WECC

White Paper on Model Power System Testing

Relay Work Group

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Executive Summary

This document was developed by the Relay Work Group to emphasize the need for model power system testing of protection and control schemes applied to the Bulk Electric System (BES) and to provide a helpful guide to setting up the system model and conducting the tests.

Model power system testing is a valuable tool to use when evaluating the overall performance of a protective relaying scheme because it tests the hardware, relay algorithms, relay firmware, settings, configuration, speed of operation and transient performance of the scheme. This type of testing is strongly recommended for BES protection schemes. The response of these schemes cannot be evaluated analytically or by conventional test methods due to the complex interaction of various power system components during faults and the high-speed communications schemes required. Also, model power system testing provides a good measure of the overall dependability and security of the scheme.

The recommendations contained in this guide are the result of experience of members of WECC Relay Work Group in trying to obtain acceptably reliable relay equipment for use on systems that may include equipment such as heavily loaded long lines, series capacitors, flexible AC transmission systems (FACT), and shunt reactors especially for BES or bulk transmission applications, including HVDC. If a WECC member decides to perform model power system testing, there are certain items that must be considered during the planning and execution of model power system testing to have meaningful test results. Therefore, the language in this guide specifies items that should be done or must be done to assure a more successful model power system test even though they are not requirements.

Introduction and Purpose

The purpose of this guide is to aid WECC members in the use of model power system testing to evaluate the transient performance of protective relaying systems. This guide describes the benefits of testing, items that should be considered during the planning of tests, and the subsequent evaluation of relay system performance. This guide is the result of experience of members of WECC Relay Work Group in trying to obtain acceptably reliable relay equipment for use on systems that may include heavily loaded long lines, series capacitors, and shunt reactors especially for BES applications.

Model power system testing of protection scheme applications check that operating speed, relay settings, algorithms, scheme configuration and hardware performance meet power system dependability and security requirements. Telecommunication system characteristics must be carefully modeled in the testing since modern BES protection schemes depend heavily on telecommunication signals or data.

General

The desired performance of relay systems can be calculated for steady state conditions using manufacturers' published information and the calculations verified by established test methods. However, the performance of the relay system during transient conditions (i.e., power swings, inter-area oscillations, subharmonic oscillations) cannot be completely evaluated analytically or by conventional test methods.

Transients may originate in the high voltage system where their magnitudes and durations are a function of the X/R ratio of the system. Many power system operations generate transients. The principal transients that affect relay performance occur during:

a. Fault inception and fault clearing.
b. Developing faults such as evolving or cross-country faults.
c. Series capacitor bypass and insertion operations.
d. Large source impedance ratios (SIR).

Primary transients affect the secondary circuits through common electrical connections, electromagnetic induction and electrostatic coupling, as well as the transformation through current and voltage transformers. Other transients, which are not considered further in this guide, may originate in the control and secondary circuits.

Power swings, inter-area oscillations, or subharmonic oscillations may originate in the high-voltage system where power flows are rapidly changed due to fault clearing or other switching. The principal oscillations that affect relay performance occur during and after:

1. Fault inception and fault clearing.
2. Intertie or system separation

3. Major Load/generator tripping events
4. Remedial Action Scheme operations
5. Off-nominal Frequency or Voltage load/generation tripping events

For transient or power swing testing purposes, a computer-based power system model can be used to simulate the conditions of an actual transmission system. The relays under test are connected to the model as they would be on an actual power system including applicable telecommunications system performance and delays. The model can be used to duplicate switching and faults, thus subjecting the relay system to transients and power swings that it would be subject to when in service. Useful evaluation of a relay's transient or power swing performance depends on the careful system representation in the model system. The model power system testing should also be used to confirm all aspects of the algorithms being used in the application of modern computerized relaying schemes.

The advantage of model power system testing is that it provides a means of thoroughly investigating the transient and power swing performance of the relay system, without subjecting the system to primary fault conditions. Model power system testing permits many easily accomplished variations in:

1. Fault location
2. Fault type
3. Fault incidence angle
4. Fault impedance
5. Source impedance magnitudes
6. Source impedance ratios; Z1/Z0, X/R, etc.
7. System configuration
8. System hardware performance; stuck breaker, communication failure, etc.
9. System loading conditions

However, the accuracy of the computer-based power system model is paramount in ensuring acceptable results.

System Representation

The power system parameters, as viewed from the relay terminals, for the testing should be as close a representation of the actual system as practicable. The user and manufacturer must agree on the representation used.

1. Source impedance; positive, negative, and zero sequences (normal system and unusual configurations, weak feed, etc.).
2. Generator and motor machine models, including excitation and governing systems.
3. Positive and zero-sequence line impedances.
4. Positive and zero-sequence shunt admittances.
5. Mutual coupling between lines.

6. Series capacitors; location, reactance, gap flashing, metal oxide varistor (MOV), and reinsertion magnitudes and times.
7. Shunt reactors; location, reactance and excitation characteristics.
8. Power transformer impedances and winding configurations.
9. Steady state active and reactive power flows.
10. Capacitive coupled voltage transformers, potential transformers, and current transformers
11. Power circuit breaker dissymmetry:
    a. Normal pole timing difference in closing and tripping (set at maximum specified by manufacturer)
    b. Power circuit breaker with stuck pole
    c. Single-pole tripping
    d. Presence of closing resistors, point on wave control, or staggered pole closing
12. Phase impedance dissymmetry:
    a. Untransposed lines
    b. Unsymmetrical series capacitor gap flashing or MOV conduction
    c. One-phase out of service in a three-phase bank of shunt reactors

NOTES:

1. The relay input current magnitudes must be the same during testing as in service on the power system. Considerations should be made regarding the accuracy of amplifier test sets (if used) and the simulator to relay interface. The output of the simulator may inject low level voltage and current signals directly to the relay processor boards bypassing the CT and PT input modules and analog/digital converters in microprocessor relays.
2. For tests on impedance relays, both the secondary currents and impedances must be the same during testing as in service on the power system.
    a. The use of different relay taps to compensate for model discrepancies can cause differences in transient performance between model tests and the power system.
    b. The relay current magnitudes affect the relay operating speeds.
3. It is very important that the model X/R ratio be the same as the power system X/R ratio.
4. The actual telecommunications channel delays should be included. However, if practicable, the actual system equipment should be used.
5. Modeling of generators is preferable, although this may not always be feasible, to using system equivalents since the machine dynamics will increase the accuracy of transient oscillations and power swings.
6. A model built out at least two buses from the system under test should provide sufficiently accurate results.

Preparation for Model Power System Testing

Prior to the actual testing of the relay system on the model line, considerable preparation is required as follows:

1. Obtain specifications of the power system model that will be used for testing. These specifications should include:
   a. Possible transmission network configurations
   b. Transformer and regulator taps/steps
   c. Primary voltage
   d. PT and available CT ratios
   e. CCVT response and CT excitation characteristics
2. Prepare a traveling wave, pi, or sequence impedance model built from the physical conductor parameters and tower geometry of the protected line and its associated power system, including the following parameters:
   a. Positive and zero-sequence line impedance
   b. Positive and zero-sequence shunt admittance
   c. Mutual coupling to other lines
   d. Shunt reactors; location and reactance
   e. Series capacitors; location and reactance
   f. CT arrangement accounting for dual breakers or inclusion of line reactor
3. Flexible AC transmission systems (FACT); location and reactance
4. Verify source impedances; positive, negative, and zero (for normal and abnormal system configurations)
5. Determine the following:
   a. Series capacitor gap flashing and reinsertion levels and times
   b. Maximum and minimum anticipated steady state active and reactive power flows through the protected line
   c. Maximum anticipated steady state voltage angle across the protected line
6. Verify fault current accuracy compared against known short circuit values:
   a. At the buses at each end of the line
   b. At various points in the protected line including at least very close-in to terminals and At impedance zone transitions
   c. External faults of special interest to ensure security
7. Verify transmission line impedances match with known values used in short circuit studies or power flow/stability studies. If the power system model results do not match the short circuit studies the following steps may aid in troubleshooting:
   a. Convert the impedance diagramto relay secondary equivalents using the planned in-service PT and CT ratios for the relay system that is to be tested.

b. Select the model elements that are the closest to the corresponding equivalents
c. Prepare a primary impedance diagram of the model using the elements selected.
d. Prepare a secondary impedance diagram of the model using the PT and CT ratios.
e. Verify that the relay system secondary currents for faults on the power system model correspond to those in Item 6 above.
f. Evaluate the model in the following manner:
g. Compare relay secondary impedance as was determined in Item above.
h. Compare the relay secondary currents for the studies of Item e above.
i. Change the model if necessary to minimize the differences in currents and impedances between the relay quantities on the model and the power system.

Test Conditions

The following list of test conditions is intended to provide sufficient data for comprehensive evaluation of a line relay system. All the tests listed may not be required for the evaluation of any particular system. For some special cases, there may be additional test conditions or variations not included in this list.

Model power system testing requires either injecting secondary voltages and currents into the equipment or injecting a DC signal directly into the equipment's control board, bypassing the analog/digital converters. Injecting secondary voltages and currents into the equipment may require the use of amplifier test sets and, depending on the amount of fault current, the test set may not be able to inject enough secondary current for every test scenario.

All the following tests should be monitored, and the relay performance documented with oscillography at each relay terminal under test. At a minimum, the output should record the relay currents, relay potentials, time marker, relay trip output, and appropriate communication equipment and channel quantities. Additional data to be recorded should be specified at the time of arrangements for the model testing.

1. Test all four fault types (single-line-to-ground, double-line-to-ground, phase-to-phase, and three-phase) at each fault location available in the model and other combination faults as desired. Fault location increments of 5-to-10 percent are typical.
2. Test at 30° increments of fault incidence angles from 0° to 90°. Testing at 30° increments provides minimum and maximum offset due to X/R and a few points in between. This technique searches for the most difficult relay operating conditions. In addition, these tests should be performed for the maximum- and minimum-expected steady-state active and reactive power flows on the protected line.
3. Test with fault conditions for the effect of series capacitors on the relay performance. The fault and series capacitor locations should be both internal and external to the line section. The series

capacitor performance under fault conditions is of importance and all conditions should be investigated including:

   a. Normal gap flashing/bypassing
   b. Gap not flashing/not bypassing
   c. Unsymmetrical flashing on faults and insertion attempts
   d. Metal Oxide Varistor conduction

4. Test for sequential faults; i.e., external followed by internal faults.
5. Test for breaker failure protection operation at each terminal if included in the relay system.
6. Test with evolving faults such as single-line-to-ground evolving to a double-line-to-ground within the relay operating time.
7. Test for fault current reversals that may occur during sequential tripping of a parallel line.
8. Test with open conductor line faults, with and without power flow and with and without simultaneous ground faults. This often isn't a concern at EHV levels which usually consist of 2, 3, or 4 bundled conductors.
9. Test with variation in fault resistance (arcing fault or high ground resistance).
10. Test by closing into:
    a. A fault on the protected line at one terminal
    b. An external fault on a parallel line
11. Test with zero voltage fault.
12. Test for the effect of current transformer saturation or difference in current transformer performance at each terminal. A configuration at one terminal having two or more parallel current transformers to provide one input to the relays is of particular concern when one of the current transformers saturate.
13. Test for the effects of capacitor voltage transformer transients on the relay system.
14. Test for the effects of noise, attenuation, frequency translation, and delay times on the pilot relay communication channel.
15. Test with variation in source impedance values at each terminal.
16. Test for response to out-of-step swing conditions if the model power system has the capability to simulate this condition.
17. Test with variation in line compensation values where compensation can be switched.
18. Test for the effect of variations in fundamental frequency of current and voltage inputs to the relay. (Under an islanded condition the frequency may vary as much as + 3 Hz.)
19. Test for the effect of subsynchronous currents in series-compensated lines during fault conditions with variations in source impedance values at each terminal.
20. Test single-pole tripping functionality (if applicable) including the following:
    a. The protection selects the faulted phase and initiates single-pole tripping for internal single-line-to-ground faults

b. The protection initiates three-pole trip if an internal fault occurs on another phase during the open-pole period (evolving fault)
c. The protection is secure from misoperation due to an external fault during the open-pole period
d. The protection is secure from misoperation due to unbalance during the open-pole period
e. The secondary arc extinguishes on the line prior to the automatic-reclosing attempt

21. Test automatic reclosing functionality (if applicable) including:
    a. Three-pole reclosing following three-pole trip operations for which reclosing is intended
    b. Single-pole reclosing following single-pole trip operations
    c. Three-pole reclosing following conversion of a single-pole trip to a three-pole trip due to an evolving fault if reclosing is intended for this situation
    d. Reclose blocking for applicable conditions
    e. Reclosing onto a permanent fault
    f. Reclosing successfully then initiating a fault, between lead/follower terminal closing and after follower terminal closing
22. Test time-delayed tripping functionality for loss of communication including:
    a. Directionality, if applicable
    b. Coordination with adjacent protection

Version History

Modified Date	Modified By	Description
September 7, 2022	EPAS	EPAS Approval, Recommend RRC Approval of Document
December 9, 2022	RWG	Approved Revised Document
October 2014	OC	Approval of Document
August 2014	TOS	Recommends OC Approval of Document
July 3, 2014	RWG	Approved Guideline/Redlines

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