A Practical Approach to Line Current Differential Testing

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***Abstract*—Line current differential (87L) protection of transmission lines is preferred because of its speed, sensitivity, security, and selectivity. 87L scheme performance is dependent on reliable communications, because measured currents from all terminals must be communicated and time-aligned.**

Several misoperations due to channel problems and noise led to the implementation of disturbance detectors and watchdog counters to increase scheme security in newer relay designs. While these features increase security, they can complicate testing and led to the implementation of "test mode," the ability to simplify 87L testing while bypassing some of the relay security logic.

Practical testing recommendations are presented in this paper. Several common 87L testing scenarios are discussed, including single-relay tests using loopback communications, single-relay tests of the operating and restrain characteristics of the relay using test mode, multiple-relay tests of the characteristics and channel using test mode, and multiple-relay tests of the characteristics and channel without test mode where real-world conditions are simulated.

I. Introduction

Line current differential (87L) protection is applied on long and short lines and on various voltage levels. Because the relays are located independently at each terminal of a line, 87L schemes depend on reliable communications to exchange and align the currents. Modern 87L schemes account for actual power system conditions more than their predecessors by implementing security improvements such as local and remote disturbance detection, watchdog counters, advanced time alignment and fallback methods, line charging current compensation, and external fault detection.

Some of these advancements affect 87L scheme testing by making it necessary for engineers and technicians to apply system conditions that more closely replicate power system conditions or, in some cases, to use a "test mode" for testing certain functions.

This paper presents some practical recommendations for testing 87L schemes. Several single-ended and multi-ended scenarios are discussed, including multi-ended 87L scheme testing where real-world conditions are simulated.

II. Review of Modern 87L Protection

Digital 87L systems are popular for a number of reasons. As with any differential scheme, 87L systems offer sensitivity, security, and selectivity. These systems provide fast and simultaneous fault clearing for faults located anywhere along a protected transmission line. Fig. 1 shows a one-line diagram of a typical two-terminal 87L scheme.

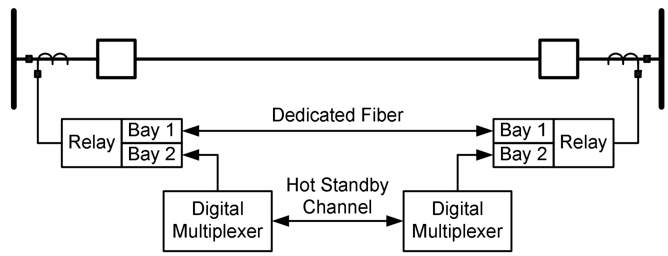

Fig. 1. Two-Terminal Digital 87L Application.

87L systems are applicable to both long and short lines and are a good solution for complicated applications, such as series-compensated lines, multiple-terminal lines, and lines with zero-sequence mutual coupling. They perform well for evolving faults, intercircuit and cross-country faults, internal faults with outfeed, current reversals, and power swings. Typical challenges for these systems include line charging current, in-line and tapped transformers, and current transformer (CT) saturation during external faults [1]. Also, these systems require a reliable, high-capacity, low-latency communications channel and must reliably time-align currents sampled at remote terminals in spite of channel noise, delays, and asymmetry [2].

Traditional current differential schemes use a percentage restraint characteristic. Operate, or difference, current is calculated as the magnitude of the sum of the terminal current phasors. Restraint current is a measure of the terminal current magnitudes and, depending on design, could be the sum of the terminal current magnitudes, the average of the terminal current magnitudes, and so on. The differential relay traditionally operates when the operate current exceeds a percentage of restraint, as determined by a slope setting. A limitation to this design is that sensitivity and security are inversely proportional. The slope-based characteristic increases security for higher restraint values by lowering sensitivity. Security can be increased by manipulating the restraint values and slope characteristics.

Reference [1] introduced the original concept of a digital 87L principle that used a restraint characteristic implemented in the Alpha Plane. The Alpha Plane is a current-ratio plane (see Fig. 2).

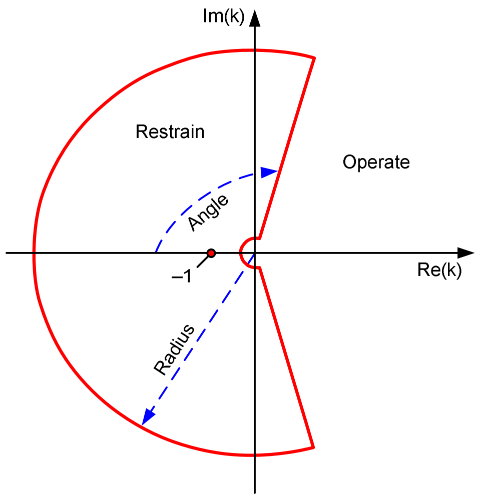

Fig. 2. Alpha Plane.

The ratio of remote terminal current to local current is plotted on the Alpha Plane. Ratios that lie within the restraint region prevent the differential element from operating. This characteristic responds well to phase alignment errors by explicitly looking at the angle difference between the local and remote currents. Sensitivity is further controlled by a separate comparison of operate current versus a minimum sensitivity setting. Sensitivity is further enhanced by the presence of zero-sequence and negative-sequence elements, in addition to segregated phase elements [3].

Reference [4] introduced an enhanced generalized Alpha Plane method. The generalized Alpha Plane develops two equivalent currents, $I_{L(EQ)}$ and $I_{R(EQ)}$, that produce the same operate and restraint as any number of original terminal current phasors. The ratio of smaller current to larger current is always plotted; thus, the ratio on the generalized Alpha Plane always has a magnitude of one or less. Because the Alpha Plane is symmetrical, all ratios are reflected to positive angles in the first and second quadrant (see Fig. 3).

$I_{L(EQ)}$ and $I_{R(EQ)}$ themselves are composite signals, made up of operate and restraint values, as shown in (1).

$$I_{L(EQ)} = \left(\frac{\mathrm{Im}(I_x)^2 - \left[I_{RST} - \mathrm{Re}(I_x) \right]^2}{2 \bullet \left[I_{RST} - \mathrm{Re}(I_x) \right]} + j \bullet \mathrm{Im}(I_x) \right) \bullet 1\angle\beta$$
$$I_{R(EQ)} = \left(I_{RST} - \left| I_{L(EQ)} \right| \right) \bullet 1\angle\beta \qquad (1)$$

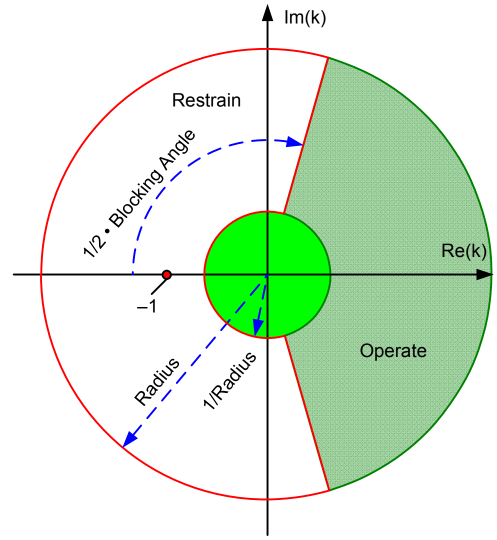

Fig. 3. Generalized Alpha Plane.

This generalized Alpha Plane allows for manipulation of the operate and restraint values to improve security and performance. The difference current can be reduced after compensating for line charging current, improving relay sensitivity. The restraint current can be increased, for example, during in-line or tapped transformer energization, improving relay security.

I_x is the difference phasor, rotated by a reference angle β. The reference angle β is chosen so that $I_{R(EQ)}$ sits at 0 degrees, eliminating one unknown. β is chosen by determining which terminal current has the longest projection on, or is most in phase with, the difference current.

To accommodate CTs with different nominal ratings, the generalized Alpha Plane relay automatically calculates taps and performs difference calculations in per unit. The original Alpha Plane-based relay used secondary amperes normalized to the local relay nominal rating and the highest CT ratio within the differential scheme. The generalized Alpha Plane relay also employs an external fault detector that uses raw samples to determine if a fault is external to the zone of protection within one-quarter of a cycle. Once an external fault is detected, the relay switches automatically from normal to more secure settings, improving security in case a CT saturates during the external fault. Further, for data alignment, a traditional ping-pong method is used for symmetrical channels. However, the generalized Alpha Plane relay employs Global Positioning System (GPS) satellite time, wide-area terrestrial time from an integrated communications optical network, or a well-established fallback time source to improve data alignment with asymmetrical channels.

As technology has advanced, relay designs have been improved and enhanced. With these enhancements have come changes in testing practices. For example, overcurrent schemes are now combined with light sensing for arc-flash protection, so we must use current and light together for testing [5]. Bus and transformer differential relays now automatically switch to a higher percentage slope setting for better security during external faults, so we must apply dynamic state simulations to precisely test the higher slope setting [6]. Similarly, technology advancements have been introduced in 87L elements.

Some of these advancements have led to improvements in the security of the 87L performance and with it, changes in the approach to testing. As we see in the following section, 87L elements have proven to be more secure, on the average, than most protection schemes. Still, we evaluate several system events to root cause to show why we wish to further improve 87L security.

III. 87L Performance With Case Studies

The rate of total observed undesired operations in numerical relays is extremely low, 0.0333 percent per year (a failure rate of $333 \bullet 10^{-6}$). By comparison, relay application and setting errors (human factors) are 0.1 percent per year (a failure rate of $1{,}000 \bullet 10^{-6}$) [7]. The rate of total observed undesired operations in 87L schemes is even lower, 0.016 percent per year (a failure rate of $160 \bullet 10^{-6}$). If disturbance detection (described later in this paper) had been applied in all cases, this number would drop even lower, to 0.009 percent per year (a failure rate of $90 \bullet 10^{-6}$).

Some of these undesired operations were due to single event upsets (SEUs) [8], sometimes called soft memory errors, in relays. Diagnostics have greatly improved and reduced these errors in the last several years. The rate of observed 87L undesired operations due to channel problems is less than 0.002 percent per year (a failure rate of $20 \bullet 10^{-6}$). Had disturbance detection been applied in all cases, this number would drop even lower, to less than 0.0005 percent per year (a failure rate of $5 \bullet 10^{-6}$).

All this is to say that protective relays are very secure. Still, every undesired operation is cause for concern and drives efforts to identify, measure, and improve. In the following discussion, we analyze three actual events that produced an undesired 87L operation.

A. Case Study 1: 87L Misoperation Caused by an SEU

Fig. 4 shows an event where there was no apparent fault. In this case, 87L asserted and produced an undesired trip, and the root cause was attributed to an SEU, also called a soft memory error. An SEU is a temporary unintended change of state in a single memory location. Soft memory failures are transient, infrequent events occurring at a rate of about one per million memory-device operating hours. Such errors are caused by high-energy particles striking a memory storage capacitance and disturbing the charge stored at a particular location. These high-energy particles can come from high-energy cosmic rays or from the emission of alpha particles from impurities in some microcircuit packaging materials. Improvements in internal diagnostics and memory storage design have been implemented to reduce the occurrence of these events. Enhanced firmware now detects the soft memory error event, automatically resets the relay, pulses the alarm contact, and logs an entry in the sequence-of-events record. In rare cases, SEUs can cause a change of state in an element that produces a trip, like that shown in Fig. 4.

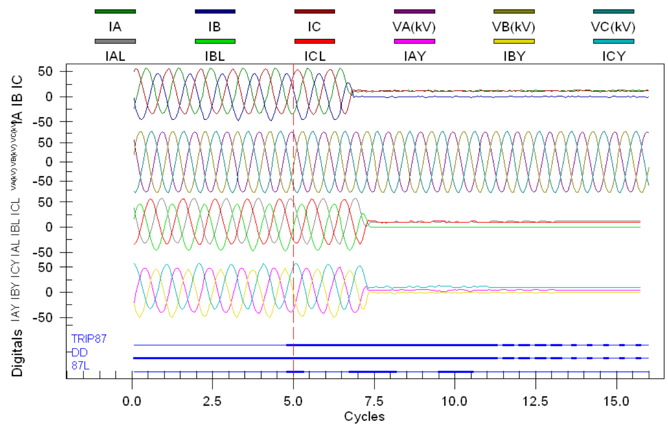

Fig. 4. 87L Asserts for an SEU.

B. Case Study 2: 87L Misoperation Due to a Channel Problem With Disturbance Detector Disabled

In the system event shown in Fig. 5, the channel experiences a degradation of the output of one of the optical fiber transmitters used in the 87L scheme. We can observe the ROKX bit chattering (it should be solidly asserted). Eventually, bad data (erroneous remote current IBX) make it through error checking to cause an undesired 87L operation.

In this case, disturbance detection was disabled. If it had been enabled, the 87L element would have been prevented from tripping instantaneously, and the undesired operation would have been avoided. Early 87L relays had a setting to enable (or disable) disturbance detection at the local terminal. Newer relays use disturbance detection at all terminals by design.

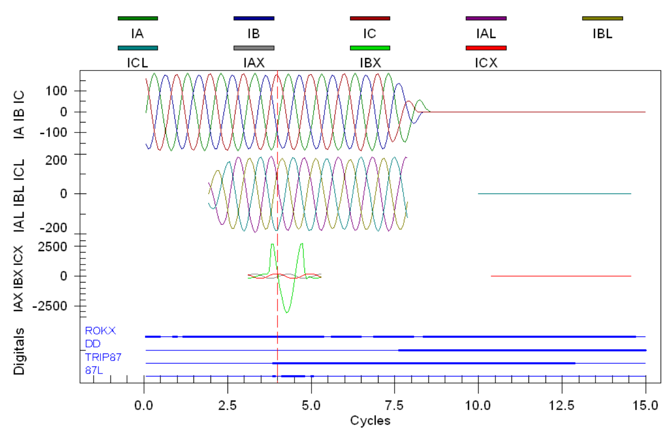

Fig. 5. 87L Produces Undesired Trip During Communications Failure With Disturbance Detection Not Enabled.

C. *Case Study 3: 87L Misoperates With Disturbance Detector Enabled*

In Fig. 6, an apparent communications error produces a trip condition. In this case, even with disturbance detection logic enabled, the trip was not prevented.

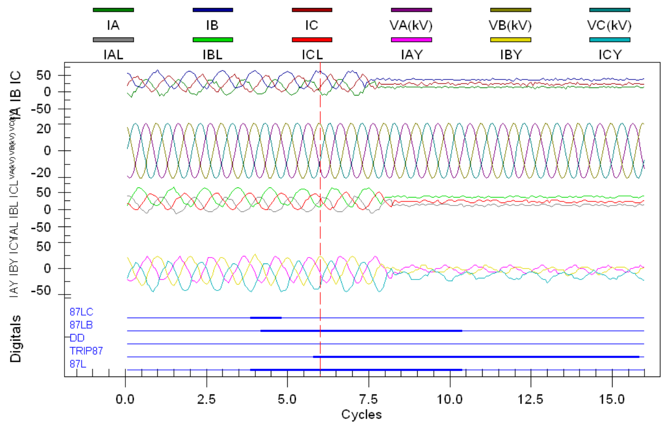

Fig. 6. Apparent Communications Error Produces 87L Misoperation With Disturbance Detection Logic Enabled.

Monitoring the performance of the 87L scheme over time using advanced channel diagnostics and alarms is a method to secure the relay for such events, as discussed in the following section. In original designs, channel monitoring and poor channel performance could be ignored or missed by users. Watchdog counters now disable the 87L element for repeated close calls.

IV. Security Improvements

A. *Data Integrity Check*

Noise in the communications channel can corrupt data. The term *noise* refers to such issues as interference coupled to the channel media or electronics, failing components used in the network, poor quality of fiber terminations and associated losses, and marginal power budget for fiber transceivers. In multiplexed networks, frame slips can corrupt the data.

Noise is not necessarily a sporadic event. A failing component in the communications channel can create a persistent noise that is constantly threatening the integrity of the transmitted 87L data. Undetected errors can lead to 87L misoperation. Detected errors cause a temporary loss of dependability because the relay needs to flush the bad data or to resynchronize.

Solutions include using a data integrity check, such as a Bose, Ray-Chaudhuri, Hocquenghem (BCH) code check. The security is based on the bit check resolution and packet size. For example, a 32-bit BCH code used on a 255-bit packet size secures the data so that the probability of undetected error is less than $1.2 \bullet 10^{-10}$ [9] [10].

B. *Disturbance Detection Supervision*

Even with powerful data integrity checks, additional security is needed because 87L schemes exchange so much data. For example, by sending packets every 4 milliseconds, a relay transmits and receives 7.884 billion packets per year. Even with a very small probability of an undetected error ($1.2 \bullet 10^{-10}$), a standing noise in the communications channel could possibly produce corrupted data and potentially an undesired 87L operation [11].

As seen in Section III, Subsection B, applying disturbance detection improves security. Typically, a disturbance detector (DD) looks for a change in measured current compared to the current one cycle ago (or within a similar window). Schemes can use the local data, or both the local and remote data, to supervise instantaneous tripping of an 87L element. Typically, the raw (unsupervised) 87L is allowed to trip without DD supervision after a short time delay (for example, two cycles). Fig. 7 shows disturbance detection logic using both local and remote (87DDL and 87DDR) data to supervise 87L trips as well as a received direct transfer trip (87DTT).

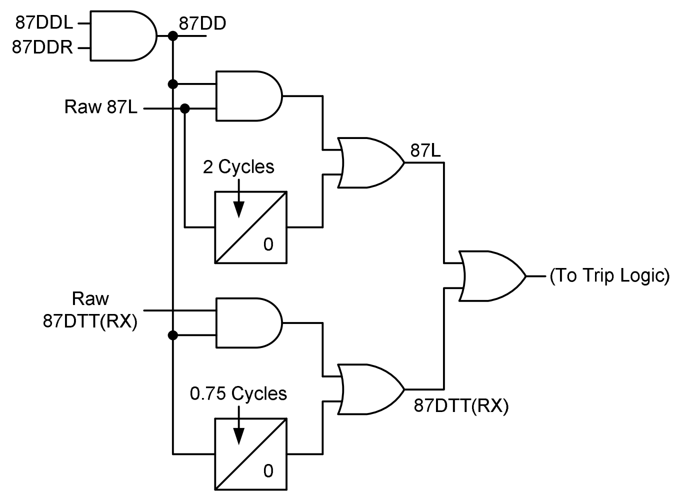

Fig. 7. 87L Disturbance Detection Logic.

Disturbance detection logic impacts testing in three ways. First, if DD uses local and remote data, a single-ended test is inadequate. The local 87L would always experience a time delay. Second, slowly ramping a current from a prefault to a fault value is inadequate. A step change in current (or voltage, if used) is realistic and required; otherwise, DDs will not assert. The relay would again trip with a time delay. Third, raw 87L operations without accompanying DD may eventually disable the 87L element due to channel monitoring and improved security. This will be discussed in more detail shortly.

As we can see, to properly test an 87L element with disturbance detection, the test quantities must closely replicate an actual fault.

C. *Watchdog Counters*

It may happen that the raw 87L element picks up due to noise but does not operate because it is initially stopped by the lack of disturbance (no sensitive DDs assert at the same time as the 87L operation). Afterwards, the 87L resets itself when the channel problem disappears.

For this reason, it is important to log such events as close calls and incorporate logic that responds to unexpected and persistent events that impact the 87L function. This logic, called a watchdog counter, maintains the security of the 87L function by first alerting the user about significant channel issues through alarms to force rectification of the channel problems. Second, watchdog counters may inhibit the 87L function after a significant number of persistent events or close calls so that misoperations are prevented.

Watchdog counters impact testing. If users insist on testing relay schemes with in-service settings and no special test mode(s), then the testing method must emulate actual power system conditions. If testing is not realistic, the watchdog counters log unexpected 87L events and eventually inhibit the 87L element during testing.

Consider an analogy to loss-of-potential (LOP) logic in distance (21) or directional (67) element schemes. In the case of a failed voltage transformer (VT), VT wiring problem, or blown VT fuse, users can decide through relay settings whether to inhibit 21 or 67 elements, or both. Alternatively, the user may decide to simply leave the elements to operate based on unreliable voltages. In either case, the user may choose to alarm and call immediate attention to the problem. Similarly, the user must decide to enable or to disable 87L watchdog counter supervision to determine how the 87L element behaves if a communications channel is deemed to have had too many close calls.

D. Generalized Alpha Plane Increases Security for Advanced Requirements

The generalized Alpha Plane is transparent for common two-terminal applications, while allowing the same principle to be applied to three-terminal (or *x*-terminal) lines by reducing the system to a two-terminal equivalent, as described in Section II. Keep in mind, a two-terminal transmission line with dual breakers at each terminal is a four-terminal differential problem.

Moreover, if applied on lines with charging current, the total charging current can be removed, bringing the balanced current closer to the ideal blocking point (1 per unit at 180 degrees). For applications with in-line transformers or any other case where higher restraint is required, harmonics can be added to the restraint, thus moving the Alpha Plane point closer to the ideal blocking point. By using external fault detection, the differential can be placed in a high-security mode—essentially increasing the Alpha Plane restraint region. Moreover, these principles can be applied on segregated phase, negative-sequence, and zero-sequence quantities alike.

E. Advanced Time Alignment

In addition to traditional channel-based data alignment using a ping-pong method, modern relays can use external time sources, if desired. These time sources are useful when applying 87L over a network that may experience asymmetrical channel delays.

When high-accuracy GPS clocks are used, data can be synchronized without compensating for clock offset. This reduces concerns of channel asymmetry and channel switching because the time source is independent of the channel.

Finally, if a time source is lost or degrades, schemes must have graceful fallback modes, so 87L integrity is maintained during any loss or degradation of the time source.

V. 87L Testing Considerations

A. Purpose of Testing

This section deals with considerations for testing the 87L element. Many papers on comprehensive test practices have been published. The content of this section is not intended to provide a complete discussion on testing. Rather, it deals with some specific issues related to, and methods of, testing 87L elements. Testers must comply with North American Electric Reliability Corporation (NERC) standards and manufacturer recommendations and use other good practices. These good practices include developing test plans and checklists, creating complete documentation, moving testing to the lab when possible, performing peer review, and improving training.

There are different categories of testing—type or acceptance testing, commissioning testing, and maintenance testing [12]. Type or acceptance testing is performed on a new relay make or model to qualify it for use on a given system. One important aspect of type or acceptance testing is to validate performance, such as speed, security, and sensitivity. Another aspect is to verify adherence to specifications, such as dielectric strength, output contact current interruption, shock, and vibration. Lastly, this type of testing serves to provide familiarity, proficiency, and training.

Commissioning testing encompasses a wide range of goals. Commissioning tests verify, among other things, the correct installation and operation of the following:

- Polarity, ratio, phasing, and grounding of ac signals.
- Metering.
- DC power supply.
- Input and output wiring.
- All communications (protection channels, supervisory control and data acquisition [SCADA], remote engineering access, security).
- Relay settings and logic.
- Application and documentation.

In short, the goal of commissioning tests is to verify that the protection system is ready to go into service. Further, proper commissioning certifies with 100 percent confidence that the protection system trips for in-section faults within a prescribed time and that it does not trip for out-of-section faults or nonfault conditions [13].

Maintenance testing is performed to supplement automated self-tests, which extensively monitor the relay health. It is recommended that relay users perform the following actions:

- Monitor self-test alarm contacts via SCADA systems and annunciators in real time, and investigate any alarms immediately.
- Compare metering and input statuses between independent devices with automated systems.

- Investigate event and fault records to determine root cause and validate protection system performance, including output contact closure.
- Perform minimal periodic testing to supplement automated self-testing and the practices above by validating inputs, outputs, and metering.

In short, maintenance testing is performed to ensure that the protection system is still healthy and available [14].

B. Considerations When Testing 87L Schemes

Many challenges must be addressed when testing an 87L scheme. 87L protection is inherently a distributed protection scheme with relays located at different line terminals, in most cases separated by considerable distance. While current differential schemes are ubiquitous, line 87L schemes are more complex because of the communications and data alignment requirements. We must consider how channel characteristics, multiplexers, and external clocks impact the data exchange between the relays. For example, channel noise can produce delayed operation, and asymmetrical delays can produce standing differential current.

The testing requirements for an 87L scheme can be complicated. Supervising logic, including disturbance and external fault detection, channel status, and enabling control logic, secures in-service relays but can obstruct testing. Unfamiliarity with supervising logic can create contradictory or confusing results and lead the tester to waste time trying to determine root cause. One of the purposes of testing a microprocessor-based relay is to confirm that it has been configured correctly; therefore, the application of temporary settings changes should not be required for testing. Crews are required at multiple line terminals using GPS-synchronized test sets to perform complete system end-to-end testing [15] [16].

Finally, we must consider the risks of testing lines that are in service, including human errors during testing that could potentially lead to undesired trips. 87L trip outputs must be isolated locally and remotely. However, it may be desirable to allow remote distance and directional overcurrent elements to remain in service. Microprocessor-based relays have configurable front-panel control switches that can be used for functions such as enabling or disabling the 87L element altogether (87L enabled), putting the entire relay into test mode (relay test mode), or putting the 87L element into test mode (87L test mode). Independent control switches or test switches can be used for these purposes, too.

C. 87L Enabled or Disabled

87L Enable pushbuttons or switches simply turn the 87L element on and off, locally and at all remote terminals. We use such an isolation mechanism to allow distance and directional overcurrent elements within a multifunction relay to be tested without worry of operating a local or remote 87L element. As with any differential scheme, the 87L element should be turned off locally and at all remote terminals anytime current circuits are disturbed.

D. Relay Test Mode

The first objective of a *Relay Test Mode* pushbutton or switch is to allow all the protection functions to be thoroughly tested but to avoid closing actual trip output contacts. The same functionality has traditionally been supplied by external test and isolation switches. Relay test mode does not interfere with any relay element operation; the relay merely blocks the normal output contacts used for breaker tripping, closing, and pilot scheme keying. In addition to isolating normal tripping contacts, relay test mode may be used to enable specific output contacts for test purposes.

The other significant function of this pushbutton or switch is to supervise the communications command to enter 87L test mode. In other words, to further specify 87L element testing and enter 87L test mode, the relay must first be in relay test mode, with normal tripping contacts isolated from doing harm.

E. 87L Test Mode

When a relay is in 87L test mode, a signal should be transmitted over 87L channels to all remote relays to block the 87L element in those devices while the test mode is active. Note that other protection functions, such as the distance elements, are free to operate in both the local relay and at the remote terminals. Fig. 8 shows a screen capture of the 87L test mode.

```
=>>TEST 87L
Entering 87L Test Mode.

  Select Test: Characteristic or Loopback (C,L)       ? L
  Loopback Test Channel: (1,2)                        ? 1
  Loopback Duration: (1-60 minutes)                   ? 5

 Are you sure (Y/N)? Y

The 87L element inhibited, address checking overwritten,
Testing is enabled
Type "COM 87L" to check the loopback status

Warning!
Ctrl X does not exit test mode
Type "TEST 87L OFF" to exit
```

Fig. 8. Entering 87L Test Mode.

During maintenance testing, for example, a technician can put the local relay into relay test mode via a front-panel pushbutton and put the 87L protection scheme into 87L test mode. The normal tripping output contacts will be isolated. Further, this disables 87L tripping at the local and remote terminals and allows element testing in the local relay using the specific testing output contacts. Remote relay backup elements, such as distance and directional overcurrent elements, remain functional.

F. 87L Test Mode 1: Loopback Test

A single relay and single test set can be used, either in the lab or in the field, to test an 87L element to a minimal degree. No working channel to the remote line terminal is available in this scenario. Therefore, the relay is tested with a loopback test, where the single relay transmit output is looped back to its own receive input (see Fig. 9). When a loopback test is active, the local relay ignores channel transmit and receive addresses to allow the 87L element to respond to the data it transmits. A loopback duration is added to prevent the relay from being stuck in loopback mode indefinitely. Alternately, a communications command can be used to disable loopback testing when complete.

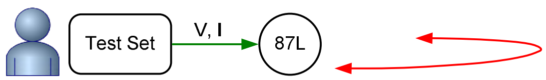

Fig. 9. Loopback Test.

Because any current injected into the local relay is measured as local and remote current, it is not possible to test restraint characteristics with a loopback test. There is no way to vary the angle of local and remote currents with respect to one another. The Alpha Plane in the differential metering is inactive during loopback tests. However, simple pickup sensitivity tests of the differential element can be performed; any current injected is viewed as operate or difference current.

While loopback tests are not so good at checking the characteristics of the differential element in detail, they are handy for determining where a communications channel or network problem exists. Use all channel monitoring and statistics to determine root cause.

In loopback mode, we physically apply an external loopback connection or condition. We can perform the loopback test at several points, such as at the relay terminals, at a local patch panel, at a local or remote multiplexer, and so on. The placement of the loopback at various locations allows testers to troubleshoot and isolate communications problems systematically.

G. 87L Test Mode 2: Single-Relay Characteristic Test

Another innovative testing scheme involves a single relay with no need for a working channel or loopback connection. Test currents are injected at one terminal with one test set. 87L test mode is used to specify and allow a single-relay characteristic test.

Locally injected currents represent local and remote currents via an analog substitution used only during testing. Internally, the locally injected remote current is placed into an alignment table in the correct order for proper operation. Because local and remote currents are measured and phase magnitudes and angles can be independently controlled, the restraint characteristic of the 87L element can be fully tested [17] [18].

Differential and Alpha Plane restraint ratio (*k*) results are observed in metering commands for the element under test (see Fig. 10). Note that the angle of *k* is always displayed in positive degrees for simplicity.

The idea for the single-terminal test comes from the fact that each of the phase elements does not require information from other phases in order to operate; the phases are segregated. Therefore, a particular phase (A, for example) can be chosen as the local test phase, and an unused phase (B, in this case of the 87LA element) can be used to simulate the current coming from the remote terminal (see Fig. 11).

```
=>>MET DIF

Relay 1                   Date: 05/11/2012 Time: 10:42:35.698
Station R                 Serial Number: 1111240304


87L Communication: Master
87L Function: Available
Stub Bus:      Disabled

                                  Local Terminal
               IA     IB     IC     I1     3I2    3I0
MAG (pu)       1.634  0.000  0.000  0.545  1.634  1.634
ANG (DEG)       0.00  37.44  37.44   0.00   0.00   0.00
THROUGH (pu)   1.634  0.000  0.000         0.000  0.000

                                Remote Terminal 1
               IA     IB     IC     I1     3I2    3I0
MAG (pu)       6.535  0.000  0.000  2.178  6.535  6.535
ANG (DEG)      79.97  37.44  37.44  79.97  79.97  79.97
THROUGH (pu)   6.534  0.000  0.000         0.000  0.000

                                  Differential
               IA     IB     IC            3I2    3I0
MAG (pu)       7.007  0.000  0.000         7.007  7.007
ANG (DEG)      66.70  37.44  37.44         66.70  66.70

                                   Alpha Plane
               87LA   87LB   87LC          87LQ   87LG
k              0.250  1.000  1.000         0.000  0.000
alpha (DEG)    79.94 180.00 180.00          0.00   0.00
```

Fig. 10. Operate and Restraint Quantities—Single-Relay Test.

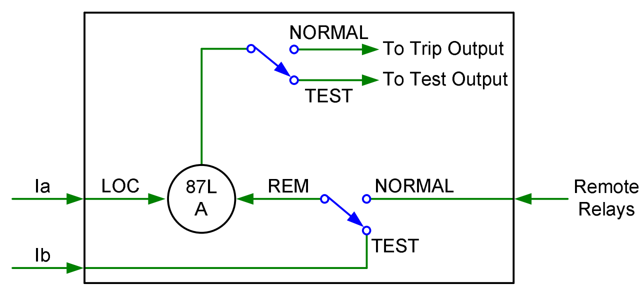

Fig. 11. Single-Relay Characteristic Test.

This methodology enables tests to be conducted using the 87L element logic in its entirety and allows testers to gain familiarity with the relay and prove scheme operation before a working end-to-end channel is in place. A simple analog substitution table defines which terminal currents to use for specific differential element tests (see Table I).

TABLE I
SINGLE-RELAY ANALOG SUBSTITUTION

87L Quantity	Fault Element				
	A	**B**	**C**	**Q**	**G**
Local IA	IA			IA	IA
Local IB		IB			
Local IC			IC		
Remote IA	IB			IB	IB
Remote IB		IC			
Remote IC			IA		

When performing a characteristic test, specify the phase (A, B, or C) or sequence element (3I0, 3I2) under test and either normal or secure mode. Specifying the phase or sequence element eliminates confusion that can occur when multiple elements pick up and operate for the same test or fault condition. When in secure mode, the Alpha Plane restraint region becomes larger and the protection becomes more secure to protect against misoperation with extreme CT saturation during an external fault.

No channel is required for a single-relay characteristic test. This testing method is therefore useful in the lab for settings and scheme testing, without need for a channel or even a second relay. If a channel is in place and working, remote terminals ignore locally injected test quantities based on a signal that is permanently keyed over the channel to all remote relays, which blocks the normal 87L element in those devices. Other protection functions, such as the distance elements, are free to operate at the remote terminals. Single-relay characteristic tests can also be performed at multiple terminals simultaneously.

H. 87L Test Mode 3: Multiple-Relay Characteristic Test

A third test mode involves multiple relays, one at each terminal of the line, and a working channel. This test can also be done in the lab, but still, a working channel is required. 87L test mode in the relay is used to specify and allow a multiple-relay characteristic test.

Currents can be injected at one terminal with one test set or at multiple terminals at the same time (see Fig. 12). If testing is performed in the lab, a single test set can be used to simultaneously inject currents into multiple relays. By definition, the test signals provided to each relay from the common test source are synchronized; the current phase angles are absolutely referenced to one another.

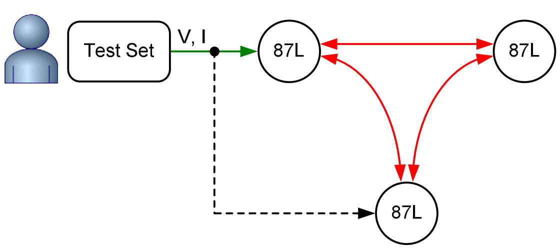

Fig. 12. Multiple-Relay Characteristic Test With One Test Set.

If the test is done in the field, satellite synchronization of the test sets must be used so that the current phase angles in different test sets are absolutely referenced to one another (see Fig. 13).

Disturbance detection and watchdog logic dramatically improve the security of the 87L function. Disturbance detection requires that local and remote currents change before differential elements and transfer trip signals are acted on. Watchdog logic inhibits 87L tripping after a number of persistent close calls. Close calls are momentary pickups of the raw differential element without accompanying disturbance detection and can indicate significant channel or hardware problems.

The watchdog logic has two levels. The first stage is correlated with channel activity in order to provide an actionable alarm to the user. When the counted illegitimate 87L pickup events are associated with the channel problems, the channel is suspected as the root cause and should be inspected. The second stage counts all unexpected 87L pickup events. Stage 2 inhibits only the 87L function and does not inhibit other local protection functions of the relay.

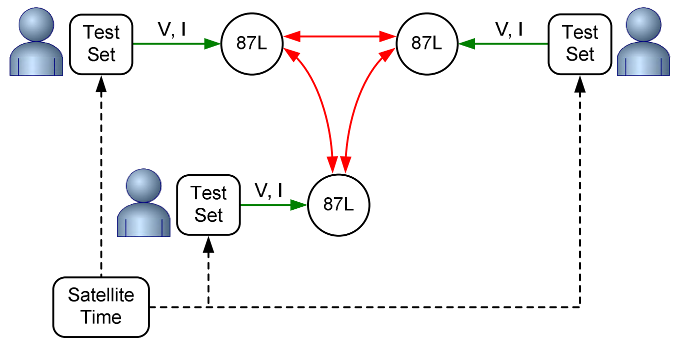

Fig. 13. Characteristic Test With Multiple Relays and Test Sets.

While improving system security during real-world operation, these features complicate traditional, simple test methods. Ramping currents during testing can quickly generate many pickups and dropouts, increment the watchdog counters, and disable the 87L element. Without a specific 87L test mode, a communications command would be needed to reset watchdog counters, but this could become a tedious process after each test [19]. Fig. 14 shows a traditional test where one terminal is held constant while another terminal is modified. This is an unrealistic power system fault simulation and will increment watchdog counters without 87L test mode.

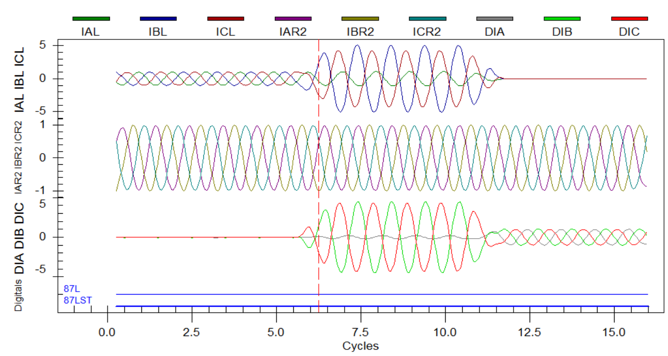

Fig. 14. Unrealistic Power System Fault Simulations Require 87L Test Mode.

When performing a multiple-relay characteristic test in 87L test mode, currents at one terminal can be held constant while currents at the other terminal(s) are changed. In 87L test mode, the relay ignores local and remote disturbance detectors and watchdog logic to allow simpler testing. While ramping one terminal current while holding another current constant does not simulate a realistic power system fault, it works well to test the 87L operate and restraint characteristics.

The advantage to multiterminal testing is that the 87L protection can be treated as a complete system. It allows charging current compensation and in-line transformer functions to be tested as well. Multiterminal testing ensures that the communications system is running properly and that the dynamic behavior of the communication is reliable enough for the protection.

Differential element metering can be observed. The operate and Alpha Plane restraint results are valid for the element under test. Fig. 15 shows a C-phase element under test, using multiterminal characteristic testing.

```
=>>MET DIF

Relay 1                 Date: 05/11/2012 Time: 13:59:54.456
Station R               Serial Number: 1111240304

87L Communication: Master
87L Function: Not Available
Stub Bus:      Disabled

                               Local Terminal
              IA      IB      IC      I1      3I2     3I0
MAG (pu)      0.001   0.000   0.327   0.109   0.328   0.326
ANG (DEG)    -88.10    2.56  120.15    0.00 -119.78  120.21
THROUGH (pu)  0.000   0.000   0.327           0.327   0.327

                             Remote Terminal 1
              IA      IB      IC      I1      3I2     3I0
MAG (pu)      0.000   0.000   0.409   0.137   0.409   0.408
ANG (DEG)    -80.87 -118.66  119.57   -0.48 -120.47  119.64
THROUGH (pu)  0.000   0.000   0.408           0.410   0.408

                                Differential
              IA      IB      IC              3I2     3I0
MAG (pu)      0.001   0.000   0.736           0.737   0.735
ANG (DEG)    -86.09  -108.81 119.83         -120.16  119.89

                                Alpha Plane
              87LA    87LB    87LC            87LQ    87LG
k             1.000   1.000   0.000           0.000   0.000
alpha (DEG)  180.00  180.00    0.00            0.00    0.00
```

Fig. 15. Operate and Restraint Quantities—Multiple-Relay Test.

The Alpha Plane result defaults to 0 per unit at 0 degrees when the differential and restraint currents are nearly equal. The reason for this is that the (I_{RST} – I_x) term in the denominator of the generalized Alpha Plane *k* calculation converges to zero for this condition and the calculation is therefore unsolvable. This is always the case when we use one injected current in a multiterminal test.

When the differential current is less than 50 percent of pickup, the Alpha Plane is forced to 1 per unit at 180 degrees. This makes the relay more secure by forcing the relay to the ideal blocking point.

I. Real-World Testing—No Use of 87L Test Mode

The last method of testing the 87L element is by simulating a realistic power system event and not using 87L test mode at all. 87L test mode can be disabled if all relays at all terminals are available, the channel is working and available, and we have the ability to synchronously inject test signals into all relays simultaneously. Note that realistic test values must be injected. In other words, we cannot inject current into only one terminal to simulate a fault; on a real power system, all closed and in-service terminals would assert a disturbance detector during internal and external faults.

Some testers will be philosophically opposed to using any sort of test mode. They may want to challenge the relay as it exists in service. This method can be used; however, problems can arise by using test sets at each end of the line that are not applying realistic test values (i.e., current is changed at one terminal only) or using test sets that are not perfectly synchronized. For example, the authors have witnessed problems with satellite-synchronized test equipment that does not turn off state simulations simultaneously. In these cases, the tester must reset the watchdog counters manually after each test.

For multiterminal system testing, we apply signals at each end of the line simultaneously for complete system testing. Multiterminal testing verifies the overall performance of the relays and the associated channel equipment.

VI. CONCLUSION

Modern digital relays offer dramatic improvements in capabilities, sensitivity, speed, and security. Improvements include enhanced channel monitoring, satellite time-based time alignment, disturbance detection, the generalized Alpha Plane, external fault detection, adaptive characteristics, charging current compensation, in-line and tapped transformer compensation, watchdog counters, improved relay self-test diagnostics, and more.

Security failures are rare. Still, every undesired operation is cause for concern. Three real-world cases are shared in this paper. In one, an SEU caused a misoperation; improved diagnostics and memory storage prevent this from reoccurring. In the second, a communications error produced a misoperation; disturbance detection would prevent this from reoccurring. In the third, another communications error produced a misoperation, in spite of disturbance detection being enabled; monitoring channel alarms and performance, in addition to allowing watchdog counters to disable the 87L element after a number of close calls, improves security.

As 87L protection has advanced, so have testing capabilities and requirements. Channel statistics and monitoring help diagnose problems more easily today. Loopback test mode allows channel problems to be pinpointed quickly and allows simple relay testing to be done without the need of a working channel. Full characteristic testing in the lab is allowed with new test modes, including the ability to substitute a locally injected current for a remote terminal current. Traditional, simple tests using ramped currents or changing currents at only one terminal are still allowed, but test mode must be used. If this is not done, disturbance detection and watchdog counters may log 87L element assertions without accompanying disturbance detection as close calls and eventually disable the 87L element.

If real-world testing is preferred without altering settings or using special test modes, the tester must simultaneously inject realistic power system values into all terminals. If this is not done, disturbance detection and watchdog counters may log 87L element assertions without accompanying disturbance detection as close calls and eventually disable the 87L element.

As protective relay algorithms and capabilities adapt and evolve, so must the engineer, technician, and test practices.

VII. Acknowledgments

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IX. Biographies

Karl Zimmerman is a regional technical manager with Schweitzer Engineering Laboratories, Inc. in Fairview Heights, Illinois. His work includes providing application and product support and technical training for protective relay users. He is a senior member of the IEEE Power System Relaying Committee and chairman of Working Group D25, Distance Element Response to Distorted Waveforms. Karl received his BSEE degree at the University of Illinois at Urbana-Champaign and has over 20 years of experience in the area of system protection. He has authored over 25 papers and application guides on protective relaying and was honored to receive the 2008 Walter A. Elmore Best Paper Award from the Georgia Institute of Technology Protective Relaying Conference.

David Costello graduated from Texas A&M University in 1991 with a BSEE. He worked as a system protection engineer at Central Power and Light and Central and Southwest Services in Texas and Oklahoma and served on the System Protection Task Force for ERCOT. In 1996, David joined Schweitzer Engineering Laboratories, Inc., where he has served as a field application engineer, regional service manager, and senior application engineer. He presently holds the title of technical support director and works in Fair Oaks Ranch, Texas. In 2008, he was the recipient of the Walter A. Elmore Best Paper Award from the Georgia Institute of Technology Protective Relaying Conference. David is a senior member of the IEEE and a member of the planning committee for the Modern Solutions Power Systems Conference and the Conference for Protective Relay Engineers at Texas A&M University.

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