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Evaluation of the GE N60 Relay

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by

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Executive Summary

The GE N60 relay evaluation project was conducted by Brenna Andrews with help from Richard Setterstrom and Daniel Kachmarik from NorthWestern Energy. The goal of the project was to determine if the GE N60 relay was a sufficient replacement candidate for the Acceleration Trend Relays (ATRs) currently being utilized on four stem-coal generators in Colstrip, Montana, to protect the power system. The ATRs protect the power system from events such as faults or equipment damage. The criteria used to evaluate the GE N60 relay's capabilities included the following:

1. The GE N60 relay must have a sampling frequency equal to or greater than that of the ATRs.
2. The GE N60 relay must have minimal noise so as not to affect trip decisions in the relay.
3. The GE N60 relay must be able to accurately detect events.
4. The GE N60 relay must be able to create and store event records of adequate length.

The GE N60 relay was programmed to emulate the functions of the ATRs. Two Colstrip-Broadview transmission-line events were captured simultaneously by the ATRs and the GE N60 relay. Comparison of the speed deviation, acceleration, and power responses from these two events showed that the GE N60 relay is an adequate replacement candidate for the GE N60 relay. Refer to Figures 27 through 40.

The GE N60 relay proved to have a variable sampling frequency. The relay determined events based on the frequency deviation and frequency rate of change threshold values. The frequency deviation value was sampled at 60Hz in the GE N60 relay, whereas the ATRs could sample at 150Hz. The decision was made that, until further testing could be completed, the lower frequency deviation sampling rate would not make the collected data unusable. From qualitative analysis, the noise level was proved to be acceptable, since the GE N60 relay trip decisions were not affected by what noise was present in the event responses. The decision was made that additional filtering could be implemented so long as the trip decision speed is not compromised. Finally, the GE N60 relay proved to accurately detect and store events. The GE N60 relay was able to detect events simultaneously with the ATRs, showing that the ATR functions were correctly emulated in the GE N60 relay. The GE N60 relay event records were of acceptable length and exceptional quality. Based on these results, the GE N60 relay was found to be an adequate replacement candidate for the ATRs in Colstrip and should move on to the next stages of testing.

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1. Introduction

Currently in Colstrip, Montana, four steam-coal generators are running that provide power to much of the western power system. If an event occurs on the power system such as lightning striking a transmission line, wind whipping the transmission lines, or equipment failure, then the rest of the power system is at risk of being damaged. To keep the power system healthy during an event, the Colstrip generators need to be monitored continuously to ensure that they are operating correctly.

Today, devices called Acceleration Trend Relays (ATRs) belonging to NorthWestern Energy are being used to monitor the Colstrip generators. The purpose of the ATR is to monitor quantities from the four steam-coal generators such as the frequency, rate of change of frequency, voltage, current, and power outputs to see if they are within safe operating limits. These limits exist in the ATRs programming, and if any of these quantities exceed the safety thresholds, the ATRs will execute the necessary commands to protect the power system. The commands can range from simply recording data, to sending out warnings, to making trip decisions that can isolate a Colstrip generator from the rest of the system.

Because the Acceleration Trend Relay is a custom piece of equipment, it is difficult to teach new NorthWestern employees about how to maintain such a unique relay and perform hardware fixes and software updates. As new employees are hired and older employees retire, an eventual replacement candidate for the ATRs needs to be considered. A relay with more universal functions will be evaluated as a potential replacement candidate for the Acceleration Trend Relays. The chosen relay to be evaluated is the GE N60 relay, which specializes in frequency measurements. Through testing and comparison, the GE N60 relay will be assessed to determine if its capabilities adequately replicate the functions of the ATRs.

2. Problem Statement

The ATRs have been running in Colstrip for many years and are unique in that they are mostly custom-designed pieces of hardware with custom software. Having such a distinctive piece of equipment makes it difficult to teach new employees how to operate and maintain the ATRs, especially as the current ATR specialists will eventually retire. In order to protect the future health of the generators at Colstrip, a more universal solution is needed that new employees can better understand and operate. This solution will ideally be a future replacement for the ATRs in Colstrip.

In 2013, the current ATR specialists started looking at a potential replacement for the Acceleration Trend Relays. They decided to test the GE N60 relay, which specializes in gathering frequency and rate of change of frequency measurements, as a future replacement candidate for the Colstrip ATRs. The assessment of the GE N60 relay will include an analysis of the GE N60 relay's data quality, event recording capabilities, and trip determination accuracy.

To test the capabilities of the GE N60 relay, a GE N60 relay will be set up in Colstrip to monitor the Unit 3 and Unit 4 Colstrip generators. The GE N60 relay will then be configured to emulate the functions of the ATRs, if possible. At this stage, the GE N60 will be configured to execute the most important ATR functions, including programming logic on which quantities to measure and how to record events and make trip decisions. If the GE N60 relay and an ATR can simultaneously record an event on the system, then the data collected from each will be plotted and compared. This data comparison will tell us how much noise is in the system, the quality of the event data, as well as how well the GE N60 relay is able to detect events on the system. Lastly, a final recommendation will be made on whether the GE N60 could be an adequate replacement for the Acceleration Trend Relays in Colstrip.

3. Objectives

3.1. Criteria

For the GE N60 relay to be an adequate replacement for the Acceleration Trend Relays in Colstrip, it must have specific capabilities and meet certain requirements. Four requirements were developed by which to evaluate the GE N60 relay. The first requirement is for the GE N60 relay to have an adequate sampling time. The sampling time determines how quickly a relay can make a trip decision. Preferably, the GE N60 relay should have a sampling rate equal to or better than the ATR sampling rate according to the Nyquist theorem, where the sampling frequency is at least twice the Nyquist frequency.

The second requirement for the GE N60 relay is to have minimal signal noise. Noise on a system makes it more difficult for relays to detect irregularities in the values that they are monitoring. Often, too much noise can cause a relay to cause a false trip when there is no actual event to trip for. Similarly, the relay may not trip during an event because it cannot distinguish the event from the noise. Ideally, the noise level in the GE N60 relay should be small enough that the relay is not making false trips and that the relay can detect events.

While the sampling time and noise level determine the data quality of the relay, it is also important for the relay to be able to collect and output data records. The third requirement of the GE N60 relay is for the relay to be able to capture event records based on the measurement thresholds programmed into the GE N60 relay. The GE N60 relay will need to be able to monitor the frequency, rate of change of frequency, and power measurements. The GE N60 relay should also be able to make trip decisions and capture event records should one of these measurements stray outside their safety limits. Capturing an event record will prove that the GE N60 relay can detect events and then make decisions based on the kind of event that it sees.

Finally, for the fourth requirement, the GE N60 relay must be able to create and store an event record of adequate length. The purpose of collecting event records is to look at the behavior of the transient state of the electrical grid during an event. The GE N60 relay must be able to provide a certain amount of pre- and post- event data so that the event record may be compared to the ATR event records.

3.2. Deliverables

Once the capabilities of the GE N60 relay are analyzed and tested, the results will be presented through a final report documenting process taken to test the relay and analyze the results. Finally, a summarization of the results will be displayed on a poster.

4. Budget

The estimated budget for this project is shown in Table 1 below. Estimated costs included working wages for three NorthWestern Energy employees, transportation fees, and new equipment costs. Let it be understood that the GE N60 relays and other associated equipment were bought before the commencement of this project and do not affect the project budget.

Table I: Budget Estimate for 3 NortWestern Energy Employees

GE N60 Evaluation Project Estimated Budget

	Wages	Transportation	Equipment	Total:
Brenna Andrews	$4,200	$29	$100	$4,329
Richard Setterstrom	$7,000	$123	$200	$7,323
Daniel Kachmarik	$7,000	$123	$200	$7,323
			OVERALL TOTAL:	$18,974

The wages were calculated by taking an estimate of how much each NorthWestern Energy employee was paid each hour and determining how much they would get paid over a 28 week project. Brenna Andrews estimated working 10 hours each week, and Daniel Kachmarik and Richard Setterstrom estimated 5 hours each working on the project. The transportation amount was determined by using an estimated $3.5/gallon gasoline cost and a 20 miles/gallon gas mileage. Brenna Andrews estimated that she would have to drive 6 miles from the Control Center to Montana Tech every Monday. Daniel Kachmarik and Richard Setterstrom estimated a trip from Butte to Colstrip for each of them, with an estimated distance of 700 miles roundtrip. The equipment cost was based on miscellaneous parts that each employee might need. This includes wire, wire terminals, fuses, light bulb holders, tools, and cabinet equipment needed for the relay.

By the conclusion of the project, the estimated budget was about equivalent to the actual budget. Table 2 shows the actual spending and final cost of the project. Brenna Andrews worked on the project for two weeks longer than estimated, but the projected budget was not exceeded due to lower gasoline rates and equipment spending being less than anticipated. The estimated budget was only $98 more than the actual cost of the project. In the end, the estimated budget was accurately projected, and the evaluation of the GE N60 relay project finished under budget.

Table 2: Final Budget for 3 NorthWestern Energy Employees

GE N60 Evaluation Project Final Budget

	Wages	Transportation	Equipment	Total:
Brenna Andrews	$4,495	$21	$50	$4,566
Richard Setterstrom	$7,000	$105	$50	$7,155
Daniel Kachmarik	$7,000	$105	$50	$7,155
			OVERALL TOTAL:	$18,876

5. Procedure

The given requirements for the GE N60 relay were first implemented on a test relay located at the Control Center in Butte, Montana. The test relay provided a medium by which the setup, software, and interface with the relay could be familiarized with. The test relay also helped uncover how the relay connected to voltage and current sources and how it captured and displayed event records. Once the test relay was configured and tested, a production GE N60 relay was set up in Colstrip. The production relay connected to the Unit 3 and Unit 4 Colstrip generator current and voltage transformers banks. The frequency and rate of change of frequency measurement thresholds were programmed into the production relay. Then the production relay was configured to capture event records based on programmed limits of the input measurements. The production relay detected and captured data from an event, and the event record data from the GE N60 relay was compared to that of the Acceleration Trend Relays. Then the data quality, noise level, and event recording requirements were analyzed, and a conclusion was drawn on whether the GE N60 is an adequate replacement candidate for the ATRs in Colstrip.

5.1. Relay Familiarization and Setup

For the relay familiarization, the GE N60 Relay manual for the 7.2x version firmware was read over to gain familiarization of the overall manual layout, section navigation, and general terminology used in the manual. Additional documentation supplied by Richard Setterstrom was read through to gain an understating of the Acceleration Trend Relays (ATRs). Knowing how the ATRs work was imperative to understanding how the GE 60 relays needed to be configured and what was needed from the GE N60 relay.

Next, the relay needed to be powered and connected to a computer network. The GE N60 relay setup process was researched. A GE N60 Relay test relay was already in place in a cabinet in the Butte, Montana, Control Center. The first step was to power up the relay. A 125V to 250V AC nominal source was needed by the GE N60 relay. Figure 1 on the next page shows the wiring diagram for powering the relay. The HIGH control power terminal B5b was used, where B is the module indicator on the back of the relay, 5 is the row number, and b/a is the column indicator. The negative voltage was connected to terminal B6a. A 12 gauge wire connected the relay to a power supply providing 129V AC.

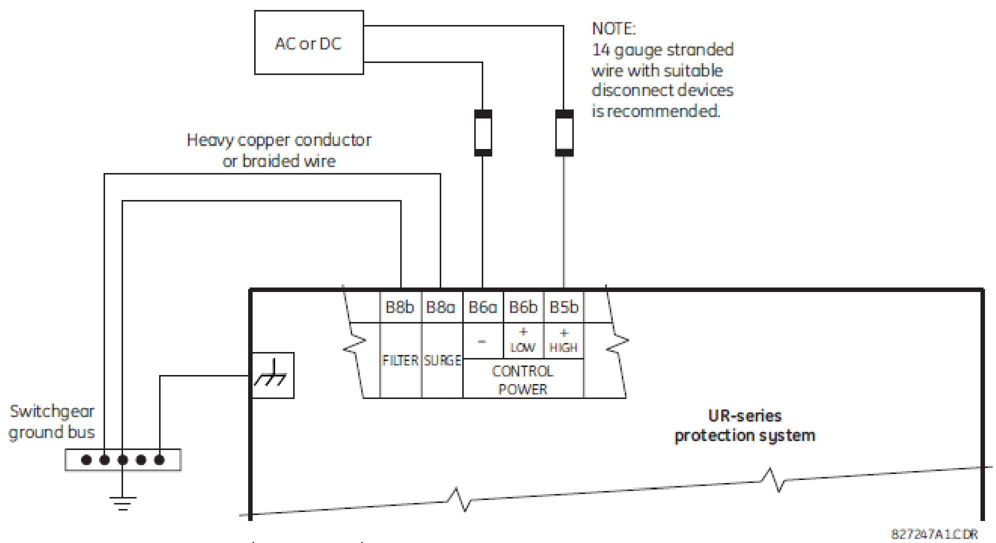

Figure 1: GE N60 Relay Wiring Diagram

Once the relay was powered up, the relay was connected to an Ethernet network. To do this, an Ethernet cable was used to connect the relay to a switch, which was connected to a desktop computer on the test network. The appropriate IP addresses were entered into the relay using the relay faceplate commands. Then, using the desktop computer, the relay was pinged using the command line. Once communication between the computer and relay was established, the software portion of the project could begin.

About two-thirds of the way through the semester, a network change had to be made, and the test relay could no longer connect to the desktop computer on the Ethernet network. Attempts were made to ping the test relay from the desktop computer, and the pings were successful, but the test relay would not connect in the necessary relay software. The problem was hypothesized to be due to a network change. Troubleshooting attempts such as re-writing firewall rules and pinging the relay were made, but a solution to this problem was not found. For the remainder of the project, the test relay was connected via a serial to USB connector that connected a laptop computer to the front port of the test relay.

The production relay in Colstrip was similarly wired up and powered. The production relay was also connected to a desktop computer through an Ethernet connection. In order to connect to the desktop computer in Colstrip, a Keyboard, Video, and Mouse (KVM) system was utilized. This system allowed members to log in on a computer at the Control Center in Butte and control the desktop computer in Colstrip. A user could see and control the keyboard, video, and mouse of the Colstrip computer via a secured internet connection.

5.2. Software Familiarization and Setup

The preferred software for the GE N60 relay was the EnerVista Viewpoint Engineering software due to its enhanced reporting, display, and logic implementation capabilities. The Viewpoint Engineering software was downloaded from the GE website and installed on the test relay desktop and laptop computer. Once the software was installed and opened, the relay manual was used to look up how to connect the Viewpoint Engineering software to the GE N60 relay. The GE N60 relay has a Quick Connect feature that uses either the serial or Ethernet communication methods and the IP address of the relay to connect the software to the relay.

Once the relay and the software were communicating to each other, the relay firmware could be updated. The Viewpoint Engineering software for the relay worked on firmware versions 7.2x and lower. As such, the test relay firmware was not upgraded. The relay manual was then used to discover the layout of the EnerVista software as well as its interfacing capabilities. The software for the production relay was installed while Richard Setterstrom and Daniel Kachmarik were setting up the production relay in Colstrip. They set it up similarly to the test relay and ensured the Viewpoint Engineering software was communicating with the GE N60 relay.

5.3. Source Input Configuration

5.3.1. Single Phase Input Settings and Setup

Voltage transformer (VT) and current transformer (CT) supply banks could be connected directly to the GE N60 relay or through a device called a HardFiber Brick. The HardFiber Bricks were a convenient and efficient way to get inputs directly from components on the grid, help reduce component wiring that could otherwise quickly become a mess, and make source input troubleshooting easier. The HardFiber Bricks were connected to the GE N60 relay through a Cross Connect Panel, which can connect to up to eight HardFiber Bricks at a time. Each Brick provided up to eight AC signal inputs. Daniel Kachmarik and Richard Setterstrom connected the HardFiber Bricks to the Cross Connect Panel and then to the relay.

To configure the relay to see the Bricks, the Remote Resources settings were found in the Viewpoint Engineering software. First, the Brick settings had to be enabled, and the Brick serial numbers had to be read by the relay. If the serial numbers were successfully read, and communication to the HardFiber Bricks was successful, then the status indication light in the software would turn green and say “OK”. Once communication was successful, a source could be connected to the HardFiber Brick. Figure 2 shows the required VT and CT wiring with respect to the numbered wires from the HardFiber Brick.

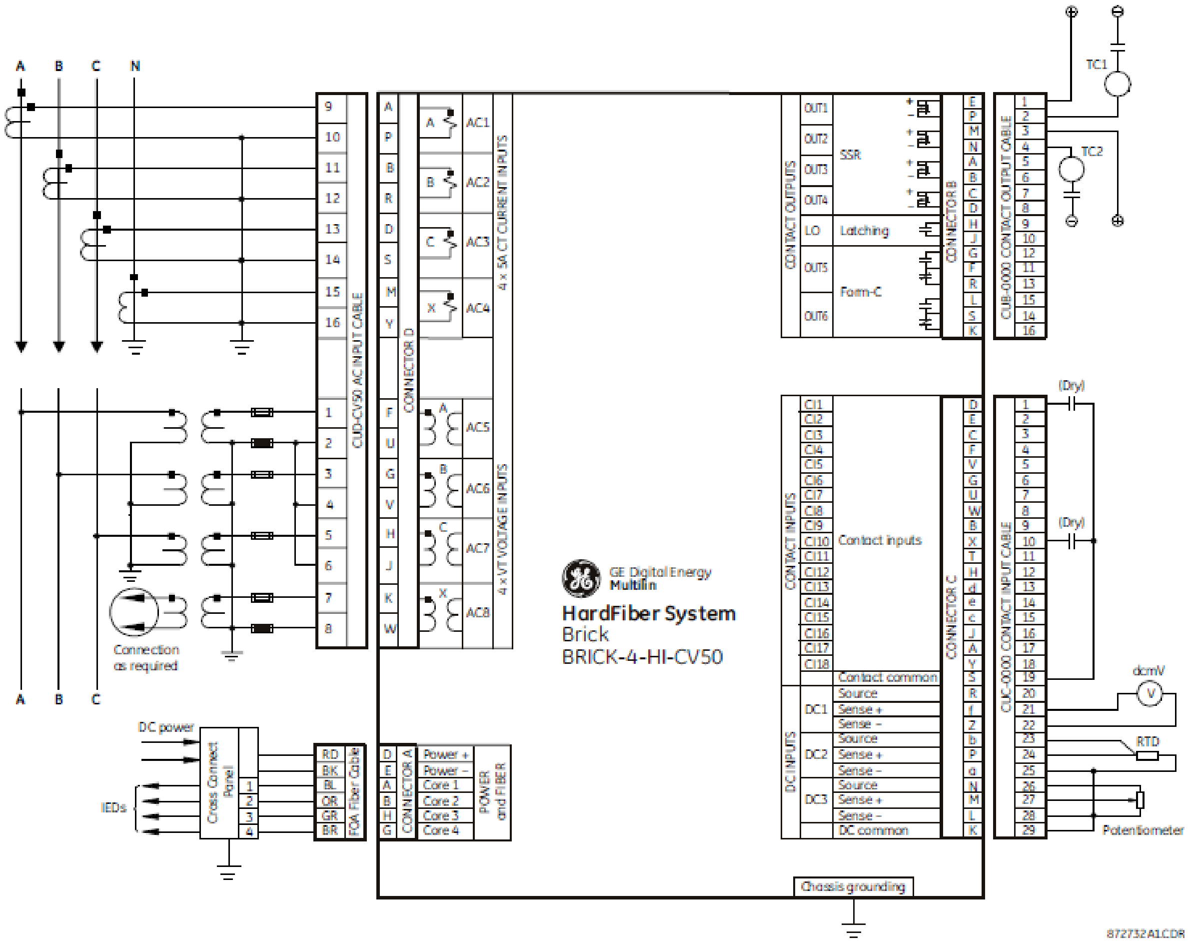

Figure 2: HardFiber Brick CT and VT Wiring Diagram

First, only a single phase was connected to the A-phase input on the VT source bank of the test relay. This was to make sure that the HardFiber Brick was seeing the correct input and that the software settings were set up correctly. In the software, the numbered wires for banks AC5, AC6, and AC7 were entered into Phase Origin 1. The AUX Origin 1 entry was set to AC8. The current ratings were entered, and since the HardFiber Bricks are rated for 5A current inputs, all the entries were 5 or 5A. The VT ratios and secondary nominal voltage settings were not changed from what previously existed in the software. Under Source 1, the Phase Voltage entry was filled in with B1. This means that the HardFiber Brick B1 is referenced as Source 1. The settings can be verified in Figure 3, Figure 4, and Figure 5 below.

Field Unit #	ID	Function	Brick Order Code	Brick Serial Number
U1	U 1	Enabled	CV-05	M84A12000192
U2	U 2	Disabled	CV-05	M84A13000061
U3	U 3	Disabled	CV-05	M84A13000060
U4	U 4	Disabled	CV-05	M84A13000059
U5	U 5	Disabled	CC-05	000000000000
U6	U 6	Disabled	CC-05	000000000000
U7	U 7	Disabled	CC-05	000000000000
U8	U 8	Disabled	CC-05	000000000000
				Auto Populate S/N

Figure 3: HardFiber Brick Serial Number Configuration

Field Unit #	Brick Order Code	Brick Serial Number	Brick Core	Process Card Port	Actual Value Status
U1	CV-05	M84A12000192	1	H1a	OK
U2	CV-05	M84A13000061	1	H2a	Disabled
U3	CV-05	M84A13000060	1	H3a	Disabled
U4	CV-05	M84A13000059	1	H4a	Disabled
U5	CC-05	000000000000	1	H1b	Disabled
U6	CC-05	000000000000	1	H2b	Disabled
U7	CC-05	000000000000	1	H3b	Disabled
U8	CC-05	000000000000	1	H4b	Disabled
		Auto Populate S/N			

Figure 4: HardFiber Brick Status Indication

AC Bank #	B1
Phase Origin 1	U1/AC5..7
Phase Origin 2	None
AUX Origin 1	U1/AC8
AUX Origin 2	None
Crosschecking	Dependability Biased
Phase CT Primary	5
Phase CT Secondary	5 A
AUX CT Primary	5
AUX CT Secondary	5 A
Phase VT Ratio	1.00
Phase VT Secondary	66.4
Phase VT Connection	Wye
AUX VT Ratio	1.00
AUX VT Secondary	66.4
AUX VT Connection	Vag
PARAMETER	**SOURCE 1**
Name	SRC 1
Phase CT	None
Ground CT	None
Phase VT	B1
Aux VT	None

Figure 5: HardFiber Brick VT Source Settings

Once the Brick was connected to a single phase input, the software was used to verify that the single-phase input was being detected. By going to Actual Values and looking at the raw values, it was confirmed that the HardFiber Brick was accurately detecting the single phase source input. I single phasor could be seen on the phasor diagram.

5.3.2. Three-Phase Input Settings and FT Switch Circuit Implementation

Once it was confirmed that the HardFiber Brick could accurately detect a single phase source input, a three phase source was wired up to the Brick. This was done by connecting each phase to a separate spot on a terminal strip, then to a 1A fuse, then to a Flexitest (FT) switch, and then to the inputs on the Brick. All these components were mounted to a chassis in the test relay cabinet. 1A fuses were used since only a VT source was being connected and very little current would be drawn. An FT switch is a set of up to 10 switches that can be specialized to have any combination of CT and VT switches. Figure 6 shows a picture of an FT switch. The FT switch was an added protection measure to break the test relay circuit if needed. For this project, the FT Switch used for the test relay had four CT and four VT switches, and only the VT switches were used. Once everything was wired up, a portable oscilloscope was used to verify that the three-phase source was correctly supplying three phases.

Figure 6: Flexitest Switch

The steps in 5.4.1 used to configure the Viewpoint Engineering software with the HardFiber Brick with a single phase were repeated, with the exception that the GE N60 relay was given a reboot command before opening the software to verify correct operation. To verify correct operation, the source phase voltage option (under Actual Values in the Viewpoint Engineering software) was selected. Figure 7 shows the Raw Value results of the phase voltage source measurements from the HardFiber Brick. These results confirm that the test relay accurately detected the line-to-neutral three-phase VT source, as indicated by the three phasors each 120° apart.

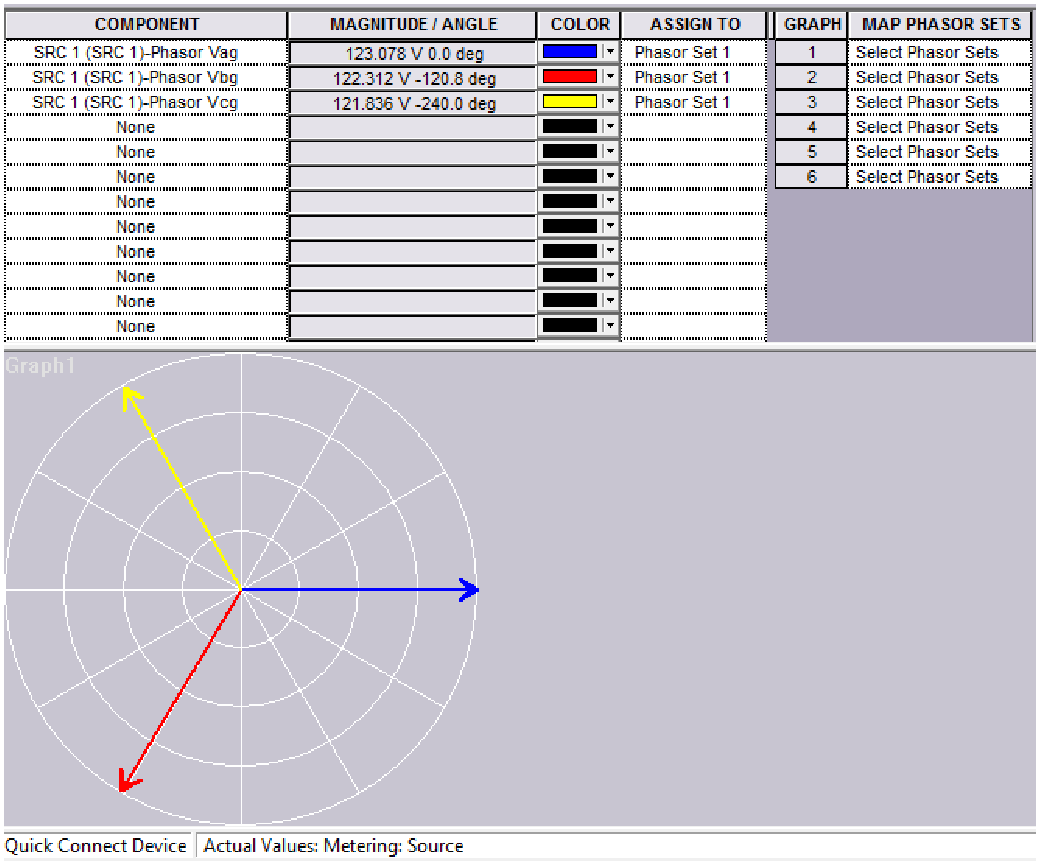

Figure 7: Test Relay Three-Phase Voltage Source Detection

The original plan was to set up both a CT source and a VT source using 60W lightbulbs for load. However, once the VT three-phase source was connected and detection from the GE N60 relay was verified, adding a three-phase CT source was no longer necessary. There was also limited chassis and cabinet space, especially if 60W bulbs were to be used as load.

The production relay was similarly set up to the test relay but with a CT source also connected to the HardFiber Bricks. Refer to Figure 2 for CT source connections. The production relay was set up to see both VT and CT three-phase inputs on two HardFiber Bricks connected to the Unit 3 and Unit 4 generators. The software settings were similarly configured as for the test relay and are shown in Figures 8 and 9, and the phasor diagrams shown in Figure 10 prove the correct detection of the voltage and current three-phase sources.

AC Bank #	B1	B2	B3
Phase Origin 1	U3/AC1..3	U3/AC5..7	U4/AC1..3
Phase Origin 2	None	None	None
AUX Origin 1	None	None	None
AUX Origin 2	None	None	None
Crosschecking	None	None	None
Phase CT Primary	25000	25000	25000
Phase CT Secondary	5 A	5 A	5 A
AUX CT Primary	25000	25000	25000
AUX CT Secondary	5 A	5 A	5 A
Phase VT Ratio	240.00	240.00	240.00
Phase VT Secondary	108.3	108.3	108.3
Phase VT Connection	Delta	Delta	Delta
AUX VT Ratio	240.00	240.00	240.00
AUX VT Secondary	115.0	115.0	115.0
AUX VT Connection	Vag	Vag	Vag
PARAMETER	**SOURCE 1**	**SOURCE 2**	**SOURCE 3**
Name	SRC 1	SRC 2	SRC 3
Phase CT	None	None	B1
Ground CT	None	None	None
Phase VT	None	None	B2

Figure 8: Production Relay HardFiber Brick Settings

AC Bank #	B4
Phase Origin 1	U4/AC5..7
Phase Origin 2	None
AUX Origin 1	None
AUX Origin 2	None
Crosschecking	None
Phase CT Primary	25000
Phase CT Secondary	5 A
AUX CT Primary	25000
AUX CT Secondary	5 A
Phase VT Ratio	240.00
Phase VT Secondary	108.3
Phase VT Connection	Delta
AUX VT Ratio	240.00
AUX VT Secondary	115.0
AUX VT Connection	Vag
PARAMETER	**SOURCE 4**
Name	SRC 4
Phase CT	B3
Ground CT	None
Phase VT	B4

Figure 9: Production Relay HardFiber Brick Settings

COMPONENT	MAGNITUDE / ANGLE	COLOR	ASSIGN TO
SRC 3 (SRC 3)-Phasor Ia	17.646 kA -35.3 deg		Phasor Set 1
SRC 3 (SRC 3)-Phasor Ib	17.457 kA -155.8 deg		Phasor Set 1
SRC 3 (SRC 3)-Phasor Ic	17.457 kA -275.0 deg		Phasor Set 1
SRC 3 (SRC 3)-Phasor Vab	26.527 kV 0.0 deg		Phasor Set 2
SRC 3 (SRC 3)-Phasor Vbc	26.606 kV -119.9 deg		Phasor Set 2
SRC 3 (SRC 3)-Phasor Vca	26.612 kV -240.1 deg		Phasor Set 2
SRC 4 (SRC 4)-Phasor Ia	17.905 kA -35.7 deg		Phasor Set 3
SRC 4 (SRC 4)-Phasor Ib	17.711 kA -156.0 deg		Phasor Set 3
SRC 4 (SRC 4)-Phasor Ic	17.757 kA -275.2 deg		Phasor Set 3
SRC 4 (SRC 4)-Phasor Vab	26.560 kV -0.1 deg		Phasor Set 4
SRC 4 (SRC 4)-Phasor Vbc	26.603 kV -119.9 deg		Phasor Set 4
SRC 4 (SRC 4)-Phasor Vca	26.613 kV -240.1 deg		Phasor Set 4

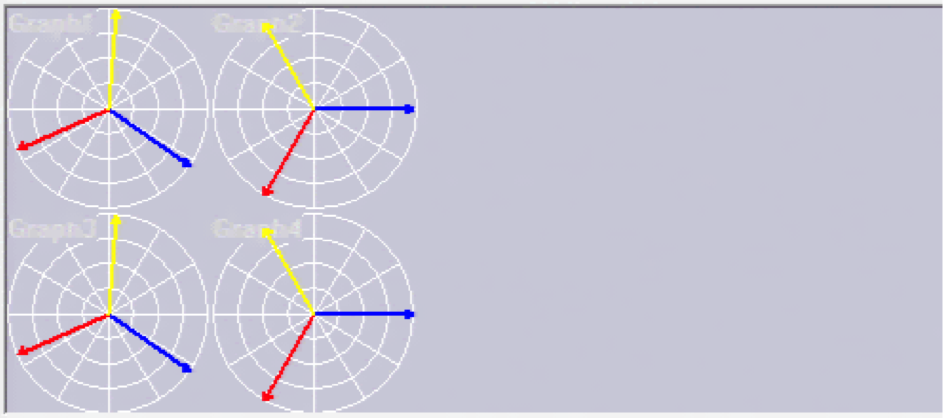

Figure 10: Production Relay Three-Phase Voltage and Current Source Detection

5.4. Implementation of the ATR Accumulator Code

One of the major functions in the Acceleration Trend Relay is a piece of code that creates a frequency accumulator. Basically, the frequency accumulator acts like a low pass filter. The accumulator takes in the raw frequency and outputs frequency deviation and frequency long-term average values. The ATRs take the frequency deviation value and use it to make trip decisions. If the frequency deviation value goes beyond its defined limits of -150 or 100 per unit speed, then the relay will make a trip decision and/or collect an event record.

Conceptually, the raw frequency measured by the relay is inputted into a summator. The summator subtracts the long-term frequency average from the raw frequency. This new value could be thought of as the frequency deviation and is a measure of how far the input frequency is from the long-term average frequency. Next, the frequency deviation value is multiplied by a constant, which is dependent on the sampling frequency of the relay. In this case, the GE N60 summator dictates the sampling frequency value. The summator function of the relay is implemented once every power system cycle, whereas the relay itself can sample 16 times every cycle for oscillography records. [add what the constant units are and why it exists] 100000 per unit = 60Hz.

After the frequency deviation is multiplied by the derived constant, it is inputted into a second summator. This second summator adds the inputted value to its previously calculated long-term frequency average value and multiplied by another constant. This value, in turn is the long-term frequency average. Figure 11 on the next page shows the conceptual diagram of the frequency accumulator. Figure 12 and Figure 13 on the next two pages, show the accumulator code as implemented in the summator functions of the GE N60 relay software. Using the summator sampling frequency of the GE N60, the accumulator constant was solved for, using the method in Appendix B. The inverse of the constant was inputted into the second summator of the GE N60, as shown in the “Summator 2 Scale Factor 1” entry in Figure 13.

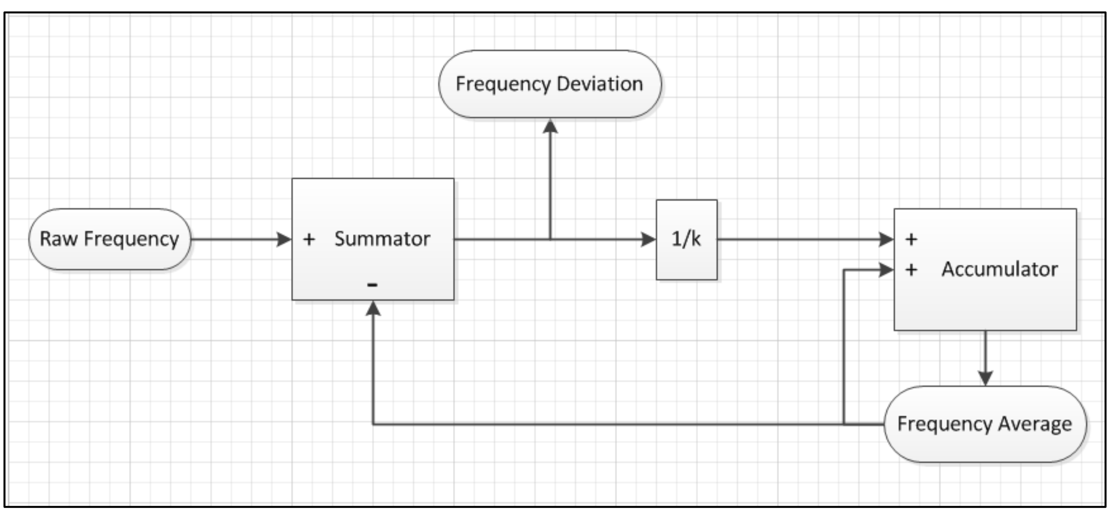

Figure 11: Accumulator Code Conceptual Diagram

SETTING	PARAMETER
Summator 1 Function	Enabled
Summator 1 Input Mode	SIGNED
Summator 1 Hold	OFF
Summator 1 Pickup	100.000
Summator 1 Hysteresis	3.0 %
Summator 1 Units	
Summator 1 PU Base	1
Summator 1 Input 1	SRC1 Frequency
Summator 1 Input 2	Summator 2 Output
Summator 1 Input 3	OFF
Summator 1 Input 4	OFF
Summator 1 Input 5	OFF
Summator 1 Input 6	OFF
Summator 1 Scale Factor 1	1666.666667
Summator 1 Scale Factor 2	-1.000000
Summator 1 Scale Factor 3	1.000000
Summator 1 Scale Factor 4	1.000000
Summator 1 Scale Factor 5	1.000000
Summator 1 Scale Factor 6	1.000000
Summator 1 Position Selector 1	ON
Summator 1 Position Selector 2	ON
Summator 1 Position Selector 3	OFF
Summator 1 Position Selector 4	OFF
Summator 1 Position Selector 5	OFF
Summator 1 Position Selector 6	OFF
Summator 1 Events	Disabled

Figure 12: Summator 1 Settings in the Viewpoint Engineering Software

Summator 2 Function	Enabled
Summator 2 Input Mode	SIGNED
Summator 2 Hold	OFF
Summator 2 Pickup	1000.000
Summator 2 Hysteresis	3.0 %
Summator 2 Units	
Summator 2 PU Base	1
Summator 2 Input 1	Summator 1 Output
Summator 2 Input 2	Summator 2 Output
Summator 2 Input 3	OFF
Summator 2 Input 4	OFF
Summator 2 Input 5	OFF
Summator 2 Input 6	OFF
Summator 2 Scale Factor 1	0.004876
Summator 2 Scale Factor 2	1.000000
Summator 2 Scale Factor 3	1.000000
Summator 2 Scale Factor 4	1.000000
Summator 2 Scale Factor 5	1.000000
Summator 2 Scale Factor 6	1.000000
Summator 2 Position Selector 1	ON
Summator 2 Position Selector 2	ON
Summator 2 Position Selector 3	OFF
Summator 2 Position Selector 4	OFF
Summator 2 Position Selector 5	OFF
Summator 2 Position Selector 6	OFF
Summator 2 Events	Disabled

Figure 13: Summator 2 Settings in the Viewpoint Engineering Software

The production relay used four summators to accomplish the implementation of the accumulator code. Summators 1 and 2 were configured similarly to Figures 12 and 13 respectively, and they used the input frequency from the Unit 3 generator. Summators 3 and 4 were configured similarly to Figures 12 and 13 respectively, and they used the input frequency from the Unit 4 generator.

5.5. Event Record and Oscillography Record Capture

5.5.1. Setup

The values recorded in the oscillography records could be chosen so as to only capture the relevant quantities. The chosen quantities included the Unit 3 and Unit 4 frequency deviations, the Unit 3 frequency rate of change, the real power for Units 3 and 4, and the Reactive power for Units 3 and 4. The Unit 4 frequency rate of change was accidentally not included. In the oscillography settings in the GE N60 relay, the oscillography records were chosen to capture 30% pre-event data and 70% post-event data. The sampling rate was chosen to be 16 samples/cycle. Figure 14 shows the implementation of the oscillography settings. In order to capture an oscillography record, a virtual output was created in the GE N60 relay. A virtual output is basically a variable that is assigned trip logic. If the logic conditions are met that set the virtual output to 1, then an oscillography record is taken. Otherwise the virtual output is 0. This is how an event was determined and captured in the GE N60 relay.

For this project, the virtual output would be set to 1 if the Unit 3 frequency deviation OR the Unit 4 frequency deviation OR the Unit 3 frequency rate of change OR the Unit 4 frequency rate of change values crossed their safety boundaries. The virtual output implementation is shown in Figure 15. Figures 16 and 17 show the frequency deviation settings in the Unit 3 and Unit 4 summators, which had a pickup value of 100 per unit speed, or 0.06Hz. Note that from the code in the ATRs, 100000 per unit speed is equivalent to 60Hz. Figure 18 shows the frequency rate of change settings, which had safety boundaries of ±0.43Hz/s.

SETTING	PARAMETER
Number Of Records	15
Trigger Mode	Protected
Trigger Position	30 %
Trigger Source	Virt Op 1 On (VO1)
AC Input Waveforms	16 samples/cycle
Digital Channel 1	OFF
Digital Channel 2	OFF
Digital Channel 3	OFF
Digital Channel 4	OFF
Digital Channel 5	OFF
Digital Channel 6	OFF
Digital Channel 7	OFF
Digital Channel 8	OFF
Digital Channel 9	OFF
Digital Channel 10	OFF
Digital Channel 11	OFF
Digital Channel 12	OFF
Digital Channel 13	OFF
Digital Channel 14	OFF
Digital Channel 15	OFF
Digital Channel 16	OFF
Digital Channel 17	OFF
Digital Channel 18	OFF
Digital Channel 19	OFF

Figure 14: Oscillography Record Settings

FLEXLOGIC ENTRY	TYPE	SYNTAX
View Graphic	View	View
FlexLogic Entry 1	Protection Element	FREQ RATE 1 PKP
FlexLogic Entry 2	Protection Element	SUMMATOR 3 OP
FlexLogic Entry 3	Protection Element	SUMMATOR 1 OP
FlexLogic Entry 4	Protection Element	FREQ RATE 2 PKP
FlexLogic Entry 5	OR	4 Input
FlexLogic Entry 6	Assign Virtual Output	= Virt Op 1 (VO1)

Figure 15: Virtual Output Settings

SETTING	PARAMETER
Summator 1 Function	Enabled
Summator 1 Input Mode	SIGNED
Summator 1 Hold	OFF
Summator 1 Pickup	100.000
Summator 1 Hysteresis	3.0 %
Summator 1 Units	
Summator 1 PU Base	1
Summator 1 Input 1	SRC3 Frequency
Summator 1 Input 2	Summator 2 Output
Summator 1 Input 3	OFF
Summator 1 Input 4	OFF
Summator 1 Input 5	OFF
Summator 1 Input 6	OFF
Summator 1 Scale Factor 1	1666.666667
Summator 1 Scale Factor 2	-1.000000
Summator 1 Scale Factor 3	1.000000
Summator 1 Scale Factor 4	1.000000
Summator 1 Scale Factor 5	1.000000
Summator 1 Scale Factor 6	1.000000
Summator 1 Position Selector 1	ON
Summator 1 Position Selector 2	ON
Summator 1 Position Selector 3	OFF
Summator 1 Position Selector 4	OFF
Summator 1 Position Selector 5	OFF
Summator 1 Position Selector 6	OFF
Summator 1 Events	Enabled

Figure 16: Summator Settings for Unit 3

SETTING	PARAMETER
Summator 3 Function	Enabled
Summator 3 Input Mode	SIGNED
Summator 3 Hold	OFF
Summator 3 Pickup	100.000
Summator 3 Hysteresis	3.0 %
Summator 3 Units	
Summator 3 PU Base	1
Summator 3 Input 1	SRC4 Frequency
Summator 3 Input 2	Summator 4 Output
Summator 3 Input 3	OFF
Summator 3 Input 4	OFF
Summator 3 Input 5	OFF
Summator 3 Input 6	OFF
Summator 3 Scale Factor 1	1666.666667
Summator 3 Scale Factor 2	-1.000000
Summator 3 Scale Factor 3	1.000000
Summator 3 Scale Factor 4	1.000000
Summator 3 Scale Factor 5	1.000000
Summator 3 Scale Factor 6	1.000000
Summator 3 Position Selector 1	ON
Summator 3 Position Selector 2	ON
Summator 3 Position Selector 3	OFF
Summator 3 Position Selector 4	OFF
Summator 3 Position Selector 5	OFF
Summator 3 Position Selector 6	OFF
Summator 3 Events	Enabled

Figure 17: Summator Settings for Unit 3

PARAMETER	FREQ RATE 1	FREQ RATE 2
Function	Enabled	Enabled
Source	SRC 3 (SRC 3)	SRC 4 (SRC 4)
Trend	Bidirectional	Bidirectional
Pickup	0.43 Hz/s	0.43 Hz/s
OV Supv	0.700 pu	0.700 pu
OC Supv	0.200 pu	0.200 pu
Min	45.00 Hz	45.00 Hz
Max	65.00 Hz	65.00 Hz
Pickup Delay	0.000 s	0.000 s
Reset Delay	0.000 s	0.000 s
Block	OFF	OFF
Target	Self-reset	Self-reset
Events	Enabled	Enabled

Figure 18: Frequency Rate of Change Settings

5.5.2. Implementation

In order to capture data from the relay, events had to be triggered in the relay, and oscillography records were outputted for comparison against the ATR data records. The GE N60 relay can force an event trigger to get an oscillography record, as shown in Figure 19. Once an event is triggered, the oscillography record can be displayed. As shown in Figure 20, the oscillography record displayed in the Viewpoint Engineering software shows the three-phase voltage source waveforms from the test relay. The oscillography record can be saved as a COMTRADE file, which is the IEEE standard file format for power system data.

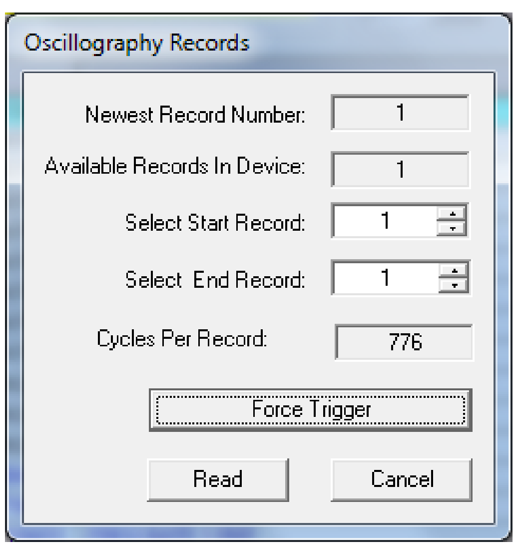

Figure 19: Oscillography Record Force Trigger Menu

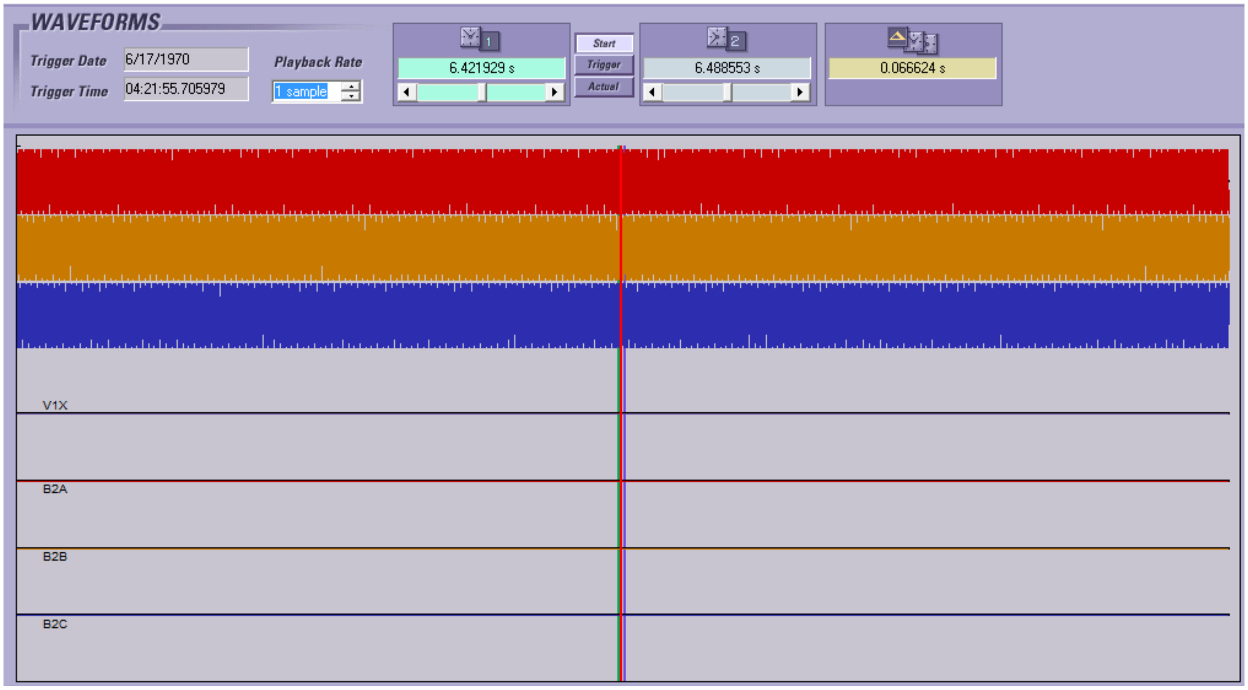

Figure 20: Test Relay Oscillography Record Showing the Three-Phase Voltage Waveforms

The original design was to use a program called Viewpoint Monitoring that could interface with the GE N60 relay and automatically collect and store oscillography records. The benefit of using the Viewpoint Monitoring software is that it could collect longer even records from the relay and store them on a separate server. Rather than storing the event records in the internal memory of the GE N60 relay, the files could automatically be extracted and saved to a separate system. Using the Viewpoint Monitoring system would have also made it much easier to collect records from the relay. The Viewpoint Monitoring software was installed according to the Quick Start Guide found in the documentation on the GE website. When Viewpoint Monitoring was installed, it automatically installed the demo version of the product. By entering the company license information for the Viewpoint Monitoring software, the full version of the program should have been launched. However, due to a licensing mix up, the full product could not be launched. Once the demo version of the program was installed, the relay would never connect to the software, even when communicating directly using serial protocol on the test relay. Two requests were sent to GE support – one to inquire about the licensing mix up and a second to ask for assistance setting up communication between the Viewpoint Monitoring program and the test relay. Until the problems could be solved, it was determined that the relay had enough internal event capture, display, and output capabilities on its own.

a steady-state event was captured by doing a force-triggered event on both the ATRs and the GE N60 relay at around the same time. These files had to be time-aligned manually due to slightly varying times between the ATRs and the GE N60 relay. Then, a Colstrip-Broadview transmission line had a single-phase fault which was captured simultaneously on the ATRs and the GE N60 relay. Event records were captured directly from the relay, and the resulting oscillography files were downloaded from the GE N60 relay so that the data could be plotted in Matlab.

5.6. Plotting Oscillography Records in Matlab

Saving oscillography records as COMTRADE files was very simple. Once the oscillography file was created, it could be saved directly as a COMTRADE file to a thumb drive. Plotting the COMTRADE file in Matlab proved a more challenging task. As it turns out, Matlab does not have a built in COMTRADE file reader function. On the Matlab website, a COMTRADE file reader was found and downloaded. However, the function was unable to read the COMTRADE file due to what could be a file version discrepancy. The advisor for the GE N60 relay project provided Matlab functions that could read and plot the COMTRADE files.

Unfortunately, function was only able to work on the 2013 version of Matlab on the advisor's work computer and not on the 2014 version of Matlab on the student computers at Montana Tech. As such, once the COMTRADE files were saved, they were sent to the advisor and converted into Matlab structures. Matlab script files were created to plot both force triggered data and actual event data from the ATRs and the GE N60 relay in Colstrip. The Matlab code may be viewed in Appendix C. The Matlab code compared the frequency deviation, frequency rate of change, real power, and reactive power responses for both a force-triggered, steady-state event as well as a dynamic event record captured as a result of a single-phase to ground fault on a Colstrip-Broadview transmission line.

6. Results

The first set of comparison plots from the GE N60 and the ATR show the results from the force-triggered event. Figures 21 - 26 compare the Unit 4 GE N60 relay speed deviation, real power, and reactive power responses with the ATR-A and ATR-B relays. Unit 3 was not running during the time of the force-trigger event. The second set of comparison plots show the results from the Colstrip-Broadview 12/22/2015 events. Figures 27 - 33 show the 08:21 event comparison plots, and Figures 34 - 40 show the 10:13 event comparison plots for speed deviation, acceleration, real power, and reactive power. A configuration error was made in the oscillography settings, and the frequency rate of change for Unit 4 was not captured. Note that the Colstrip-Broadview event plots had to be time-aligned due to a date mismatch between the GE N60 relay and the ATRs, and these comparison plots begin at zero seconds.

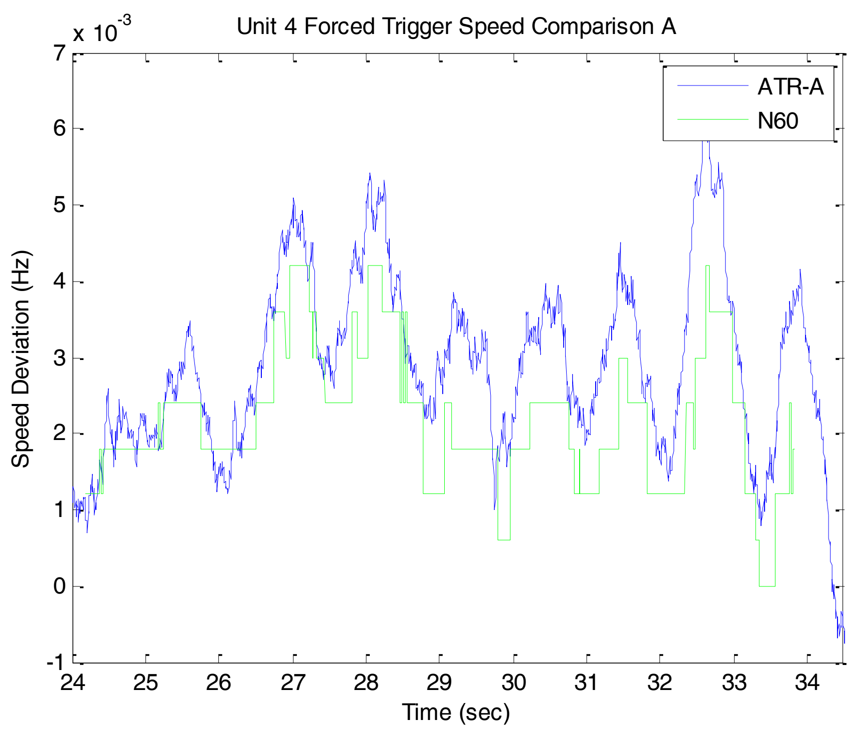

Figure 21: ATR-A Unit 4 Forced Trigger Speed Deviation Comparison

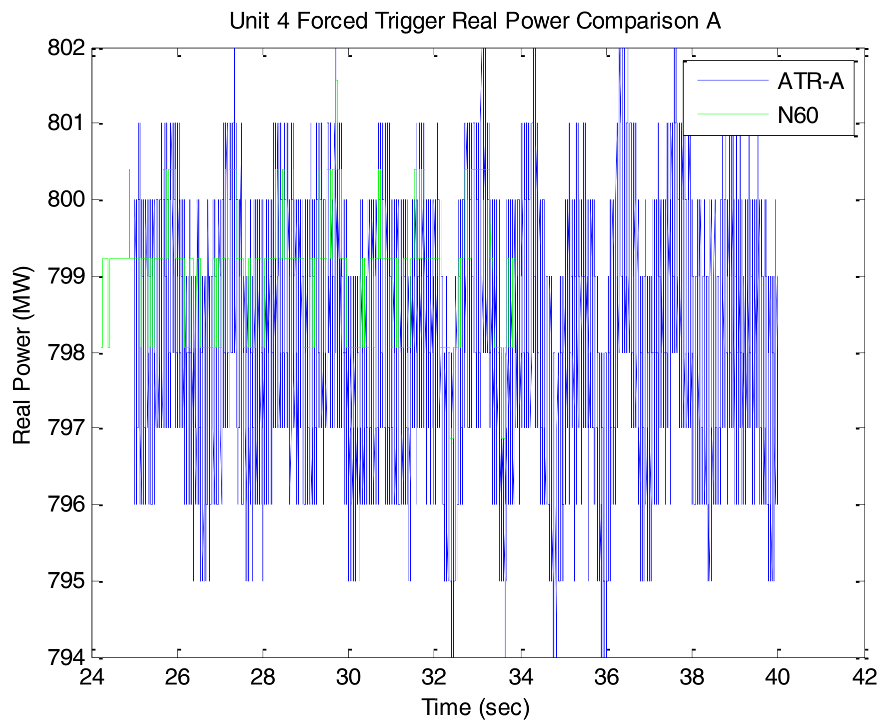

Figure 22: ATR-A Unit 4 Forced Trigger Real Power Comparison

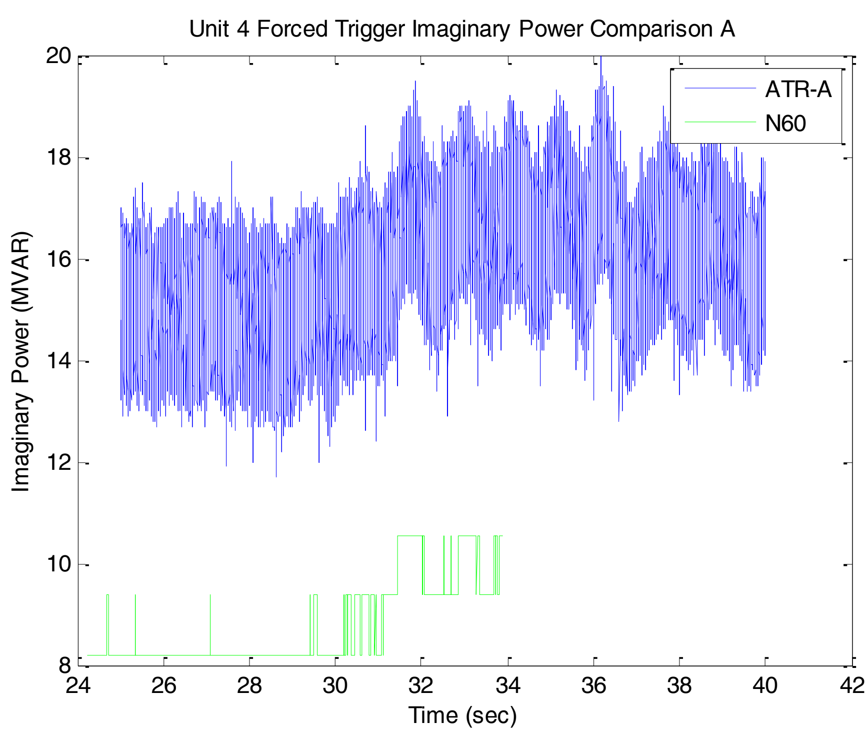

Figure 23: ATR-A Unit 4 Forced Trigger Reactive Power Comparison

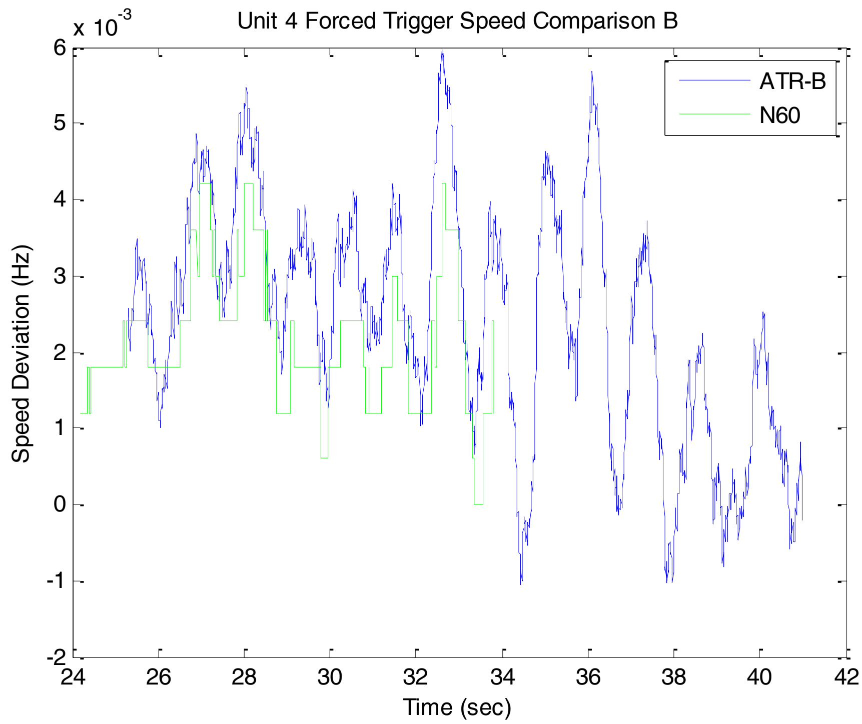

Figure 24: ATR-B Unit 4 Forced Trigger Speed Deviation Comparison

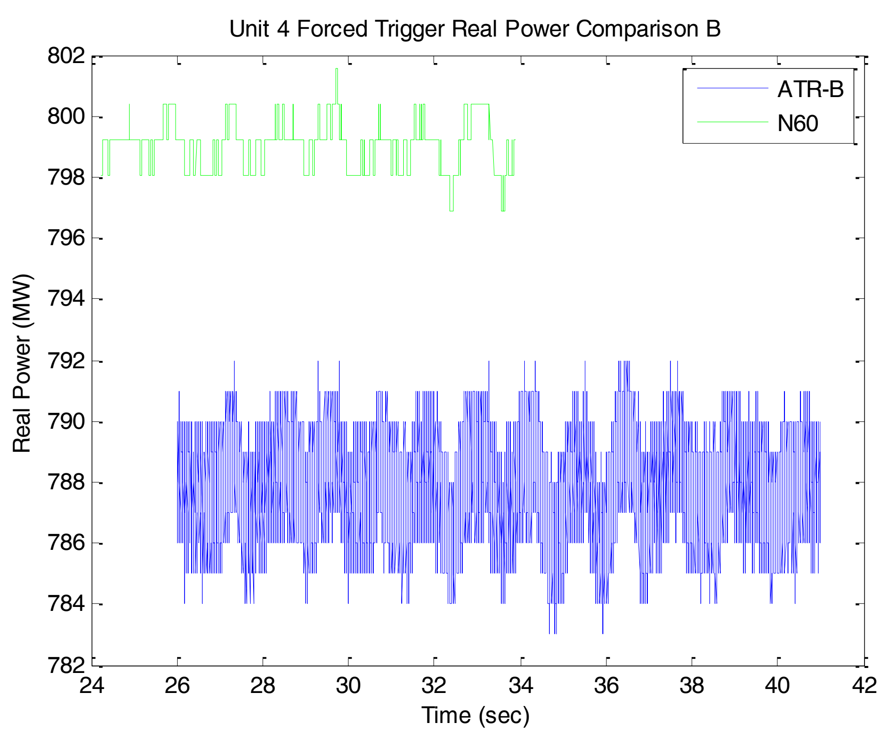

Figure 25: ATR-B Unit 4 Forced Trigger Real Power Comparison

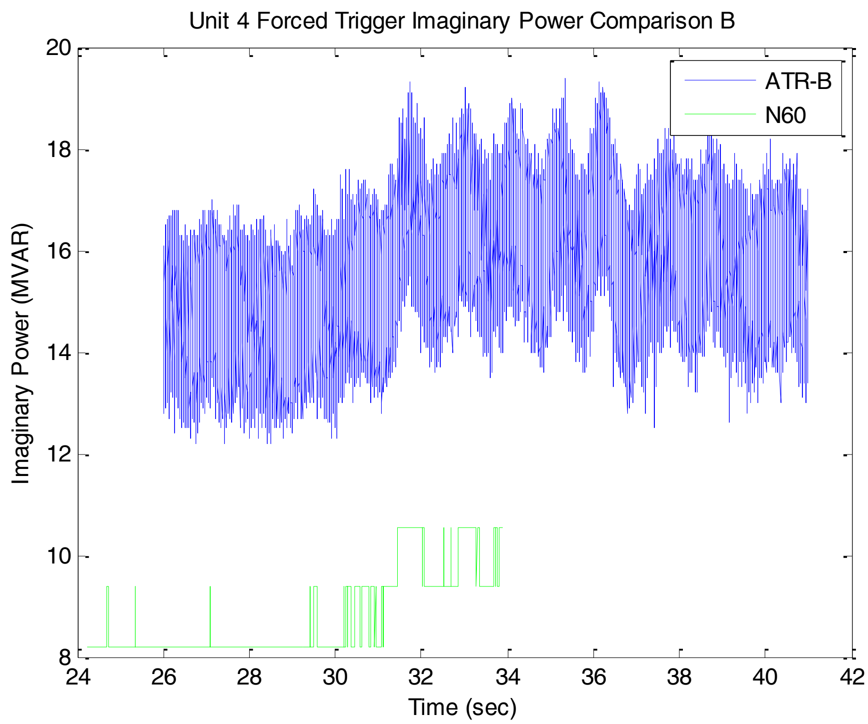

Figure 26: ATR-B Unit 4 Forced Trigger Reactive Power Comparison

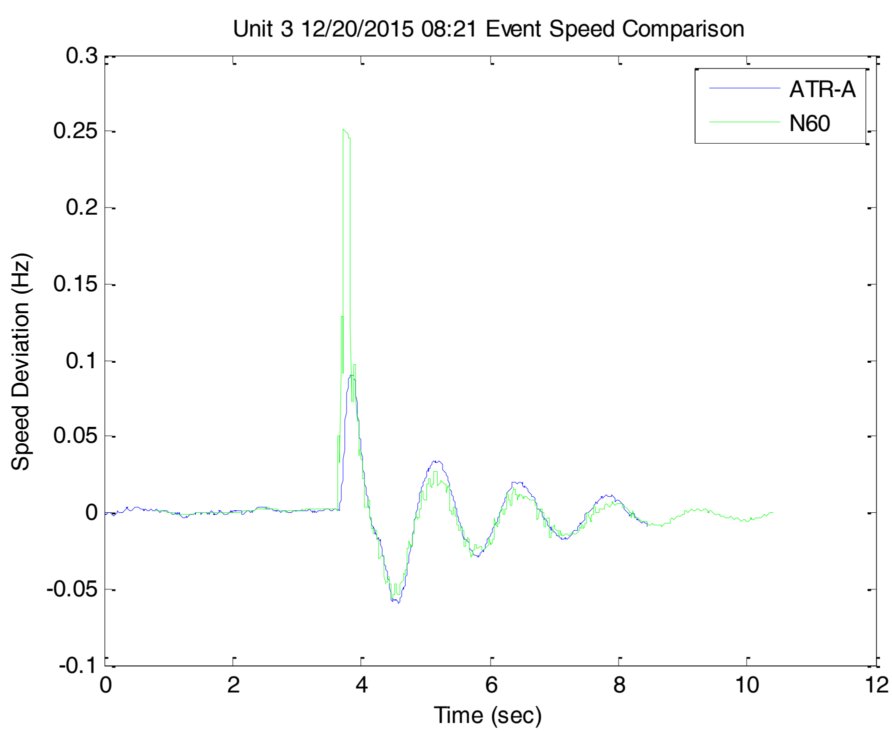

Figure 27: Unit 3 08:21 Event Speed Deviation Comparison

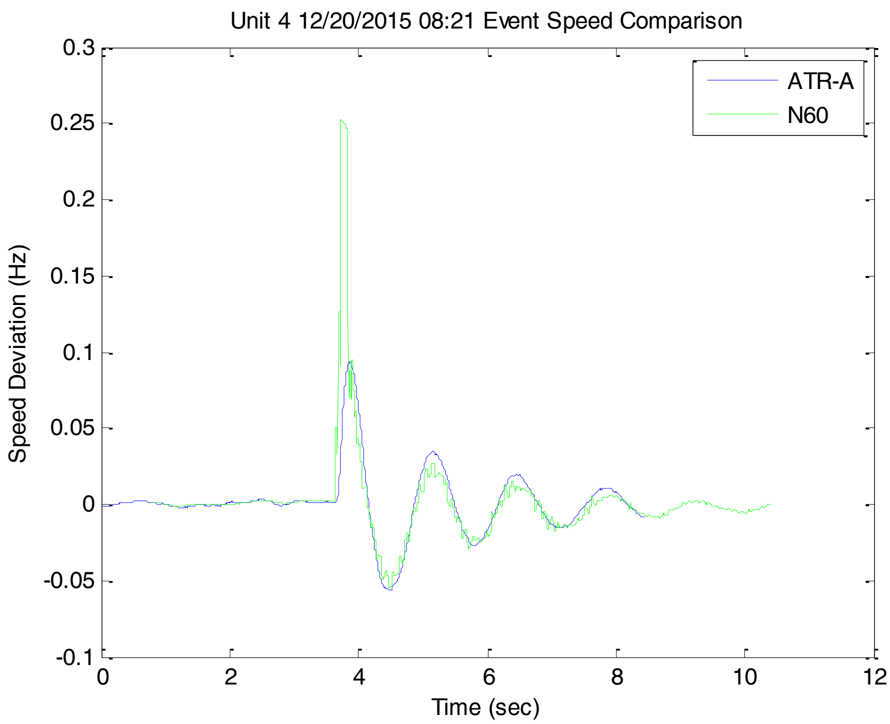

Figure 28: Unit 4 08:21 Event Speed Deviation Comparison Plot

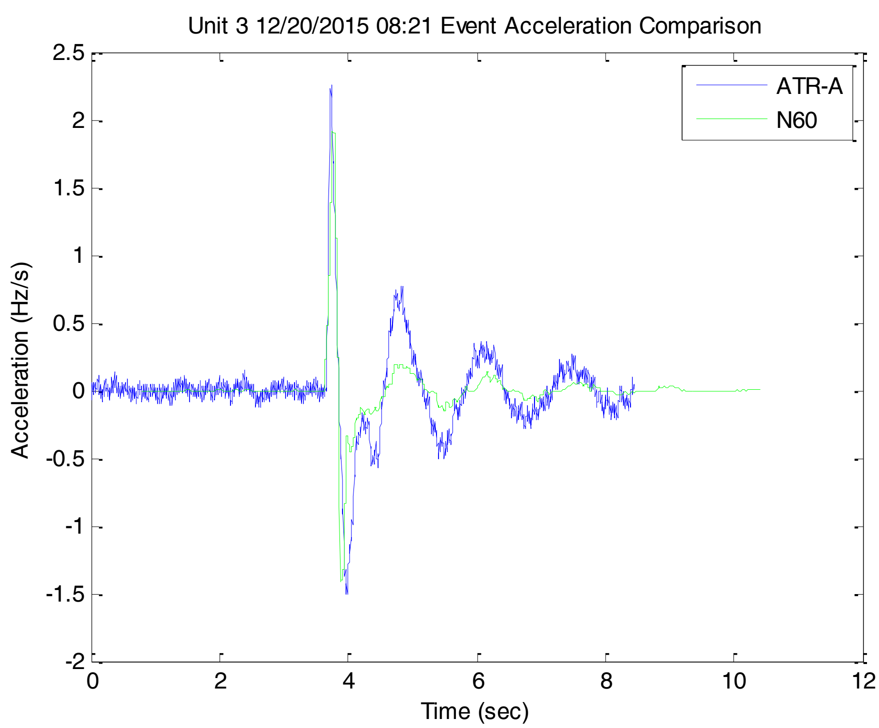

Figure 29: Unit 3 08:21 Event Acceleration Comparison

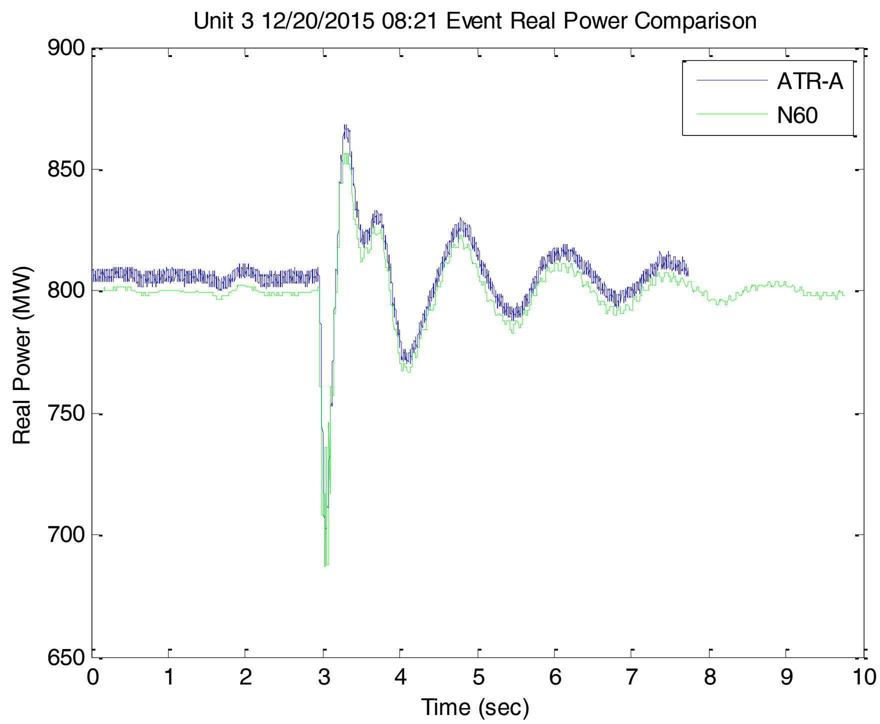

Figure 30: Unit 3 08:21 Event Real Power Comparison

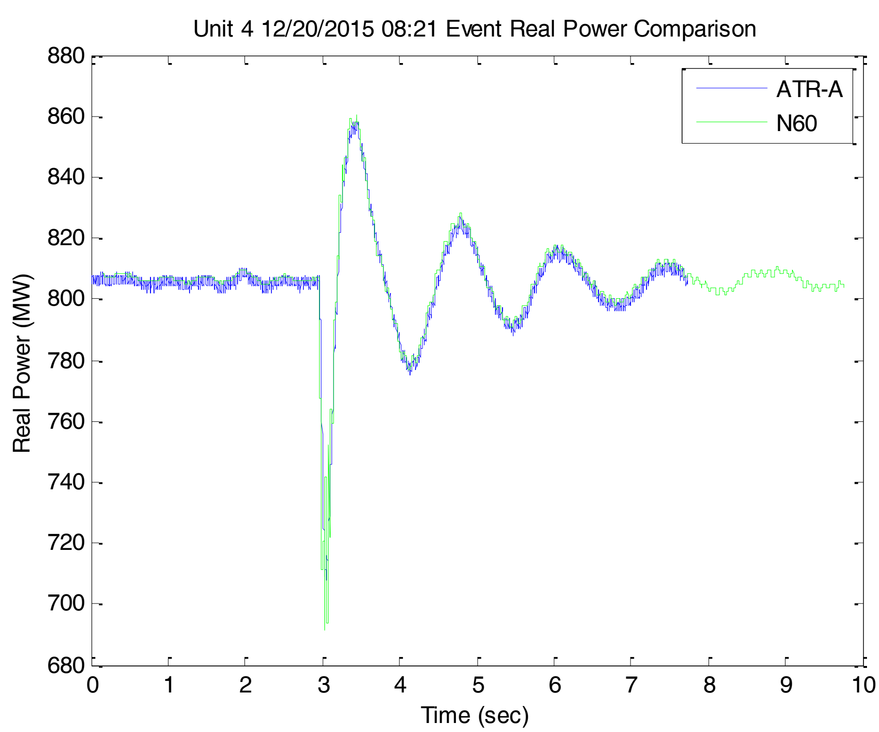

Figure 31: Unit 4 08:21 Event Real Power Comparison

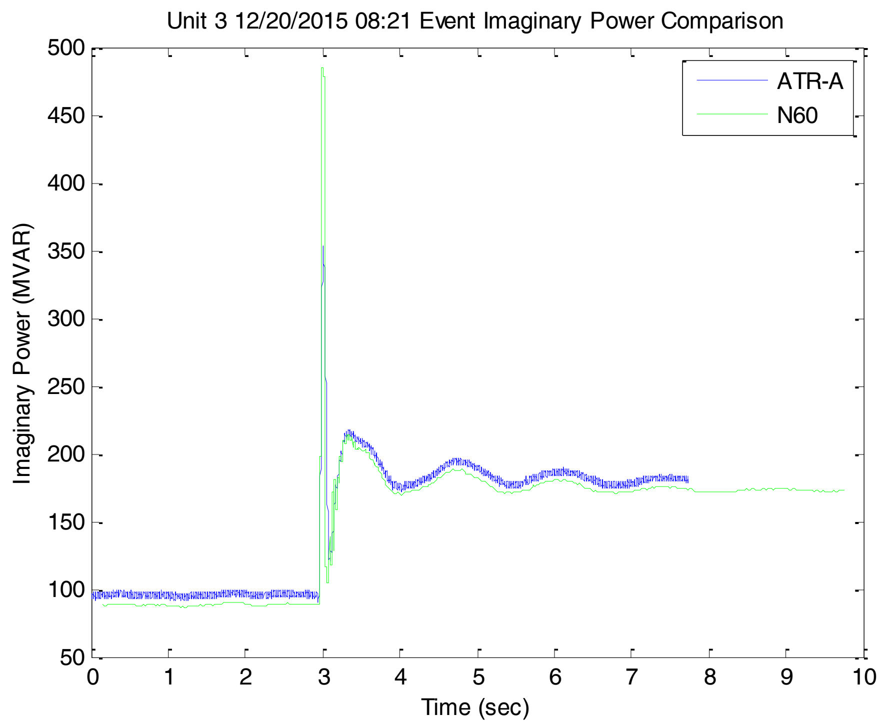

Figure 32: Unit 3 08:21 Event Reactive Power Comparison

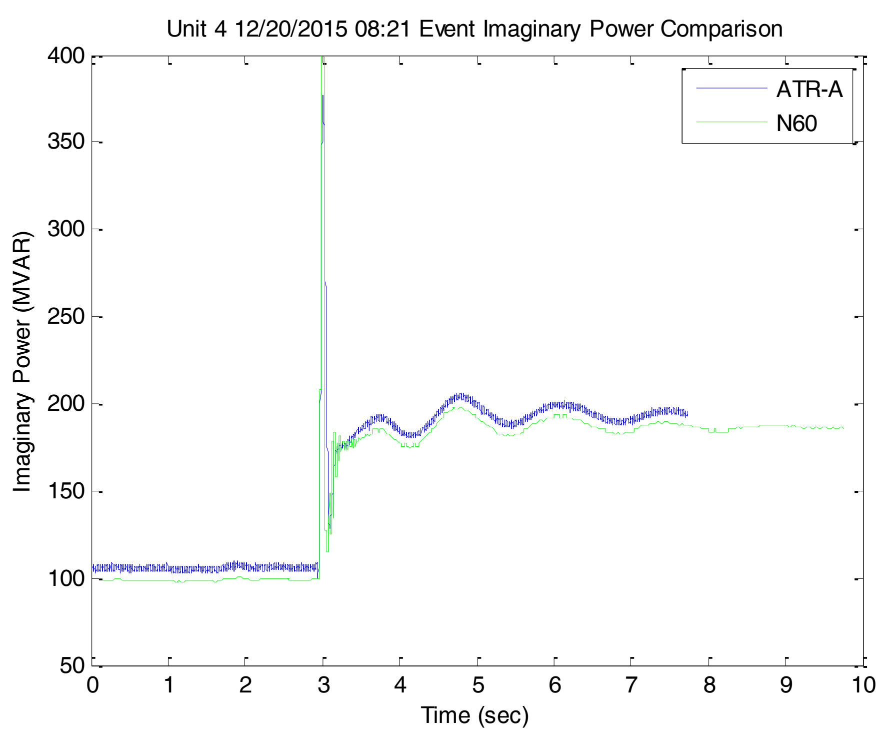

Figure 33: Unit 4 08:21 Event Reactive Power Comparison

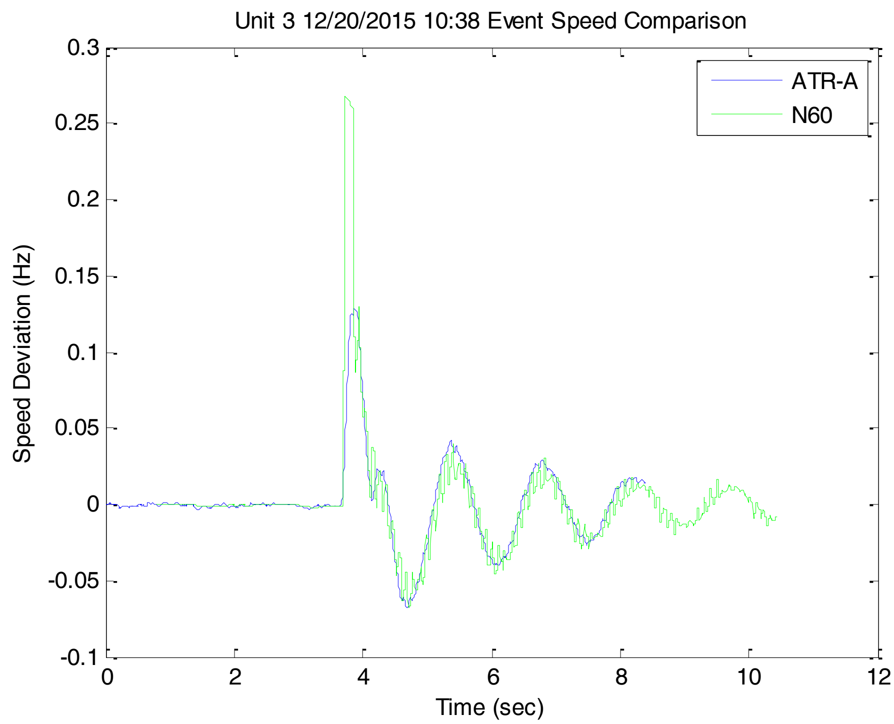

Figure 34: Unit 3 10:38 Event Speed Deviation Comparison

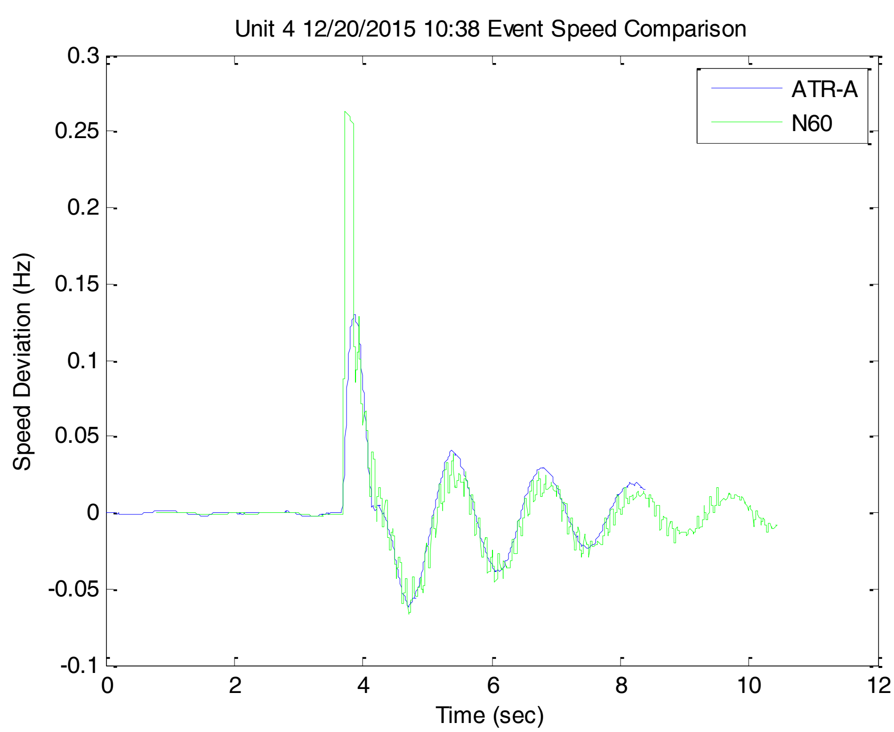

Figure 35: Unit 4 10:38 Event Speed Deviation Comparison

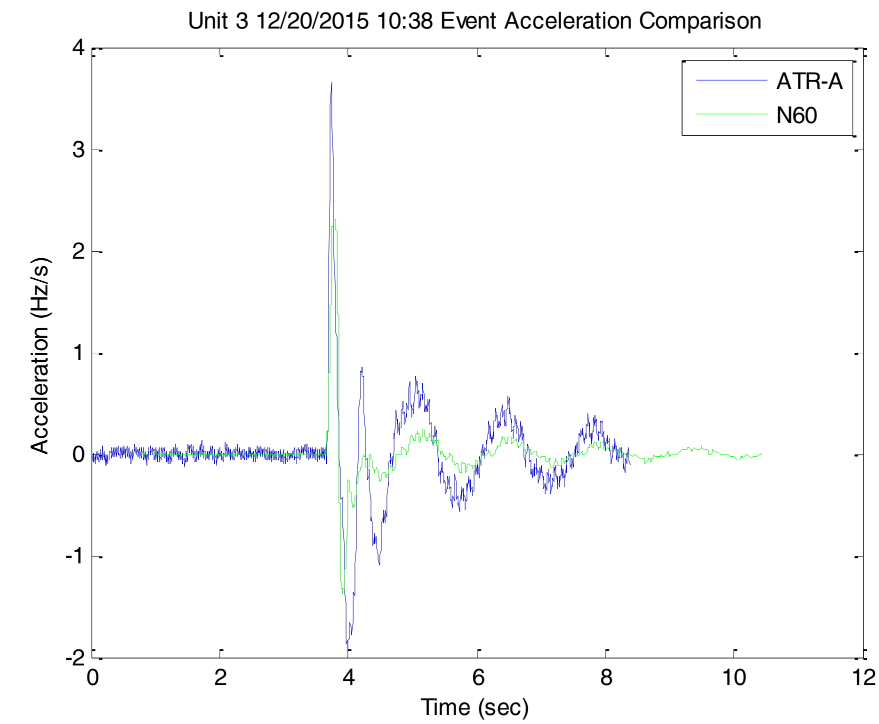

Figure 36: Unit 3 10:38 Event Acceleration Comparison

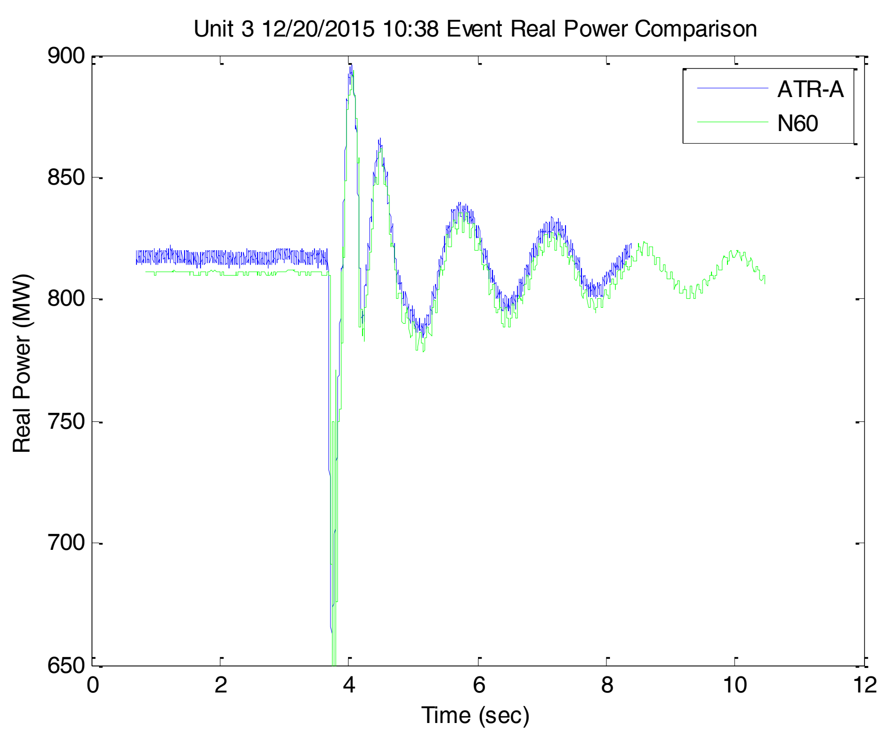

Figure 37: Unit 3 10:38 Event Real Power Comparison

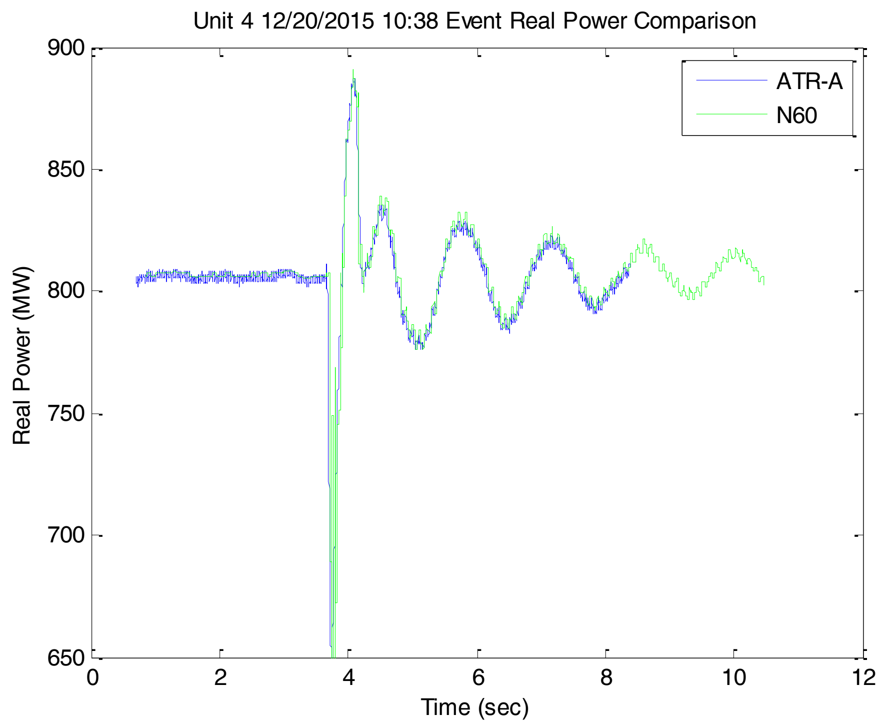

Figure 38: Unit 4 10:38 Event Real Power Comparison

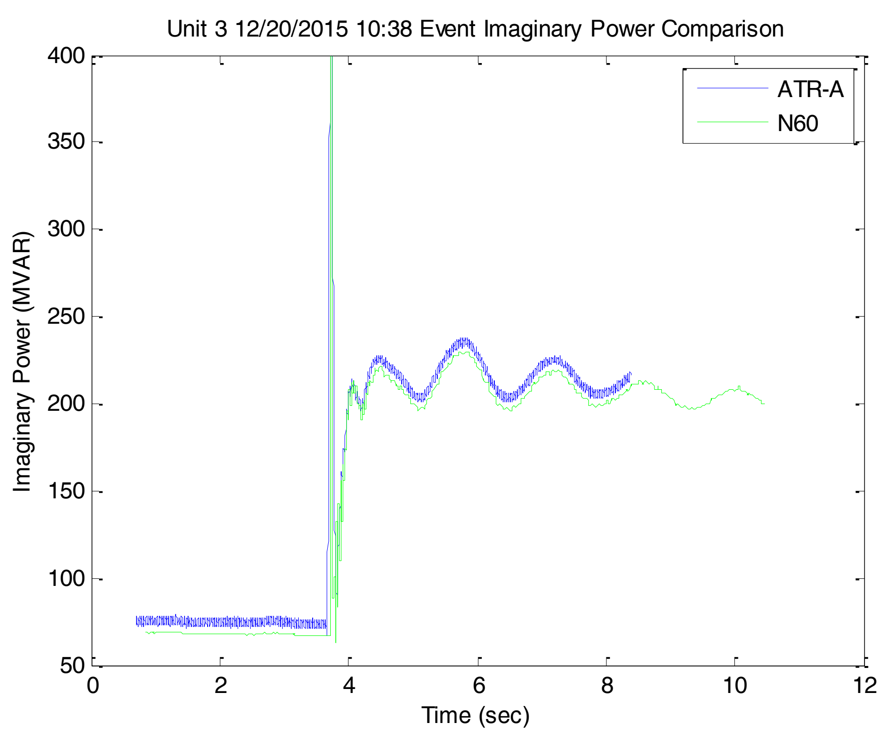

Figure 39: Unit 3 10:38 Event Reactive Power Comparison

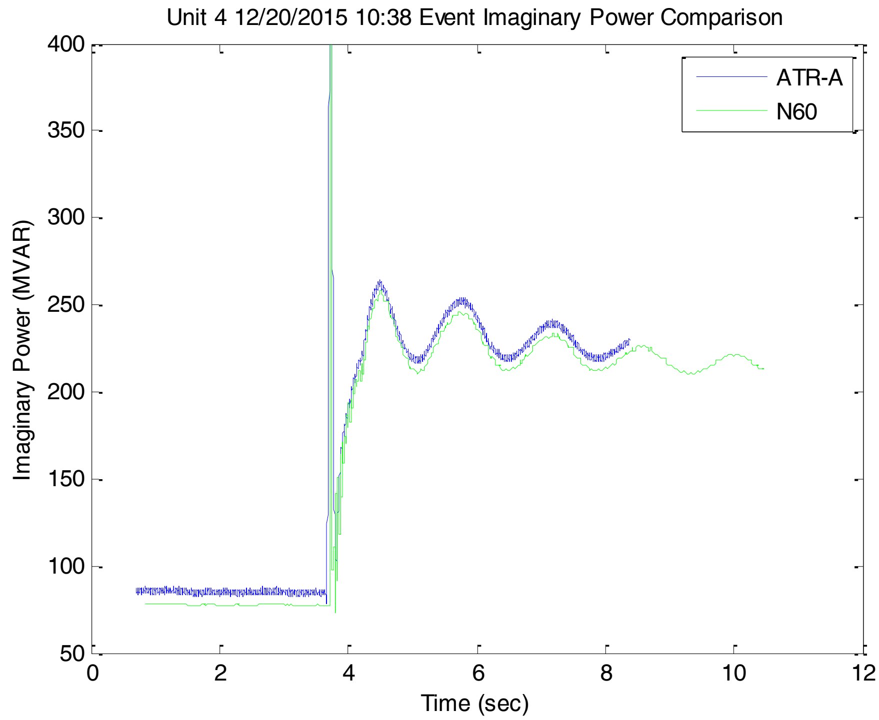

Figure 40: Unit 4 10:38 Event Reactive Power Comparison

7. Conclusion and Recommendation

From the tests, research, and event comparison plot results, the capabilities of the GE N60 were evaluated. The first criteria of the project was that the GE N60 relay had to have a sampling frequency equal to or better than the Acceleration Trend Relays (ATRs). The ATRs had a sampling frequency of 150 Hz. The oscillography records could have varying sample frequencies, depending on the length of the records collected. As seen in Figure 14, the chosen sampling frequency was 16 samples/cycle, or 960Hz. However, the summators used to implement the accumulator functions from the ATRs, and ultimately the trip logic, are only sampled once every cycle – which translates to 60Hz. 60Hz is far below the 150Hz sampling frequency of the ATRs. According to the Nyquist theorem, the sampling frequency of the GE N60 relay should be at least twice the Nyquist frequency of the ATRs, which is half of 150Hz. So, the GE N60 relay sampling frequency must be 150Hz or better. While the oscillography records are sampled at a greater frequency than the ATRs, the summators, which dictate the trip decisions of the GE N60 relay, are not sampled fast enough to meet the criteria.

The next requirement of the GE N60 relay was that they had to have minimal noise in their responses. Looking qualitatively at the Unit 3 and Unit 4 speed deviation and acceleration responses in Figures 27, 28, 29, 34, 35, and 36, the GE N60 relay responses all show visible levels of noise. In comparison to the ATRs, the GE N60 relay speed deviation responses showed significantly more noise. However, the level of noise in the speed deviation and acceleration responses was not so great as to cause false trips or prevent a trip decision from being made. In fact, apart from the initial spike at the beginning of each event, the magnitude of the GE N60 responses was generally smaller than that of the ATRs. This could be due to input impedances needing to be compensated for. The initial spike in the GE N60 relay responses could be due to how the GE N60 relay calculates the speed deviation and acceleration values. More research will be needed to determine the exact causes for these behaviors. In order to reduce the level of noise that is present in the GE N60 relay responses, filtering may need to be added to smooth out the signal, especially the initial spike in magnitude at the onset of an event, so long as the speed of the relay is not compromised. Even though the GE N60 relay responses all show significant noise, it was qualitatively determined that the noise was not significant enough to cause false trips or hinder trip decisions to be made. Therefore, the GE N60 relay met the second requirement.

The third piece of criteria for the GE N60 relay was that it had to be able to detect events based on the ATR speed deviation and acceleration thresholds. This requirement was certainly met. The GE N60 relay was able to catch two events simultaneously with the ATRs. Let it be noted that the GE N60 relay did capture some events that the ATRs did not. However, these events were from maintenance on the Colstrip generators, and the GE N60 relay did not have logic in place to classify these events as irrelevant. Because the GE N60 relay was able to capture event records simultaneously with the relay, it proves that the GE N60 relay has met the third requirement. Simply more programming is needed to make it operate more closely to the ATRs.

The fourth requirement of the GE N60 relay was that it had to be able to create and store event records of adequate length. Based on the figures provided in the results section, this requirement was easily met. The GE N60 relay had enough internal memory to be able to capture and store oscillography records that could be outputted and plotted in Matlab. The amount of pre- and post-data can be chosen in the GE N60 relay, meaning that this setting can be adjusted to match the ATRs amount of pre-event data. The chosen level of 30% pre-event and 70% post data in the GE N60 relay turned out to be more than sufficient length for the oscillography records. The overall length of the GE N60 oscillography records proved to be longer than that of all of the ATR Colstrip-Broadview event responses. The forced trigger oscillography records from the GE N60 relay were much shorter than that of the ATRs. However, the force triggered event was to determine how similar the steady-state system was between the ATRs and the GE N60 relay. Even though the signals show such small change, the speed deviation responses definitely showed similarities. The automatically detected event records show that the GE N60 relay is more than capable of collecting event records of adequate length.

In conclusion, three of the four GE N60 relay evaluation criteria were met. The GE N60 relay has shown great quality in its event detection and event recording capabilities. Overall, the GE N60 relay was able to emulate the most important functions of the ATRs. While the GE N60 met all but one of the criteria, the overall performance of the relay and the quality of the event responses have proven that the GE N60 relay can operate in a comparable manner to the ATRs. With some further finessing, such as adding filtering and more advanced trip decision logic, the GE N60 relay functions could be even closer to that of the ATRs. Because the GE N60 relay has more capabilities that were not utilized in this project, it would be worthwhile to explore those capabilities and see if the GE N60 relay can perform the same level of protection as the ATRs but in a potentially different manner. The final recommendation is to continue testing and research on the GE N60 relay as a potential replacement candidate for the Acceleration Trend Relays in Colstrip.

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Appendix A: Accumulator Constant Derivation

Calculations provided by Richard Setterstrom

Filter divide constant to filter time constant relationship:

$$\sigma_1 = \sigma_0 + \frac{i_1 - \sigma_0}{k}$$

$$\sigma_1 = \frac{(k-1)}{k}\sigma_0 + \frac{1}{k}i_1$$

$$\sigma_2 = \frac{(k-1)}{k}\sigma_1 + \frac{1}{k}i_2$$

$$\sigma_2 = \left(\frac{(k-1)}{k}\right)^2 \sigma_0 + \frac{(k-1)}{k^2}i_1 + \frac{1}{k}i_2$$

$$\sigma_3 = \left(\frac{(k-1)}{k}\right)^3 \sigma_0 + \left(\frac{(k-1)}{k}\right)^2 \frac{1}{k}i_1 + \frac{(k-1)}{k}\frac{1}{k}i_2 + \frac{1}{k}i_3$$

$$\sigma_n = \left(\frac{k-1}{k}\right)^n \sigma_0 + \frac{1}{k}\sum_{j=1}^{n}\left(\frac{k-1}{k}\right)^{j-1} i_{(n-j+1)}$$

$$\sum_{j=1}^{n} b^{n-1} = \frac{b^n - 1}{b - 1}$$

$$Let\ S_n = \sum_{j=1}^{n} b^{j-1}$$

$$Note\ that{:}\ S_{n+1} = S_n + b^n = 1 + bS_n$$

$$S_n + b^n = 1 + bS_n$$

$$S_n(1-b) = 1 - b^n$$

$$S_n = \frac{1 - b^n}{1 - b}$$

$$For\ i\ constant: \sigma_n = \left(\frac{k-1}{k}\right)^n \sigma_0 + \frac{1}{k}\left[\frac{1-\left(\frac{k-1}{k}\right)^n}{1-\frac{k-1}{k}}\right] i$$

$$\sigma_n = \left(\frac{k-1}{k}\right)^n \sigma_0 + \frac{1}{k}\left[\frac{1-\left(\frac{k-1}{k}\right)^n}{1-\frac{k-1}{k}}\right] i$$

$$\sigma_n = \left(\frac{k-1}{k}\right)^n \sigma_0 + \left[1-\left(\frac{k-1}{k}\right)^n\right] i$$

$$\sigma_n = i + \left(\frac{k-1}{k}\right)^n (\sigma_0 - i)$$

$$\frac{\sigma_n - i}{\sigma_0 - i} = \left(\frac{k-1}{k}\right)^n$$

$Let\ \mathrm{t}_0 be\ the\ time\ between\ updates.$

$Let\ \mathrm{n}_\mathrm{T}\ be\ the\ number\ of\ time\ steps\ associated\ with\ one\ time\ constant.$

$Let\ \mathrm{T} be\ equal\ to\ one\ time\ constant.$

$$T = n_T t_0$$

$$\frac{1}{e} = \left(\frac{k-1}{k}\right)^{n_T}$$

$$e = \left(\frac{k}{k-1}\right)^{n_T}$$

$$1 = n_T \ln\left(\frac{k}{k-1}\right)$$

$$n_T = \frac{1}{\ln\left(\frac{k}{k-1}\right)}$$

$$\ln(x+1) = x\sum_{j=0}^{\infty}\frac{-x^j}{j+1}$$

$$n_T = \frac{1}{-\ln\left(\frac{k-1}{k}\right)} = \frac{1}{-\ln\left(1-\frac{1}{k}\right)}$$

$$n_T = \frac{1}{-\left(-\frac{1}{k}\sum_{j=0}^{\infty}\frac{\left(\frac{1}{k}\right)^j}{j+1}\right)}$$

$$n_T = \frac{k}{\sum_{j=0}^{\infty}\frac{(\frac{1}{k})^j}{j+1}}$$

$$n_T = \frac{k}{1+\frac{1}{2k}+\frac{1}{3k^2}+\frac{1}{4k^3}+\cdots}$$

$$n_T \approx \frac{k}{1+\frac{1}{2k}} \approx k\left(1-\frac{1}{2k}\right)$$

$$n_T \approx k - \frac{1}{2} \;\; if\ k\ is\ large$$

$$t_0 = \frac{1}{600} sec$$

$$Note: T\ in\ cycles = \frac{n_T}{10}\ for\ t_o = \frac{1}{600} sec$$

For a GE N60 frequency deviation calculation from the previous time constant page, the ATR uses k=512 for the "speed deviation" calculation at $\frac{1}{150} sec$ intervals, giving a time constant of 3.4100 seconds. Using the approximation $n_T \approx k - \frac{1}{2}$, we can estimate k_{N60} as follows:

From the N60 documentation, the calculation rate for the GE N60 summators is $\frac{1}{60} sec$.

$$3.4100 = \frac{1}{60}\left(k_{N60-}\frac{1}{2}\right)$$

$$k_{N60} = (3.4100 * 60) + \frac{1}{2}$$

$$k_{N60} = 205.1$$

We can check our approximation using

$$n_T = \frac{1}{\ln(\frac{k}{k-1})} = \frac{1}{\ln(\frac{205.1}{204.1})} = 204.5996$$

$$T_{N60} = \frac{1}{60} * 204.5996 = 3.40999$$

This would round t_0 to 3.4100.

Table 3: ATR Accumulator Constant Calculations

k	n_T	**T (seconds)**	**T(seconds) for** $t_0 = \frac{1}{150} sec$
2	1.44	0.0024	0.0096
4	3.48	0.0058	0.0232
8	7.49	0.0125	0.0499
16	15.49	0.0258	0.1033
32	31.50	0.525	0.2100
64	63.50	0.1058	0.4233
128	127.50	0.2125	0.8500
256	255.50	0.4258	1.7033
512	511.50	0.8525	3.4100
1024	1023.50	1.7058	6.8233
2048	2047.50	3.4215	13.6500
4096	4095.50	6.8258	27.3033
8192	8191.50	13.6525	54.6100

Appendix B: Matlab Code

Forced-Trigger Event:

```
% Brenna Andrews
% Senior Design Project
% Evaluation of the GE N60 Relay
% Forced Trigger Comparison Code

clear
clc
close all

% Read in the necessary CSV files from the ATR for Units 3 and 4
    ATR_A_Dec7U1 = csvread('ATR_A_flt4fDataU1_2015_1207_2038_FINAL.csv');
    ATR_A_Dec7U4 = csvread('ATR_A_flt4fDataU4_2015_1207_2038_FINAL.csv');
    ATR_A_Dec7In12 = csvread('ATR_A_inputDataU12_2015_1207_2038_FINAL.csv');
    ATR_A_Dec7In34 = csvread('ATR_A_inputDataU34_2015_1207_2038_FINAL.csv');
    ATR_B_Dec7U1 = csvread('ATR_B_flt4fDataU1_2015_1207_2038_FINAL.csv');
    ATR_B_Dec7U2 = csvread('ATR_B_flt4fDataU2_2015_1207_2038_FINAL.csv');
    ATR_B_Dec7U4 = csvread('ATR_B_flt4fDataU4_2015_1207_2038_FINAL.csv');
    ATR_B_Dec7In12 = csvread('ATR_B_inputDataU12_2015_1207_2038_FINAL.csv');
    ATR_B_Dec7In34 = csvread('ATR_B_inputDataU34_2015_1207_2038_FINAL.csv');

% Read in the necessary N60 files
    N60Dec7_ForceTrig = load('12_07_2015_ForceTrig.mat');
% Remove the trailing zeros from each Data column
    for j=1:41
        for i=1:length(N60Dec7_ForceTrig.y.Data(:,1))-20
            N60_ForceTrig(i,j) = N60Dec7_ForceTrig.y.Data(i,j);
       end
    end

% % Define the time vector for each ATR file
    atrA_U4time = ATR_A_Dec7U4(:,5);
    atrA_U34time = ATR_A_Dec7In34(:,5);
    atrB_U4time = ATR_B_Dec7U4(:,5);
    atrB_U34time = ATR_B_Dec7In34(:,5);

% % Define the time vector for each N60 file
    % The date is 12/07/2015 20:38
    % Isolate the necessary vector from the structure
    n60len = length(N60_ForceTrig(:,1));
    n60time = zeros(n60len,1);
    % Define the total time based on the start time
    % and the time at 30% completion
    tstart = 23.835685;
    t30 = 26.727583;
    n60Tot = (t30 - tstart)/0.3;
    % Determine the time step from the number of data points
    n60dt = n60Tot/9264;
    % Define the time vector
    n60time(1) = tstart;
    for i=1:n60len-1
        n60time(i+1) = n60time(i)+n60dt;
```

```
    end


% Isolate the necessary vectors for plotting
    % For the ATR
    % ATR-A Unit 4
    atrA_Accel4 = ATR_A_Dec7U4(:,8);
    atrA_Speed4 = ATR_A_Dec7U4(:,9);
    atrA_AbsSpd4 = ATR_A_Dec7U4(:,14);

    % ATR-A Input for Units 3 & 4
    atrA_MW4 = ATR_A_Dec7In34(:,10);
    atrA_MVAR4 = ATR_A_Dec7In34(:,11);

    % ATR-B Unit 4
    atrB_Accel4 = ATR_B_Dec7U4(:,8);
    atrB_Speed4 = ATR_B_Dec7U4(:,9);
    atrB_AbsSpd4 = ATR_B_Dec7U4(:,14);

    % ATR-B Units 3 & 4
    atrB_MW4 = ATR_B_Dec7In34(:,10);
    atrB_MVAR4 = ATR_B_Dec7In34(:,11);

    % For the N60
    % Unit 3
    n60SpdDev3 = N60_ForceTrig(:,26);
    n60FreqRate3 = N60_ForceTrig(:,30);
    n60Q3 = N60_ForceTrig(:,37);
    n60P3 = N60_ForceTrig(:,39);

    % Unit 4
    n60SpdDev4 = N60_ForceTrig(:,27);
    n60Q4 = N60_ForceTrig(:,38);
    n60P4 = N60_ForceTrig(:,40);


% Plot the values for comparison

    % Define the per unit to Hertz relationship 100000pu = 60Hz
    pu2Hz = 60/100000;

    % ATR-A records
    % Plot the speed records
    figure(1)
    plot(atrA_U4time,atrA_Speed4*pu2Hz)
    hold on
    plot(n60time+0.35,n60SpdDev4*pu2Hz,'g')
    title('Unit 4 Forced Trigger Speed Comparison A')
    ylabel('Speed Deviation (Hz)')
    xlabel('Time (sec)')
    legend('ATR-A','N60')
    xlim([24,34.5])

    % Plot the acceleration records
```

```
% There is only an acceleration record for Unit 3,
% which was not running at this time

% Plot the angle records
% The incorrect angle value was selected for the GE N60 relay
% So the angle comparison cannot be made

% Plot the real power records
figure(2)
plot(atrA_U34time,atrA_MW4)
hold on
plot(n60time+0.4,n60P4,'g')
title('Unit 4 Forced Trigger Real Power Comparison A')
ylabel('Real Power (MW)')
xlabel('Time (sec)')
legend('ATR-A','N60')

% Plot the imaginary power records
figure(3)
plot(atrA_U34time,atrA_MVAR4)
hold on
plot(n60time+0.4,n60Q4,'g')
title('Unit 4 Forced Trigger Imaginary Power Comparison A')
ylabel('Imaginary Power (MVAR)')
xlabel('Time (sec)')
legend('ATR-A','N60')


% ATR-B records
% Plot the speed records
figure(4)
plot(atrB_U4time,atrB_Speed4*pu2Hz)
hold on
plot(n60time+0.35,n60SpdDev4*pu2Hz,'g')
title('Unit 4 Forced Trigger Speed Comparison B')
ylabel('Speed Deviation (Hz)')
xlabel('Time (sec)')
legend('ATR-B','N60')

% Plot the acceleration records
% There is only an acceleration record for Unit 3,
% which was not running at this time

% Plot the angle records
% The incorrect angle value was selected for the GE N60 relay
% So the angle comparison cannot be made

% Plot the power records
figure(6)
plot(atrB_U34time,atrB_MW4)
hold on
plot(n60time+0.4,n60P4,'g')
title('Unit 4 Forced Trigger Real Power Comparison B')
ylabel('Real Power (MW)')
xlabel('Time (sec)')
```

```
    legend('ATR-B','N60')

    % Plot the imaginary power records
    figure(7)
    plot(atrB_U34time,atrB_MVAR4)
    hold on
    plot(n60time+0.4,n60Q4,'g')
    title('Unit 4 Forced Trigger Imaginary Power Comparison B')
    ylabel('Imaginary Power (MVAR)')
    xlabel('Time (sec)')
    legend('ATR-B','N60')
```

Colstrip-Broadview Events:

```
% Brenna Andrews
% Senior Design Project
% Evaluation of the GE N60 Relay
% Event Comparison Code

clear
clc
close all

% Read in the necessary CSV files from the ATR for Units 3 and 4
    ATRDec20_0821_3 = csvread('DataAtrA2015_1220_0821_flt4f_U3_FINAL.csv');
    ATRDec20_0821_4 = csvread('DataAtrA2015_1220_0821_flt4f_U4_FINAL.csv');
    ATRDec20_0821_In34 =
csvread('DataAtrA2015_1220_0821_input_U34_FINAL2.csv');
    ATRDec20_1038_3 = csvread('DataAtrA2015_1220_1038_flt4f_U3_FINAL.csv');
    ATRDec20_1038_4 = csvread('DataAtrA2015_1220_1038_flt4f_U4_FINAL.csv');
    ATRDec20_1038_In34 =
csvread('DataAtrA2015_1220_1038_input_U34_FINAL.csv');

% Read in the necessary N60 files
    N60Dec20_082131 = load('082131.mat');
    N60Dec20_103813 = load('103813.mat');
% Remove the trailing zeros from each Data column
    for j=1:41
        for i=1:length(N60Dec20_082131.y.Data(:,1))-20
            N60_082131(i,j) = N60Dec20_082131.y.Data(i,j);
            N60_103813(i,j) = N60Dec20_103813.y.Data(i,j);
       end
    end

% Define the time vector for each ATR file
    atrT0821_3 = ATRDec20_0821_3(:,5);
    atrT0821_4 = ATRDec20_0821_4(:,5);
    atrT0821_In34 = ATRDec20_0821_In34(:,5);
    atrT1038_3 = ATRDec20_1038_3(:,5);
    atrT1038_4 = ATRDec20_1038_4(:,5);
    atrT1038_In34 = ATRDec20_1038_In34(:,5);

% Define the time vector for each N60 file
    % The date is 12/20/2015 08:21
```

```
    % Isolate the necessary vector from the structure
    n60len1 = length(N60_082131(:,1));
    n60time082131 = zeros(n60len1,1);
    % Define the total time based on the start time
    % and the time at 30% completion
    tstart1 = 28.963587;
    t301 = 31.849201;
    n60Tot1 = (t301 - tstart1)/0.3;
    % Determine the time step from the number of data points
    n60dt1 = n60Tot1/9264;
    % Define the time vector
    n60time082131(1) = tstart1;
    for i=1:n60len1-1
        n60time082131(i+1) = n60time082131(i)+n60dt1;
    end

    % The date is 12/20/2015 10:38
    % Isolate the necessary vector from the structure
    n60len2 = length(N60_103813(:,1));
    n60time103813 = zeros(n60len2,1);
    % Define the total time based on the start time
    % and the time at 30% completion
    tstart2 = 10.934661;
    t302 = 13.822725;
    n60Tot2 = (t302 - tstart2)/0.3;
    % Determine the time step from the number of data points
    n60dt2 = n60Tot2/9264;
    % Define the time vector
%     n60time103813 = (0:n60dt2:n60Tot2)+10.934661;
    n60time103813(1) = tstart2;
    for i=1:n60len2-1
        n60time103813(i+1) = n60time103813(i)+n60dt2;
    end


% Isolate the necessary vectors for plotting
    % For the ATR
    % Event 0821
    % Unit 3
    atr0821Accel3 = ATRDec20_0821_3(:,8);
    atr0821Speed3 = ATRDec20_0821_3(:,9);

    % Unit 4
    atr0821Accel4 = ATRDec20_0821_4(:,8);
    atr0821Speed4 = ATRDec20_0821_4(:,9);

    % Units 3 & 4 Input Data
    atr0821MW3 = ATRDec20_0821_In34(:,7);
    atr0821MVAR3 = ATRDec20_0821_In34(:,8);
    atr0821MW4 = ATRDec20_0821_In34(:,10);
    atr0821MVAR4 = ATRDec20_0821_In34(:,11);

    % Event 1038
    % Unit 3
    atr1038Accel3 = ATRDec20_1038_3(:,8);
    atr1038Speed3 = ATRDec20_1038_3(:,9);
```

```
    % Unit 4
    atr1038Accel4 = ATRDec20_1038_4(:,8);
    atr1038Speed4 = ATRDec20_1038_4(:,9);

    % Units 3 & 4 Input Data
    atr1038MW3 = ATRDec20_1038_In34(:,7);
    atr1038MVAR3 = ATRDec20_1038_In34(:,8);
    atr1038MW4 = ATRDec20_1038_In34(:,10);
    atr1038MVAR4 = ATRDec20_1038_In34(:,11);

    % For the N60
    % Event 082131
    % Unit 3
    n60082131SpdDev3 = N60_082131(:,26);
    n60082131FreqRate3 = N60_082131(:,30);
    n60082131Q3 = N60_082131(:,37);
    n60082131P3 = N60_082131(:,39);

    % Unit 4
    n60082131SpdDev4 = N60_082131(:,27);
    n60082131Q4 = N60_082131(:,38);
    n60082131P4 = N60_082131(:,40);

    % Event 103813
    % Unit 3
    n60103813SpdDev3 = N60_103813(:,26);
    n60103813FreqRate3 = N60_103813(:,30);
    n60103813Q3 = N60_103813(:,37);
    n60103813P3 = N60_103813(:,39);

    % Unit 4
    n60103813SpdDev4 = N60_103813(:,27);
    n60103813Q4 = N60_103813(:,38);
    n60103813P4 = N60_103813(:,40);


% Plot the values for comparison

    % Define the per unit to Hertz relationship 100000pu = 60Hz
    pu2Hz = 60/100000;

    % 0821 records
    % Plot the speed records
    % Unit 3
    figure(1)
    plot(atrT0821_3-atrT0821_3(1),atr0821Speed3*pu2Hz)
    hold on
    plot(n60time082131-tstart1+0.8,n60082131SpdDev3*pu2Hz,'g')
    title('Unit 3 12/20/2015 08:21 Event Speed Comparison')
    ylabel('Speed Deviation (Hz)')
    xlabel('Time (sec)')
    legend('ATR-A','N60')

    % Unit 4
```

```
figure(2)
plot(atrT0821_4-atrT0821_4(1),atr0821Speed4*pu2Hz)
hold on
plot(n60time082131-tstart1+0.8,n60082131SpdDev4*pu2Hz,'g')
title('Unit 4 12/20/2015 08:21 Event Speed Comparison')
ylabel('Speed Deviation (Hz)')
xlabel('Time (sec)')
legend('ATR-A','N60')

% Plot the acceleration records

% Define the conversion for MW/small unit inertia to Hz/sec
% 15 MW/small unit inertia = 0.4294 Hz/sec
smi2accel = 15/0.4294;

% Unit 3
figure(3)
plot(atrT0821_3-atrT0821_3(1),atr0821Accel3/smi2accel)
hold on
plot(n60time082131-tstart1+0.8,n60082131FreqRate3,'g')
title('Unit 3 12/20/2015 08:21 Event Acceleration Comparison')
ylabel('Acceleration (Hz/s)')
xlabel('Time (sec)')
legend('ATR-A','N60')

% Plot the real power records
% Unit 3
figure(4)
plot(atrT0821_In34-atrT0821_In34(1),atr0821MW3)
hold on
plot(n60time082131-tstart1+0.15,n60082131P3,'g')
title('Unit 3 12/20/2015 08:21 Event Real Power Comparison')
ylabel('Real Power (MW)')
xlabel('Time (sec)')
legend('ATR-A','N60')
ylim([650,900])

% Unit 4
figure(5)
plot(atrT0821_In34-atrT0821_In34(1),atr0821MW4)
hold on
plot(n60time082131-tstart1+0.15,n60082131P4,'g')
title('Unit 4 12/20/2015 08:21 Event Real Power Comparison')
ylabel('Real Power (MW)')
xlabel('Time (sec)')
legend('ATR-A','N60')

% Plot the imaginary power records
% Unit 3
figure(6)
plot(atrT0821_In34-atrT0821_In34(1),atr0821MVAR3)
hold on
plot(n60time082131-tstart1+0.15,n60082131Q3,'g')
title('Unit 3 12/20/2015 08:21 Event Imaginary Power Comparison')
ylabel('Imaginary Power (MVAR)')
xlabel('Time (sec)')
```

```
legend('ATR-A','N60')

% Unit 4
figure(7)
plot(atrT0821_In34-atrT0821_In34(1),atr0821MVAR4)
hold on
plot(n60time082131-tstart1+0.15,n60082131Q4,'g')
title('Unit 4 12/20/2015 08:21 Event Imaginary Power Comparison')
ylabel('Imaginary Power (MVAR)')
xlabel('Time (sec)')
legend('ATR-A','N60')
ylim([50,400])


% 103813 records
% Plot the speed records
% Unit 3
figure(8)
plot(atrT1038_3-atrT1038_3(1),atr1038Speed3*pu2Hz)
hold on
plot(n60time103813-tstart2+0.8,n60103813SpdDev3*pu2Hz,'g')
title('Unit 3 12/20/2015 10:38 Event Speed Comparison')
ylabel('Speed Deviation (Hz)')
xlabel('Time (sec)')
legend('ATR-A','N60')

% Unit 4
figure(9)
plot(atrT1038_4-atrT1038_4(1),atr1038Speed4*pu2Hz)
hold on
plot(n60time103813-tstart2+0.8,n60103813SpdDev4*pu2Hz,'g')
title('Unit 4 12/20/2015 10:38 Event Speed Comparison')
ylabel('Speed Deviation (Hz)')
xlabel('Time (sec)')
legend('ATR-A','N60')

% Plot the acceleration records
% Unit 3
figure(10)
plot(atrT1038_3-atrT1038_3(1),atr1038Accel3/smi2accel)
hold on
plot(n60time103813-tstart2+0.8,n60103813FreqRate3,'g')
title('Unit 3 12/20/2015 10:38 Event Acceleration Comparison')
ylabel('Acceleration (Hz/s)')
xlabel('Time (sec)')
legend('ATR-A','N60')

% Plot the real power records
% Unit 3
figure(11)
plot(atrT1038_In34-atrT1038_3(1),atr1038MW3)
hold on
plot(n60time103813-tstart2+0.85,n60103813P3,'g')
title('Unit 3 12/20/2015 10:38 Event Real Power Comparison')
ylabel('Real Power (MW)')
xlabel('Time (sec)')
```

```
legend('ATR-A','N60')
ylim([650,900])


% Unit 4
figure(12)
plot(atrT1038_In34-atrT1038_3(1),atr1038MW4)
hold on
plot(n60time103813-tstart2+0.85,n60103813P4,'g')
title('Unit 4 12/20/2015 10:38 Event Real Power Comparison')
ylabel('Real Power (MW)')
xlabel('Time (sec)')
legend('ATR-A','N60')
ylim([650,900])
```