Can End-to-End Testing Satisfy NERC / FERC?

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Abstract - The paper discusses the typical utility approach to End-to-End testing and the suitability of using those results and documentation to satisfy the current revised NERC/FERC reliability standard PRC-005-2. This testing method provides great operational and economic advantages and analyzing problem areas in a protection scheme. Proper end to end testing techniques can greatly reduce the chances of wide area blackouts due to improper relay system coordination, operation, and application.

The paper provides examples where some End-to-End test cases may not be adequate to cover the requirements of the standard and what improvements should be considered. It focuses on areas where the fault clearing system can be verified using proper End-to-End test cases while avoiding invasive tests that require changing the commissioned status of the system devices - making the overall testing process more economical and beneficial. The paper later describes the engineering reasons why this testing should be "up front" when the fault clearing system is designed or re-designed. Further, new industry standards are discussed that will impact not only the testing of these systems but also the test equipment being used.

Index Terms— Protection system, maintenance, testing, reliability, NERC, FERC, IEC 61850

I. INTRODUCTION

The testing of protection relays plays a very important role toward ensuring the security of the electric power system during abnormal system conditions. Although various test and maintenance philosophies have been used by utilities based on manufacturer recommendations and past operational histories, most were defined by the testing technology available and this resulted in fixed time based intervals and single function testing for most devices. However, this served the industry quite well since testing was usually periodic enough to find problems and avoid major outages.

In the past few decades however, changes in the industry caused by deregulation, questionable business economics, reduction of work force, and subsequent loss of protection knowledge and field expertise caused many utilities and operators to extend or eliminate these test intervals regardless of the need and testing technology available. Introduction of advanced microprocessor based relays were nearly considered "maintenance free" and routine testing was even skipped entirely. Save for a few inconvenient blackouts, this may have become the industry standard practice. But accumulating pressures from government regulatory changes and new reliability rules, plus needs to integrate “green” and/or “smart grid” technologies and systems, and the economic pressure to extend the life of existing infrastructure, mandated re-thinking of the scope of commissioning and routine testing.

Without resurrecting the entire history of NERC/FERC, suffice it to say that grid operators are under federal mandate to operate the power system within certain reliability guidelines. A series of standards define the rules of compliance for each stakeholder within the power system. Our focus is the Bulk Electric System (BES) and the defined maintenance program outlined under the proposed [1] PRC-005-2. At the writing of this paper, this revised form of the proposed standard is scheduled for comment and ballot during March/April 2012 with a recirculation ballot in June, and if passed will require changes to most every maintenance program.

II. Protection System, "Components" and the Fault Clearing System

Protection relays are not the only component of a Fault Clearing System (FCS), even though they are primarily responsible for detecting a fault condition, determining its cause and taking specific action to clear it. They are not the only component that requires maintenance or testing in order to ensure the proper operation of the FCS under normal and abnormal system conditions.

This fact resulted in a new definition of Protection System under PRC-005-2. The NERC approved definition is:

- Protective relays which respond to electrical quantities,
- Communications systems necessary for correct operation of protective functions,
- Voltage and current sensing devices providing inputs to protective relays,
- Station dc supply associated with protective functions (including station batteries, battery chargers, and non-battery-based dc supply), and
- Control circuitry associated with protective functions through the trip coil(s) of the circuit breakers or other interrupting devices.

One of the results of the investigation into the Northeast Blackout of 2003 was the FERC (Federal Energy Regulatory Commission) order 693 [2] and the NERC audit recommendation that the "entire" fault clearing system be tested.

If we analyze the components of a typical FCS (see Figure 1), we see that potential failure of each individual component may lead to a failure to operate (clear a fault) when required, or an undesired operation under normal or borderline operational conditions.

Some of the components of the FCS provide the source measurements of the primary system that are used by the relays to detect an abnormal condition. They include the instrument transformers and the wiring between them and the analog inputs of the relays.

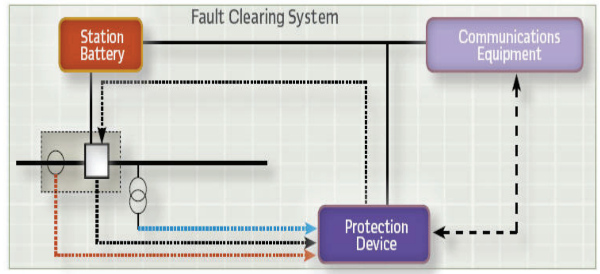

Figure 1: Fault clearing system

Another group of components responsible for the actual fault clearing are the circuit breakers (or switches) and their control circuitry with the protection device and station battery. The station battery also plays an important role, since its failure will result in the complete failure of the protection system if N+1 redundancy is not implemented. (See Figure 2)

Consider an example line distance protection system that is using communications between the two ends of the protected transmission line section. The components of the communications equipment and physical link between the relays are also part of the FCS that must be fully considered even if a true main protection redundancy exists.

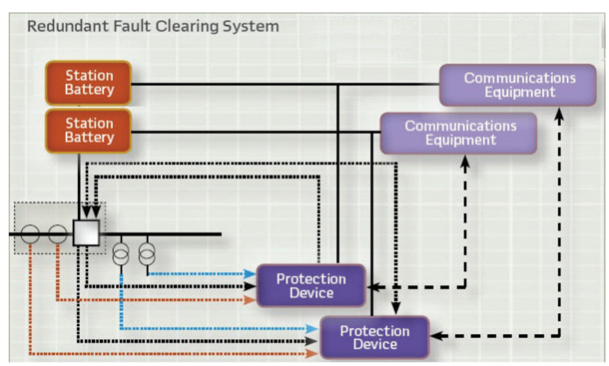

Figure 2: Redundant Mains FCS

Further consideration must be given to the protection device (relay) itself, with its binary inputs and outputs, analog input modules, protection functions, control and logic functions, measuring and metering, etc. Single function testing invokes changing or disabling conflicting elements and settings; this in effect de-commissions the relay and requires more time and tedious effort to accomplish correctly.

Another definition in PRC-005-2 that has a bearing on our test case definition is that of a "component". Whereas a "component" is "any individual discrete piece of equipment included in a Protection System" (noted above); the scope of "control circuit component" is left to how you track and perform testing of that control circuitry. This could be based on apparatus circuitry, local zone of protection, or three-phase vs. single-phase device.

To achieve efficiency, we should set requirements for maintenance or testing of protection relays based in the context of the FCS and not as individual devices. At the same time we need to analyze the reason for the test, since it will determine what levels of testing need to be performed and what test equipment and tools are most suitable to efficiently get the job done.

Modern test equipment must be able to perform all traditional functional tests for legacy devices of course, but should also excel in testing multifunctional IED's including the newest technology of IEC 61850 enabled devices. For our optimization of End-to-End test cases it should also leverage a Network Simulation Tool and COMTRADE playback with high precision GPS synchronization.

From a system or scheme testing perspective the test equipment or synchronized multiples of them must be capable of simulating the entire FCS, this is also an advantage for other systems like a PMU/PDC system or SIPS/WAPS.

III. Traditional Testing Methods

Can traditional relay testing methods be used to comply with the standard? By that I mean the separate test of each relay element to its given setting on a time based schedule?

Absolutely, the standard specifies that for any unmonitored protective relay you must verify the settings are as specified and verify calibration within a six year period. With the addition that for microprocessor relays you verify the unmonitored I/O used by the relay and you verify that it also measures correctly the power system inputs if so equipped.

But the impact is testing ALL your relays within a six year maximum interval. This could be quite a challenge of both manpower and financial impact over your present practice.

What if we want to extend the test interval? The standard allows for a 12 year cycle but it would only apply to monitored microprocessor relays, leaving legacy relays still under the six year cycle. Plus the effort of testing them functionally is still essentially the same.

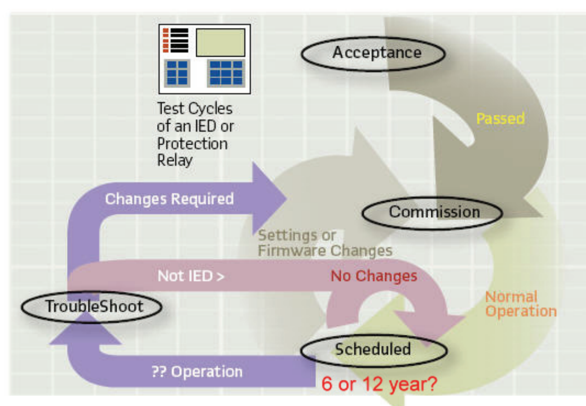

Figure 3: Traditional IED/Relay Testing Cycle

The only way to reduce the testing burden is to have monitored microprocessor relays that incorporate the defined continuous monitoring and alarming requirements in the standard. Then, only unmonitored I/O and control circuitry would have to be tested within the 12 year cycle.

IV. ADVANTAGE OF END TO END TESTING

Still, legacy tests on the relay functional level do not really add value to the overall availability and reliability of the Protection System, nor do these tests prove anything on the ability of the overall FCS to function as required. For that we must expand our testing scope to the system level, this is where End-to-End tests can be most beneficial.

Some have been using End-to-End testing in their commissioning phase to improve their odds that the overall line protection scheme works as designed, a "system check" if you will. However, static state sequences, over-simplified network models and non-dynamic system and operational test cases will limit the true value of these test results for proving the protection device and FCS.

End-to-End test cases limited to just basic zone operations, (10%, 50%, 90%) of a typical step distance scheme using step change sequences are still better than functional element tests, (assuming proper acceptance testing is performed) but lacks in providing key scheme performance benchmarks and exercising internal logic schemes. Even so, the analysis of even these simple tests provides far greater insight into the operational health of our example line protection system than not doing them. Further, they would meet many of the requirements for verifying the "control circuitry component" part of the standard's specification:

- The communication system's operation,
- The protection relay's internal logic,
- The unmonitored I/O of the relay scheme,
- The Station DC Supply circuitry

This optimization of testing effort can reduce the testing time by over 60% alone over functional tests and applies to both legacy relay systems and microprocessor relay systems too. (Figure 4) Only a correct group of End-to-End test cases will catch problems with internal logic, interconnection issues of legacy relays, and interlocking between panels and other devices.

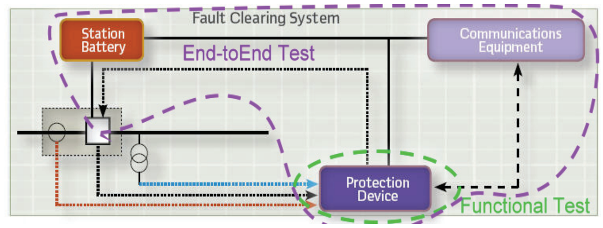

Figure 4: Scope of Tests on FCS

A key requirement for doing any testing is the reason for the test and accuracy of the test data used. The intent of the standard is to ensure the proper operation of the Protection System for the BES reliability. As such, the tests we want included in the End-to-End test cases should depend on what best satisfies our requirement to prove that the Protection System is operating as designed.

For instance, if we use a communication based protection scheme (i.e. POTT) we should include the minimum six test cases that would prove it is functioning correctly. But if the echo logic or weak infeed logic is enabled, then there are two to three additional test cases required. In addition to these, there are other protection logic schemes to consider and each will require specific test cases to prove them.

IEEE Standard C37.233 [5] is a great reference to consider when determining these system test cases. Although, not a specific requirement of PRC-005-2, if End-to-End testing is to be effectively used for compliance this would be a cornerstone of your documentation for doing them.

V. TEST CASES FOR INCORRECT PROTECTION SYSTEM OPERATION

One issue of compliance is documentation of the Protection System Maintenance Program (PSMP) which comprises activities to Verify, Monitor, Test, Inspect, and Calibrate your Protection System. There is no direct requirement to test for potential or unknown issues. However the implication is there because the owners/operators are to design, build, and implement a reliable Protection System for the BES and proof of that design's operation is required.

Problems of the different elements of the FCS can be of two main types – if the system does not operate when it has to and if it operates when it should not. These two types of problems are usually detected when the system is in service and an event occurs.

- Failure to operate

Failure to operate under fault conditions may have severe impact on the stability of the electric power system due to the increased duration of the fault caused by the operation of backup protection functions or the switching-off of healthy system components. An example (see Figure 5) of this would be a fault occurring during a power swing when the protection system is set to block tripping, but when the fault occurs it should then trip, but does not.

- Undesired operation

As many system disturbances and blackouts have shown, one of their main causes has been operations of the protection system under non-fault conditions. These failures also need to be prevented since they may also have a negative impact on the stability of the BES and result in deterioration of the conditions that promote a wide area disturbance.

The problem operation needs to be analyzed in order to determine what happened and some corrective action taken to prevent future incorrect operation of the Protection System. Further, if this misoperation involves a "Segment" which is defined as a group of at least (60) individual "components" of a particular model or design; then a required change to one such Component (say a firmware update to correct the problem) may have to be implemented to the entire Segment to stay in compliance. Documentation and tracking of this would be a critical point of compliance.

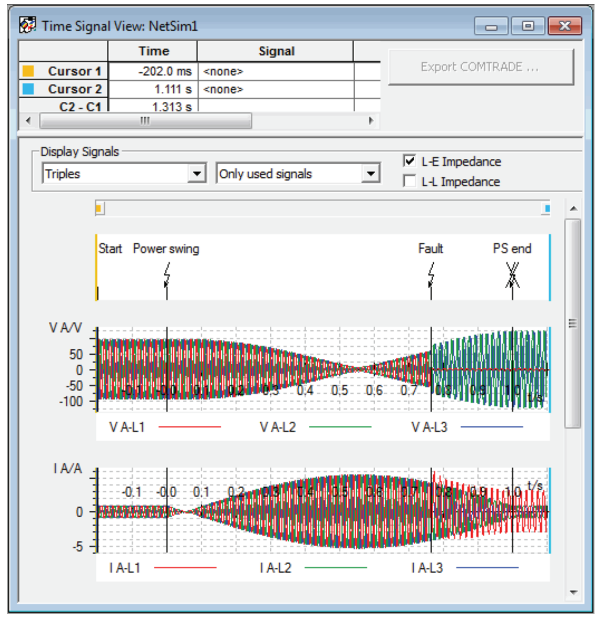

Figure 5: Asynchronous Power Swing w/Fault

The example makes the point that it would be better to know such issues, deficiencies, or limitations prior to system wide implementation of this "component". And this makes the point for improved and more detailed system testing both in the lab and in the field. If such testing is performed – say in the lab – to prove a device or scheme as suitable for the system, then a subset of these lab test cases would be appropriate as part of the End-to-End test case portfolio for routine testing, particularly when other modifications or updates of the FCS are made.

In some cases, a recorded disturbance or particular event occurs in the system and this is identified as a critical test case for a line protection system. for example, a double circuit line in a common right of way experiences a fault and causes a trip of the unfaulted parallel line. These protection settings can be easily verified and a misoperation avoided with a proper End-to-End test case of the logic. (Figure 6)

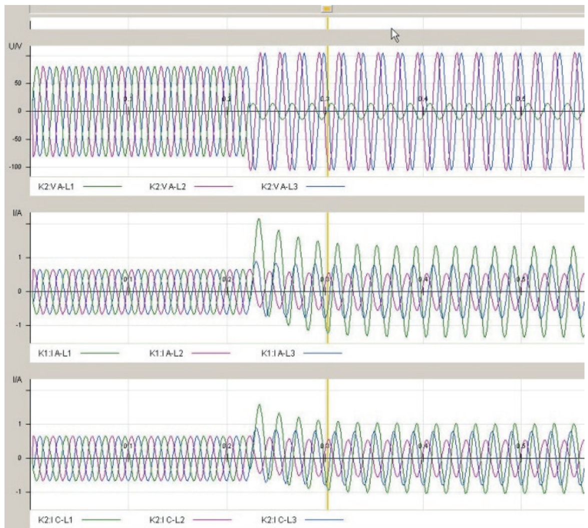

Figure 6: Waveform record - double circuit line

The end-to-End tests in this case can be based on replay of recorded waveforms from actual Disturbance Recorders or based on accurate system models used in adequate Network Simulation software. The same files used to determine the cause of the incorrect operation, or some other test issue can be used to verify changes in settings or programmable scheme logic that corrects it.

VI. IMPACT OF IEC 61850 ON PRC-005-2 COMPLIANCE

Understanding the engineering principles of IEC 61850 and especially the peer-to-peer communications used for protection can significantly change the requirements for routine testing.

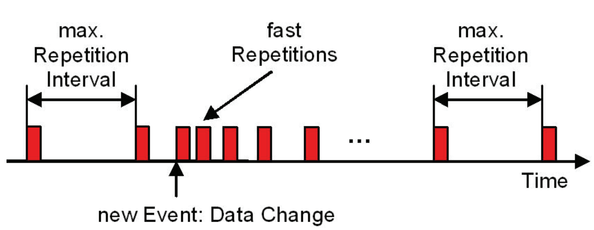

Figure 7: GOOSE repetition mechanism

GOOSE messages are used in IEC 61850 based applications to replace the hard-wiring between different components of the traditional FCS. Since they are used for protection and control applications that require high reliability and availability, IEC 61850 introduces mechanisms that ensure the delivery of the required information. As shown in Figure 6, at the new change event the interval is very short – a few milliseconds, which later increases until it reaches a value of one or a few seconds. This method achieves several important tasks:

- Ensures that a loss of a single message is not going to affect the functionality of the system
- Allows any new device to inform all subscribing devices about its state
- Allows any new device to learn the state of all publishing devices it subscribes to
- Allows any device requiring information from a publisher to supervise that the publisher is still alive, even if no change event occurs

From the point of view of maintenance, it allows continuous monitoring of the connections between all devices that are part of the substation protection, automation and control system, i.e. instead of the need for periodic testing of the hard-wired connections; we can use monitoring tools to ensure that the communication links between all devices are working as required. This also provides for an automatic "wire-break" monitoring capability.

The case with process bus connections is a little different due to the publishing mechanism used. In this case there is no repetition mechanism but a continuous stream of new sampled values (SV) – in the case of devices implementing the agreement defined in IEC 61850 9-2 LE it will be 80 samples/cycle, i.e. one message every 250 microseconds. Loss of any sampled values can be detected by the communications monitoring system, thus ensuring the required levels of reliability and availability.

VII. END-TO-END TESTING WITH IEC 61850

If one has access over the network to all such GOOSE and SV messages from the various Merging Units, IEDs and Bay Controllers, then it is easy to imagine how future End-to-End testing could cover almost the entire FCS. Since virtually all status and measured data is there, it only requires the correct test tools to realize the test cases for the defined system. Since this technology will lend itself to much higher monitoring capabilities – compliance will require more focus on problem identification, notification and correction with appropriate follow-up documentation. The IEC-61850 based FCS (see figure 8) will present new challenges as the move from hard wired systems to messaging systems redefine the testing requirements as known today.

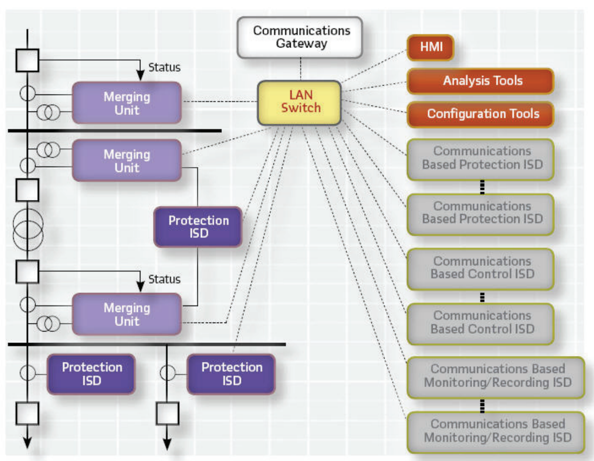

Figure 8: IEC-61850 Based FCS

VIII. CONCLUSIONS

Maintenance testing plays an important role in the asset management of today's fault clearing system. Changes in government regulations have significantly impacted what and how utilities and grid operators handle maintenance testing and documentation. The fundamental principles for Maintenance testing should be performed according to the reason for the test.

Where monitoring is not possible the use of End-to-End Testing can greatly improve the economics of scheduled testing and provide better quality information for Protection System assessment. Proper consideration for test cases is required to establish performance benchmarks that confirm the FCS design and operation. Properly applied and documented – Yes, this test method could help satisfy required testing compliance.

New technology and proper use of all monitoring functions [6] available in state-of-the-art multifunctional protection IEDs allow a significant reduction in the requirements for intrusive scheduled testing and covers not only the protection devices themselves, but also other components of the FCS.

IX. REFERENCES

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[6] A. Apostolov, B. Vandiver III: "The Primary Reason for Adopting System Testing Methods", PAC World Conference, Dublin, Ireland, June 2011.

X. BIOGRAPHIES

Alexander Apostolov received a MS degree in Electrical Engineering, MS in Applied Mathematics and Ph.D. from the Technical University in Sofia, Bulgaria. He has more than thirty years experience in the field of electric power systems protection, control and communications.

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