THREE-TERMINAL LINES: WHICH IS BETTER, PERMISSIVE TRANSFER TRIPPING SCHEMES, BLOCKING SCHEMES, OR SOMETHING ELSE?

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INTRODUCTION

Power system operation in today's deregulated market is different from operation in the regulated era. There is continuing pressure to reduce expenditures for both generation and power transmission systems. In this deregulated electric environment, power systems are open to market access by qualified generation suppliers, presenting power engineers with new challenges daily.

One such challenge is creating a tap to connect new generation to an existing line in the power system. When a circuit breaker is added at the tap this becomes a three-terminal line. The goal of this design is to save both the time and cost of constructing either a longer transmission line, a new substation switching yard, or both. Three-terminal lines can be problematic to protect, however. An IEEE Power System Relaying Committee report [4] states:

> Protection of multi-terminal lines is never as simple as that of a two-terminal line. The infinite number of variations of line arrangements, system loading requirements and system operating conditions make some proposed lines acceptable while others cannot be protected satisfactorily.

In GPU Energy's experience, three-terminal lines are notorious for delayed fault clearing. They are also a common source of overtripping, tripping the line for a fault on an adjacent part of the power system caused by a failure of the blocking power line carrier (PLC). As a result, protection engineers are considering more complex relay protection schemes integrated with complex communications systems to address the challenges of three-terminal lines.

When GPU Energy was confronted with the task of splitting existing two-terminal lines and creating a three-terminal line, plus the addition of a 750 MW independent power producer (IPP) generation plant, they decided on an evaluation program that would include extensive testing to verify the relay and communications system performance.

BACKGROUND

GPU Energy covers territory in central Pennsylvania and New Jersey. They were approached by AES Enterprise, an IPP interested in building a 750 MW generation facility and connecting it to the existing GPU Energy transmission system in Lebanon County, about twenty miles east of Hershey, Pennsylvania. Figure 1 shows the original line configuration. In the original configuration, Lyons is a transformer tap without a local circuit breaker.

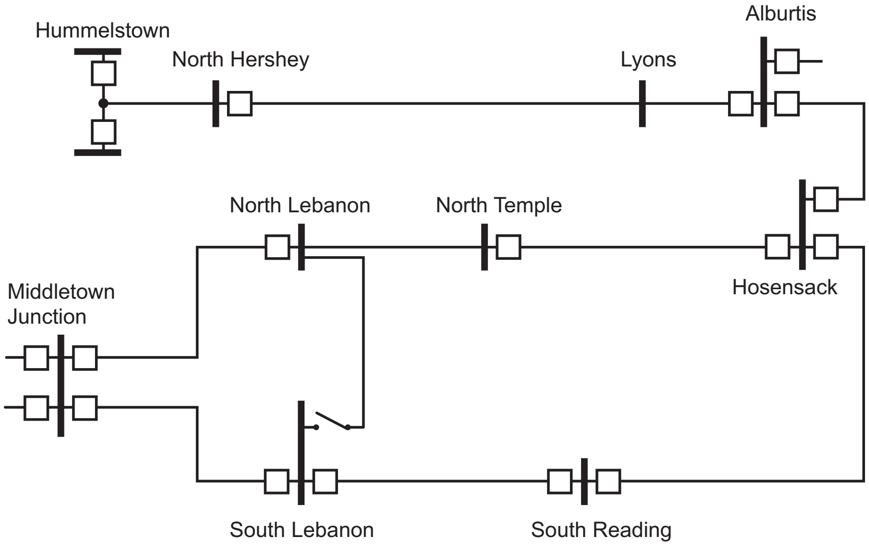


Figure 1 Original 230 KV System

After evaluating several possible plans, GPU engineers decided that the most desirable course of action was to reconfigure the existing North Hershey–Alburtis 230 kV transmission line and the North Lebanon–South Lebanon tie into a short two-terminal line and a much longer three-terminal line. The line length from Alburtis to North Hershey is about 69 miles. This required the installation of a breaker at the Lyons substation. The length of the three-terminal line from Lyons to North Hershey was reduced to 53 miles. The distance from the common tap to each terminal is 41.4 miles to Lyons, 11.4 miles to North Hershey, and 5 miles to the Ironwood substation. This configuration also resulted in a 2.8-mile line from Ironwood to South Lebanon. Figure 2 depicts the system with the addition of the AES generation and the creation of the three-terminal line.

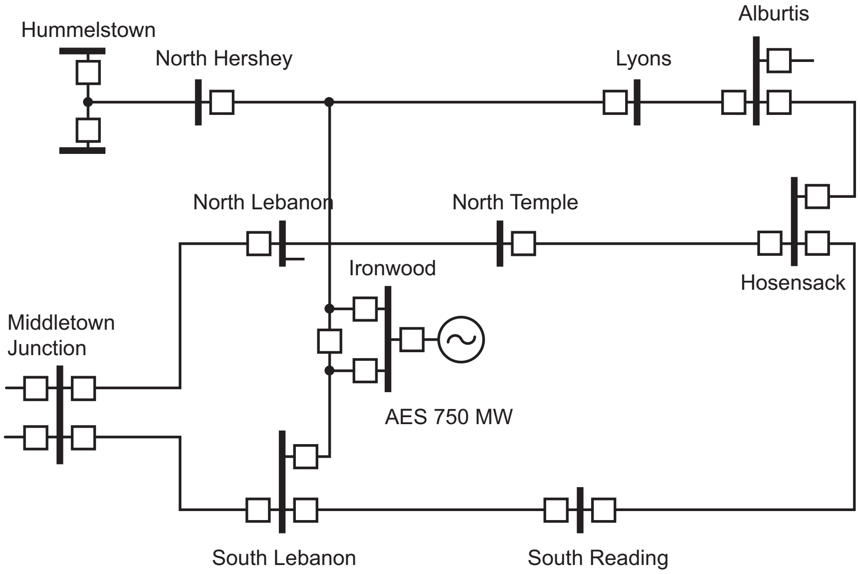


Figure 2 230 KV System With AES Generation at Ironwood

AES and GPU analyzed the power system and realized that faults persisting more than 10 cycles on the proposed three-terminal line would destabilize the Ironwood generators. The existing protection on the North Hershey–Alburtis line consisted of electro-mechanical relays applied in a directional comparison blocking scheme employing an Amplitude Modulated (AM) power line carrier. The proposed three-terminal line would need a state-of-the-art relaying scheme to provide fast clearing while maintaining security for external faults.

OBJECTIVES

The objectives for the new protection system were:

- Use the existing fiber-optic multiplexed communications system between the North Hershey, Lyons, and Ironwood substations for the protective relay communications to avoid problems associated with Frequency Shift Keying (FSK) and AM power line carrier communications.
- Clear faults on the new three-terminal line as quickly as possible when the communications system is intact.
- Clear faults on the new three-terminal line in 10 cycles or less when the communications system is out-of-service.
- Provide a relaying system that has multichannel capability and can adapt to changing system conditions.
- Provide a cost-effective overall protection system design.

About the time the Ironwood project was started, another generating station near the North Temple substation was proposed. This necessitated reconfiguring North Temple into a five-breaker ring bus. This configuration is shown in Figure 3.

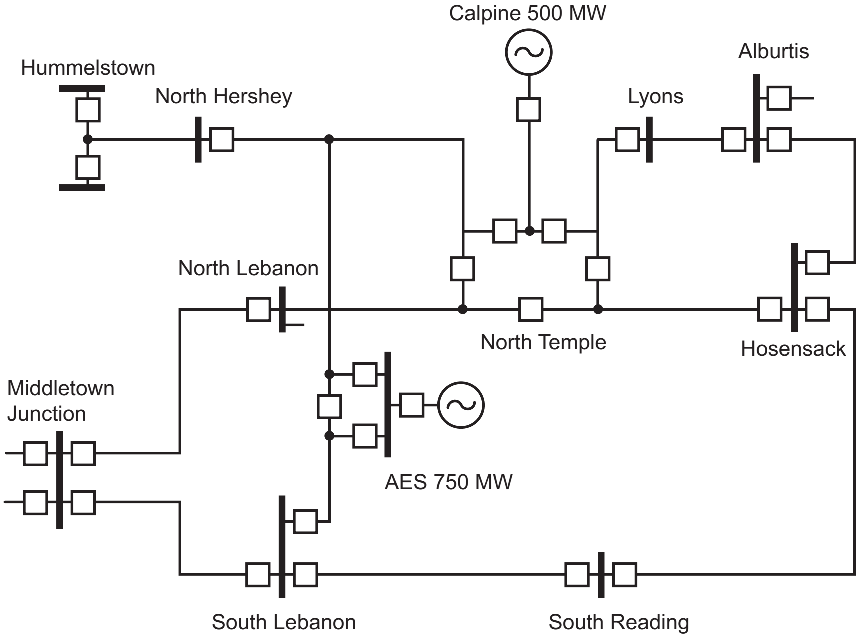


Figure 3 230 KV System With AES and Calpine Generation

COMMUNICATIONS SYSTEM

The GPU communications system, illustrated in Figure 4, consists of various fiber-optic multiplexed units set up in a loop configuration off a main backbone. The times shown are the propagation delays and do not include multiplexer delays. As in most multiplexed systems, a variety of modular plug-in interface methods are available to the units. The system is capable of a direct contact conversion between external devices and units, as well as low- or high-speed synchronous or asynchronous I/O interfaces to external devices.

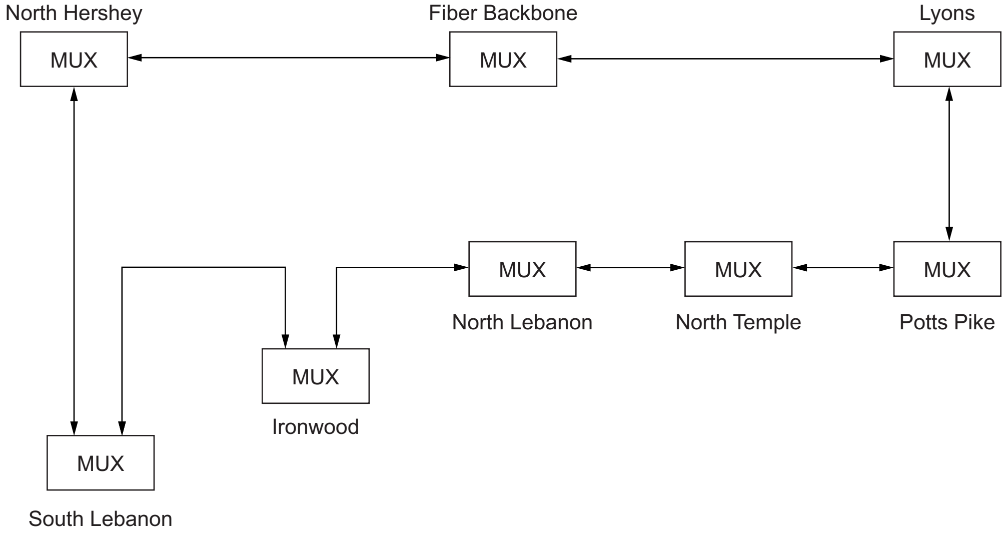


Figure 4 Multiplexer Configuration

Direct contact conversion interfaces allow two contacts per plug-in module. EIA-232C-capable asynchronous interfaces provide variable interfaces depending on the speed of the data stream: four full duplex connections at 9600 baud, two connections at 19200 baud, and only one connection per interface card at 38400 baud. Designers decided to use the EIA-232C interface directly to the relay for several reasons:

- Digital interface directly to the relay typically allows up to 8 and sometimes 16 channels of digital I/O and some newer designs allow analog data transmission, providing more capability for the dollar and allowing future expansion.
- Digital communication to the relay precludes external wiring and any chances for stray voltage to falsely initiate a sensitive input.
- Digital interface to the relay is faster overall because it eliminates time requirements for physical contact closure and input sense.

RELAY SYSTEM

Two overall requirements for the relaying systems were that they be capable of digital communication over the existing multiplexed network and flexible enough for an adaptable relaying scheme that would clear faults quickly under all circumstances. Modern microprocessor-based relaying systems typically have multiple programmable inputs and outputs. However, digital relay-to-relay communications provide additional I/O capabilities that are very important in communications-based protection schemes as well as in interfacing to various data collection and automation systems.

These newest relays also provide programming logic that allows customization of schemes and adaptable relaying based on changing system conditions.

The second objective, fast clearing of all faults on the three-terminal line during communications system failures, requires special logic within the relay. This logic is described in the following section.

PROTECTION SCHEME CHOICES

The current differential protection scheme selected by GPU uses phase and residual currents in a "charge comparison" differential algorithm. The differential calculation is performed at each terminal. This scheme does not require potential, so there is no issue with capacitive coupled voltage transformer transients. The scheme is totally dependant on communication, however, and should always be backed up with a directional comparison scheme and stepped-distance scheme.

The most common communications-based distance tripping schemes are Permissive Overreaching Transfer Trip (POTT), Directional Comparison Blocking (DCB), and Direct Underreaching Transfer Trip (DUTT). The POTT scheme also has variations such as Echo-Back and Weak-Infeed Tripping.

Permissive schemes are generally more secure than blocking schemes. In the most popular, POTT, all terminals must have an overreaching forward zone picked up and receive a permissive trip signal from all remote terminals for any breaker to trip. Because of this requirement, when permissive schemes are used with Power Line Carrier (PLC) there is a question of whether the signal will propagate through the fault if the fault occurs on the phase(s) to which the carrier is coupled. Modifications to this scheme are weak-infeed tripping and echo-back functions and are discussed later as hybrid schemes.

Blocking schemes are generally more dependable than permissive schemes, often at the expense of security. In the most popular, DCB, any one terminal can trip after a short time delay as long as the overreaching forward zone is picked up and no blocking signal is received from any remote end. This also allows overtripping if the blocking signal cannot be received because of a failure in the communications system. The very nature of this scheme allows sequential clearing: that is, the stronger terminal can open first, then the remaining terminals may have enough fault current to operate the overreaching forward zone and trip a few cycles later. This is an advantage when applied to three-terminal lines because in most cases the relative strength of the three terminals is not equal, creating one or possibly two weak terminals on the line. Figure 5 illustrates this concept.

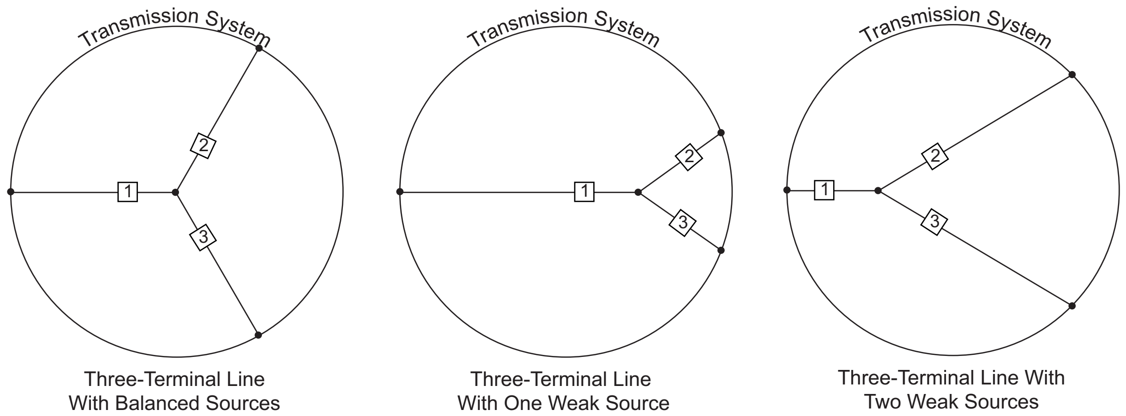


Figure 5 Three-Terminal Line Configurations

Direct Underreaching Transfer Trip (DUTT) schemes use the Zone 1 relay at any terminal to send a direct trip to the other two terminals. This scheme requires great care to not let the Zone 1 relay overreach either remote terminal under any circumstances, yet still ensure that at least one of the relays will see all internal faults. The DUTT scheme is not appropriate for three-terminal lines.

Hybrid schemes are generally variations on blocking or permissive schemes that incorporate the best characteristics of both schemes in addition to the benefits of the primary scheme. The permissive schemes have evolved to have echo-back functionality. This function performs a check of a reverse set distance or directional overcurrent element at a weak terminal and sends the received permissive signal back to the sending relay if the reverse element is not picked up. This adds the blocking scheme functionality of allowing individual terminals to clear sequentially. In this way the permissive scheme becomes very much like the blocking scheme.

With modern fiber-optic digital end-to-end communications and microprocessor-based relays with programmable logic, the distinctions between some of these schemes have diminished. DCB schemes use a forward overreaching element to trip and a reverse reaching element to block tripping. The same is also true with most hybrid permissive schemes. The overreaching element will do the tripping and the reverse reaching element at the remote ends will not allow tripping. It then becomes, to some extent, semantics of whether the communications system is sending a trip or not trip signal to the remote ends.

To address the problems of one or two weak-feed terminals on the three-terminal lines, a Zone 1 direct trip can be added at each terminal. This will add some speed to the both the DCB and POTT schemes by tripping the weak remote terminals instead of waiting for the line to clear sequentially.

The programmable logic present in many of microprocessor based relays allows for the development of custom protection schemes. For example, a loss of relay-to-relay communications instantaneously sets a flag or bit in the distance relay. This bit is ANDed with a Zone 2 distance element that overreaches the further of the two remote terminals and provides a high-speed trip of the local breaker. A simplified logic diagram is shown in Figure 6.

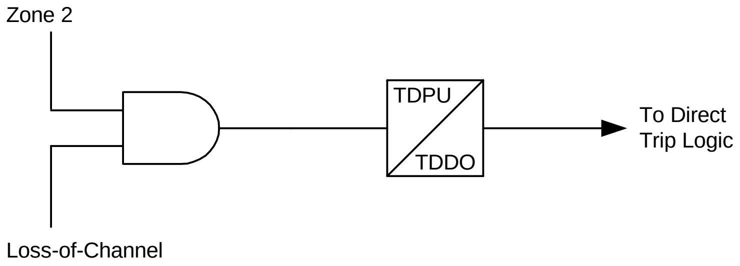


Figure 6 Zone 2 Acceleration

In the event of a communications channel failure, the time-delay pickup (TDPU) can be set long enough to provide time for the protection on adjacent lines to clear an external fault, but short enough to meet the maximum 10-cycle fault clearing time.

Because these distance relays have the ability to transmit up to 8 bits of data, much more information can be shared between the relays than with a traditional FSK or AM channel. For example, a direct transfer bit signal can be sent from any terminal at which a direct Zone 1 element operates. This allows all terminals to be cleared at the fastest possible time. It is also possible to send system information such as breaker status. In conjunction with the multiple relay settings groups, this allows the protection engineer to modify the relay settings to provide the best performance for the existing system conditions.

GPU Energy wanted to have two pilot schemes, each of which could provide high-speed clearing of the three-terminal line. Because they also preferred to have relays with different operating principles, they chose one current differential scheme and one distance-based scheme. For further diversity, they chose relays from two manufacturers.

GPU evaluated two distance relay systems. Both were microprocessor-based relays with the capability of direct digital communication between relays. The first relay had one EIA-232 port configurable for digital relay-to-relay serial communication. Eight bits of data can be transmitted. Because this relay had only a single communications port, it had to be configured to send data in a loop between the three terminals. This is illustrated in Figure 7. The disadvantage of this loop configuration is that it requires two one-way communications times to complete a trip or block transmittal. However, this relay processed protection and communication every one-eighth cycle, which helped to offset the slower communication.

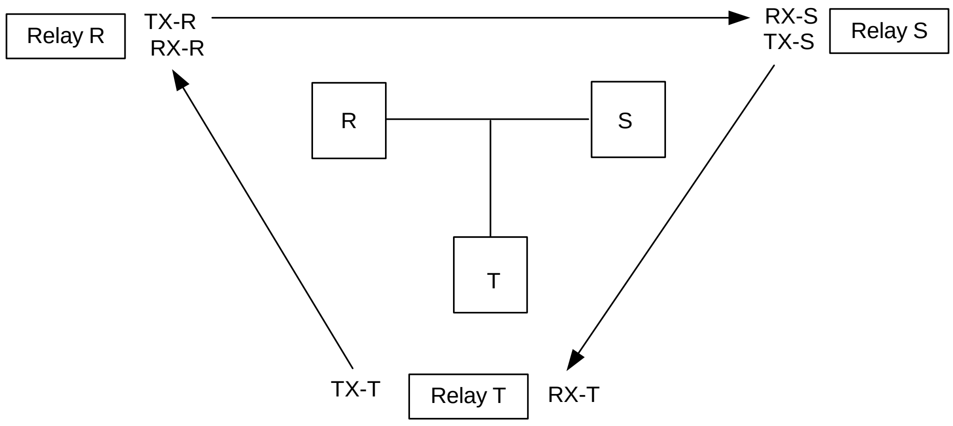


Figure 7 Single Port Communication

The second relay system was similar in design, but was capable of sending digital data on two ports simultaneously, so only one communications time was required to complete a trip or block transmittal. This is illustrated in Figure 8. This second relay processed protection and communication every one-quarter cycle. Thus, this system had faster communication but slower protection processing compared to the first system.

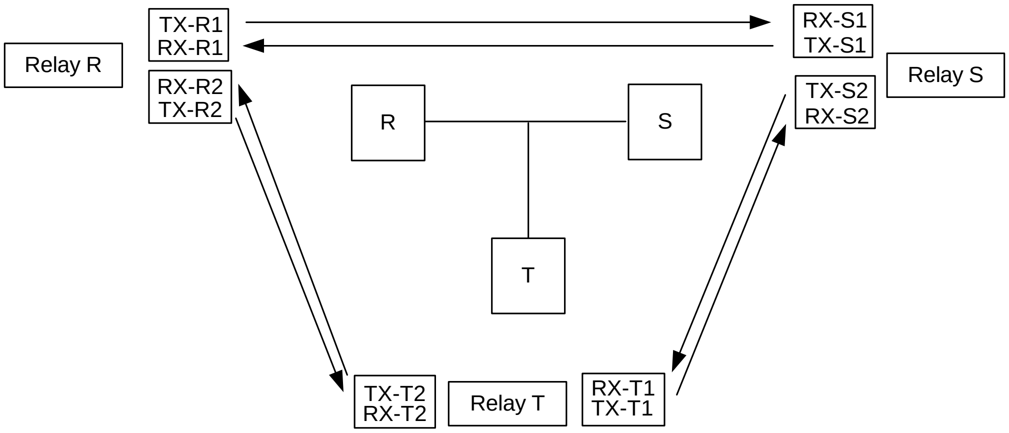


Figure 8 Dual Port Communication

In addition to determining which of the two relays systems to choose, GPU also wanted to evaluate which type of pilot scheme to employ.

TESTING SYSTEM

Testing System Requirements

Determining the required test system accuracy

To test these relay systems the test system must simulate true system conditions simultaneously at each of the three terminals (called end-to-end testing). This requires the three voltage signals and the three current signals at each location. The amplitudes, the relative phase angles, and the frequency of these signals should be more accurate than the relays acting upon these signals at each line terminal. In addition, the synchronization of the test signals between each terminal end must also be more accurate than the relays comparing the phasing between the three terminal ends.

To ensure the testing system does not distort the test results, the statistically accepted minimum ratio of accuracy between the testing system and the system being tested is 10–to–1and a greater ratio is often preferred. In other words, the testing system should not supply more error to the test than 10 percent of the accuracy tolerance of the relays being tested. When the system is this critical, many argue that the testing system should supply less than one percent of the total error.

Today, microprocessor-based relays have a setting accuracy greater than one percent, with a relay repeatability accuracy of 0.1 percent, meaning the test system signals should have better than 0.1 percent accuracy.

Many line-current differential comparison relays allow a synchronization error of up to 10 degrees assuming a phase comparison error of less than one degree. This means the three test systems must synchronize the testing start time to less than 0.1 degree.

Selecting the Test System Synchronization Method

The requirements for accuracy determine the selection of test equipment and testing methods.

The following test methods synchronize the start time of the end-to-end tests:

- Connecting the three test sets by hardwire or pilot wire (possible only for short distances)
- Synchronizing with the power system (accuracy 1 ms and error ~22 degrees on 60 Hz systems)
- Synchronizing with special fiber synchronizing link (requires dedicated fiber plus special relays and equipment)
- Synchronizing using the GPS satellite system (presently the most common method)

The Global Positioning System, GPS, was created by the Department of Defense primarily to provide a high accuracy navigation aid for both military and civil purposes. Twenty-four satellites are permanently in operation, each with a highly accurate atomic clock. Each satellite transmits a synchronized time code to earth. The code contains the accurate time and data specific to the satellite, such as information about the satellite orbit, its position with respect to time. If a GPS receiver locks on four satellites, the propagation time is a direct measure of the distance between the GPS receiver and each of the satellites. The accurate time is calculated using the surveying principle. If the receiver tracks four satellites, the time accuracy is 100 ns. If the receiver tracks one satellite, the actual position of the GPS receiver is known within 25 meters.

Using the time signal for synchronization requires a GPS clock, which provides a number of timing signals including IRIG-B, one pulse per second, one pulse per minute (PPM), and programmable pulse signal. These signals are available in a TTL type output on most modern GPS clocks. The latter two signals, in particular, can be used to synchronize test equipment at any two or more locations around the world to the nearest 100 ns. Figure 9 illustrates a testing scheme that uses a GPS satellite system for test synchronization.

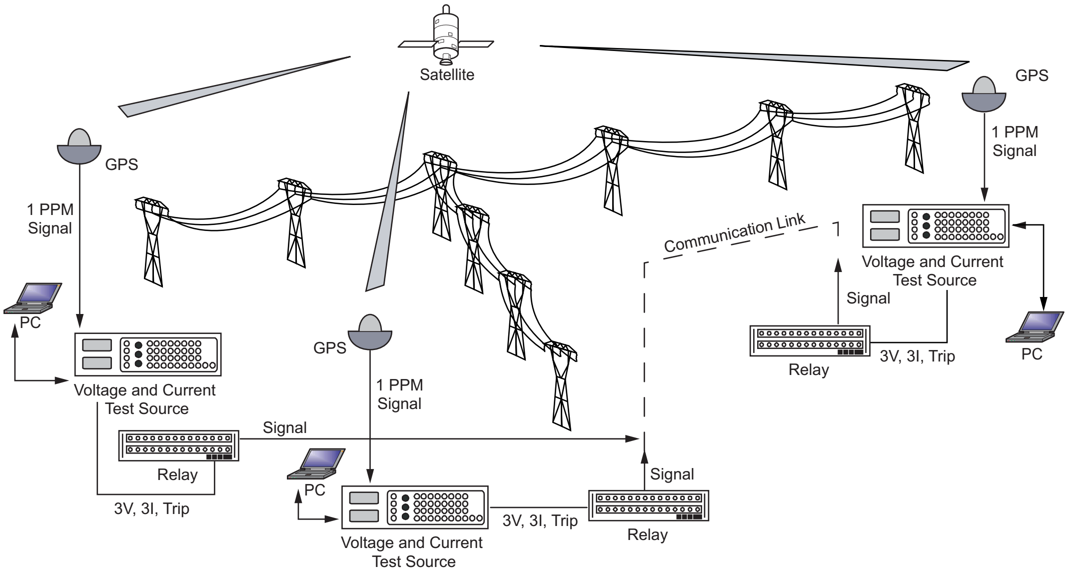


Figure 9 Testing of the Communications-Based Power System Protection Schemes Using a GPS Satellite System for Test Synchronization

Standard end-to-end testing methods use the following equipment and personnel on each side of the transmission line:

- Protection relay test equipment (Signal generators 3xl, 3xV suitable to replay fault simulation)
- GPS-satellite receiver for time synchronization of the three test devices
- Fault simulation can use one of the following sources:
  - EMTP Electromagnetic Transient Program
  - Real Disturbance (Transient) Files recorder from Disturbance Recorders (IEEE standard COMTRADE files)
- Steady-state voltage and current test sequences (for evaluation of the setting thresholds)
- Special application testing software
- Teams of two-to-three test engineers on each side

The end-to-end test procedure for each substation is:

1. Prepare the test sequences.
2. Connect the test equipment to the protection equipment.
3. Connect the GPS receivers and lock them to the appropriate number of satellites.
4. Prepare the test software for starting the test.
5. Coordinate with other test teams regarding starting time, locking of the GPS receiver, and other testing items.
6. Coordinate with other test teams about starting the first test sequence.
7. Start the first sequence and wait for the satellite trigger.
8. Coordinate with other test teams regarding success of start.

9. After first test sequence run: coordinate with other test teams regarding test results and editing of the test sequence, such as correction of the nominal time.
10. Before and after each test sequence: communicate with other test team about test flow.

Problems with End-To-End Testing Methods

The end-to-end testing method just described was established several years ago and is suitable for verifying whole communications schemes and behavior of the power system protection at the same time. This method accurately simulates the real fault condition and is the most accurate way to test communications-based protection schemes.

However, actually applying this testing method revealed several problems:

- Time consuming (testing of one protection system with teleprotection requires one day)
- Expensive (high personnel and equipment costs)
- Complicated testing control (coordinating teams at each substation)
- Complicated testing procedures
- Lack of fully automatic test procedures
- No direct communication between GPS receiver and protection test equipment (synchronization not part of the test procedure)
- Complicated onsite test procedure editing (two PCs and two protection testers in each substation)
- Supervision and full evaluation of the test results possible only via direct communication (e.g., telephone) between testing teams (verbal communication after each test step and synchronizing the test results)
- Complicated canceling and repeating of testing procedure
- Synchronization accuracy strongly influences fault current error

Because of these problems, end-to-end testing methods have not become standard routine today. Many electrical utilities avoid this type of testing and the eventual separate testing of the communications device. Utilities try to satisfy testing standards with classic one-side protection tests. Because the results of one-side testing are only partial, however, they cannot be used for the verification of the whole power protection system. Trip time and selectivity can only be evaluated with real simulation.

Goals for Improvements to Standard GPS Synchronization Method

Optimizing end-to-end testing was a major challenge [3]. After defining the fundamental problems of the present testing methods, engineers established several goals:

- Reduce the time required to perform the setup and testing tasks
- Simplify the complexity of the preparation tasks
- Reduce the actual preparation time and testing time required in the field
- Reduce the number of testing personnel required at each test site
- Reduce the number of PCs and other equipment needed to test and communicate with the protection system being tested
- Simplify the GPS synchronization

- Improve the overall accuracy of synchronizing the test times between stations
- Simplify the analysis and reduce the analysis time for the test results

Improved Standard GPS Synchronization Method

The new approach to GPS-controlled testing included development of a new GPS satellite receiver and new software, plus integrating both into the existing hardware and software. With the following changes, the new GPS-synchronization testing method met or exceeded the above goals:

- Developing a high accuracy GPS receiver with synchronization accuracy better than ±1 ms, an improvement of 10, 100, and even 1000 times better than other test systems.
- Integrating the automatic tracking and locking onto satellites upon power-up of the receiver into the GPS receiver firmware. This allows the system to lock onto the satellites while test personnel are performing other setup tasks.
- Developing the GPS synchronization software to allow the test personnel to select the start pulse intervals from simple but flexible menus.
- Integrating the GPS synchronization software into the test software to allow a series of fault cases to be run from a single initiate from the test personnel. This system allows the 'ONE BUTTON' test plan to automatically run hundreds of fault cases in succession with each fault case automatically synchronized.
- Ensuring that all test plans are created prior to going into the field, including setting the pass/fail limits for automatic assessments.
- Ensuring that test plans can be simply and quickly edited in the field when desired.
- Using a high-speed parallel port for test equipment operation. This allows the PC serial port to remain free for communicating to the protection system.
- Ensuring that all software is fully Windows®-compatible so that third party software (protection equipment software) can be run in the background while the test plans are being run.

This improved test system can also remotely operate/control two or more systems for even greater efficiency [3].

TESTING

GPU Energy had limited experience with microprocessor-based relay systems applied to three-terminal lines. The utility did not have previous experience with digital communication directly between relaying systems. Therefore, GPU decided to perform functional tests on the three-terminal relaying system and perform the tests in two stages, with GPU Energy standard settings applied in each case. First, test the relaying system at a GPU Energy laboratory, but connected to the communications system in a manner similar to the final field connection. This adds the proper delays between the relaying system while allowing the convenience of performing the testing in one place. As the second stage, test the installed relaying system at its final substation locations. The functional tests also provided a way to evaluate whether a permissive (POTT) or blocking (DCB) scheme would be the most effective scheme for the distance relay system in this application.

The test plan applied actual system secondary fault currents and voltages at each relay, to test the overall protection system as closely as possible without actually faulting the line. The test plan also applied several sets of relay settings at each terminal to analyze the performance of different settings and relaying schemes. The tests used two different relay platforms, each with three multifunction distance relays. As noted previously, one system had a faster relay with slower communications, and the other a slower relay with faster communications. The first part of the testing was to determine which relay platform would be faster overall on the three-terminal line.

As a first step, GPU ran a fault study for the three-terminal line. The fault study placed single-phase-to-ground and three-phase faults in front of each breaker and then twenty percent per unit along each line section up to the tap. For these tests, GPU selected bolted faults because high-resistance faults are not common on the GPU system. The purpose of these tests was to measure the speed and reliability of the settings and relay scheme. GPU also ran faults just behind each breaker and one bus back. The purpose of these tests was to measure the settings and relay scheme security by determining whether a trip occurred for faults off the three-terminal line. Initial studies indicated that outfeed (current flow out of one terminal for an internal fault) was not a problem on this system.

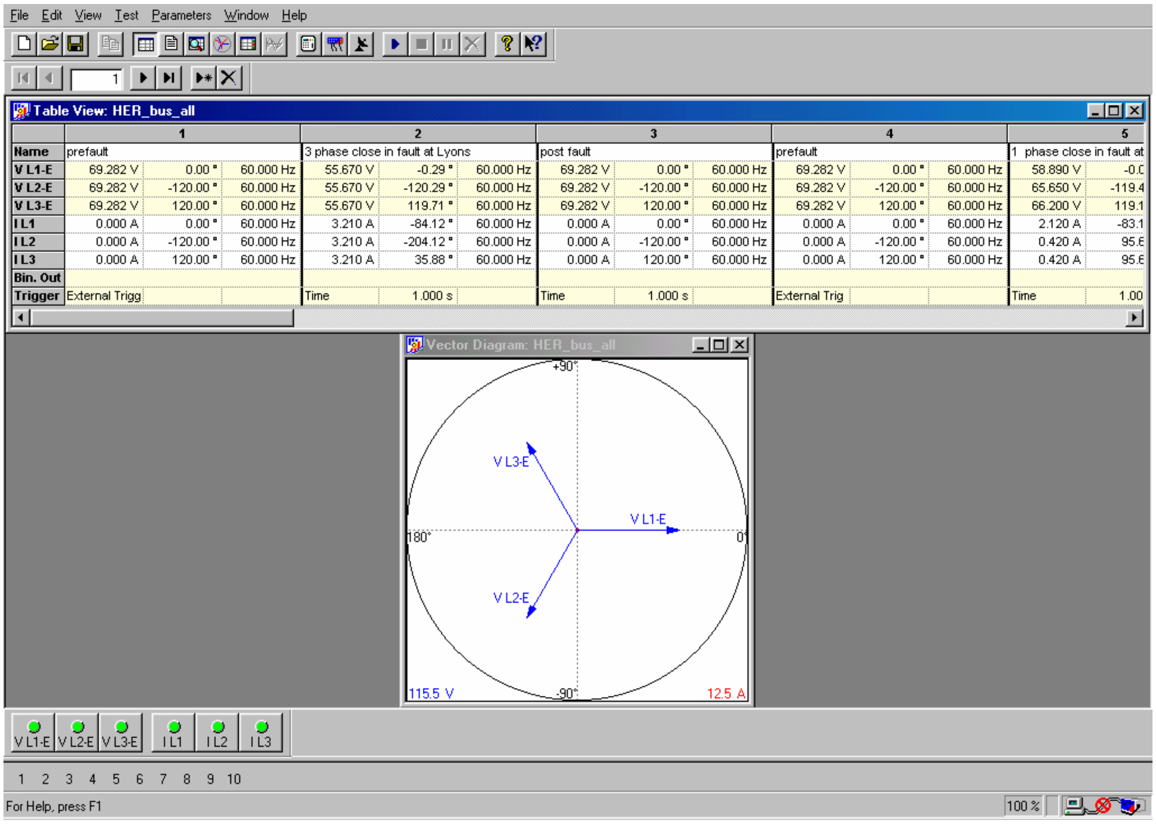
All tests were dynamic three-state tests using a state simulator. Capacitive coupled voltage transformers were of high quality and source impedance ratios were not high, so there was no need to run transient tests using an electromagnetic transient simulation program and COMTRADE. Dedicating the available time to running extensive dynamic tests on the system, rather than a few complex transient tests, seemed a better choice.

The first test state was a prefault state with balanced three-phase voltage on the relay for one second. The second was the fault state in which data was entered from the fault study. Voltages were divided by the potential transformer ratio to one and the currents were divided by the current transformer ratio to one. The third test state was a post-fault state identical to the prefault. The unique test plan for each relay terminal included a fault sequence that was carefully checked and matched for each terminal. A sequence of many faults in each test plan ensured that the operators of the test equipment would only have to start the tests a minimum number of times.

For the first test session, held at the GPU laboratory facility, the multiplexed system was configured on the GPU communications system to introduce delays into the test system similar to those experienced at each terminal on the line. The tests used two different relay platforms, each with three multifunction distance relays. The first part of the testing was to determine which distance relay platform would be applied on the three-terminal line.

The first round of tests were state simulations with three states per fault, fifteen to twenty faults per test plan, and a starting pulse configured to occur every fifteen seconds. These tests were run on the first relay system. They used three relay test sets and three GPS clocks. The GPS antennas had long extension cables that could be routed far down the hall and outside the building. Test setup, which was minimal, took less than an hour. Operators with open phone lines between different areas of the building controlled each test set. Each operator followed this testing procedure:

1. Sent test plans and relay settings, built beforehand, to the relay and test sets, as shown in Figure 10.
2. Called up the test file, then pressed “go” during the same fifteen-second interval.
3. Test plans all started simultaneously at the next pulse.
4. Each sequence of one fault initiated every fifteen seconds
5. Saved results directly in the test plans under a unique file name.
6. Changed settings on each relay and ran the test plans again.



	1			2			3			4			5	
Name	prefault			3 phase close in fault at Lyons			post fault			prefault			1 phase close in fault at	
V L1-E	69.282 V	0.00 °	60.000 Hz	55.670 V	-0.29 °	60.000 Hz	69.282 V	0.00 °	60.000 Hz	69.282 V	0.00 °	60.000 Hz	58.890 V	-0.
V L2-E	69.282 V	-120.00 °	60.000 Hz	55.670 V	-120.29 °	60.000 Hz	69.282 V	-120.00 °	60.000 Hz	69.282 V	-120.00 °	60.000 Hz	65.650 V	-119.4
V L3-E	69.282 V	120.00 °	60.000 Hz	55.670 V	119.71 °	60.000 Hz	69.282 V	120.00 °	60.000 Hz	69.282 V	120.00 °	60.000 Hz	66.200 V	119.1
I L1	0.000 A	0.00 °	60.000 Hz	3.210 A	-84.12 °	60.000 Hz	0.000 A	0.00 °	60.000 Hz	0.000 A	0.00 °	60.000 Hz	2.120 A	-83.1
I L2	0.000 A	-120.00 °	60.000 Hz	3.210 A	-204.12 °	60.000 Hz	0.000 A	-120.00 °	60.000 Hz	0.000 A	-120.00 °	60.000 Hz	0.420 A	95.
I L3	0.000 A	120.00 °	60.000 Hz	3.210 A	35.88 °	60.000 Hz	0.000 A	120.00 °	60.000 Hz	0.000 A	120.00 °	60.000 Hz	0.420 A	95.
Bin. Out														
Trigger	External Trigg			Time	1.000 s		Time	1.000 s		External Trig			Time	1.00

Figure 10 Test Plans and Relay Settings Sent to Relay and Test Sets

Running the same test plan on various settings meant that much data was obtained for different relay settings and different relay schemes.

The same tests were then repeated on the second relay system so overall clearing times between the two different relay systems could be compared. Although the data showed that the fault clearing times were about the same on both relay systems, engineers chose the second relay system with two communications ports. Even though this relay was slightly slower, the faster communication obtained with the use of two ports improved the overall times. In addition, the relay logic was more advanced, and the end-to-end communications I/O was more straightforward to program in the point-to-point configuration.

About six months later the newly installed relay system was ready to be tested in its final location. Three groups conducted tests at each substation, communicating through an open party phone line on the company's multiplexed fiber network. In the same manner as the first test, all three test operators initiated the test plan during the same fifteen-second interval. The entire test plan executed automatically after that initial synchronization. Once the tests were complete, operators saved the results in the test plan with just one click of a button.

The end-to-end method of testing proved its worth early on when some of the relay terminals tripped incorrectly during the tests that simulated external bus faults. Investigation revealed problems with the programming logic in all three distance relays: settings problems that would not have been detected with single-end tests because they were set per the settings sheets. The dynamic end-to-end testing showed errors in the chosen coordination timer settings. Repeated tests on the corrected settings used both Directional Comparison Blocking schemes and Permissive Overreaching Transfer Trip schemes with various settings and variations on each scheme. After each test, operators saved the data in the test plans with a unique name that included the terminal name, type of scheme, and variation of the scheme. Finally, data from running the test plan on the current differential relay was saved for comparison to data from the backup relays.

The testing just described took about two days because of unfamiliarity with the test sets and testing software. Experimentation with settings and different schemes also took additional time. Technicians familiar with the test equipment could probably set up and run the tests on a three-terminal line in about half a day. Engineer time for preparing the test plan is approximately one day. Most of the work is in transferring the fault study data to the test software. Overall, this seems a small price compared to the utility and customer costs of misoperations.

The three-terminal line configuration, as tested, is shown in Figure 11.

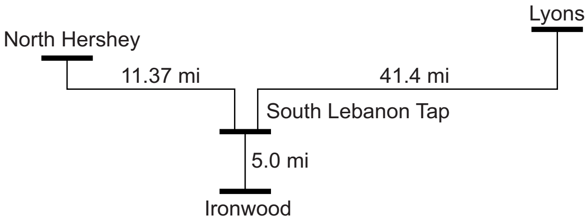


Figure 11 GPU Energy Three-Terminal Line Configuration

TEST RESULTS

The first set of tests was on a standard POTT scheme on the three-terminal line. Relay settings were based on the GPU Energy standard, with overreaching Zone 2 permissive tripping elements set at twice the maximum length between two terminals. The Zone 2 reach setting was not based on the results of the fault studies, but rather on a standard reach that can be applied in DCB schemes and ensures at least sequential clearing.

The resulting relay operating times are shown in Table 1.

Table 1 Test Results: Standard POTT

Fault Type	**Minimum Time**	**Maximum Time**	**Average Time**
Three-Phase	25.5 ms	39.0 ms	30.2 ms
Single-Phase	25.7 ms	39.3 ms	30.4 ms

In one case the line failed to clear with a communications-assisted trip because infeed at the tap prevented the far terminal from seeing the three-phase fault at the other remote terminal. This problem could be handled by:

- Extending the reach of the Zone 2 element.
- Enabling echo-back tripping in POTT and allowing the weak terminal to clear sequentially.
- Enabling a Zone 1 direct trip.

The second test used two of these methods: longer Zone 2 reaches and Zone 1 direct tripping. For this portion of the tests, we adjusted the GPU settings to match the apparent impedance as seen by each terminal. It also used forward reaching directional overcurrent elements but did not simulate sequential clearing, which might occur as the result of a Zone 1 trip. In addition to eliminating the failure to trip noted previously, the changes also resulted in faster operating times for the protection. The test results for the combined changes are shown in Table 2.

Table 2 Test Results: Modified POTT

Fault Type	Minimum Time	Maximum Time	Average Time
Three-Phase	22.3 ms	30.3 ms	26.8
Single-Phase	22.9 ms	30.7 ms	27.0

DCB tests were performed using the longer Zone 2 reaches. The carrier start block is provided with an instantaneous nondirectional overcurrent element and shifts to trip when the forward directional overcurrent picks up. The operating time results are shown in Table 3.

Table 3 Test Results: DCB With Longer Zone 2 Reaches

Fault Type	Minimum Time	Maximum Time	Average Time
Three-Phase	18.3 ms	28.6 ms	22.4 ms
Single-Phase	9.4 ms	22.9 ms	14.4 ms

This set of tests revealed a misoperation for external bus faults behind each terminal caused by an improper relay setting. This error prevented a coordinating time delay from being inserted into tripping for forward overreaching elements. This omission also accounts for faster tripping on internal faults.

The relay settings were corrected and the test sequence repeated. Testing on the corrected DCB settings produced the results shown in Table 4.

Table 4 Test Results: Corrected DCB

Fault Type	Minimum Time	Maximum Time	Average Time
Three-Phase	21.9 ms	29.4 ms	25.0 ms
Single-Phase	21.9 ms	29.5 ms	25.3 ms

It was GPU Energy’s intent to test both the distance protection and the current differential protection. However, problems were encountered with the current differential protection that could not be solved in time for the testing. Later bench tests using a different test signal generator and a different line differential relay set up in a similar configuration showed this current differential scheme to be the fastest scheme with no evident loss of security. This particular system had the advantage of incorporating all of the distance protection in the same package as the current differential, thus providing better backup protection in the event of a current differential channel failure. The times for these tests included fiber-optic propagation delays and multiplexer processing delays for the N. Hershey–Ironwood–Lyons line shown in Figure 12. Test results are shown in Table 5.

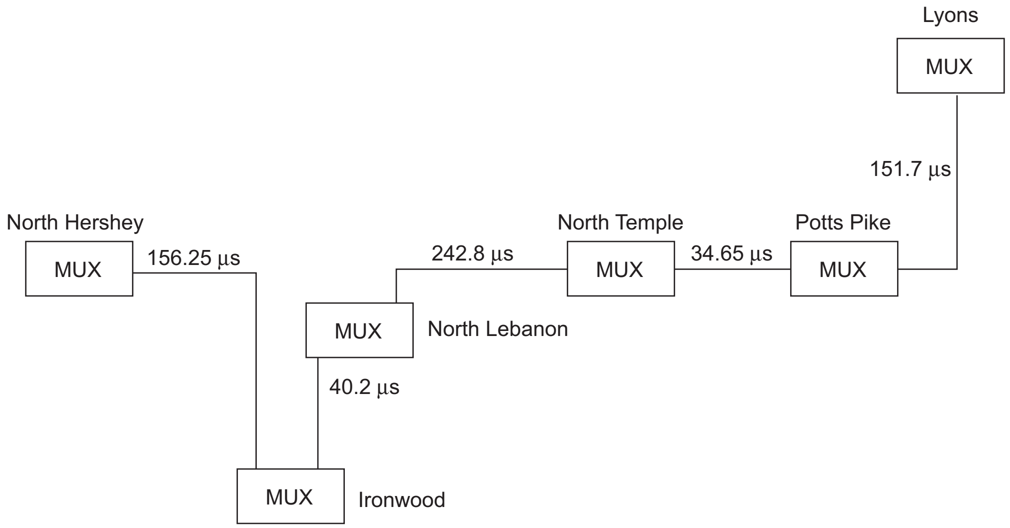


Figure 12 Simulated Bench Test Delays

Table 5 Bench Test Results: Current Differential

Fault Type	Minimum Time	Maximum Time	Average Time
Single-Phase	17.9 ms	21.1 ms	19.8

CONCLUSIONS

Unfortunately, the onsite end-to-end testing of the current differential could not be completed at the same time as the testing of the distance protection. Later bench testing of a different current differential relay indicated that the operating times were faster than the distance relay with no loss of security on external faults. The current differential protection has several advantages over distance-based protection on three-terminal line applications. As noted previously, the current differential relay does not require voltage and is therefore immune to CVT transients. A current differential relay, unlike distance or phase-comparison protection, is not affected by current infeed, provided that there is a relay at each line terminal. Therefore, the current differential relay is easier to apply to three-terminal lines. Modern fiber-optic communications systems have greatly increased the reliability of these schemes, but distance backup is still recommended in the event of a channel failure.

Analysis of operating times of the pilot distance schemes shows that the DCB scheme is slightly faster than the POTT or hybrid schemes. This is expected, because in the DCB scheme any relay can issue a trip after a coordinating time delay, provided that it does not receive a block from a remote terminal. In the POTT scheme, no relay can issue a trip until the slowest Zone 2 element has operated and transmitted the permissive signal. In the hybrid scheme, tripping is permitted before the slowest Zone 2 via the echo-back logic, but there is a time delay caused by an additional channel time. When these schemes are applied with traditional FSK and AM channels, the channel design helps determine the overall security and dependability of the protection system. The DCB scheme used with AM PLC is known for its dependability and its lack of security. Any failure of the blocking channel, including small “holes,” may result in an overtrip for an external fault. This problem is compounded by the nature of the AM channel. The AM channel has two states: On and Off. In normal quiescent conditions, there is no transmission and thus there is no means to monitor the channel status. The channel may not be functioning properly when it is needed to prevent an overtrip. Using the digital relay-to-relay communications channel allows the state of the communications channel to be monitored continuously. This monitoring, in conjunction with the flexible programming logic in the relay, can improve the security of the DCB scheme. Consider the simple logic shown in Figure 13.

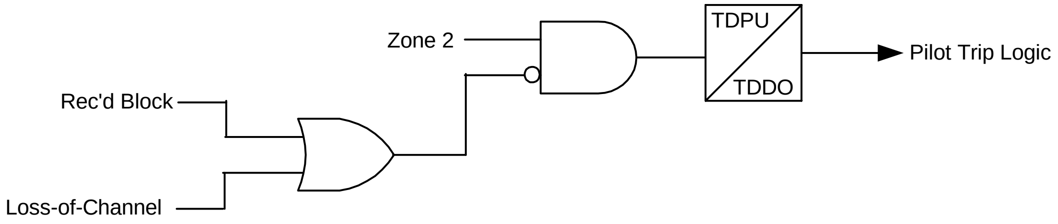


Figure 13 Loss-of-Channel Blocking Logic

Implementing the logic of Figure 13 prevents the DCB scheme from operating when there is a loss of the blocking channel. The logic of Figure 6 can be added to the DCB scheme to provide accelerated Zone 2 time-delayed tripping if it is required. Based on the results of this testing and analysis, GPU Energy chose the DCB scheme for this application.

The use of microprocessor relays with their programmability and enhanced communications capability, along with the availability of reliable fiber communications, is changing the traditional view of DCB and hybrid POTT schemes. With the proper relay logic and channels these schemes are virtually equal in security and dependability.

The performance of protection schemes that integrate complex communications systems with several complex protection systems is difficult to evaluate unless the complete protection scheme has been tested as a whole system. The cost and time commitment required to perform this testing was justified by the confidence gained in the protection and communications systems and the relay settings. The discovery of settings errors that might have caused a misoperation on an external fault prevented the utility from incurring losses that could amount to several hundred thousand dollars.

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BIOGRAPHIES

John Koehler began his career with GPU Energy in 1980 as an instrumentation and control technician at the Three Mile Island nuclear generating station. The majority of his career has been with GPU Energy's operation department as a system operator at both the distribution and transmission levels. While working full-time, he attended evening classes at the Berks Campus of Pennsylvania State University, receiving an ASEET in 1992 and his BSEET in 1998. ~~Koehler~~ He has been employed as a Relay and Control Engineer since 1995, is a member of the Susquehanna Valley Chapter of the IEEE, and has received his Engineer-in-Training Certificate in Pennsylvania.

David Marble began his OMICRON Electronics career four years ago as a Sales and Applications Engineer, managing the regions of northeastern US and eastern Canada. The majority of his career has been 26 years at Burlington Electric, a utility in Burlington, Vermont. He worked in a number of engineering roles including Distribution Engineer, Senior Protection Engineer, Senior Systems Engineer, plus various supervisory and management roles. He installed the first microprocessor-based distribution protection system in the US by 1990. In the Vermont Section of IEEE, he has held a number of offices, including PACE Chairman, PES Chairman, and Section Chairman, plus others. He is a registered Professional Engineer in Vermont.

James E. Mack graduated from Louisiana State University in 1983 with a BSEE. He began by working as a Startup Engineer for the construction of various nuclear power plants. Later he was responsible for training and engineering at the Western Power Administration training center in Golden, Colorado. He was the Engineering Manager at City of Longmont Electric and Braintree Light before starting at Schweitzer Engineering Laboratories in 1996 where he is an Application Engineer. He is a registered Professional Engineer in the states of Massachusetts, Colorado, and Maine.

APPENDIX A - TEST RESULTS

The following data are the results of the testing for the Lyons terminal.

TEST 1

Test Module
Name:OMICRON State Sequencer Version: 1.41
Test Results for Lyons Terminal POTT

Name	Ignore before	Start	Stop	Tnom [s]	Tdev- [s]	Tdev+ [s]	Tact [s]	Tdev [s]	Assess
Lyons 3Ph	3 phase		3 phase	SEL Trip 0				0.0273	+
Lyons 1Ph	1 phase		1 phase	SEL Trip 0				0.0256	+
Hershey 3P	3 phase		3 phase	SEL Trip 0				no trip	x
Hershey 1P	1 phase		1 phase	SEL Trip 0				0.0335	+
Ironwood 3	3 phase		3 phase	SEL Trip 0				0.0292	+
Ironwood 1	1 phase		1 phase	SEL Trip 0				0.0290	+
trip time	3 phase .2		3 phase .2	SEL Trip 0				0.0283	+
trip time	1 ph .2 fr		1 ph .2 fr	SEL Trip 0				0.0269	+
trip time	3 ph .4 fr		3 ph .4 fr	SEL Trip 0				0.0293	+
trip time	1 ph .4 fr		1 ph .4 fr	SEL Trip 0				0.0299	+
trip time	3 ph .2 fr		3 ph .2 fr	SEL Trip 0				0.0304	+
trip time	1ph .2 fro		1ph .2 fro	SEL Trip 0				0.0318	+
trip time	3ph .4 fro		3ph .4 fro	SEL Trip 0				0.0247	+
trip time	1ph .4 fro		1ph .4 fro	SEL Trip 0				0.0292	+
trip time	3 phase .2		3 phase .2	SEL Trip 0				0.0310	+
trip time	1 phase .		1 phase .	SEL Trip 0				0.0321	+
trip time	3 ph .4 fr		3 ph .4 fr	SEL Trip 0				0.0289	+
trip time	1 ph .4 fr		1 ph .4 fr	SEL Trip 0				0.0309	+
trip time	3 ph .2 fr		3 ph .2 fr	SEL Trip 0				0.0262	+
trip time	1 ph .2 fr		1 ph .2 fr	SEL Trip 0				0.0303	+
trip time	3 ph .4 fr		3 ph .4 fr	SEL Trip 0				0.0370	+
trip time	1 ph .4 fr		1 ph .4 fr	SEL Trip 0				0.0360	+
Lyons 3Ph	reverse		3 phase cl	SEL Trip 0				no trip	+
Lyons 1Ph	reverse		1 phase c	SEL Trip 0				no trip	+
Hershey 3P	reverse		3 phase cl	SEL Trip 0				no trip	+
Hershey 1P	reverse		1 phase cl	SEL Trip 0				no trip	+
Ironwood 3	reverse		3 phase cl	SEL Trip 0				no trip	+
Ironwood 1	reverse		1 phase cl	SEL Trip 0				no trip	+

Assess: + .. Passed x .. Failed o .. Not assessed

TEST 2

Test Module

Name:OMICRON State Sequencer Version: 1.41

Test Results for Lyons Terminal POTT Hybrid

Name	Ignore before	Start	Stop	Tnom [s]	Tdev- [s]	Tdev+ [s]	Tact [s]	Tdev [s]	Assess
Lyons 3Ph	3 phase		3 phase	SEL Trip 0				0.0302	+
Lyons 1Ph	1 phase		1 phase	SEL Trip 0				0.0307	+
Hershey 3P	3 phase		3 phase	SEL Trip 0				0.0247	+
Hershey 1P	1 phase		1 phase	SEL Trip 0				0.0253	+
Ironwood 3	3 phase		3 phase	SEL Trip 0				0.0243	+
Ironwood 1	1 phase		1 phase	SEL Trip 0				0.0245	+
trip time	3 phase .2		3 phase .2	SEL Trip 0				0.0236	+
trip time	1 ph .2 fr		1 ph .2 fr	SEL Trip 0				0.0241	+
trip time	3 ph .4 fr		3 ph .4 fr	SEL Trip 0				0.0226	+
trip time	1 ph .4 fr		1 ph .4 fr	SEL Trip 0				0.0229	+
trip time	3 ph .2 fr		3 ph .2 fr	SEL Trip 0				0.0261	+
trip time	1ph .2 fro		1ph .2 fro	SEL Trip 0				0.0265	+
trip time	3ph .4 fro		3ph .4 fro	SEL Trip 0				0.0252	+
trip time	1ph .4 fro		1ph .4 fro	SEL Trip 0				0.0255	+
trip time	3 phase .2		3 phase .2	SEL Trip 0				0.0287	+
trip time	1 phase .		1 phase .	SEL Trip 0				0.0291	+
trip time	3 ph .4 fr		3 ph .4 fr	SEL Trip 0				0.0274	+
trip time	1 ph .4 fr		1 ph .4 fr	SEL Trip 0				0.0279	+
trip time	3 ph .2 fr		3 ph .2 fr	SEL Trip 0				0.0272	+
trip time	1 ph .2 fr		1 ph .2 fr	SEL Trip 0				0.0279	+
trip time	3 ph .4 fr		3 ph .4 fr	SEL Trip 0				0.0259	+
trip time	1 ph .4 fr		1 ph .4 fr	SEL Trip 0				0.0267	+
Lyons 3Ph	reverse		3 phase cl	SEL Trip 0				no trip	+
Lyons 1Ph	reverse		1 phase c	SEL Trip 0				no trip	+
Hershey 3P	reverse		3 phase cl	SEL Trip 0				no trip	+
Hershey 1P	reverse		1 phase cl	SEL Trip 0				no trip	+
Ironwood 3	reverse		3 phase cl	SEL Trip 0				no trip	+
Ironwood 1	reverse		1 phase cl	SEL Trip 0				no trip	+

Assess: + .. Passed x .. Failed o .. Not assessed

TEST 3

Test Module

Name:OMICRON State Sequencer Version: 1.41

Test Results for Lyons Terminal DCB

Name	Ignore before	Start	Stop	Tnom [s]	Tdev- [s]	Tdev+ [s]	Tact [s]	Tdev [s]	Assess
Lyons 3Ph		3 phase cl	3 phase cl	SEL Trip 0				0.0183	+
Lyons 1Ph		1 phase c	1 phase c	SEL Trip 0				0.0110	+
Hershey 3P		3 phase cl	3 phase cl	SEL Trip 0				0.0228	+
Hershey 1P		1 phase cl	1 phase cl	SEL Trip 0				0.0229	+
Ironwood 3		3 phase cl	3 phase cl	SEL Trip 0				0.0261	+
Ironwood 1		1 phase cl	1 phase cl	SEL Trip 0				0.0173	+
trip time		3 phase .2	3 phase .2	SEL Trip 0				0.0231	+
trip time		1 ph .2 fr	1 ph .2 fr	SEL Trip 0				0.0127	+
trip time		3 ph .4 fr	3 ph .4 fr	SEL Trip 0				0.0220	+
trip time		1 ph .4 fr	1 ph .4 fr	SEL Trip 0				0.0180	+
trip time		3 ph .2 fr	3 ph .2 fr	SEL Trip 0				0.0286	+
trip time		1ph .2 fro	1ph .2 fro	SEL Trip 0				0.0184	+
trip time		3ph .4 fro	3ph .4 fro	SEL Trip 0				0.0276	+
trip time		1ph .4 fro	1ph .4 fro	SEL Trip 0				0.0151	+
trip time		3 phase .2	3 phase .2	SEL Trip 0				0.0190	+
trip time		1 phase .	1 phase .	SEL Trip 0				0.0094	+
trip time		3 ph .4 fr	3 ph .4 fr	SEL Trip 0				0.0194	+
trip time		1 ph .4 fr	1 ph .4 fr	SEL Trip 0				0.0118	+
trip time		3 ph .2 fr	3 ph .2 fr	SEL Trip 0				0.0206	+
trip time		1 ph .2 fr	1 ph .2 fr	SEL Trip 0				0.0111	+
trip time		3 ph .4 fr	3 ph .4 fr	SEL Trip 0				0.0193	+
trip time		1 ph .4 fr	1 ph .4 fr	SEL Trip 0				0.0110	+
Lyons 3Ph		reverse	3 phase cl	SEL Trip 0				no trip	+
Lyons 1Ph		reverse	1 phase c	SEL Trip 0				0.0079	x
Hershey 3P		reverse	3 phase cl	SEL Trip 0				no trip	+
Hershey 1P		reverse	1 phase cl	SEL Trip 0				0.0224	x
Ironwood 3		reverse	3 phase cl	SEL Trip 0				0.0336	x
Ironwood 1		reverse	1 phase cl	SEL Trip 0				0.0177	x

Assess: + .. Passed x .. Failed o .. Not assessed

TEST 4

Test Module

Name:OMICRON State Sequencer Version: 1.41

Test Results for Lyons Terminal DCB_fix

Name	Ignore before	Start	Stop	Tnom [s]	Tdev- [s]	Tdev+ [s]	Tact [s]	Tdev [s]	Assess
Lyons 3Ph	3 phase cl		3 phase cl	SEL Trip 0				0.0239	+
Lyons 1Ph	1 phase c		1 phase c	SEL Trip 0				0.0245	+
Hershey 3P	3 phase cl		3 phase cl	SEL Trip 0				0.0264	+
Hershey 1P	1 phase cl		1 phase cl	SEL Trip 0				0.0271	+
Ironwood 3	3 phase cl		3 phase cl	SEL Trip 0				0.0261	+
Ironwood 1	1 phase cl		1 phase cl	SEL Trip 0				0.0271	+
trip time	3 phase .2		3 phase .2	SEL Trip 0				0.0257	+
trip time	1 ph .2 fr		1 ph .2 fr	SEL Trip 0				0.0259	+
trip time	3 ph .4 fr		3 ph .4 fr	SEL Trip 0				0.0255	+
trip time	1 ph .4 fr		1 ph .4 fr	SEL Trip 0				0.0259	+
trip time	3 ph .2 fr		3 ph .2 fr	SEL Trip 0				0.0243	+
trip time	1ph .2 fro		1ph .2 fro	SEL Trip 0				0.0245	+
trip time	3ph .4 fro		3ph .4 fro	SEL Trip 0				0.0248	+
trip time	1ph .4 fro		1ph .4 fro	SEL Trip 0				0.0247	+
trip time	3 phase .2		3 phase .2	SEL Trip 0				0.0236	+
trip time	1 phase .		1 phase .	SEL Trip 0				0.0233	+
trip time	3 ph .4 fr		3 ph .4 fr	SEL Trip 0				0.0273	+
trip time	1 ph .4 fr		1 ph .4 fr	SEL Trip 0				0.0271	+
trip time	3 ph .2 fr		3 ph .2 fr	SEL Trip 0				0.0259	+
trip time	1 ph .2 fr		1 ph .2 fr	SEL Trip 0				0.0261	+
trip time	3 ph .4 fr		3 ph .4 fr	SEL Trip 0				0.0243	+
trip time	1 ph .4 fr		1 ph .4 fr	SEL Trip 0				0.0249	+
Lyons 3Ph	reverse		3 phase cl	SEL Trip 0				no trip	+
Lyons 1Ph	reverse		1 phase c	SEL Trip 0				no trip	+
Hershey 3P	reverse		3 phase cl	SEL Trip 0				no trip	+
Hershey 1P	reverse		1 phase cl	SEL Trip 0				no trip	+
Ironwood 3	reverse		3 phase cl	SEL Trip 0				no trip	+
Ironwood 1	reverse		1 phase cl	SEL Trip 0				no trip	+

Assess: + .. Passed x .. Failed o .. Not assessed

TEST 5

Test Module

Test Results for Bench Test, Current Differential Relay

Lyons 1Ph	1 phase c	1 phase c	SEL Trip 0	0.0197
Hershey 1P	1 phase cl	1 phase cl	SEL Trip 0	0.0195
Ironwood 1	1 phase cl	1 phase cl	SEL Trip 0	0.0191
trip time	1 ph .2 fr	1 ph .2 fr	SEL Trip 0	0.0179
trip time	1 ph .4 fr	1 ph .4 fr	SEL Trip 0	0.0205
trip time	1ph .2 fro	1ph .2 fro	SEL Trip 0	0.0195
trip time	1ph .4 fro	1ph .4 fro	SEL Trip 0	0.0201
trip time	1 phase .	1 phase .	SEL Trip 0	0.0199
trip time	1 ph .4 fr	1 ph .4 fr	SEL Trip 0	0.0195
trip time	1 ph .2 fr	1 ph .2 fr	SEL Trip 0	0.0205
trip time	1 ph .4 fr	1 ph .4 fr	SEL Trip 0	0.0211
Lyons 1Ph	reverse	1 phase c	SEL Trip 0	no trip
Hershey 1P	reverse	1 phase cl	SEL Trip 0	no trip
Ironwood 1	reverse	1 phase cl	SEL Trip 0	no trip

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