AN ADVANCED METHOD FOR TESTING OF DISTANCE RELAY OPERATING CHARACTERISTIC

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Abstract: This paper describes a test method for distance relays using an advanced open-loop digital simulator. Derivation of test signals during prefault and fault, and test procedure are introduced. It is demonstrated that the method of generating test signals and the procedure of applying them to a relay under test directly affect test results. Prefault voltage and current are also a very important factor. The decaying dc offset is considered as well. Test results for five different relays using this new method are presented in this paper. The results demonstrate practical benefits of the test method.

INTRODUCTION

There are various test methods for distance relays. The simplest and most straight-forward way is to follow the manufacture's recommendation. This assumes testing a relay at several given points inside and outside a characteristic. The overall operating characteristics can not easily be verified using this approach. The traditional way of tracing the operating characteristic is a commonly used steady-state test. This test is performed by applying ac phasor quantities at the inputs of the protective relay and varying the voltages slowly while the currents are kept constant; or varying the currents keeping the voltages constant, until the operating boundary at a given angle is found [1]. The characteristics obtained in this way is not an appropriate one at least for cross- and quadrature polarized relays [2,3]. Cross-polarized MHO distance relays develop an offset in the presence of an unbalanced fault which is dependent upon the source impedance seen by the relay. Holding voltage constant and varying current has the effect of varying not only the fault impedance but the source impedance as well. This is not a realistic case encountered by a relay in service. Kennedy et. al. raised this problem and introduce a test method for the cross- and quadrature polarized relays [2].

It is well known that the dynamic characteristic of a distance relay is different from the steady-state characteristic, especially for memory-polarized relays [4]. Prefault values of the input signals affect performance of the relay. Utilities' test methods using traditional test set to test polarized relays have been discussed in [5-8]. Prefault and fault voltages and currents are synthesized with a test set. Several points on and inside a theoretical characteristic are tested [5]. Another method is testing of a relay using simulated faults at different location on a line [6]. The simulated phase quantities for each fault location were taken from the computer printout and pre-dialed on the test sets. These test quantities were applied to the relay by simultaneously turning on all voltages and currents from the test sets. The relay operation is observed. In another approach [7], the dynamic characteristic is tested using the procedure discussed in [1,2]. In a recent publication, Henville and Jodice discussed a pseudo-transient test method to discover relay design and application problems [8]. Overreach and failures of directional integrity of several relays have been found using this method. Effects of the prefault load current on the dynamic characteristic of a distance relay are well understood [9,10]. If a fault occurs through a fault resistance, the situation is more complex [11]. The question is how to define an appropriate test methodology to cover all phasor quantities that affect the characteristic. Computer controlled relay test sets and digital simulator are available which make it possible to implement more accurate and sophisticated tests [12,13].

This paper introduces a new phasor-based method for testing relay characteristic. Regardless what is the principle the relay design is based on; cross polarizing, memory polarizing or no-polarizing at all; electromagnetic, static or micro-processor based; we treat the relays as black boxes and provide them with right test signals which are quite close to the real situation a relay would encounter under service. The system parameters, prefault and fault signals, and the transition period from prefault to fault should be correctly presented. Although the phasor-based test method uses just the fundamental frequency test signals, it simulates a fault by instantaneously switching all signals between prefault, fault and postfault states while monitoring relay outputs. The results are much closer to the relay performance under service than what has been demonstrated by the existing steady-state and dynamic test method. The results can also be used as a very good reference point for interpreting test results of transient testing in which the dc and high frequency components are naturally presented.

PHASOR QUANTITIES USED FOR TESTING

The operating characteristic of a relay resulting from a test without correct test signals and corresponding procedure is unrealistic. Certain conditions are required to obtain a characteristic that determines relay performance under service situations:

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- -- correct prefault voltages and currents;
- -- correct fault voltages and currents;
- -- correct transition from prefault to fault;
- -- load current effect on the fault signals;
- -- presence of the dc decaying offset;
- -- presence of the high frequency transients;
- -- the far-end infeed/outfeed conditions.

A simplified power system representation as shown in Fig.1 is used as a model to obtain test quantities. In the figure, Z_S is the equivalent source impedance, E is the phase-A source voltage which drives the fault current, I_L is the phase-A load current. We use Z_f to represent the fault impedance which includes the line impedance from the relaying point to the fault and the fault impedance combined with the infeed effect. A reason of using the single-source model instead of two-source model is the goal of testing relay design characteristic without the far-end infeed effect taken into account. To obtain a complete characteristic, we assume that phase angle of Z_f changes from 0° to 360°. Using this model with different types of faults at F, we have derived the relaying voltages and currents for the single-line-to-ground (A-G), double-line-to-ground (BC-G), line-to-line (BC) and three-phase faults (ABC). The phasor quantities are derived based on a symmetrical fault analysis method [14].

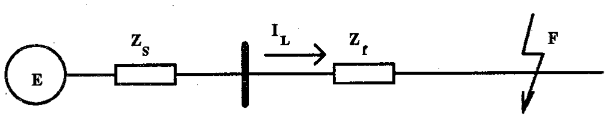


Fig.1 System representation model

For the relay under test, the input signals (three phase voltages and currents) involve at least two sets of different phasor quantities, namely, prefault and fault signals. Taking the single-line-to-ground fault as an example, we can express the prefault and the fault signals as follows:

Prefault signals:

$$I_A = I_L \ ; \quad I_B = a^2 I_L \ ; \quad I_C = aI_L \ ;$$

$$U_A = E - Z_{S1}I_L \ ; \ U_B = a^2(E - Z_{S1}I_L) \ ; \ U_C = a(E - Z_{S1}I_L)$$

Fault signals:

$$I_A = \frac{3E}{(2+p)Z_{s1} + (2+q)Z_{f1}} + \frac{(p-1)Z_{s1} + (q-1)Z_{f1}}{(2+p)Z_{s1} + (2+q)Z_{f1}} I_L$$

$$I_B = a^2 I_L \ : \quad I_C = aI_L$$

$$U_A = \frac{(2+q)Z_{f1}}{(2+p)Z_{s1} + (2+q)Z_{f1}} E + \frac{(p-q)Z_{s1}Z_{f1}}{(2+p)Z_{s1} + (2+q)Z_{f1}} I_L$$

$$U_B = a^2 E + \frac{(1-p)Z_{s1}}{(2+p)Z_{s1} + (2+q)Z_{f1}} E + \frac{K_1 Z_{s1}^2 + K_2 Z_{s1} Z_{f1}}{(2+p)Z_{s1} + (2+q)Z_{f1}} I_L$$

$$U_C = aE + \frac{(1-p)Z_{s1}}{(2+p)Z_{s1} + (2+q)Z_{f1}} E + \frac{K_3 Z_{s1}^2 + K_4 Z_{s1} Z_{f1}}{(2+p)Z_{s1} + (2+q)Z_{f1}} I_L$$

where

$$p = Z_{s0} / Z_{s1}; \ K_1 = (1-a^2)p - 1 - 2a^2; \ K_3 = (1-a)p - 1 - 2a;$$
$$q = Z_{f0} / Z_{f1}; \ K_2 = p - a^2 q - 1 - 2a^2; \ K_4 = p - aq - 1 - 2a.$$

TEST PROCEDURE

System Parameters

There are several system parameters in the formulas used to calculate test signals. They are positive- and zero-sequence source impedance Z_{S1}, Z_{S0}; positive- and zero-sequence fault impedance Z_{f1}, Z_{f0}. For simplicity reason we use $p=Z_{S0}/Z_{S1}$, $q=Z_{f0}/Z_{f1}$ and assume they remain constant for a given system configuration. For utilities to conduct application tests, the parameters E, I_L, Z_{S1}, p, q can be set according to their given system. For manufactures, tests can be done with different values for line length, source-to-line impedance ratio, load current. Once these parameters are given, the prefault and fault voltages and currents can be calculated for a certain value and angle of Z_f. In this paper we use a section of the Houston Lighting & Power system as an example.

Relay Settings

Five different distance relays (A, B, C, D, E) have been tested using the new method with the DYNA-TEST simulator developed at Texas A&M University [12,13]. These relays are set for a short line (10.15 miles, the NBelt--King line) in the Houston Lighting & Power system. The zone 1 setting is 85% of the line (1.04Ω secondary value). The maximum torque angle is 84° (the line angle). The equivalent positive- and zero-sequence source impedance of the local end are 1.522∠81°Ω and 2.635∠82°Ω respectively. The test was confined to zone 1 characteristic. We enabled only the zone 1 distance related elements and blocked other ones to be able to test the zone 1 distance characteristic.

Test Waveform

A PC is used to compute and generate test signals, and to control the DYNA-TEST simulator. The phasor testing quantities are generated at 40kHz sampling rate. They are send to the simulator interface cabinets where the signals are converted into analog waveforms and amplified to a proper value. The sampling rate can be set by the users. The relay under test receives the signals as inputs. The contacts generated by the relay are sent back to the computer through the simulator interface. The length of the test waveform for each test is set at 60 cycles; 30 cycles prefault and 30 cycles fault. The time interval between two test is about 6 to 10 seconds. In any case, the calculated current value of in the third or the fourth quadrant Z_f may be very large. Due to a safety concern for the relay, the current was limited below a certain value according to the relay specification manual. The transition period from prefault to fault of a typical waveform is shown in Fig.2.

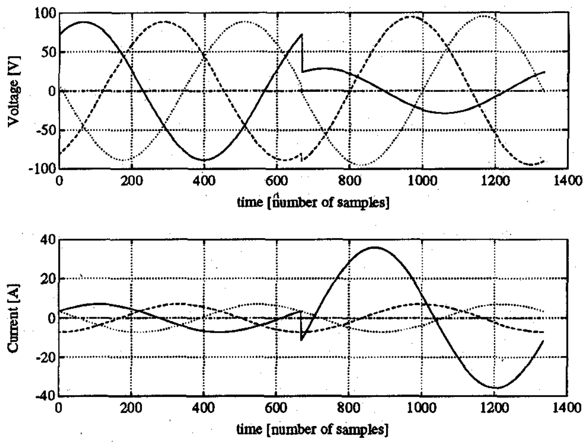


Fig.2 Three phase voltages and three line currents

Program for Test Control

A computer program is used to control the test. At the beginning, the angle of Z_f remains at the maximum torque angle value. The amplitude of Z_f is selected to be the relay reach value multiplied by a factor k (k is selected from 1.2 to 1.8). The program calculates the prefault and fault phasor quantities using the corresponding formula. The prefault signals are applied to the relay followed by the fault signals. The relay contact state is feed back to the computer through the simulator interface. If the relay does not trip, the value of Z_f will be reduced by a step of Δm and the program will repeat calculation and test execution until the relay trips. The value of Δm relates to test accuracy and searching speed for the operating boundary. We used two values to obtain satisfactory test accuracy and speed. A larger value is used first. Once the relay trips, the value of Z_f is set back to the latest no-trip value and then a smaller value of Δm is used until the next trip. The program saves the value of Z_f for the result print out and then the angle of Z_f is increased by a step of Δa and the searching for the boundary value at a new angle is repeated. We used $\Delta a=15°$ in the first and second quadrants, and $\Delta a=30°$ in the third and fourth quadrants. After all angles around 360° are finished, one of the relay characteristic is obtained. The program automatically controls the test flow and sends the test result, as well as the measured characteristic, to the computer screen or a printer.

Fault Types and Test Cases

For each relay, we tested the three-phase fault (ABC), the phase-to-phase fault (BC), the single-line-to-ground fault (A-G) and the double-line-to-ground fault (BC-G). To demonstrate the effect of prefault voltage and current on the characteristic, three cases for each fault type have been implemented:

Case I: prefault voltage = 0;
prefault current = 0;

Case II: prefault voltage = rated value ($E=67\angle 0°$ V);
prefault current = 0;

Case III: prefault voltage = rated value ($E=67\angle 0°$ V);
prefault current = selected value ($5\angle -30°$ A);

The Case I is equivalent to the situation of reclosing in to fault. The Case II is the no-load or light prefault condition.

The program automatically controls the test procedure. All tests with various fault types and cases can be completed within 2 to 4 hours for each relay.

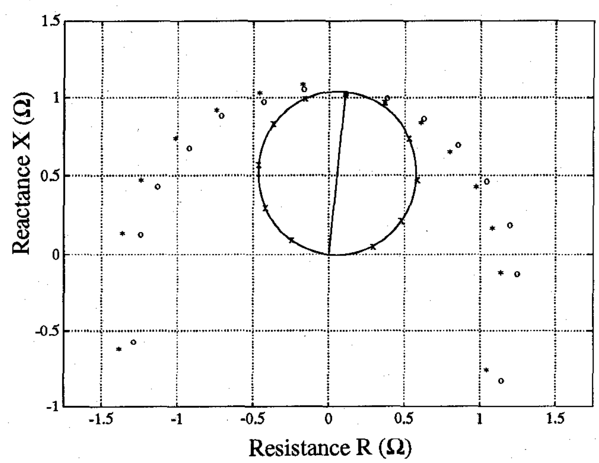
TEST RESULTS

Different Test Cases

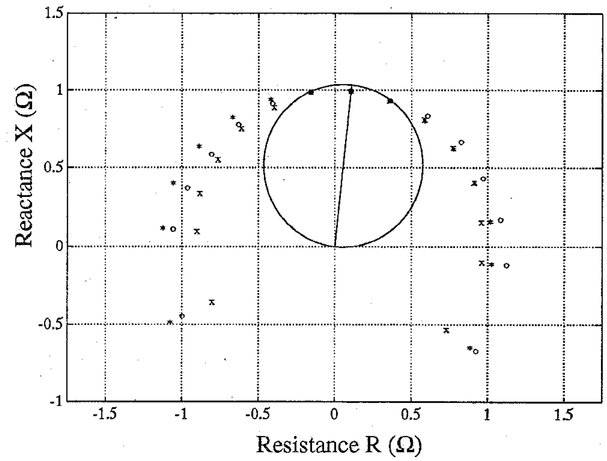
The three-phase fault test results for relay A are shown in Fig.3.a, in which the solid-line circle is the steady-state reference. The steady-state characteristic is defined by the diameter from the origin to the setting point with the maximum torque angle (it is not obtained as a test result but through a theoretical consideration). The symbols 'x' are used for test results of Case I, 'o' for Case II and '*' for Case III. It is obvious that the effect of the prefault signals on the characteristic is significant. It can be seen that the memory polarizing characteristic is apparent and the load current significantly affects the characteristic.

Different Fault Types

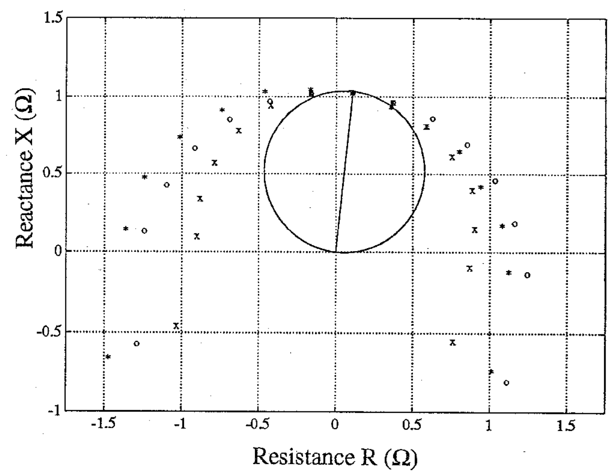
The A-G, BC, BC-G fault test results for relay A are shown in Fig.3.b-d respectively. It can be seen that the characteristics of different faults are different. The prefault voltages and currents affect the characteristic for each fault differently.



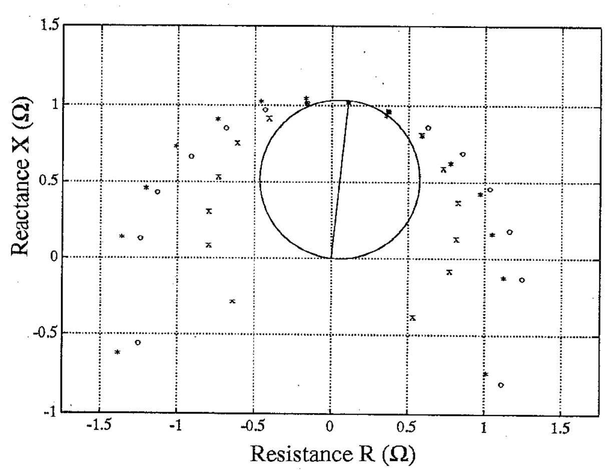
(a) ABC fault



(b) A-G fault



(c) BC fault



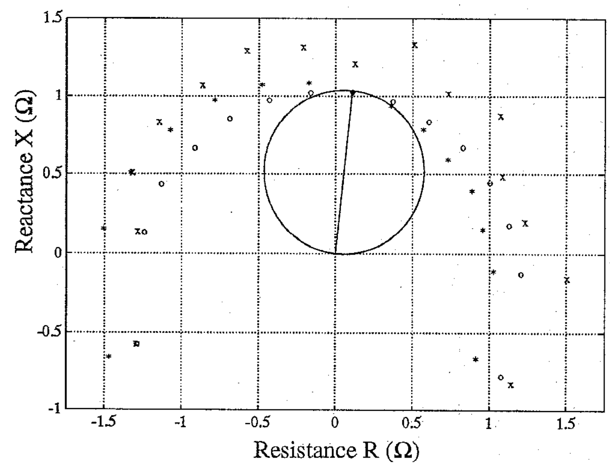
(d) BC-G fault

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

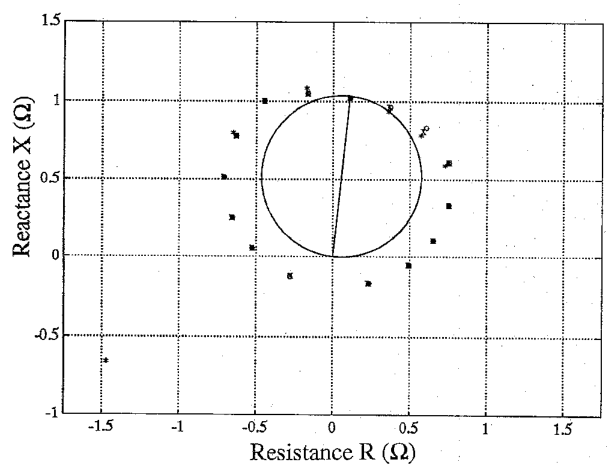
Fig.3 Test results for Relay A

Comparison of Test Results for Different Relays

The test results also reveal that different relays have different response to the prefault voltage and currents. The phase-to-phase test results for relay B and C are shown in Fig.4.a and 4.b respectively. It can been seen that the fault of Case I will cause significant overreach for relay B while the effect of prefault voltages and currents on relay C is negligible. The effect of prefault load current on the characteristic of relay B is significant.



(a) BC fault test results for Relay B



(b) BC fault test results for Relay C

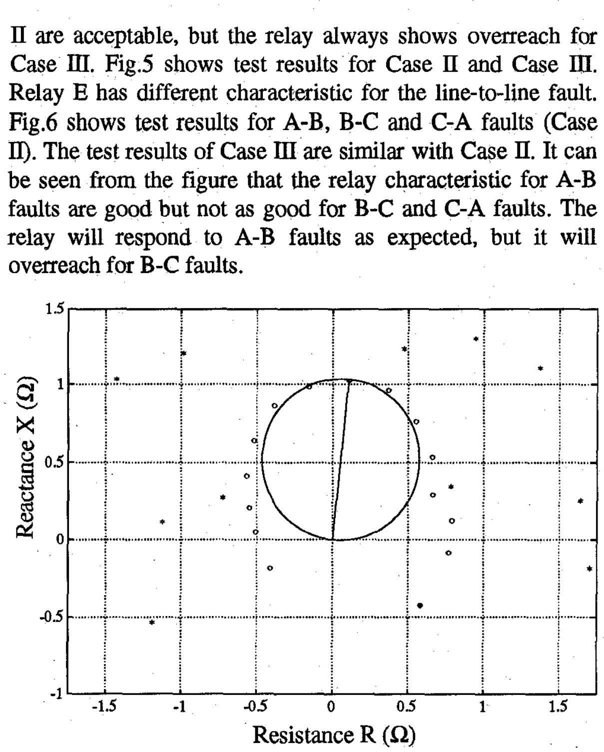
x : for Case I; o : for Case II; * : for Case III

Fig.4 Comparison of test results for Relays B and C

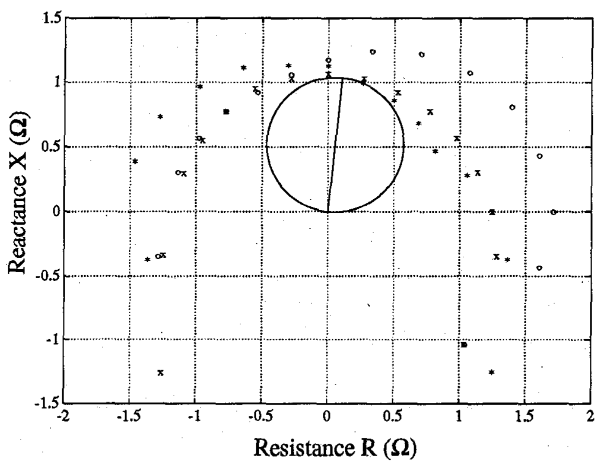
Application and Design Problems

All the five relays had been tested using a traditional 'ramp' method before they were tested using the new method. The tests using the 'ramp' method show small difference between relays. Especially for Relay D and Relay E, the results look almost the same. The tested tripping boundaries are exactly on the theoretical characteristics. However, the new test method reveals weaknesses of Relay D and Relay E. Relay D absolutely losses selectivity for Case I. Test results for Case

II are acceptable, but the relay always shows overreach for Case III. Fig.5 shows test results for Case II and Case III. Relay E has different characteristic for the line-to-line fault. Fig.6 shows test results for A-B, B-C and C-A faults (Case II). The test results of Case III are similar with Case II. It can be seen from the figure that the relay characteristic for A-B faults are good but not as good for B-C and C-A faults. The relay will respond to A-B faults as expected, but it will overreach for B-C faults.



o : for Case II ; * : for Case III
Fig.5 ABC fault test result for Relay D



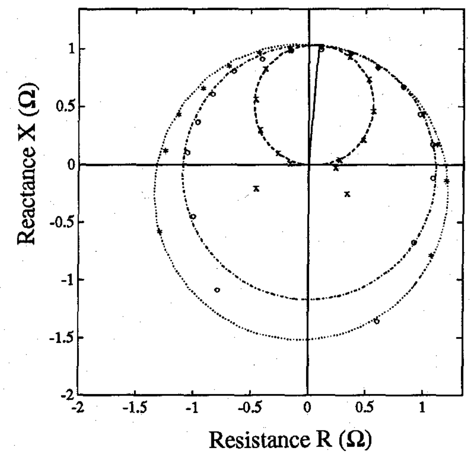
x : for A-B fault ; o : for B-C fault ; * : for C-A fault
Fig.6 Line-to-line fault test results for Relay E

RESULT ANALYSIS

Comparison of the Tested and the Theoretical Characteristic

The Relay B is used as an example for comparison of the tested and the theoretical characteristic. In accordance with the design principle, a program is used to draw the theoretical characteristics in the R-jX plane as shown in Fig.7. The test results, the traced boundaries for different angles, are plotted in the same figure. The three-phase fault theoretical characteristic is an origin-crossing circle since there is no polarizing signals used. The traced operating boundary well fits the theoretical characteristic from 10° to 175°. For the angles in the third and fourth quadrant, the tested points are scattered in a nearby area outside the theoretical characteristic due to an error caused by very low voltage signals.

The tested boundaries for the single-line-to-ground fault and the line-to-line fault are very close to the theoretical ones.



- - - - : Three-phase fault theoretical characteristic
-.-.-.- : Single-line-to-ground fault theoretical characteristic
.... : Line-to-line fault theoretical characteristic
x : Three-phase fault test results
o : Single-line-to-ground fault test results
* : Line-to-line fault test results

Fig.7 Comparison of theoretical analysis and test for Relay B

Different polarization scheme is used in Relay C. Partial cross-polarizing and partial memory polarizing signals are used to synthesize square wave forms. The polarizing quantities mixed from the sine and the square signals result in a unique polarized characteristic as shown in Fig.8 (taken from the manufacture's manual). The test results shown in Fig.4.b are coincident with the theoretical characteristic. The coincidence is much more clear from the test results for a larger source impedance. The test results are shown in Fig.9.

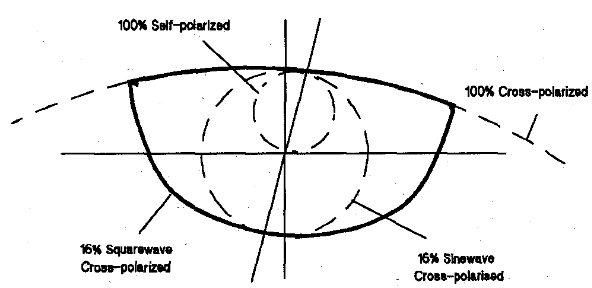
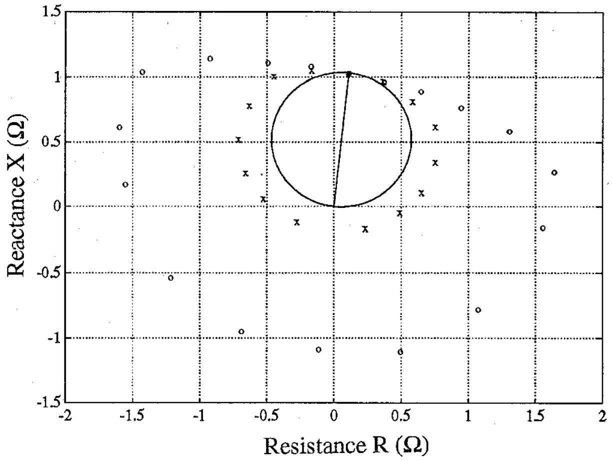


Fig.8 Unique polarized characteristic of Relay C



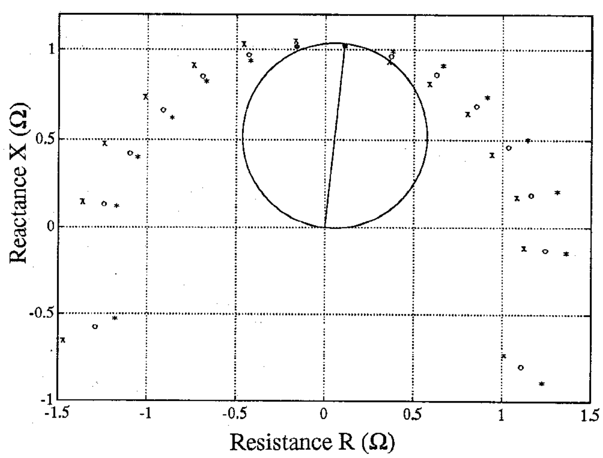
x : for Z_S ; o : for $6Z_S$

Fig.9 Comparison of different source impedance for Relay C

Description of the polarization scheme of Relay A is not available from the manufacture's manual. It is not clear how large the polarizing co-efficient are, but it can be seen from the traced characteristic (Fig.3.a to 3.d), that they belong to memory and cross-polarizing designs.

Prefault Load Current Effect

Theoretical analysis of prefault load current influence on cross-polarizing and memory polarizing have been discussed in [4] and [15] respectively. The voltage drop on the source impedance, caused by the load current, is the main factor to affect the characteristic of the relay. Fig.10 shows test result comparison of different prefault load condition for Relay A.



x : prefault load current = 5∠-30° A

0 : prefault load current = 0 A

* : prefault load current = 5∠150° A

Fig.10 Comparison of different load conditions for Relay A

DECAYING DC OFFSET CONSIDERATION

The decaying dc offset may affect performance of relays. The non-natural transition from prefault to fault signals, as shown in Fig.2, is different from the case with natural transition from prefault to fault with the decaying dc offset component. The relays have been tested using a program with the dc signal generation capability added. The decaying constant τ and the inception angle can be controlled in the program. Distortions caused by CTs are not considered. Fig.11 shows the transition from prefault to fault. The five relays have been tested using signals containing the decaying dc offset for different faults. The test results for the five relays show that there is no significant difference for the relay characteristics obtained with or without the decaying dc offset.

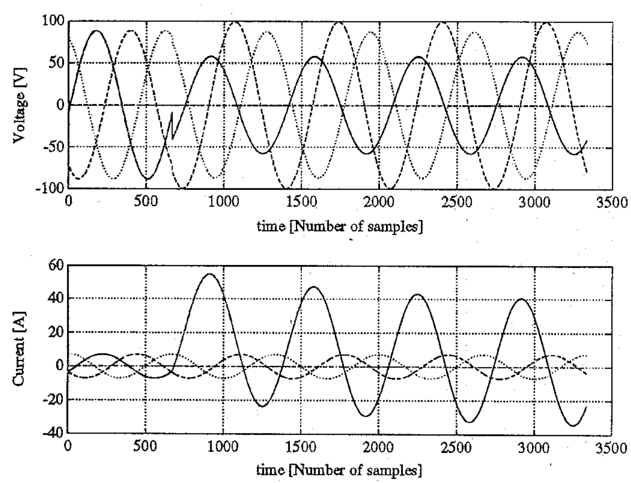


Fig.11 Test signals with decaying dc offset

CONCLUSIONS

A new phasor-based test method to determine relay characteristics has been discussed. Test cases of different prefault signals have been conducted on five distance relays. The method can be used for manufactures to identify design problems and for utilities to discover application problems. The test results reveal that the prefault voltage and current have significant effect on the relay characteristic, but the influence is different for different relays. To test the performance of a relay, the prefault quantities should be properly presented.

ACKNOWLEDGMENTS

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Discussion

G. D. **Rockefeller** (96 Sylvan Drive, Morris Plains, NJ 07950):

What is it with this method that makes it "advanced" and better than other dynamic methods? Fig. 2 shows what appears to be an instantaneous change in the current, a practical impossibility. This apparent impossibility may explain the gross overreaching exemplified by Figs. 4a, 5 & 6.

The source-impedance ratio (SIR) was a relatively small 1.5 for which the relay speed and overreach tendencies are higher than for larger SIR values. SIR variations should be added to the authors' list of test variables.

It might be helpful if the authors characterized the five relays as electromechanical, solid-state or numerical, self or cross polarized, etc.

Given a test facility that can generate transients, such as current offsets and ccvt subsidence transients, why do phasor testing?

Manuscript received February 7, 1995.

R.J. MARTTILA, (Ontario Hydro Technologies, Toronto, Canada): The authors have presented an interesting and a timely paper on testing distance relay characteristics. I would like to offer the comments below for the authors' consideration.

1. Reference 15, which was cited on page 6, middle of the first column, is not in the list of references.

2. The performance of a particular mho element may be dependent on the test procedure. For example, in your test procedure, the relay is provided with 30 cycles of non-zero prefault data. This would not be sufficient conditioning for distance elements in which the polarizing signal, containing the memory signal, is not activated until seconds after appearance of the voltages. A time of 2.5 seconds is used in some relays. To understand and appreciate your results, could the authors provide the information on the type of cross-polarizing and memory polarizing that are used in each of the elements tested?

3. The effective time for the memory signal is usually based on the breaker failure time, which defines the time for which the distance element should remain secure on reverse faults. This time in many cases is about 250 ms. In your tests, what constituted a trip from the Zone 1 element that was under test?

4. The accuracy of some distance elements is influenced by the point-on-wave at which the fault occurs. In your tests, was the point-on-wave varied? Could the step change in the current signal (as per typical waveforms shown in Figure 2) be an influencing factor in any of the results?

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M. Kezunovic, Y.Q. Xia, Y. Guo, C.W. Fromen, D.R. Sevcik The authors thank the discussers for their interest, comments and questions. To Mr. Rockefeller's questions and comments, we offer the following responses:

- The test method proposed in our paper is considered advanced since it is:
  - more complex than what is usually described in the user's manuals for protective relays
  - more elaborate than what is presently used in the industry as an on-going practice
  - implemented in an automated mode using specialized software not readily available on the market
  - comprehensive since it had revealed some relay performance characteristics that were not readily known from either the relay manuals or the results obtained using testing procedures suggested in the manuals.
- The instantaneous change in the current as shown in Fig.2 is an inherent constraint of the method initially used for the waveform generation. However, the same tests were repeated with the DYNA-TEST simulator when a new method for waveform generation was used to obtain a "natural" behavior of the current. The relay performance characteristics remained almost the same for both tests. Therefore, the apparent impossibility in the current behavior has not significantly contributed to the outcome of the tests.
- The source impedance ratio (SIR) used in the various tests reported in the paper is between SIR = 1.3 and SIR = 6 x 1.3 = 7.8. The Fig.9 gives some of the results obtained with different SIR used.
- The following additional information on the relays tested is available in the manuals:

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

- The phasor testing is considered important for characterizing a relay design before a transient test is performed. It serves as a check of the basic relay design characteristics and as a comparison to what is defined in the manuals. Once the relay design is characterized, then an application test using actual transients can be performed. As indicated at the end of the Introduction of the paper, "The results can also be used as a very good reference point for interpreting test results of transient testing in which the dc and high frequency components are naturally presented".

As for the questions and comments from Mr. Marttila, the following are our responses:

- We appreciate the correction regarding the reference 15, which was cited on page 6. It should be corrected to reference 9.

- As indicated in the Introduction of the paper, "... we treat the relays as black boxes and provide them with right test signals which are quite close to the real situation a relay would encounter under service". Based on such an assumption, extensive tests have been conducted using different prefault lengths. Our experience shows that 30 cycles of non-zero prefault data were sufficient for the relays that we have tested.

- The available information on the relays tested is given in the answers to Mr. Rockefeller's questions.

- In our tests, a trip time for Zone 1 element is the time between the moment of change in the relay input waveforms caused by the fault and the moment the relay trip signal has occurred. However, for the phasor testing aimed at characterizing the relay operating characteristic, this time was not measured. Those trip times are measured for the transient testing aimed at evaluating relay application performance.

- The specific wave shape of the current signal shown in Fig.2 was not an influencing factor as previously explained in an answer given to a similar question posed by Mr. Rockefeller.

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