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Injected Waveforms and Their Effect on Protection Element Response

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Abstract - The paper is a continuation in a series that identifies more of the developing issues in relay testing - what was once well understood in a protection element's response is today a challenge in testing modern protection systems. Modern algorithms and the complexity of the combined protection element(s) scheme logic creates variable and sometimes unacceptable testing results when compared to manufacturer specifications or other performance criteria. Legacy testing methods and techniques will never yield correct results.

The paper compares various types of test waveforms based on test methods used over the past 30 years. Why they are used, when they are effective and for what types of protective elements they are intended. It also compares various protective element responses to the various waveforms of the test methods discussed. This includes overcurrent, directional overcurrent, over/under voltage, frequency elements, distance elements, and differential elements comparing electromechanical, static, and digital relay designs. The paper summarizes these comparisons and explains why great care must be used when choosing a test injection method.

Index Terms— Protection, testing, relay, characteristic

1 Introduction

Testing of today's digital protection relays requires an understanding of their characteristics, algorithms, and embedded logic in order to be successful. These modern protection devices are not the single function electromechanical or static electronic designs of the past. Using simplified test methods for today's modern protection systems which ignores proper fault simulations will likely not result in a satisfactory operation of the overall protection scheme, much less its individual functions or elements. If we were simply testing a traditional electro-mechanical single function overcurrent element, then it would not be as critical. Visually verifying a single phase overcurrent relay's initial condition before injecting a test current (e.g. multiple of the tap value) has always been straight forward and easy to instruct someone on what to expect. But the operating principles and algorithms implemented in a modern digital Overcurrent relay now consider more than "is the disk returned to the stop" as the initial condition for an element test. The application, including the protected object, CT performance, scheme logic employed, and the operational power system conditions force us to take into consideration and apply a much different testing approach.

2 Test Methods Used

Protection and Control devices and systems are designed to respond to the real events of the power system. Testing these systems for their proper response, reaction, and control sequences has always challenged the industry.

Since Tesla's era when the first AC power system apparatus were designed and built, the need for protection of those apparatus while in operation drove innovation of sensors, detectors, comparators, and actuators. Combined, these devices became the protection relays we know today. Testing these early devices required the ability to generate a voltage or current or both. The test method was a simple ON or OFF state. (Fig 1)

As can be seen in the figure, one issue was control of the timing of the injected signal(s), when it actually turned on and when it turned off. The problem is compounded when more than one signal is used. Other issues were stability of the signal values, control of phase relationships, frequency stability, and purity of the signal waveform.

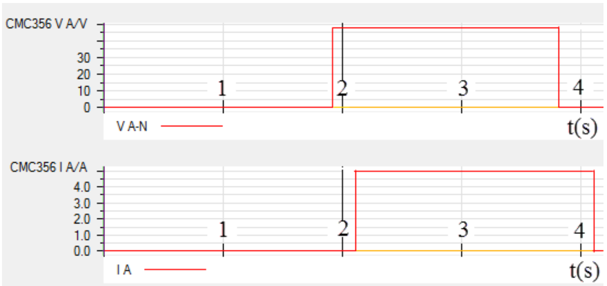

Figure 1 – ON/OFF Test Method

As the technology of the relays were improved to meet the evolution of the power system and its apparatus, so did the technology to test them, that is to a point. The staple of test equipment up to the 1970's was the load box, Variac, dual timer, voltmeter and ammeter.

Figure 2 – Load Box and Variac

There were many utility "in house" test jigs made from various combinations of these devices but it wasn't until the early 1970's when they were combined into commercially available test kits. These were capable of single phase voltage and current output, and later combining three of these units would provide the holy grail of 3-phase test injection. This was just in time for the introduction of the early electronic-based protection relays.

With some effort, 3-phase static injections were possible and continuously improved upon as control of the waveforms improved with microprocessor control. (Fig 3)

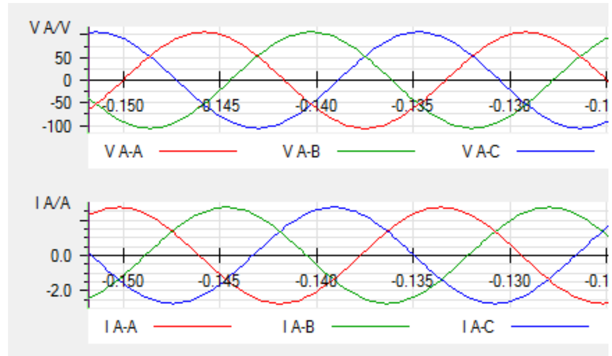

Figure 3 – Voltage and Current 3-phase Injection

The 1980's brought improvements with the ability to "play" a recorded waveform from a disturbance fault recorder – the IEEE COMTRADE standard of 1991 allowed exchange of these data files between programs, devices, and manufacturers.

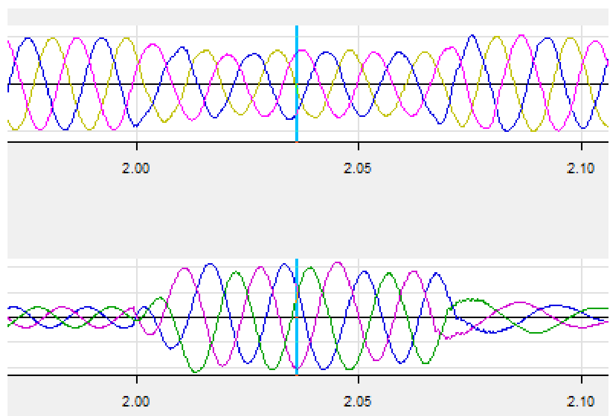

Figure 4 – Recorded Waveform in COMTRADE

Still the inherent capability of the test kits for protection testing was relegated to simple step change events and ramps created manually or with a controller. (Fig 5)

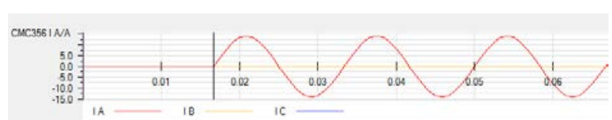

Figure 5 – Step Change Current Injection

This test method allowed for basic timing tests and element pickup verification. Creating a ramped quantity was achieved by control over the step size and step duration using a controller, this was similar to using the Variac, starting at an output value and then turning the dial to increase or decrease the output but with much better control and accuracy.

As the test kit's controller became more sophisticated it could create more complex injections by combining sequences of these techniques while controlling multiple output signals. These test methods were necessary as the relays became more intelligent, implementing microprocessors and algorithms that required truer simulations. (Fig 6)

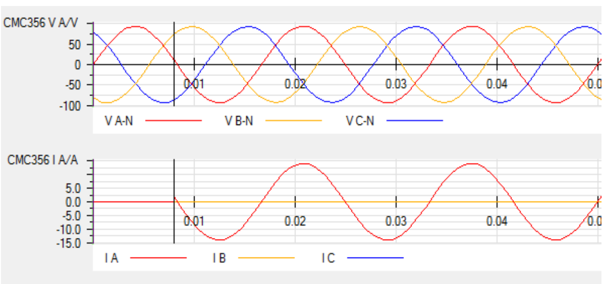

Figure 6 – Multi-Signal Injection @ Power Freq.

However, this too was a short lived victory as the modern digital relays increased in complexity exponentially. In this decade, to test and verify these modern protection relays it requires a near actual power system event or simulation based on correct data specific to the relay's application. Even a once simple single-phase fault must be representative of the actual power system event for the modern relay to operate correctly and be fairly evaluated. (Fig 7)

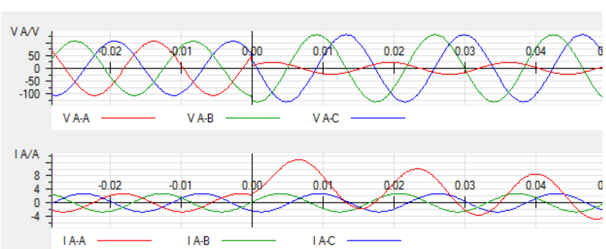

Figure 7 – Simulation with PreFault, Fault, Correct Incident Angle, Transition, and DC Decay

These more realistic fault simulations require a lot more information to construct them, and a very good tool to create them. The days of using the test methods of the Load Box and Variac have gone the way of the sliderule and protractor – functional but not productive today.

To summarize, the test methods that have been used over the years include:

1. Static Injection
2. Step Change of a Quantity
3. Ramp of a Quantity
4. Combination of 1, 2, or 3 in a Sequence
5. Replay of a Recorded Waveform
6. Multi-Signal Injections (including 1-4)
7. Realistic Fault Simulations (Best)

3 Testing Protection Functions

Our legacy testing traditionally applied test current magnitudes with no respect to phase angles (Generally because we were only injecting a single current.) unless voltage was included for wattmetric or impedance tests. But as protection relays evolved into digital protection systems, multi-phase current and voltage injections became the norm, and correct phase angles and fault transitions critical. And if we also add in all the other applied logic functions, like prefault conditions, switch and breaker status, control and interlocking of adjacent apparatus, communications, and other logic status; we nearly have the entire substation configuration to consider. Where previously we had two goals in our tests; one to verify the element characteristic or setting, and two, to verify the relay's calibration - modern digital protection presents us with new testing challenges.

Legacy overcurrent protection elements were/are simple non-directional elements. There were three basic tests performed: 1) minimum pickup of the Overcurrent (OC) inverse element, 2) timing test of the Overcurrent (OC) inverse element, and 3) pickup test of the Instantaneous (INST) element (also verifying its operate time).

The test methods utilized were static output, step change, and ramping. Performing test #1 & #2 were typically much easier than #3 which could require fairly high currents, and using the ramping method often lead to failed Instantaneous coils as the ramped current was applied much too long. An improved test method was to use a Pulse Ramp which would limit the quantity output time to just long enough for the Instantaneous element to pick up, usually about 100mS. During the "off time" the current was put to zero.

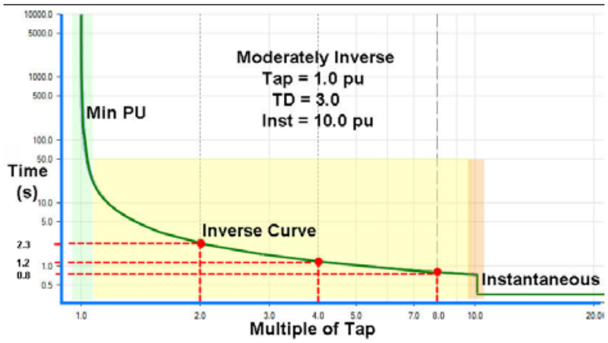

Figure 8 - Overcurrent relay MI characteristic

There are inherently complications with trying to apply the same test methods to a modern digital overcurrent relay. For one, it's not just an Overcurrent relay, as can be seen in Figure 9 the complexity of using modern digital overcurrent protection is that it is a system - with so many protection and control elements being integrated together and today's protection engineers eager to use them.

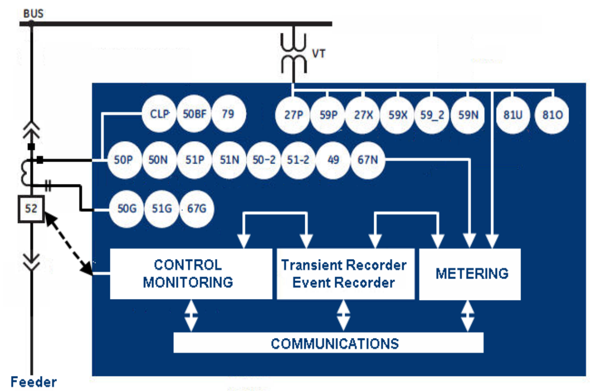

Figure 9 - Digital Overcurrent Protection Relay

There are always multiple elements, logic, and programmed variables applied to tripping masks that are mapped to a single trip output creating conflicts for isolation and testing. (Fig 10)

To properly test just the OC phase (51P) element there are several other conditions that must be met if conflicting elements are to be satisfied and not impact the element timing. Reprogramming it just for testing de-commissions the relay, not a good practice. Using a correct test method resolves the issues.

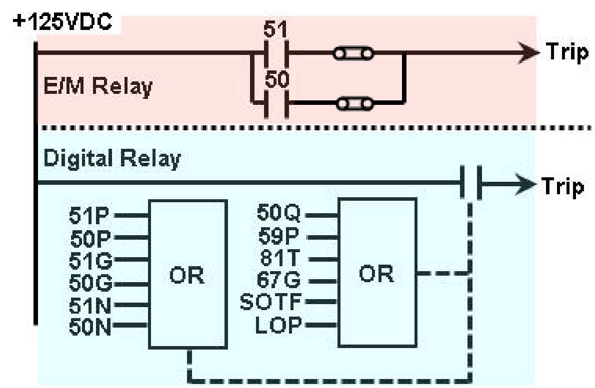

Figure 10 - Tripping Element Comparison

As a minimum, a proper test kit and software tools should provide - 3-phase voltage/current sources with control of magnitude, phase, frequency, and proper fault simulations using a 3-phase power system fault calculator or optionally (Fig 11) single/double ended system models, or a configurable multi-bus/node system model.

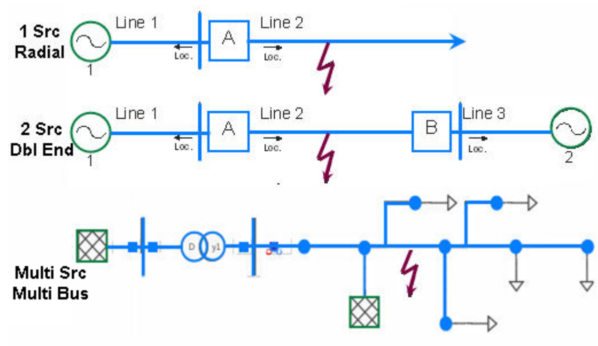

Figure 11 - System Models in Test Software

Using a proper Fault Calculator, 52a simulation, adequate prefault times, and system configuration will allow conflict free testing of the digital relay mapped elements from Figure 10. No reprogramming required, just proper test cases used in context of the application. Switch On To Fault (SOTF), Loss of Potential (LOP), Cold Load Pickup (CLP) Sympathetic Trip (STL) and other logic schemes will not interfere with the element tests and each can be tested easily with correct test cases. Even better, the number of overall tests can be reduced significantly by using a model based system test approach. This saves both time and money.

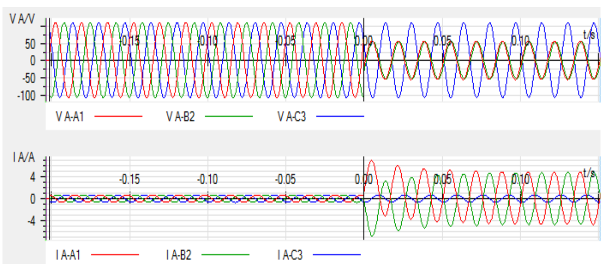

Figure 12 - Fault simulation, radial model of Fig.8

A system test approach also reveals the true coordination of the protection scheme. This is because each part has to pickup/dropout or time out correctly for everything to work as designed. So that means the Overvoltage, Undervoltage, Overfrequency, Underfrequency, Directional, Differential, Distance, etc. elements - and any applied logic conditions must also work correctly. Otherwise the test would fail.

A proper simulation requires all scheme logic AND protection elements to work together correctly. The same efficiencies realized in HV Line Protection End to End testing can be realized for any of today's modern protection relays, and this is especially important for Distribution Automation, and Distributed Energy Resource applications.

It may seem excessive to some to use this system test approach, but if you are presently reprograming and therefore decommissioning any digital relay just to test some element discretely, then who is being excessive?

If performing proper system simulations for routine tests is outside your scope, then at least perform routine testing responsibly and discontinue the excessive and invasive testing procedures of reprogramming your relays.

It would be more effective to perform adequate Acceptance/Commissioning tests and then for routine testing a meter check, I/O verification, file settings comparison, and then actual CB trip check from the relay than continuing a process of using 1970's test methods in your invasive routine testing.

4 Proper Simulations Required

Relays using advanced distance elements have long needed proper fault simulations to properly test them. Using any test method other than a relevant COMTRADE playback or an application specific fault model will never provide the true operational performance of these impedance elements.

This is especially true considering the fact that some of the most commonly used transmission line protection schemes are based on distance elements in communications schemes. Testing such schemes for example on double circuit lines with mutual coupling is practically impossible without the use of a transient simulation based on a network model.

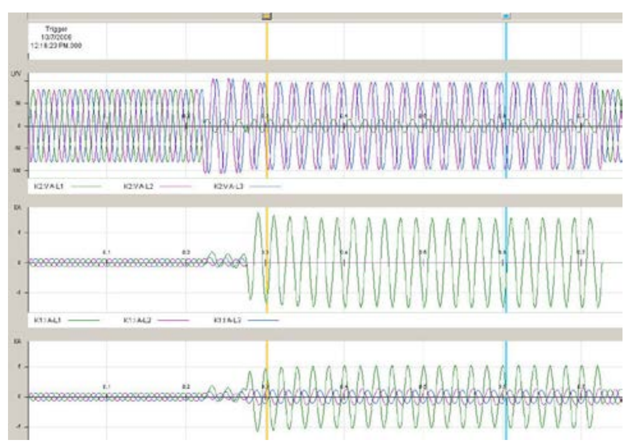

Fig. 13 Single-phase fault with current reversal simulation

Another example of the need of proper simulation for the testing of protection devices with distance functions is the testing of their behavior during power swings, and especially if a fault occurs during the power swing as shown in Figure 14.

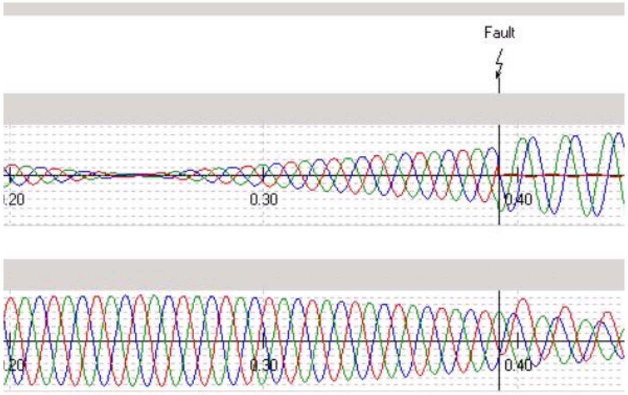

Fig. 14 Power swing and fault transient simulation

5 Conclusions

Now there are traveling wave based protection elements that cannot even be tested with any of the test methods presented. Modern test kits AND the simulation software used with them must evolve yet again in order to provide the proper system waveforms that allow them to operate at all, much less to the point of performance verification.

As digital relays continue to evolve and become more complex, our methods for testing them must also evolve. Legacy test methods cannot properly quantify the health, status, and availability of these complex relays nor simulate the power system adequately in order to prove their operational performance and compliance. Education, training, proper testing tools, and power system testing knowledge are required for today's protection devices.

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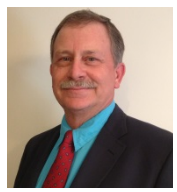
7 Biography



Benton Vandiver III received BSEE from the University of Houston in 1979.

He was with Houston Lighting & Power for 14 years and Multilin Corp. for 4 years and OMICRON electronics for 22 years. He is currently the Technical Sales Engineer for ABB located in Houston, TX. A registered Professional Engineer in TX, he is also an IEEE / PSRC senior member, USNC member, CIGRE corresponding member. He has authored, co-authored, and presented over 95 technical papers and published numerous articles.

Dr. Alexander Apostolov received MSEE, MSAM and Ph.D. from the Technical University in Sofia, Bulgaria. He has 40+ years' experience in power systems protection, automation, control and communications.

He is presently Principal Engineer for OMICRON electronics in Los Angeles, CA. He is IEEE Fellow and Member of the Power Systems Relaying and Control Committee He is past Chairman of the Relay Communications Subcommittee, serves on many IEEE PES PSRC, CIGRE and IEC Working Groups.

He holds four patents and has authored and presented more than 500 technical papers. He is Editor-in-Chief of PAC World.