Transient Testing of Protective Relays: Study of Benefits and Methodology

Final Project Report

Power Systems Engineering Research Center

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PSERC Publication 08-05

March 2008

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Power Systems Engineering Research Center

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Acknowledgements

We wish to thank the industry advisors that actively participated in the discussions during the course of this project: Bajarang Agrawal (Arizona Public Service), Ali A. Chowdhury (California Independent System Operator), John Horwath (Exelon), Joseph Hughes (Electric Power Research Institute), Richard Hunt (NxtPhase), Bill Middaugh (Tri-State Generation and Transmission), and Don Sevcik (CenterPoint Energy).

Graduate students and research staff who carried out project activities over the years were Jinfeng Ren and Chengzong Pang (Texas A&M University); Q. Binh Dam, George Stefopoulos, and Dr. George Cokkinides, Visiting Professor (Georgia Institute of Technology); and Miaolei Shao and Piyasak Poonpun (Wichita State University).

Executive Summary

The operational security of the power system depends upon the successful performance of the thousands of relays that protect the system from cascading failures, that protect equipment, and that help balance load with generation when system frequency is too low or too high. The failure of a relay to operate as intended may jeopardize the stability of the entire system and equipment in it. In fact, major system failures after a disturbance are more likely to be caused by unintended protective relay operation rather than by the failure of a relay to take an action at all.

Appropriate relay testing provides one line of defense against relay failures. Relay testing can help validate the design of relay logic, compare the performance of different relays, verify selection of relay settings, identify system conditions that might cause unintended relay operation, and carry out post-event analysis to understand the causes of unintended or incorrect relay actions.

Relay testing improvements need to continue because of the new demands placed on relays from power system conditions that are more variable in the past, because of high customer expectations for power delivery reliability, and because of changing relay technologies. The research described in this report describes new approaches for testing distance relays, generator protection relays, and underfrequency load shedding relays. Results are provided for actual relay testing.

Part I: Distance Relay Tests (Texas A&M University)

Distance relay testing can evaluate relay performance, calibrate relay settings, and identify system conditions that could cause unexpected relay operation. Developing a relay testing methodology requires consideration of how to model the power system to simulate specific system disturbances, how to select and generate test scenarios, and how to execute relay tests efficiently. The efficiency and effectiveness of relay testing can be enhanced with a test case library containing scenarios that enable consistent yet robust testing. In this research, a laboratory was used to test three different distance relays using a proposed test methodology with associated test tools and test case library. The testing focused on protective relay operation under transients. Conformance and compliance tests were conducted.

- *Conformance Test*: The objective is to test the basic functionality of a relay, to verify is operating characteristics, to calibrate the relay settings, and to implement periodic maintenance testing. Statistical performance data are collected on relay operating characteristics and tripping times using wide-ranging disturbance conditions generated through simulation.
- *Compliance Test*: The objective is to test if actual relay performance matches expected performance under atypical yet possible power system conditions. The trip/no trip responses and relay operating time performance are measured under specific scenarios. Compliance tests can be used in a post-event analysis to analyze the causes of an unwanted relay operation

The IEEE Power System Relaying Committee (PSRC) reference model and IEEE 14-bus system were used to simulate disturbance scenarios. Software programs were developed for automated testing for creating test cases, executing batch tests, and

collecting relay event reports. The test case library included test scenarios, records from digital fault recorders (DFRs) and blackout scenarios of interest.

Test results provided information that was not documented in the relay manuals, and that definitely could affect proper coordination and performance of the relaying schemes. The conformance test results indicated that relay operating characteristics should be carefully selected applied to improve the dependability of the relaying scheme. The compliance test results indicated that the zone 3 relays operated incorrectly in a few unusual power system operating conditions. Thus, quadrilateral operating characteristic may be needed to assure correct relay responses.

Part II: Generator Relay Tests (Georgia Institute of Technology)

Protective generator relays are usually tested against simplified generator models or simplified test signals. Many factors may vary with the location and generator, including the impedances of the network to where the generator is connected to, operating point, grounding arrangements, etc. The testing also should ensure that the settings of the relay are consistent with the intended protection scheme. Generator relay tests using realistic models of the generator and the electric power system can verify consistent behavior of a relay regardless of the protected generator, and assert that the intended protection schemes are robust for a variety of fault conditions.

A comprehensive testing platform was built to reproduce and simulate conditions in the system as close to reality as possible. The platform included (a) a power system simulator to accurately compute short-circuit conditions as seen in an actual system by the protective relays; (b) a signal conditioning unit that reproduces the simulated voltages and currents at relay instrumentation voltage and current level, as if they were delivered by actual potential and current transformers; and (c) a set of procedures to conduct and validate the different tests of the generator relay, including relay connections, software configuration, and different test scenarios. A comprehensive set of generator transient events were created to exercise all the functions of a modern generator relay.

For accurate testing, as many common characteristics of all generators are needed to simulate generator responses that are as close to field observations as possible. To achieve the highest accuracy possible, the software platform included a full time domain, transient, two-axis synchronous generator model with access to generator windings for fault creation in the windings.

The simulation software models the power system more accurately than most other existing approaches. The simulation software is based on full three-phase models of power system components that are described by their physical parameters. The simulator accurately simulates the dynamics of the models by using the quadratic numerical integration method, which is more precise compared to other methods commonly used methods in power system analysis.

Using virtual relay testing, configuration and waveform data were sent directly to the inputs of the relay functions, and the relay outputs were processed on the host computer with the benefits of specialized analysis software. Virtual testing facilitates relay testing by eliminating the constraints of a hardware setup, including waveform generation, wiring, and communications.

Comprehensive transient testing was conducted on two different generator protective relays. The detailed results are given in the report.

Part III: Underfrequency Load Shedding Relay Tests (Wichita State University Researchers)

If insufficient generation is available on the system to maintain stability, non-critical loads can be removed (or shed) from the system to restore a balanced condition. Such methods of automatic load shedding are designed as a last resort to prevent a major system outage. Underfrequency load shedding (UFLS) relays detect overload conditions by sensing low system frequency and shedding enough load to rebalance generation and load, and reestablish the nominal frequency. UFLS relays are able to automatically restore load after frequency recovery. UFLS is an effective and reliable method that helps to prevent blackouts.

A review of the *Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations*, prepared by the U.S.-Canada Power System Outage Task Force, indicates that, during the cascading events leading up to the widespread blackout:

- UFLS relays operated properly, according to their settings
- Settings for some UFLS relays may not have been appropriate for their applications
- Regardless of settings, load shedding by UFLS and undervoltage relays would not be expected to mitigate the magnitude of events that occurred during this disturbance.

While UFLS relays appeared to operate as set during the 2003 blackout, a number of issues regarding their operation were nevertheless identified. These issues, which are not addressed by conventional relay test methods, include the effects on relay operation of:

- Rate of change of frequency
- Continuous, rather than step, changes in frequency
- Rapid fluctuations, including both increases and decreases, in frequency
- Overfrequency events
- Other events identified by simulation or recording of actual events.

To address these issues, two test protocols, which go beyond those tests usually performed using commercial UFLS relay test systems, were developed. The conformance test protocol subjects a relay to a series of tests whose values are determined by the relay specifications. The application test protocol subjects the relay to events generated through simulations of a typical system using electromagnetic transients software. A third set of tests can also be performed if actual recorded event data is available. Recorded events can be played back in the laboratory to determine relay response to actual events.

Both conformance and application tests were performed on two commonly-used digital UFLS relays. Relay response was out of manufacturers' specifications for some of the tests. Industry team members indicated, that the magnitude of the errors identified were well within tolerances expected by industry, and that such errors had no practical effect on the relays' abilities to shed load as expected during underfrequency events.

Future Work:

It has been recognized that forming a library of test cases using records from blackouts or common power system model would be quite beneficial. Developing methodology and tools for both laboratory and field testing aimed at evaluating how GPS synchronized IEDs, including relays, will perform under various operating conditions is also needed.