Testing Requirements for Microprocessor Relays

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1. Introduction

Modern Microprocessor relays are much more powerful than their predecessors and testing one of these relays can be a daunting task for the average relay tester. All of this new power increases the relay's complexity exponentially which can make installation mistakes easier to create and harder to find. The modern relay tester needs to adapt to new technologies to find the most effective test plan possible to make sure the relay has been installed correctly, and will operate when required after the testing is completed. The purpose of this paper is to discuss the possible test techniques available to help the reader determine which techniques will be most effective for his/her skill level and available technology.

2. A Brief History of Protective Relays

We will start with a brief history of protective relays to compare the different generations and understand their basic operation.

A) Electro-Mechanical Relays

Electro-mechanical relays are considered the simplest form of protective relays. Although these relays have very limited operating parameters, functions, and output schemes, they are the foundation for all relays to follow and can have very complicated mechanical operating systems. The creators of these relays were true geniuses as they were able to apply their knowledge of electrical systems and protection to create protective relays using magnetism, polarizing elements, and other mechanical devices that mimicked the characteristics they desired.

The simplest electro-mechanical relay is constructed with an input coil and a clapper contact. When the input signal (current or voltage) creates a magnetic field greater than the mechanical force holding the clapper open, the clapper closes to activate the appropriate control function. The relay's pickup is adjusted by changing the coil taps and/or varying the core material via an adjusting screw. The relay has no intentional time delay but has an inherent delay due to mechanical operating times.

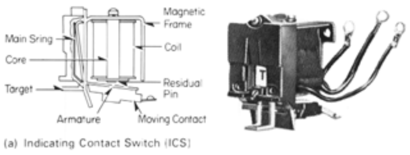


Figure 1: Example of Clapper Style Relay

The next level of Electro-mechanical relay incorporates an internal time delay using a rotating disk suspended between two poles of a magnet. When the input coil's magnetic strength is greater than the mechanical force holding the disk in the reset position, the disk will begin to turn toward the trip position. As the input signal (voltage or current) increases, the magnetic force increases, and the disk turns faster. The relay's pick up is adjusted by changing input coil taps and/or adjusting the holding spring tension. The time delay is altered by moving the starting position and varying the magnet strength around the disk. Time characteristics are preset by model.

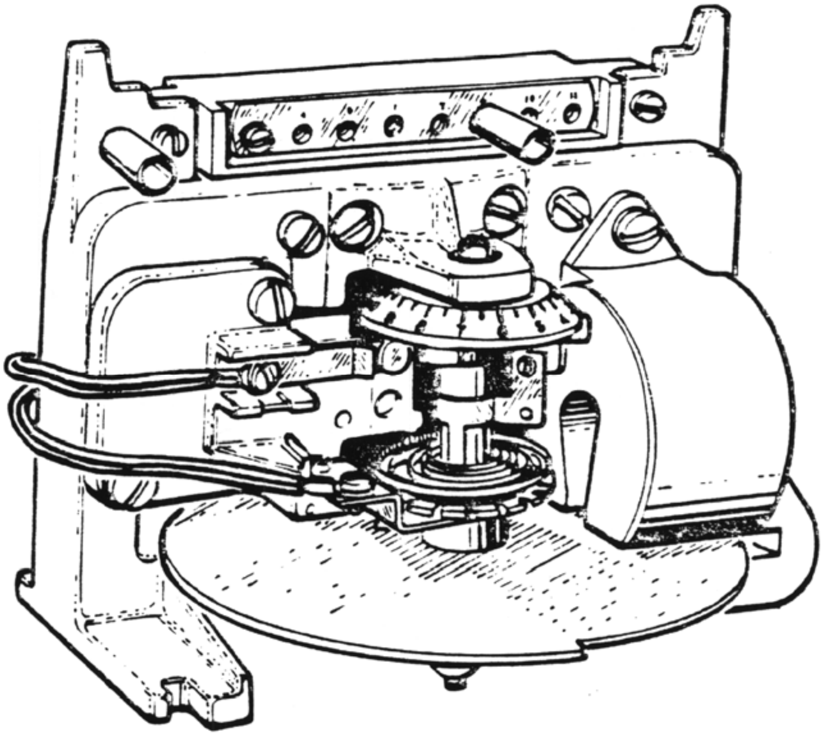


Figure 2: Typical Electro-Mechanical Relay with Timing Disk

The next level of complexity included polarizing elements to determine the direction of current flow. This element is necessary for protective functions, such as the following, to operate correctly:

- Distance (21)
- Reverse Power (32)
- Loss of Field (40)
- Directional Overcurrent (67)

These relays used the components described previously, but their operation is blocked until the polarizing element detects that current is flowing in the correct direction. Polarizing elements use resistors, capacitors, and comparator circuits to monitor current flow and operate a clapper style contact to shunt or block the protective functions accordingly.

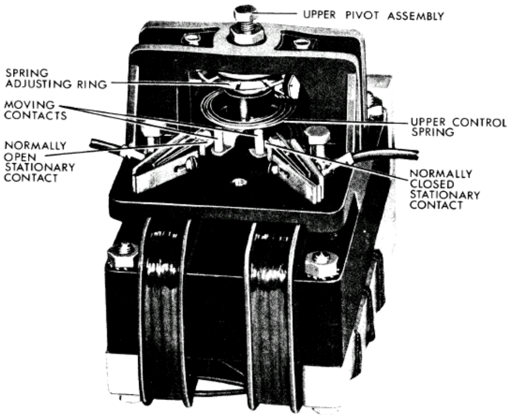
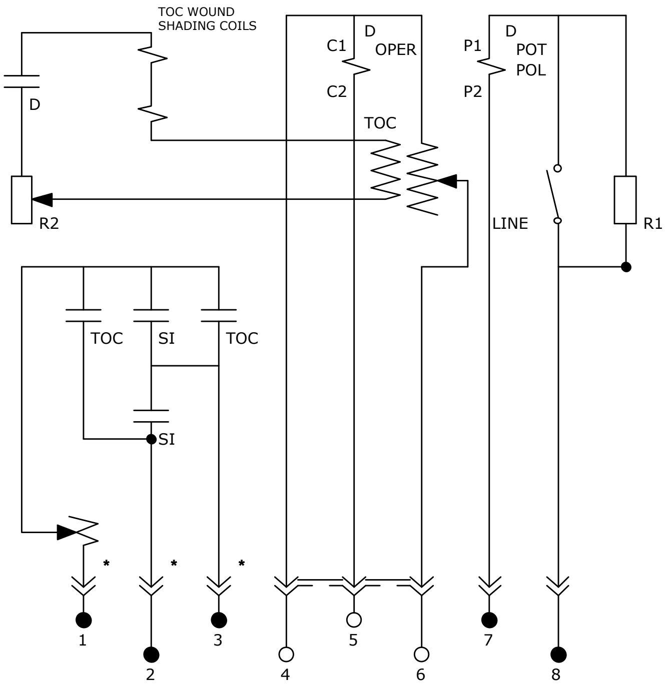


Figure 3: Example of an Electro-Mechanical Relay Polarizing Element



SI =SEAL IN
TOC = TIME OVERCURRENT UNIT
D = DIRECTIONAL UNIT
* = SHORT FINGERS

Figure 4: Typical Polarizing Element Electrical Schematic

As electro-mechanical relays are largely dependant on the interaction between magnets and mechanical parts, their primary problems are shared with all mechanical devices. Dirt, dust, corrosion, temperature, moisture, and nearby magnetic fields can affect relay operation. The magnetic relationship between devices can also deteriorate over time and cause the pick up and timing characteristics of the relays to change or drift without regular testing and maintenance.

These relays usually only have one or two output contacts and auxiliary devices are often required for more complex protection schemes. Figure 5 depicts a simple overcurrent protection scheme using electromechanical relays for one feeder. Notice that four relays are used to provide optimum protection and any single-phase relay can be removed for testing or maintenance without compromising the protection scheme.

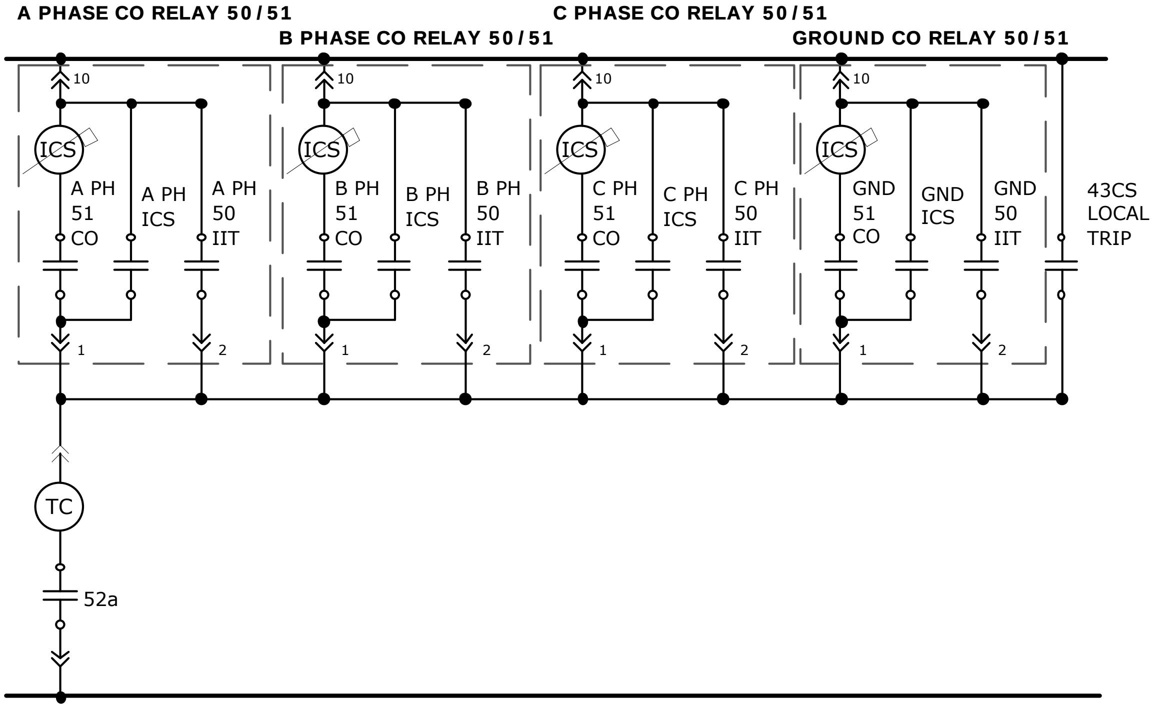


Figure 5: Typical Electromechanical Overcurrent Trip Schematic

B) Solid State Relays

As technology progressed and electronic components shrunk in size, solid-state relays began to appear. The smaller, lighter, and cost-effective solid-state relays were designed to be direct replacements for electro-mechanical relays. However, this generation of relays introduced new, unforeseen problems including; power supply failures and electronic component failures that prevented relays from operating, and sensitivity to harmonics that caused nuisance trips. Protective relays are the last line of defense during an electrical fault, and they must operate reliably. Unfortunately, early solid-state relays were often unreliable, and you will probably find many more electro-mechanical relays than solid state relays in older installations.

Solid-state relays used electronic components to convert the analog inputs into very small voltages that were monitored by electronic components. Pick up and timing settings were adjusted via dip switches and/or dials. If a pick up was detected, a timer was initiated which caused an output relay to operate. Although the new electronics made the relays smaller, many models were made so they could be inserted directly into existing relay cases allowing upgrades without expensive retrofitting expenses. Early models were direct replacements with no additional benefits other than new technology, but later models were multi-phase or multi-function.

C) Microprocessor Based Relays

Microprocessor based relays are computers with preset programming using inputs from the analog-digital cards (converts CT and PT inputs into digital signals), digital inputs, communications, and other external devices. The digital signals are analyzed by the microprocessor using algorithms (computer programs) to determine operational parameters, pick up, and timing based on settings provided by the end user. All these tasks are controlled by the algorithms, and each task can be represented by lines of computer code.

The microprocessor relay, like all other computing devices, can only perform one task at a time. These relays will analyze each line of computer code in predefined order until it reaches the end of the programming where it will begin analyzing from the beginning again. The relay scan time refers to the amount of time the relay takes to analyze the complete program once. A simplified program might operate as follows:

- Start
- Perform self check
- Record CT inputs
- Record PT inputs
- Record digital input Status'
- Overcurrent pick up? If yes, start timer
- Instantaneous Pick up? If yes, start timer
- Any element for OUT101 On (1)? If yes turn OUT101 on.
- Any element for OUT102 On (1)? If yes, turn OUT102 on.
- Back to Start

Electrical faults must be detected and cleared by the relay and circuit breaker as quickly as possible because an electrical fault can create an incredible amount of damage in a few cycles. The microprocessor relay's response time is directly related to the amount of programming and its processor speed. Early microprocessor speeds were comparatively slow, but they were also simple with smaller programs. As each additional feature or level of complexity is added, the processor speed must be increased to compensate for the additional lines of computer code that must be processed or the relay response time will increase.

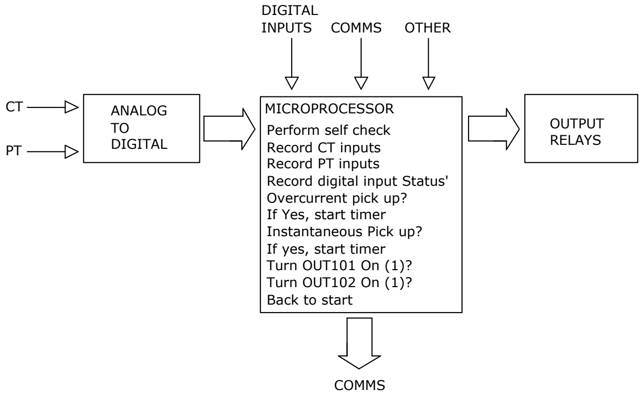


Figure 6: Simple Microprocessor Operation Flowchart

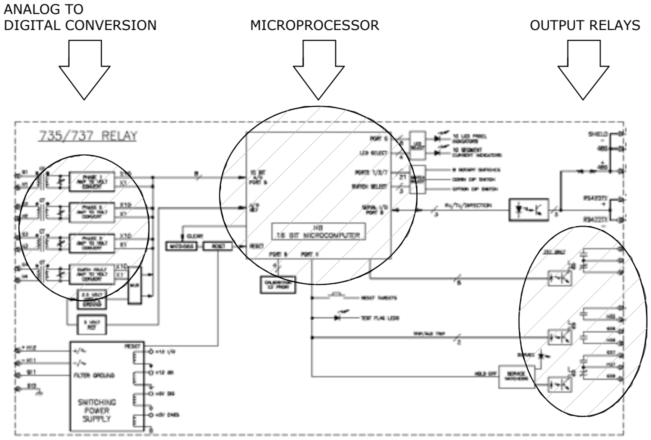


Figure 7: Simple Microprocessor Internal Schematic

D) Simple Digital Relays

Early microprocessor based relays were nothing more than direct replacements for electro-mechanical and solid state relays. Most were simple multiphase, single function relays with limited outputs. These relays were typically cheaper than comparable relays from previous generations and added additional benefits including:

- More sensitive settings,
- Multiple time curve selections
- Metering functions,
- Remote communications,
- Self test functions that monitored key components to operate an LED on the front display or operate an output contact.
- Simple fault recording

These relays were relatively simple to install, set, and test as they had limited functions and limited contact configurations. The General Electric MIF/MIV Series or Multilin 735/737 are good examples of simple digital relays.

E) Multi-Function Digital Relays

As technology improved and microprocessors became faster and more powerful, manufacturers began to create relays with the all-in-one-box philosophy we see today. These relays were designed to provide all the protective functions for an application instead of a protective element as seen in previous relay generations. Instead of installing four overcurrent (50/51), three Undervoltage (27), three overvoltage (59), two (81) frequency, and 1 synchronizing (25) relays; just install one feeder management relay such as the SEL-351 or GE Multilin 750 relay to provide all these functions in one box for significantly less money than any one of the previous relays. As a bonus, you also receive metering functions, a fault recorder, oscillography records, remote communication options, and additional protection functions you probably haven't even heard of. Because all the protective functions are processed by one microprocessor, individual elements become interlinked. For example, the distance relay functions are automatically blocked if a PT fuse failure is detected.

The all-in-one-box philosophy caused some problems as all protection was now supplied by one device and if that device failed for any reason; your equipment was left without protection. Periodic testing could easily be performed in the past with minimal risk or system disruption because only one element was tested at a time. Periodic testing with digital relays is a much more intrusive process as the protected device must either be shut down or left without protection during testing. Relay manufacturers downplay this problem by explaining that periodic testing is not required because of the self-check functions of the relay and the protection is constant because there is no operational drift. However, output cards, power supplies, input cards, and analog-to-digital converters can fail without warning or detection and leave equipment or the system without protection. Also, as everyone who uses a personal computer can attest, software can be prone to unexpected system crashes and digital relays are controlled by software.

Testing Requirements for Microprocessor Relays

As relays became more complex, relay settings became increasingly confusing. In previous generations a fault/coordination study was performed and the relay pick up and time dial settings were determined then applied to the relay in secondary amps. Today we can have multiple elements providing the same protection but now have to determine whether the pick up is in primary values, secondary values, or per unit. There can also be additional settings for even the simplest overcurrent (51) element including selecting the correct curve, voltage controlled or restraint functions, reset intervals, etc. Adding to the confusion is the concept of programmable outputs where each relay output contact could be initiated by any combination of protective elements and/or external inputs, and/or remote inputs via communications. These outputs are programmed with different setting interfaces based on the relay model or manufacturer with no standard for schematic drawings.

Multifunction digital relays have also added a new problem through software revisions. The computer software industry appears to be driven by the desire to add new features, improve operation, and correct bugs from previous versions. Relay programmers from some manufacturers are not immune to these tendencies. It is important to realize that each new revision changes the relay's programming and, therefore creates a brand new relay that must be tested after every revision change to ensure it will operate when required. In the past, the relay manufacturers and consumers, specifically the utility industry, extensively tested new relay models for months — simulating various conditions to ensure the relay was suitable for their systems. The testing today is either faster or less stringent as the relays are infinitely more complex, and new revisions or models disappear before some end users approve their replacements for use in their systems.

Examples of multifunction digital relays include the Schweitzer Laboratories Product line, the GE Multilin SR series and the Beckwith M Series.

F) The Future of Protective Relays

A paradigm shift occurred when relay designers realized that all digital relays use the same components (analog-to-digital cards, input cards, output cards, microprocessor, and communication cards) and the only real differences between relays is programming. With this principle in mind, new relays are being produced that use interchangeable analog/digital input/output, communication, and microprocessor cards. Using this model, features can be added to existing relays by simply adding cards and uploading the correct software or simply change a relay's function by changing the relay software. While the manufacturers will always have different interfaces, the protective relays produced by each manufacture will have the same look and feel as their counterparts across the product line.

These relays will be infinitely configurable but will also be infinitely complex, requiring specialized knowledge to be able to operate and test. Also, software revisions will likely become more frequent. Another potential physical problem is also created if the modules are incorrectly ordered or installed. Examples of this kind of relay include the Alstom M series, General Electric UR series, and the ABB REL series.

3. Reasons for Relay Testing

Before a test plan for any relay is created, the relay tester should understand their expected outcome or what the testing is intended to achieve. Is the relay tester looking for the best relay for a certain application? Or, is the relay tester performing a comprehensive test for a specific installation? Here are some of the reasons for relay testing:

A) Type Testing

Type testing is a very extensive process performed by a manufacturer or end user that runs a relay through all of its paces. The manufacturer uses type testing to either prove a prospective relay model (or software revision) or as quality control for a recently manufactured relay. The end user, usually a utility or large corporation, can also perform type tests to ensure the relay will operate as promised and is acceptable for use in their system.

This kind of testing is very involved and, in the past, would take months to complete on complicated electro-mechanical relays. Every conceivable scenario that could be simulated was applied to the relay to evaluate its response under various conditions. Today, all of these scenarios are now stored as computer simulations that are replayed through advanced test equipment to prove the relay's performance in hours instead of weeks.

Type testing is very demanding and specific to manufacturer and/or end-user standards. Independent type testing is a very important part of a relay's life span and should be performed by end users before choosing a relay model.

B) Acceptance Testing

There are many different definitions of acceptance testing. For the purposes of this paper, acceptance testing ensures that:

- the relay is the correct model with the correct features
- it is operating correctly
- has not been damaged in any way during transport.

This kind of testing should be limited to functional tests of the inputs, outputs, metering, communications, displays, and could also include pickup/timing tests at pre-defined values. Acceptance test procedures are often found in the manufacturer's supplied literature.

C) Commissioning

Commissioning and acceptance testing are often confused with each other but can be combined into one test process. Acceptance testing ensures that the relay is not damaged. Commissioning confirms that the relay’s protective element and logic settings are appropriate to the application and will operate correctly. Acceptance tests are generic and commissioning is site specific. Commissioning is the most important test in a digital relay’s lifetime.

D) Maintenance Testing

Maintenance tests are performed at specified intervals to ensure that the relay continues to operate correctly after it has been placed into service. In the past, an electro-mechanical relay was removed from service, cleaned, and fully tested using as-found settings to ensure that its functions had not drifted or connections had not become contaminated. These tests were necessary due to the inherent nature of electro-mechanical relays.

Today, removing a relay from service effectively disables all equipment protection in most applications. In addition, digital relay characteristics do not drift and internal self-check functions test for many errors. There is a heated debate in the industry regarding maintenance intervals and testing due to the inherent differences between relay generations.

E) Troubleshooting

Troubleshooting is usually performed after a fault to determine why the relay operated or why it did not operate when it was supposed to. The first step in troubleshooting is to review the event recorder logs to find out what happened during the fault. Subsequent steps can include the following, depending on what you discover in the post-fault investigation.

- Change the relay settings accordingly.
- Change the event record or oscillography initiate commands.
- Re-test the relay.
- Test the relay's associated control schemes.
- Replay the event record through the relay or similar relay to see if the event can be replicated.

4. Evolution of Relay Testing

This section will outline the evolution of relay testing to better understand the choices available to the relay tester when testing modern digital relays.

A) Electromechanical Relay Testing Techniques

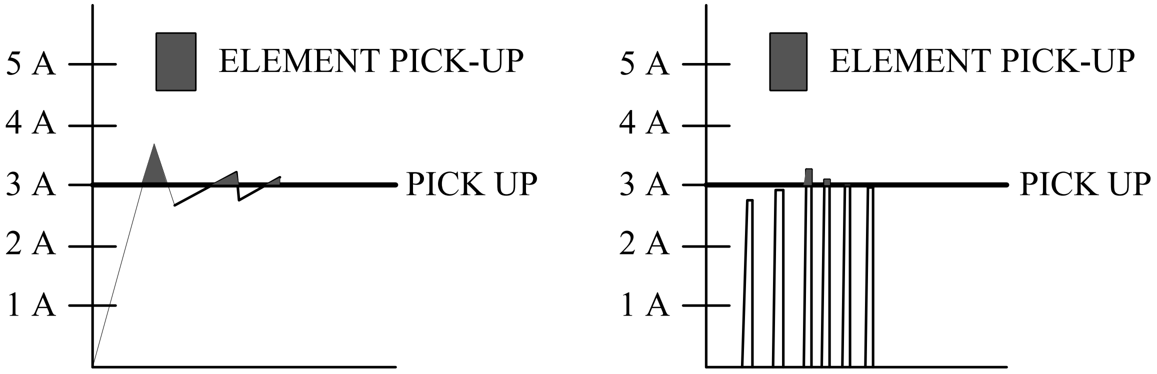
Electromechanical relays operated based on mechanics and magnetism and it was important to test all of the relay's characteristics to make sure that the relay was in tolerance. Various tests were applied to ensure all of the related parts were functioning correctly and, if the relay was not in tolerance; the relay resistors, capacitors, connections, and magnets were adjusted to bring the relay into tolerance. With enough patience, almost any relay could be adjusted to acceptable parameters.

Relay testing in the electromechanical age was very primitive primary due to the limitations of the test equipment available. The most advanced test equipment of this age would include a variac for current output, another variac for voltage signals, a built in timer with contact sensing, and a phase shifter for more advanced applications. With this equipment, detailed test plans and connection diagrams, and a hefty dose of patience; the relay tester was able to test the pickup, timing, and characteristics of the electromechanical relays installed as well as most solid state relays. Test plans and connections for currents and voltages often had very little resemblance to the actual operating connections because the limited test equipment could not create simulations of actual system conditions during a fault. Electro-mechanical relays were also built with inter-related components that needed to be isolated for calibration.

The following techniques were used when testing electrical-mechanical relays:

i) Steady State

Steady state testing is usually used for pickup tests. The injected current/voltage/frequency is raised/lowered until the relay responds accordingly. Steady state testing can be replaced by jogging the injected value up/down until the relay responds.



STEADY-STATE PICK-UP TEST **JOGGING PICK-UP TEST**

Figure 8: Steady State Pickup Testing

ii) Dynamic On/Off Testing

Dynamic on/off testing is the simplest form of fault simulation and was the first test used to determine timing. A fault condition is suddenly applied at the test value by closing a switch between the source and relay or activating a test set's output.

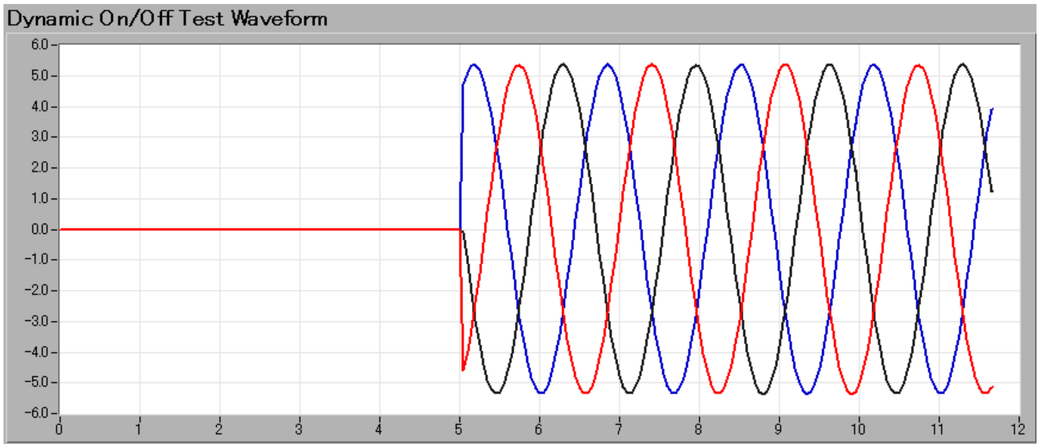


Figure 9: Dynamic On/Off Waveform

iii) Simple Dynamic State Testing

Some protective elements such as under-frequency (81) and under-voltage (27) require voltages and/or current before the fault condition is applied or the element will not operate correctly. Simple dynamic state testing uses pre-fault and/or post-fault values to allow the relay tester to obtain accurate time tests. A normal current/voltage/frequency applied to the relay suddenly changes to a fault value. The relay-response timer starts at the transition between pre-fault and fault, and the timer ends when the relay operates. Simple dynamic state testing can be performed manually with two sources separated by contacts or switches; applying nominal signals and suddenly ramping the signals to fault levels; or using different states such as pre-fault and fault modes.

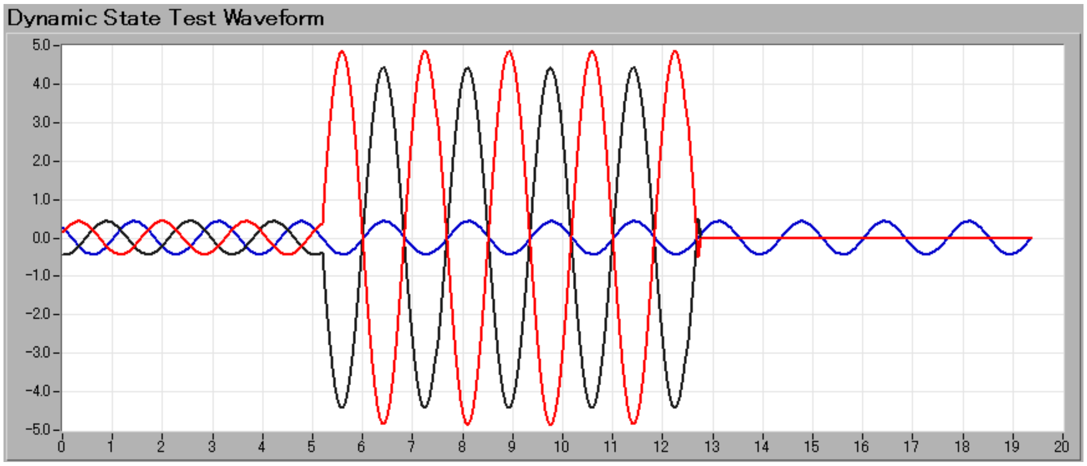


Figure 10: Simple Dynamic Test Waveform

B) Solid State Relay Testing Techniques

Solid state relays were primarily created to be direct replacements for electro-mechanical relays and the same test techniques were used for these relays. However, these solid state relays were constructed with silicon chips, digital logic, and mathematical formulas instead of steel and magnetism so the test plans were the same but the results were often very different. When an electro-mechanical relay was found out of tolerance, there were resistors or springs to adjust. Solid state relays did not have many adjustments besides the initial pickup setting and these relays either operated correctly or did not operate at all. Relay Testers typically replaced entire cards instead of adjusting components when the relay failed.

Test equipment did not evolve much during this period and the typical test set changed all of it’s analog displays to digital and made the previously described tests easier to perform.

C) Microprocessor Relay Testing Techniques

Simple microprocessor relays were almost identical in operation to the solid state relays they replaced and the test techniques for these relays were identical to the techniques previously described.

Complex microprocessor relays with their large number of settings and interlinked elements created confusion in the relay testing industry because a relay tester could spend an entire week testing one relay and barely scratch the surface of the relay's potential. The confusion increased when relay manufacturers claimed that relay testing was not required because the relay performed self-check functions and the end user would be informed if a problem occurred. Some manufacturers even argued that the relay could test itself by using its own fault recording feature to perform all timing tests. Eventually a consensus was reached where the relay tester would test all of the enabled features in the relay. Relay testers began modifying and combining their test sheets to account for all of the different elements installed in one relay but the basic fundamentals of relay testing didn't change very much.

The first problem that a relay tester experienced when testing a microprocessor relay element was that different elements inside the relay often overlapped. For example, an instantaneous (50) element set at 20A would operate first when trying to test a time-overcurrent (51) element at 6x (24A) its pickup setting (4A). The relay tester wanted to isolate the element under test and would usually change the relay settings to set one output, preferably an unused one, to operate only if the element under test operated. Now they could perform that 6x test without interference from the 50-element.

Relay testers often use the steady-state and simple-dynamic test procedures described previously to perform their element tests on microprocessor relays which created another problem. These complex relays were constantly monitoring their input signals to determine if those signals were valid and the steady-state and simple-dynamic test procedures were often considered invalid system conditions by the relay and the protection elements would not operate. For example, if a relay tester tried to perform a standard electromechanical impedance test (21) on a microprocessor relay the relay assumed that a PT fuse had operated and blocked the element; or the switch-on-to-fault (SOTF) setting would cause the relay to trip instantaneously. Relay testers who encountered this problem often disabled those blocking signals to perform their tests and, hopefully, turned the blocking settings back on when they were complete.

i) Computer-Assisted Testing

Because modern test equipment is controlled by electronics, computer-assisted testing became available. Standard test techniques could be repetitive on relays that were functioning correctly. Computer programs were created that would ramp currents and voltages at fixed rates in an effort to make relay testing faster with more repeatable results because every test would be performed identically. Computer-assisted testing has evolved to the point where the software will:

- connect to the relay
- read the relay settings
- create a test plan based on the enabled settings
- modify the settings needed to isolate an element and prevent interference
- test the enabled elements
- restore the relay settings to as found values

By following the steps above, computer-assisted relay testing can replace the relay tester on a perfectly functioning relay and can theoretically perform the tests faster than a human relay tester can. This type of testing works extremely well when testing micro-processor relays because these relays are computer programs themselves and it is very unlikely that these basic test procedures, initiated by a computer or human, will discover a problem. However when the relay malfunctions, a relay tester who has experience performing the actual tests and understands the interactions will be better equipped to solve the problem if it can be solved in the field.

ii) Logic Testing

The relay testing methods described so far have limitations when applied to microprocessor relays and are more suited to acceptance testing because they only prove that the analog inputs (voltage and current signals) are operating correctly, at least one output is operating correctly, and the relay will do what it is programmed to do when elements are isolated.

There are some serious flaws when you use these methods when performing commissioning tests. Commissioning is performed to ensure that the relay will operate correctly when applied to a specific application using the installed settings. This requires testing with the applied settings and ensuring the relay has been properly configured. Are you really performing a commissioning test of as-left settings when you are changing settings to test? If OUT101 is connected to your trip circuit and all of your testing is performed on OUT107, how do you know that OUT101 is operating correctly? Does your output logic equation include all of the enabled elements? Are all of the enabled elements in your trip equation?

Testing Requirements for Microprocessor Relays

Almost all problems found in the field with microprocessor relays have absolutely nothing to do with the actual relay and occur because of drawing and/or relay setting mistakes. Here are some examples of some common mistakes found during relay testing.

- A differential relay element tests correctly on all three phases when isolated but a GE T-60 relay's output setting is "XFMR PCNT DIFF OP A" which will only operate if an A Phase fault is detected. B and C differential protection is effectively disabled. The correct element was "XFMR PCNT DIFF OP". A one character mistake could have made a B or C phase differential fault much worse than it could have been.
- The 50N1 (Instantaneous Overcurrent on I_N input) setting is in the trip equation but 50N1 is off in the element settings. 50G1 (Residual Instantaneous Overcurrent) is on in the element settings but missing from the trip equation. All ground protection is disabled.
- A generator step-up transformer differential element is to be disabled by the lower voltage starting breaker 52a signal when the generator is run up to speed. However, a 52b breaker signal is actually sent which disabled differential protection when the generator is online. The relay will never trip and could cause millions of dollars in damage and lost revenue for a year waiting for a replacement transformer.
- A transformer's primary winding CTs are connected to the Winding 1 terminals of the relay but the settings have assigned W2 to be the primary winding. The relay will likely trip whenever a certain load is exceeded.

None of the examples described above would have been discovered using traditional testing techniques. Several of these problems were found several years after the relay was placed into service during maintenance testing by a different relay tester.

The first step in finding the kind of problems described above requires the relay tester to collect all of the project documentation in one place, review and compare all of the site drawings to manufacturer drawings, and then compare all of the drawings to the relay settings. Astounding as it might sound, 80% of modern relay errors can be discovered and corrected before the relay tester arrives on-site by comparing the site documentation. It often seems like the design engineers creates their settings from thin air when you discover that the CT or PT ratios don't match, or CTs are connected to the wrong inputs, or the breaker status is reversed, or the wrong output is used. Unfortunately, the relay setting engineers are often creating their settings from templates and miss changes, or are given original drawings instead of the final revisions for their settings.

Once you have compared all of the onsite documentation to the settings and everything appears to be in order, you can create your test plan based on the relay settings. It is important to look at the settings objectively and look for inconsistencies inside the settings themselves. Look for impossible logic conditions and make sure that an element that is enabled and setup is also found in the output logic. Look for elements in the output logic that aren't turned on or set. If there are no obvious errors, note the logic for each output, including signals sent over communication channels and LED or front panel displays. Once you have a comprehensive list of all of the output logic, create a checklist for each output broken down into simple OR statements. For example, a simple SEL overcurrent relay might have the following settings.

- TRIP = 51P1T + 51N1T + 50P1 + 50N1
- (Trip Breaker) OUT101 = TRIP
- (Scada/Remote Trip Indication) OUT107 = TRIP
- (Front Panel Display) 52A = IN101, DP1 = 52A, DP_1 = Breaker Closed, DP_2 = Breaker Open

If you wish to combine traditional pickup and timing testing with logic testing, your test plan could look like the two test plans described below.

Test Plan #1

1. Perform 51P1T pickup test using steady state technique and use pickup LED/Display/computer to determine pickup (recommended) or assign unused output for pickup indication (not recommended)
2. Perform 51P1T timing test at 2xpickup and use OUT101 for timer stop.
3. Perform 51P1T timing test at 2xpickup and use OUT107 for timer stop.
4. Perform 51P1T timing test at 4xpickup and use OUT101 for timer stop.
5. Perform 51P1T timing test at 4xpickup and use OUT107 for timer stop.
6. Perform 51P1T timing test at 6xpickup and use OUT101 for timer stop.
7. Perform 51P1T timing test at 6xpickup and use OUT107 for timer stop.
8. Perform 51N1T pickup test using steady state technique and use pickup LED/Display/computer to determine pickup (recommended) or assign unused output for pickup indication (not recommended)
9. Perform 51N1T timing test at 2xpickup and use OUT101 for timer stop.
10. Perform 51N1T timing test at 2xpickup and use OUT107 for timer stop.
11. Perform 51N1T timing test at 4xpickup and use OUT101 for timer stop.
12. Perform 51N1T timing test at 4xpickup and use OUT107 for timer stop.
13. Perform 51N1T timing test at 6xpickup and use OUT101 for timer stop.
14. Perform 51N1T timing test at 6xpickup and use OUT107 for timer stop.
15. Perform 50P1 pickup test using steady state technique and use pickup LED/Display/computer to determine pickup (recommended) or assign unused output for pickup indication (not recommended)
16. Perform 50P1 timing test at 1.1xpickup and use OUT101 for timer stop.
17. Perform 50P1 timing test at 1.1xpickup and use OUT107 for timer stop.
18. Perform 50N1 pickup test using steady state technique and use pickup LED/Display/computer to determine pickup (recommended) or assign unused output for pickup indication (not recommended)
19. Perform 50N1 timing test at 1.1xpickup and use OUT101 for timer stop.

20. Perform 50N1 timing test at 1.1xpickup and use OUT107 for timer stop.
21. Check breaker status and compare to front panel display. (If breaker is open, then display should indicate open)
22. Change breaker status and compare front panel display.

Test Plan #2 (Streamlined using alternating outputs)

1. Perform 51P1T pickup test using steady state technique and use pickup LED/Display/computer to determine pickup (recommended) or assign unused output for pickup indication (not recommended)
2. Perform 51P1T timing test at 2xpickup and use OUT101 for timer stop.
3. Perform 51P1T timing test at 4xpickup and use OUT107 for timer stop.
4. Perform 51P1T timing test at 6xpickup and use OUT107 for timer stop.
5. Perform 51N1T pickup test using steady state technique and use pickup LED/Display/computer to determine pickup (recommended) or assign unused output for pickup indication (not recommended)
6. Perform 51N1T timing test at 2xpickup and use OUT107 for timer stop.
7. Perform 51N1T timing test at 4xpickup and use OUT107 for timer stop.
8. Perform 51N1T timing test at 6xpickup and use OUT101 for timer stop.
9. Perform 50P1 pickup test using steady state technique and use pickup LED/Display/computer to determine pickup (recommended) or assign unused output for pickup indication (not recommended)
10. Perform 50P1 timing test at 1.1xpickup and use OUT101 for timer stop.
11. Perform 50P1 timing test at 1.1xpickup and use OUT107 for timer stop.
12. Perform 50N1 pickup test using steady state technique and use pickup LED/Display/computer to determine pickup (recommended) or assign unused output for pickup indication (not recommended)
13. Perform 50N1 timing test at 1.1xpickup and use OUT101 for timer stop.
14. Perform 50N1 timing test at 1.1xpickup and use OUT107 for timer stop.
15. Check breaker status and compare to front panel display. (If breaker is open, then display should indicate open)
16. Change breaker status and compare front panel display.

Test Plan #3 (Streamlined using multiple inputs)

1. Perform 51P1T pickup test using steady state technique and use pickup LED/Display/computer to determine pickup (recommended) or assign unused output for pickup indication (not recommended)
2. Perform 51P1T timing test at 2xpickup and verify OUT101 and OUT107 operates.
3. Perform 51P1T timing test at 4xpickup and verify OUT101 and OUT107 operates.
4. Perform 51P1T timing test at 6xpickup and verify OUT101 and OUT107 operates.
5. Perform 51N1T pickup test using steady state technique and use pickup LED/Display/computer to determine pickup (recommended) or assign unused output for pickup indication (not recommended)
6. Perform 51N1T timing test at 2xpickup and verify OUT101 and OUT107 operates.
7. Perform 51N1T timing test at 4xpickup and verify OUT101 and OUT107 operates.
8. Perform 51N1T timing test at 6xpickup and verify OUT101 and OUT107 operates.
9. Perform 50P1 pickup test using steady state technique and use pickup LED/Display/computer to determine pickup (recommended) or assign unused output for pickup indication (not recommended)
10. Perform 50P1 timing test at 1.1xpickup and verify OUT101 and OUT107 operates.
11. Perform 50N1 pickup test using steady state technique and use pickup LED/Display/computer to determine pickup (recommended) or assign unused output for pickup indication (not recommended)
12. Perform 50N1 timing test at 1.1xpickup and verify OUT101 and OUT107 operates.
13. Check breaker status and compare to front panel display. (If breaker is open, then display should indicate open)
14. Change breaker status and compare front panel display.

Notice that we do not simulate the breaker when performing the logic test for the 52A (IN101) front panel display. You should always use the actual end device to prove input status and logic to make sure the actual device status contact:

- uses the correct status indication
- is connected correctly
- uses the correct input voltage. Different relays use an internally supplied voltage source or external source to determine input status. Some relays can use both methods and an easily be connected incorrectly.

Relay logic is often more complex than the previous example and more complicated logic schemes should be broken down to a simple OR statement. For example, a breaker failure logic scheme could be written as:

- SV1 = (50P2 [0.5 A] + 50N2 [0.5 A]) *(SV1T [Seal-in] + TRIP [Initiate]) [Breaker fail operate logic]
- SV1PU = 15 cycles [Breaker Failure Timer]
- OUT102 = SV1T [Breaker Fail Signal = Current is still flowing through the breaker 15 cycles after the trip signal is sent and will stay closed until the current is lower than 0.5A. Send trip signal to the next upstream breaker)

This logic can be broken down into the following logic equations:

- OUT102 = 50P2 * TRIP
- OUT102 = 50N2 * TRIP
- OUT102 = 50P2 * SV1T
- OUT102 = 50N2 * SV1T

Broken down into is base components, we can now test each of these equations using the following test plan.

Breaker Fail (OUT102) Test Plan

1. OUT102 = 50P2 * TRIP. Perform 51P1T timing test at 2xpickup and set timer to start when OUT101 operates and to stop when OUT102 operates.
2. OUT102 = 50N2 * TRIP. Perform 51N1T timing test at 2xpickup and set timer to start when OUT101 operates and to stop when OUT102 operates.
3. OUT102 = 50P2 * SV1T. Perform 51P1T timing test at 2xpickup. Do not stop test after OUT101 and OUT102 operate. Lower fault current below 51P1 pickup setting but greater than 50P2 setting. OUT101 should open but OUT102 should still be closed. Lower fault current below 50P2 setting. Both outputs should now be open.
4. OUT102 = 50N2 * SV1T. Perform 51N1T timing test at 2xpickup. Do not stop test after OUT101 and OUT102 operate. Lower fault current below 51N1 pickup setting but greater than 50N2 setting. OUT101 should open but OUT102 should still be closed. Lower fault current below 50N2 setting. Both outputs should now be open.

Applying logic testing will not find every problem but it will allow the relay tester to feel reasonably confident that the relay has been set correctly, there are no obvious logic errors, and the relay will operate when required and is connected properly.

Logic testing combined with dynamic testing is a very powerful and effective test method when applied by an experienced relay tester who has a good understanding of the relay elements and the system the relay protection is applied to. However, there is a fatal flaw when performing relay testing based on supplied setting files…do the settings match the engineer's intent? As mentioned before, a modern microprocessor relay will perform the tasks that it is instructed to perform and cannot determine if the engineer has understood the relay's operation or not. This problem was coined Garbage in = Garbage Out when computers were first implemented in society but we appear to become far more trusting as computers became part of our daily life. Neither the relay tester nor the relay can determine whether the pickup setting is intended to be 0.5 instead of the 5.0 amps the engineer accidently applied unless they have the engineer's notes or a coordination study or it is an obvious error. Testing a relay to its applied settings with no comparison to intent or common sense will almost always create a successful test unless there are gross mechanical or setting problems. A relay's mechanical problems can be more easily detected by simply applying voltage and current and performing a meter test followed by exercising each digital input and output. Gross setting errors can be detected by a combination of dynamic and logic testing. But what happens when the logic is too complex to decipher like this real world example of a capacitor control circuit:

Opening the Capacitor Bank

```
SV8   =(RB15 * !LT6 + PB7 * LT5) * LT10 + RB13 * !LT10 + /SV3T
```

Closing the Capacitor Bank Switches

```
SV9   =(RB16 * !LT6 + PB8 * LT5) * LT10 * SV10T + RB14 * !LT10 * SV10T
```

This logic doesn't look that complicated until you realize that any word bit that begins with RB is logic from another device that has over 100 lines of programming. If the logic was expanded to represent just what is inside this one relay, it would look like:

Opening the Capacitor Bank

```
SV8   =(RB15 * ! (PB10 * !LT6 * (!LT5 * PB5)) + PB7 * (!LT5 * PB5)) * (!LT10 *
(PB6 * LT5 + RB12 * !LT6)) + RB13 * ! (!LT10 * (PB6 * LT5 + RB12 * !LT6)) +
/3P27 * !50L * 52A
```

Closing the Capacitor Bank Switches

```
SV9   =(RB16 * ! (PB10 * !LT6 * (!LT5 * PB5)) + PB8 * (!LT5 * PB5)) * (!LT10 *
(PB6 * LT5 + RB12 * !LT6)) * SV10T + RB14 * ! (!LT10 * (PB6 * LT5 + RB12 *
!LT6)) * IN104
```

It turns out that the testing this logic was quite simple after the engineer was contacted. This logic translates into the following bullet points:

Closing the Capacitor Bank Switches

1. If the capacitor switches are open and the capacitor control is in "Manual", close the capacitor switches when the "Close Capacitor" button is pushed.

2. If the capacitor switches are open and the capacitor control is in “Auto”, the capacitor switches will close if:
    i. If the phase to phase voltage is below 6.84 kV.
    ii. If there is a lagging power factor and the load is above 10 MW.
    iii. If there is a leading power factor between 0.99 and 1.00 and the load is above 15 MW.

Opening the Capacitor Bank

1. If the capacitor switches are closed and the capacitor control is in “Manual”, open the capacitor switches when the “Open Capacitor” button is pushed.
2. If the capacitor switches are closed and the circuit breaker opens, open the capacitor switches.
3. If the capacitor switches are closed and the capacitor control is in “Auto”, the capacitor will close if:
    i. If the phase to phase voltage is above 7.74 kV.
    ii. If there is a leading power factor of 0.96 or less.

A very complex logic equation was translated into simple, easy to simulate conditions and all of the settings worked perfectly. If the logic had been tested without understanding the engineer’s intent, it could take hours or days to reverse engineer and unless something obvious went wrong, no errors would have been detected because the relay would perform as programmed.

iii) Combining Pickup, Timing Tests, and Logic Testing

Modern test equipment uses a minimum of three voltage and three current outputs with the ability to independently vary the phase angles between any of the outputs. With this equipment, you can use different states to create more complicated dynamic tests which can make relay testing more realistic, effective, and efficient.

A microprocessor relay element does not fall out of calibration…It either works correctly or it doesn't. Using this principal, the pickup and timing test can be combined into one test. The simplest element to test this technique on is the instantaneous overcurrent (50) element. If the applied current is greater than the pickup setting, the element will operate. If the 50-element settings is 25A, the element will not operate if the current is less than 25 A, and will operate instantaneously if the current is greater than 25 A in an ideal world. The test plan to test the 50-element in one test would set as per the following chart.

Pre-Fault	Fault 1	Fault 2
Nominal Current (4.0 A) for 2 seconds	24.99 A for 1 second	25.00 A Start timer Stop timer when relay output operates. Time should be instantaneous.

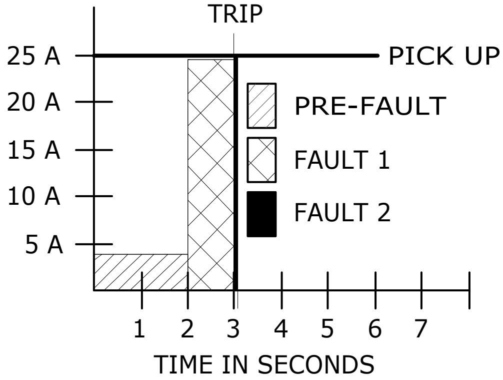


Figure 11: 50-Element Ideal Combination Test

We do not live in an ideal world and this test would probably fail due to accuracy errors of the relay and the relay test set. In digital relays and modern test equipment, the combined error is usually less than 5%. We can modify our test set to allow for the inherent error in relay testing using the following chart.

Pre-Fault	Fault 1	Fault 2
Nominal Current (4.0 A) for 2 seconds	23.75 A for 1 second (25 A - 5% = 25 - (25 x 0.05) = 25 - 1.25 = 23.75 A)	26.25 A (25 A + 5% = 25 + (25 x 0.05) = 25 + 1.25 = 26.25 A) Start timer Stop timer when relay output operates. Time should be less than 5 cycles

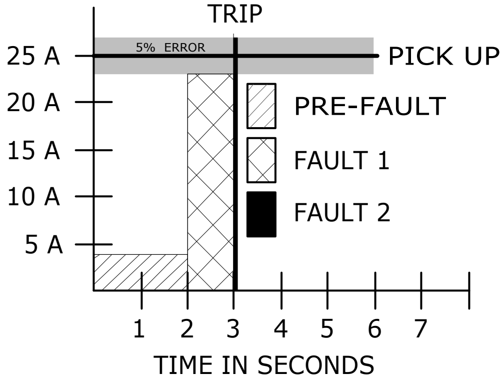


Figure 12: 50-Element Combination Test

This method will work for all relay elements, including elements with time delays such as the time overcurrent (51) element.

Multiple timing tests were performed on electromechanical relays to ensure the relay magnets and mechanical time dials were in the proper location. If the relay timing did not match the manufacturer's curve, a magnet or time dial setting was adjusted to bring the relay into tolerance. There are no possible adjustments to a microprocessor relay so the timing will be correct, or the relay is set wrong and it will be incorrect. The following test plan will allow the user to test the pickup and timing of a microprocessor based 51-element with a pickup of 5A.

Pre-Fault	Fault 1	Fault 2
Nominal Current (4.0 A) for 2 seconds	4.75 A for 5 second (5 A - 5% = 5 - (5 x 0.05) = 5 - 0.25 = 4.75 A)	10.0 A (2x nominal pickup) Start timer Stop timer when relay output operates. Time should be expected result for 2xpickup +/- 5%
Nominal Current (4.0 A) for 2 seconds	4.75 A for 5 seconds (5 A - 5% = 5 - (5 x 0.05) = 5 - 0.25 = 4.75 A)	20.0 A (4x nominal pickup) Start timer Stop timer when relay output operates. Time should be expected result for 4xpickup +/- 5%
Nominal Current (4.0 A) for 2 seconds	4.75 A for 5 seconds (5 A - 5% = 5 - (5 x 0.05) = 5 - 0.25 = 4.75 A)	30.0 A (6x nominal pickup) Start timer Stop timer when relay output operates. Time should be expected result for 6xpickup +/- 5%

You should notice that the timing test current was equal to the multiple of current without adding 5% to compensate for test set and relay error. The 5% error is used when comparing the time in fault…not the applied current. If there was a problem with the applied settings, the measured time delay would be significantly shorter than the expected time delay to indicate the problem.

Another problem would become evident if you were testing this relay and the 50 and 51-elements were assigned to the same trip coil because the 50-element (25A) would operate when the relay tester was trying to perform the 6x timing test (30 A). The relay tester could isolate the 51-element to another relay output to perform their 6x test without interference…or they could step back and review their procedure. Two different issues come into play when protective elements overlap. The microprocessor relay's 51-element does not have any possible adjustments, so is a third test really necessary to prove the characteristic curve if two other tests are successful? The primary reason for choosing whole numbers for 51-element tests in electro-mechanical relays is that it is easier to determine the expected result on the graph using whole numbers. Most relay testers are using the formulas to determine expected values when testing microprocessor relays, so changing the third test current to 24 A or 4.8x pickup should be no problem when calculating the expected result. The second issue in play is commissioning vs. acceptance testing. Testing without changing settings proves that the settings have been applied correctly. If 30 Amps are applied to the relay in-service, would the 51 or 50 element operate? Is there any advantage to testing an element at a test point where it will never operate in-service?

This technique works for more complicated relay elements such as distance protection (21). 21-elements use the measured impedance and angle between the current and voltage to detect a fault on a transmission line or other electrical apparatus. The most typically applied characteristic is a MHO circle. If the measured impedance falls within the circle, the 21-element operates after a pre-set time delay. A typical setting for a zone 2 element could be 3.4 Ω @ 87º with a 20 cycle time delay as shown in the following figure.

The test plan for this element is much like the 50-element because there is a fixed time delay. We apply a pre-fault with nominal conditions and its impedance is near the x-axis, far away from the circle. Fault 1 impedance falls just outside of the circle and fault 2 is measured inside the circle. Don't forget that there is also a 5% error to account for and that is shown by the shaded band around the original circle. If the measured time between fault 2 and the relay output operating is 20 cycles +/- 5%, the test is successful. You could use the same technique to plot the entire circle, but it is extremely unlikely you will find a problem with the relay's programming.

Pre-Fault	Fault 1	Fault 2
Voltage (69.28V) Current (3.0 A @ -30º) (23.09 Ω @ 30 º) for 2 seconds	Voltage (30.0V) Current (8.40 A) @ -87º (3.57 Ω @ 87 º) for 1 seconds	Voltage (30.0V) Current (9.29 A) @ -87º (3.23 Ω @ -87 º) Start timer Stop timer relay output operates. Time should be 20 cycles +/- 5%

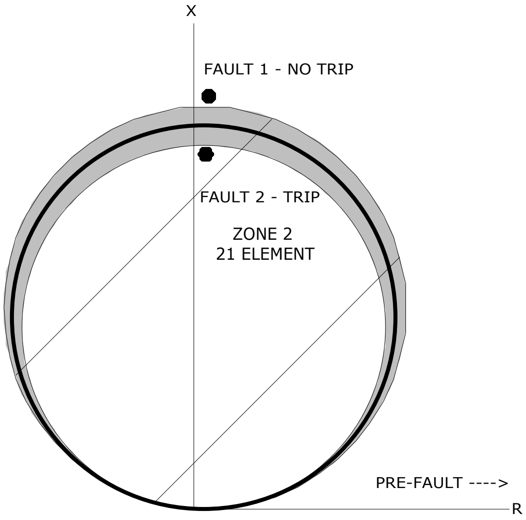


Figure 13: 21-Element Combination Test

This test technique can also be applied to the zone 1 distance protection element which could be set for 1.5 Ω @ -87º with no intentional delay. If the previous test plan was modified for the new impedance it might look like the following.

Pre-Fault	Fault 1	Fault 2
Voltage (69.28V) Current (3.0 A) @ -30º (23.09 Ω @ 30 º) for 2 seconds	Voltage (20.0V) Current (12.73 A) @ -87º (1.57 Ω @ 87 º) for 1 seconds	Voltage (30.0V) Current (14.08 A) @ -87º (1.42 Ω @ -87 º) Start timer Stop timer relay output operates. Time should be less than 5 cycles

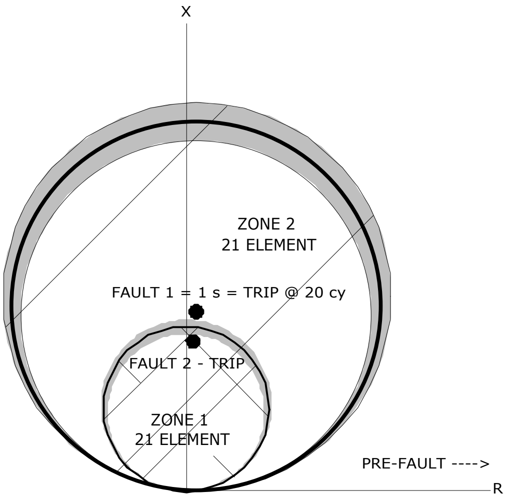


Figure 14: 21-Element Dual Zone Combination Test

This test would fail if the relay tester used the in-service contacts to perform the tests because the Fault 1 impedance falls within the zone 2 circle and zone 2 will trip in 20 cycles, a shorter time than the fault 1 duration. A simple modification of the fault 1 time to a value greater than the zone 1 time but less than the zone 2 time delay will make this a practical test. Change the fault 1 time delay to 10 cycles (Zone 1 time (5 cycles) < Fault 1 time < (Zone 2 time (20 cycles) - Zone 1 time (5 cycles)) = 5 cycles < Fault 1 time < 15 cycles = fault 1 time = 10 cycles)

Pre-Fault	Fault 1	Fault 2
Voltage (69.28V) Current (3.0 A) @ -30º (23.09 Ω @ 30 º) for 2 seconds	Voltage (20.0V) Current (12.73 A) @ -87º (1.57 Ω @ 87 º) for 10 cycles	Voltage (30.0V) Current (14.08 A) @ -87º (1.42 Ω @ -87 º) Start timer Stop timer relay output operates. Time should be less than 5 cycles

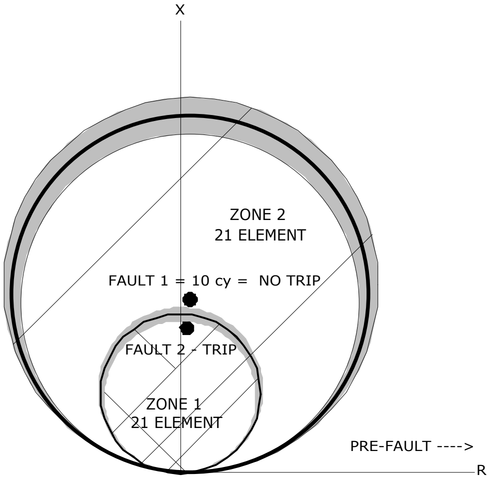


Figure 15: 21-Element Dual Zone Combination Test

Adding logic testing to this step is as simple as connecting all of the relay outputs used by the relay settings and monitoring all contacts during the test. If OUT101 and OUT102 are supposed to operate when a 50 element operates, make sure both elements operate during the 50-element test. Or, you could perform the test twice using each output for timing.

When this test technique is applied to the relay in the Logic Testing example, the test plan has fewer steps and is more comprehensive.

Relay Settings

- SV1PU = 15 cycles [Breaker Failure Timer]
- TRIP = 51P1T + 51N1T + 50P1 + 50N1
- SV1 = (50P2 + 50N2) *(IN101 + TRIP) [Breaker fail operate logic]
- OUT101 = TRIP [Trip Breaker]
- OUT102 = SV1T [Trip upstream breaker]
- OUT107 = TRIP [Scada/Remote Trip Indication]
- 52A = IN101
- DP1 = 52A [Front Panel Display]
- DP_1 = Breaker Closed
- DP_2 = Breaker Open

Test Plan

1. Perform 51P1T combination test at 2xpickup and verify OUT101 and OUT107 operates.
2. Perform 51P1T combination test at 4xpickup and verify OUT101 and OUT107 operates.
3. Perform 51N1T combination test at 2xpickup and verify OUT101 and OUT107 operates.
4. Perform 51N1T combination test at 4xpickup and verify OUT101 and OUT107 operates.
5. Perform 50P1 combination test at 1.1xpickup and verify OUT101 and OUT107 operates.
6. Perform 50N1 combination test at 1.1xpickup and verify OUT101 and OUT107 operates.
7. Change breaker status and compare front panel display.
8. Perform 51P1T combination test at 2xpickup and set timer to start when OUT101 operates and stop the timer and test when OUT102 operates.
9. Perform 51N1T combination test at 2xpickup and set timer to start when OUT101 operates and stop the timer and test when OUT102 operates.
10. Perform 51N1T combination test at 2xpickup and set timer to start when OUT101 operates and stop the timer and test when OUT102 operates. Do not stop the test when OUT102 operates. Lower the current to 0.525 A and verify OUT102 is still in the trip state. Lower the current to 0.475 A and verify that OUT102 has changed state.
11. Perform 51P1T combination test at 2xpickup and set timer to start when OUT101 operates and stop the timer and test when OUT102 operates. Do not stop the test when OUT102 operates. Lower the current to 0.525 A and verify OUT102 is still in the trip state. Lower the current to 0.475 A and verify that OUT102 has changed state.

This technique, when applied correctly:

- Can be faster than traditional testing techniques
- Is more efficient than traditional testing techniques
- Is more comprehensive because it tests the pickup, timing, and logic in one step

- Provides true commissioning results because no settings are changed and tests are more realistic
- Can make maintenance testing simple if the tests are saved and re-played at maintenance intervals.

iv) Dynamic System-Model Testing

Dynamic system model based testing uses a computer program to create a mathematical model of the electrical system and create fault simulations based on the specific application. These modeled faults (or actual events recorded by a relay) are replayed through a sophisticated relay test-set to the relay and, if performed correctly, is the ultimate test to prove an entire protection system as a whole. Dynamic System Model based testing can also provide more realism by creating waveforms that can incorporate real system conditions such as DC offset, transients, or CCVT distortions as shown in the example waveform in figure 17.

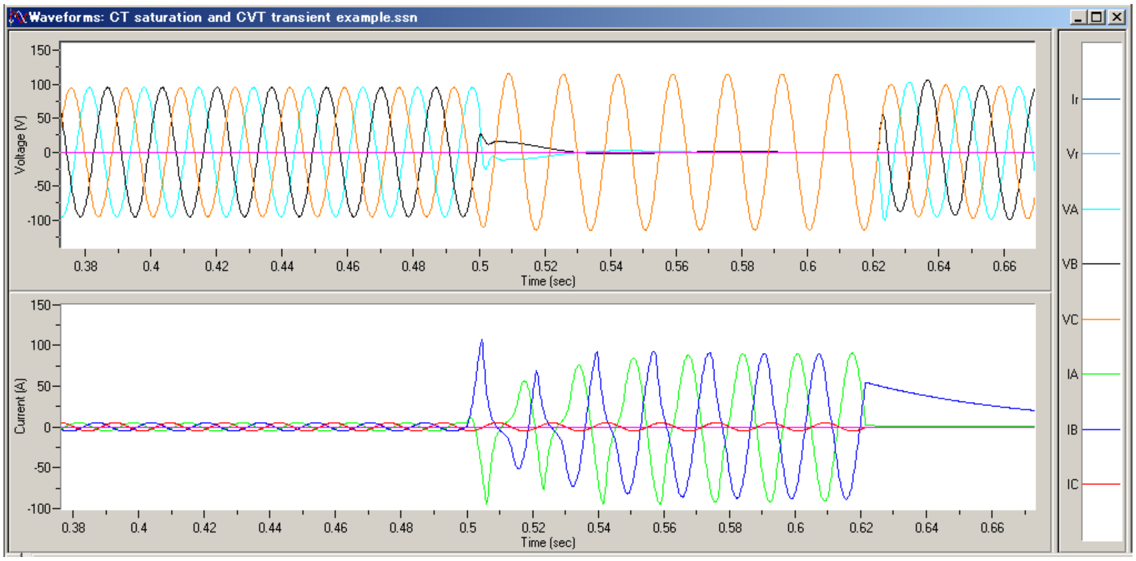


Figure 16: System Modeling Waveform (Compliments of Manta Test Systems)

This test is typically limited to type testing or end-end testing because it requires specialized knowledge of a system, complex computer programs, advanced test equipment, and a very complex test plan with many possibilities for error.

v) End to End Testing

End to end testing is performed when two or more relays are connected to protect a transmission line. These relays can transfer status or metering information between each other to constantly monitor the transmission line in order to detect faults and isolate the faulted transmission line more quickly and reliably than single relay applications. The relays can communicate to each other through a wide range of possibilities including telecom equipment, fibre optic channels, or wave traps that isolate signals transferred over the transmission line.

Testing these complicated schemes in the past was limited to functional tests of the individual components with a simplified system test to prove that the basic functions were operating correctly. For example, a relay tester would configure and test the relay, configure and test the communication equipment, then inject a fault condition into the relay. A relay tester at the other location would verify that they received the signal and they would repeat the process at the remote end. This procedure tested the base components of the system but they often failed to detect problems that occurred with faults in real time. For example, a fault on parallel feeders could change direction in fractions of cycles when one breaker in the system operated that often caused the protection schemes to mis-operate.

Relay testers could only test one end at a time because there was no way to have two test sets at remote locations start at exactly the same moment. If the test sets do not provide co-ordinated currents and voltages with a fraction of a cycle, the protection scheme would detect a problem and mis-operate. Global Positioning System (GPS) technology uses satellites with precise clocks to communicate with equipment on earth which allowed test set manufacturers to synchronize test sets at remote distances. After the test sets are synchronized, test plans could be created with simulated faults for each end of the transmission line. To perform a test, the relay testers synchronize their test sets, load the same fault simulation with the values for their respective ends, set the test sets to start at the exact same moment, and initiate the countdown. The test sets will inject the fault into the relays simultaneously and they should respond as if the fault occurred on the line. The relays' reactions are analyzed and determined to be correct before proceeding to the next test. Any mis-operations are investigated to see where the problem originates and corrected.

End to end testing is typically considered to be the ultimate test of a system and should ideally perform using Dynamic System Model Testing to ensure that the system is tested with the most comprehensive test conditions. Simpler end-end schemes such as line differential schemes can be tested using Simple Dynamic State testing.

5. Conclusion

Microprocessor based relays have become increasingly complex but modern test equipment with 3 or more voltage/current channels and multi-state controls provide the tools needed to perform relay testing with greater efficiency and, more importantly, effectiveness. Relay tester should first ask the question "Why am I testing this relay?" then apply all of the tools in their tool belt to determine what combination of test techniques to use. For example, the following test plans could be performed on the same relay with different reasons for testing:

Acceptance Testing	1. Perform a metering check on all analog current and voltage channels 2. Perform a function test of all digital inputs and outputs. 3. Perform a relay self test
Commissioning	1. Perform a metering check on all analog current and voltage channels 2. Perform a function test of all digital inputs and outputs. 3. Perform a relay self test 4. Test each element enabled in output logic using: 5. Steady State for pickup testing, simple dynamic testing for timing, and logic testing, OR 6. Combine Pickup, Timing Tests, and Logic Testing, OR 7. Dynamic System-Model Testing
Maintenance Testing	1. Perform a metering check on all analog current and voltage channels 2. Perform a function test of all digital inputs. 3. Perform a relay self test 4. Perform a trip test for each output by applying one logic test for each enabled output, OR 5. Perform Logic Testing, OR 6. Combine Pickup, Timing Tests, and Logic Testing, OR 7. Dynamic System-Model Testing

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