Use of Advanced Digital Simulators for Distance Relay Design and Application Testing

J. Schilleci, G. Breaux
Entergy Services, Inc.
New Orleans, LA

M. Kezunovic, Z. Galijasevic
Texas A&M University
College Station, TX

T. Popovic
Test Laboratories International, Inc.
College Station, TX

Abstract – **This paper presents a novel methodology for testing modern protective relays. Its primary focus is a distance relay. The proposed methodology consists of both design and application testing. Design testing is aimed at assessing predictive relay behavior by measuring its real operating characteristic. Application testing has the form of transient testing and it is aimed at assessing the random aspects of relay behavior. The paper discusses the test methods as well as advanced software and hardware tools needed for implementing the proposed test methodology. Discussion specially emphasizes automation aspects of the test methods and tools. The use of the methodology is demonstrated using the results obtained by testing several distance relays as an example.**

Index Terms **– Protective Relays, Design Testing, Application Testing, Digital Simulators, Electromagnetic Transients, Automated Testing**

I. INTRODUCTION

Traditionally, protection relays were defined and analyzed using phasor concepts. Such concepts are easy to understand and lend themselves well to the practice of using analog relays. Most relay test methods and equipment today adhere to phasor concepts. Standard practice of relay testing in majority of electric utilities is to use conventional relay test sets and perform mostly calibration of relay settings.

Modern relays are mostly microprocessor-based. They increasingly use advanced processing of transient signals to reach trip decision. The introduction of such relays is changing the approach to power system protection. This holds for selection and evaluation as well as for installation and maintenance of the relays. In particular, new approaches may be used for tuning relay settings and performing application testing. The essential approach here is evaluation of the relay performance using test quantities that closely resemble actual power system quantities. Two approaches are possible in obtaining such test data: performing network simulations based on accurate system models or using actual system data recorded in the field. In both cases, test data aim to represent transient phenomena associated with short-circuit faults.

Transient approaches in relaying and testing are not new. The advent of analog power system simulators (transient network analyzers) in the sixties has enabled their broader use. However, their wide acceptance was delayed, as these simulators were rather expensive and impractical. This has changed with the arrival of the first digital simulators in the late eighties and early nineties [1]. Today, well-established simulator vendors and relatively inexpensive simulator products are available. Quite different options are offered for users with different application needs and financial capabilities: PC-, workstation-, and dedicated hardware-based simulators [2].

Unfortunately, due to relatively recent introduction, as well as its increased complexity and lack of understanding, transient relay testing methods and tools remain underutilized. In order to accelerate acceptance of transient relay testing, a coherent testing methodology needs to be established. This paper publishes the initial results of an effort undertaken in such direction.

Two types of relay tests make the basis of the proposed testing methodology: design testing [3] and application testing [4]. The measurement of the operating characteristic of the relay is utilized to express results in case of design testing. A method for measuring the relay characteristics in an automated way is described. An approach to performing automated application testing is described as well. Statistical measures that may be used for expressing the results obtained by the new testing approach are pointed out [5].

To demonstrate the use of the test methodology this paper summarizes the results from testing several distance relays. The results are accompanied with details on test cases including ATP models, relay settings, test procedure and simulator set-up. Some conclusions and recommendations for future use of the new test methods are also outlined.

II. BACKGROUND

This section provides a short overview of the test methodology used for relay testing described in this paper.

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J. Schilleci is with Entergy Services, Inc., P.O. Box 6100, New Orleans, LA 70161 (e-mail: jschill@entergy.com)

G. Breaux is with Entergy Services, Inc., P.O. Box 6100, New Orleans, LA 70161 (e-mail: gbreaux@entergy.com)

Mladen Kezunovic is with Dept. of Electrical Engineering, Texas A&M University, College Station, TX 77843 (e-mail: kezunov@ee.tamu.edu).

Zijad Galijasevic is with Dept. of Electrical Engineering, Texas A&M University, College Station, TX 77843 (e-mail: zijad@ee.tamu.edu).

Tomo Popovic is with Test Laboratories International, Inc., 1701 Southwest Parkway #99, College Station, TX 77840, (tomo@tli-inc.com)

A. Relay Behavior

The relay behavior can be analyzed in the context of various influential factors: power network applications, fault characteristics, relay algorithms, etc. The analysis reveals that the relay behavior can be considered as either predictive or random.

1) Predictive Behavior

If the input signals are ideal sine functions, the relay algorithm has a predictive behavior. Other elements may affect the output, but the overall performance should be predictive. The operating characteristic of the relay can be obtained by recording operating points related to variety of input signals. Comparison of the measured and theoretical characteristic gives an assessment of the predictive relay behavior.

2) Random Behavior

Random behavior of the relay is related to transients. In this case, the relay behavior may not match the one observed for phasor-based test waveforms. In particular, the calculated relaying quantity and the processing time are variable. Measuring the direct trip time and determining if the relay should have tripped constitutes the assessment approach in this case.

B. Current Testing Practice

The prevailing testing practice is to use steady-state phasor-based methods. In such tests, the test signals are usually pure sine waveforms. If the test signal changes, the change is much smaller than the resolution of the relay. Such testing suits well purposes aimed at verifying and calibrating relay settings and is not aimed at evaluating relay transient performance.

Most vendors of the relay test equipment offer microprocessor-based test devices capable of performing steady-state tests. Many of these devices also provide dynamic testing functions and some include rudimentary transient testing capabilities. Test equipment truly capable of transient testing is rather rare and expensive especially in case of the real-time simulators.

C. New Needs and Requirements

Phasor-based test methods and devices may not be adequate for all applications e.g. checking suitability of a particular relay to a specific application, checking performance characteristics of a new relay design, analyzing in-service relay operations, etc. Improvement in both phasor-based and transient-based methods is needed to fully meet these requirements.

1) Phasor-Based Test Methods

The relay under test is subjected to test signals that can be described using simple sine functions. Static tests are examples of phasor-based testing. Dynamic tests also fall into this category, as the test signals are pure sine functions (with possible addition of an exponentially decaying DC component).

The operating characteristic of the relay can be obtained by forcing operation at several points (for various line angles). Several approaches are used: suddenly applying fault voltage and current, keeping the voltage constant and suddenly applying fault current, changing both voltage and current from pre-fault to fault values. For some relays (cross- and quadrature-polarized relays), the obtained characteristics may not be accurate due to source impedance and load effects. The transition between steady state and fault may also be important. Phasor-based methods cannot represent this transition accurately, which may produce unrealistic test results for some relays [3].

2) Transient-Based Test Methods

The relay under test is subjected to signals that resemble actual fault conditions. These signals have complex frequency spectrum caused by the power system disturbance. In addition, they are characterized by certain time-localized features. They include pre-fault, fault and post-fault quantities. Such signals cannot be easily described using simple harmonic functions. Therefore, the sampled forms of these signals are usually used.

The transient tests have different goals from the phasor-based tests. The emphasis is on the overall relay performance under simulated "actual" operating conditions. Specific relaying applications may have big impact on the relay behavior (parallel lines, series capacitor compensation, etc.). Accurately simulating these conditions is necessary for transient testing.

D. Outline of the New Methodology

The new methodology tries to propose a better way for relay testing taking into account advancements in relay testing tools. Following types of tests are addressed:

1) Design Testing

The objective of design testing is to verify design specifications for a given relay type or even for an individual relay. Typically, this type of testing is carried out only once, before or after the relay purchase.

Design testing needs to confirm the design features and operating characteristics of a relay. Usually phasor-based methods are used to verify the operating characteristic. Test quantities are derived using a simple model of the power system. Sometimes, transient-based methods may be used as well to verify characteristics of the A/D conversion and input signal filtering.

2) Application Testing

The objective of application testing is to verify suitability of an individual relay and its settings for a given application (operating conditions). Typically, this testing is carried out before the commissioning and after the change of settings. Although, some application tests may be conducted using phasor-based methods, transient testing is usually needed. The reason lies in the fact that transient simulation produces test signals that are closer to the signals encountered by a relay in the actual power system.

Application tests evaluate relay performance related to a specific transmission line or power system. Different pre-fault and fault conditions are used to test the relay in a variety of situations that may occur in practice. Both one-terminal and multi-terminal testing and applications are possible. In one-terminal testing, operating time, reach accuracy and transient characteristics are evaluated. In multi-terminal testing, the emphasis is on evaluating the relay coordination performance.

III. Testing Tools

This section describes how commercially new test devices and simulation programs can be combined to implement advanced testing procedures of the new test methodology.

A. Requirements

To conduct relay testing according to new testing methodology advanced test hardware and software is needed. This section briefly discusses the main requirements that apply when selecting test hardware and software.

1) General Requirements

First set of requirements aims at minimizing the cost and overcoming the flexibility limits of existing test simulators:

- Simulator computer should be a personal computer (PC) due its popularity, price and performances.
- Simulator hardware should be interchangeable, and the use of existing test sets should be possible.
- System software should be commercially available and should not require substantial investment.
- Application software should support horizontal and vertical portability across different platforms.

Second set of design requirements is constrained with some specifics of relay test applications:

- The simulator should operate in open-loop mode, but future extensions could include real-time operation.
- The simulator should be able to use both recorded (DFRs) and simulated waveforms (EMTP/ATP).
- An easy-to-use GUI for test waveform processing and test results visualization must be provided.
- The Integration with internal and external transient simulation programs should be supported.

The architecture that can meet above-mentioned requirements is shown in Fig. 1.

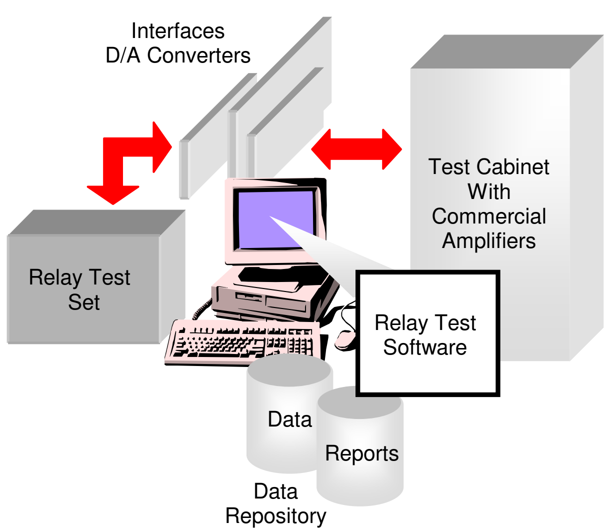

Fig. 1. The architecture of the simulator

2) Requirements for Automated Testing

Efficient testing requires hardware and software tools designed or customized for automated testing. The most important automation aspects are: test preparation, test execution, result collection, result processing and result reporting. These requirements are aimed at reducing the time and cost of testing, while increasing the accuracy and reliability of the test results.

In transient relay testing, a variety of network operating and fault conditions must be considered. The relay is tested using fault cases related to different combinations of fault locations, types and network parameters. To efficiently build and execute such cases (batch testing) automated test methods and test systems are needed. Automating relay testing requires elaborate user interfacing, data processing and system modeling capabilities.

3) Requirements for Automated Reporting

Automating the test result reporting is very important aspect of the testing. Both collecting the relay responses and generating the test reports must be automated. While collecting the relay responses, the following data must be recorded: relay response (trip/no trip), relay trip time and relay zone of operation. The test report should include general data, test data and relay data. Finally, performance indices such as the number of failures, the number of misoperations and the operating time should be calculated and included [5].

B. Test Setup

The following independent software elements were used as part of test setup (simulator):

- ATP
- ATPDraw
- BGEN
- Relay Assistant
- Miscellaneous tools

ATP [6] is used for the electromagnetic transient simulation. The input files were previously generated by the ATPDraw and BGEN. ATP was run in a loop using BGEN and related MS DOS batch files.

ATPDraw [7] is graphical user interface used for the preparation of the basic test case models. The embedded file converter generates ATP input files. The ATPDraw is also used as the top-level user interface for starting BGEN.

BGEN [8] is an add-on utility for the ATP and Relay Assistant. The roles of BGEN were: a) to create ATP input files based on the user input and basic test case model; b) to run ATP simulation for each of the created ATP model files; c) to convert ATP output files into Relay Assistant format; d) to create test session (batch file) that integrates all tests.

Relay Assistant [9] is used for executing the test cases prepared by ATP and BGEN as well as for collecting, processing and archiving the test results. Relay Assistant is invoked automatically and minimal user interaction is required thereafter.

Miscellaneous Tools are used for the final test results processing and presentation (Matlab, MS Excel, MS Word).

As shown in Fig. 1, simulator architecture allows for interchangeable output hardware (a relay test set and, a custom D/A converter with commercial amplifiers, etc.).

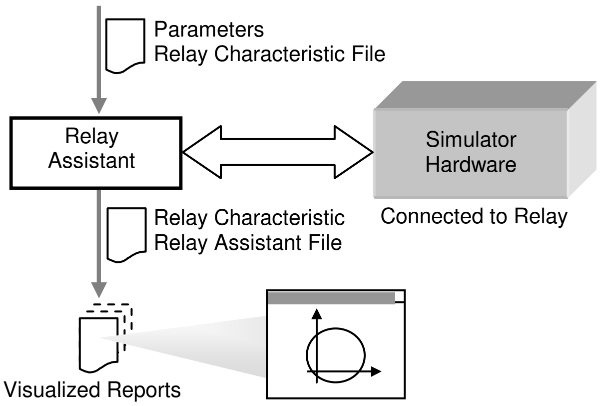

Fig. 2. Test setup for design testing

Fig. 2 depicts the software and hardware setup needed for design testing approach. Relay Assistant may be used for specifying the parameters for capturing the operating characteristic. Tests are automatically performed in a loop to acquire the points of the relay characteristic. Data describing characteristics are collected and used for creating comprehensive test reports.

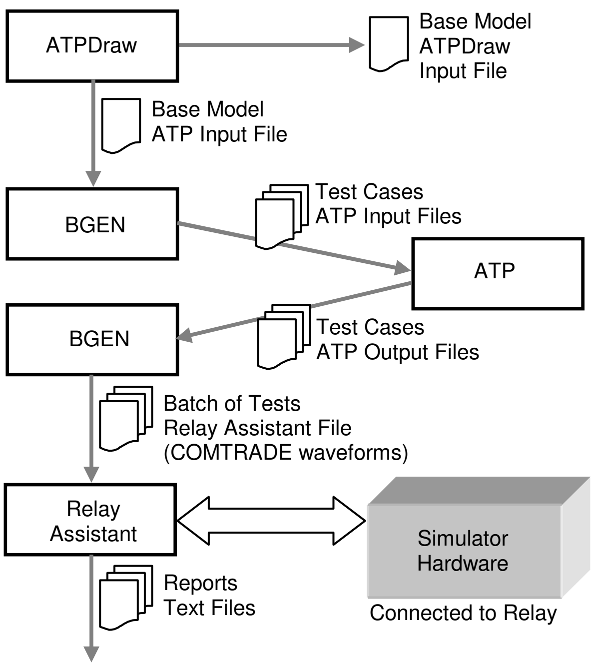

Fig. 3. Application testing setup

Test setup for application testing is shown in Fig. 3. Base model is normally created by using ATPDraw. BGEN reads the base model information from the ATP input file. BGEN is also used for specifying the measurements (relay position, CT and CCVT ratios). After the user defines the batch of possible faults, BGEN automatically generates ATP input files, perform ATP simulations and converts the simulation results into COMTRADE format. In addition, it creates a Relay Assistant test session file. Each test can be automatically repeated several times, which allows a statistical approach to testing.

IV. Testing

This section describes the testing performed in order to demonstrate the application of the test methodology. Details on test plan, test setup and test results are included.

A. Test Plan

Test plan has been prepared ahead of testing. The plan covers both design and application testing. However, as the main focus was on the transient testing at the time, design testing was not performed.

1) Test Cases

The test cases were selected based on the application relevance of the operating condition represented. The test cases listed in Table I have been identified for this study.

Table I Selected test cases

ID	Application Characteristic
A	Mix of long and short lines; Distributed parameter models
B	Short, parallel, mutually-coupled lines; Lumped parameter models
C	Long, untransposed, parallel lines; Series-compensation with MOV protection

For the illustration sake, the one-line network diagram used for case “C” is shown in Fig. 4 below.

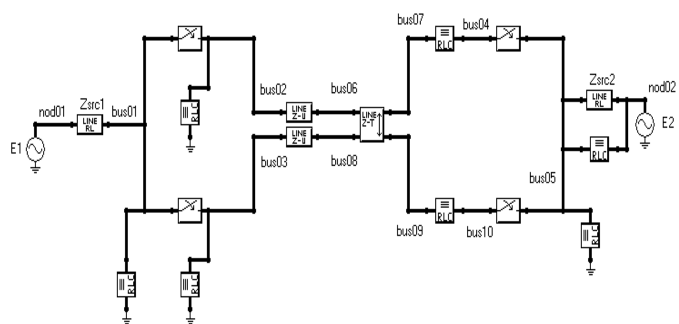

Fig. 4. One-line diagram for test case “C”

2) Test Scenarios

As mentioned in the background section, the relay behavior shows both random and deterministic characteristics. Design testing can successfully verify deterministic characteristics of relay behavior through relatively limited number of tests. On the other hand, application testing attempts to discover and quantify random characteristics of relay behavior. For such a task, a large number of test cases may need to be defined.

In any practical testing, an upper limit of the number of test cases must be adopted. Therefore, test scenarios need to be selected in such a way that good "coverage" of the global relay behavior is ensured. As this testing only demonstrates the methodology, the number and choice of the test cases need not be exhaustive. Rather, the attention is limited to analyzing relay performance depending on fault location, fault parameters and operating conditions (Table II, Table III).

Table II Fault conditions

Parameter	Values
Fault types	1-ph, 2-ph, 3-ph (with and without ground)
Fault location	50, 70, 90 % line length
Inception angle	0, 30, 60, 90 degrees
Fault resistance	0, 5, 10, 20 Ω
Sampling rate	1 [KS/sec], 5 [KS/sec], 10 [KS/sec]
Pre-fault loading	Normal, but may vary for parallel lines
Pre-fault length	Three (3) cycles
Fault Duration	Permanent

Table III Miscellaneous test conditions

Parameter	Values
CT/VT models	Ideal models
No. of repetitions	Each case repeated 30 or 20 times
No. of terminals	One

For each system model, one or more transmission lines have been selected for the analysis (protected line). Table IV identifies these locations.

Table IV Protected line

Test Case	Studied Lines
A	BUS1-BUS7
B	BUS11 - BUS4 and BUS13 - BUS7
C	BUS02 - BUS04

In actual testing, varying some other parameters may be found beneficial. Such cases would need to be added to the test plan.

3) Design Tests

The relays also need to be tested for the correctness of the operating characteristic. The goal of such testing is to discover relays with design flaws and to exclude them from application testing. As the design tests are phasor-based, this may result in time savings since fewer relays might need to be subjected to the transient testing. The following test cases may be identified:

Table V Protected line

Test Case	Studied Lines
Fault type	AG, BC, BCG and ABC
Fault Location	Zone I and Zone II
Pre-fault to fault transition	$V_{pre} = 0$, $I_{pre} = 0$ (to emulate reclosing into ongoing fault)
	$V_{pre} = V_{rated}$, $I_{pre} = 0$ (to emulate no load or light load conditions in pre-fault)
	$V_{pre} = V_{rated}$, $I_{pre} = I_{rated}$ (to emulate “normal” load conditions in pre-fault)

The test signals for these cases may be calculated using the procedure explained in the reference [3]. Such an approach ensures that measured relay operating characteristics are the realistic ones. Relays with flawed characteristics can be excluded from further testing.

B. Relays under Test

To demonstrate the use of the proposed testing methodology, three relays have been used. The main characteristics of these relays are given below.

1) Relay A

This is a digital relay with single- and three-pole tripping. It has four zones of phase and ground distance protection with MHO characteristics and additional quadrilateral characteristics for the ground unit. It supports standard tripping scheme, with or without communications. Phase, negative-sequence, and residual overcurrent elements exist.

2) Relay B

This is a digital relay for transmission line protection applications with three-pole tripping. It includes four zones of distance protection. Phase and ground distance units have variable dynamic MHO characteristic. Directional functions are polarized with negative sequence voltage. It has high speed tripping, typically 0.75 to 1.5 cycles.

3) Relay C

This is a digital transmission line relay with three zones of distance protection. Both phase and ground elements have variable MHO characteristics. Directional measurements are polarized with negative sequence voltage. High-speed tripping is possible, typically 0.75 to 1.5 cycles.

C. Test Result Processing

Test results need to be systemized in the form of the comprehensive test report. Key elements of the report must be the applicable performance indices defined and discussed in [5].

1) Application Testing:

The results of the application test need to be expressed using the performance indices for various combinations of test variables:

1. Operating time:
   - Average, Standard deviation, Min, Max
2. Dependability:
   - Percentage value
3. Security:
   - Percentage value
4. Composite Performance Index (J):
   - Percentage value

2) Design Testing:

The results of the design testing can be expressed using a graphical representation of the measured and theoretical operating characteristic of the relay. Such representation is easy to understand for most protection engineers and technicians.

D. Test Results

Some results of the application testing for relays and test cases described in the test plan are included here for faults in Zone I and relay setting at 85% (note that the number of tests cases performed was much larger than reported in this paper).

Table VI Test case "A", fault AG, Relay A

Rf [Ω]	α [°]	Fault Location 70% # times failed	Mean trip time	Max. trip time	90% # times failed	Mean trip time	Max. trip time
0	0	0	0.044	0.046	8	-	-
	30	0	0.044	0.045	11	-	-
	60	0	0.044	0.046	11	-	-
	90	0	0.043	0.045	9	-	-
5	0	0	0.044	0.046	0	-	-
	30	0	0.043	0.045	0	-	-
	60	0	0.043	0.045	1	-	-
	90	0	0.043	0.045	0	-	-
15	0	0	0.044	0.046	0	-	-
	30	0	0.043	0.045	0	-	-
	60	0	0.043	0.045	0	-	-
	90	0	0.047	0.049	0	-	-

Table VII Test case "A", fault AG, Relay B

Rf [Ω]	α [°]	Fault Location 70% # times failed	Mean trip time	Max. trip time	90% # times failed	Mean trip time	Max. trip time
0	0	0	0.034	0.035	0	-	-
	30	0	0.036	0.036	0	-	-
	60	0	0.036	0.037	0	-	-
	90	0	0.036	0.037	0	-	-
5	0	0	0.038	0.039	0	-	-
	30	1	0.037	0.037	0	-	-
	60	0	0.036	0.037	0	-	-
	90	0	0.040	0.042	0	-	-
15	0	30	-	-	0	-	-
	30	30	-	-	0	-	-
	60	30	-	-	0	-	-
	90	30	-	-	0	-	-

Table VIII Test case "A", fault AG, Relay C

Rf [Ω]	α [°]	Fault Location 70% # times failed	Mean trip time	Max. trip time	90% # times failed	Mean trip time	Max. trip time
0	0	0	0.030	0.031	3	-	-
	30	0	0.030	0.032	0	-	-
	60	0	0.030	0.032	0	-	-
	90	0	0.030	0.031	0	-	-
5	0	0	0.030	0.031	0	-	-
	30	0	0.030	0.031	0	-	-
	60	0	0.030	0.031	0	-	-
	90	0	0.030	0.031	0	-	-
15	0	0	0.029	0.030	0	-	-
	30	0	0.029	0.030	0	-	-
	60	0	0.029	0.031	0	-	-
	90	1	0.042	0.046	0	-	-

V. CONCLUSIONS

This paper describes the essential elements of a systematic methodology for testing distance relays. Software and hardware needed for implementing the methodology is describes as well. The use of the test methodology is discussed and summarized using the results from testing several distance relays.

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