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DISTANCE RELAY APPLICATION TESTING USING A DIGITAL SIMULATOR

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Abstract This paper reports on distance relay application testing using simulated transient waveforms. Power system modeling and test procedure for using modern digital simulators are presented. Extensive study of five commercial relays comparing the application for a 345kV transmission line is carried out by performing thousands of one-terminal and synchronized two-terminal transient tests. The approach using digital simulators has proved to be an efficient technique. This paper presents a methodology for evaluating distance relay transient performance based on extensive laboratory testing. Important issues regarding application testing, such as CT and CCVT effects and selection of prefault waveform length, are also addressed and investigated in this paper.

INTRODUCTION

The concept of digital power system simulators for protective relay testing has been developing since the early eighties [1-6]. The applications in testing of different relays have been reported in recent years [7-9]. Distance relay design testing using phasors has been discussed in a previous paper [10]. This paper is a successive report on digital simulator utilization in distance relay application testing using simulated transients.

The goals for distance relay testing may be quite different, spanning from evaluation of the relay designs undertaken by vendors, to the application evaluation done by the utilities, and investigation of the relaying principles undertaken by the universities. Although the goals are different, protective relay testing can be performed by using phasors or transients. Relay testing using phasors is sufficient to evaluate the operating characteristics under different prefault conditions [10]. It can also be used as a reference and explanation for the test results obtained by using transients. Usually, conventional relay test sets can be employed to perform phasor tests. Test waveforms can be derived by a calculation based on a simple power system model.

Modern digital simulators are capable of modeling details of complex power systems. Equipped with high power amplifiers, modern digital simulators are to play a major role in transient testing instead of analog simulators because of the modeling efficiency and economic concern. Tools such as electromagnetic transient program (EMTP) provide good power system representation [11]. For distance relay application testing, the studied line(s) and the first layer of busbars and lines neighboring the relay location are precisely modeled to simulate realistic fault-induced transients. Therefore, relay transient performance, such as sensitivity to the DC decaying offset and high frequency components can be evaluated. The power system modeling capability, high power outputs, graphical interface for fault study set-up, automation of large numbers of relay tests, and extensive data base arrangement for test result acquisition and automated analysis make the digital simulator technology more capable and convenient for relay application testing than what is available and possible with the existing portable test set technology.

Operating time and reach accuracy are two important indices for a distance relay design. Limitations in achieving both high speed and reach accuracy have been analyzed in previous papers [12-14]. Evaluation of these two indices is the main target for design and application testing.

This paper presents results from an extensive study of transient testing aimed at comparing the performance of five selected relays when applied on a 345kV transmission line of interest to the Houston Lighting and Power Company (HL&P). Details of modeling the studied line and its neighboring lines, boundary busbar equivalents and instrument transformers, as well as the test procedure and results are given in this paper. Besides the one-terminal transient performance evaluation, two-terminal coordination performance is also tested. Digital simulators designed and implemented at Texas A&M University [3-6] have been used for the testing.

SYSTEM MODELING USING EMTP

Reduced Power System

A one-line diagram of a power system section of interest to Houston Lighting and Power Company (HL&P) is given in Fig.1. The relay application for the line from STP to SKY is to be studied. The system has been studied using an EMTP simulation. Considerations for power system modeling are given as follows.

Thevenin equivalents for the boundary buses Thevenin equivalents for the boundary buses are derived from a calculation based on the power flow and the 60Hz short circuit data provided by the HL&P. Each boundary bus is modeled by a Thevenin equivalent. An ideal three-phase sinusoidal source (Type 14) and a lumped three-phase coupled R-L branch are used.

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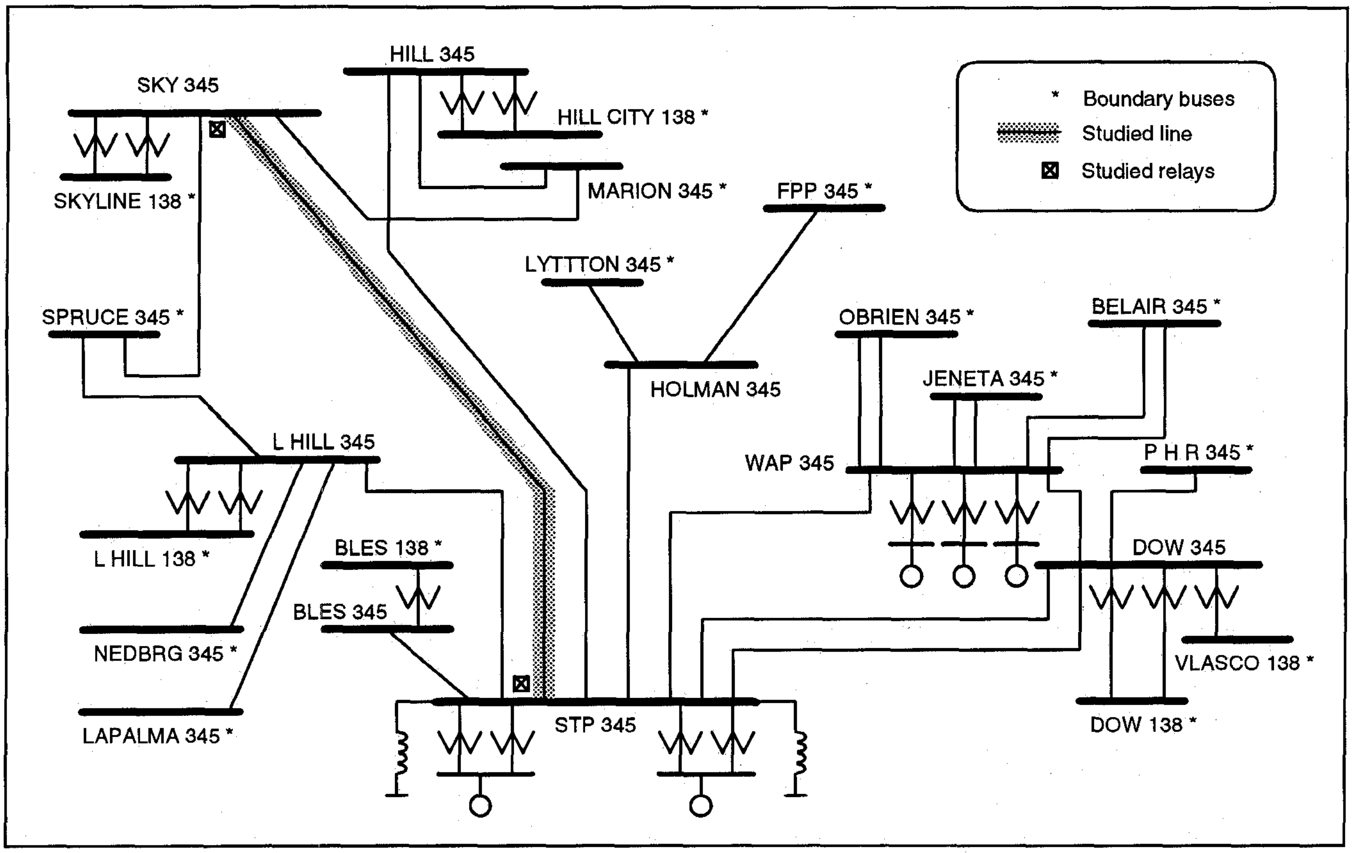


Fig.1 One-line diagram of the STP-SKY section in HL&P system

Line models: Selection of the line models is based on a trade off between simulation accuracy and simulation time. Among the available transmission line models in EMTP, the frequency dependent (FD) and constant parameter (CP) line models are selected as the appropriate ones for transient simulations. Since the FD line model is very involved both in terms of its data requirements and CPU time, it is used only for those lines which are of primary importance in the simulation study. The other transmission lines in the system studied in this paper are modeled using different line models. The line from STP to SKY and the line from STP to HILL are coupled parallel lines. They are modeled as FD lines. The lines from STP to L HILL, HOLMAN, WAP and DOW are modeled as CP lines. The rest of the lines are modeled as lumped parameter (LP) coupled lines. The line parameters are obtained by using the EMTP auxiliary routine based on the tower geometry data provided by the HL&P.

Power transformer and generator model In order to simplify the system model and reduce the simulation time, the zero- and positive-sequence R-L data are used to represent the power transformers, and the ideal Type-14 source model is used for the generators.

CT and CCVT Models

A diagram of a relay application for the line with current transformers (CT) and capacitor coupling voltage transformers (CCVT) is given in Fig.2. Detailed CT and CCVT digital models were developed based on the manufacturer's data and tests on the actual types used at STP and SKY substations, and included in the simulation.

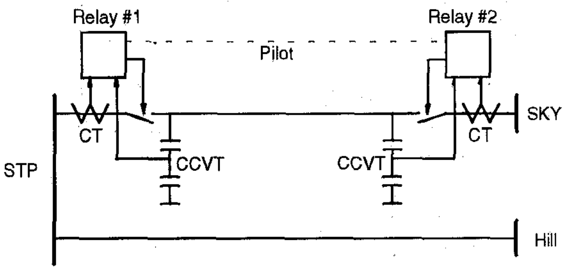


Fig.2 Relay installation with CT and CCVT

CT Models EMTP-based CT models developed at TAMU [15] are used in this study. Fig.3 shows the CT model diagram. The model was built around an ideal transformer with the Type-98 nonlinear inductor model available in EMTP. The V-I characteristics of the CTs used at the two busbars are shown in Fig.4. Different CT burdens were modeled to study saturation conditions.

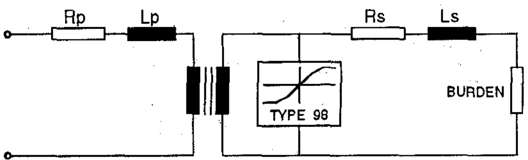
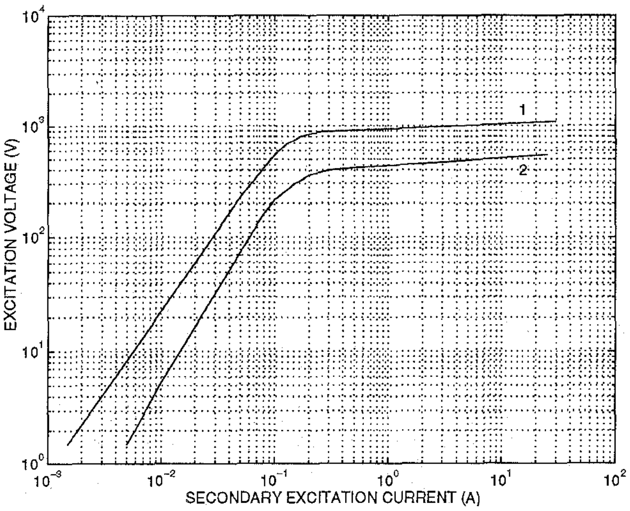


Fig.3 EMTP based CT model



1 -- Mitsubishi (3000/5A) at STP
2 -- ACT-130 (1200/5A) at SKY
Fig.4 V-I curves of CTs used at STP and SKY

CCVT Models Diagrams of the CCVT models used in this study are shown in Fig.5 and Fig.6. Details of development of the models, parameter selection and performance evaluation have been discussed in Ref.[16]. Burden of 100Ω is used in the study.

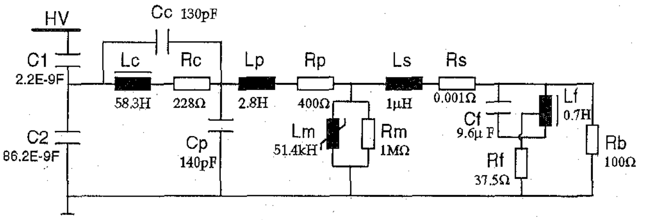


Fig.5 PCA5 (345kV/115V) used at STP

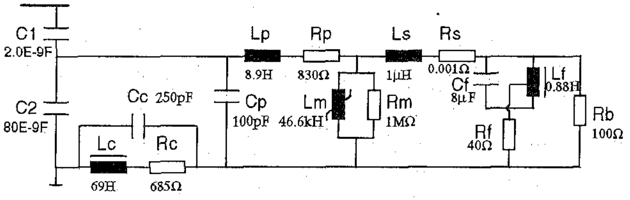


Fig.6 CD31D (345kV/115V) used at SKY

Validating Modeling Accuracy

The accuracy of the complete EMTP model for the studied system has been validated by comparing the fault data recorded by a digital fault recorder (DFR) with a corresponding simulation result. The steady-state power flow data were also used to confirm accuracy of the modeling. It has been proven that the modeling is quite accurate for both steady state and transient studies.

A fault captured by the DFRs located at several substations was used to verify the EMTP model. An airplane flew through both phase-A conductors of the parallel lines from STP to SKY and to HILL at around 40 miles from the STP substation as shown in Fig.1 making the location of the "fault" well known. The voltage and current waveforms recorded at the STP substation were compared with the ones obtained from the EMTP simulation of the given "fault" case by overlaying the waveforms in the time domain. The comparison has proved a close resemblance between the recorded and the simulated waveforms.

DISTANCE RELAYS TESTED

Five types of commercial distance relays were selected for testing. The following information on the relays is available:

Relays	Technology	Polarization
-- Relay A*	Numerical	Not available
-- Relay B	Numerical	Cross and memory
-- Relay C	Solid state	Cross and memory
-- Relay D	Numerical	Cross and memory
-- Relay E	Electromechanical	Cross and memory

* Two versions of the relay were used for the test

ONE-TERMINAL TESTING

Test Procedure

One terminal testing is sufficient to test relay transient performance. Fault cases are generated from the developed EMTP model and used to test the relays. Three-phase voltages and three-phase currents for relays located at STP are generated. Different faults with different fault location along the line are simulated. Fault cases with different combination of various fault types, locations, inception angles and fault resistance are essential to evaluate relay transient performance.

Test Case Generation A program has been developed to generate large numbers of test cases automatically using the EMTP software.

Test Set Up The test is performed by using a digital simulator as shown in Fig.7. The digital simulator used in this study was designed at TAMU [5]. An IBM RISC/6000 computer is used for generating test waveforms, signal processing and converting data files, data displaying and test result reporting. The DSP board and the I/O subsystem are used for data dispatching, data channel synchronization and D/A conversion. The DSP board is connected by a fast serial data link to the I/O board for transient waveform and contact interfacing. The amplifiers used are either an in-house design (voltage amplifiers) or a commercial product (current and voltage amplifier). Trip contacts of the relay under test are feed back to the simulator through the I/O subsystem.

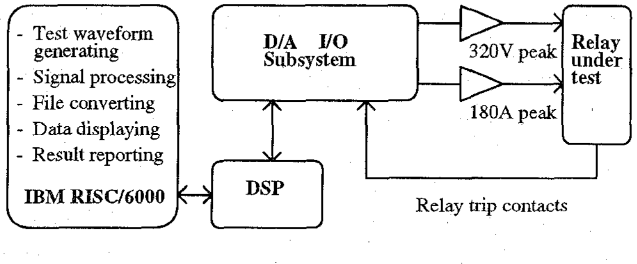


Fig.7 Test set-up diagram

Relay Setting The numerical and solid state relays have some other relaying functions besides the distance relaying element. In order to test and compare the distance relay performance, relaying functions other than the distance element and the associated logic units are disabled. The zone-1 reach was set at 85% of the protected line. The main objective focuses on testing the zone-1 selectivity and operating time.

Execution of Tests Execution of a large number of test cases is controlled by the software of the simulator. A batch of test data is converted to a specific format and sent to the DSP board. Analog signals from the D/A are amplified to the level of the relaying voltages and currents appearing on the secondary of the instrument transformers. The relay trip contacts are monitored through a capture file. Test results are stored on the disk.

Fault Parameter Sensitivity Study

The purpose of the fault parameter sensitivity study is to test the zone-1 selectivity and operating time using a large number of cases. Thousands of tests have been conducted for each relay. A group of cases tested in a batch file are demonstrated here as an example.

Test Cases (4 x 5 x 3 = 60) The following cases are generated:

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 The simulation specification is as follows:

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

Test Results

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 computer including the number of trips out of 30 tests, average, maximum and minimum operating time as well as the standard deviation for the 30 tests. A typical test result sheet for Relay A is given as follows:

A test result sheet for Relay A

```
Type  Loc   No.T   AvrgT    MaxT     MinT    Devtn
      (%)           (ms)    (ms)     (ms)
---------------------------------------------------
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 selectivity and operating time are the two most critical indices for distance relays.

Selectivity The number of trips out of 30 tests for each fault type and location are tabulated in Table I for the five relays tested. 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 I Number of trips out of 30 tests

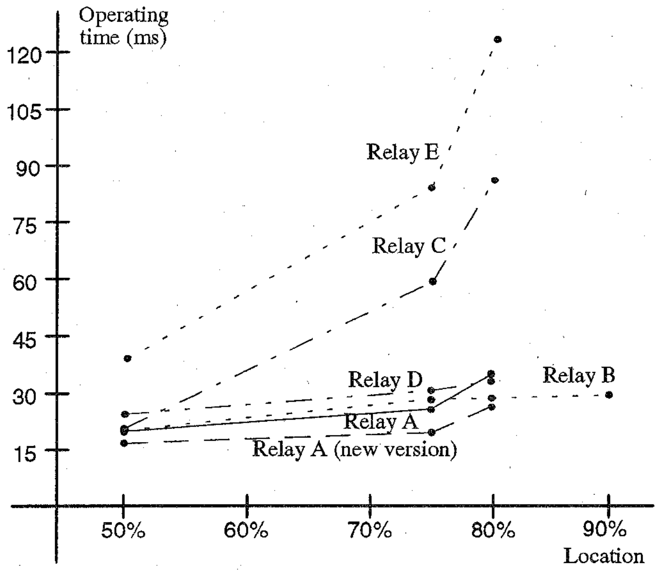
Fault type & locations	Rly A	Rly B	Rly C	Rly D*	Rly E*
A-G 50%	30	30	30	0	0
A-G 75%	30	30	30	0	0
A-G 80%	30	30	30	0	0
A-G 90%	0	20	0	0	0
A-G 95%	0	19	0	0	0
BC 50%	30	30	30	30	30
BC 75%	30	30	30	30	30
BC 80%	30	30	30	30	30
BC 90%	0	12	0	0	0
BC 95%	0	0	0	0	0
ABC 50%	30	30	30	30	30
ABC 75%	30	30	30	30	30
ABC 80%	30	30	30	30	30
ABC 90%	0	30	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	14	0	0	0
BC-G 95%	0	0	0	0	0

* Relay D and Relay E do not have a ground distance element

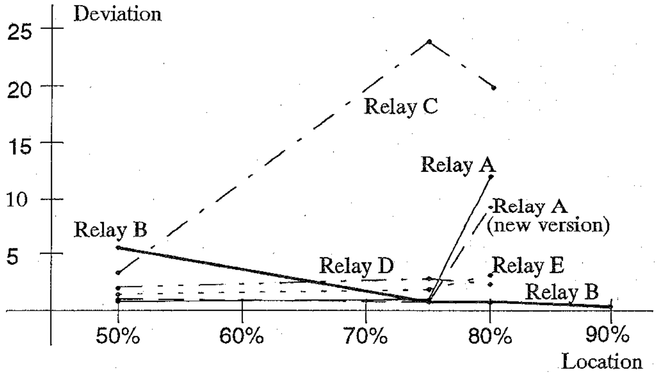
The shaded areas indicate the numbers of maloperating trips.

Operating Time Comparisons of the operating time and standard deviation among the relays tested for phase-to-phase and single-line-to-ground faults are shown in Fig.8 and 9 respectively. From the test results and the performance comparison, it is easy for a utility to select 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° [17]. The most important inception angles are those which result in different DC component and high frequency components in the waveform. The angles at 0° and 90° are two extremities. Test results show that some relays are more sensitive to the non-fundamental components than the others. Test results for Relay B are tabulated in Table II for different inception angles. Various faults at 90% of the line are used as an example. The numbers of trip operations out of 10 tests repeated and the average operating times for different inception angles are included in the table. It is obvious that Relay B will overreach for single-line-to-ground faults with 0° and 45° inception angles. This results in higher DC offset values than for the angle of 90°.

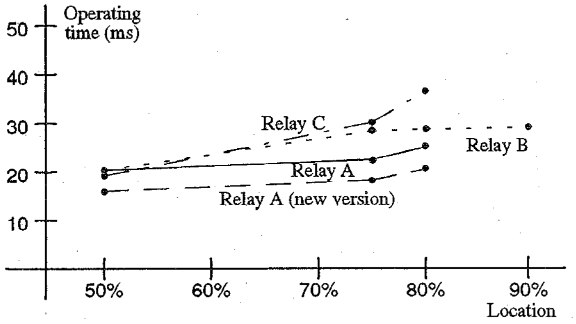


(a) Operating time

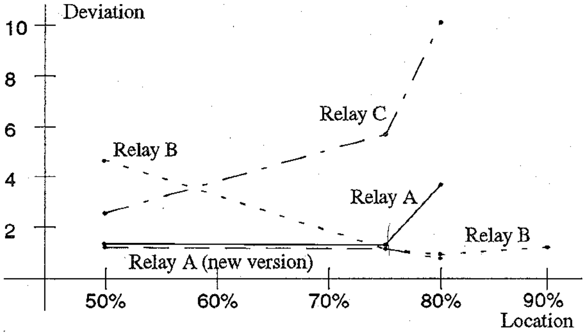


(b) Standard deviation

Fig.8 Average operating time and deviation for BC fault



(a) Operating time



(b) Standard deviation

Fig.9 Average operating time and deviation for A-G fault

Table II Test results of different inception angles for Relay B (Fault location: 90%, Number of tests repeated: 10)

Fault type	Inception angle	Trip number	Average operating time (ms)
A-G	0°	10	29.98
	45°	10	27.93
	90°	0	
B-C	0°	2	28.10
	45°	10	28.14
	90°	0	
ABC	0°	10	27.67
	45°	10	27.72
	90°	10	27.61
BC-G	0°	4	28.52
	45°	10	28.32
	90°	0	

Effect of Prefault Waveform Length

Different relays have different requirement for prefault length to stabilize the polarizing signals especially the memory polarizing signals. Too short length of a prefault waveform may not be sufficient conditioning for distance relays. If the prefault waveform is too long, it may affect testing efficiency. Longer prefault waveforms need longer CPU time to generate test cases and more space to store the data. To investigate prefault length effects, 4 cycle and 30 cycle prefault waveforms were used to test the five relays. Three-phase faults were used to test the relays, as an example. Faults at 50%, 75%, 80%, 90%, 95% were simulated with different inception angles: 0°, 45° and 90°.

Each test was repeated for 30 times. The results reveal that 4 cycle prefault length is sufficient for Relay B, C, D and E but not for Relay A. The same number of trips out of 30 tests for each fault type and location was obtained by using 4- and 30-cycle prefault waveforms for the five relays tested. Relay B, C, D and E also have the same average operating times for the two different prefault length waveforms. Relay A responds differently. Although the number of trips for every fault type and location are the same, average operating times are different. The difference of the average operating time is given in Fig.10. The test results revealed that the 30-cycle prefault waveform length is sufficient for the five relays under test.

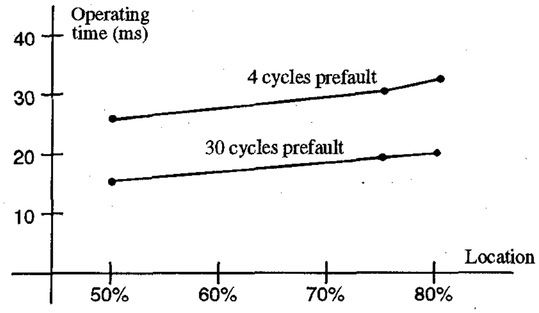
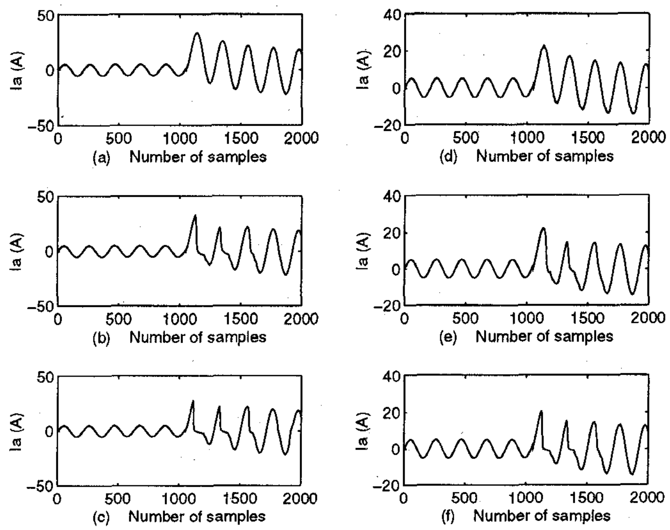


Fig.10 Average operating time of Relay A

CT and CCVT effects

CT Effects The ACT-130 (1200/5A) model (see Fig.3 and 4) was used to investigate CT effects. The CT saturation level will change if different CT burdens are used. Single-line-to-ground faults at 50%, 80% and 90% of the line from STP with different CT burdens were simulated to test the relay. Inception angle of 0° is selected which results in a maximum DC decaying offset. The faulted-phase saturated current waveforms are given in Fig.11.



(a) 50% fault, burden = 4Ω (d) 80% fault, burden = 4Ω
(b) 50% fault, burden = 16Ω (e) 80% fault, burden = 16Ω
(c) 50% fault, burden = 30Ω (f) 80% fault, burden = 30Ω

Fig.11 Fault-phase currents for different CT burden

Each fault case was repeated 30 times to test Relay A, B and C. Average operating times for each relay are given in Table III. The test results reveal that the CT saturation does not affect selectivity of the relays. The operating time is slowed down due to CT saturation.

CCVT Effects Various faults with and without CCVT, as well as using the different CCVT models have been used to test the relays for the STP-SKY line application. Test results show no significant effects from CCVT.

Table III Average operating time for different CT saturation

Fault location	CT burden	Relay A (ms)	Relay B (ms)	Relay C (ms)
50%	4 Ω	16.23	18.31	25.66
	16 Ω	37.53	61.47	64.03
	30 Ω	58.04	62.41	65.12
80%	4 Ω	19.13	29.46	40.71
	16 Ω	77.40	68.94	78.50
	30 Ω	77.38	78.93	81.21

TWO-TERMINAL TESTING

Two-Terminal Test Configuration

Fig.12 represents the two-terminal test configuration used for relay testing discussed in this paper. Test waveforms for relays at terminals STP and SKY are simulated using the EMTP. A data file for each test case contains three phase voltages and three phase currents for one terminal and three phase voltage and three phase current for the other terminal. The data file for one test case is split into two and each one is sent to the specified terminal. The waveform replay synchronization is governed by the DSP board. Test waveforms are applied to the two relays through the voltage and current amplifiers. A time delay device is used to emulate the pilot time delay. Relay trip contact and pilot signals (signals send and receive) are feed back to the I/O board. Two capture files are generated and saved on the disk for each test.

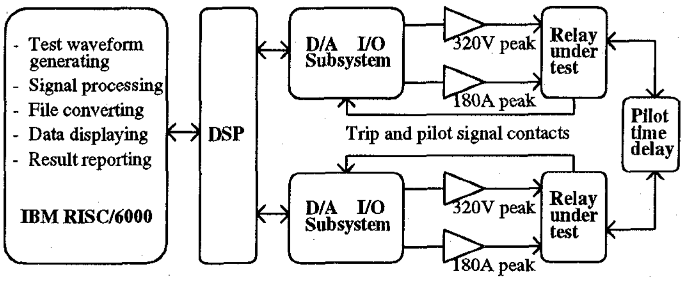


Fig.12 Two-terminal test configuration

Test Results

Extensive two-terminal tests have been conducted using the open-loop two-terminal configuration design. A set of reclosing related test cases are demonstrated here as an example.

Relay Setting The test was performed on five pairs of the commercial relays. They are set with similar setting: zone 1 was set to 85% of the protected line and the pilot aided trip was enabled. All relays except Relay E have been tested for two different relaying schemes:

-- Permissive Overreach Transfer Trip
-- Blocking

Relay E is an electromechanical relay. It was tested just for blocking scheme in accordance with the actual practice in the HL&P system. The 'pilot' time delay was set to 5ms.

Test Cases and Waveforms Five three-phase faults on the line have been simulated at: 25%, 50%, 75%, 90% and at the MARION Busbar. Waveform specification is given as follows:

Simulation sampling rate:	12.5 kHz
Length of the test signals:	700ms
Prefault waveform length:	200ms
Fault waveform length :	80ms
Breaker opening time :	220ms
Breaker re-closing time:	150ms
Breaker re-opening time:	50ms

Test Results: The five pairs of relays have been tested. A graphical test report is generated for each case and each relay. A typical graphical report for Relay C is shown in Fig.13 where test waveforms for the two terminals, the trip contact, and send and receive pilot signals are plotted for both relays. A test result summary for all the relays is given in Table IV.

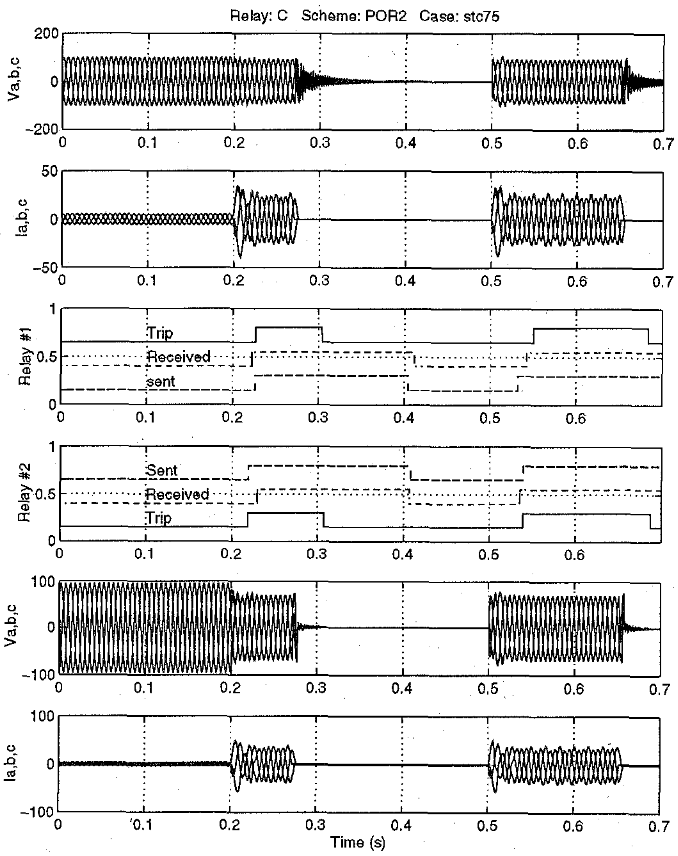


Fig.13 A typical graphical two-terminal test result for Relay C

Table IV Test result summary for two-terminal testing

Test	Rly A		Rly B		Rly C		Rly D		E*
case	BK	PO	BK	PO	BK	PO	BK	PO	BK
25%	•	•	•	•	•	•	•	•	•
50%	•	•	•	•	•	•	•	•	•
75%	•	•	•	•	•	•	•	•	•
90%	•	•	•	•	•	•	•	•	•
out	•	•	x	x	•	•	•	•	•

BK -- Blocking; PO -- Permissive Overreach;
Rly -- Relay; • -- Pass; x -- Fail

* Test results for permissive overreach relaying scheme are not applicable due to the electromechanical relays utilized.

CONCLUSIONS

The results given in this paper demonstrate how the new testing methodology and the use of digital simulator technology have revealed the following properties of some of the distance relays tested:

- One of the relay designs (Relay B) does not have the required selectivity for the faults located at the end of zone 1.
- Relay A (new version) has the highest operating speed and the best repeatability for both phase and ground faults. The electromechanical relay has the lowest operating speed compared with the digital relays, but it possesses very good repeatability. One of the relay design (Relay C) has a distinct reverse distance-operating speed property.
- The length of prefault waveforms does affect the test results for distance relays. Different relay designs have different requirement for prefault length to stabilize the memory polarizing signals.
- CT saturation reduces the operating speed of the distance relays but overreach due to CT saturation did not occur during the extensive testing.
- One the relay design (Relay B) may have some problems for closing into a fault located on the neighbor line.

ACKNOWLEDGMENTS

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BIOGRAPHY

Mladen Kezunovic (S'77, M'80, SM'85) received his Dipl. Ing. degree in electrical engineering in 1974, and the M.Sc. and Ph.D. degree from the University of Kansas, in electrical engineering in 1977 and 1980 respectively. His industrial experience is with Westinghouse Electric Corporation in the U.S.A., and the Energoinvest Company in Sarajevo. His academic experience is with the University of Sarajevo and Washington State University. He has been with Texas A&M University since 1987 where he is an Associate Professor. He is a member of the IEEE PSRC, CIGRE and a registered Professional Engineer in the State of Texas.

Yanquan Xia (M'94) received his B.Sc. and M.Sc. degree from the Tianjin University, China, the Ph.D. degree from the Hong Kong Polytechnic University, Hong Kong, all in Electrical Engineering in 1986, 1989 and 1993 respectively. He entered the universities with six years of apprenticeship and work experience in power transmission and distribution industry. His post-college experience is on various research and development projects in the area of power system control and protections as well as computer applications in the power system. He is a Postdoctoral Research Associate at Texas A&M University since 1993.

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Donald R. Sevcik (M'81) received his B.Sc. in Electrical Engineering from Texas A&M University in 1975. He was employed by Houston Lighting & Power Company in 1975 and is currently a Lead Engineer. He has worked in the following areas: Power Plant Electrical System (1975 to 1977), System Studies (1977 to 1979), and Transmission and Generation Protection (1979 to present). He is a registered Professional Engineer in the State of Texas.

Discussion

T. Seegers, Southwestern Public Service Company:

The authors have presented an interesting paper on the subject of distance relay testing with a digital simulator. Of particular interest was the notable increase in operating times for tests near the reach setting (balance point). How much increase occurs for faults nearly at the balance point?

A typical utility would perform relay tests using less sophisticated equipment under more ideal input conditions. How do the results of this paper compare to the operating time and selectivity results that might be obtained using more conventional test equipment on a typical utility test bench?

The results of the tests reveal a variance in the operating time and selectivity of the relays for any given configuration of the test inputs. With this in mind, could the authors comment on the suitability of applying this type of testing to post-mortem type studies on a given system?

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Walter A. Elmore (ABB Power T&D Company Inc., Coral Springs, Florida) 1) The conclusions of the paper show very well the important benefits to be gained by extensive system testing, and all of the contributors are to be encouraged to continue in this type of effort. 2) Some of the relays seem to be unjustly shown in a poor light as a result of defining overreach as the detection of faults beyond the set point of the relay. Indeed, the reason for recommending such settings as 75 to 90% of line length for zone 1 phase and ground distance relays is to allow the unique imperfections of a particular relay, its associated voltage supply (cvt or vt), all possible variations of source/line impedance ratio, and the maximum dc offset expected for the application to be considered so that avoidance of operation for a fault (any fault) at the next bus may be realized. A fault at 90% of the line length that is recognized by a relay that is set for 85% poses no detrimental effect and, to the contrary, may be beneficial. Any operation of a zone 1 relay for faults at 100% of the line are unacceptable. It would add light to the comparisons in the paper if a 100% fault location point were included. 3) To classify relays D and E in any way for phase-to-ground faults is unfair to them because of the fact that neither system is equipped with provision for detecting line-to-ground faults. It is interesting to note that for all of the BC-G faults, these phase relays did respond correctly, however. 4) Were all of the fault inception angles measured from the same reference or were they varied for each different fault type? 5) The use of a linear interpolation in figures 8 and 9 appears to do a disservice to relays C and E. The actual curve of operating time vs fault location is more of an exponential character and for example for relay E at 60% fault location, its operating time would be expected to be more like 40 ms than the 55 ms shown. 6) The effect of different pre-energization time is of little consequence. All modern relaying systems are equipped with line-energization logic which allows re-tripping to occur if a fault is present. This is done, as it has to be, considering the use of line-side-voltage transformers, without the need for memory action tripping. 7) In figure 13, tripping occurred, with this POTT scheme, before the channel trip was received. Was this due to zone 1 action? 8) Breaker opening time is listed as 220 ms. The graphical plots of figure 13 appear to indicate more nearly a 50 ms trip time. 9) In table IV what was the significance of "out", for which the "B" system failed?

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P.G. McLaren (University of Manitoba.) This paper illustrates the capability of a digital "Playback" power system simulator in testing relays.

The authors have commented on the polarisation technique used in the relays but have not reported on any reverse faults? The major reason for polarisation is to distinguish between close up forward and reverse faults but neither of these fault locations have been reported? One presumes that all the relays behaved properly on such faults? What about relay A in particular with a short prefault signal?

As expected transient CT saturation slows down relay operation.

The authors state that there were no significant effects due to CCVT's. Were the relays subjected to CCVT subsidence transients? (Close up faults would have been the correct fault location for such effects to be examined.) Did any of the tests include ferroresonance (suppressed or not suppressed) in the CCVT, e.g. during a reclose operation?

In order for relay engineers to interpret the results of the various test findings it would be very helpful if the authors could give some indication of the relay design principle. For instance, was the relay a phase comparator type or a one cycle Fourier type or a differential equation type, or what? Such detail might help explain why the length of the prefault signal (relay A) would affect the operating time for forward faults and why relay C has an *inverse* (not *reverse*) distance operating speed characteristic.

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M. Kezunović (Texas A&M University, College Station, Texas), C. W. Fromen, D. R. Sevcik (Houston Lighting & Power Company, Houston, Texas): The authors would like to thank discussers for their interest and valuable comments. Before answering the specific questions, the authors would like to emphasize the following goals and constraints of the study reported in the paper:

- This study was aimed at demonstrating how digital simulators could be used to evaluate distance relay application performance. The goal **was not** to make a final decision about performance of specific relays or their suitability for a given application.

- Since the goal **was not** to use the test results to make a final comparison between relays, the results are often only illustrative and not all encompassing.

- The test approach taken **was not** aimed at being as comprehensive as it may have had to be if it was to be used for selection of the "best" relay.

- The tests were performed with an intentional goal of using a minimum knowledge about relay design and implementation details, since the intended environment for such testing are utility companies where this information about relays may not be readily available.

With these general comments in mind, the following are our answers to the specific questions raised by the discussers.

In reference to Mr. Seegers's comments, the replies are:

- Our test results are obtained for 80% and 90% locations. The balance point for the relays tested was 85%. Based on what we were able to observe, the operating time increases near the balance point differently for various relay designs. The Relays C and E have the most significant increase in the operating time compared with other relays. Since the operating time increase for the balance point was not an explicit target of the study, no further results are available, and hence, no further comments are possible.
- Our test results were not compared with the corresponding results that may have been possible to obtain with conventional test sets. However, it was demonstrated what can be done with digital simulators. It would be possible to carry out a further study in the future where the test results obtained by conventional test sets could be compared with the reference results obtained by digital simulators.
- The post-mortem type studies could definitely be enhanced if the results as comprehensive as reported in the paper are made available for the given relay and application.

Mr. McLaren's comments and questions are very interesting, but for the reasons explained earlier, our study was not aimed at providing detailed results or answers related to the subjects raised. However, the following information is deemed relevant:

- Some limited tests for reverse faults were performed and the relays operated correctly. However, more "difficult" cases where extensive variation of the SIR could be performed, but were not carried out.
- The relays were subjected to the subsidence transients. No particular problems with relay operations were noted. The tests did not include an intentional simulation of ferroresonance phenomena, but the models of the ferroresonance suppression circuit in the CCVT were used all the time.
- For the reasons explained earlier, no intent was made to explain relay operations, and hence, no data on the relay designs was taken into account and studied. It is conceivable that this data can be obtained and used to fully explain the relay design features contributing to the performance as seen from the results of this study.

Per comments by Mr. Elmore, it is important to note the goals of the study mentioned earlier. Once the goals are observed, it will become clear that the authors did not have a reason to be "unfair" in the assessments of the relays or to show the performance of any of the relays in an "unjustly" way since a detailed assessment of the relays was not the goal of this study. In the same light, the authors did not have a reason to present any relay test results so that a "disservice" to a given relay is intentionally made. As per the other comments by Mr. Elmore, the following can be indicated (in the order of the original comments):

- The authors agree that it would have been beneficial if a 100% fault location points were included. The tests for such a case were performed and the results are as follows. The Relay B was the only one that has experienced an operation for location 100%. The operation was only for A–C fault. The respective performance was: No. of trips (20); average time (29.02 ms); maximum time (30.84 ms); minimum time (27.06 ms); deviation (0.91).
- The authors still consider the test results shown (Table I in the original paper) being quite informative since they indicate some problems with the operation of phase distance relays for ground faults.
- All of the fault inception angles were measured from the same reference.
- The authors agree that a better approximation than linear could have been used in Figures 8 and 9 in the original paper. However, with the scope of study as indicated earlier, the linear approximation was considered sufficient.
- As per discussion of the pre–energization time, the authors do not have additional results to support, or negate, the arguments of Mr. Elmore. However, it should be pointed out that the pre–energization tests were done with a different goal in mind. The authors wanted to investigate how long prefault conditions need to be applied to a relay before a fault is initiated. This had to do with automated testing where a batch of tests can be executed automatically and sequentially and it becomes important to decide how long the pre–energization of the relay should be.
- The observation made by Mr. Elmore regarding Figure 13, is correct, i.e., the tripping occurred due to the Zone 1 action.
- The authors are grateful to Mr. Elmore for his comments related to Figure 13 since the wording used to explain various times is quite unclear, and inappropriately contributed to the breaker. The correct wording in the section "Test Cases and Waveforms" given on pp. 7, above Figure 13 should be: "fault waveform removed" for 220 ms, instead of "breaker opening time"; "fault waveform applied" for 150 ms instead of "breaker re–closing time"; "fault waveform removed" for 50 ms instead of "breaker re–opening time".

- The authors would like to clarify the meaning of the term "out" in Table IV. The test case considered is shown in Figure A.1 given below. The scenario for the test sequence is as follows: Relays at locations 1 and 2 have operated for some reason (loss of directionality, for example) for a fault in the adjacent line ("out"); relays at locations 1 and 2 have reclosed and the "out" fault is still there; the case in Table IV marked "out" is indicating operation of relays at locations 1 and 2 after the reclosing took place.

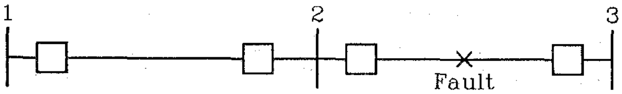

Fig. A.1. Case of an "Out" Fault

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