A New Approach to Distant Relay Evaluation Using Digital Simulators

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Abstract: This paper presents a new methodology for testing of distance relays for transmission line protection. Design and application testing approaches using phasor and transient test waveforms generated by modern digital simulators are outlined Extensive one-terminal and two-terminal tests have been conducted on five different relays using the new methodology. Test procedures and results are discussed in the paper.

Keywords: Protection, Relay Testing, Simulation

1. INTRODUCTION

Typical protective relay testing procedures described in the relay manuals are related to confirmation of the settings. This, in turn, reduces to the testing of the relay operating characteristics. This type of testing is conveniently done using standard portable test sets. A comprehensive set of guidelines for such a test methodology exists in the literature [1].

Recent developments in the digital simulator area have enabled implementation of more elaborate approaches to relay testing [2]. The "true' phasor testing can be performed without the pseudo-transient approximations presently introduced by the standard test sets [3]. In addition, actual fault transients can be generated either by using electromagnetic transients programs or replaying actual fault waveforms recorded by digital fault recorders [4]. The new simulator designs also provide for both single terminal and multi-terminal testing. This feature enables back-to-back testing of the overall relaying system such as a line protection scheme with relays located at each line terminal and connected via a communication link [5].

The reduction in cost achieved through the use of the digital technology led to the development of real-time digital simulators [6]. This provides for an additional possibility of testing the real-time interactions between the relay and the power system such as found when testing transmission line relays with auto -reclosing features.

As a result of the digital simulator developments, a new methodology for relay testing is made possible. This paper illustrates the application of the new methodology to the testing of distance relays for transmission line protection. A comprehensive phasor testing has been performed on five different distance relays from various vendors [7]. In order to perform such testing, a new software package had to be developed and used with an advanced digital simulator design. The background theory for the software and the implementation details for the simulator design are discussed. The most interesting test results are also shown.

The same distance relay batch is used to perform transient testing. The EMTP based models of actual power system sections are developed for this testing. The modeling details and the simulator implementation of the transient testing are summarized in the paper. Again, some of the most interesting test results are also outline.

2. PRESENT RELAY TEST PRACTICE

2.1. Relay Test Equipment

Passive, active and computerized test sets are the commonly used test equipment by utilities based on a recently survey conducted by an IEEE Power System Relaying Committee working group [8]. Passive test sets are referred to equipment comprised of load boxes, phase shifter, etc.; while active test sets are referred to electronically regulated voltage and current source. Most utilities have only steady-state test equipment while some utilities have dynamic test equipment capable of simulating prefault but not being able to produce DC and transient waveform components.

2.2 Relay Test Method

Tests for power system protective relays can be divided into type tests and individual tests. Type tests are normally performed once on a given type of relay. Individual tests are performed on individual relays for acceptance, commissioning and routine maintenance. Acceptance testing is usually described in the relay manuals. Utilities typically require tests of each relay before the relays are placed in service. These tests are referred to as commissioning or installation tests. Routine maintenance is performed periodically with a specified interval between tests. The topic of this paper mainly focuses on type test rather than individual tests. Although there is no international standard on type tests, a comprehensive set of guideline for existing type test method have been outlined in literature [1]. In the CIGRE report type tests are divided into steady-state test, single-source and double-source tests.

3. NEW TEST METHODOLOGY

The new methodology developed in this paper takes the advantages of the development of modern digital simulators. It is divided into phasor tests and transient tests. Both phasor and transient tests are subdivided into one-terminal and two-terminal tests. They can be also categorized as design and application tests.

3.1 Availability of New Test Equipment

New digital simulators for protective relay testing have been developed all over the world in recent years [2]. Flexibility of generating phasor and transient test waveforms using different electromagnetic transient programs available on the markets, including EMTP (EPRI, BPA), ATP (American-Canadian-European User's Group), EMTDC (Manitoba Hydro), MORGAT (EDF), MICROTRAN (UBC), and utilization of high power amplifiers are the main advantages of the modern digital simulator [5]. In addition, actual fault waveforms recorded by digital recorders can be replayed. Test procedures can easily be controlled by programming. These capabilities enable implementation of more advanced testing methodology to test the relay operating characteristics and performance more precisely regarding the design and application features.

3.2 Phasor Testing

Phasor testing designates testing using pure sinusoidal waveforms with the fundamental power frequency generated based on a simple power system model. It is intended to test the relay operating characteristic. It can be used to verify the characteristic design, and can be also used to test the relay performance under different application conditions. Power system model and prefault and fault conditions should be specified for the application tests.

One-Terminal Phasor Testing: Test waveforms for one-terminal phasor testing can be derived based on a one-terminal or a two-terminal power system model as shown in Fig.1 and 2 respectively. The relay under test is placed at the local terminal. Utilization of the one-terminal power system model is sufficient to verify the design dynamic characteristics; while the two-terminal model is useful to test the far-end infeed/outfeed effect on the relay measurement. The external equivalent source impedance and prefault load conditions can be derived based on an actual power system if the relay performance needs to be investigated for a specified application. In order to get a full characterization of the relay design, the phasor testing is performed for three cases: Case I - zero prefault voltage and current; Case II - rated prefault voltage and zero prefault current; Case III - rated prefault voltage and current. These three test cases represent three different operating conditions. Case I represents reclosing into a fault where the line-side potentials are used. Case II represents no load or light load conditions prior to a fault. Case III represents full load conditions. Derivation of the test waveforms, procedure of the tests and test results for five relays have been reported in a previous paper [7].

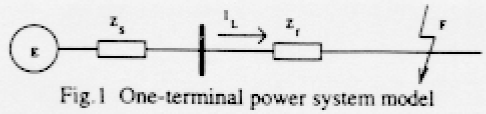


Fig.1 One-terminal power system model

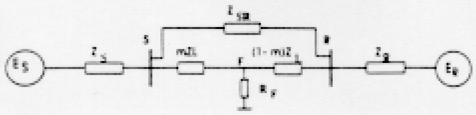


Fig.2 Two-terminal power system model

<u>Two-Terminal Phasor Testing:</u> Two-terminal phasor testing relates to back-to-back testing of a pair of relays using phasors. Test waveforms for both relays at the two-terminals are derived based on a two-terminal power system model as shown in Fig.2. The relays under test are placed each at one end of the line. The main purpose of the two-terminal phasor testing is to test the relay coordination performance for different relaying schemes. The communication channel time delay needs to be simulated.

3.3 Transient Testing

Phasor testing can be used to verify the operating characteristic design, to test the relay performance under different application conditions and to test the relay coordination performance for different relaying schemes. Transient testing designates testing using transients to evaluate relay performance under actual fault conditions. The test waveforms may comprised of different DC and high frequency components generated under different power system and fault conditions. To be able to generate test waveforms that closely reflect the application, a full EMTP model of an actual system needs to be developed. Once the model is made available, a number of different fault cases can be generated by changing various fault and system parameters. Typically, for the transmission line faults, the following faults parameters are varied: fault location, type, incidence angle and resistance. Usually, different prefault conditions such as load flow and system configuration changes may affect transient performance of the relays. Different instrument transformer (CT and CCVT) designs are also considered as a changing test parameter.

Transient testing can also be divided into one-terminal and two-terminal case. One-terminal transient testing is used to test transient performance such as operating time, reach accuracy and transient characteristics; while two-terminal transient testing focuses on testing coordination performance of the relays under transient conditions.

3.4 Design Testing

Design tests are intended to confirm or verify the design characteristics and features. Both phasor and transient testing can be used for design testing. Phasor testing is used to verify the phasor operating characteristics based on the measurement principle. Transient testing is used to evaluate transient performance related to input signal filtering and A/D conversion as well as algorithm design and implementation. Different power system models are usually selected for extensive tests.

3.5 Application Testing

Application tests are intended to evaluate relay performance for a specified power system or line. Once the power system or line is specified, different prefault and fault condition are usually changed to test the relay extensively. Both phasors and transients can be used for application testing. Usually, design and application testing are not totally separated. Analysis of the application test results may reveal design weakness; while design test results may be used to recommend particular relays for the specified applications.

4. ILLUSTRATION OF TESTS

4.1 Test Set Up

The tests have been performed using a modern digital simulator design [5]. Fig.3 and 4 show the diagrams of digital simulator and test set up for one- and two-terminal testing respectively. The digital simulator consists of an IBM RISC/6000 computer, a DSP board, and one or two sets of D/A I/O subsystems and voltage and current amplifiers depending on whether one- or two-terminal test configuration are considered. A communication channel is simulated for two-terminal testing. Different time delays due to the communication channel are applied for different relaying schemes. Trip signals and pilot signals for two-terminal testing are feed back to the simulator to be used by the test program to control the test process.

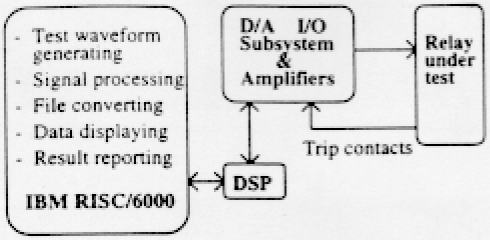


Fig.3 One-terminal testing set up

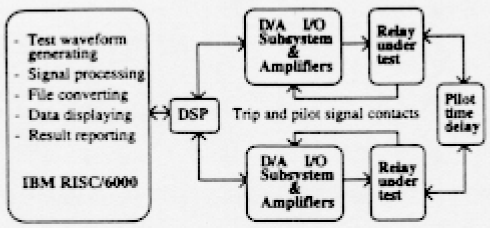


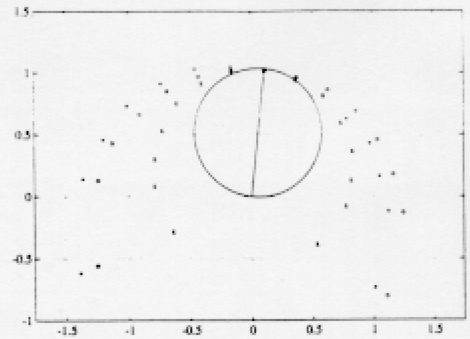
Fig.4 Two-terminal testing set up

4.2 One-Terminal Phasor Testing Examples

Operating Characteristics Under Different Prefault Conditions: A set of equations representing prefault and fault waveforms has been derived based on the one-terminal power system model as shown in Fig.1. Extensive tests have been conducted on five different commercial distance relays. The test signals were applied with different prefault conditions: Case I: zero prefault voltage and current; Case II: rated prefault voltage and zero prefault current; Case III: rated prefault voltage and current.

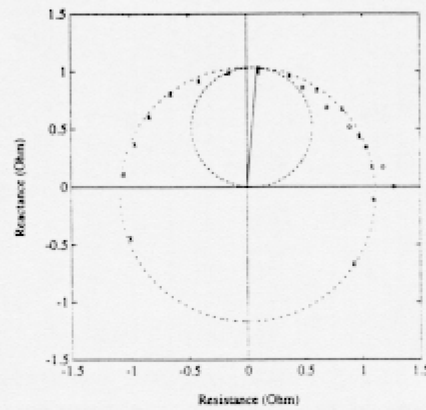
A typical set of test results for Relay A (double-line-to-ground fault) are shown in Fig.5, where the solid circle is the theoretical steady-state characteristic. It is obvious that the relay has different operating characteristics under different prefault conditions.

Operating Characteristics Using One- and Two-Terminal Power System Models: Prefault and fault test waveforms have been derived based on the one- and two-terminal models as shown in Fig.1 and 2. Extensive tests have been conducted to investigate the difference in test results obtained by using the two different models. Fig.6 shows a typical set of test results for Relay B, single-line-to-ground fault.



x : for Case I; o : for Case II ; * : for Case III

Fig.5 Test results for Relay A, BC-G fault



'------': Theoretical steady-state characteristic
'-.-.-.-': Theoretical dynamic characteristic
'x': Test results using one-terminal model
'o': Test results using two-terminal model

Fig.6 Comparison of characteristics

It can be seen from the test results that the operating characteristic obtained by using the one-terminal model is very close to the theoretical characteristic. The results obtained by using the two-terminal model are different due to the far-end in-feed effect. The far-end in-feed effect depends on the fault resistance, the source impedance and the fault location.

4.3 Two-Terminal Phasor Testing Examples

A set of equations for generating prefault and fault test waveforms has been derived based on the two-terminal representation model as shown in Fig.2. The fault voltage and current are functions of the line length between the relaying point and the fault, the fault resistance, and the system equivalent parameters. A set of prefault and fault test waveforms can be obtained for a given fault location and a fault resistance. Test set up is shown in Fig.4. Five pairs of different distance relays have been tested for various fault types and relaying schemes. A portion of test results for Relay C, three-phase fault are shown in Table I.

Table I Three-phase fault test result for Relay C with permissive overreach scheme

R_F (Ω)	M	TT#1 (ms)	SST#1 (ms)	TT#2 (ms)	SST#2 (ms)
0.00	0.10	14.42	14.39	23.94	12.74
0.00	0.30	12.94	12.79	13.14	12.94
0.00	0.50	14.77	14.52	14.14	14.02
0.00	0.70	14.27	14.02	13.34	13.22
0.00	0.90	25.61	14.39	13.37	15.19
0.25	0.10	15.92	15.77	24.84	17.59
0.25	0.30	16.69	16.37	25.91	16.34
0.25	0.50	19.49	16.82	18.27	15.67
0.25	0.70	23.79	16.92	15.57	15.27
0.25	0.90	25.66	18.82	17.39	17.07
0.50	0.10	xxxx	22.09	xxxx	xxxx
0.50	0.30	xxxx	21.41	xxxx	xxxx
0.50	0.50	33.96	20.59	30.04	24.86
0.50	0.70	xxxx	14.34	23.04	16.04
0.50	0.90	xxxx	xxxx	xxxx	xxxx

R_F - Fault resistance
M - Line proportion
TT#1 - Tripping time for Relay #1
SST#1 - Pilot signal send time for Relay #1
TT#2 - Tripping time for Relay #2
SST#2 - Pilot signal send time for Relay #2

It can be seen from the test results that the relays have good coordination performance. At the same time, the test results reveal that the fault resistance coverage is different for different fault type and relaying scheme.

4.4 One-Terminal Transient Testing Examples

A section of an actual power system has been modeled using EMTP. Different line models are used. The frequency dependent (FD) and constant parameter (CP) line models are selected as the appropriate ones for transient simulations. Detailed CT and CCVT models are included in the simulations [9, 10]. A large number of cases have been simulated and used to test the relays. Thousands of tests have been conducted on each relay using an automated test procedure. A group of test cases are demonstrated here as an example.

Test Cases (4 x 5 x 3 = 60):
Fault types (4) -- A-G, BC, ABC and BC-G
Fault locations (5) -- 50%, 75%, 80%, 90%, 95%
Inception angles (3) -- 0°, 45°, 90°

Test Waveform Specification:

Simulation sampling rate	12.5 kHz
Length of the test signals	42 cycles
Prefault waveform length	34 cycles
Fault waveform length	8 cycles

For each case of the 60 tests, the test was repeated 10 times. A program is used to conduct the 600 tests in a batch-file. Since there are three different inception angles, there are 30 tests for each fault location of each fault type. A test result sheet is generated automatically by the simulator, including the number of trips out of the 30 tests, average, maximum and minimum operating times and the standard deviation for the 30 tests. A typical test result sheet automatically generated by the simulator for Relay A is shown in Table II.

Table II Test results for Relay A

Type	Loc (%)	No.T	AvrgT (ms)	MaxT (ms)	MinT (ms)	Devtn
A-G	50	30	20.68	23.12	17.94	1.49
A-G	75	30	22.75	25.04	20.34	1.48
A-G	80	30	25.67	41.72	23.62	3.17
A-G	90	0	*****	*****	*****	****
A-G	95	0	*****	*****	*****	****
B-C	50	30	20.57	22.90	18.46	1.36
B-C	75	30	26.04	28.50	23.66	1.44
B-C	80	30	35.23	66.26	25.02	12.36
B-C	90	0	*****	*****	*****	*****
B-C	95	0	*****	*****	*****	*****
ABC	50	30	19.21	20.44	18.34	0.61
ABC	75	30	24.68	25.40	23.68	0.54
ABC	80	30	25.63	27.24	24.26	0.81
ABC	90	0	*****	*****	*****	****
ABC	95	0	*****	*****	*****	****
BCG	50	30	20.27	23.06	17.98	1.45
BCG	75	30	26.10	28.58	23.66	1.47
BCG	80	30	34.53	66.18	24.86	12.28
BCG	90	0	*****	*****	*****	*****
BCG	95	0	*****	*****	*****	*****

Type -- Fault type
Loc -- Fault location
No.T -- Number of trips out of 30 tests
AvrgT -- Average operating time
MaxT -- Maximum operating time
MinT -- Minimum operating time
Devtn -- Standard deviation

Transient performance of a relay can easily be judged from the test results. The operating time and selectivity are the two most critical performance indicators for distance relays.

Selectivity: The number of trips out of 30 tests for each fault type and location are tabulated in Table III for the five relays under test. It can be seen that all the relays except Relay B possess good selectivity. There are 30 trips out of 30 tests for the faults within the setting zone, while no trip out of 30 tests for the faults outside the setting zone. Relay B overreaches for all types of faults especially for the single-line-to-ground faults.

Table III Number of trips out of 30 tests

Fault type & locations	Relay A	Relay B	Relay C	Relay D*	Relay E*
A-G 50%	30	30	30	0	0
A-G 75%	30	30	30	0	0
A-G 80%	30	30	30	0	0
A-G 90%	0	[redacted]	0	0	0
A-G 95%	0	[redacted]	0	0	0
BC 50%	30	30	30	30	30
BC 75%	30	30	30	30	30
BC 80%	30	30	30	30	30
BC 90%	0	[redacted]	0	0	0
BC 95%	0	0	0	0	0
ABC 50%	30	30	30	30	30
ABC 75%	30	30	30	30	30
ABC 80%	30	30	30	30	30
ABC 90%	0	[redacted]	0	0	0
ABC 95%	0	0	0	0	0
BC-G 50%	30	30	30	30	30
BC-G 75%	30	30	30	30	30
BC-G 80%	30	30	30	30	30
BC-G 90%	0	[redacted]	0	0	0
BC-G 95%	0	0	0	0	0

* Relay D and Relay E do not have a ground distance element. The shaded areas indicate the numbers of maloperating trips.

Operating Time: Comparison of the operating times among the relays under test for BC fault is shown in Fig.7. From the test results, it is easy for a utility to pick up the relay(s) suitable for their applications.

Inception Angle: It is essential to generate cases of different inception angles or point-on-wave from 0° to 180° [1]. The most important inception angles are those which result in different DC and high frequency components in the waveform. The angles of 0° and 90° are two extremities and the angle of 45° is in between. Test results show that some relays are more sensitive to the non-fundamental components than the others. For example, the results reveal that Relay B overreaches for single-line-to-ground faults with 0° and 45° inception angles but not for the fault with 90° inception angle.

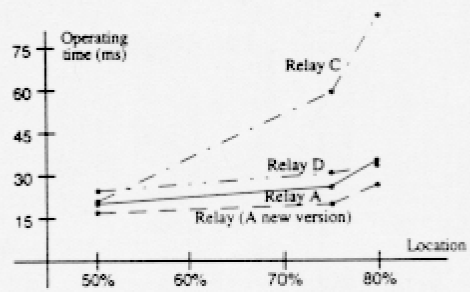


Fig.7 Comparison of operating times

4.5 Two-Terminal Transient Testing Examples

Extensive two-terminal tests have been conducted on the five relays for different relaying schemes. A graphical test report is generated for each case and each relay. A typical graphical report for Relay C is shown in Fig.8 where the test, the trip contact status and the send and receive pilot signals of the relays at both ends are included. Relay transient coordination performance can easily be seen by studying the trip and pilot signals corresponding to the test waveforms for both ends.

5. CONCLUSIONS

Based on the discussions and results presented, the following can be concluded:

- Recent developments of digital simulators enabled consideration and implementation of new test methodologies.

- The test methodology described in the paper enables full characterization of the design and application performance characteristics of a given relay.

- Application of the new test methodology reveals more information than what is possible with the standard portable test sets. This ability may profoundly affect selection , application and evaluation of the relays and relaying systems in the future.

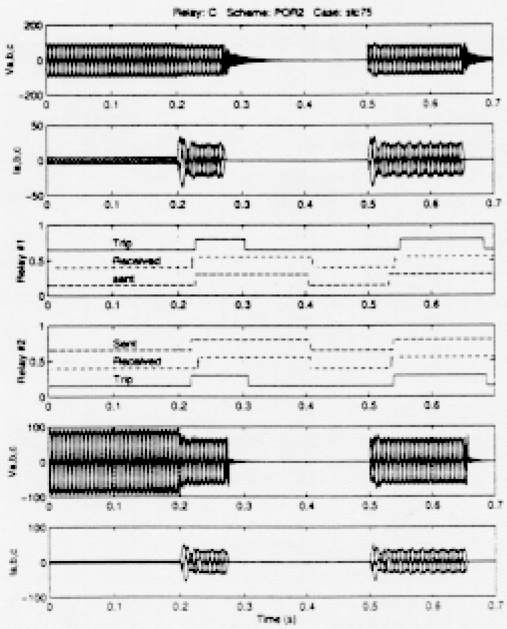


Fig.12 A typical graphical two-terminal test result for Relay C

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