Digital Simulator Applications in Protective Relay Testing

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Abstract – This document discusses applications of digital simulators in protective relay testing with an emphasis on end-user evaluation and testing of relays in laboratory facilities. A background on digital simulators and transient testing together with a description of a two-terminal simulator test setup are given first. Description of a transmission network model and its use for generation of transient tests is given next. Methodologies for testing transmission line and bus differential relays are presented. Finally, examples of results obtained using digital simulator and transient testing are given at the end.

Keywords: **Protective Relays, Application Testing, Digital Simulator, Electromagnetic Transients**

I. INTRODUCTION

Protective relay technology and relay testing philosophies have undergone tremendous transformations over the years, especially since the advent and advancement of the digital era. It has already been acknowledged in the industry that traditional steady-state relay testing procedure alone is no longer sufficient or suitable to evaluate microprocessor-based relay response to power system transients [1]. Digital simulators have been developed and commercialized in the past decade with the purpose of accommodating the need for testing digital relay response to transient conditions. This paper will describe some end-user application test examples for digital relays using this technology. A two-terminal transmission line protection scheme and a bus-differential protection relaying scheme will be evaluated with a three-phase, two-terminal, open-loop, PC-based digital simulator system.

A description of a 345-kV transmission network model, developed with the Alternative Transients Program (ATP) to generate relay inputs for the two line terminals, will be included [2]. This ATP model was developed with the intent of simulating faults in an actual transmission network, and using simulation results as the digital simulator inputs for testing the transmission line relays. Various types of simulated internal and external faults will be described, as well as the batch test signal generation process that was adopted using commercial software that links with ATP. Testing results are discussed at the end of this paper.

Waveform files from several fault simulations involving a six-feeder bus will used to test a six-input digital bus differential relay. These COMTRADE files were generated by a different power system transients program and were supplied by a relay manufacturer. A description of the simulator connection, fault cases applied, and relay response is given as well.

II. BACKGROUND

Steady-state and/or dynamic testing of protection relays includes the use of phasors to calibrate the relay settings and evaluate the operating characteristics [3]. This practice is widely spread and is performed in the field using portable test sets. Typically, one relay is tested at a time using a test set. This type of testing is performed in order to confirm basic characteristics of the relay, which may not require the use of transients. By applying the input signals that are ideal sine functions, the relay algorithms have a predictive behavior. The operating characteristic of the relay can be obtained by recording the operating points and used for comparing the measured and theoretical operating characteristic to assess relay behavior. This type of testing is called design testing [3].

A different set of end-user tests is needed when the application properties are to be evaluated. In order to assess relay performance under actual fault conditions, the test equipment has to generate fault transients that closely resemble actual transients occurring in the field. These types of test are typically needed when troubleshooting relay misoperation or when evaluating a new relay for a purchase [1]. There is no wide understanding of the methodology that may be used to perform such tests, but the industry is getting closer (such as work being done by IEEE PES PSRC Line Protection Subcommittee – Working Group D10 “Electro Magnetic Transients Program-EMTP Reference Models For Transmission Line Relay Testing”) to definitions of this approach, and more and more companies are using tests based on transients. Any unexpected behavior of the relay is related to transients. When presented with transients, the relay behavior may not match the one observed for phasor-based test waveforms. In particular, the relay response and the operating time are variable. Measuring the direct-trip time and determining if the relay should have tripped constitutes the assessment approach in this case. This type of testing is called application testing [1].

III. SIMULATOR TEST SETUP

For the purpose of application testing, CenterPoint Energy has equipped its test lab with a two-terminal, open loop simulator.

A. Simulator Hardware

The architecture of the simulator hardware is shown in Fig. 1.

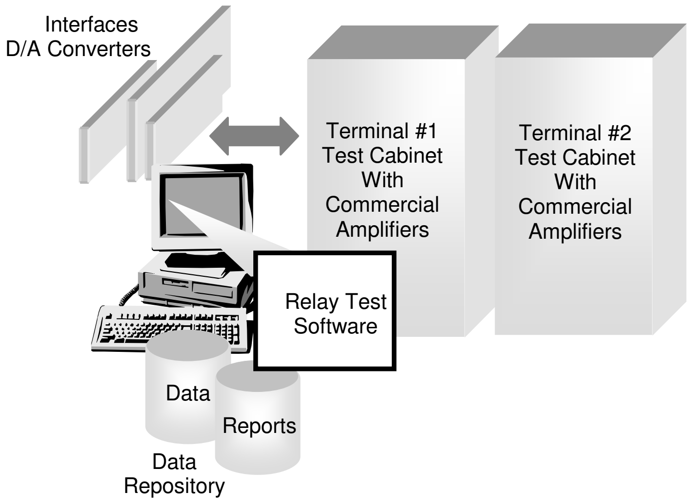

Fig. 1. Two-terminal, open-loop simulator

The test system is a personal computer (PC) based open-loop simulator [4]. A PC platform was selected due to its low price, hardware/operating system familarity, and performance. Selected simulator hardware can be easily upgraded to three terminals. A possibility of using existing test sets for waveform replaying is available, too. The customized relay test software is easy to use and did not require substantial investment.

The simulator used for this application testing is able to utilize both recorded (obtained from Digital Fault Records - DFRs) and simulated (obtained from EMTP/ATP) waveforms. An easy-to-use GUI with signal editing features for waveform processing, and test results visualization is provided. The integration with transient simulation programs was supported by the presence of several importing/exporting file filters.

The implemented hardware configuration, based on a custom communication interface and 16-bit D/A conversion, offers flexibility in meeting the application testing requirements. This D/A resolution, with a possibility of selecting different sampling rates up to 40kHz, enables reproducing transients accurately for relay testing. The frequency response of the amplifiers allows reproducing transient signals with high signal power which enables accurate replaying of a wider spectrum of simulated test waveforms. In addition, all the waveforms can be reproduced in the field using standard test sets. A hardware setup, shown in Fig. 1, has been installed and used at CenterPoint Energy for the last three years.

B. Simulator Testing Software Tools

Efficient testing requires 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 test results.

Automating the test result reporting is very important aspect of testing. Both collection of the relay responses and test report generation must be automated. After collecting the relay responses, the following information must be recorded: relay response (trip/no trip), relay trip time and relay zone of operation. The test report should also include scenario 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.

The relay test software implemented at CenterPoint Energy's testing lab conforms to above mentioned requirements and consists of four modules [4]: 1) import filters for reading several waveform file formats (COMTRADE, ATP, native DFR) and creating arbitrary test waveforms [5]; 2) waveform processing and editing (cut/paste, copy, crop, insert, rescale, resample, invert, pre- and post-fault extension etc.); 3) user-friendly access to simulator functions (displaying waveforms, reviewing test results, editing test reports, signal massaging etc.); 4) automated waveform replaying that includes drivers for variety of supported I/O hardware.

DFR records may be imported into the relay test software, modified, and then replayed back into the relay in order to repeat faulted conditions experienced in the field. Tools for handling and retrieving DFR records such as DFR master station software can be useful for that purpose. There are also more advanced universal solutions for handling DFR records that provide automated analysis, sorting, archiving and reporting [6]. The records converted into COMTRADE file format, together with the reports are kept in a centralized database and available for easy retrieval. Such a solution is currently being deployed at CenterPoint and is expected to be used in digital simulation applications in the near future.

In addition, a useful integration with ATP and ATPDraw is achieved by a new software tool called Batch Generator (BGEN) [4,7]. BGEN is an add-on module that facilitates an automatic way of generating several test cases and reduces time needed for both training on how to use the simulation tools and producing actual test waveforms.

IV. TRANSMISSION LINE RELAY TESTING APPLICATION

A. ATP Test System Model

1. <u>345-KV Network</u>

A 345-KV transmission network, shown in the figure in Appendix I, was modeled using the Alternative Transients Program [2] for the purpose of simulating various types of faults and generating the relaying signals for the tests. Circuits X and Y -- 180 and 170 miles long, respectively -- were modeled in sections as distributed (constant) parameter transmission lines. Actual transmission line data, such as tower configurations, conductor characteristics, etc., were used in ATP as input data to calculate the line parameters. All other transmission lines, with the exception of the double circuit between Buses 4 and 5 (also modeled with distributed parameters), were lumped-parameter π models. Thevenin equivalents derived from load flow and short circuit studies were placed at each bus shown. ATP simulations generated terminal voltages and currents for Circuit X, which was the protected line under scrutiny during relay testing.

Although the frequency-dependent (FD) model would have been the preferred representation for the long Circuits X and Y lines instead of the Constant Parameter (CP) models, there were limitations imposed by the digital simulator software when generating batch tests for sliding faults. At the present time, the program does not allow the recalculation of the desired FD line parameters after "splitting" the line in two sections. The batch-test generating process will be discussed at a later section.

2. <u>Model Validation</u>

In order to validate the ATP model, results from short-circuit and load flow studies were compared with ATP simulation. These systems studies were performed using independent software, and their results were used to "fine-tune" the ATP model. Additional confirmation of the model's accuracy was obtained after comparing a fault record of an operation that occurred on February 10, 2001, on Circuit Y with the ATP simulation of that same fault.

B. Relaying Scheme

The digital relay under evaluation was configured for a Directional Comparison Blocking (DCB) scheme that includes the following characteristics:

- 21P (set for 120% of line impedance) for forward instantaneous protection used for phase fault protection;
- 67NP Forward ground directional instantaneous over-current (IOC) for ground fault protection;
- 21S reverse zone set above line loading for phase fault starting carrier-blocking signal.
- 67NS reverse ground directional instantaneous over-current for ground fault starting carrier-blocking signal.

For over-reaching fault cases, the DCB scheme remote-end 21S or 67NS relay will transmit a pilot signal to block 21P instantaneous pilot and forward ground directional IOC relay from tripping.

For faults within the protected line section, the remote-end relay does not transmit a pilot signal in order to allow fast tripping of the circuit breaker by 21P or 67NP elements. Historically, zero-sequence voltage polarization has been used by CenterPoint Energy, but negative-sequence voltage polarization was adopted for these tests for evaluation. Also, for these tests the pilot signal was simulated by appropriate wiring between the inputs and outputs of the two relays.

C. Simulation Set-up

1. <u>Batch Test Generation</u>

A software tool called BGEN was used in conjunction with the ATP 345 kV network "base case" in order to generate voltage and current waveforms for the line relay batch testing. These waveforms were generated simultaneously for relays at both ends of the line.

BGEN facilitated the generation of test cases by allowing the user to specify location of signal measurement and instrument transformer ratios; fault types (shunt faults only); batch parameters such as fault location, fault initiation and clearing times, line-to-line and line-to-ground fault resistances, and fault inception times. Batch parameters were further defined by their respective starting points, number of points used, and the step size between them. For these line relay tests, ideal current and voltage transformers were utilized.

Once all these parameters were specified, BGEN automatically generated ATP input files for each fault case by altering the ATP base case accordingly. Next, BGEN automatically invoked ATP to solve each of the fault cases generated. The ATP output voltages and currents, previously defined by the location of instrument transformers, were then converted automatically to a format suitable for the digital simulator playback software.

If any other type of system reconfiguration or disturbance, such as breaker operation, change in loading, etc, is required, the ATP base needs to be modified manually prior to the batch test generation. Batch test parameters need to be chosen carefully in order to coordinate with any changes made in the base case prior to simulation.

2. <u>Fault Types</u>

The fault types generated by BGEN were chosen with the intention of simulating the worst-case scenarios in the vicinity of circuit X. Descriptions of the simulated faults follow:

a. Internal Faults:

- Sliding 3-ϕ and SLG bolted and resistive faults between the two line terminals of circuit X;
- Fault location at 1, 50, 75, 80, 85, and 99% of line impedance from Bus 4.

b. External Faults:

- 3-ϕ and SLG bolted bus faults at Buses 4 and 8;
- 3-ϕ and SLG bolted faults at 50% of adjacent circuit Y.

c. External Faults with Current Reversal

- 3-ϕ and SLG bolted faults at 94% of adjacent circuit Y;
- Fault clearance by circuit Y breaker closest to fault, 4 cycles after fault inception (breaker operation simulated "manually" in ATP).

Voltage incidence angles of 0°, 30°, 60°, and 90° were simulated for all fault cases.

3. Results

A total of 304 tests were applied to relays A and B using the Directional Comparison Blocking (DCB) scheme. Out of these tests, 240 cases were simulations of internal faults (see Table I). Trip times and operation status of both relays were recorded for each test.

Table I: Internal Faults Simulation Results

TABLE OF SIMULATION RESULTS						
TEST NO.	TEST CASE	EVENT	RELAY A OP	RELAY A TRIP Time (sec)	RELAY B OP	RELAY B TRIP Time (sec)
INTERNAL BOLTED FAULT ON LINE						
1	3PH 1%	1	trip	0.02292	trip	0.02811
2		2	"	0.02397	"	0.02707
3		3	"	0.02291	"	0.02811
4		4	"	0.02501	"	0.03022
5		5	"	0.02602	"	0.03019
6		6	"	0.02291	"	0.02811
7		7	"	0.02501	"	0.03022
8		8	"	0.02605	"	0.03022
9	3PH 50%	1	trip	0.02084	trip	0.02188
10		2	"	0.02188	"	0.02186
:	:	:	:	:	:	:
INTERNAL RESISTIVE FAULT ON LINE						
97	2L 1%	1	trip	0.02811	trip	0.03439
98		2	"	0.02605	"	0.03022
:	:	:	:	:	:	:
233	SLG 99%	1	no op	n/a	trip	0.00625
234		2	"	"	"	0.00834
235		3	"	"	"	0.01042
236		4	"	"	"	0.00937
237		5	"	"	"	0.00729
238		6	"	"	"	0.00729
239		7	"	"	"	0.00833
240		8	"	"	"	0.01041

Tables II-a and II-b summarize results for all internal fault cases. Both relays performed satisfactorily for all internal 3-ϕ and line-to-line cases, as well as for external faults (results not shown).

Table II-a: Test Results Summary – Relay A

		RELAY A			
FAULT TYPE	# OF TESTS	# OF NO OPS	AVG TRIP TIME	MAX TRIP TIME	MIN TRIP TIME
SLG	46	30	0.02285	0.02812	0.01978
SLG RESISTIVE	48	48	N/A	N/A	N/A
3PH	48	0	0.02396	0.02918	0.02082
3PH RESISTIVE	48	0	0.02495	0.03020	0.01874
2L RESISTIVE	48	0	0.02045	0.02811	0.01145

Table II-b: Test Results Summary – Relay B

		RELAY B			
FAULT TYPE	# OF TESTS	# OF NO OPS	AVG TRIP TIME	MAX TRIP TIME	MIN TRIP TIME
SLG	46	0	0.03204	0.05838	0.02290
SLG RESISTIVE	48	8	0.01221	0.04065	0.00417
3PH	48	0	0.02490	0.03022	0.02082
3PH RESISTIVE	48	0	0.02107	0.02501	0.01562
2L RESISTIVE	48	0	0.02031	0.03439	0.01353

Preliminary evaluation of the internal ground-to-fault cases where the relays failed to trip indicates that the sensitivity of the negative-sequence directional overcurrent element is not suitable for this particular application. The application and capabilities of the relay will be reviewed to determine if other line-to-ground fault detection methods may be more appropriate.

V. BUS DIFFERENTIAL RELAY TESTING APPLICATION

CenterPoint Energy has recently started utilizing its digital simulator for testing microprocessor-based bus differential relays. To evaluate this application, CenterPoint Energy obtained relay settings and COMTRADE files, containing various internal and external fault simulation cases, from a relay manufacturer. These settings and fault cases were applied to a six-circuit bus differential relay. Tests were done on a "per-phase" basis, where only a given phase of each circuit was wired to the relay at a time. The configuration also included multiple CT ratios. The simulations verified that this relay was dependable for all internal fault cases and secure for all external faults, and that the simulator equipment was suitable to test this kind of application.

As future work, CenterPoint Energy will be evaluating the development of its own ATP model – including representation of instrument transformer saturation – for testing bus differential relays using the simulator.

VI. CONCLUSIONS

Laboratory testing of microprocessor relays using a digital simulator system has several benefits:

- Capability to apply transient modeling to the system under consideration;
- Automated generation of appropriate signals, including transients, for relay testing;
- Repetition of the same test allows to evaluate relay dependability for specific system conditions;
- Use of power amplifiers enables replaying "real-life" signals into the relay;
- Two terminal simulator capability allows for testing and investigation of pilot relay schemes as well as differential relay schemes.

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BIOGRAPHIES

Don Sevcik (M'77) is a Senior Consulting Engineer in the Substation Projects Division of the Substation Operations Department at CenterPoint Energy in Houston, Texas. This department is responsible for engineering, construction, operations and maintenance of the transmission and distribution substation facilities of CenterPoint Energy. Don Sevcik has been employed for twenty-seven years at CenterPoint Energy (formerly Reliant Energy HL&P). His previous assignments involved transmission & generator protective relay application, transmission system equipment application, transmission system studies and power plant auxiliary equipment application. Don Sevcik received a B.S. degree in Electrical Engineering from Texas A&M University, is a Registered Professional Engineer in Texas and a Member of IEEE.

Hyder DoCarmo (M'98), a native of Paraná, Brasil, has bachelor and master degrees in electrical engineering from Louisiana State University and Texas A&M University, respectively. Between 1998 and 2000, he worked as an electrical design engineer for Transocean Offshore Drilling, in Houston, TX. Since 2000, he has been a protection engineer in the Substation Projects Department of CenterPoint Energy (formerly Reliant Energy), also in Houston. His current professional interests are transmission line protection, and applications and transient testing of microprocessor-based relays.

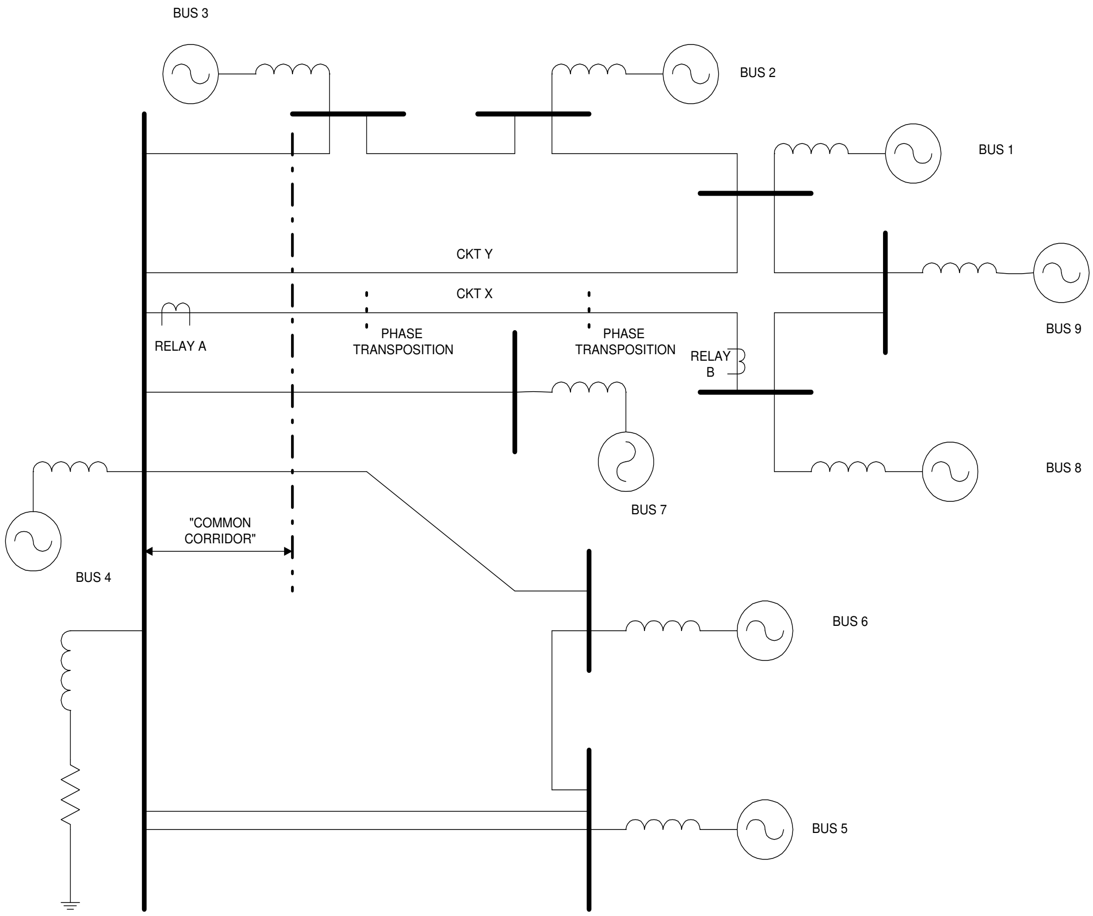
Mladen Kezunovic (S'77, M'80, SM'85, F'99) received his Dipl. Ing. Degree from the University of Sarajevo, the MS and PhD degrees from the University of Kansas, all in electrical engineering, in 1974, 1977 and 1980, respectively.

He has been with Texas A&M University since 1987 where he is the Eugene E. Webb Professor and Director of Electric Power and Power Electronics Institute. His main research interests are digital simulators and simulation methods for equipment evaluation and testing as well as application of intelligent methods to control, protection and power quality monitoring. Dr. Kezunovic is a registered professional engineer in Texas and a Fellow of IEEE.

Tomo Popovic (M'99) received his BS degree in electrical engineering in 1994 from University of Novi Sad.

He has been with Test Laboratories International Inc. since 1998 where he is a development engineer. His prior positions were with NIS-GAS, part of Petroleum Industry of Serbia, and University of Novi Sad, both in Novi Sad, Yugoslavia. His main professional interest is developing and implementing software and hardware solutions for industrial applications, especially in the field of electric power system engineering: analysis of fault records, transient testing of protective relays and digital simulators.

APPENDIX I


BUS 3
BUS 2
BUS 1
CKT Y
CKT X
BUS 9
RELAY A
PHASE TRANSPOSITION
PHASE TRANSPOSITION
RELAY B
BUS 8
BUS 7
"COMMON CORRIDOR"
BUS 4
BUS 6
BUS 5