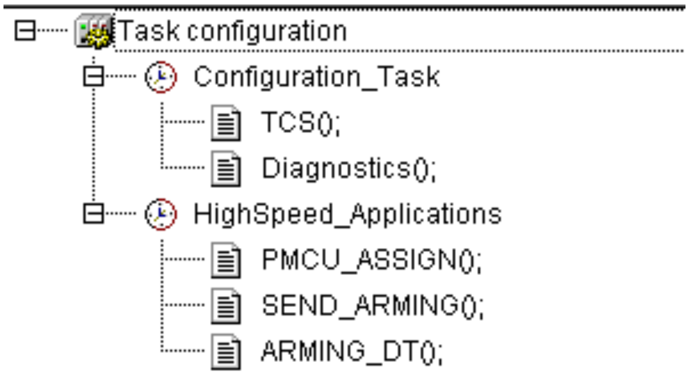


B.4.2 Voting Scheme with GE F60 Master



B.5 Task Configuration

This window shows the Task Configuration program in the SEL-3378. It lists all the programs used and the specified frequency they are run at.



Appendix C – SEL-421 PMU and SEL-RTS Settings

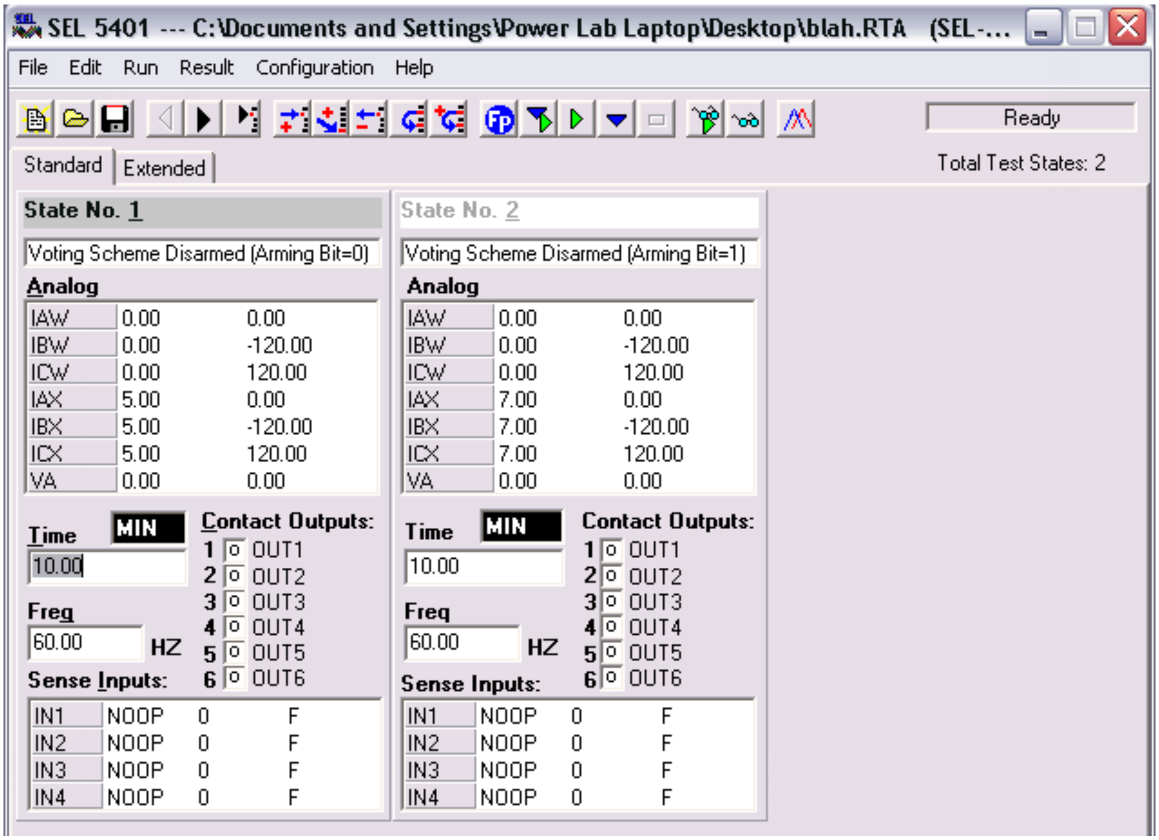
C.1 SEL-421 PMU Settings

[INFO]
RELAYTYPE=SEL-421-3
FID=SEL-421-3-R127-V0-Z012011-D20090218
BFID=SLBT-4XX-R100-V0-Z001001-D20010703
PARTNO=042134152C4AXH31XXXXX
[Global]
SID,"VT Panel 2"
RID,"Master: SEL-421"
NUMBK,"1"
BID1,"Breaker 1"
NFREQ,"60"
PHROT,"ABC"
DATE_F,"MDY"
FAULT,"NA"
EDCMON,"N"
EICIS,"N"
EDRSTC,"N"
EGADVS,"N"
EPMU,"Y"
GINP,"15"
GINDF,"80"
SS1,"NA"
SS2,"NA"
SS3,"NA"
SS4,"NA"
SS5,"NA"
SS6,"NA"
TGR,"180"
STALLTE,"NA"
LOADTE,"NA"
ESS,"N"
MFRMT,"C37.118"
MRATE,"60"
PMAPP,"N"
PHCOMP,"Y"
PMSTN,"421 VT Panel 2"
PMID,"2"
PHDATAV,"ALL"
VCOMP,"0.00"
PHDATAI,"ALL"
PHCURR,"BOTH"
IWCOMP,"0.00"
IXCOMP,"0.00"
PHNR,"I"
PHFMT,"R"
FNR,"I"
NUMANA,"0"
NUMDSW,"1"
TREA1,"NA"
TREA2,"NA"

TREA3,"NA"
TREA4,"NA"
PMTRIG,"NA"
MRTCDLY,"500"
RTCRATE,"2"
IN1XXD,"0.1250"
IN2XXD,"0.1250"
[P5]
TIMEOUT,"5"
AUTO,"Y"
FASTOP,"Y"
TERTIM1,"1"
TERSTRN,"\005"
TERTIM2,"0"
IPADDR,"192.168.1.114"
SUBNETM,"255.255.255.0"
DEFRTR,"192.168.1.1"
ETCPKA,"N"
KAIDLE,"10"
KAINTV,"1"
KACNT,"6"
NETPORT,"B"
FAILOVR,"N"
FTIME,"5"
NETASPD,"A"
NETBSPD,"A"
FTPSERV,"N"
FTPCBAN,"FTP SERVER:"
FTPIDLE,"5"
E61850,"N"
FTPANMS,"N"
FTPAUSR,""
T1CBAN,"HOST TERMINAL SERVER:"
T1INIT,"Y"
T1RECV,"Y"
T1PNUM,"23"
T2CBAN,"CARD TERMINAL SERVER:"
T2RECV,"N"
T2PNUM,"1024"
TIDLE,"5"
EPMIP,"Y"
PMOTS1,"OFF"
PMOTS2,"UDP_T"
PMOIPA1," "
PMOIPA2,"192.168.1.145"
PMOTCP1,""
PMOTCP2,"4757"
PMOUDP2,"51116"

C.2 SEL-5401 Software Settings

The SEL-5401 software is used at the human interface with the SEL-AMS source. The settings in this software tell the SEL-AMS device what to send to the SEL-421 PMU.



Appendix D – Master and Slave Relay Settings

D.1 SEL-421 Slave 1 Settings

D.1.1 Voting Scheme with Hard-Wired Trip Signals

[INFO]
RELAYTYPE=SEL-421-3
FID=SEL-421-3-R127-V0-Z012011-D20090218
BFID=SLBT-4XX-R100-V0-Z001001-D20010703
PARTNO=042134152C4AXH31XXXXX
[Global]
SID,"VT Panel 4"
RID,"SLAVE 1: SEL-421"
NUMBK,"1"
BID1,"Breaker 1"
NFREQ,"60"
PHROT,"ABC"
DATE_F,"MDY"
FAULT,"NA"
EDCMON,"N"
EICIS,"N"
EDRSTC,"N"
EGADVS,"N"
EPMU,"Y"
GINP,"85"
GINDF,"80"
SS1,"NA"
SS2,"NA"
SS3,"NA"
SS4,"NA"
SS5,"NA"
SS6,"NA"
TGR,"180"
STALLTE,"NA"
LOADTE,"NA"
ESS,"N"
[Set 1]
CTRW,"1"
CTRX,"1"
PTRY,"1"
VNOMY,"115"
PTRZ,"1"
VNOMZ,"115"
Z1MAG,"25.00"
Z1ANG,"85.00"
Z0MAG,"25.00"
Z0ANG,"85.00"
EFLOC,"N"
E21P,"N"
E21MG,"N"
E21XG,"N"
ECVT,"N"
ESERCMP,"N"

ESOTF,"N"
EOOS,"N"
ELOAD,"N"
E50P,"1"
E50G,"N"
E50Q,"N"
E51S,"N"
E32,"AUTO"
ECOMM,"N"
EBFL1,"N"
E25BK1,"N"
E79,"N"
EMANCL,"N"
ELOP,"N"
EDEM,"N"
EADVS,"N"
50P1P,"1.00"
67P1D,"0.000"
67P1TC,"1"
ORDER,"QV"
E32IV,"1"
EPO,"52"
SPOD,"0.500"
3POD,"0.500"
TR,"50P1 AND NOT RB01"
DTA,"NA"
DTB,"NA"
DTC,"NA"
BK1MTR,"NA"
ULTR,"NA"
ULMTR1,"NA"
TOPD,"2.000"
TULO,"3"
Z2GTSP,"N"
67QGSP,"N"
TDUR1D,"6.000"
TDUR3D,"12.000"
E3PT,"1"
E3PT1,"1"
[O1]
OUT101,"NA"
OUT102,"NA"
OUT103,"NA
OUT104,"50P1"
OUT105,"NA"
OUT106,"NA"
OUT107,"NA"
OUT108,"NA"

[Report]
ESERDEL,"Y"
SRDLCNT,"5"
SRDLTIM,"1.0"
SITM1,"RB01"
SNAME1,"RB01"
SSET1,"Asserted"

SCLR1,"Deasserted"
SHMI1,"N"
SITM2,"50P1"
SNAME2,"50P1"
SSET2,"Asserted"
SCLR2,"Deasserted"
SHMI2,"N"
SITM3,"TRIP"
SNAME3,"TRIP"
SSET3,"Asserted"
SCLR3,"Deasserted"
SHMI3,"N"
SITM4,"OUT104"
SNAME4,"OUT104"
SSET4,"Asserted"
SCLR4,"Deasserted"

D.1.2 Voting Scheme with Mirrored Bits Trip Signals

All of the settings for Section D.1.2 are the same as Section D.1.1 except for those listed below.

OUT104,"NA"
TMB1A,"50P1"

SITM4,"TMB1A"
SNAME4,"TMB1A"
SSET4,"Asserted"
SCLR4,"Deasserted"

D.2 SEL-421 Slave 2 Settings

D.2.1 Voting Scheme with Hard-Wired Trip Signals

[INFO]
RELAYTYPE=SEL-421-3
FID=SEL-421-3-R127-V0-Z012011-D20090218
BFID=SLBT-4XX-R100-V0-Z001001-D20010703
PARTNO=042134152C4AXH31XXXXX
[Global]
SID,"VT Panel 3"
RID,"SLAVE 2: SEL-421"
NUMBK,"1"
BID1,"Breaker 1"
NFREQ,"60"
PHROT,"ABC"
DATE_F,"MDY"
FAULT,"NA"

EDCMON,"N"
EICIS,"N"
EDRSTC,"N"
EGADVS,"N"
EPMU,"Y"
GINP,"85"
GINDF,"80"
SS1,"NA"
SS2,"NA"
SS3,"NA"
SS4,"NA"
SS5,"NA"
SS6,"NA"
TGR,"180"
STALLTE,"NA"
LOADTE,"NA"
ESS,"N"
[Set 1]
CTRW,"1"
CTRX,"1"
PTRY,"1"
VNOMY,"115"
PTRZ,"1"
VNOMZ,"115"
Z1MAG,"25.00"
Z1ANG,"85.00"
Z0MAG,"25.00"
Z0ANG,"85.00"
EFLOC,"N"
E21P,"N"
E21MG,"N"
E21XG,"N"
ECVT,"N"
ESERCMP,"N"
ESOTF,"N"
EOOS,"N"
ELOAD,"N"
E50P,"1"
E50G,"N"
E50Q,"N"
E51S,"N"
E32,"AUTO"
ECOMM,"N"
EBFL1,"N"
E25BK1,"N"
E79,"N"
EMANCL,"N"
ELOP,"N"
EDEM,"N"
EADVS,"N"
50P1P,"1.00"
67P1D,"0.000"
67P1TC,"1"
ORDER,"QV"
E32IV,"1"
EPO,"52"

SPOD,"0.500"
3POD,"0.500"
TR,"50P1 AND NOT RB01"
DTA,"NA"
DTB,"NA"
DTC,"NA"
BK1MTR,"NA"
ULTR,"NA"
ULMTR1,"NA"
TOPD,"2.000"
TULO,"3"
Z2GTSP,"N"
67QGSP,"N"
TDUR1D,"6.000"
TDUR3D,"12.000"
E3PT,"1"
E3PT1,"1"
[O1]
OUT101,"NA"
OUT102,"NA"
OUT103,"NA
OUT104,"50P1"
OUT105,"NA"
OUT106,"NA"
OUT107,"NA"
OUT108,"NA"

[Report]
ESERDEL,"Y"
SRDLCNT,"5"
SRDLTIM,"1.0"
SITM1,"RB01"
SNAME1,"RB01"
SSET1,"Asserted"
SCLR1,"Deasserted"
SHMI1,"N"
SITM2,"50P1"
SNAME2,"50P1"
SSET2,"Asserted"
SCLR2,"Deasserted"
SHMI2,"N"
SITM3,"TRIP"
SNAME3,"TRIP"
SSET3,"Asserted"
SCLR3,"Deasserted"
SHMI3,"N"
SITM4,"OUT104"
SNAME4,"OUT104"
SSET4,"Asserted"
SCLR4,"Deasserted"

D.2.2 Voting Scheme with Mirrored Bits Trip Signals

All of the settings for Section D.2.2 are the same as Section D.2.1 except for those listed below.

OUT104,"NA"
TMB1A,"50P1"

SITM4,"TMB1A"
SNAME4,"TMB1A"
SSET4,"Asserted"
SCLR4,"Deasserted"

D.3 SEL-421 Master Settings

D.3.1 Voting Scheme with Hard-Wired Trip Signals

[INFO]
RELAYTYPE=SEL-421-3
FID=SEL-421-3-R127-V0-Z012011-D20090218
BFID=SLBT-4XX-R100-V0-Z001001-D20010703
PARTNO=042134152C4AXH31XXXXX
[Global]
SID,"VT Panel 2"
RID,"Master: SEL-421"
NUMBK,"1"
BID1,"Breaker 1"
NFREQ,"60"
PHROT,"ABC"
DATE_F,"MDY"
FAULT,"50P1 OR 51S1 OR M2P OR Z2G OR M3P OR Z3G"
EDCMON,"N"
EICIS,"N"
EDRSTC,"N"
EGADVS,"N"
EPMU,"Y"
GINP,"15"
GINDF,"80"
SS1,"NA"
SS2,"NA"
SS3,"NA"
SS4,"NA"
SS5,"NA"
SS6,"NA"
TGR,"180"
STALLTE,"NA"
LOADTE,"NA"
ESS,"N"
[S1]
CTRW,"1"

CTRX,"1"
PTRY,"1"
VNOMY,"115"
PTRZ,"1"
VNOMZ,"115"
Z1MAG,"25.00"
Z1ANG,"85.00"
Z0MAG,"25.00"
Z0ANG,"85.00"
EFLOC,"N"
E21P,"N"
E21MG,"N"
E21XG,"N"
ECVT,"N"
ESERCMP,"N"
ESOTF,"N"
EOOS,"N"
ELOAD,"N"
E50P,"1"
E50G,"N"
E50Q,"N"
E51S,"N"
E32,"AUTO"
ECOMM,"N"
EBFL1,"N"
E25BK1,"N"
E79,"N"
EMANCL,"N"
ELOP,"N"
EDEM,"N"
EADVS,"N"
50P1P,"1.00"
67P1D,"0.000"
67P1TC,"1"
ORDER,"QV"
E32IV,"1"
EPO,"52"
SPOD,"0.500"
3POD,"0.500"
TR,"(50P1 AND IN101 AND RB01) OR (50P1 AND IN103 AND RB01) OR (IN101 AND IN103 AND RB01) OR (50P1 AND NOT RB01)"
DTA,"NA"
DTB,"NA"
DTC,"NA"
BK1MTR,"NA"
ULTR,"NA"
ULMTR1,"NA"
TOPD,"2.000"
TULO,"3"
Z2GTSP,"N"
67QGSP,"N"
TDUR1D,"6.000"
TDUR3D,"12.000"
E3PT,"1"
E3PT1,"1"
ER,"na"

[Report]
ESERDEL,"Y"
SRDLCNT,"5"
SRDLTIM,"1.0"
SITM1,"RB01"
SNAME1,"RB01"
SSET1,"Asserted"
SCLR1,"Deasserted"
SHMI1,"N"
SITM2,"50P1"
SNAME2,"50P1"
SSET2,"Asserted"
SCLR2,"Deasserted"
SHMI2,"N"
SITM3,"IN101"
SNAME3,"IN101"
SSET3,"Asserted"
SCLR3,"Deasserted"
SHMI3,"N"
SITM4,"IN103"
SNAME4,"IN103"
SSET4,"Asserted"
SCLR4,"Deasserted"
SHMI4,"N"
SITM5,"TRIP"
SNAME5,"TRIP"
SSET5,"Asserted"
SCLR5,"Deasserted"

D.3.2 Voting Scheme with Mirrored Bits Trip Signals

All of the settings for Section C.3.2 are the same as Section C.2.1 except for those listed below.

TR,"(50P1 AND RMB1B AND RB01) OR (50P1 AND RMB1A AND RB01) OR (RMB1B AND RMB1A AND RB01) OR (50P1 AND NOT RB01)"

SITM3,"RMB1A"
SNAME3,"RMB1A"
SSET3,"Asserted"
SCLR3,"Deasserted"
SHMI3,"N"
SITM4,"RMB1B"
SNAME4,"RMB1B"
SSET4,"Asserted"
SCLR4,"Deasserted"
SHMI4,"N"

D.4 GE F60 Master Settings

D.4.1 FlexLogic Equation Editor

FLEXLOGIC ENTRY	TYPE	SYNTAX
View Graphic	View	View
FlexLogic Entry 1	Protection Element	PHASE IOC1 PKP
FlexLogic Entry 2	Contact Inputs On	Cont Ip 5 On(M5A)
FlexLogic Entry 3	Contact Inputs On	Cont Ip 8 On(M6C)
FlexLogic Entry 4	AND	3 Input
FlexLogic Entry 5	Protection Element	PHASE IOC1 PKP
FlexLogic Entry 6	Contact Inputs On	Cont Ip 7 On(M6A)
FlexLogic Entry 7	Contact Inputs On	Cont Ip 8 On(M6C)
FlexLogic Entry 8	AND	3 Input
FlexLogic Entry 9	Contact Inputs On	Cont Ip 5 On(M5A)
FlexLogic Entry 10	Contact Inputs On	Cont Ip 7 On(M6A)
FlexLogic Entry 11	Contact Inputs On	Cont Ip 8 On(M6C)
FlexLogic Entry 12	AND	3 Input
FlexLogic Entry 13	OR	3 Input
FlexLogic Entry 14	Protection Element	PHASE IOC1 PKP
FlexLogic Entry 15	Contact Inputs On	Cont Ip 8 On(M6C)
FlexLogic Entry 16	NOT	1 Input
FlexLogic Entry 17	AND	2 Input
FlexLogic Entry 18	OR	2 Input
FlexLogic Entry 19	Assign Virtual Output	= Virt Op 1 (VO1)
FlexLogic Entry 20	End of List	

D.4.2 Phase Instantaneous Overcurrent

PARAMETER	PHASE IOC1
Function	Enabled
Source	SRC 1 (SRC 1)
Pickup	0.200 pu
Delay	0.00 s
Reset Delay	0.00 s
Block A	OFF
Block B	OFF
Block C	OFF
Target	Self-reset
Events	Enabled

D.4.3 Digital Contact Inputs

SETTING	PARAMETER
[M5A] Contact Input 5 ID	Cont Ip 5
[M5A] Contact Input 5 Debounce Time	2.0 ms
[M5A] Contact Input 5 Events	Enabled
[M5C] Contact Input 6 ID	Cont Ip 6
[M5C] Contact Input 6 Debounce Time	2.0 ms
[M5C] Contact Input 6 Events	Disabled
[M6A] Contact Input 7 ID	Cont Ip 7
[M6A] Contact Input 7 Debounce Time	2.0 ms
[M6A] Contact Input 7 Events	Enabled
[M6C] Contact Input 8 ID	Cont Ip 8
[M6C] Contact Input 8 Debounce Time	2.0 ms
[M6C] Contact Input 8 Events	Enabled