A Comparison of Line Relay System Testing Methods

Chris Araujo
National Grid Co.

Fred Horvath
FPL Seabrook Station

Jim Mack
Schweitzer Engineering Laboratories, Inc.

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***Abstract*—Testing is the last line of defense for relay system performance before the switch is thrown. The power supplier must be assured the system will protect for all possible faults, over- and undervoltage, and other actionable conditions under continuingly varying system status. The power supplier must also be assured the protective system will not generate false trips or overtrip, causing undue outages or other adverse power quality conditions for its customers. Installing a relaying system, performing basic tests, and then hoping for the best is no longer an acceptable way to do business in light of problems that have occurred in the last few years. The relaying system must be "dialed in" before the line is energized.**

Throughout the power industry, there are a variety of philosophies on testing relays that vary from basic go/no-go tests, to power system simulation, to installed system end-to-end tests. We will explore these various methods by compiling field testing experience and comparing the results achieved. We will analyze how many potential problems were found with equipment, relay settings, relay logic, or other things.

Modern relays provide sophisticated logic to provide traditional functionality but can be used to provide more complex custom control. The typical engineer does not have the means to reliably test programming from behind the desk. These tests are normally performed in the field. Training and guidance are needed for engineers and technicians so they can develop comprehensive and fool-proof tests to ferret out any potential problems.

I. Introduction

Relay testing has evolved over the years. This evolution has seen technical advances that allow computers to control the test set, making automatic testing possible. Automated tests require very little participation by the tester, provide many tests in a short period, and present the data in a user-friendly way. But, has the evolution of the protective relay driven the need for automated tests, or has the availability of inexpensive computers and software driven the move to automated tests? Which tests are most productive? How much time is spent performing a particular test, and what are the returns? Are we more or less productive after the evolution, and why? What do we concentrate on, and what should we cut out of our testing routine? This paper addresses some of these questions.

Protective relays have evolved greatly over the years. Test sets and testing practices have evolved along with them. Modern relays are essentially digital replications of electromechanical devices with enhancements and will mostly test the same way the electromechanical version will. This is verified by the fact that modern electromechanical and digital test routines are very similar. Need this be so? Digital relays will not change their characteristics over time as an electromechanical device will, which suggests that we can eliminate some testing from our routines. How much of the testing that we perform is a carryover from the electromechanical relay days? Are there any tests that we need to add to accommodate new technology? What changes are needed in the way tests are performed to accommodate protective relaying in the twenty-first century?

We will look in detail at various testing methods to evaluate effectiveness versus effort expended. When evaluating each of these methods, we should ask these questions:

- How much time and effort is expended to perform the test?
- What are the potential benefits of the test?
- Is the test straightforward and easy to interpret?
- Will the test uncover settings errors?
- Will the test uncover wiring errors?

This paper will concentrate on microprocessor-based relay testing.

II. Testing Methods

A. Meter Tests

Testing the analog input section of a digital relay need not be a complex task. A simple meter check will prove the relay accuracy. The testing day should begin with this test to prove proper connections before relay element testing begins. Much time has been wasted troubleshooting test plans because of incorrect test connections to the relay.

B. Input and Output Contact Testing

The vast majority of relay problems are failure or misapplication of I/O. This is the most serious form of problem that can cause failure to trip the breaker for a fault, resulting in outage and equipment damage. Many hours can be spent testing all the elements in a relay, but a bad output contact will prevent those perfectly calibrated elements from tripping the breaker, reclosing, or performing a needed control action. Testing of I/O can be performed rather quickly and easily. Microprocessor-based relays have commands available to easily exercise the outputs. Inputs can be verified by jumpering station battery voltage or dc from a test set to the proper terminals. The relay will provide target information to indicate the input is active. Extreme care must be taken to fully isolate I/O before testing begins to avoid inadvertent tripping or activation of control schemes. Typically, test switches will isolate all I/O on a relay in a couple of minutes. Verify that this has been done before you begin testing. Take the time to understand the total control scheme so all ramifications will be known. Testing takes less than a minute per I/O position, allowing a full relay to be tested in under 30 minutes in most cases.

Some of the most common output failures are welded contacts due to misapplication of the output contact in a circuit. Remember, standard contacts are designed for 30 amperes make and 6 amperes carry but can only break about 0.25 amperes at 125 Vdc. Keep this in mind when testing the contact because many failures are caused during testing and commissioning. Less common are outputs that fail to close due to mechanical problems or bad coils.

Input failures are rare, but there have been many misapplications of inputs, for example, a relay that was purchased with 48-volt rated inputs installed on a 125-volt system or vice versa. The inputs may work correctly for some time but eventually will fail. For these reasons, checking the pickup voltage of an input is very important in initial commissioning. In routine testing of inputs, all that needs to be verified is that the input asserts with rated battery voltage.

C. Impedance Characteristic Testing

Impedance characteristic tests have become popular with the advent of computer-based control of test sets. This is probably the number one most common testing method for distance relays. Many hours have been spent plotting mho and quad characteristics on distance relays. These tests involve setting up fairly complex software programs called macros that place multiple tests to the relay in a sequence much faster than possible with manual tests. The computer-based software will plot these multiple test points on an R versus X impedance diagram, providing data that are pleasing to the eye. On the other hand, this method of testing causes much confusion and consternation and consumes many man-hours troubleshooting incorrectly set up tests that mask themselves as problems with the relay.

Benefits of automated impedance plotting are that many tests can be run in a short amount of time and data are presented in a graphical format to quickly verify that the relay responds correctly to every test point. Maximum torque angle can be visualized quickly and any errant test points are plainly obvious. Depending on how many points are tested, this test method may take anywhere from a few minutes to 10 minutes, analyzing the data in a matter of seconds with a quick glance. Tests are usually performed on each phase of each zone of protection for phase, ground, and quad elements. The average time to complete characteristic tests on the multiple impedance elements (typically 12 to 24) of a microprocessor-based relay is about 2.5 hours.

Drawbacks to automated impedance testing arise from the fact that it is a complex test with lots of variables. Depending on the relay settings, adjustments may have to be made to get correct results. It is crucial for relay testers to familiarize themselves with the behavior and workings of automated test macros to avoid many hours of unproductive experimenting at the test site. The fact that the test is an automatic one does not mean that we do not have to put careful thought and planning into its successful execution. When a macro does not achieve expected results, a manual test should be run to verify relay operation. Troubleshooting should progress from that point using logic diagrams for the distance element being tested. Relay instruction manuals show the permissive and blocking elements required to achieve operation of the element in the form of logic diagrams.

Many times, the relay operates mostly as expected except for a single or few apparent errant points on the plot. In most cases, the problem is with the test, not the relay. Lets take a look at some of these common errors. Fig. 1 shows a plot of a phase-to-ground mho element that is truncated as it approaches the origin. This anomaly shows up quite often as a result of testing a relay with a settable impedance-based directional element with the incorrect system voltage for those directional impedance settings. The directional element limits the operation of the impedance element for faults that fall below the negative- or zero-sequence limitation. The relay needs to see faults that exhibit a higher source-impedance ratio because the directional element was set with knowledge of the source impedance as well as the line impedance.

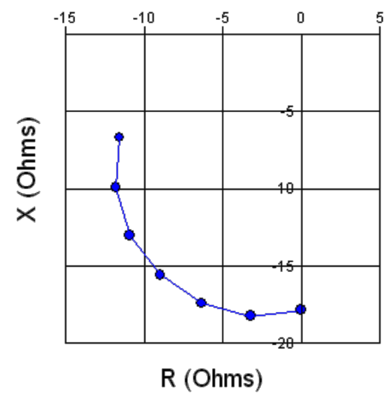

Fig. 1. Zone 3 reverse plot at 50 volts with negative-sequence impedance directional element set at +8 ohms

Microprocessor-based relays tend to out smart the relay tester as they have more knowledge of the system than the tester typically has on hand. The simple answer to achieve a correct-looking characteristic is to retest at a lower voltage that will provide a larger source-impedance ratio for the faults being simulated. The plot in Fig. 2 shows that the test voltage should be reduced even further to allow the full mho characteristic to be plotted. Fig. 3 shows the same Zone 3 distance element with revised directional element impedance settings of 0.1 and –0.1 ohms of negative-sequence impedance. These settings make the directional element operate in a more conventional manner.

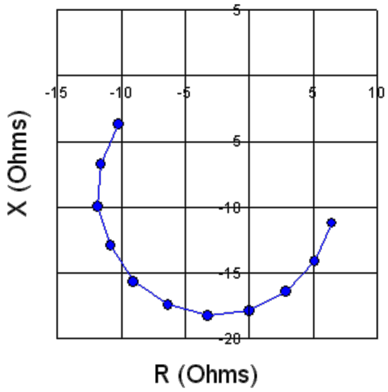

Fig. 2. Zone 3 reverse plot at 30 volts with negative-sequence impedance directional element set at +8 ohms

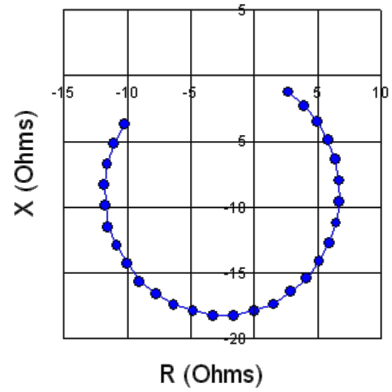

Fig. 3. Zone 3 reverse plot at 30 volts with negative-sequence impedance directional element set at +0.1 ohms

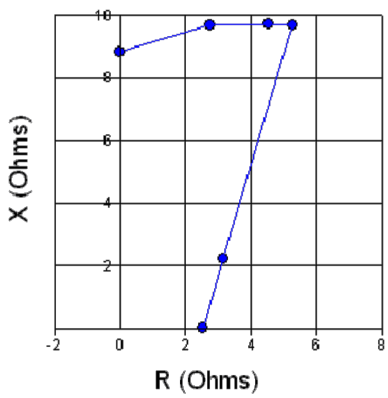

Fig. 4. Confusing plot of quad characteristic

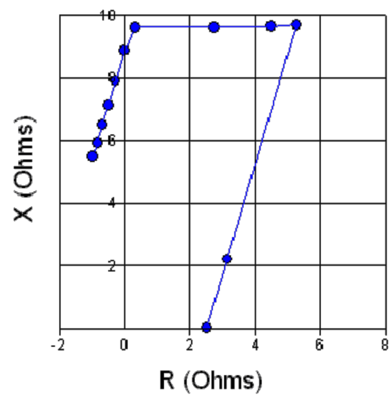

Fig. 5. Quad element retest with additional test points resolves confusion

The plot in Fig. 4 is from Brayton Point Substation in Fall River, Massachusetts. The relay tester used an impedance macro to plot a quad characteristic. The characteristic appears to have an errant test point at the 90-degree point. After much discussion and investigation, it was determined that the relay had very short resistive reach, causing the left-hand blinder to intersect the positive Y axis on the plot instead of the top blinder as we usually expect. This confusion could have been resolved rather quickly by adding more test points to the macro to find the corner of the characteristic. A revised test with more test points shows a better picture of the characteristic (Fig. 5).

D. Directional Tests

It was shown in the previous section that a settable impedance directional element could affect the results of impedance plots and reach tests. In this section, we will discuss how to isolate and test this element. The benefit of directional testing is that it will create a better understanding of how it affects the impedance element and directional overcurrent elements in the relay. The drawback is that the test is redundant because the directional element is part of the overall zone distance logic in most relays.

Settable directional elements have impedance thresholds that can be tested. If a setting is positive, the impedance threshold, whether forward or reverse, will be tested as a reverse fault. If a setting is negative, the impedance threshold, whether forward or reverse, will be tested as a forward fault. Results are normally expressed in negative- or zero-sequence ohms depending on the element type.

To get a better intuitive understanding of the nature of these directional elements we can plot them in the positive-sequence plane. Figs. 6 and 7 plot the results of tests on settable impedance directional element characteristics in the positive-sequence plane. The test plots the effective positive-sequence impedance at equal intervals between 0 and 359 degrees. The set impedances are both positive, with 0.1 ohm separation. These settings tell the relay that the fault duty is higher in front of the relay than behind the relay. The low-impedance forward threshold in Fig. 6 appears as a slightly curved line, offset in the reverse direction due to the setting of +8 negative-sequence ohms. This offset in the reverse direction is a result of applying incorrect system voltage for the test. This effect was seen as a truncated mho element in the previous section (Figs. 1 and 2).

The reverse plot in Fig. 7 shows the minimum sensitivity of the directional element. The reverse maximum threshold cannot be found using forward fault tests because it is also offset in the reverse direction, not encompassing the origin. A different test macro would be needed to find the low-impedance threshold portion of the reverse directional element.

In Figs. 8–11, additional impedance plots of directional elements are shown to illustrate possible combinations of directional element settings and resulting impedance characteristics.

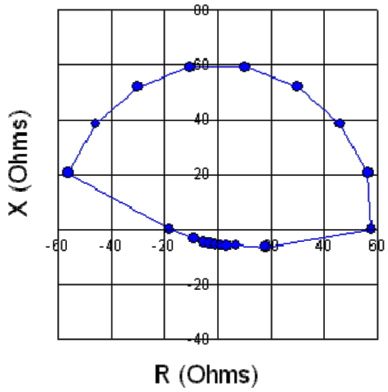

Fig. 6. Plot of forward settable impedance directional element threshold

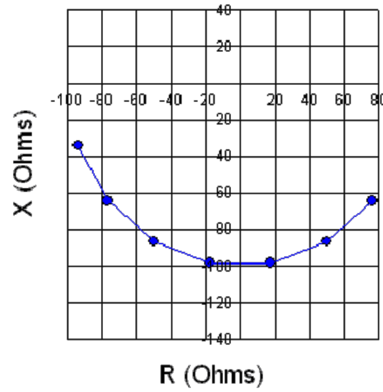

Fig. 7. Plot of reverse settable impedance directional element threshold

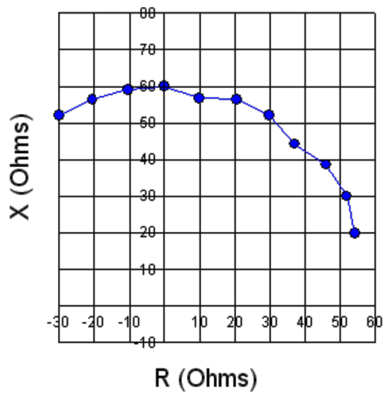

Fig. 8. Forward impedance plot with –2 ohms setting

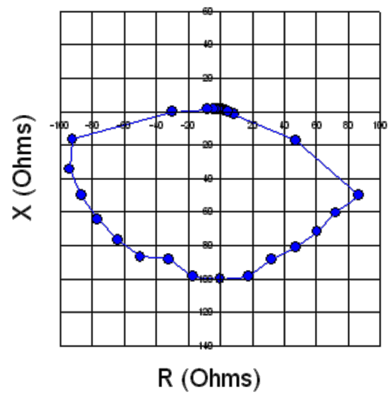

Fig. 9. Impedance plot of reverse directional element at –1.9 ohms

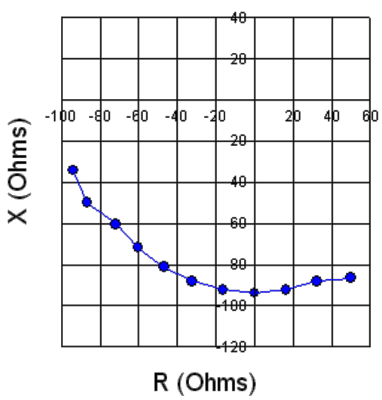

Fig. 10. Reverse directional impedance plot at 2 ohms

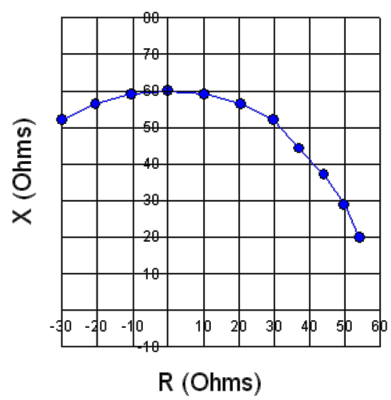

Fig. 11. Forward directional element impedance plot Z2F = –2 ohms

Figs. 8–9 show the case of both forward and reverse thresholds set negative, telling the relay the fault duty is higher behind the relay than in front of the relay.

Figs. 10–11 show the case of the forward threshold set negative and the reverse threshold set positive, telling the relay the fault duty is symmetrical.

E. Logic Testing

Microprocessor-based relays have evolved to provide full Programmable Logic Controller (PLC) capability. Relays are now being programmed to provide complex control tasks based on system conditions. For this reason, logic is the number one most challenging thing to test in a relay. It can be difficult, or sometimes impossible, to simulate the correct system conditions in the precise timing needed to test a scheme. Substation safety considerations and working environment often make logic scheme testing of in-service relays even more impractical. Testing of complex logic may have to be performed with a spare relay on a test bench. Another option is computer simulation of logic with special programs available, in some cases, with relay programming software (Fig. 12).

When testing logic, keep in mind inherent timing delays associated with the following:

- Processing intervals—know what the processing interval and element processing order is for a given relay
- I/O processing time and mechanical time of contacts
- Effect of digital filter on processing voltages and currents

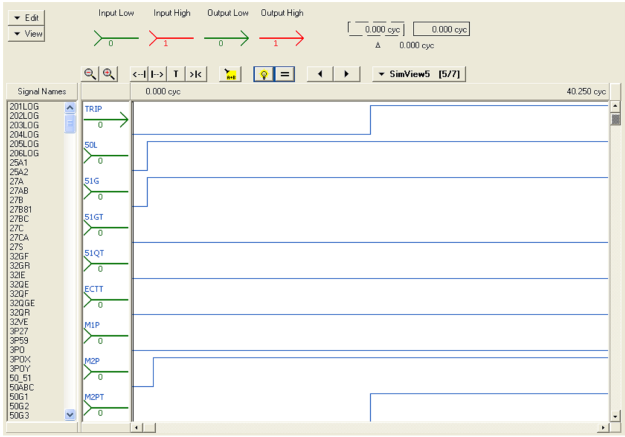

Fig. 12 Computer-based relay logic simulator

As an aid to testing schemes that cannot be fully replicated in the field, internal timers, control bits, and latches can be used. Inputs, voltage, and current elements can be simulated with these internal functions (Fig. 13).

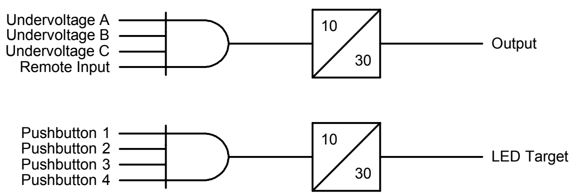

Fig. 13 Relay pushbuttons used to simulate relay elements

F. Reclosing Tests

Reclosing can be a complex and difficult thing to test. Relays are now so sophisticated that the precise sequence-of-events must be simulated to assure a correct test (Fig. 14). One challenge is to correctly simulate the breaker status input on the relay. When the status does not change at the precise time the relay expects, in many cases, the relay will consider it an improper operation of the breaker and proceed to lockout. For this reason, it is best and easiest to do a full-functional reclosing test, allowing the breaker to cycle. The downside is that it puts wear and tear on the breaker. If the breaker is in service, it would have to be bypassed, placing system protection in an abnormal state in many instances.

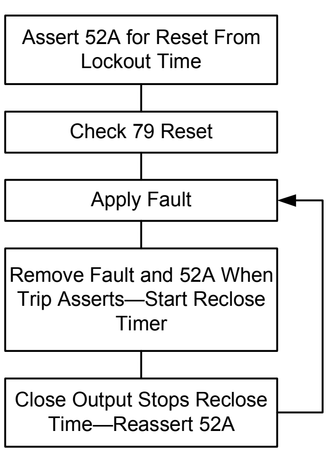

Fig. 14 Flow diagram for recloser test

Breaker status can be simulated using a state simulation macro test. Thought must be put into each state created, replicating the expected state of the breaker correctly at every instant. For example, if the breaker state goes closed before the close signal is outputted by the relay, it will assume another device performed an incorrect operation and drive the recloser into the lockout state. In the past, electromechanical latching relays have been used to simulate the breaker (Fig. 15), but it takes a lot of time to wire everything and can be too much work in a two-breaker scheme.

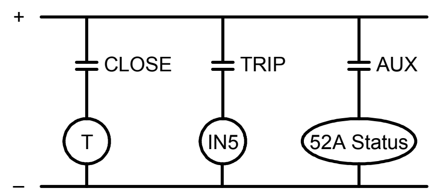

Fig. 15 Hardwire latching relay to simulate breaker status

Recently, it has become popular to use a spare internal latch in the relay to simulate the breaker contact (Fig. 16). This works very well but involves changing the relay settings to a state that would be incorrect for normal system operation. If available, an unused settings group should be used for this simulation so there is less chance that a temporary change to an in-service relay would be forgotten before it is returned to service.

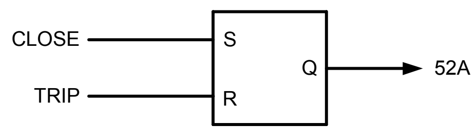

Fig. 16 Internal latch simulates breaker status

G. Overcurrent Element Tests

Overcurrent testing is normally very easy and straightforward, consisting of pickup and timing tests. In programmable relays, the pickup and time function will have separate programming bits. These bits can be isolated to a contact and tested separately, or the test can be performed by visualizing the internal targets without any program change. Reporting features in the relay make it possible to internally test the timed element if no test-set timer is available.

The relay tester should take a glance and double check that the proper bits are assigned to tripping, as this is a common source of error and overtripping. Assure the timed tripping bit is programmed in the trip equation rather than the pickup bit. When testing an inverse-time overcurrent element, pay close attention to the specification for the element. In many cases, the specification gives a percent error to expect with an additional definite-time error (e.g., plus or minus three percent and plus or minus one cycle). When testing inverse-time overcurrent elements at high multiples of tap, the additional definite-time error plays a significant role in overall error and must be included in overall error calculation to properly evaluate the element (Fig. 17).

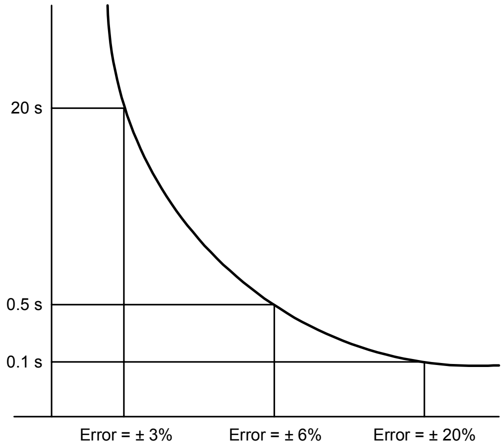

Fig. 17 Percent error increases on fast portion of curve

Take notice of any directional supervision as well as torque control of the overcurrent element. An element may be forward only and have an additional programmed torque control equation that must be satisfied to allow the element to time and trip.

Because of the relative ease with which overcurrent elements can be tested manually, it is recommended that automated plans not be used because more time can be consumed troubleshooting the test plan than would have been taken by the manual tests.

H. State Simulation Tests

State simulation tests can sound intimidating to most testers, but, in reality, they are simple, understandable tests that are easy to set up. State simulation is exactly that, a semi-accurate simulation of a fault on the primary system. The simplest test plans have three timed snapshots of voltage and current applied to the relay in succession. The first state is system normal voltage and load current applied to the relay just long enough to satisfy memory polarization and let the relay stabilize. The second state applies the fault simulation of voltage and current, and the third state simulates the conditions following opening of the breaker. The state simulation is a very simple and true way to test because it closely approximates actual fault conditions that the relay will experience in service.

Fault values can be calculated based on the reach of the relay in secondary ohms, using simple hand calculations. There are also computer-based programs that will quickly perform more rigorous calculations based on relay reach, with settable source-impedance ratio and ground fault impedance. It only takes a few seconds to enter the relay impedance data and enter the test values directly into the state simulator. If current test values exceed the capability of the test set, simply enter a higher source-impedance ratio. The source-impedance ratio is simply related to the relative strength of the fault (e.g., a one-ohm three-phase fault can be 30 volts/30 amperes or 10 volts/10 amperes). The second value easily falls within most test set capabilities. The third and most accurate way to simulate a fault using this method is to take primary values directly from a system fault analysis program, scale those values for secondary inputs, and apply to the relay. This can sound intimidating but merely involves dividing voltages by the VT (voltage transformer) ratio and currents by the CT (current transformer) ratio. This method ensures the applied values are realistic for the protected system.

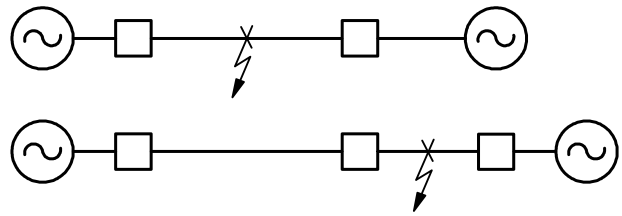

Fig. 18 Calculate fault voltages and currents for on- and off-section faults

I. End-to-End Tests

End-to-end testing takes state simulator testing to the next level, creating the most comprehensive testing possible on an installed relay system. Testing is performed simultaneously at each end of the line using time-aligned state simulation macros. Fault values are normally taken from computer-based fault analysis programs, as described in the previous section, for each end of the line. This most accurately simulates a true fault-system condition with actual different and independent contributions from each end of the line. If actual fault numbers are not available, values can be hand calculated or taken from a generic computer-based program that has no knowledge of the system. Test sets are connected to a satellite-synchronized time source to initiate the fault simulation precisely at the same point in time at each end. From the relay's standpoint, it is seeing nearly exactly what it would see for a real system fault. This tests the whole relay system, including the communications channel, as a single unit, ferreting out any potential problems in the complete hardware, logic, and settings chain. Figs. 19–20 show actual end–to-end tests for an underwater cable connecting Cape Cod to Nantucket island.

	Default		State 2		State 3	
	Ampl	Phs	Ampl	Phs	Ampl	Phs
	115	0	0	-13	115	0
	115	-120	0	-133	115	-120
	115	120	0	107	115	120
	1	0	13.12	109	0	0
	1	-120	13.12	-11	0	0
	1	120	13.12	-131	0	0
First State Type						
Go At						
Max Duration:	60	Cycles	120	Cycles	10	Cycles
L/R Time:	0	L/R mSecs	0	L/R mSecs	0	L/R mSecs
Trigger/Event:						
	Default		State 2		State 3	
	Ampl	Phs	Ampl	Phs	Ampl	Phs
	115	0	63.9	-13	115	0
	115	-120	63.9	-133	115	-120
	115	120	63.9	107	115	120
	1	0	13.6	-71	0	0
	1	-120	13.6	169	0	-120
	1	120	13.6	49	0	120
First State Type						
Go At						
Max Duration:	60	Cycles	120	Cycles	10	Cycles
L/R Time:	0	L/R mSecs	0	L/R mSecs	0	L/R mSecs
Trigger/Event:						

Fig. 19 End-to-end through fault test

	Default		State 2		State 3	
	Ampl	Phs	Ampl	Phs	Ampl	Phs
	115	0	110.9	-3	115	0
	115	-120	116.1	-121	115	-120
	115	120	114.8	121	115	120
	1	0	.3	7	0	0
	1	-120	.1	-169	0	-120
	1	120	.22	-174	0	120
First State Type						
Go At						
Max Duration:	60	Cycles	5	Cycles	10	Cycles
L/R Time:	0	L/R mSecs	0	L/R mSecs	0	L/R mSecs
Trigger/Event:						
	Default		State 2		State 3	
	Ampl	Phs	Ampl	Phs	Ampl	Phs
	115	0	113.9	-2	115	0
	115	-120	114.8	-120	115	-120
	115	120	114.3	120	115	120
	1	0	1.15	-7	0	0
	1	-120	.09	7	0	-120
	1	120	.22	4	0	120
First State Type						
Go At						
Max Duration:	60	Cycles	5	Cycles	10	Cycles
L/R Time:	0	L/R mSecs	0	L/R mSecs	0	L/R mSecs
Trigger/Event:						

Fig. 20 End-to-end high-impedance internal fault test

Normally, special software and a satellite clock compatible with the test set are needed to perform end-to-end tests. In cases where two test sets are available but are not capable of time-synchronization, some relay-compatible satellite clocks can be programmed to provide output contact pulses on the one minute or half minute mark that can easily initiate the test set. With this method, the installed clock that provides an IRIG-B signal to the relay operates double duty and also initiates the test set. Because custom clocks and software are not involved, the test sets could be different models or different manufacturers.

The communications channel could also be used to initiate the remote test set in a semi-time-aligned test. This type of test can be used for pilot tripping schemes where tolerances of one-half cycle to one cycle are acceptable, but this test is not suitable for current differential or phase comparison systems. Set one test to initiate a state simulator test, keying a contact on initiation. With the receipt of the signal, that contact keys the communications channel, closing a contact to initiate the test set on the other end. Set the master to time for a few extra quarter-cycle increments based on the one-way channel time, input recognition time, and output contact time at the receiving end.

Benefits to end-to-end testing are numerous. The end-to-end method tests the whole relaying system as a unit. There is more chance that a problem will be uncovered this way rather than in piece-wise testing. Communications scheme timers are very critical to maintain security while, at the same time, pushing the total clearing time as fast as it can be. End-to-end testing can be used to try different channel settings until a good compromise is reached, rather than making educated guesses. Definitive testing of such systems requires the use of synchronized test sets. Testing the communications channel separately and estimating processing intervals and I/O times will not be as accurate as actually testing everything together as a unit.

Some types of settings errors will become evident with this testing method. Targets and event reports should be gathered and analyzed to make sure the system provides the results that were expected. Settings errors have been found using this method of testing, but settings enhancements have been made as well. Results have allowed engineers to rethink philosophy when simple targeting was different than expected.

A drawback to end-to-end tests is that two crews are needed to perform the tests. The two crews must be in constant communication to coordinate tests. Some time and effort is needed to create custom test plans from fault program data, so more engineering time is required as well.

J. Manual Testing

Ten to twenty years ago, everyone tested relays manually. Today some utilities rely only on fully automated test plans, but other utilities test everything manually. There is certainly nothing wrong with some manual testing, but the down side is that very beneficial state simulation and end-to-end tests can not be performed with a manual-only testing philosophy. Manual tests keep the skills of the relay tester sharp by giving them a better intuitive feel for how the relay elements work. Some relay testers have started to forget the basics because they rely on the computer too much. Computer-based testing software includes a manual-test window where voltages and currents can be manipulated directly (Fig. 21). Most elements in a protective relay can be tested in this way. A manual test should be performed as a double check when an automated test does not provide expected results.

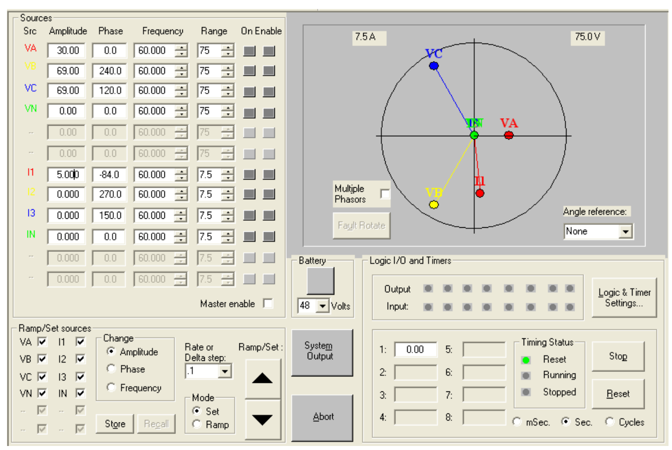

Fig. 21 Manual test using a computer

K. In-Service Tests and Checks

In-service checks are very important components of relay system testing that have been neglected over the years. There have been many problems that could have been avoided with just a few simple checks after the relay goes into service. Many hours of tests can be performed using the most modern and sophisticated test equipment, but there is still a need to perform a few minutes of data recording and analyzing to perform checks that are not done by previous testing.

Meter checks will confirm proper system rotation and RMS quantities present in the relay. A CT that is on the wrong ratio or performing improperly will be immediately evident. In the same way, voltage transformers (VTs) are immediately checked to see that they provide expected rotation and voltage at the relay. An overburdened or improperly calibrated VT will be easy to detect. The example in Fig. 22 shows a system with ABC rotation. High negative-sequence voltage and current quantities, along with very low positive-sequence quantities, flag an incorrect phase rotation setting in the relay.

```
                   Phase Currents
               IA        IB        IC
I MAG (A)   2204.87   2200.18   2209.18
I ANG (DEG)  59.42    -60.79    179.05

                   Phase Voltages                 Phase-Phase Voltages
               VA        VB        VC        VAB       VBC       VCA
V MAG (kV)  69.015    69.007    69.055   119.564   119.56    119.544
V ANG (DEG)  29.15    -90.90    149.11    59.12    -60.89    179.12

                 Sequence Currents (A)          Sequence Voltages (kV)
               I1        3I2       3I0       V1        3V2       3V0
MAG          2.127    6614.2    20.137     0.003   207.077     0.097
ANG (DEG)  -157.35     59.22    133.40    122.68    29.12     137.36
```

Fig. 22 In-service meter check—sequence components flag problem

Target checks should also be made. A record of all internal elements in the relay should be saved for immediate and future analysis. Are asserted elements expected? Are there any asserted elements that were not expected? Logic, wiring, and some settings errors can be detected quickly by taking a few minutes to record these data.

For the initial operating period, event and sequence-of-event triggers should be programmed to collect as much data as required to determine proper operation or inoperation of elements during system events on remote and adjacent sections. Check the relay frequently for these data and look at them right away to head off any potential problems. For assistance, send the data to experts that have seen many relay events. The industry needs to improve as a whole in this area. Better to put work in up front than to be scrambling to analyze why a system that was not working as expected caused an outage or equipment damage at two o'clock in the morning.

L. Communications Tests

Testing a communications channel is very important in pilot-based protection schemes. Channel time and I/O time must be known so that overreaching zone short-time delays can be set properly in Directional Comparison Blocking (DCB) schemes or echo back wait times in Permissive Overreaching Transfer Trip (POTT) schemes.

Microprocessor-based relays have powerful reporting features that can be used to perform communications validation and timing tests. A simple keying of a carrier can be recorded in an event report. The event report can be programmed to show when the communications channel was keyed and echo back a signal received if applicable. The event report feature at one end is set to trigger based on the input from the communications equipment. The receive output at the remote end is temporarily jumpered to the transmit input to echo the signal back with no time delay (Fig. 23a). The loopback can also be made using temporary internal relay logic reassignment (Fig. 23b). The round-trip communications time can easily be determined by inspecting the event report and counting the fractions of cycle from the transmit assertion to the receive of the signal. Some relays also have sequence-of-event (sometimes called SOE or SER) reporting that can be used in a similar manner.

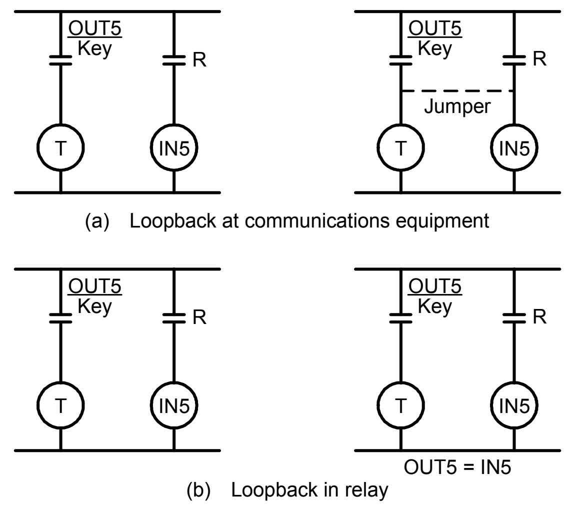

Fig. 23 Loopback timing test

M. CT and Voltage Potential Device Testing

Often times, relay system testing excludes important devices such as CT and voltage potential devices. If these elements of the system do not perform accurately, even the best performing relays will not be able to do their job properly. CT ratio and excitation tests should be performed and wiring double-checked for errors. New voltage devices can be compared against existing ones to double check secondary voltage ratios. Simple meter tests flagged a problem with voltage potential devices at Brayton Point substation. Recalibration of the potential devices prevented a potential relay system misoperation.

N. Synchronized Phasor Measurements

Recently there have been significant new developments in microprocessor-based relays that revolutionize the way we perform testing. Synchronized phasor measurements are timestamped magnitude and phase angle voltage and current metering. This measurement system was conceived and designed to analyze system stability in real time, providing streaming meter data over various communications media to a control scheme or system operators so corrective action can be performed before the system becomes overstressed. It turns out that this measuring system is a very useful tool for relay-system testing to the extent that we recommend that the synchrophasor feature be enabled expressly for commissioning and ongoing monitoring.

Synchronized phasor measurements can be accessed with simple meter commands in the relay. The meter command is sent to each individual relay at a specified future time in much the same way that satellite-synchronized tests are performed. For instance, if the present time is 12:00, the phasor measurement command could be specified at 12:02 on each relay from a computer. At 12:02 all the relays will take a measurement at exactly that instant. This allows us to perform metering checks with all phase angles based on a common universal reference. There are many important checks that can be performed using this simple procedure and more are being devised as this technology proliferates.

Previously we discussed the importance of performing tests and checks on voltage and current transformers. A perfectly calibrated and correctly set relay cannot perform its task accurately without properly functioning instrument transformers. Synchronized phasor measurement commands should be issued on each relay at the substation and at opposite line ends. Any unintentional phase shift between voltage transformers on the same bus or between line ends can quickly and easily be seen, and further action or investigation can be taken. Currents entering and leaving a bus can be summed as a quick and easy health check of current transformers.

Before placing a generator online for the first time or after major repair, synchronized phasor measurements should be used to check proper phase rotation. If using a single-phase voltage transformer on one side of the relay, it is possible to appear to be in synchronism even when there is reverse phase rotation on one side. Checking the three-phase voltages and phase angles at the local and remote ends of the line simultaneously with a synchronized phasor measurement command prevents costly mistakes. It only takes a minute or two to perform this test that can be performed by a single person at either relay if a relay-to-relay communications pilot scheme is installed.

Most relays today are set based on calculated conductor impedance and estimated ground impedance. How close are those values to actual? If they are off by ten percent, then our zones of protection will be inaccurate by the same amount. Synchronized phasor measurements allow us to calculate the actual line impedance based on the three-phase voltage and current magnitude and angle at each end of the line when the line is loaded. More accurate settings are another step towards preventing underreach or overreach of protection zones resulting in an improper operation.

The next step in ongoing system monitoring is to set up a computer-based collection center for synchronized phasor data. When a fault or abnormal condition occurs, such as an overload, the collection software is triggered to capture data from many relays across the system. This gives a graphical view of fault voltage and current infeeds from various points on the system, providing a better way to evaluate the condition of your system. Sampled values can be compared to fault, load flow, and state estimator models; then corrections can be made as necessary.

The best, most effective testing is performed under real-world varying system load and fault conditions. Synchronized phasor measurements are emerging as a testing methodology to accomplish this task quickly and easily.

III. Other Tests and Testing Factors

A. Relay-Assisted Testing

The microprocessor-based relay provides the relay tester with many aids for testing and for troubleshooting tests. The meter report verifies proper test set connections. Target information provides instantaneous indication of internal relay element status. When troubleshooting a test, target information combined with relay logic drawings provide feedback to the tester to quickly determine problems with test plans. SER information provides valuable information when testing complex logic. Relay elements can be internally timed using SER information if the relay tester does not have an accurate means of measuring time. Event reports can be triggered to obtain a snapshot of the applied current and voltage along with the sample-by-sample status of all internal relay elements, inputs, and outputs.

B. Discrete Element Versus Combined Element Testing

The practice of programming a single relay element to a contact to isolate and test only that element has been very popular. This practice makes it very easy to build a test, whether automated or manual, without having to carefully plan to operate only the intended element. There are some advantages to testing the relay with its actual in-service tripping contact settings. The biggest reason is that there have been many errors in trip contact programming that have caused some overtripping in the past, so some quick testing and inspection will quickly make mistakes obvious. Custom logic settings that test fine independently may not work properly because of errors when being combined in a tripping equation. Any settings errors with trip latch programming will also be found. Some testing of the relay output with the actual in-service programming should be considered.

C. Firmware Upgrade Tests

Many companies perform a complete new battery of tests whenever relay firmware is updated. This practice is mainly a precaution and gives the user an extra level of comfort retesting an already proven system. There is no need, however, to repeat the test on every relay of the same type being upgraded with the same firmware level. Performing redundant testing takes away from time needed to do other important things such as retrieving and analyzing data from the relay and performing basic meter and I/O tests.

D. Relay Test Quantities

Typically, a tester chooses a voltage at random and calculates the current based on that voltage and the relay reach in secondary ohms. As discussed before, the newer settable impedance directional elements will make their directional decision based on the ratio between the system source and line impedance. It then becomes more important to pick realistic test values that more accurately replicate the voltage and current the relay will see under actual fault conditions.

Engineers should think about getting more involved in the testing process to help the relay tester with creating test values. The engineer typically creates settings based on numbers generated by a computer-based fault analysis program. It would not take much more effort to create realistic test plans based on these same numbers. A side benefit is that the test then provides a basic level of affirmation of your settings.

E. Test Set Capability

Relay test sets have evolved greatly, most of which have the capability to run automated tests from software operating on a computer. This allows the user to perform more sophisticated testing, much of which was discussed earlier. Older, less sophisticated test equipment will serve quite well in the performance of manual testing, the merits of which have been touted earlier in the paper. When selecting older test sets, be sure that the output generates a clean voltage and current sine wave free of unintended harmonics. Be aware of any transients that may be developed when switching on or changing test quantities. Have calibrations checked when in doubt. Many of today's relays are as accurate or more accurate than some older relay test sets.

F. Static Versus Dynamic Testing

Static tests ramp the current or voltage around to find pickup points. Most manual and many automated testing macros use this testing method. Dynamic tests attempt to more accurately simulate actual system faults, placing a prefault state on the relay for a relatively long time to let the memory voltage come up to nominal and allow everything to stabilize before applying a fault state. This provides the truest response of the mho element, allowing the characteristic to expand depending on the test values used. Dynamic testing is certainly not a must but is inherent in the simpler state simulation testing macros, providing another reason to move towards this method of testing.

IV. Common Problems Missed in Testing

Relay application engineers see relay system problems from all over the United States and the world. Lets take a look at some common problems and predict which testing method would have prevented the problem.

1. Relay overtrips because wrong relay element was programmed to trip equation.

   This is a very simple and basic error but happens more often than one would think. Most times, it involves an overcurrent element with the pickup being programmed to trip instead of the timed-delayed version of the same element. Popular discrete element testing does not catch this error because the tester programs the pickup element to a spare output contact and the timed element to a spare output contact, testing each individually with correct results. Testing the relay with its in-service logic would probably have allowed the tester to find this mistake.

2. Failure to wire breaker status contact to relay causes overtrip on POTT scheme.

   The relay expected a 52A status contact to be asserted. Under lightly loaded conditions, the current detector did not declare the breaker closed, causing the relay to go into switch-onto-fault (SOTF) mode where it stayed until the out-of-section fault triggered the SOTF, tripping the breaker. Simple relay target verification and recording the in-service test would have led the relay tester to ask why the breaker was not showing closed after being placed in service.

3. Wrong relay elements in DCB scheme program cause relay to overtrip.

   Instantaneous versions of tripping bits were used in communications logic instead of short time-delayed versions. This settings error was found during satellite-synchronized testing of a three-terminal line in the eastern United States.

4. Incorrect logic settings disable sensitive instantaneous overcurrent element during a hot-line order condition on the line.

   A simple manual test of in-service settings would have flagged this error. End-to-end testing also may have found the logic error.

5. Incorrect directional element impedance setting causes DCB scheme overtrip.

   Directional element setting was improper for Zone 3 reverse-looking elements. This caused a no-operation and allowed the remote terminal to trip. End-to-end testing with system fault current data would have found this settings error.

6. Incorrect phase rotation causes relay to trip.

   A simple in-service meter check to inspect for proper phase rotation and lack of high negative- and zero-sequence quantities would have prevented this problem.

7. Miscalibrated potential devices cause relay to overreach.

   A simple in-service meter check to inspect for balanced phase voltage would have prevented this problem.

8. Coupling capacitor voltage transformer (CCVT) transient causes relay overtrip.

   Download and inspection of relay events prior to trip may have warned of potential CCVT transient issue.

V. Test Method Comparison

The matrix in Table I compares testing methods discussed above. The aim is to perform tests that provide the most benefit to the system while being understandable and easy to perform and that consume a minimum of test personnel man-hours. This matrix was built by the authors and is somewhat subjective. The reader should formulate his or her own matrix with varying degrees of differences depending on testing history, experience, resources, and system. This is an important step in developing a test philosophy that works best for your company.

Without calculating any numbers, it is easy to see that meter and I/O tests should always be performed. They take very little time and provide tests of relay hardware and settings logic. In-service tests provide verification of wiring and CT and VT connections. They also provide a basic check of performance, settings, and relay logic. Overcurrent tests are quick and straightforward, providing relay hardware and firmware verification as well as a basic level of settings verification. Communications testing provides some relay logic and wiring verification but is very important in determining proper timer settings in communications schemes. It is imperative to set these timers correctly. Verifying actual times, comparing them against predicted settings, and then making any necessary changes is extremely important.

From here, it takes a bit more consideration and thought about your test capabilities, time, and personnel. Performing a battery of automated single-ended tests will provide some returns, at the cost of much greater test difficulty and time spent, as a higher proportion to results achieved. The unknown factor is how much time will be consumed in the troubleshooting of more complex test macros. At this point, a full end-to-end test should be considered as an alternative and upgrade to single-ended methods. As discussed previously, the end-to-end test provides more in the way of relay system functionality, logic verification, and settings checks. Although end-to-end tests normally require more time to set up, state simulation testing is simpler and easier to troubleshoot than many single-ended testing macros, so some gain will be realized. End-to-end testing based on system fault data provides the best test of a relaying system possible in the field.

Short of a full end-to-end test, single-ended state simulation tests based on system fault data should be considered as a compromise. These tests are also relatively straightforward, easy to troubleshoot, and still provide a good verification of relay settings in addition to hardware and firmware verification.

VI. Testing Pyramids

In an effort to consolidate and simplify the information presented in the previous section, the concept of testing pyramids, developed by the authors, is introduced here. The base of the pyramid is the most fundamental and important part of the structure, providing the foundation. As you work up to higher levels of the structure, the design becomes more intricate. These higher levels, although progressively less structurally important, provide increasing levels of sophistication that form a complete structure, making it as strong as it can be.

Relay system testing normally begins at commissioning of the substation. The testing being performed at this stage will fundamentally differ from tests performed at substation energization and from tests performed routinely through the years.

The substation commissioning pyramid foundation is I/O testing and meter tests (Fig. 24). These two tests provide the most simple, yet fundamentally important, checks on relay system health. The next level contains functional tests of reclosing and logic settings to assure the system will operate as intended. These tests are likely to uncover programming mistakes. Manual element testing should be considered before progressing to more sophisticated tests. A few manual tests will provide assurance that relay elements are performing as set before progressing to automated testing, where it can be difficult to know immediately whether there is a settings or element problem versus a problem with the test. Once assured the relay elements are picking up as expected, the preferred automated tests are state simulation tests. These tests provide a good dynamic test of relay elements going a step further in sophistication and relay element integrity verification than manual or impedance plotting tests provide. The peak of the pyramid is end-to-end tests. These more time-intensive tests will provide greater assurance that the entire line-protective system will work in harmony as a unit.

Table I
Comparison Matrix

	Time	NPT	RF	RH	SC	SL	Wiring	CT/PT	Simplicity	Total Time	Total Score
Meter and target checks	0.5	0.1	1	5	0	0	4	3	5	0.6	18
I/O contact tests	0.5	0.1	1	5	0	0	3	0	4	0.6	13
Impedance characteristic tests	2	2	3	5	1	0	0	0	0	4	9
Directional element test	1	1	2	1	1	0	0	0	2	2	6
Logic testing	2	2	4	3	0	5	3	0	0	4	15
Reclosing test	2	2	4	2	0	4	4	0	0	4	14
Overcurrent tests	0.5	0.1	2	1	1	0	0	0	4	0.6	8
State simulation tests	2	0.5	4	1	2	3	2	0	3	2.5	15
End-to-end tests	8	2	5	2	5	4	3	0	0	10	19
Manual testing	4	1	3	3	1	2	1	0	3	5	13
In-service tests	0.5	0.5	1	1	2	2	5	4	5	1	20
Communications testing	1	0.5	2	1	3	1	2	0	3	1.5	12
CT and CCVT tests	4	0.5	0	0	0	0	3	5	1	4.5	9
Synchronized Phasor Measurements	0.5	0.1	1	5	3	1	5	5	5	0.6	25

NPT = Nonproductive time
RF = Relay firmware
RH = Relay hardware
SC = Settings check
SL = Settings logic
0 = Least effective
5 = Most effective

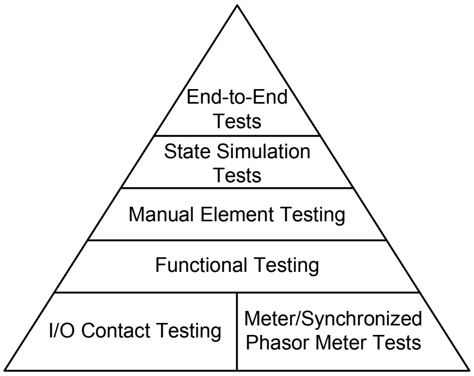

Fig. 24. Commissioning tests

The next progression in the testing sequence on a new installation are those tests that will be performed immediately after energizing the substation or line section (Fig. 25). This is a segment of testing where, typically, not enough has been done. We need to take a fresh look to see what else can be done in this area because there is much potential to avert improper operations by spending a little time performing basic checks and tests and reviewing reports the modern relay provides to the user.

Again, we begin with a meter test or check. This assures proper CT and VT connections as well as proper functioning and calibration of those devices. Relay target checks will verify proper breaker statuses and show that the expected relay internal elements are asserted or nonasserted, depending upon system conditions. In-service testing and checking should not end here. Keep a close watch on the relay system to notice if any reports are generated, and retrieve and inspect those reports as soon as is practical. The relay system is providing feedback to the user/operator that must not be ignored. Get help in analyzing data if needed.

The final and ultimate piece of the in-service testing pyramid is to create COMTRADE files from relay event reports and use a spare relay to play back those files. This is very beneficial when an unexpected operation occurs but can also prevent any future unexpected operation, or nonoperation when operation is expected, by repeating the fault with a variety of slightly different settings applied to the test relay.

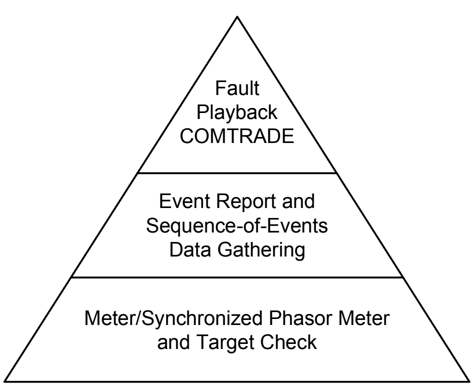

Fig. 25. In-service tests/checks

Routine testing (Fig. 26) is another segment of testing that could use some "overhauling." Most power suppliers use the same testing program for routine testing that is used for their commissioning tests. Microprocessor-based relay elements do not change their characteristics over time as electromechanical relays do. As long as the input section is operating within specification, the relay elements will perform to specification as well. A simple meter calibration test is sufficient to prove all relay elements will perform as they did in the commissioning test. There is no need to repeat hours and hours of relay element tests on a routine basis.

I/O tests are very important in routine testing. Contacts will wear over time and that wear will be accelerated if there is a problem or misapplication. Inputs can be damaged by transient overvoltages and lightning.

Relay status checks are very important. The microprocessor-based relay will provide information that tells the user far in advance that there is a problem developing before the problem degrades into a failure.

Finally, end-to-end tests can be performed on lines that have never had the test done before in the pursuit of improving total clearing time or making an existing relaying system that has had some overtripping more secure. The time to do these tests comes from eliminating single-ended relay element tests that are normally repeated every routine testing interval.

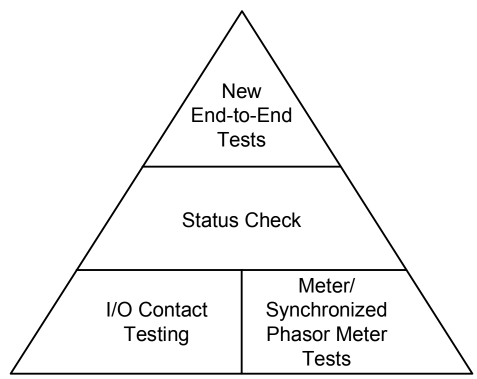

Fig. 26 Routine tests

VII. Training

Unfortunately, over the past several years, training has not been emphasized in the electric industry. There are many testers using sophisticated test sets who have little understanding of how automated tests are performed behind the scenes. Pushing the "go" button on an automated test and crossing your fingers is not a recipe for success. There is much need for the relay tester to receive testing training, whether formal or self-taught. A three-pronged approach to training will go a long way towards providing more success and productivity.

1. Learn how your automated tests work.

   Consider taking a course on automated testing. If that is not possible, dedicate some time to practice these tests with relays set up in your shop. This is the place to practice, experiment, and learn how the tests work by doing them, not in the field with a commissioning deadline looming. Call your local application engineer and discuss your results.

2. Learn how to manually test your relays.

   Practice manual tests. This is the best way to learn how relay elements work and get an intuitive understanding. Practice hand calculations and memorize basic formulas. Write them down in your notebook. Manual tests will always be your fallback position when any automated test does not produce expected results. Make it a habit to perform a few manual tests as a double check of automated tests every time you perform testing. This is common practice for engineers when performing fault studies. Never blindly trust numbers being provided by a computer or by someone else.

3. Sharpen your troubleshooting skills.

   Half of relay testing is troubleshooting when your results are not as expected. Think ahead of time about what course of action to take when things go wrong. Develop troubleshooting flowcharts to aid you when testing under-the-gun in the field. Simple troubleshooting flowcharts, such as the one in Fig. 27 for testing a distance element, will save you time looking through instruction manuals.

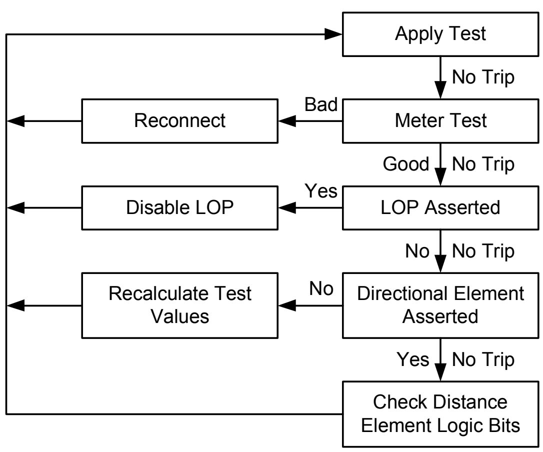

Fig. 27 Develop simple troubleshooting flowcharts to save time in the field

VIII. Conclusion

The question is, which tests should be performed? The answer will depend on time and resources available and how important the transmission system is. The number of tests and effort expended varies widely throughout the industry. The system owner will have to decide their level of commitment and work their way up the testing pyramid until they are satisfied the system is problem free and reliable, as well as secure. If the system is the first of a kind, extra effort should be expended in the testing process. If the same system has been installed many times, tests that have proven to be beneficial should be retained while weeding out redundant tests and tests that did not uncover problems.

Commitment does not end after the system goes in service. The relay system should be checked frequently during the first months for data and those data analyzed to provide confirmation of viability. This allows personnel to become familiar with the system and reporting features before the first fault occurs. Unexpected event report triggers should be examined closely to determine if the relay is close to operation so that settings changes can be made, if necessary. Unexpected operations can be replicated by using spare relays for playing back COMTRADE files to understand what happened and to see how settings changes would have improved system response.

Routine tests and analysis of relay report data should be performed. Routine tests should be weighed towards testing of the analog section of the relay, discrete inputs, and output contacts. Relay events and SER reports provide invaluable data to evaluate the performance of your protection system. Replace reoccurring automated tests with end-to-end tests if they have not been performed previously.

Microprocessor-based protective relays provide many tools that relay test personnel can and should make use of for commissioning, in-service testing, and routine testing. Relay self-tests alert system dispatchers immediately of problems so relay technicians can take quick action. Ongoing collection and analysis of event reports allows the relay system to be tuned, enhancing both security and dependability. These benefits of microprocessor-based relaying have quickened their proliferation in the industry.

IX. References

[1] Z. Zhou, X. Shen, D. Hou, and S. Chen, “Analog Simulator Tests Qualify Distance Relay Designs to Today’s Stringent Protection Requirements,” presented at the 32nd Annual Western Protective Relay Conference, Spokane, WA, October 2005.

[2] J. Roberts and E. O. Schweitzer III, “Analysis of Event Reports,” presented at the 16th Annual Western Protective Relay Conference, Spokane, WA, October 1989.

[3] R. Moxley, “Analyze Relay Data to Improve Service Reliability,” presented at the 30th Annual Western Protective Relay Conference, Spokane, WA, October 2003.

[4] J. J. Kumm, E. O. Schweitzer III, and D. Hou, “Assessing the Effectiveness of Self-Tests and Other Monitoring Means in Protective Relays,” presented at the PEA Relay Committee Spring Meeting, Matamoras, PA, May 1995.

[5] D. Hou and J. Roberts, “Capacitive Voltage Transformers: Transient Overreach Concerns and Solutions for Distance Relaying,” presented at the 22nd Annual Western Protective Relay Conference, Spokane, WA, October 1995.

[6] S. E. Zocholl, “Current Transformer Accuracy Ratings.” [Online]. Available: http://www.selinc.com/techpprs.htm

[7] S. E. Zocholl and D. W. Smaha, “Current Transformer Concepts,” presented at the 19th Annual Western Protective Relay Conference, Spokane, WA, October 1992.

[8] M. Thompson, “Integrated Protection and Control Systems With Continuous Self-Testing,” presented at the 52nd Annual IEEE Pulp and Paper Industry Conference, Appleton, WI, June 2006.

[9] B. Fleming, “Negative-Sequence Impedance Directional Element,” presented at the 10th Annual ProTest User Group Meeting, Pasadena, CA, February 1998.

[10] J. J. Kumm, M. S. Weber, E. O. Schweitzer III, and D. Hou, “Philosophies for Testing Protective Relays,” presented at the 48th Annual Georgia Tech Protective Relaying Conference, Atlanta, GA, May 1994.

[11] J. J. Kumm, M. Weber, D. Hou, and E. O. Schweitzer III, “Predicting the Optimum Routine Test Interval for Protective Relays,” presented at the IEEE/PES Summer Meeting, San Francisco, CA, July 1994, 94 SM 426-7 PWRD, © 1994 IEEE.

[12] C. Labuschagne and N. Fischer, “Relay-Assisted Commissioning,” presented at the 32nd Annual Western Protective Relay Conference, Spokane, WA, October 2005.

[13] D. Costello, "Understanding and Analyzing Event Report Information," presented at the 32nd Annual Western Protective Relay Conference, Spokane, WA, October 2005.

[14] J. Littman and B. Ryan, "Satellite Synchronized End-End Testing on Transmission Line Protection Schemes, Including Recent Field Experience," presented at the 21st Annual Western Protective Relay Conference, Spokane, WA, October 1994.

[15] J. Koehler, D. Marble, and J. Mack, "Three-Terminal Lines: Which Is Better, Permissive Transfer Tripping Schemes, Blocking Schemes, or Something Else?" presented at the 28th Annual Western Protective Relay Conference, Spokane, WA, October 2001.

[16] E. O. Schweitzer III, "Ten Synchrophasor Application Tips," August 2006.

X. Biographies

Chris Araujo graduated with a BS in electronics engineering technology from New England Institute of Technology in 1991. After college, he worked as an engineering assistant for a small engineering company in Bristol, Rhode Island. In 1993, Chris started working for New England Electric Systems in Providence that, through mergers and acquisitions, became National Grid in 2000. As a lead relay technician, he tests, repairs, maintains, and monitors operation of electromechanical and solid-state relay systems; fiber optic, telephone circuit, and power line carrier communications systems; sequence-of-event recorders; load management systems; annunciators; and programmable logic controllers. He also prepares wiring and schematic diagrams for system changes, verifies accuracy of new control wiring and interconnections, and performs operational and load testing at substations and generating stations. As a member of the National Grid Automated Testing committee, Chris' responsibilities include designing, testing, and approving automated test plans for electromechanical and microprocessor-based relays.

Fred Horvath is currently employed by Florida Power Light Energy (FPLE) Seabrook Nuclear Generating Station and has twenty-three years of electrical and supervisory experience. Previously, he served 6 years in the US Navy Nuclear Program as an electrician mate stationed aboard the nuclear carrier CVN-70 Carl Vinson. At FPLE Seabrook, he functions as a maintenance analyst for the Electrical Maintenance department helping to develop and maintain all aspects of the Training and Qualification program. From 1990 to 2001, Fred functioned as a Senior Relay Technician at FPLE Seabrook. He performed electrical tests and repairs associated with the performance evaluation of in-service relays to prevent and remedy abnormal behavior or failure of medium and high-voltage transmission and distribution lines and equipment. He is experienced with General Electric, Schweitzer Engineering Laboratories, Inc., and Westinghouse protective relays and relaying schemes. He has been involved in numerous equipment design modifications, new installations, and wiring change projects. In 1997, he developed 18 detailed test procedures for the high-voltage transmission and distribution system protective relays and relaying schemes at FPLE Seabrook.

Jim Mack has a BSEE degree from Louisiana State University. Jim has held various positions in his 23 years in the electric utility industry, including experience with transmission, distribution, and SCADA systems and nuclear power plant construction. He joined Schweitzer Engineering Labs, Inc. in 1996 as a field application engineer where he assists customers in the application of SEL relays and integration systems.

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