NEW METHODOLOGY FOR TRANSMISSION LINE RELAY TESTING AND EVALUATION USING ADVANCED TOOLS

A Thesis

by

DRAGAN RISTANOVIC

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2003

Major Subject: Electrical Engineering

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ABSTRACT

New Methodology for Transmission Line Relay Testing and Evaluation
Using Advanced Tools. (December 2003)
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Protective relays are important parts of the power system. The protection guards valuable equipment, and protective relays play a vital role in performing the task. The relay detects fault conditions within an assigned area, opens and closes output contacts to cause the operation of other devices under its control. The relay acts to operate the appropriate circuit breakers to prevent damage to personnel and property. To ensure consistent reliability and proper operation, protective relay equipment must be evaluated and tested.

The importance of the relay evaluation issue is linked to capability to test the relays and relaying systems using very accurate waveform representation of a fault event. The purpose of testing protective relays is to ensure correct operation of the relay for all possible power system conditions and disturbances. To fulfill this purpose, relay testing in varying network configurations and with different fault types is required. There are a variety of options that have different performance potentials and implementation constraints. Use of digital simulators to test protective relays has proven to be an invaluable mean to evaluate relay performance under realistic conditions.

This thesis describes a new methodology that attempts to improve the existing practices in testing relays by using advanced digital simulator hardware, different software packages for network modeling, and new software tools for generating and replaying test waveforms.

Various types of microprocessor relays are tested and evaluated through the set of scenarios. New methodology that combines different software packages to facilitate particular testing objectives is applied.

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INTRODUCTION

Problem Definition

Modern power transmission and distribution systems need high-performance protection devices. Relays must have high speed of operation for internal system fault conditions and high level of discrimination between internal and external power system faults. Relays, together with the circuit breakers, shall disconnect faulty parts of the power system. Their main role is to protect the primary equipment against unnecessary damages, save people in vicinity of the electrical plant from injuries, and enable continued service in the undamaged parts of the network [1].

To accomplish its main tasks, requirements on protection system are: speed, sensitivity, selectivity and reliability [2], [3]. Evaluation and testing protective devices must be conducted to check and predict how capable the relays are to fulfill the main requirements for system protection.

Two major approaches in relay testing exist in practice. The first, conventional approach uses phasor values of currents and voltages to verify the operating characteristic of a protective relay and tripping time for steady state currents and voltages [4]. The second, advanced approach uses transient values of currents and voltages to check selectivity of a protective relay and to check if the average tripping time is within tolerances [5]. Modern approaches in transient testing are to test the relays using the inputs the relays will see in the actual system during faults [5], [6].

Transient testing becomes necessary with modern microprocessor based relays. Information-processing techniques and random properties of numerical relay responses require testing with current and voltage waveforms similar to the ones that the relay would be exposed to in a real network. Faults and disturbances that occur in a real network are of a transient nature. Testing numerical protective relays and verifying their

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This thesis follows the style and format of *IEEE Transactions on Power Delivery.*

characteristics by conventional methods using steady state fault quantities, may not be sufficient to conclude whether these relays would operate correctly in a real system. The crucial issue is selectivity and operating time of the relays exposed to transients.

Two cases where transient testing evaluations proved very useful were observed. One situation where such approach can be used is in trouble-shooting relay misoperations. Being able to recreate the conditions of the fault and associated relay operation allows one to reconstruct the course of events very accurately. Another case is when the new relays need to be procured. User can assure weather a given relay is suitable for the specific power system application by testing a relay under realistic conditions. Although the benefits of transient testing are identified in these two cases, transient tests are still not widely used in practice. There is no methodology to use when the transient tests are to be performed.

While considerable activity continues in the research and development of microprocessor based relays, generally, little work is being done in developing a testing methodology for the microprocessor relays. When used, transient testing procedures are defined randomly and intuitively, to achieve particular task to test relay for a specific scenario. There is no methodology established for transient testing procedures.

In the analysis of the existing transient testing approaches, it is important to observe that for the same fault location, but different fault type and fault inception time, which is a random value, transient waveform may look different [7]. Operating time of numerical relay is also a random value. It is necessary to perform a large number of tests, to determine statistical properties of the relay responses, to check its selectivity and average tripping time. There is no methodology defined with theoretical background and explicit recommendations how the transient tests should be conducted to evaluate random behavior of numerical relays.

In summary, the new methodology would need to give the answers to the following important questions:

- Why and when the transient tests are needed?
- What procedures should be applied in transient testing?

- How the transient tests should be created and implemented?

Development of a new methodology that will improve transient testing and its implementation is the major focus of this thesis.

Existing Testing Tools and Practices

Several concepts are realized in practice to conduct transient testing. These concepts include application of various hardware and software tools to create test cases and generate transient waveforms. These concepts do not provide comprehensively defined methodology. Theoretical considerations of transient testing and its application with numerical relays are not well understood. Existing concepts in transient testing are focused on testing tools application with random and intuitive definition of test scenarios.

The latest approaches in transient testing use digital simulators and model the power network and faults with electromagnetic transient programs for testing protective relays. This offers the user flexibility and accuracy while performing tests. Researchers designed such simulator modeling the transients similar to those occurring in real networks [8], [9], [10]. Such simulators may be used not only for protective relays testing, but also for research related to evaluation of power systems performance.

Another advanced practice in transient testing of protective relays is the use of digital real time simulators, together with replaying software and software for transient simulations. Such arrangement provides flexible adjustment of testing parameters and rapid execution of test cases [6]. The flexibility to change the power system network model connected to protective relays being tested is important. Using a batch-testing feature, it is possible to automatically test the relay in varying network configurations and with different fault types. The batch testing mode meets the need to have many simulation cases for varying parameters, for example: length of a line, source impedance, location of a fault, fault type, fault resistance, etc.

Relay test sets and digital simulators can also utilize recordings from digital fault recorders [11]. Waveforms from a real event can be replayed to the relay under test. That is very useful in diagnostic applications, particularly if some unexpected or wrong relay operation has taken place in the field. The IEEE COMTRADE standardizes the format of such files and greatly facilitates the transportability of recorded or simulated files between different platforms [12].

The existing approaches do not define methodology for transient testing of protective relays.

Conclusion

This thesis explores the current state of relay test practices, analyzes possible trends and finally demonstrates how a new methodology is needed to enhance relay testing. The new methodology for transient tests of numerical transmission line relays will be defined, with main objective to emphasize why the transient tests are necessary, what procedures should be applied in transient tests and how these tests should be created and conducted.

To answer why the transient tests are necessary, theoretical background of protective relay responses will be given. Random behavior of numerical relay responses will be considered.

After describing software and hardware tools used in relay testing, procedures for transient testing of transmission line relays will be defined. It will be explained when the transient tests should be applied. Procedures will be established to check selectivity and average tripping time of protective relays. Criteria for proper relay operation and cases for relay testing will be proposed. It will be explained how to execute the test cases in repetitive shots. Several aspects in implementation will be analyzed: advanced hardware tools for relay testing, software packages for network modeling and event simulation, new software tools for generating test signals and replaying the waveforms obtained in different applications. Defining scenarios for relay tests will be discussed in detail. Practical implementation of the new methodology to test and evaluate various types of microprocessor relays will be presented.

CHAPTER II

THEORETICAL CONSIDERATION OF RELAY RESPONSES

Introduction

System protection has evolved, over the years, from relatively primitive devices with limited capability, to complex systems that involve extensive use of modern hardware components and software solutions. These modern protective systems are more selective in their detection and operation. They often require greater analytical effort in the analysis and application as well as advanced methods for evaluation and testing.

This chapter provides basic theoretical background of protective relay responses. Functional elements of protective relays will be presented and basic types of relay operating characteristics will be given. Difference between protective relay responses for steady state voltages and currents and for transient voltages and currents will be explained with particular emphasis on random characteristics of numerical relay responses. Basic operation principle of numerical relays will be shown. It will be explained why the transient tests are required. Theoretical background given in this chapter will be used in further considerations of how the transient tests should be conducted to reflect the random nature of relay responses.

Functional Elements of Protective Relays

Before proceeding with analysis of protective relay responses, functional elements of protective relays will be described. The protective device usually consists of several elements that are arranged to detect the system condition, make a decision if the observed variables are over/under the acceptable limit, and take proper action if acceptable limits are crossed [2]. These elements are arranged as shown in Fig. 1

Protective system measures system quantities such as voltages and currents, and compares these quantities or their combination against a threshold setting. If this comparison indicates that the thresholds are crossed, a decision element is triggered. This may involve a timing element, to determine if the condition is permanent or temporary. If all checks are satisfied, the relay (action element) operates.

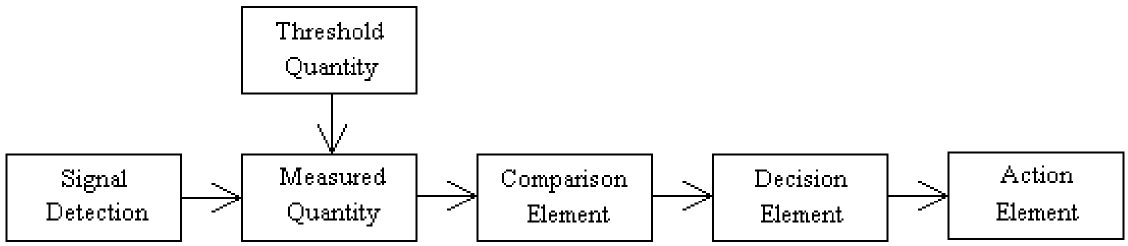

Fig. 1 Protective device functional elements

Operating Characteristics of Protective Relays

Operating characteristics of protective relays are important because protective relays respond and operate according to defined operating characteristic and applied settings. Each type of protective relays has distinctive operating characteristic to achieve implementation objective: sensitivity, selectivity, reliability and adequate speed of operation in protecting elements of the power system. Relays are available in many implementations, serving different purposes and having distinctive design characteristics [13]. This section describes basic operating characteristics of protective relays of the following types:

- Overcurrent relay: A relay that operates or picks up when its input current exceeds a predetermined value
- Directional relay: A relay that picks up for faults in one direction, and remains stable for faults in the other direction.
- Differential relay: A relay that is intended to respond to a difference between incoming and outgoing electrical quantities associated with the protected apparatus
- Distance relay: A relay used for protection of transmission lines whose response to the input quantities is primarily a function of the electrical distance between the relay location and the fault point

- Pilot protection: A form of the transmission line protection that uses a communication channel as the means of comparing electrical quantities at the line terminals

Overcurrent relays

Overcurrent protection picks up if the measured current exceeds the setting threshold. Inverse time characteristic of overcurrent protection is given in Fig. 2. Characteristic presented in Fig. 2 is the current versus time characteristic of a time overcurrent relay.

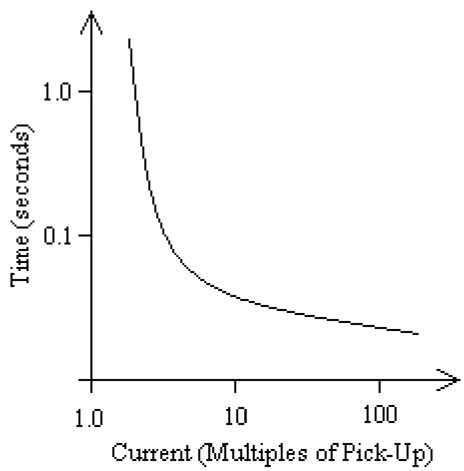

Fig. 2 Inverse time overcurrent characteristic

Overcurrent relays can be designed to operate with other types of current versus time characteristics, depending on their application. They can be designed to operate or pick up on unbalance condition i.e. if $3{\cdot}I_0$ current exceeds the setting threshold, as in ground overcurrent relays.

In some cases, it is difficult to achieve proper coordination with non-directional overcurrent relays. Directional overcurrent relays are then used. Directional overcurrent relay schemes are identical in operation and design to those used in non-directional overcurrent relay schemes, with the exception that the operation will be controlled and supervised by the directional unit. Directional overcurrent relays respond to faults in only one direction which allows the relay to be set in coordination with other relays downstream from the relay location. Testing the directional overcurrent relays by applying new methodology will be analyzed in this research.

Differential relays

Differential relays are commonly used to protect generators, buses and transformers. Although not used in this research, they are widely used in practice and their operation characteristic is explained. Differential relay is applied on a multi terminal element such as two-winding power transformer. In case there is no internal fault and assuming CT's with matching ratios, currents measured at terminals are identical I1 = I2. Current in the relay operating coil is zero and relay does not operate.

For the internal fault, I1 ≠ I2, and differential current I1 – I2 flows in the relay operating coil, which may cause the relay to operate. Since the relay operation depends on a differential current, it is called a differential relay.

In reality, if protected element (i.e. power transformer) is in a normal service, there will be a small differential current due to a mismatch of the CT ratio (auxiliary CT's normally have limited number of taps and will not get an exact adjustment), power transformer magnetizing current and position of the tap changer.

Differential current increases for an external fault. A "through-fault" current of 10 times the rated current (with a tap changer at end position) can cause a differential current of 1 to 2 times the power transformer rated current. In order to avoid operation under these conditions, the differential protection is provided with a percentage, "through-fault", restraint circuit. The percentage restraint ensures that tripping is obtained only if the differential current reaches a certain percentage of the total "through-fault" current. A typical operating characteristic is given in Fig. 3.

The current $(I_1 + I_2)/2$ is the measured "through-fault" current and the differential current required for operation will increase with increasing "through-fault" current, and stabilization for the differential current occurring due to tap changer in an offset position will be achieved.

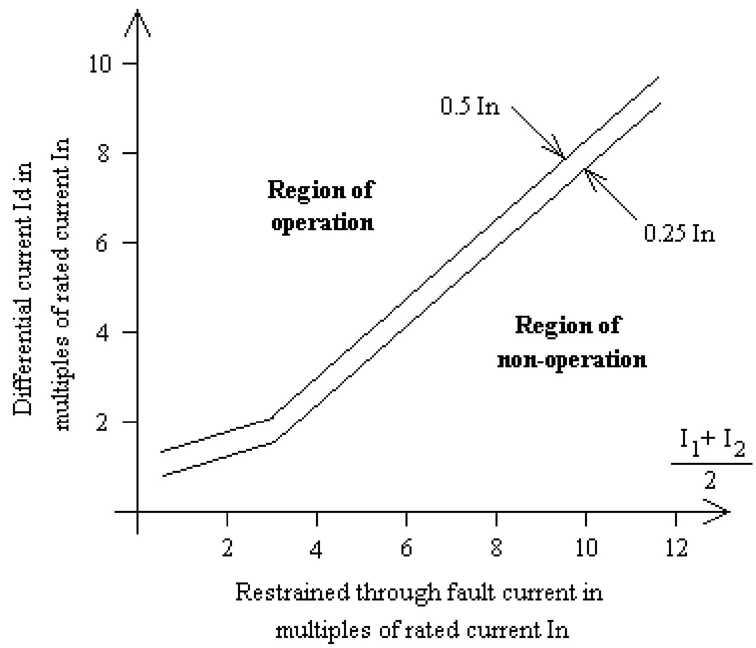

Fig. 3 An operating characteristic of a percentage differential relay

Distance relays

Distance relays are the most common on transmission lines. Testing distance protection relays will be analyzed in this thesis. Basically, the distance relay measures the quotient V/I, considering the phase angle between the voltage V and the current I. The measured V/I is then compared against the set value. The relay will trip if the measured value of the impedance is less then the value set.

Operating characteristics of distance relays are usually represented using R-X diagrams. Fig. 4 shows an example of Mho R-X operating characteristic.

The measured impedance at a certain fault position must not depend on the fault type. The correct voltages and currents must be measured for each fault loop and evaluation of the loop impedance and phase impedance to the fault must be done. The distance relay settings are practically based on the phase impedance of the fault.

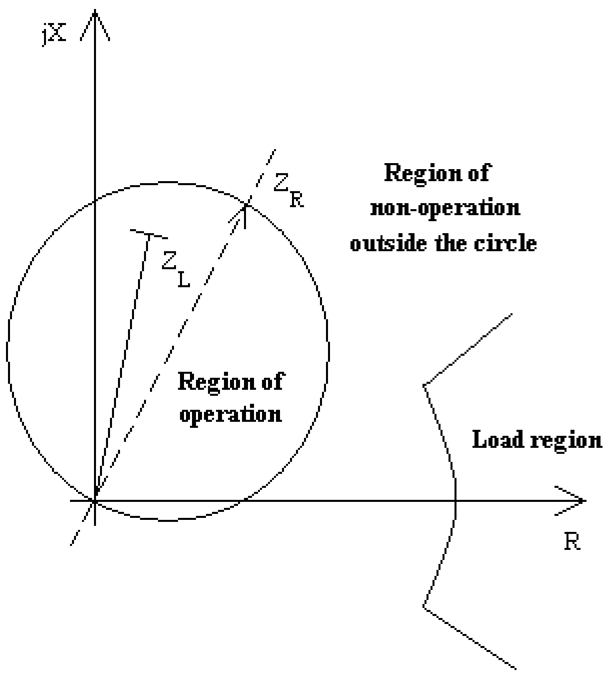

Fig. 4 Mho operating characteristic of a distance relay

For two and three phase faults, the phase voltage and the difference between line currents are used. With this principle the measured impedance is equal to the positive sequence impedance at the fault location.

The ground fault measurement is more complicated. Measuring phase currents and phase voltages gives impedance as a function of the positive and zero sequence impedance of the fault loop:

$$V = I_0 \cdot Z_0 + I_1 \cdot Z_1 + I_2 \cdot Z_2 , \quad (1)$$

where $Z_1 = Z_2$

$$V = Z_1 \cdot (I_0 + I_1 + I_2) + I_0 \cdot Z_0 - I_0 \cdot Z_1 \tag{2}$$

$$I = I_0 + I_1 + I_2 \tag{3}$$

$$V = I \cdot Z_1 + I_0 \cdot Z_1 \cdot \left(\frac{Z_0}{Z_1} - 1 \right) = I \cdot Z_1 + \frac{I_N}{3} \cdot Z_1 \cdot \left(\frac{Z_0}{Z_1} - 1 \right) \tag{4}$$

Fundamental equation for impedance measurement of a single line to ground fault is:

$$Z_1 = \frac{V}{I + K_N \cdot I_N} \tag{5}$$

The current used is the phase current plus the neutral current times a factor K_N. The zero sequence compensation factor is $K_N = (Z_0 - Z_1)/3 \cdot Z_1$. The factor K_N is a transmission line constant and Z_0/Z_1 is assumed to be identical throughout the whole line length. The total loop impedance for the ground loop can be described with $(1+K_N) \cdot Z_1$. Neutral compensation factor K_N should be taken into account when checking the distance relay characteristics for ground faults.

Pilot protection

In most distance protection scheme applications, at least at voltages ≥130kV, communication channel between the two ends are utilized to improve the protection system behavior. The most common communication link is the power line carrier (PLC) equipment. The distance protection relays can communicate in two basic schemes “Permissive” or “Blocking” or in a number of versions of these two basic schemes [2].

In the permissive scheme, an acceleration signal is sent by a relay at one end to the relay at the remote end when the fault is detected in a forward direction. Tripping is initiated when the acceleration signal is received and if the local relay has detected a forward fault as well.

In the blocking scheme, a blocking signal is sent by a relay at one end to the relay at the remote end when the fault is detected in reverse direction. Tripping is initiated when the blocking signal is not received within a time of T_0 and if the local relay has detected a forward fault. A time margin T_0 of 20 – 40 ms is always needed to check if the blocking signal is received.

Testing pilot protection schemes will not be analyzed in this research, but basic explanation was given because pilot protection schemes are commonly applied in power systems.

Conclusion

Operating characteristics play important role in implementation of protective relays. This section described the most common operating characteristics and schemes. These characteristics are defined by relay design and settings. They can be obtained from relay manuals or calculated according to the relay manufacturer recommendations. It is expected that protective relay responds and operates according to its operating characteristic, and therefore it is usual practice to verify the operating characteristic by testing. Shape of the operating characteristic is defined for steady state values of currents and voltages. Classical approach in relay testing with phasors of currents and voltages is used to verify the operating characteristics. When transient test is used, shape of the operating characteristic cannot be verified, but transient tests are aimed at another important goal: to check selectivity of protective relay and average speed of operation. Although the shape of the operating characteristic is not explicitly verified in transient testing, the main functional purposes of the operating characteristic to provide selectivity, reliability, sensitivity and satisfactory speed of operation are implicitly checked in transient testing.

Relay Responses to Transients

When settings of protective relays are calculated and applied, it is expected that the relay responds to currents and voltages measured at its terminals according to its settings and applied characteristics. In a real network, protective relays are exposed to transients. Electromechanical and solid state protective relays respond to such transients similarly as if they would respond to steady state fault currents and voltages, because of the inertia and averaging effect in measuring and processing the analogue transient fault signal.

Numerical relays respond to transients differently. They use signal processing techniques and numerical algorithms to calculate the fault. In each calculation step, samples of transient voltages and currents are processed [14]. Based on sampled values, measurement element calculates the fundamental frequency component or desired harmonic component in some applications. Decision-making element makes decision whether the relay will trip or not. Operating time (time from fault detection to making decision and tripping) and selectivity of relays exposed to transients are the most critical and the most important properties in applying the numerical relays. Basic principles of operation of numerical relays are given in the sequel.

Numerical relays

A numerical relay can be presented with three major blocks, as given in Fig. 5

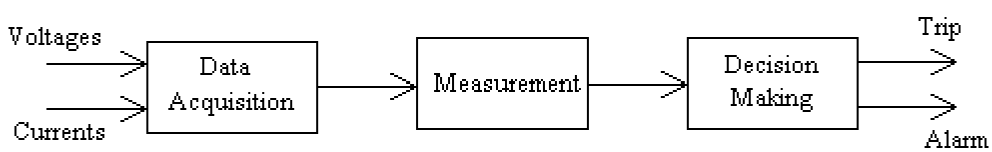

Fig. 5 Major components of a digital relay

Data acquisition block constitutes the front end of the relay and links the digital-processing segment of the relay with its analog inputs. Measuring block estimates certain input signal parameters (magnitude, phase angle, resistance and reactance, as well as the active and reactive power). A decision making block applies basic relaying principles to compare estimated signal parameters with given settings (thresholds). It also applies certain delays and logic functions in order to issue the tripping and alarm signals.

Data acquisition

The front end of a digital relay consists of the following four elements: input transducer, signal conditioner, analog anti-aliasing filter and analog to digital (A/D) converter, as shown in Fig. 6.

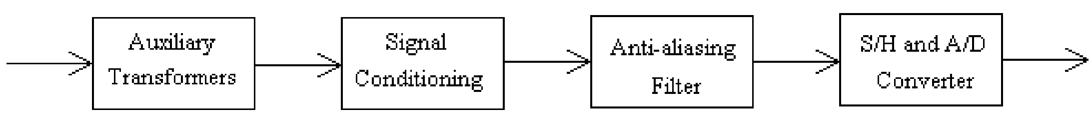

Fig. 6 The front end of a digital relay

The auxiliary transformers ensure that the level of standard secondary voltages and currents match the rated values of input signals for numerical protective relays. They also convert currents into voltages and isolate the relay circuits from the secondary wiring of the substation. The signal conditioner then scales the signal down to match the input rate of the subsequent signal processing elements.

The analog filter provides the necessary anti-aliasing filtering. It passes all the signal components that are used by the relaying algorithm, but it blocks out all the remaining components. For example, if samples are taken at frequency ω the raw data should be digitally filtered to cutoff below one half that frequency $\omega_c = 0.5 \cdot \omega$.

The sample and hold (S/H) together with analog to digital (A/D) converter samples the input signal at regular time intervals and converts the samples into their digital representation. The sampling process is essential for numerical protection in that the analog signals must be converted into appropriate digital form so that the processor can perform calculations and reach relaying decisions. Most relay applications involve sampling at a fixed rate that is a multiple of the nominal power frequency. Sampling is a process in which values of an analog signal are sampled at regular time intervals and then converted into digital representation. This operation is accomplished by a sample and hold (S/H) element.

Algorithms used in numerical relays - measurement

A large class of relaying algorithms is based on extracting information about the waveforms from current and voltage signals for making relaying decisions [14], [15]. Examples include:

- the rms value of current computed from samples for use in an overcurrent relay
- current and voltage phasors computed from samples for calculating impedance
- the harmonic content of a current for restraining a transformer differential relay during magnetizing inrush

Many analog and digital distance relays use phasors as the operating signals in the distance functions. The phase angle comparator is a well known operating principle that uses the phasor information contained in the input signals. A digital filter that both removes the non-fundamental frequencies and also provides phasor information is therefore desirable for a digital implementation of a phase angle comparator distance relay. One such filter, which is widely used in digital distance relays, is the Discrete Time Fourier Transform (DTFT) [14], [15].

Discrete Time Fourier Transform will be described on a simple example of voltage signal. A steady state voltage signal in the analog time domain can be described by the equation:

$$v(t) = V_{max}(\omega t + \theta) \tag{6}$$

In a digital relay, this signal is sampled N times per cycle. Thus the input signal can be represented by a series of samples, V_k, where k = 0 to N – 1

Digital filters process the sampled data points, V_k, by multiplying each sample by one or more coefficients determined by the type of digital filter employed. In the traditional Fourier calculation, each sampled value is multiplied by a sine term and a cosine term. The Discrete Fourier Transform calculation of the fundamental components can be defined by the following equations:

$$V_{real} = \left(\frac{2}{N}\right) \cdot \sum_{k=0}^{N-1} \left[V_k \cdot \cos\left(2 \cdot \pi \cdot \frac{k}{N}\right)\right] \tag{7}$$

$$V_{imag} = \left(\frac{2}{N}\right) \cdot \sum_{k=0}^{N-1} \left[-V_k \cdot \sin\left(2 \cdot \pi \cdot \frac{k}{N}\right)\right] \tag{8}$$

The magnitude of the voltage phasor can be calculated by the following equation:

$$V_{mag} = \sqrt{V_{real}^2 + V_{imag}^2} \tag{9}$$

The phase angle of the voltage phasor can be calculated by the following equations:

$$V_{angle} = \arctan \frac{V_{imag}}{V_{real}} \tag{10}$$

$$V_{angle} = \theta_V \tag{11}$$

With these definitions, the Fourier Transform calculation is able to convert the sinusoidal voltage waveform to a phasor. The phasor is represented by two forms, the first form is the rectangular form where the real and imaginary components define the phasor; the second form is the polar form where the magnitude and phase angle define the phasor.

It is essential that numerical relays recognize fundamental frequency component of measured quantities (i.e. currents and/or voltages) during transients and make the right decision by comparing estimated signal parameters with given settings (thresholds).

Transient Responses of Numerical Relays

Transient response of numerical distance relay depends on signal processing technique and numerical algorithm applied [16]. The R-jX impedance plane provides a convenient tool for visualizing the results of numerical algorithm and response of numerical relay during transients. Computed values of impedance for fault and non-fault conditions are plotted on the plane and compared with reach characteristics. Typical trajectory of fault computation during transients, using eight-sample DTFT algorithm with full cycle window is given in Fig. 7.

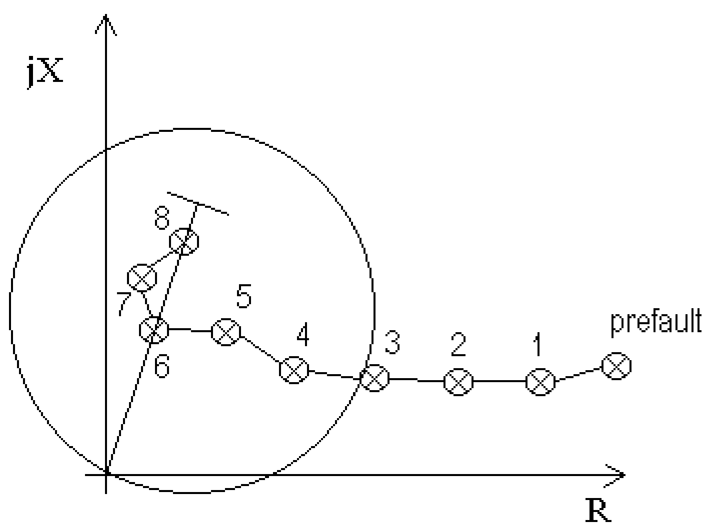

Fig. 7 DTFT Algorithm with eight sample full cycle window

When a fault strikes the protected line, the voltage and current signals change to their fault values via a transient disturbance. If the algorithm properly estimates the fundamental frequency from transient waveform, the calculated voltage and current signals change smoothly and stabilize after the window is full of fault data samples. In each step voltage V, current I and impedance V/I are computed.

It is important to notice that if numerical distance relay was exposed to steady state values of currents and voltages; calculated impedance would be fixed at desired point in R-jX plain. That is not happening in reality when numerical relays are used. Numerical relay exposed to transients calculates the fault impedance, which encroaches characteristic at some point and represents a trajectory inside the characteristic. It shows excursion alternatively inside and outside, until its value eventually settles down. It is crucial for relay design to provide proper interpretation of calculated values and to define adequate criteria for relay operation.

Random nature of the numerical relay operation

Random nature of the numerical relay operation is described and criteria for relaying algorithm sensitivity and evaluation are defined based on a random response of various relaying algorithms [17]. The raw algorithm outputs are the estimates of R, X or Z at each sampling instant.

The following analysis illustrates the random nature of the response [17]. The actual value of the parameter used to make a tripping decision is denoted by Z(t). This parameter changes from a prefault value of Z_{pr} to a post fault value of Z_{po}. The calculated or estimated values of this parameter in discrete time n are Z(n), where

$$Z(n) = Z_{po} + S(n) \tag{12}$$

S(n) is the error of the estimate. A common technique to optimize the estimate is to apply the minimum mean square error criterion

$$\min E\{S^2(n)\} \tag{13}$$

subject to the constraint

$$E\{S(n)\} = 0 \tag{14}$$

where E denotes the expected value averaged over the population.

To implement the above principles in a protective relay testing, we consider that for a given test run r, $Z_r^{(k,N)}$ is the average value of Z(n) calculated over a time interval T=NΔt beginning with discrete time constant k, i.e.,

$$Z_r^{(k,N)} = \frac{1}{N} \cdot \sum_{n=k}^{k+N-1} Z(n) \tag{15}$$

If the number of test conditions used to evaluate the algorithm is R, then the average value of $Z_r^{(k,N)}$ for the algorithm is:

$$MEAN = \frac{1}{R} \cdot \sum_{r=1}^{R} Z_r^{(k,N)} \tag{16}$$

In an ideal situation the following expression could be applied:

$$E\{MEAN - Z_{po}\} = 0 \tag{17}$$

Hence, the following can be taken as one measure of algorithm random performance:

$$\left| MEAN - Z_{po} \right| \tag{18}$$

The parameter Z(n), for the algorithm can be expressed as:

$$Z(n) = MEAN + D(n) \tag{19}$$

where D(n) denotes the deviation of the estimated value from the MEAN. For a decision to be based on an estimated value of Z(n) it is not only important that the MEAN is close to Zpo, but also that D(n) is small. Hence, an additional measure of algorithm performance for the r-th test run is:

$$STD_r = \left[\frac{1}{(N-1)} \cdot \sum_{n=k}^{k+N-1} D^2(n) \right]^{\frac{1}{2}} \tag{20}$$

If there are R total test conditions applied, then the following provides a second measure of algorithm performance:

$$STD = \left[\frac{1}{R-1} \cdot \sum_{r=1}^{R} STD_r{}^2 \right]^{\frac{1}{2}} \tag{21}$$

Two quantities, $\left| MEAN - Z_{po} \right|$ and STD are measures of algorithm performance. When using these measures to evaluate the performance of algorithms for a set of test conditions, care must be taken in choosing the value of k, the discrete time instant for beginning the calculations of the measures. The estimates for the algorithm are calculated from M_i consecutive samples. All of them must be post fault samples to best estimate Z_{po}. This imposes the following constraint on k:

$$k \geq \max_i(M_i) \tag{22}$$

The proposed criterion function is a linear combination of these performance measures as follows:

$$J = \left| MEAN - Z_{po} \right| + a \cdot STD \quad (23)$$

where the coefficient “a” is zero or a positive real number which determines the relative importance of the STD term. Lower value of J indicates better relative performance.

If we assume that the values of D(n) have characteristics of stationary Gaussian noise, then the characteristics of the Gaussian probability function can be utilized. For example, the probability is 0.99 that the estimate Z(n) will lie in the following interval:

$$MEAN - 2.58 \cdot STD \leq Z(n) \leq MEAN + 2.58 \cdot STD \quad (24)$$

This means that the estimate should fall in the region between the lines MEAN – 2.58 · STD and MEAN + 2.58 · STD which is shown in Fig. 8. It also means that the maximum distance between the actual value and the estimate is equal to |MEAN – Za| + 2.58 · STD with the probability 0.99.

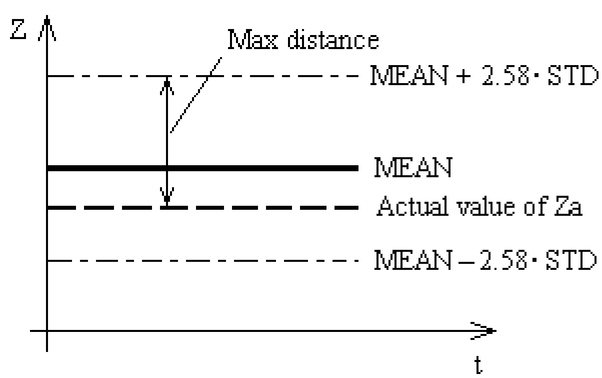

Fig. 8 Algorithm evaluation criterion function

Criterion function, based on random behavior of relaying algorithms, is defined by four parameters. These are: the weight coefficient “a”, the post fault sample “k” in which the first estimate is taken for the time averaging, the number N, the number of samples used in the time average and the number R, the number of test conditions or simulation runs in the test.

Impedance reach of a numerical distance relay exposed to transients is random. Statistical properties of reach decision (selectivity) of numerical distance relays depends on signal processing techniques and algorithms applied in relay design.

Different transient waveforms, with different fault inception time and harmonic content are of stochastic nature. Time for a numerical relay to process the fault signal, calculate the fault loop impedance and reach its decision depends on shape of the transient waveform and is a random value. In other words, tripping time of a numerical distance relay exposed to transients is a random value.

Conclusion

The following conclusions are derived from the analysis of transient response of numerical relays:

- Transient response of numerical relays is random. To take into account the random nature of numerical relay's response, it is essential to test its selectivity and average tripping time.
- To conclude if operation of a numerical relay is satisfactory, it is not sufficient to verify its operating characteristic by phasors of currents and voltages. Phasors cannot be used to test selectivity and average tripping time of a numerical relay. To test numerical relays it is necessary to utilize transient tests.
- Because of random response of numerical relays exposed to transients, transient tests should be defined accordingly. To perform transient tests, it is necessary to define test cases with different fault types, fault inception angles for the same scenario and to apply large number of repetitive tests.

Conclusion

This chapter briefly described some of the most common operating characteristics of protective relays. It also described commonly applied principles of operation of numerical relays and addressed the issues of relaying responses to system transients. This chapter provided background and explanations for random behavior of protective relays exposed to transients. It gave reasons why the transient tests are necessary.

It was concluded that testing numerical relays and verifying their characteristics by conventional methods using steady state fault currents, may not be sufficient to test whether these relays would operate correctly in a real system. It was shown that random nature of numerical relays' response cannot be analyzed by applying phasor values of currents and voltages. In a real system protective relays are exposed to different types of transients and they must be capable of responding correctly in such cases, as well as in various scenarios involving faults and disturbances. Random response of numerical relay must be checked by testing relay's selectivity and average tripping time. It was concluded that selectivity and average tripping time can only be checked in transient tests.

It was shown that because of the random nature of numerical relay responses, it is necessary to perform tests with large number of cases, and several shots for each case. Criteria for satisfactory operation of protective relay were given in this chapter. These criteria are selectivity in operation and average tripping time within acceptable limits. To check if those criteria are satisfied, it is necessary to establish procedures for comprehensive testing of numerical relays with large number of scenarios and large number of test cases. This chapter gave directions how to establish procedures in transient testing. Basic idea will be developed in further chapters.

CHAPTER III

PROTECTIVE RELAY TESTING BACKGROUND

Introduction

Two major concepts in protective relay testing exist in practice. Conventional approach uses phasors of currents and voltages to test the operating characteristic and tripping time of protective relays. Advanced approach uses transient waveforms of currents and voltages to test selectivity and average tripping time of protective relays. Hardware and software tools have been developed to create test cases, generate test signals and apply them to protective relays. Different concepts have been used to define test cases and to apply them in practice.

Before proceeding with a new methodology for evaluation and transient testing protective relays in the next chapter, a background of relay test practices will be discussed. This review will give basic definitions, analyze test equipment, hardware and software components and different concepts in protective relays' testing and evaluation. Examples of how the classical approach and advanced approach in relay testing can be implemented will be given. Analysis of present approaches in transient testing will include explanation when the transient tests are needed.

Generating Test Signals

Three approaches can be used to generate signals for testing relays. The first approach is to use the outputs of a waveform generator. The second option is to simulate disturbances, create analog signals and use the outputs of the simulations to test the relays. The third option is to use fault waveforms recorded by relays or fault recorders. The first approach is used in phasor testing of protective relays, the second and the third one are used in transient tests.

Waveform generators

The initial design of test sets provided facilities to generate voltages and currents of the fundamental frequency [18]. These instruments provide one to six outputs. The levels of the outputs and to some degree the phase angle between the outputs, could be controlled. Later designs included provisions for outputs that were linear combinations of signals of the fundamental and harmonic frequencies [19]. Some designs could add a DC offset [19], [20].

Traditionally, electromechanical and solid state relays were and are being tested using waveform generators. The tests provide information on the performance of relays under steady-state fundamental frequency conditions. Operating characteristics and tripping time for steady state quantities are checked using these instruments. The performance of many electromechanical relays and solid state relays during system disturbances matched that observed during the tests because of the inertia of the relays. These instruments cannot effectively test numerical relays because numerical relays do not have inertia and signals generated by the test sets are not similar to those encountered during system disturbances.

Simulated waveforms

To overcome the downsides of waveform generators, digital or hybrid simulators are being used for testing relays [21], [22]. The issues involved in digital and hybrid approach are generating numerical data, converting the data to analog form and then using the data to test the relays.

For testing numerical relays, it is essential to generate waveforms that closely resemble waveforms experienced during power system disturbances. It is important to use such tools to generate signals in transient tests in order to check selectivity and average tripping time of numerical protective relay. One of the popular techniques used for this purpose is to simulate disturbances using transient programs such as EMTP, EMTDC and ATP [23], [24].

Three important issues must be considered when simulations are performed [11]:

- The first issue concerns the size of the power system used for modeling. To keep the computation effort and time, reduced-size models are used. It is essential that the reduced size model represents the large-scale system adequately. The components of the power system such as lines, transformers and the generators must be modeled in such manner that the results provided by the simulator are accurate. Therefore, attention must be paid to the selection of models for these and other components.

- The current and voltage transformers, used to convert the high current and voltage signals to the relay level signals, are non-linear devices. They must be properly modeled including the impacts of the core of the transformers and inductances and capacitances in the secondary circuitry.
- Since a time continuous process is modeled in discrete steps, attention must be paid to the time step used in simulations. Using larger than needed time step would provide information that does not represent the waveforms of the disturbance adequately. On the other hand, using smaller than needed steps would increase the computation time as well as the size of the waveform files.

Once the transient data have been generated in a sampled form, they are converted to the analog form. This is done by taking the numerical data and converting them to the analog form using digital to analog (D/A) converters. The outputs provided by the D/A conversion are staircase representations of smooth waveforms of voltages and currents [15]. To remove the high frequency components from these outputs, low-pass filters are used. It is essential that the bandwidth of the amplifiers should be suitable to faithfully amplify the signals without introducing the additional noise.

Recorded fault waveforms

Digital fault recorders are intelligent electronic devices primarily used for recording waveforms with high accuracy. They do not perform real time processing of obtained waveforms [25]. This allows them to use the whole processing power for converting and storing samples, which in turn enables using very high sampling frequency. Therefore, monitored signals are recorded with great precision in both the magnitude and higher frequency harmonics.

Sampled waveforms of input signals and contact data are used in variety of monitoring applications. DFRs are usually connected in parallel with protective relays.

They do not continuously store the waveforms, but start upon being triggered by relay trip signals. They provide detailed information about transient waveforms of monitored quantities during the fault. Triggering may also be accomplished through a separate triggering function being provided by DFR. Capability of triggering function to detect desired disturbance reflects on DFR’s ability to capture relevant waveform.

Digital protective relays can also record the waveforms. They use analog current and voltage signals acquired by instrument transformers and digitize them by A/D converters. Process of digitizing assumes sampling analog signals with certain sampling rate and representing the created samples by certain number of binary digits. Protective relaying function requires fast operation and therefore the digitization process must not be a bottleneck of the operation. In order to speed up A/D conversion, relatively low sampling rate is implemented. Obtained signal samples are enough for protective relaying purposes, but the content of higher harmonics is limited. However, developments in microprocessor technology increased the processing power of digital relays and made them capable of sampling signals with faster rate. Since the digital fault recorder may not be connected to the same instrument transformers as protective relay under investigation, relay recordings are preferable when available. Typical relay recording rates are now 16 to 64 samples in a 60 Hz period [11]. With 64 samples per cycle, acceptable waveforms can be obtained. They require minimal smoothing when played out through a D/A converter. Digital Fault Recorders and data obtained from digital protective relays are used in transient testing of protective relays.

In some testing practices, recorded fault waveforms are replayed through testing equipment to test protective relays.

Test Apparatus for Relay Testing

Manufacturers offer three types of equipment that use analogue data generated by simulations for testing relays. They are relay test sets, playback digital simulators and real time digital simulators [11]. Simulator is a system of software and hardware that generates output waveforms that are, ideally, identical to the secondary level waveforms produced by the power system being modeled [26]. These waveforms are used to drive a relay under test.

Relay test sets

Most commercial relay test sets have facilities for simulating fundamental frequency and transient waveforms. They can also use sampled waveforms recorded from power systems or generated by simulations. These test sets consist of two major components, a personal computer and a test set. The disturbances are modeled in the PC and the outputs of the simulations are applied to the test set. The numerical data generated by the PC is converted to the analog form by using D/A converters and smoothing filters.

Steady state testing usually provides 6 analogue channels in a balanced three phase format with 3 voltage channels and 3 current channels. The control features of the test set usually allow controlling the channels to be set independently to simulate unbalanced conditions. Some test sets provide the feature of adding harmonics and exponential components to specific signals. One example of current and voltage parameters for steady state relay testing is given in Fig. 9.

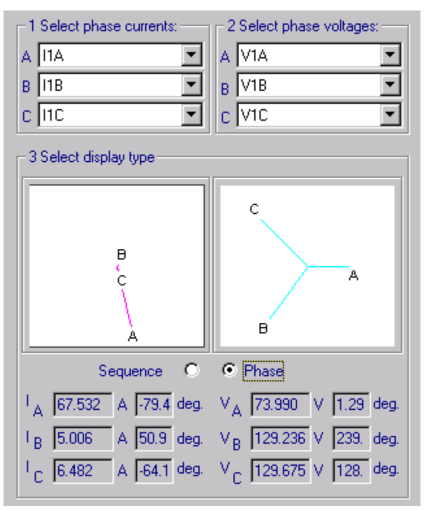

Fig. 9. Steady state representation of a set of current and voltage signals

For dynamic tests it is necessary to build two or more states to represent the sequence of events. For example, sequence of events may start in normal load condition, then change abruptly to the sine waves representing the steady state faults and then again change abruptly to the state representing a cleared fault. There is no attempt to represent transients in changing from one state to another. Example is given in Fig. 10.

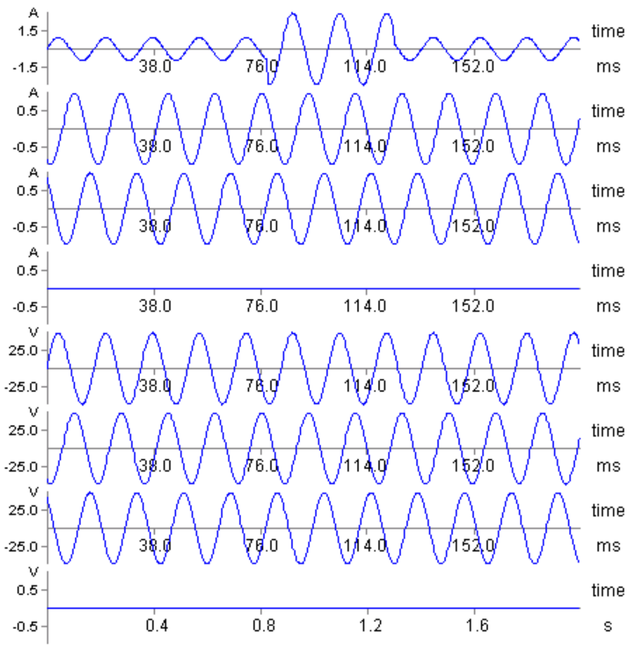

Fig. 10. Dynamic representation of a set of current and voltage signals

Playback feature of the relay test set is identical to that of the digital simulator described next. As technology advances, relay test set and digital simulator are likely to become the same device. Transient waveforms used in digital simulations are given in Fig. 11.

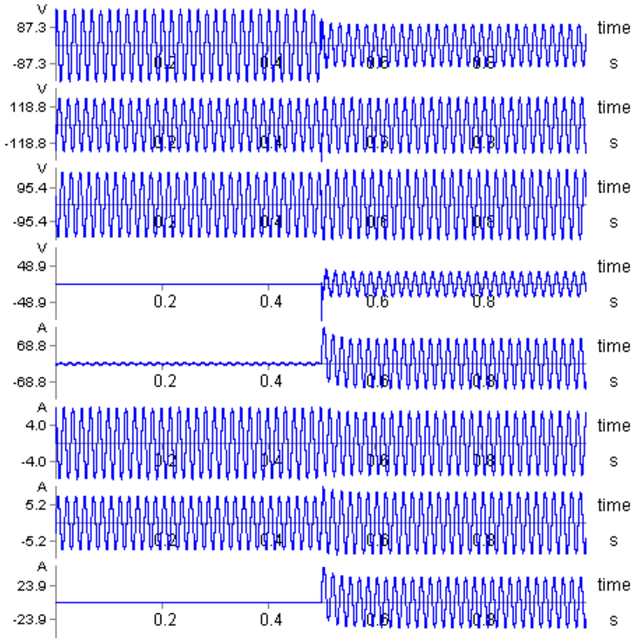

Fig. 11. Transient representation of a set of voltage and current signals

Playback digital simulators

Some manufacturers are now offering Playback digital simulators [20]. These simulators work like Relay Test Sets except that the functions performed in the PC and the Test Set are integrated in one device. Like the Relay Test Sets they are able to:

- simulate fundamental frequency and transient waveforms
- use sampled waveforms obtained from devices, such as relays and fault recorders, installed in power systems, and
- use data files from simulations

A major advantage of these simulators is that a user can run a variety of PC based simulation program to generate data and use them for testing relays.

Real time digital simulators

The signal source in a real time digital simulator is a computer that uses a real time operating system and completes the simulation for each time step within the step

[22], [26], [27], [28], [29]. The operating system passes data to the relay under test and receives in real time the output of the relay. Real time digital simulators do not store simulated waveforms but use the instantaneous values provided by the simulations at the end of each time step. Computer must be capable of completing the calculations for each time step within one time step and it must have real time operating system.

An alternative approach uses a multi-processor based system in which several DSPs operate in parallel and share the tasks to provide results in real time [30]. At the end of each time step, the processors exchange data over the backplane and proceed to perform calculations for the next time step.

The size of the power system that can be modeled on these simulators depends on the computing facility of the simulator, such as the number of DSPs in it.

Real Time Digital Simulators are time-effective for studies that must take into account interactions between the relays, power system, other controllers etc. The real time computations allow many outputs and inputs to be connected to the relays being tested.

Real Time Digital Simulators are rather expensive solutions and they are not available in a portable format at present time.

Relay Tests

Approaches used for relay testing can be classified into two categories. The first category uses phasor values of voltages and currents to test the operating characteristics of protective relays. That category is designated as phasor testing or classical approach in relay testing. The second category uses transient waveforms of fault voltages and currents to test selectivity and average operation time of protective relays. That category is designated as transient testing or advanced approach in relay testing. Basic explanations and examples of both approaches are given in this section.

Classical approach in relay testing

The classical approach in relay testing is well defined and supported by the existing engineering tools. Relay settings are calculated using short circuit programs and relay setting coordination programs. Setting computation is based on the knowledge about the relay setting options (described in the relay manuals) and assumptions about the worst case faults (obtained from a short circuit study). Phasor simulation of steady state fault values can be utilized to test the relays [4]. Standard relay test sets are usually used. As mentioned earlier, classical approach using phasor values of currents and voltages is used primarily to check the operating characteristic of a protective relay.

One method to test the distance relay operating characteristic is described [4]. Example of Mho operating characteristic is given in Fig. 12

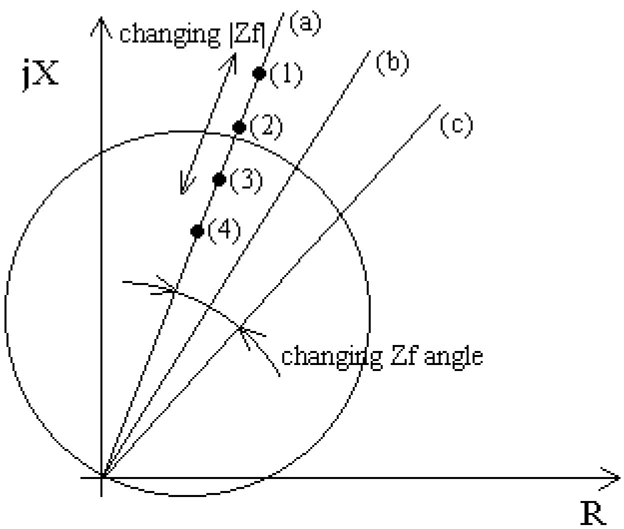

Fig. 12. Operating characteristic – phasor testing

Basic idea given in Fig. 12 is to test the Mho operating characteristic using phasor values of currents and voltages. Voltage V and current I are kept at values that would correspond to point (1) shown in Fig. 12, with fixed angle between V and I. By increasing magnitude of I, or reducing magnitude of V by step size, impedance Zf is reduced along the slope (a), until the relay trips. Value of Zf is recorded. Angle of I or angle of V is changed to match the slope (b). Then, the whole procedure is repeated, but now with impedance Zf being reduced along the slope (b). Again, the whole procedure is repeated in steps moving to slope (c), etc. until the entire Mho characteristic is checked.

Basic procedure would assume that pre fault currents and voltages were zero. More realistic tests would be conducted with pre fault voltages and currents applied before the steady state fault voltages and currents. Flow chart of one method in classical approach in relay testing is given in Fig. 13

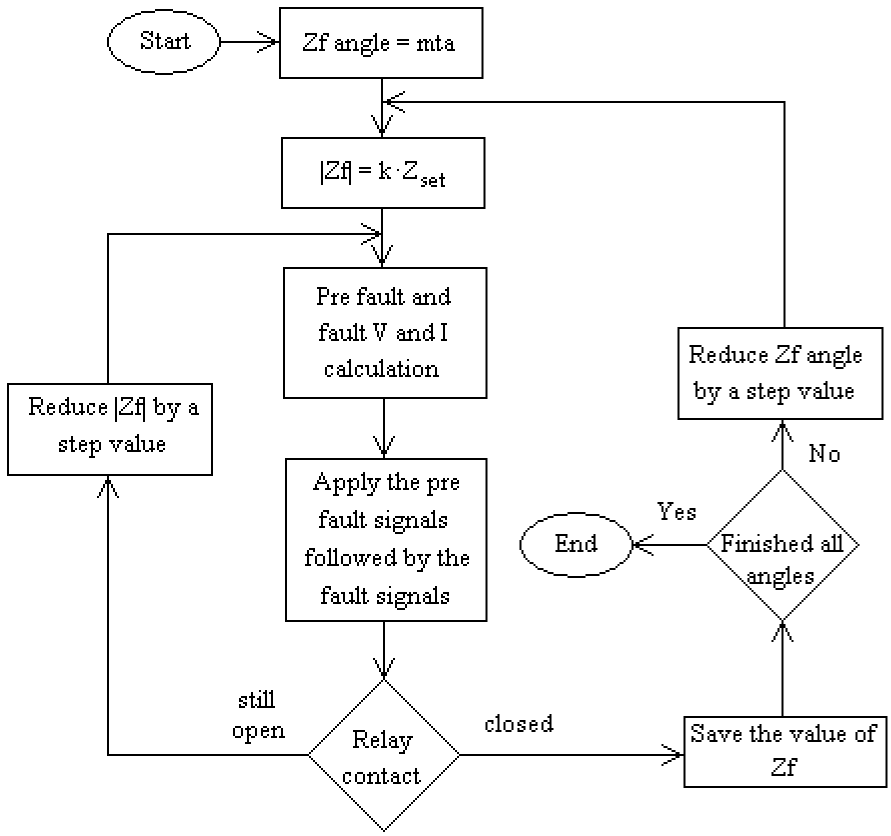

Fig. 13. Flow chart – one method for phasor testing of distance relays

Important issue in phasor testing of protective relays is to what accuracy a relay should be tested. This depends very much on the quoted accuracy of the relay under test. Classification of protective relays, based on accuracy is given in Table I.

Table I. Test accuracies for relays

Category	Reach	Trip time
Electromechanical relays	10%	10%
Static relays	5-10%	5%
Numerical relays	2-5%	5%

Phasor testing of protective relays are improved further if different cases with or without pre fault values of currents and voltages are applied, if the relay is checked for all standard fault types, if the load current and source to impedance ratio are changed to create different testing conditions. Modern test equipment for phasor testing does provide such possibilities.

Advanced approach in relay testing

In some situations, digital relays are tested in transient tests. Their acceptance and routine tests, the analysis of operating incidents and even the study of new principles require tests with transient currents and voltages. Overall performance of protection schemes has to be analyzed, with main focus on selectivity and operating time in realistic transient conditions.

Two situations can be identified when transient tests are needed. These situations are troubleshooting relay misoperations and procurement of new protective relays. Misoperation of protective relays usually occurs during transient events and therefore trouble shooting protective relays needs to be performed by reconstructing such events in transient simulations. When new relays are procured, it is necessary to check if relays are suitable for specific power system applications. Testing protective relays under realistic conditions i.e. by applying transient waveforms would provide invaluable means to analyze if protective relays are suitable for future application.

To conduct advanced relay testing, the following test techniques are applied: open loop test, closed loop test, semi-closed loop test, end-to-end test. Each of these approaches in transient testing usually use one hardware tool for generating test signals, a simulation software package for creating test cases and a software package for replaying test cases.

One concept in advanced relay testing is presented here as illustration. To check the transient performance of a distance relay, approach that uses open loop simulation, one terminal testing and two terminals testing can be performed [5]. Checking transient performance means that selectivity and tripping time (average tripping time) should be analyzed by applying transients. A computer is used for generating test waveforms, signal processing and converting data files, data displaying and tests result reporting. The DSP board and the I/O subsystem are used for data dispatching, data channel synchronization and D/A conversion. Trip contacts of the relay under test are fed back to the simulator through the I/O subsystem. Test set-up diagram for one terminal testing is shown in Fig. 14

To test the selectivity and tripping time that is of a random nature, large number of tests is executed. 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 currents and voltages as they would appear on secondaries of the instrument transformers.

Sensitivity study to test the Zone-1 selectivity and operating time is performed using a large number of cases. Fault types AG, BC, ABC and BCG, at five different fault locations 50%, 75%, 80%, 90% and 95%, at three inception angles 0°, 45° and 90° are applied. Each test is repeated for 10 times.

Influence of the CTs and CCVTs is taken into account by incorporating EMTP models. The CT saturation level changes if different CT burdens are used. AG faults at 50%, 80% and 90% of the line, with different CT burdens are applied to check the influence of CTs and CCVTs.

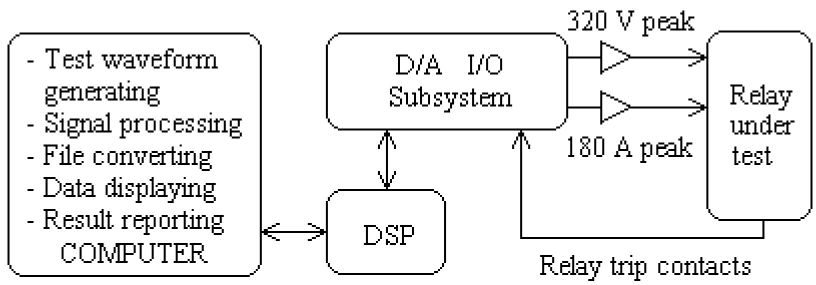

Fig. 14. One terminal test configuration

In the next stage, two terminal test configuration is used to test permissive overreach and blocking underreach schemes of distance relays. Two terminal configuration is presented in Fig. 15 [5]

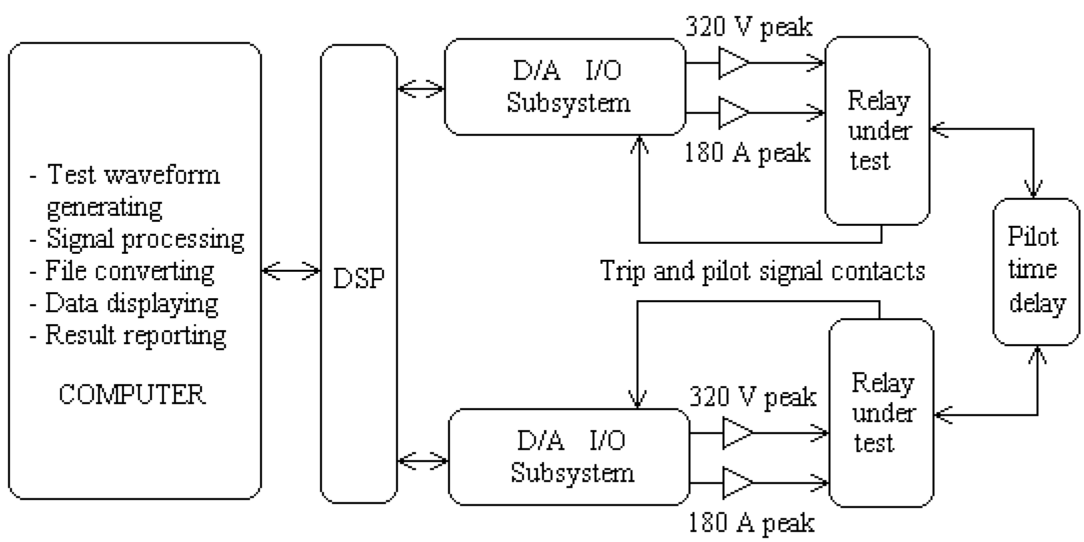

Fig. 15. Two terminals test configuration

The pilot time delay is set to 5 ms. Five three phase faults on the line are simulated at 25%, 50%, 75%, 90% and at remote busbar.

Equipment and Tools in Transient Testing

The focus of this Thesis is on advanced transient testing of protective relays. In advanced testing of protective relays that exists in practice, a complex system of hardware components and software tools is used. Hardware and software tools need to comply to performance requirements of transient tests [31]. Several main parts of transient test set-up can be identified: simulation computer with its functions, hardware, software and user interface, then I/O subsystem and power amplifier subsystem. In this section equipment and tools and their functions for advanced approach in testing protective relays are discussed. Some of these tools will be used to achieve different testing objectives of the new methodology in transient testing of transmission line relays.

Simulation computer - functions

The simulation computer is primarily devoted to computation of the fault transients using one of the commercial packages such as EMTP, ATP, EMTDC, etc. Simulation computer may also be used to perform signal analysis, signal replaying, signal acquisition and operator interfacing.

Signal analysis is related to the signal processing and editing needed to generate a set of test waveforms. A common example is preparation of the digital fault recorder files for replaying. Study of the influence of the instrument transformers is yet another example of the signal analysis needs.

A dedicated controller, separate from a simulation computer, may perform signal replaying in an open loop simulation application. In this case, the simulation computer may be used to download test signals to the controller, which is not a particularly demanding requirement. The simulation computer should also be capable of taking DFR files.

If relay testing is conducted in real time, that requires a very demanding I/O performance for the simulation computer since an interaction between the simulator and the relay has to be carried out on-line and in real time.

Signal acquisition is related to recording of the test waveforms and contacts presented to the relay and contacts generated by the relay. This may be done by dedicated instrumentation, but the simulation computer may do it as well.

Operator interfacing is one of the main functions of the simulation computer since the simulation, as well as the signal analysis, replaying and acquisition require intensive interaction between the operator and the system. Depending on the type of the user interaction, the requirements may be quite demanding. This is, in particular, the case if a graphical user interface is used for interaction with several application programs in a multi tasking, multi user environment.

Simulation computer - hardware

The simulation computer may have a number of different configurations. It could be a workstation dedicated to electromagnetic transient simulations and user interfaces. The waveforms are downloaded to a controller which takes care of signal replaying. In some other instances, the simulator may be a PC, which serves both as the electromagnetic transient program workstation and the signal-replaying controller. In other instances, the simulation computer may be a multiprocessor system capable of parallel processing and I/O interactions in real time.

The I/O requirements for signal replaying and signal acquisition as well as the requirements for electromagnetic transient simulation and signal analysis determine the performance requirements in selection of the simulator hardware. User interfaces also place a requirement for a particular type of the graphical interface standards. The other considerations are the memory space, both the hard disk and for the working memory. More elaborate system and application software may require demanding memory specifications.

Simulation computer – system software

System software primarily relates to the choice of an operating system. Simulator applications require careful selection of the operating system that supports a particular version of the electromagnetic transient program package and signal processing package. Software tools for development of graphical user interfaces are also a part of this consideration. A choice of a data management requires compatibility with the operating system. If several commercial packages are used, then the type of user interaction is directly driven by the choice of the operating system.

Simulation computer – user interface

The choice of the user interface may be considered as the most important aspect of the simulator computer requirements. The simulator computer hardware and software represent a complex computer environment. This may require a complex solution to the user interface in order to allow an operator to efficiently use the simulator.

Application software requirements may be reduced to the selection of the commercial packages used for various applications. A typical choice may include: EMTP, a signal processing package, a database management package and a graphical user interface package. Advanced software applications comprise signal processing, database management and graphical user interface packages in one software tool [21].

Special categories are real time simulators that may have custom EMTP implementation and I/O interactions to support the real time capability [22].

Graphical user interfaces are an essential feature of an easy to use operator interface. Typical features of such an interface include data entry using an editing window, graphical entry of a sequence of events scenario, plotting of analog waveforms as the simulation proceeds, or at the end of the simulation run, mouse driven editing of waveforms and multi-window control of application programs [21].

COMTRADE files

COMTRADE Standard defines a common format for the exchange of electrical power system transient data [12]. These files comprise a record of real or simulated power system events. They contain digitalized records of voltage and current waveforms, and logical events, such as relay operations, in a time coherent record. The format is intended for use when individuals who use different proprietary recording or simulation systems need to exchange data. COMTRADE provides common format in which those interested in power system and protection analysis may exchange digital data files. It is very important that data files generated in computer simulations or recorded by digital fault recorders are in COMTRADE format. It is very important that software packages designed for editing and generating test waveforms are compatible with COMTRADE format. Even if simulation software is not designed to generate test signals, data created in simulations or data recorded in a fault recorder can be used in relay tests through specialized software packages utilized to generate test waveforms. That is only possible if COMTRADE Standard is applied in all software components.

I/O subsystem

The Input/Output subsystem is the portion of the simulator concerned with converting the digital information generated by the simulation program into analog waveforms that will be applied to the relay under test. In general, the I/O system is responsible for converting the digital data into low level analog signals (±10 to ±20 V peak) required by the main amplifier system, filtering those signals to remove unwanted high frequency components, synchronizing the signals on all channels, activating the appropriate digital outputs, and continuously monitoring all available digital inputs.

Specifying the I/O subsystem is one of the most critical elements in designing a simulator. This subsystem must be able to accept high speed digital data transfers, perform necessary processing in both analog and digital domain, and drive the final output amplifier stages. The exact demands are determined by the number of relay terminals to be driven, the desired output signal bandwidth, and the characteristic of the main system amplifiers.

Power amplifier subsystem

The power amplifier subsystem is critical to accurate testing of relays. Even if the digital portion of the simulator followed by the I/O subsystem performs perfectly and the power system model is accurate, improper amplifier performance may affect the test results.

The amplifiers, used to supply currents and voltages to a protective relay in a test system, must not only be able to deliver the signal magnitude required but also to deliver it into the burden of the relay under test. If it is a requirement to test electro-mechanical relays, a higher output VA rating and higher compliance voltage are needed than if only solid state or digital systems are to be tested.

Conclusion

It can be concluded that the following equipment and tools used in advanced testing of protective relays need to be specified:

- simulation computer options, including simulator functions, hardware, software and user interfaces
- I/O subsystem design, including input and output capabilities as well as AC performance and environmental impacts
- power amplifier specifications, including input and output capabilities, AC performance and load constraints

Relay Test Procedures in Transient Testing

The existing approaches in transient testing provide basic idea how the transient tests should be conducted. The existing approaches do not provide precise formulation when the transient tests are needed, general recommendations what procedures should be applied and what approach should be used to conduct transient tests. The existing approaches are in most cases aimed at some specific situation when transient tests are required, they are conducted by random definition of testing scenarios. In many cases transient tests of protective relays are defined intuitively based on experience of relay engineers.

Test cases and scenarios

Defining test cases and scenarios is very important part of relay testing procedures. The main purpose of transient tests, to check selectivity and average tripping time of protective relays, should be achieved by proper definition of test cases and scenarios.

If a relay misoperates for a condition that occurs in a power system, it is necessary to examine reasons for relay’s misoperation. Intuitive approach in troubleshooting relay’s misoperation is to recreate such condition and to apply waveforms similar or the same as those that really occurred. If a relay misoperates, it means that selectivity of protective relay was not achieved, or relay's operation was unacceptably slow or fast. Test cases are formed either by using digital fault recorder data, or by modeling the event using EMTP transient software. Possible reasons for relay's misbehavior are: malfunctioning of protective relay, relay may not be appropriate for a given application or incorrect settings may have been applied to the relay.

In case when new relays are purchased, it is very useful to analyze their behavior under transient tests. By performing transient tests, possible problems in relay application in the future may be avoided. It is already mentioned that misbehavior of protective relays usually occurs because of malfunction, inappropriate application or incorrect settings. By performing transient tests on new relays, first in procurement stage and later in commissioning stage, various network conditions and scenarios can be analyzed beforehand to avoid problems in future service. When protective relays are purchased, they should be exposed to large number of test cases and scenarios to check if their operation is selective and if their average operation time is within the limits. One such approach how to test basic selectivity and average tripping time is already given in this chapter. In a given example, test scenarios were created to check basic selectivity by testing zone reach and average operating time for faults inside and outside the zone. Complex scenarios that include large scale of fault or event cases relevant for relay selectivity are not yet defined. They will be defined in the new methodology for transient testing of transmission line relays.

Number of tests

Operation of numerical relays is random. Transient waveform that occurs during fault may have different shape depending on fault type and fault inception angle. Signal processing techniques used in protective relays for data acquisition, measurement and decision making interpret the transient waveforms in a random fashion. Such behavior has been identified and test cases were defined accordingly in some existing transient test applications [5]. Example given in this chapter takes care of random nature of numerical relay responses. Large number of repetitive tests has been performed to check selectivity and average tripping time. Such approach shall be used as general recommendation for all transient tests. It will be used in the new methodology for transient testing of transmission line relays.

Conclusion

It can be concluded that the following facts should be considered in applying new test procedures in transient testing:

- transient tests are very useful in troubleshooting protective relays and in procurement and commissioning stage of the new relays
- test cases and scenarios need to be defined to cover a large number of relevant events with aim to test selectivity and average tripping time of numerical relays under test
- large number of repetitive tests need to be performed because relay operation is random

Conclusion

This chapter gave examples of different concepts and approaches used in relay testing. It addressed some background aspects of classical and advanced tools for relay testing and evaluation used today. Most of the assumptions taken in the thesis will be based on the material given in this chapter.

It was observed that the existing solutions do not provide methodological approach to transient testing. They do not provide precise formulation why and when the transient tests are needed. Comprehensively defined procedures to test protective relays with transient waveforms are not yet available.

It was explained that transient tests are needed in two situations: troubleshooting relay’s misoperations and when evaluating new relays to be purchased.

It was shown that hardware and software tools exist in practice to perform transient tests. These tools have different performance characteristics and are utilized in different applications. Some of these tools will be used in practical implementation of the new methodology.

To recapitulate, new methodology in transient testing of protective relays need to be established because there is no methodology defined so far in that area. New methodology should define when the transient tests are needed. It should define comprehensive procedures for transient testing. The new methodology should propose solutions how to conduct transient testing of protective relays using available hardware and software tools. New methodology that will be described in this thesis will use advanced software tools to combine different simulation packages in order to create test cases. Conventional test set as well as digital simulator will be used in practical implementation of the new methodology.

CHAPTER IV

NEW METHODOLOGY FOR RELAY TESTING AND EVALUATION

Introduction

To improve existing practice in transient relay testing, new methodology with testing scenarios and procedures will be defined. The new methodology will summarize when the transient tests are needed and what the criteria for proper relay operation are when transient tests are performed. The procedures and scenarios for transient tests of protective relays will be defined. The new methodology will be applied by using advanced software packages and hardware tools.

In previous chapters, it was already explained why and when the transient tests are needed. Basic idea that transient tests should be performed with large number of tests was set forth. Background of the existing relay testing practices with definitions of test equipment, hardware and software components and different concepts in protective relays' testing and evaluation was presented.

Summary of previous conclusions will be given in this chapter as well. The focus is to establish procedures and scenarios for transient testing of protective relays and to propose hardware and software tools for implementation of the new methodology.

Procedures and scenarios for evaluation will allow detailed assessment of various features of modern numerical protective relays and check random characteristic of their responses. The existing approaches in transient relay testing do not offer comprehensive definition of scenarios and procedures for relay testing. Criteria for proper relay operation, cases for relay testing and number of shots in each case will be proposed as a part of the new methodology.

Hardware and software tools used to implement the new methodology will be capable of recreating transient events similar to those that the relay will be exposed to in a real network. Simulation environment will be user friendly and suitable for application in various conditions: in laboratory and in the field. When new protective relays are procured, transient tests need to be performed in laboratory conditions with a large set of simulated events and network conditions. In troubleshooting relay misoperations, it may be required that transient tests are performed in the field by simulating smaller set of events or by replaying data files from digital fault recorder. To achieve these tasks, implementation of the new methodology will be possible with different types of testing tools and equipment.

Definition of the New Methodology

New methodology in transient testing of protective relays developed in this research explains why the transient testing of numerical protective relays is necessary and in what situations such tests should be applied. It proposes solution how to create scenarios and procedures to test numerical relays.

As already pointed out, the main purpose of existing approaches in transient testing of protective relays is to check selectivity and average tripping time. The new methodology is developed for the same purpose. It improves existing practices with particular emphasis on the fact that relay responses are random and large number of tests needs to be performed to derive conclusion if protective relay operates properly.

Finally, hardware and software environment will be created for the new methodology. The new methodology defines how to perform the tests and what procedures to apply to achieve main objectives of transient testing.

Why and when the transient tests are needed?

Conventional approach is still the most common approach used in relay testing. Relays are tested with phasors of currents and voltages, whereas in the real power system relays are exposed to transients. By testing protective relays with phasor quantities, operating characteristic can be verified and tripping time of protective relay can be checked.

Development of the new technologies in protective relay design and application requires more sophisticated techniques for relay testing. Numerical protective devices use digital signal processing to extract phasors from transient current and voltage waveforms that occur in a real network. Shape of a transient waveform is random even for the same fault location. Transient waveforms are different for different faults and fault inception times. Reach decision and average tripping time of a numerical relay are random. It is necessary to check if the numerical relay will operate properly when exposed to transients. When operation of protective relay is analyzed for a fault at a given fault location, it is necessary to generate large number of transient waveforms, with different fault inception times. Several repetitive shots have to be applied for each case. Selectivity of protective relay and average tripping time should be tested.

In summary, there are two main reasons why the transient tests are necessary:

- Current and voltage waveforms that occur in a real power system during faults are transient. Protective relays should be tested by applying waveforms similar to the ones that will occur in a real network.
- Transient responses of numerical relays are random. Selectivity and average tripping time of numerical relays need to be tested with large number of transient tests.

Although application of transient testing is justified and proven as very useful, transient tests are still not commonly used in practice. In regular testing practice, protective relays are tested with conventional test sets. There are several possible reasons why the transient tests are not yet widely implemented. One of the reasons is that hardware and software tools used in transient tests are still not quite affordable. A lot of tools are custom made solutions, sometimes relatively expensive, or more expensive then classical solutions. Another reason is that implementation of these sophisticated tools requires greater effort for maintenance personnel training. Yet another reason is that testing procedures and practices in transient testing are not elaborately defined.

Two situations are identified where transient testing evaluations proved indispensable:

- The first situation is in trouble-shooting relay misoperations. To reconstruct the fault condition and course of events very accurately, transient tests need to be used.

- The second situation is when the new relays need to be procured. User can assure weather a given relay is suitable for the specific power system application by testing the relay under realistic conditions.

What procedures should be applied in transient testing?

To conduct transient tests of protective relays, it is necessary to establish procedures how the transient tests should be performed and what criteria should be followed to conclude if relay operation is satisfactory.

Two different situations are already identified where transient tests are useful: trouble-shooting relay misoperations and procurement of new protective relays. In both situations testing procedures need to be defined.

When trouble-shooting relay misoperations, two approaches can be used. The first approach is to use data from digital fault recorder and analyze specific fault condition. The second approach is to reconstruct the fault condition and course of events with modeling software. Combination of both approaches can also be used for detailed investigations. New methodology will be applied by software and hardware tools capable to create and execute such tests.

When new protective relays are procured, it is useful to test the relay under realistic conditions and check if protective relay is suitable for specific power system application. Procedures and scenarios in this research are defined for such relays, but basic principles can be applied in trouble-shooting relay misoperations as well.

Procedures and scenarios should be defined to check if criteria for satisfactory operation of protective relay are satisfied. To summarize, these criteria are:

- The first criterion is to check if selectivity of protective relay is achieved for various network conditions.
- The second criterion is to check if the average tripping time is within the acceptable limits, or as expected, for different test cases.

Various test scenarios should be created by modeling standard faults and special faults. Because of random nature of protective relay response, it is very important that each test is repeated several times, for different fault inception angles. Selectivity and average tripping time should be determined after repeating several tests for each simulation case. Detailed explanation of test scenarios and procedures will be given in the following sections.

How the transient tests should be created and implemented?

To create and implement the transient tests, it is necessary to create hardware and software environment for relay testing and to define simulation scenarios and procedures. Clearly, major components used to implement the new methodology are: hardware tools, software packages and testing procedures. Main characteristics of the components used to implement the new methodology are given next.

The first component in implementation of the new methodology is the simulation hardware. Application of the new methodology should be possible for practically all test scenarios in laboratory conditions using digital simulators. At the same time, new simulation approach should provide options to conduct large number of tests directly inside the substation, using less expensive equipment such as standard test sets. Digital simulator and standard test set are utilized to implement the new methodology.

The second component in implementation of the new methodology is related to modeling and simulation software. Modeling and simulation software should be capable of simulating variety of scenarios and testing conditions. Simulation software tools should be capable to perform short circuit studies in order to calculate and check settings of protective relay. In order to check selectivity and average tripping time, simulation software tools should be capable of performing transient simulations and creating variety of fault scenarios including dynamic long term events. Modeling and simulation software should contain library of protective relay models to conduct complex dynamic simulations and analyze response of protective relays at different locations in the network. It should have user friendly software platform for signal editing and replaying as well as results analysis. Software structure used in new methodology contains two transient simulation software packages, designated as Package 1 and Package 2. It contains one short circuit software package designated as Package 3. Software platform is achieved through Package 4.

The third component in implementation of the new methodology is related to defining procedures for relay testing. Modern numerical relays often contain integrated functions in one device. As an example, modern numerical distance relays are not only devices that contain zone underimpedance elements and a few auxiliary functions. They contain a variety of functions to improve their performance, primarily their dependability and security. Examples of additional functions are: weak infeed logic, power swing blocking, switching onto fault, switching on reclosing, VT fuse failure, implementation of several different setting groups, etc. These functions should be tested and evaluated. It is often difficult to generate all relevant scenarios using only one network model. To create scenarios for checking selectivity of relay operation during transients and average tripping time, different network models should be used. Three network models of different complexity, designated as Model 1, Model 2 and Model 3 are utilized for the new methodology.

Implementation of the new methodology by defining hardware options, software architecture, network models and test procedure will be analyzed in the following sections.

Hardware Options

The first component in implementation of the new methodology - hardware options are realized using digital simulator and standard test set. The major hardware building blocks used in simulations are given in Fig. 16.

Proposed hardware options provide possibilities for conventional approach to relay testing as well. Test signals can be generated through standard test set. Operating characteristics and operating time of distance protective relays and overcurrent relays can be checked by injecting phasors. Phasors of currents and voltages can be defined through standard test set's interface. The main focus remains on transient testing for zone selectivity and average tripping time.

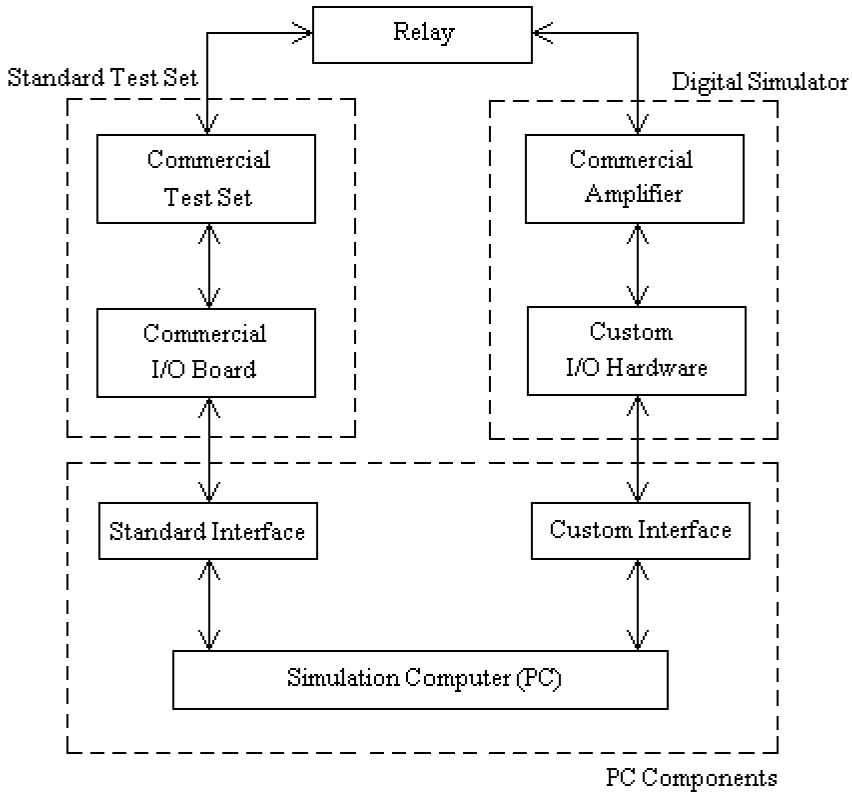

Fig. 16. Hardware options used in simulations

In transient testing, two options are available:

- Option 1: Pentium III simulation computer, standard GPIB communication interface plugged into ISA card slot of the PC, standard test set with commercial in-built I/O board
- Option 2: Pentium III computer, custom designed communication interface plugged into ISA card slot of the PC, digital simulator with custom I/O hardware and commercial amplifiers

The main characteristics of the I/O hardware for both simulator versions are listed in the Table II.

Table II. I/O hardware characteristics

Characteristic	Hardware Option 1	Hardware Option 2
Communication interface	GPIB	Custom
Vertical resolution	13 bits	16 bits
Sampling frequency	50 µHz – 20 kHz	5 Hz – 40 kHz
Current output	30 A rms, 150 VA	180 A peak, 1550 W
Voltage output	300 V rms	120 or 300 V rms
Configuration	1-, 2- or 3- channel	1-, 2-, 3- or 4- channel

Custom I/O hardware used in Option 2 offers better testing characteristics then commercial I/O board in Option 1. The vertical resolution of a custom I/O hardware (16 bits vs. 13 bits with commercial I/O board) and higher sampling rates (40 kHz in Option 2 vs. 20 kHz in Option 1) provide more sophisticated signal reconstruction [32]. Higher output power in Option 2 enables testing of virtually any protection scheme, including the ones containing high burden electromechanical relays. Using 4 output signals in Option 2 enables testing protective relays in which the neutral current is measured separately.

Hardware option 1 is suitable to implement the new methodology in the field conditions to troubleshoot relay misoperations. Hardware option 2 is suitable for laboratory testing of the new protective relays.

Software Architecture

The main elements of software architecture used to implement the new methodology are: data generating, signal processing, user interfacing, data replaying and results processing.

Three software packages are utilized for simulations. Package 1 and Package 2 are software for simulating transients. Package 3 is a short circuit program designed for calculating protective relay settings. For generating waveforms, Package 1 and Package 2 are used in transient simulations and Package 3 can be used optionally, to create steady state waveforms and perform short circuit calculations. All three software packages are capable of converting data to COMTRADE format. Simulation cases are created through batch generating auxiliary software incorporated in Package 1. Built-in functions of Package 2 and Package 3 are used to create test cases with these software packages.

The waveform files generated by all software packages sometimes require processing in order to be actually used for the testing. The signal editing and processing functions such as cut, paste, insert, resample, rescale, invert, and filter are examples of the functions supported by Package 4. Package 4 is the main tool used in signal processing.

Package 4 is also used as user interface (GUI). Its functions for test and waveform handling as well as signal processing and displaying affect the effectiveness of relay testing tremendously. In addition, GUI of Package 4 provides the required software/hardware transparency.

Prepared waveform files are replayed to the relay under test through a digital to analog conversion system. Depending on the selection of the I/O hardware, various implementations of the replaying engines are available through Package 4.

After replaying the waveform file, the Package 4 assists the user in processing the relay response. Processing extracts as much information as possible from the raw relay trip data. The results obtained through the processing are suitable both for immediate and for further analysis with independent software packages.

In summary, simulation software consists of four layers: test case creation, waveform processing, graphical user interface and waveform replaying. All four software layers are integrated in a single Windows application through Package 4.

The simulator software architecture applied in new methodology, showing all four layers and layer components is presented in Fig 17.

Combining hardware components shown in Fig. 16 and applying software architecture presented in Fig. 17 simulation environment for advanced relay testing is prepared. Network models and test cases need to be created in all three software packages: transient software packages Package 1 and Package 2 and short circuit software package designated as Package 3. Some specific test cases, with desired harmonic content can be created in Package 4 using its test signal creating capabilities. Description of network models and procedure for creating test cases is given in the following sections.

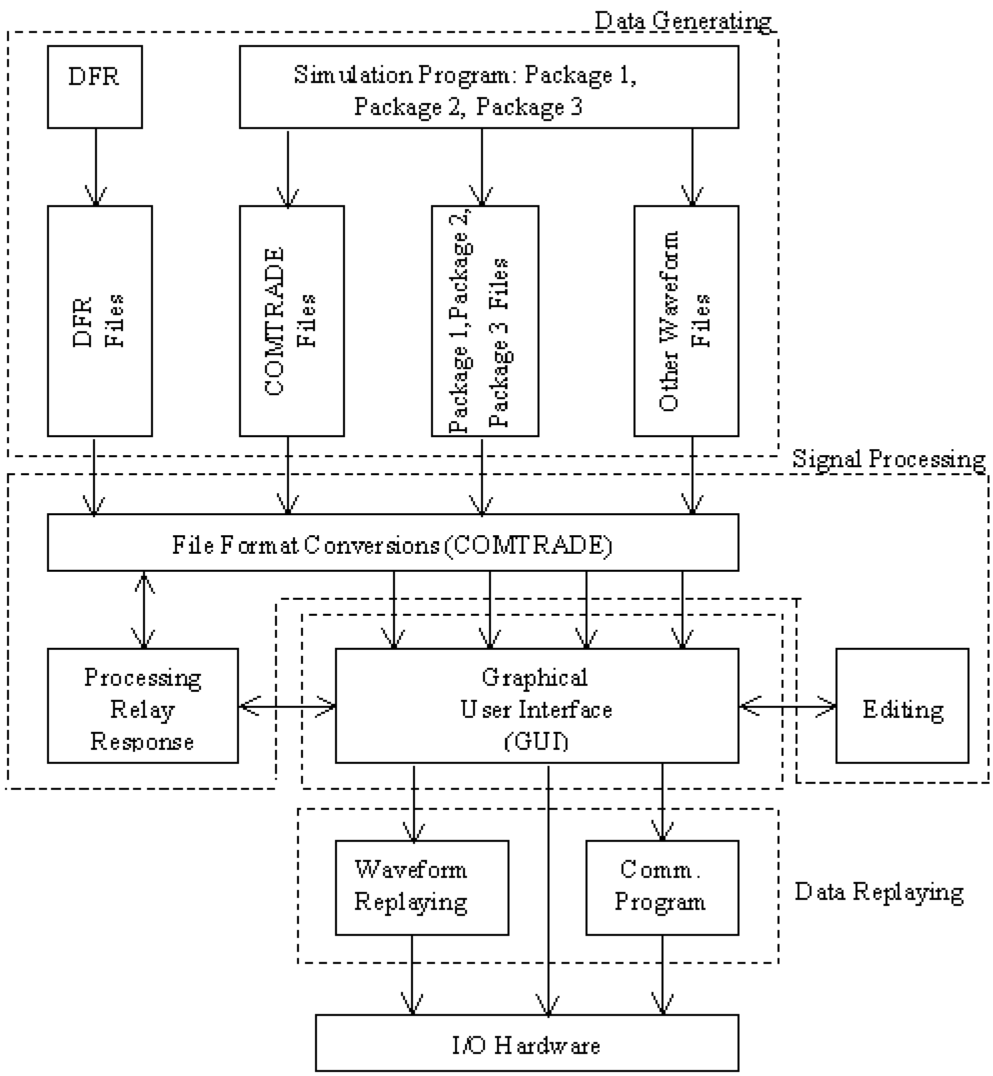

Fig. 17. Software architecture used in simulations

Network Models

Three network models used in testing are designated as Model 1, Model 2 and Model 3. All the network models are presented using the equivalent networks behind the nodes of interest. Instead of the real generator sources, equivalent sources with constant voltages (magnitude and angle) and equivalent sequence impedances were used. This simplified network representation is not quite suitable for accurate modeling of dynamic long-term processes and power network stability, but it can be used with sufficient accuracy for transient simulations.

Transmission line Π equivalents are used for modeling medium-length transmission line. Frequency dependent line model is used only when mutual-coupling influence is examined with Model 2 and Model 3.

Non-linearities that may occur in real network due to the influence of the instrument transformers are not taken into account. It is assumed that instrument transformers are properly selected and they are represented as linear elements.

Different network models are used to create various test scenarios. Model 1, presented in Fig. 18 is a good example of a complex network.

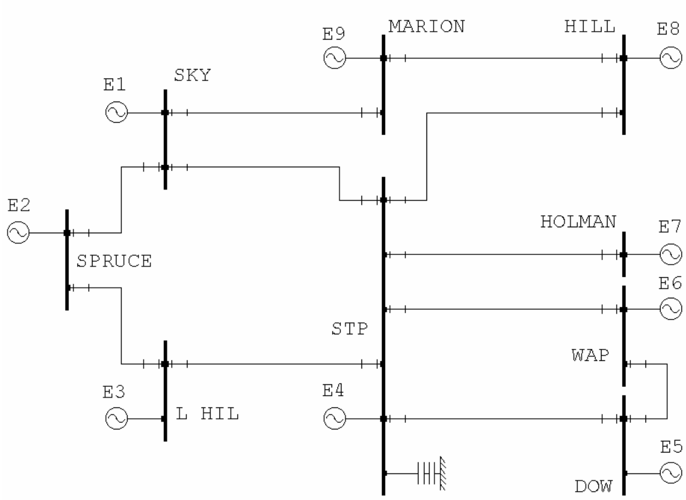

Fig. 18. Model 1

At one node (STP node), there are 5 transmission lines connecting five other nodes. Such configuration is very suitable to investigate the underreaching effect of distance protection installed at remote nodes, for faults beyond the STP node, due to the fault infeed effect. Model 1 is a 345 kV 9-bus, 11-line system. It contains shunt reactor at STP bus and equivalent network sources at all buses.

Model 2 is a power network with weak source (E4). It is presented in Fig. 19.

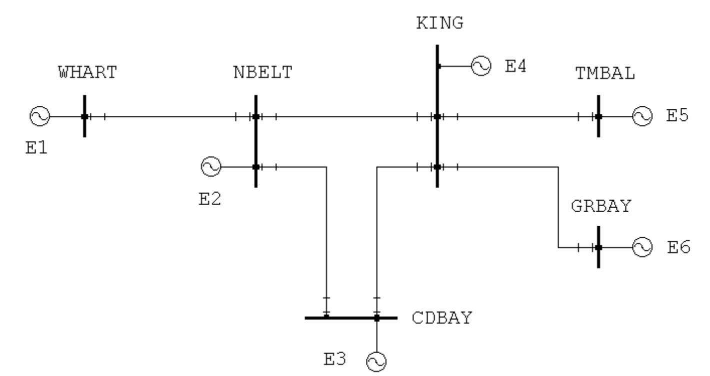

Fig. 19. Model 2

Weak source is at KING bus and it is suitable for simulation of the weak infeed effect. Model 2 can be used to test the reach accuracy as well.

Model 2 is a 345 kV 6-bus, 6-line system. Model 2 contains different lines running at the same tower. Lines Nbelt-King and CDBay-King are parallel lines. They are modeled with frequency dependent parameters to study their mutual influence. The other lines are constant parameter Π model lines. Such configuration is suitable for modeling some of the special fault events, and that will be explained in later paragraphs.

The third system used in simulations is Model 3, presented in Fig. 20. Model 3 is a detailed representation of power transmission lines running in parallel (frequency dependent model) with infeeds from both sides. Model is used to demonstrate the influence of mutual coupling.

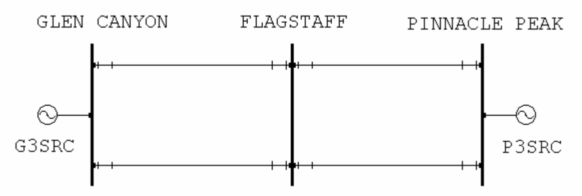

Fig. 20. Model 3

Three network models used to demonstrate the new methodology are good represent of configurations that may occur in a real network and lead to various conditions and event scenarios.

All three network models are utilized for testing the line protective relays, such as distance relays, overcurrrent and directional overcurrent relays. Different models should be used for other types of protection: transformer, generator, etc.

Test Procedure

After creating simulation environment for relay testing and after the hardware arrangement, software architecture and network models are defined, test procedure needs to be established. Creating testing environment and defining test cases is very important part of relay testing procedures [33]. To achieve the main goal of transient testing, to check selectivity of protective relays for various scenarios and to find the average tripping time, test procedure is proposed according to Fig. 21.

The first step in test procedure is to create network models in all three software packages. In Fig. 21 models and software used in simulations are abbreviated as M1, M2 and M3 that correspond to Model 1, Model 2 and Model 3 respectively, and P1, P2 and P3 that correspond to Package 1, Package 2 and Package 3 respectively. This procedure is established for testing line protection relays: distance relays, overcurrrent and directional overcurrent relays.

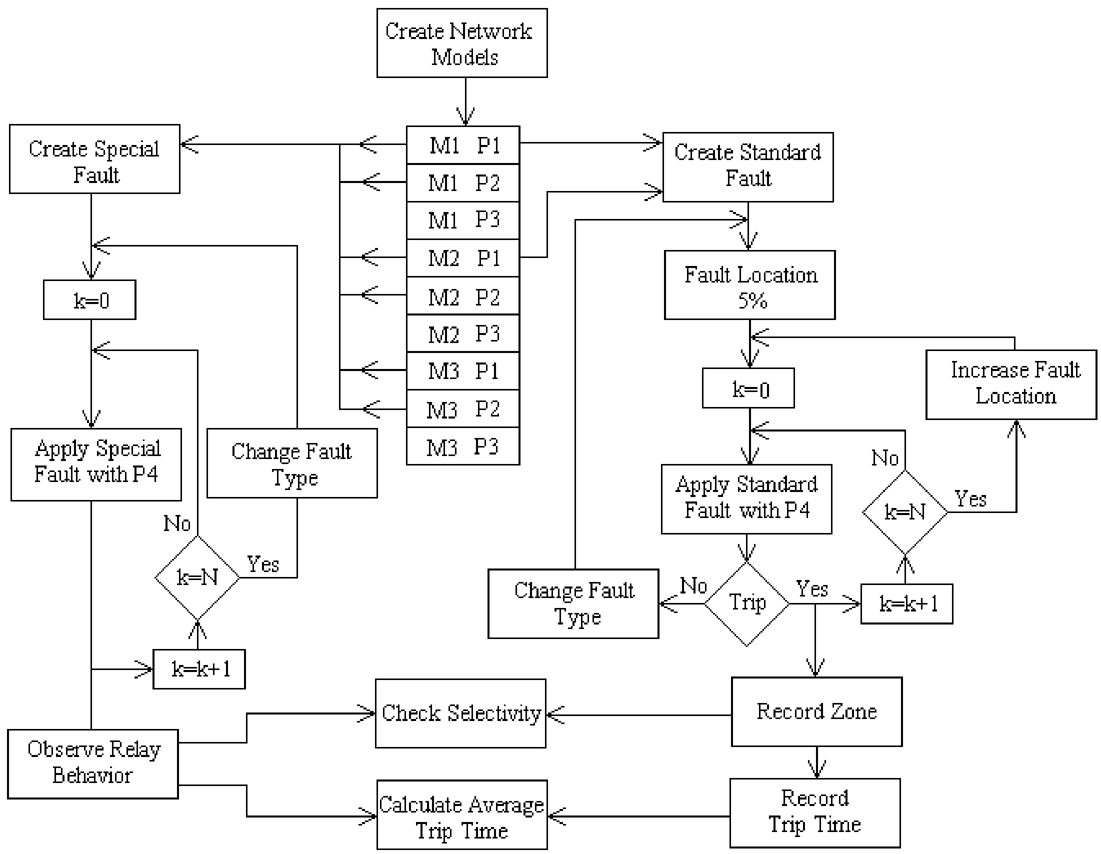

Fig. 21. Test procedure - flowchart

Although not used for transient testing, models created in short circuit software Package 3 are included in the simulation environment. Using Package 3 is optional. Package 3 can be applied in testing with phasors and in calculating relay settings. Since Package 3 has excellent library of protective relay models it can also be used for simulating complex events in dynamic simulations. These simulations are not done as a part of this research.

Standard faults

In the next step, basic selectivity of line relays and average response time should be checked. The procedure is graphically presented in Fig. 22. Assumed relay location is at Bus A. Standard faults should be applied on L1 with fault resistance equal to zero for ground faults in one set of tests, and fault resistance of 10 Ω for the next set of tests. Faults should be simulated at 5% of the transmission line and then increased to 50%, 75% and 95% of the line. After that, faults should be applied to 5%, 15% and 25% of the adjacent line L2. In reverse direction fault should be also simulated at 5%, 15% and 25% of the adjacent line LR in reverse direction. Zone 1 reach of 80% of L1, Zone 2 reach of 100% of L1 and 20% of L2 and reverse Zone 3 reach of 20% of LR are applicable for distance relays. Overcurrent relays should be also checked with the same test procedure, but zone discrimination is not applicable for these relays.

For each fault location, 15 tests should be performed in order to calculate average tripping time. It is important that the fault inception angle is changed. Three repetitive tests should be performed for each fault inception angle. Time to apply the fault is shifted by 4 ms to cover the entire period of 16.66 ms in 5 sets of tests where each set consists of 3 repetitive tests. Altogether, that is 15 tests for each fault location. Fault types should be changed: AG, BC, BCG, ABC and ABCG. The entire procedure should be repeated for all standard fault types.

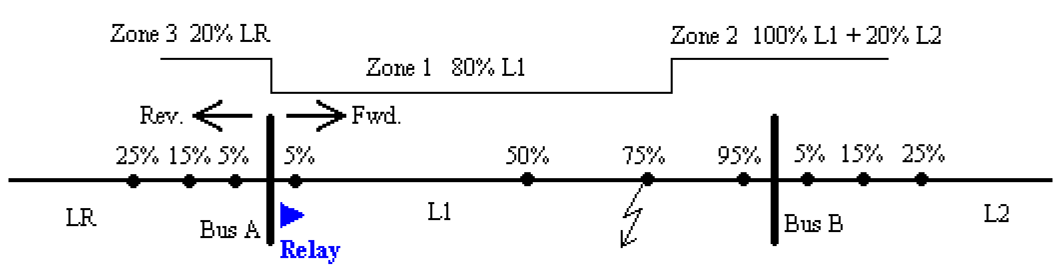

Fig. 22. Test procedure – standard faults

To create standard faults, Model 1 and Package 1 and Model 2 and Package 1 should be used. Package 4 should be used for signal replaying. Both hardware options can be utilized.

Special faults

In the next step fault events designated as special fault events are simulated [34]. Selectivity and average tripping time is checked for these events. The following events were subject to modeling and applied in testing procedure: parallel line out of service, switching on to fault, weak infeed, fault in reverse direction, cross-country fault, evolving fault. Faults are applied at location(s) relevant for the event demonstration and 15 tests are performed for each fault location, similarly as for the standard faults, with changing fault inception time in 4ms intervals i.e. 5 tests for 16ms and performing 3 repetitive shots for each fault inception time. AG fault is used as a basic case, but it should be changed if different fault type needs to be implemented in particular scenario.

Parallel line out of service

Parallel line out of service can cause unwanted operation of distance relays. When overhead lines are connected in parallel or run in close proximity for either the whole or a part of their length, mutual coupling exists between the two circuits. Typical application where the effects of mutual coupling should be addressed is the case with parallel line out of service and grounded at both ends (Fig. 23). For the case shown in Fig. 23, a ground fault at the remote bus may result in incorrect operation of the distance ground fault elements for Zones 1 and 2. It may be desirable to reduce the distance ground fault reach for Zones 1 and 2 for this application. To ensure adequate coverage an alternative reach setting may be required.

To simulate parallel line out of service, Model 3, Package 1 or Package 2 should be used. Detailed model of a transmission line that represents three phases together with grounding wires should be used. Package 4 should be used to generate the waveforms.

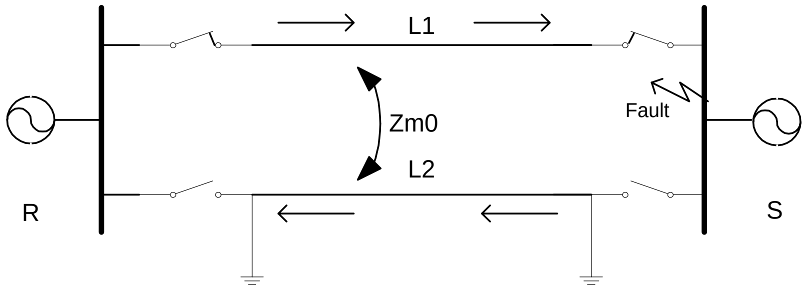

Fig. 23. Parallel line out of service

Switching on-to-fault (recognizing fault after energizing the line)

This event occurs following manual circuit breaker switching on-to a persistent fault. In such case, three pole instantaneous tripping (and auto-reclose blocking) should occur for any fault detected on the protected element. One complication is possible in case of switching on-to a fault close to the remote line end, when an underreach distance protection scheme is used. If the fault is not recognized as an immediate fault after the circuit breaker closing, fault clearance will be unnecessarily delayed.

To simulate switching on-to-fault, Model 1 or Model 2 and Package 2 should be used. Package 2 provides flexibility in modeling such kind of events. Package 4 is used to generate waveforms.

Weak infeed system

It may be considered whenever there are sources with high impedances in the network. Long line transmission systems with remote generation may have these characteristics. Weak infeed characteristics could also be found when small generators are installed and connected to the system, or when some of the generators are occasionally off line. Several protection complications may occur due to the weak infeed: there may be insufficient current contribution to a fault on the protected line for a relay to reliably detect a fault. In case of multiterminal lines with a weak source at one terminal as compared to the other terminals, protection at the weak source will not detect faults beyond the tap as successfully as relays at a strong source.

Model 2 and Package 1 or Package 2 should be used to simulate the event. Waveform is generated through Package 4.

Faults in reverse direction

Fault current direction can change in one circuit when circuit breakers open sequentially to clear the fault on the parallel circuit. A system configuration that could result in current reversals is shown in Fig. 24. For a fault on line L1, we may suppose that the circuit breakers do not operate simultaneously. We assume that the circuit breaker CB2 operates first, causing the direction of the current flow in line L2 to reverse, before the circuit breaker CB1 opens.

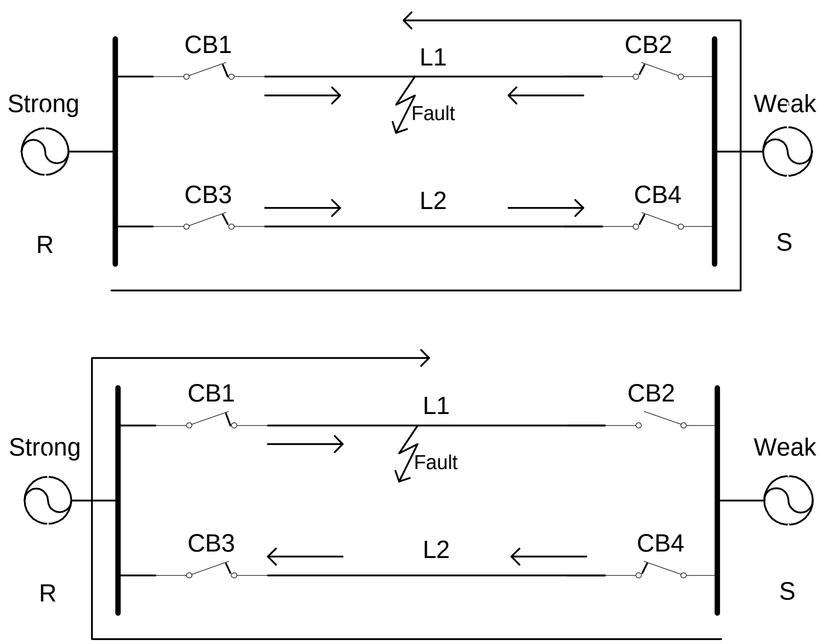

Fig. 24. Fault in reverse direction

The change in current direction may cause improper operation of permissive overreaching distance protection schemes and directional ground-fault blocking schemes. Protection can see the fault in the opposite direction to what was initially detected (distance protection settings of these elements must exceed 150% of the line impedance at each terminal). The race between the operating and resetting actions of the overreaching distance elements at each line terminal can cause the permissive overreach element to trip the healthy line. Similar situation can occur in the directional ground fault blocking scheme application.

Model 2 and Package 2 or Model 3 and Package 2 should be used in simulations. Model 2 does not contain the parallel lines exactly, but Nbelt-King line and Nbelt-CDBay-King path in Model 2 can be used to simulate the event. Example waveform presented here is obtained with Model 2. Waveform is generated through Package 4.

Cross-country faults

They can occur between mutually coupled lines (generally speaking between lines on the same tower). A fault can occur, for instance, between phases A and B but the phases belong to different lines on the same tower. An example of the system configuration is shown in Fig. 25. The situation becomes critical if the fault is near one of the substations, for instance substation S. Protective relays on both lines at substation R will detect A-B-G fault in the forward direction. At substation S, relay on L1 will detect A-G fault in the forward direction and relay on L2 will detect B-G fault in the forward direction. If the fault location is moved away from the bus at substation S, the relays in substation R will also detect correct single-phase-to-ground faults. Condition shown in Fig. 25 may result in undesired tripping of all three phases of both lines at substation R (instead of a single phase tripping of each line), and proper single phase tripping at substation S. The undesired operation of the relays at substation R can occur because they must rely on the local phase selection to determine the fault type and which phase or phases to trip.

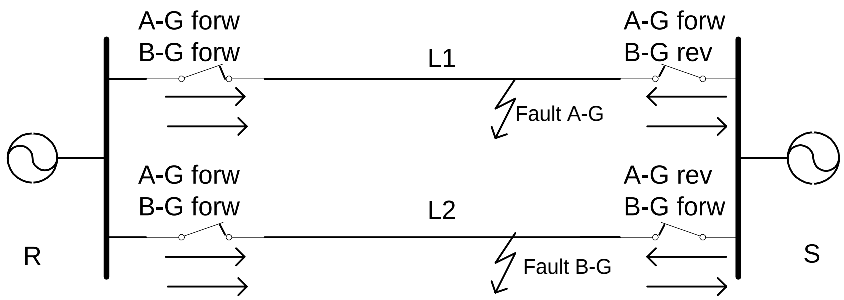

Fig. 25. Cross-country fault

To simulate the cross country fault Model 2 and Package 2 and Model 3 and Package 2 can be used. Waveforms are generated through Package 4.

Evolving faults

They start as a single-phase-to-ground fault and then involve additional phases during the time that the initial fault is being cleared or during the circuit breaker dead time of the original faulted phase. Evolving fault may lead to difficulties in coordinating the ground-fault relays and overcurrent relays.

Model 1 and Model 2 can be used in simulations. Package 2 is the best tool to simulate the event. As in all other cases software platform (Package 4) should be used to generate waveforms.

Summary of the events

Summary of software tools and network models used to create testing procedures according to the new methodology is given in Table III. Package 4 is used as software platform in all tests and it won't be mentioned separately in this Table. Package 3 is a short circuit software. It is a part of the new testing environment but it is not utilized in given examples. Arrangements presented in Table III are empirically qualified as the best and optimal solution, proved as such in a large number of test cases. Other combinations of network models and software tools can also be used to simulate particular event, but probably less efficiently. The whole process would often be more involving to utilize particular network models and tools. The list of events presented in

Table III is not the final list of all events that can occur in a real network. These are events that can be simulated with available tools.

Table III. Summary of the events

Event	Network Model			Software Tool		
	Model 1	Model 2	Model 3	Pack. 1	Pack. 2	Pack. 3*
Standard faults	■	■		■		
Parallel line out of service			■	■	■	
Switch on-to fault	■	■			■	
Weak infeed		■		■	■	
Fault in reverse direction		■	■		■	
Cross country fault		■	■		■	
Evolving fault	■	■			■	

* Package 3 is a short circuit program

Conclusion

This chapter gave summary of the objectives of the new methodology. Procedures and scenarios for transient testing of protective relays, with main focus on testing numerical transmission line relays were defined. Implementation of the new methodology to create variety of test cases and scenarios was proposed. Implementation of the new methodology was realized with compact equipment suitable for troubleshooting relay misopertaions in the field and with high performance equipment suitable for testing new protective relays in laboratory conditions.

The test cases and scenarios were selected based on the application relevance of the operating conditions. In protective relays' testing performed for this research, the attempt was to discover and quantify random characteristics of relay behavior, by checking their selectivity and average tripping time.

Different software packages were used to create test cases to demonstrate that in some cases, some software packages may be better to use then the others. It was demonstrated that to carry out a comprehensive procedure, combination of various software packages may be needed.

Because of the fact that transient response of numerical relays is random, it was emphasized that selectivity and average tripping time of numerical relays should be checked through large number of transient scenarios and test cases. Repetitive tests should be performed for a given scenario or fault location with different fault inception times.

Implementation of the new methodology was proposed through a combination of hardware options and software tools to achieve the best possible utilization of available power system modeling and waveform replaying options.

CHAPTER V

TEST METHODOLOGY APPLICATION AND RESULTS

Introduction

Application of the new methodology will be demonstrated in this chapter. The new methodology will be implemented by modeling cases and scenarios defined for the new methodology, by using software packages and utilizing hardware tools accordingly.

In the first part, description of relays under tests will be given. Setting principles as well as how these settings are changed in some cases to achieve different testing objectives defined by the new methodology will be explained.

Test cases and scenarios that include standard faults and special faults will be created and example waveforms will be shown. Implementation of the new methodology will include network modeling, waveform simulations and replays. To implement the new methodology two hardware tools for generating signals and three software packages for network modeling and simulations will be used. Software package for signal editing and replaying will be used as well. Principle to change fault inception angle for the same fault scenario and to perform several repetitive tests for the same inception angle will be used to obtain results. Selectivity and average tripping time of protective relays will be checked.

Test results will be analyzed and conclusions if selectivity criteria and average tripping time of protective relays are satisfied will be derived. Comparison of hardware and software components used to demonstrate the new methodology will be given as well.

All obtained results will be listed in appropriate tables.

Protective Relays

Protective relays that were subject to tests are the microprocessor relays of the following types: two distance relays and two overcurrent/ground fault relays. These relays are used for transmission line protection. None of the relays are the same brand and model. Brief description of protective relays used in simulations is given next.

Protective relay A: distance relay

Relay A is a flexible system available for power system protection, monitoring, and control. Relay A is a microprocessor controlled, universal platform. The same device can be used in different applications. For each application, a scheme file is created in relay software application, and downloaded to Relay A. Relay software application provides an integrated environment for the configuration and operation of Relay A, as well as a complete programming system for developing power system applications. Distance relay scheme with reclosing and POTT is uploaded to the relay.

Distance relay scheme uses three independent phase difference, or phase paired, mho operating characteristics per zone of protection to account for phase-to-phase and three phase faults. It also uses three independent residual current compensated phase mho operating characteristics per zone of protection to account for ground faults. Three forward zones and one reverse zone of ground distance protection are provided.

In addition to the distance protection provided, the distance relay scheme also incorporates overcurrent protection, ground fault protection, undervoltage and overvoltage, directional supervision and fault locator.

Distance relay scheme provides logic to prevent incorrect trip in case of current reversals, weak infeed conditions at one terminal, breaker open at one terminal, switch onto fault, load encroachment, VT fuse failure and power swing.

Hardware configuration tested has two contact terminal modules. The first module contains 4 current and 4 voltage measurement inputs for the relay, as well as two contact output drivers (one form electromechanical and one solid-state high speed trip output). The second board contains most of the peripheral and I/O ports for the relay.

Protective relay B: distance relay

Relay B is a microprocessor-based device that protects, controls and monitors EHV, HV and subtransmission lines. It is a protective relay package for pilot and non-pilot schemes. The main protective functions of Relay B are: four zones of phase and ground distance protection, independently set phase and ground distance elements, independent phase, negative-sequence and time overcurrent elements, memory polarization for directional overcurrent and ground fault elements and fault locator.

Similar to other modern digital distance relays, Relay B has logic to prevent incorrect trip in case of current reversals, weak infeed conditions at one terminal, breaker open at one terminal, switch onto fault, load encroachment, VT fuse failure and power swing.

In its two I/O board version, Relay B provides 16 contacts inputs and 32 contact outputs. The contact inputs can be assigned for control functions, monitoring logic and general indication. Except for a dedicated alarm output, each contact output is independently programmable.

The relay has six independent setting groups providing possibility to set the same relay for different operating conditions such as line configuration changes, source changes, etc.

The relay has three serial communication ports for local or remote access to relay settings, metering and fault data.

Protective relay C: overcurrent/ground fault relay

Relay C is a microprocessor-based relay designed for feeder control, monitoring and protection. This relay provides 2 phase, neutral, ground and negative sequence, instantaneous and time overcurrent protection.

Overvoltage and undervoltage protection, overfrequency and underfrequency protection, breaker failure protection, directional current supervision, fault diagnostics, RTU, and programmable logic functions are provided. The time overcurrent function has multiple curve shapes for optimum coordination. Automatic reclosing, synchrocheck, and line fault locator features are also provided. Voltage, current, and power metering is built into the relay as a standard feature.

The relay has 48 programmable leds plus fixed trip and alarm led. It has 8 user definable displays, event recorder with capacity of 1024 events, data logger and single ended fault locator. A faceplate RS232 port may be used to connect to a PC for the programming of settings and the monitoring of actual values. A variety of communications modules are available.

Protective relay D: overcurrent/ground fault relay

Relay D is a microprocessor based protection, control, metering and monitoring system. Standard features include three phase and ground instantaneous and time overcurrent function, metering, sequence of event reporting, breaker failure logic, recloser and user-configurable logic. Additional features include negative sequence instantaneous and time overcurrent functions, a phase directional function, a negative sequence directional function, under and over voltage, under and over frequency and fault location. Eight separate groups of relay settings are provided.

Configurable logic approach is implemented using custom application software package. It allows the user to program output contacts using digital inputs, internally generated protection flags, timers and latches. User interaction is provided at three levels: leds on the front of the device, keypad/display module and external PC. PC connection is established through three RS 232 ports.

The eight digital inputs and eight digital outputs are not hardwired to any function within the relay. The effect of each input and driver for each output is determined by a software definition, which is a part of each setting group.

Setting principles of distance relays A and B

Distance relays A and B are set to cover 80% of protected line in Zone 1 in forward direction, 100% of protected line and 20% of the adjacent line in Zone 2 in forward direction, and 20% of the adjacent line in Zone 3 in reverse direction. In case there are several adjacent lines to chose from to set Zone 2 and Zone 3, the line is selected arbitrarily. Time setting of Zone 1 is instantaneous, Zone 2 is set to operate after 300 ms and Zone 3 is set to operate after 600 ms.

Relay settings are based on impedances of transmission lines and guidelines from relay manuals. Settings are not compensated to take into account the influence of infeeds. Different strategies to calculate and determine settings of protective relays were not subject of this research. Primary goal is to test selectivity and average tripping time for given settings.

Setting principles of directional overcurrent/ground fault relays C and D

Directional overcurrent/ground fault relays are set to operate for faults in forward direction and block for reverse faults. They are set to operate instantaneously, with definite time operating characteristic. Current pickup setting applied is 2 times the nominal current of the CT secondary. Thus, the current pickup setting is 10 A. Selectivity and average tripping time is observed in transient tests.

Relay Testing Scenarios and Results

This section gives a summary of the results and conclusions obtained with new methodology in transient testing. Examples of the results obtained in testing of Relays A, B, C and D are given. Testing environment, cases, procedures and scenarios were applied in accordance with descriptions and explanations given in Chapter IV. Some practical applications are presented and discussed in this section.

Fault scenarios

In the first stage, all relays are tested for standard faults: AG, BC, BCG, ABC and ABCG. Network model used in testing for standard faults is Model 1 created in Package 1. Assumed location of protective relays is Sky end of Sky-STP transmission line. One set of tests is conducted with fault impedance equal to zero and another set of tests is conducted with 10 Ω fault resistance. Each test case is repeated 15 times with different fault inception times in 4ms intervals, to cover one full period of fault inception angles and with 3 repetitive tests for each angle. Selectivity of protective relays and average tripping time are checked. For distance protection relays, fault locations are selected to test if zone reaches are appropriate. For directional overcurrent relays, less number of fault locations is used then with distance relays, because with directional overcurrent relays it is only checked if correct type of fault is detected in correct direction, and if the entire line is covered with directional overcurrent protection.

In the second stage, relays are tested with special faults: fault when parallel line is out of service, switching on-to fault, fault with weak infeed, fault in reverse direction, cross country fault and evolving fault. Location of protective relay under test is changed, fault type and fault location are suitably selected to simulate different special fault events. Settings of protective relays are adjusted accordingly. Each test is repeated 5 times with different fault inception times, to cover one full period of fault inception angles and with 3 shots for each test. Selectivity and average tripping time are checked. Models 1, 2 and 3 and Package 1 and 2 are used to create scenarios.

Simulation: parallel line out of service

In simulation of the effect when parallel line is out of service, Model 3 and Package 2 are used. When both lines are in service, waveform presented in Fig. 26 is generated.

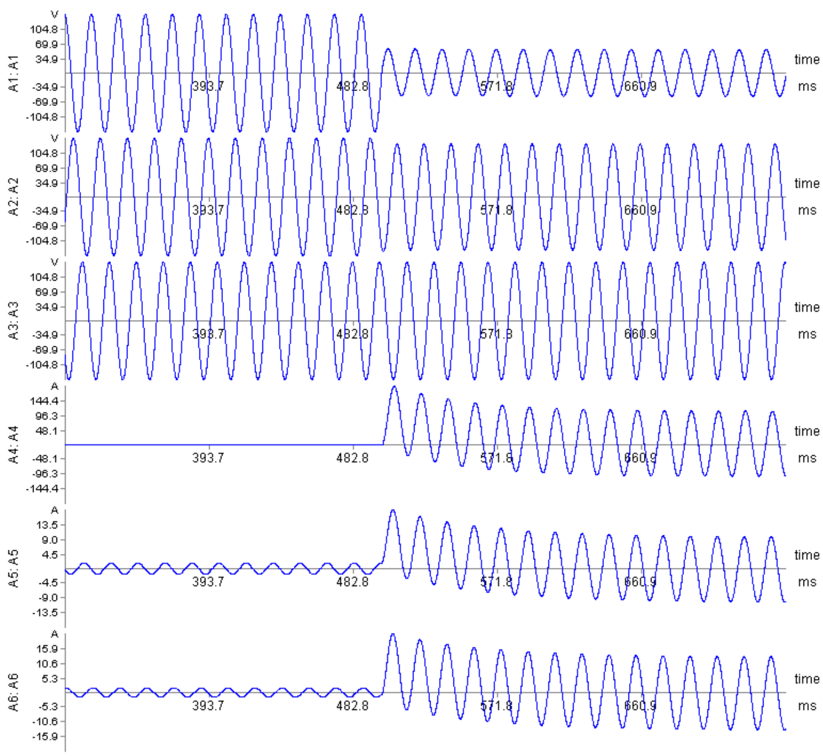

Fig. 26. Parallel line in service - waveform

Relay is located on Glen Canyon – Flagstaff line at Glen Canyon end. Fault AG is simulated at 75% of the line. Five tests are repeated for different fault inception angles.

After one line from Glen Canyon to Flagstaff is taken out of service and grounded, due to the effect of mutual coupling zero impedance of the remaining line is reduced. If AG fault occurs at the remaining line, at the same fault location i.e. 75% of the line, impedance measured at Glen Canyon is reduced and distance relay tends to overreach. Example waveform is given in Fig. 27

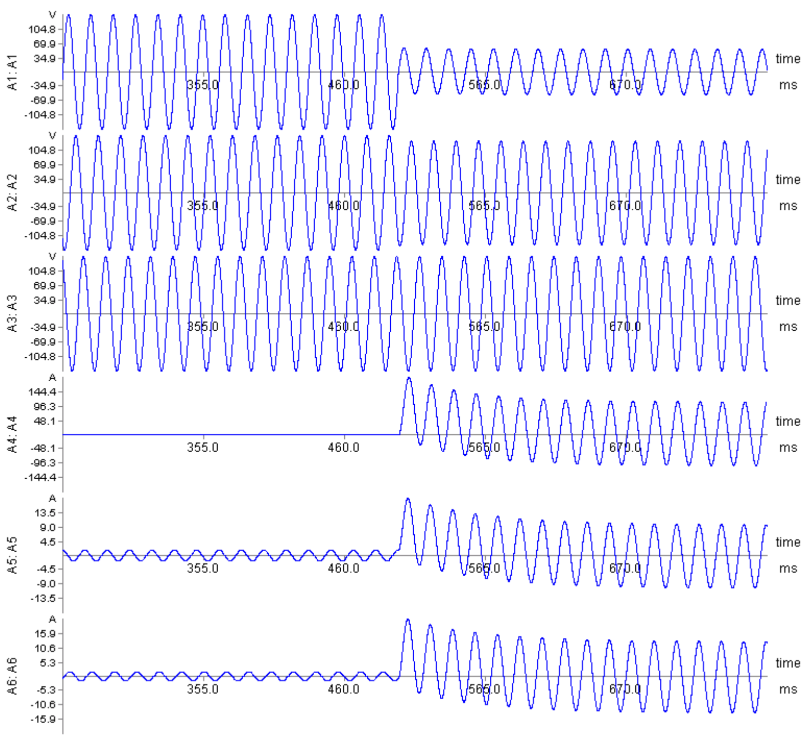

Fig. 27. Parallel line out of service - waveform

Simulation: switching on-to fault

Switching on-to fault is simulated using Model 2 and Package 2. Relay is located on Nbelt – King line at Nbelt end. Classical situation when switching on-to fault feature of a distance relay should cause instantaneous tripping is during energizing of transmission line from one end, while ground switch at remote end is in service. It is assumed that both circuit breakers are initially open, and maintenance personnel or operator, by mistake, did not open ground switch at King end (99% of the line) before line energizing. Line is first energized from NBelt end at time instant 500 ms of the simulation. Example waveform used to test switching on-to fault condition is given in Fig. 28.

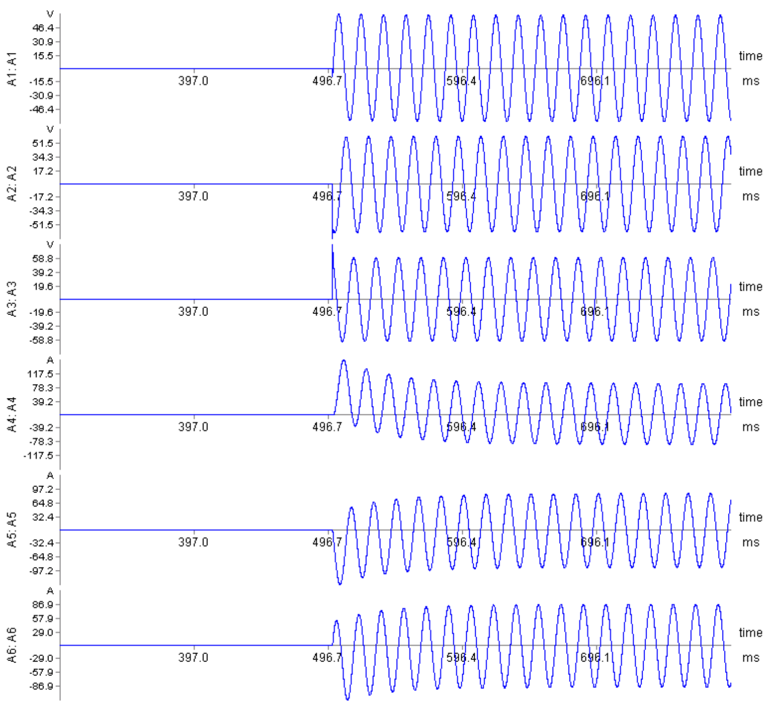

Fig. 28. Switching on-to fault - waveform

If switching on-to fault function of a distance relay at Nbelt end is not working properly, relay would recognize ABCG fault in Zone 2 and trip after Zone 2 time delay. To avoid unnecessary Zone 2 delay for a severe solid fault at remote end, relay should recognize switch-on-to fault condition and trip instantaneously.

Even if applied, distance protection scheme (permissive or blocking) is not responsible to clear such fault, because the circuit breaker at King end is open and relay at that end does not "see" the fault and cannot send carrier signal. The same situation would occur during unsuccessful autoreclosing for faults in Zone 2, where instantaneous tripping is also required.

Simulation: weak infeed system

To simulate weak infeed system, Model 2 and Package 1 are used. Example waveform is presented in Fig. 29.

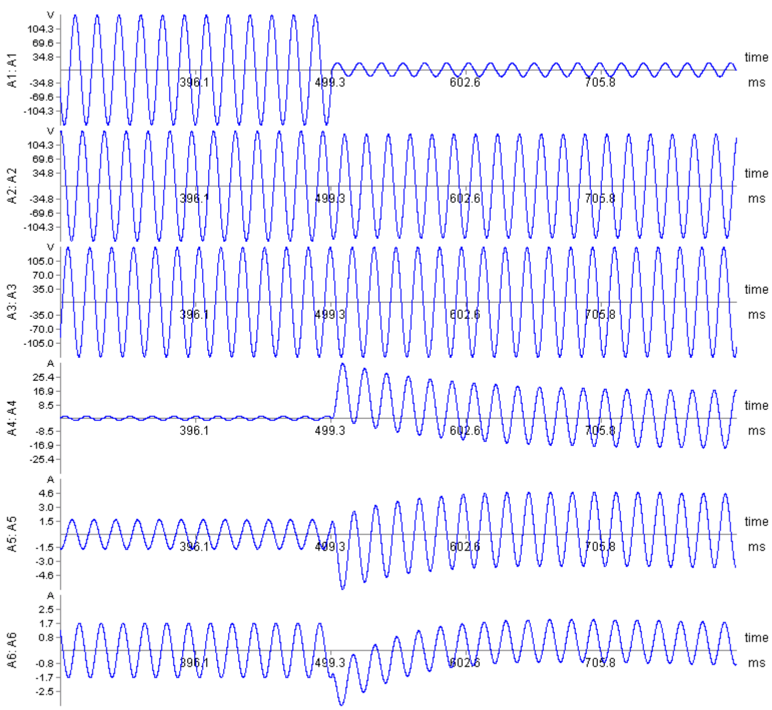

Fig. 29. Weak infeed system - waveform

Relay is located on Nbelt – King line at King end. Source E4 at King bus is a weak source. To demonstrate the effect, sources E5 and E6 are disconnected. AG fault at 95% of the line from King side is applied after 500 ms of simulation.

Simulation: faults in reverse direction

Faults in reverse direction are simulated using Model 2 and Package 2. Relay is located on CDBay – King line at CDBay end. The same principle of distance protection setting is used as in other cases. Fault is simulated on 105% of the line length, on Nbelt – King line, close to King end. Fault is in Zone 2 of distance relay at CDBay and in Zone 1 of assumed relay on Nbelt – King line at King end. Example waveform is presented in Fig. 30.

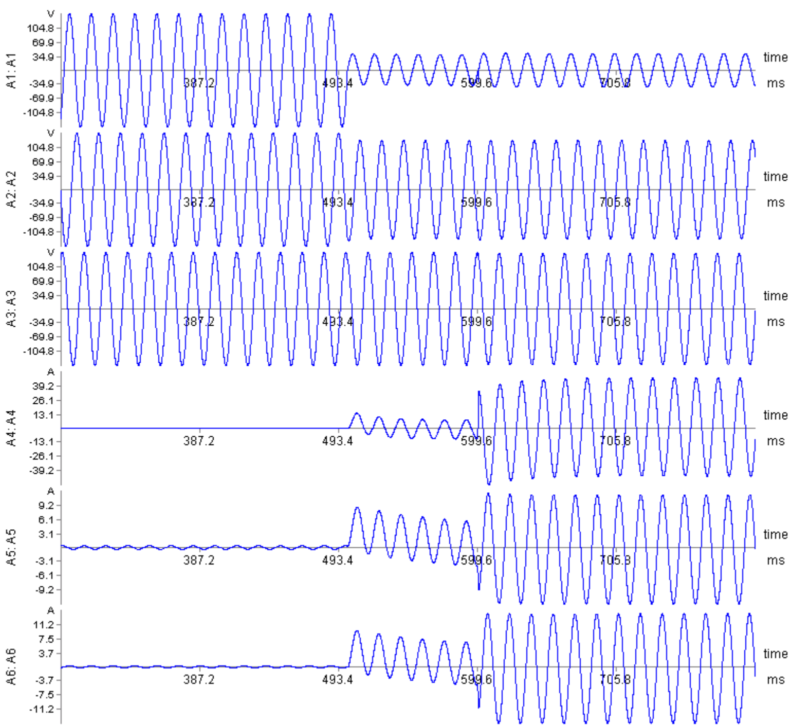

Fig. 30. Fault in reverse direction - waveform

AG fault is applied after 500 ms of simulation. Relay at CDBay should pick-up in Zone 2, and relay at King is supposed to operate in Zone 1. Assumed operation of the entire protection chain at King is 100 ms, for fault in Zone 1. Circuit breaker at King is opened in 600 ms of simulation and operation of Nbelt relay is delayed. Three pole tripping is assumed. Now, current changes its direction with respect to relay at CDBay.

Interestingly, current through CDBay relay not only changes its direction, but it also increases its magnitude. That is due to the fact that the entire fault back-feeding at Nbelt – King line from sources E4, E5 and E6 happens through CDBay relay. Behavior of protective relays is observed for such scenario.

Simulation: cross-country fault

Simulation of the cross country fault is conducted using Model 2 and Package 2. Example waveform is presented in Fig. 31.

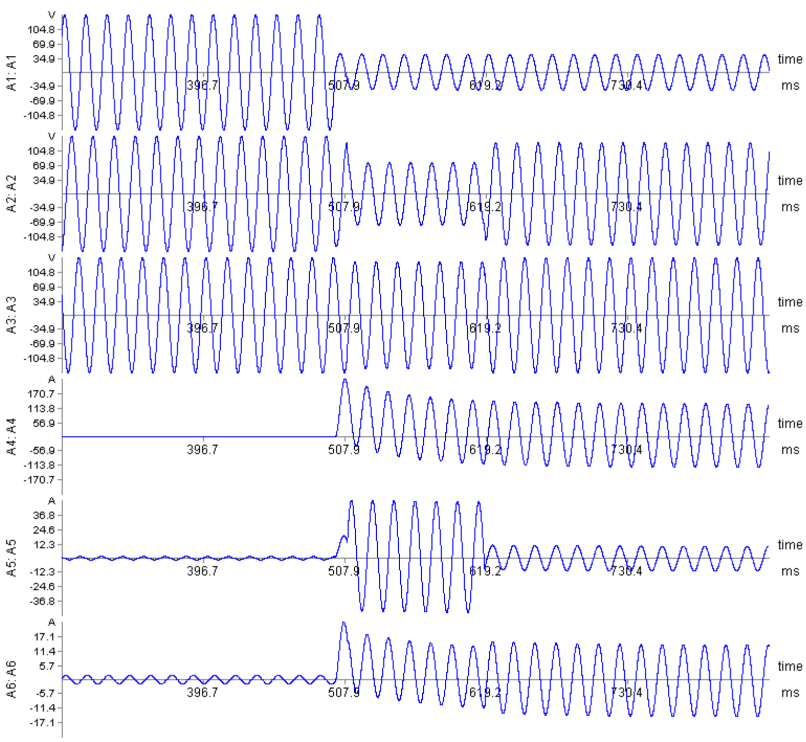

Fig. 31. Cross-country fault - waveform

Relay is located on NBelt - King line at NBelt end. AG fault is simulated on 75% of line Nbelt – King at time instant 500 ms. It is assumed that Nbelt – King line and CDBay – King line are running in parallel, on the same tower, in one part of their route approaching King substation. After 10 ms, it is assumed that the fault evolves to phase B of the parallel line CDBay – King at corresponding location. Now, fault AG is in Zone 1 of distance relay at Nbelt. Fault BG is in Zone 2 of distance relay at Nbelt (Nbelt – King line) and in Zone 1 of assumed relay at King (CDBay – King line). Distance relay at King operates and circuit breaker trips (three-phase tripping) after 100 ms to clear BG fault on CDBay – King. Behavior of protective relay at Nbelt is observed.

Simulation: evolving fault

To simulate evolving fault Model 2 and Package 2 are used. Example waveform is given in Fig. 32.

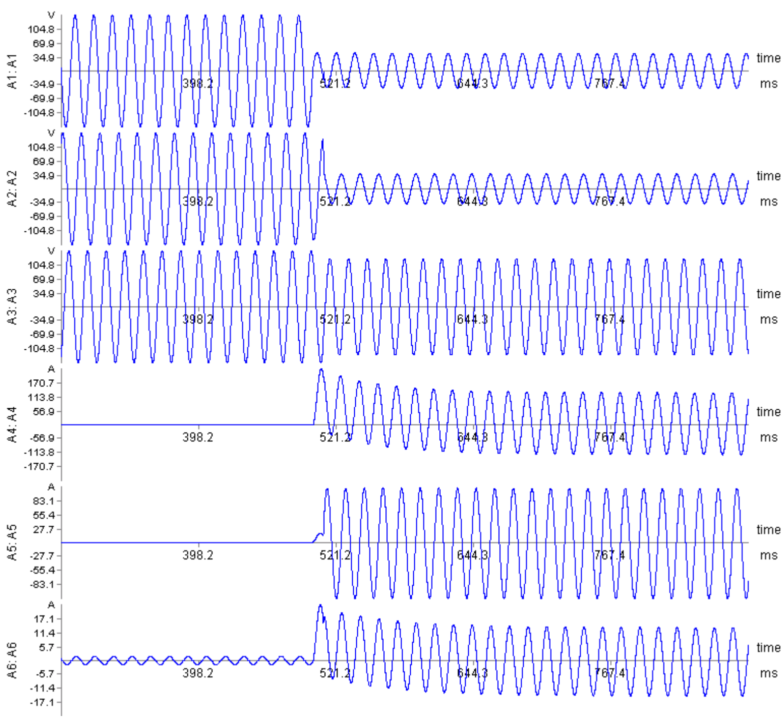

Fig. 32. Evolving fault - waveform

Fault is simulated at 50% of line Nbelt – King. The relay is located at Nbelt end. At time instant 500 ms, AG fault is applied. After 10 ms, fault evolves to phase B. Operation of protective relay is observed. As in all other cases, 15 tests are performed for different fault inception angles.

Transient testing of the distance relay: Relay A

Results of transient testing for standard faults are given in Tables IV, V, VI, VII and VIII for different fault types. Table IX presents the results for special faults. Shaded fields represent situations when protective relay did not operate as expected. Average operating times are rounded to 1 ms precision.

Table IV. Relay A – AG fault

AG Fault					
Network: Model 1	Fault Location				
Line	Sky-Stp	Sky-Stp	Sky-Stp	Sky-Stp	Stp-Wap
Fault Location	5%	50%	75%	95%	5%
Fault Direction	Forward	Forward	Forward	Forward	Forward
Expected Operation	Z 1	Z 1	Z 1	Z 2	Z 2
Actual Operation	Z 1	Z 1	Z 1	Z 2	Z 2
Actual Operation (R)	Z 1	Z 1	Z 1	Z 2	Z 2
Expected Op. Time	Inst.	Inst.	Inst.	300 ms	300 ms
Average Op. Time	24 ms	24 ms	28 ms	302 ms	302 ms
Average Op. Time (R)	25 ms	24 ms	29 ms	302 ms	301 ms
Detected Fault Type	AG	AG	AG	AG	AG
AG Fault (continued)					
Network: Model 1	Fault Location				
Line	Stp-Wap	Stp-Wap	Sky-Spruce	Sky-Spruce	Sky-Spruce
Fault Location	15%	25%	5%	15%	25%
Fault Direction	Forward	Forward	Reverse	Reverse	Reverse
Expected Operation	Z 2	No	Z 3	Z 3	No
Actual Operation	No	No	Z 3	Z 3	No
Actual Operation (R)	No	No	Z 3	Z 3	No
Expected Op. Time	300 ms	No	600 ms	600 ms	No
Average Op. Time	No	No	600 ms	601 ms	No
Average Op. Time (R)	No	No	601 ms	601 ms	No
Detected Fault Type	No	No	AG	AG	No

Table V. Relay A – BC fault

BC Fault					
Network: Model 1	Fault Location				
Line	Sky-Stp	Sky-Stp	Sky-Stp	Sky-Stp	Stp-Wap
Fault Location	5%	50%	75%	95%	5%
Fault Direction	Forward	Forward	Forward	Forward	Forward
Expected Operation	Z 1	Z 1	Z 1	Z 2	Z 2
Actual Operation	Z 1	Z 1	Z 1	Z 2	Z 2
Actual Operation (R)	Z 1	Z 1	Z 1	Z 2	Z 2
Expected Op. Time	Inst.	Inst.	Inst.	300 ms	300 ms
Average Op. Time	25 ms	26 ms	27 ms	301 ms	301 ms
Average Op. Time (R)	25 ms	26 ms	29 ms	302 ms	300 ms
Detected Fault Type	BC	BC	BC	BC	BC
BC Fault (continued)					
Network: Model 1	Fault Location				
Line	Stp-Wap	Stp-Wap	Sky-Spruce	Sky-Spruce	Sky-Spruce
Fault Location	15%	25%	5%	15%	25%
Fault Direction	Forward	Forward	Reverse	Reverse	Reverse
Expected Operation	Z 2	No	Z 3	Z 3	No
Actual Operation	No	No	Z 3	Z 3	No
Actual Operation (R)	No	No	Z 3	Z 3	No
Expected Op. Time	300 ms	No	600 ms	600 ms	No
Average Op. Time	No	No	601 ms	601 ms	No
Average Op. Time (R)	No	No	601 ms	601 ms	No
Detected Fault Type	No	No	BC	BC	No

Table VI. Relay A – BCG fault

BCG Fault					
Network: Model 1	Fault Location				
Line	Sky-Stp	Sky-Stp	Sky-Stp	Sky-Stp	Stp-Wap
Fault Location	5%	50%	75%	95%	5%
Fault Direction	Forward	Forward	Forward	Forward	Forward
Expected Operation	Z 1	Z 1	Z 1	Z 2	Z 2
Actual Operation	Z 1	Z 1	Z 1	Z 2	Z 2
Actual Operation (R)	Z 1	Z 1	Z 1	Z 2	Z 2
Expected Op. Time	Inst.	Inst.	Inst.	300 ms	300 ms
Average Op. Time	27 ms	29 ms	30 ms	301 ms	302 ms
Average Op. Time (R)	28 ms	29 ms	29 ms	302 ms	301 ms
Detected Fault Type	BCG	BCG	BCG	BCG	BCG

Table VI. (continued)

BCG Fault (continued)					
Network: Model 1	Fault Location				
Line	Stp-Wap	Stp-Wap	Sky-Spruce	Sky-Spruce	Sky-Spruce
Fault Location	15%	25%	5%	15%	25%
Fault Direction	Forward	Forward	Reverse	Reverse	Reverse
Expected Operation	Z 2	No	Z 3	Z 3	No
Actual Operation	No	No	Z 3	Z 3	No
Actual Operation (R)	No	No	Z 3	Z 3	No
Expected Op. Time	300 ms	No	600 ms	600 ms	No
Average Op. Time	No	No	602 ms	602 ms	No
Average Op. Time (R)	No	No	601 ms	601 ms	No
Detected Fault Type	No	No	BCG	BCG	No

Table VII. Relay A – ABC fault

ABC Fault					
Network: Model 1	Fault Location				
Line	Sky-Stp	Sky-Stp	Sky-Stp	Sky-Stp	Stp-Wap
Fault Location	5%	50%	75%	95%	5%
Fault Direction	Forward	Forward	Forward	Forward	Forward
Expected Operation	Z 1	Z 1	Z 1	Z 2	Z 2
Actual Operation	Z 1	Z 1	Z 1	Z 2	Z 2
Actual Operation (R)	Z 1	Z 1	Z 1	Z 2	Z 2
Expected Op. Time	Inst.	Inst.	Inst.	300 ms	300 ms
Average Op. Time	22 ms	24 ms	25 ms	300 ms	300 ms
Average Op. Time (R)	24 ms	25 ms	28 ms	301 ms	301 ms
Detected Fault Type	ABC	ABC	ABC	ABC	ABC
ABC Fault (continued)					
Network: Model 1	Fault Location				
Line	Stp-Wap	Stp-Wap	Sky-Spruce	Sky-Spruce	Sky-Spruce
Fault Location	15%	25%	5%	15%	25%
Fault Direction	Forward	Forward	Reverse	Reverse	Reverse
Expected Operation	Z 2	No	Z 3	Z 3	No
Actual Operation	No	No	Z 3	Z 3	No
Actual Operation (R)	No	No	Z 3	Z 3	No
Expected Op. Time	300 ms	No	600 ms	600 ms	No
Average Op. Time	No	No	600 ms	600 ms	No
Average Op. Time (R)	No	No	601 ms	601 ms	No
Detected Fault Type	No	No	ABC	ABC	No

Table VIII. Relay A – ABCG fault

ABCG Fault					
Network: Model 1	Fault Location				
Line	Sky-Stp	Sky-Stp	Sky-Stp	Sky-Stp	Stp-Wap
Fault Location	5%	50%	75%	95%	5%
Fault Direction	Forward	Forward	Forward	Forward	Forward
Expected Operation	Z 1	Z 1	Z 1	Z 2	Z 2
Actual Operation	Z 1	Z 1	Z 1	Z 2	Z 2
Actual Operation (R)	Z 1	Z 1	Z 1	Z 2	Z 2
Expected Op. Time	Inst.	Inst.	Inst.	300 ms	300 ms
Average Op. Time	24 ms	25 ms	27 ms	301 ms	301 ms
Average Op. Time (R)	26 ms	26 ms	28 ms	302 ms	301 ms
Detected Fault Type	ABC	ABC	ABC	ABC	ABC
ABCG Fault (continued)					
Network: Model 1	Fault Location				
Line	Stp-Wap	Stp-Wap	Sky-Spruce	Sky-Spruce	Sky-Spruce
Fault Location	15%	25%	5%	15%	25%
Fault Direction	Forward	Forward	Reverse	Reverse	Reverse
Expected Operation	Z 2	No	Z 3	Z 3	No
Actual Operation	No	No	Z 3	Z 3	No
Actual Operation (R)	No	No	Z 3	Z 3	No
Expected Op. Time	300 ms	No	600 ms	600 ms	No
Average Op. Time	No	No	602 ms	602 ms	No
Average Op. Time (R)	No	No	602 ms	601 ms	No
Detected Fault Type	No	No	ABC	ABC	No

Table IX. Relay A – special faults

Special Faults						
Event	Parallel line	SOTF	Weak infeed	Reverse dir.	Cross cntry.	Evolving flt.
Network Model	Model 3	Model 2	Model 2	Model 2	Model 2	Model 2
Protected Line	Glnc.-Flags.	Nbelt-King	Nbelt-King	Cdbay-King	Nbelt-King	Nbelt-King
Relay Location	Glen Cany.	NBelt	King	Cdbay	Nbelt	Nbelt
Fault Location	85%	99%	95%	105%	75%	75%
Fault Type	AG	ABCG	AG	AG	AG-BG	AG-BG
Expected Operation	Z2	Z1	Z2	No	Z1	Z1
Actual Operation	Z1	Z1	Z2	No	Z1	Z1
Expected Op. Time	300 ms	Inst.	300 ms	No	Inst.	Inst.
Average Op. Time	28 ms	44 ms	302 ms	No	35 ms	32 ms
Detected Fault Type	AG	ABC	AG	AG pickup	AG	ABG

Relay A operates correctly. The following can be concluded:

- Selectivity of protective relay is satisfactory
- Average tripping times were as expected for related zones
- Correct zone operation of the distance relay wasn't achieved in case of Zone 2 faults on 15% of Stp – Wap line. Zone 2 is set to cover 20% of Stp – Wap line, but relay did not operate. Relay tends to underreach due to heavy infeeds from adjacent lines at bus Stp. By compensating infeeds with appropriate relay settings, this problem can be resolved.
- Correct zone operation of the distance relay wasn't achieved in case when parallel line was out of service. Instead of operating in Zone 2, relay operates in Zone 1. The relay tends to overreach. Situation as such is expected and does not make any harm if appropriate scheme (PUTT) is applied. Relay at Sky would trip instantaneously in any case; it would receive permissive signal for faults on Sky – Stp line in Zone 2. To resolve overreaching effect for faults beyond remote bus, which is more severe case, alternative setting group should be applied to Relay A. Alternative setting group should take into account the impedance change. Alternative setting group would be activated by closing ground switches at parallel line, because such status of the switching equipment indicates that parallel line is out of service and grounded.

Transient testing of the distance relay: Relay B

Results of transient testing for standard faults are given in Tables X, XI, XII, XIII and XIV for different fault types. Table XV presents the results for special faults. Shaded fields represent situations when protective relay did not operate as expected. Average operating times are rounded to 1 ms precision.

Table X. Relay B – AG fault

AG Fault					
Network: Model 1	Fault Location				
Line	Sky-Stp	Sky-Stp	Sky-Stp	Sky-Stp	Stp-Wap
Fault Location	5%	50%	75%	95%	5%
Fault Direction	Forward	Forward	Forward	Forward	Forward
Expected Operation	Z 1	Z 1	Z 1	Z 2	Z 2
Actual Operation	Z 1	Z 1	Z 1	Z 2	Z 2
Actual Operation (R)	Z 1	Z 1	Z 1	Z 2	Z 2
Expected Op. Time	Inst.	Inst.	Inst.	300 ms	300 ms
Average Op. Time	25 ms	28 ms	35 ms	299 ms	300 ms
Average Op. Time (R)	25 ms	27 ms	38 ms	300 ms	301 ms
Detected Fault Type	AG	AG	BG	AG	AG*
AG Fault (continued)					
Network: Model 1	Fault Location				
Line	Stp-Wap	Stp-Wap	Sky-Spruce	Sky-Spruce	Sky-Spruce
Fault Location	15%	25%	5%	15%	25%
Fault Direction	Forward	Forward	Reverse	Reverse	Reverse
Expected Operation	Z 2	No	Z 3	Z 3	No
Actual Operation	No	No	Z 3	Z 3	No
Actual Operation (R)	No	No	Z 3	Z 3	No
Expected Op. Time	300 ms	No	600 ms	600 ms	No
Average Op. Time	No	No	600 ms	601 ms	No
Average Op. Time (R)	No	No	600 ms	600 ms	No
Detected Fault Type	No	No	AG	AG	No

* Relay operates correctly only for faults without R

Table XI. Relay B – BC fault

BC Fault					
Network: Model 1	Fault Location				
Line	Sky-Stp	Sky-Stp	Sky-Stp	Sky-Stp	Stp-Wap
Fault Location	5%	50%	75%	95%	5%
Fault Direction	Forward	Forward	Forward	Forward	Forward
Expected Operation	Z 1	Z 1	Z 1	Z 2	Z 2
Actual Operation	Z 1	Z 1	Z 1	Z 2	Z 2
Actual Operation (R)	Z 1	Z 1	Z 1	Z 2	Z 2
Expected Op. Time	Inst.	Inst.	Inst.	300 ms	300 ms
Average Op. Time	25 ms	26 ms	27 ms	301 ms	301 ms
Average Op. Time (R)	25 ms	26 ms	29 ms	302 ms	300 ms
Detected Fault Type	BC	BCG	BC	BC	BG

Table XI. (continued)

BC Fault (continued)					
Network: Model 1	Fault Location				
Line	Stp-Wap	Stp-Wap	Sky-Spruce	Sky-Spruce	Sky-Spruce
Fault Location	15%	25%	5%	15%	25%
Fault Direction	Forward	Forward	Reverse	Reverse	Reverse
Expected Operation	Z 2	No	Z 3	Z 3	No
Actual Operation	No	No	Z 3	Z 3	No
Actual Operation (R)	No	No	Z 3	Z 3	No
Expected Op. Time	300 ms	No	600 ms	600 ms	No
Average Op. Time	No	No	600 ms	601 ms	No
Average Op. Time (R)	No	No	599 ms	600 ms	No
Detected Fault Type	No	No	BG	BC	No

Table XII. Relay B – BCG fault

BCG Fault					
Network: Model 1	Fault Location				
Line	Sky-Stp	Sky-Stp	Sky-Stp	Sky-Stp	Stp-Wap
Fault Location	5%	50%	75%	95%	5%
Fault Direction	Forward	Forward	Forward	Forward	Forward
Expected Operation	Z 1	Z 1	Z 1	Z 2	Z 2
Actual Operation	Z 1	Z 1	Z 1	Z 2	Z 2
Actual Operation (R)	Z 1	Z 1	Z 1	Z 2	Z 2
Expected Op. Time	Inst.	Inst.	Inst.	300 ms	300 ms
Average Op. Time	27 ms	29 ms	30 ms	300 ms	302 ms
Average Op. Time (R)	28 ms	29 ms	29 ms	299 ms	300 ms
Detected Fault Type	BC	BCG	BCG	BCG	BCG*
BCG Fault (continued)					
Network: Model 1	Fault Location				
Line	Stp-Wap	Stp-Wap	Sky-Spruce	Sky-Spruce	Sky-Spruce
Fault Location	15%	25%	5%	15%	25%
Fault Direction	Forward	Forward	Reverse	Reverse	Reverse
Expected Operation	Z 2	No	Z 3	Z 3	No
Actual Operation	No	No	Z 3	No	No
Actual Operation (R)	No	No	Z 3	No	No
Expected Op. Time	300 ms	No	600 ms	600 ms	No
Average Op. Time	No	No	600 ms	No	No
Average Op. Time (R)	No	No	601 ms	No	No
Detected Fault Type	No	No	BCG	No	No

* Relay operates correctly only for faults without R

Table XIII. Relay B – ABC fault

ABC Fault					
Network: Model 1	Fault Location				
Line	Sky-Stp	Sky-Stp	Sky-Stp	Sky-Stp	Stp-Wap
Fault Location	5%	50%	75%	95%	5%
Fault Direction	Forward	Forward	Forward	Forward	Forward
Expected Operation	Z 1	Z 1	Z 1	Z 2	Z 2
Actual Operation	Z 1	Z 1	Z 1	Z 2	Z 2
Actual Operation (R)	Z 1	Z 1	Z 1	Z 2	Z 2
Expected Op. Time	Inst.	Inst.	Inst.	300 ms	300 ms
Average Op. Time	21 ms	21 ms	26 ms	300 ms	300 ms
Average Op. Time (R)	22 ms	24 ms	27 ms	301 ms	301 ms
Detected Fault Type	ABC	ABC	ABC	ABC	ABC
ABC Fault (continued)					
Network: Model 1	Fault Location				
Line	Stp-Wap	Stp-Wap	Sky-Spruce	Sky-Spruce	Sky-Spruce
Fault Location	15%	25%	5%	15%	25%
Fault Direction	Forward	Forward	Reverse	Reverse	Reverse
Expected Operation	Z 2	No	Z 3	Z 3	No
Actual Operation	No	No	Z 3	Z 3	No
Actual Operation (R)	No	No	Z 3	Z 3	No
Expected Op. Time	300 ms	No	600 ms	600 ms	No
Average Op. Time	No	No	600 ms	600 ms	No
Average Op. Time (R)	No	No	599 ms	601 ms	No
Detected Fault Type	No	No	AB	ABC	No

Table XIV. Relay B – ABCG fault

ABCG Fault					
Network: Model 1	Fault Location				
Line	Sky-Stp	Sky-Stp	Sky-Stp	Sky-Stp	Stp-Wap
Fault Location	5%	50%	75%	95%	5%
Fault Direction	Forward	Forward	Forward	Forward	Forward
Expected Operation	Z 1	Z 1	Z 1	Z 2	Z 2
Actual Operation	Z 1	Z 1	Z 1	Z 2	Z 2
Actual Operation (R)	Z 1	Z 1	Z 1	Z 2	Z 2
Expected Op. Time	Inst.	Inst.	Inst.	300 ms	300 ms
Average Op. Time	23 ms	25 ms	29 ms	299 ms	300 ms
Average Op. Time (R)	24 ms	26 ms	28 ms	300 ms	300 ms
Detected Fault Type	ABC	ABC	ABC	ABC	ABC

Table XIV. (continued)

ABCG Fault (continued)					
Network: Model 1	Fault Location				
Line	Stp-Wap	Stp-Wap	Sky-Spruce	Sky-Spruce	Sky-Spruce
Fault Location	15%	25%	5%	15%	25%
Fault Direction	Forward	Forward	Reverse	Reverse	Reverse
Expected Operation	Z 2	No	Z 3	Z 3	No
Actual Operation	No	No	Z 3	Z 3	No
Actual Operation (R)	No	No	Z 3	Z 3	No
Expected Op. Time	300 ms	No	600 ms	600 ms	No
Average Op. Time	No	No	600 ms	601 ms	No
Average Op. Time (R)	No	No	600 ms	601 ms	No
Detected Fault Type	No	No	ABC	AB	No

Table XV. Relay B – special faults

Special Faults						
Event	Parallel line	SOTF	Weak infeed	Reverse dir.	Cross cntry.	Evolving flt.
Network Model	Model 3	Model 2	Model 2	Model 2	Model 2	Model 2
Protected Line	Glnc.-Flags.	Nbelt-King	Nbelt-King	Cdbay-King	Nbelt-King	Nbelt-King
Relay Location	Glen Cany.	NBelt	King	Cdbay	Nbelt	Nbelt
Fault Location	85%	99%	95%	105%	75%	75%
Fault Type	AG	ABCG	AG	AG	AG-BG	AG-BG
Expected Operation	Z2	Z1	Z2	No	Z1	Z1
Actual Operation	Z1	Z1	Z2	No	Z1	Z1
Expected Op. Time	300 ms	Inst.	300 ms	No	Inst.	Inst.
Average Op. Time	26 ms	28 ms	301 ms	No	27 ms	28 ms
Detected Fault Type	AG	ABC	AG	No	BG	ABG

Relay B, does not operate correctly. The following can be concluded:

- Zone selectivity of protective relay is satisfactory in most of the cases
- Fault determination was not correct in unacceptably large number of tests.
- Average tripping times were as expected for related zones.
- Underreaching because of the infeeds and overreaching when parallel line is out of service are applicable for this relay. Comments are the same as for Relay A.

Transient testing of the directional overcurrent/ground fault relay: Relay C

Results of transient testing for standard faults are given in Tables XVI, XVII, XVIII, XIX and XX for different fault types. Table XI presents the results for special faults. Shaded fields represent situations when protective relay did not operate as expected. Average operating times are rounded to 1 ms precision.

Table XVI. Relay C – AG fault

AG Fault					
Network: Model 1	Fault Location				
Line	Sky-Stp	Sky-Stp	Sky-Stp	Stp-Wap	Sky-Spruce
Fault Location	5%	50%	95%	5%	5%
Fault Direction	Forward	Forward	Forward	Forward	Reverse
Expected Operation	Forward	Forward	Forward	Forward	No
Actual Operation	Forward	Forward	Forward	Forward	No
Actual Operation (R)	Forward	Forward	Forward	Forward	No
Expected Op. Time	Inst.	Inst.	Inst.	Inst.	No
Average Op. Time	19 ms	19 ms	22 ms	23 ms	No
Average Op. Time (R)	20 ms	21 ms	24 ms	25 ms	No
Detected Fault Type	AG	AG	AG	AG	No

Table XVII. Relay C – BC fault

BC Fault					
Network: Model 1	Fault Location				
Line	Sky-Stp	Sky-Stp	Sky-Stp	Stp-Wap	Sky-Spruce
Fault Location	5%	50%	95%	5%	5%
Fault Direction	Forward	Forward	Forward	Forward	Reverse
Expected Operation	Forward	Forward	Forward	Forward	No
Actual Operation	Forward	Forward	Forward	Forward	No
Actual Operation (R)	Forward	Forward	Forward	Forward	No
Expected Op. Time	Inst.	Inst.	Inst.	Inst.	No
Average Op. Time	20 ms	22 ms	23 ms	23 ms	No
Average Op. Time (R)	21 ms	22 ms	22 ms	24 ms	No
Detected Fault Type	BC	BC	BC	BC	No

Table XVIII. Relay C – BCG fault

BCG Fault					
Network: Model 1	Fault Location				
Line	Sky-Stp	Sky-Stp	Sky-Stp	Stp-Wap	Sky-Spruce
Fault Location	5%	50%	95%	5%	5%
Fault Direction	Forward	Forward	Forward	Forward	Reverse
Expected Operation	Forward	Forward	Forward	Forward	No
Actual Operation	Forward	Forward	Forward	Forward	No
Actual Operation (R)	Forward	Forward	Forward	Forward	No
Expected Op. Time	Inst.	Inst.	Inst.	Inst.	No
Average Op. Time	23 ms	23 ms	25 ms	26 ms	No
Average Op. Time (R)	23 ms	24 ms	24 ms	27 ms	No
Detected Fault Type	BCG	BCG	BCG	BCG	No

Table XIX. Relay C – ABC fault

ABC Fault					
Network: Model 1	Fault Location				
Line	Sky-Stp	Sky-Stp	Sky-Stp	Stp-Wap	Sky-Spruce
Fault Location	5%	50%	95%	5%	5%
Fault Direction	Forward	Forward	Forward	Forward	Reverse
Expected Operation	Forward	Forward	Forward	Forward	No
Actual Operation	Forward	Forward	Forward	Forward	No
Actual Operation (R)	Forward	Forward	Forward	Forward	No
Expected Op. Time	Inst.	Inst.	Inst.	Inst.	No
Average Op. Time	18 ms	20 ms	19 ms	22 ms	No
Average Op. Time (R)	19 ms	21 ms	21 ms	22 ms	No
Detected Fault Type	ABC	ABC	ABC	ABC	No

Table XX. Relay C – ABCG fault

ABCG Fault					
Network: Model 1	Fault Location				
Line	Sky-Stp	Sky-Stp	Sky-Stp	Stp-Wap	Sky-Spruce
Fault Location	5%	50%	95%	5%	5%
Fault Direction	Forward	Forward	Forward	Forward	Reverse
Expected Operation	Forward	Forward	Forward	Forward	No
Actual Operation	Forward	Forward	Forward	Forward	No
Actual Operation (R)	Forward	Forward	Forward	Forward	No
Expected Op. Time	Inst.	Inst.	Inst.	Inst.	No
Average Op. Time	21 ms	21 ms	22 ms	24 ms	No
Average Op. Time (R)	22 ms	23 ms	25 ms	26 ms	No
Detected Fault Type	ABC	ABC	ABC	ABC	No

Table XXI. Relay C – special faults

Special Faults						
Event	Parallel line	SOTF	Weak infeed	Reverse dir.	Cross cntry.	Evolving flt.
Network Model	Model 3	Model 2	Model 2	Model 2	Model 2	Model 2
Protected Line	Glnc.-Flags.	Nbelt-King	Nbelt-King	Cdbay-King	Nbelt-King	Nbelt-King
Relay Location	Glen Cany.	NBelt	King	Cdbay	Nbelt	Nbelt
Fault Location	85%	99%	95%	105%	75%	75%
Fault Direction	Forward	Forward	Forward	Forward	Forward	Forward
Fault Type	AG	ABCG	AG	AG	AG-BG	AG-BG
Expected Operation	Forward	Forward	Forward	No	Forward	Forward
Actual Operation	Forward	Forward	Forward	No	Forward	Forward
Expected Op. Time	Inst.	Inst.	Inst.	No	Inst.	Inst.
Average Op. Time	22 ms	26 ms	28 ms	No	28 ms	27 ms
Detected Fault Type	AG	ABC	AG	AG pickup	AG	ABG

Relay C operates correctly. The following can be concluded:

- Selectivity of protective relay is satisfactory in all cases
- Average tripping times were as expected

Transient testing of the directional overcurrent/ground fault relay: Relay D

Results of transient testing for standard faults are given in Tables XXII, XXIII, XXIV, XXV and XXVI for different fault types. Table XXVII presents the results for special faults. Shaded fields represent situations when protective relay did not operate as expected. Average operating times are rounded to 1 ms precision.

Table XXII. Relay D – AG fault

AG Fault					
Network: Model 1	Fault Location				
Line	Sky-Stp	Sky-Stp	Sky-Stp	Stp-Wap	Sky-Spruce
Fault Location	5%	50%	95%	5%	5%
Fault Direction	Forward	Forward	Forward	Forward	Reverse
Expected Operation	Forward	Forward	Forward	Forward	No
Actual Operation	Forward	Forward	Forward	Forward	No
Actual Operation (R)	Forward	Forward	Forward	Forward	No
Expected Op. Time	Inst.	Inst.	Inst.	Inst.	No
Average Op. Time	18 ms	20 ms	21 ms	22 ms	No
Average Op. Time (R)	18 ms	21 ms	22 ms	23 ms	No
Detected Fault Type	AG	AG	AG	AG	No

Table XXIII. Relay D – BC fault

BC Fault					
Network: Model 1	Fault Location				
Line	Sky-Stp	Sky-Stp	Sky-Stp	Stp-Wap	Sky-Spruce
Fault Location	5%	50%	95%	5%	5%
Fault Direction	Forward	Forward	Forward	Forward	Reverse
Expected Operation	Forward	Forward	Forward	Forward	No
Actual Operation	Forward	Forward	Forward	Forward	No
Actual Operation (R)	Forward	Forward	Forward	Forward	No
Expected Op. Time	Inst.	Inst.	Inst.	Inst.	No
Average Op. Time	19 ms	22 ms	22 ms	24 ms	No
Average Op. Time (R)	19 ms	23 ms	22 ms	25 ms	No
Detected Fault Type	BC	BC	BC	BC	No

Table XXIV. Relay D – BCG fault

BCG Fault					
Network: Model 1	Fault Location				
Line	Sky-Stp	Sky-Stp	Sky-Stp	Stp-Wap	Sky-Spruce
Fault Location	5%	50%	95%	5%	5%
Fault Direction	Forward	Forward	Forward	Forward	Reverse
Expected Operation	Forward	Forward	Forward	Forward	No
Actual Operation	Forward	Forward	Forward	Forward	No
Actual Operation (R)	Forward	Forward	Forward	Forward	No
Expected Op. Time	Inst.	Inst.	Inst.	Inst.	No
Average Op. Time	21 ms	22 ms	23 ms	22 ms	No
Average Op. Time (R)	21 ms	21 ms	24 ms	24 ms	No
Detected Fault Type	BCG	BCG	BCG	BCG	No

Table XXV. Relay D – ABC fault

ABC Fault					
Network: Model 1	Fault Location				
Line	Sky-Stp	Sky-Stp	Sky-Stp	Stp-Wap	Sky-Spruce
Fault Location	5%	50%	95%	5%	5%
Fault Direction	Forward	Forward	Forward	Forward	Reverse
Expected Operation	Forward	Forward	Forward	Forward	No
Actual Operation	Forward	Forward	Forward	Forward	No
Actual Operation (R)	Forward	Forward	Forward	Forward	No
Expected Op. Time	Inst.	Inst.	Inst.	Inst.	No
Average Op. Time	18 ms	19 ms	19 ms	20 ms	No
Average Op. Time (R)	18 ms	19 ms	21 ms	21 ms	No
Detected Fault Type	ABC	ABC	ABC	ABC	No

Table XXVI. Relay D – ABCG fault

ABCG Fault					
Network: Model 1	Fault Location				
Line	Sky-Stp	Sky-Stp	Sky-Stp	Stp-Wap	Sky-Spruce
Fault Location	5%	50%	95%	5%	5%
Fault Direction	Forward	Forward	Forward	Forward	Reverse
Expected Operation	Forward	Forward	Forward	Forward	No
Actual Operation	Forward	Forward	Forward	Forward	No
Actual Operation (R)	Forward	Forward	Forward	Forward	No
Expected Op. Time	Inst.	Inst.	Inst.	Inst.	No
Average Op. Time	19 ms	20 ms	21 ms	23 ms	No
Average Op. Time (R)	21 ms	22 ms	22 ms	23 ms	No
Detected Fault Type	ABC	ABC	ABC	ABC	No

Table XXVII. Relay D – special faults

Special Faults						
Event	Parallel line	SOTF	Weak infeed	Reverse dir.	Cross cntry.	Evolving flt.
Network Model	Model 3	Model 2	Model 2	Model 2	Model 2	Model 2
Protected Line	Glnc.-Flags.	Nbelt-King	Nbelt-King	Cdbay-King	Nbelt-King	Nbelt-King
Relay Location	Glen Cany.	NBelt	King	Cdbay	Nbelt	Nbelt
Fault Location	85%	99%	95%	105%	75%	75%
Fault Direction	Forward	Forward	Forward	Forward	Forward	Forward
Fault Type	AG	ABCG	AG	AG	AG-BG	AG-BG
Expected Operation	Forward	Forward	Forward	No	Forward	Forward
Actual Operation	Forward	Forward	Forward	No	Forward	Forward
Expected Op. Time	Inst.	Inst.	Inst.	No	Inst.	Inst.
Average Op. Time	22 ms	24 ms	24 ms	No	27 ms	26 ms
Detected Fault Type	AG	ABC	AG	AG pickup	AG	ABG

Relay D operates correctly. The following can be concluded:

- Selectivity of protective relay is satisfactory in all cases
- Average tripping times were as expected

Comparisons of Hardware Tools and Software Packages

To apply new methodology in transient testing, and check selectivity and tripping time of protective relays, combination of hardware tools and software packages was used. New testing environment and simulation scenarios were utilized. Relays were successfully tested with large number of scenario cases, and conclusions about their operation were derived. Such an extensive use of hardware and software tools provides good opportunity for their comparison.

Comparison: Hardware Option 1 and Hardware Option 2

Both devices can be used in transient simulations. Hardware Option 2 - digital simulator has higher output power then the Hardware Option 1 – standard test set. In transient simulations, digital simulator is capable of replaying longer signals at higher sampling frequencies.

Length of the signal generated by Standard Test Set may not become critical in most of the transient test applications. With relatively high sampling frequency, for example 10 kHz, standard test set can replay signals of 4 to 5 seconds. Usually, with a signal of a few seconds, pre fault and fault condition can be generated to analyze behavior of protective relays quite comprehensively. However, for some complex events, longer signal replay may be required. Digital simulator practically has no limitations when simulating an event.

Speed of waveform replaying may become an issue in automated testing with a large number of events. In such cases, use of standard test set in automated steady state, dynamic or transient testing may become time consuming. Depending on the sampling frequency and signal length, replaying a single test may take up to several minutes. With digital simulator, response is almost instantaneous and it doesn’t take more then a couple of seconds to perform a single test.

For comprehensive testing of stand alone protective devices, provision for checking digital inputs and outputs may be necessary. Digital inputs and outputs of test cabinet are connected to digital terminals of protective relays, to test operation of relaying schemes, alarm, control and SCADA functions. Operation can be monitored on a protective device itself and cross-checked using PC software package such as Package 4. Standard test set provides basic set of I/O terminals for tripping signals and timers. Digital simulator has 37 contacts for digital inputs and 37 contacts for digital outputs, sufficient to test almost any configuration of input and output terminals applied in protective relays.

For site testing and maintenance of protective equipment, it is convenient to use test equipment of compact dimensions that can be easily moved inside the substation’s control room and from one substation to another. For its compact design and single-phase power supply, standard test set is more practical tool then digital simulator.

In conclusion, standard test set, together with Package 4 is a good tool for performing routine test aimed at the maintenance of protective relays and troubleshooting protective relay misoperation in the field. Various types of automated steady state, dynamic and transient tests can be performed. On the other hand, the digital simulator is an excellent testing tool in evaluating new protective devices as well as in analyzing behavior of protective relays during complex events.

In summary, important characteristics of standard test set (Hardware Option 1) and digital simulator (Hardware Option 2) and compliance to requirements are presented in Table XXVIII.

Table XXVIII. Requirements: hardware options

Requirement		Hardware Option 1	Hardware Option 1 and Package 4	Hardware Option 2
Simulator hardware available "off shelf"		Yes	Yes	Some components are custom design
Simulator software available "off shelf"		Yes	Yes	Yes
Operated through PC		N/A	Yes	Yes
Elaborate GUI		N/A	Yes	Yes
Interaction with external EMTP supported		N/A	Yes	Yes
Open loop mode		N/A	Yes	Yes
Closed loop mode		N/A	No	Yes
Hybrid closed loop mode		N/A	Yes	Yes
Application software supports vertical and horizontal portability		N/A	Yes	Yes
Automated testing process		N/A	Limited	Yes
Result analysis		N/A	No	Yes
Generating pre-fault	$i = 0, v = 0$	Yes	Yes	Yes
	$i = 0, v \neq 0$	No	Yes	Yes
	$i \neq 0, v \neq 0$	No	Yes	Yes
Smooth transition between pre-fault, fault and post-fault values		N/A	Yes	Yes
Resolution		N/A	13 bits	16 bits
Current output		30 A, 150 VA	30 A, 150 VA	180 A, 1550 W
Sampling frequency		N/A	50 μH – 20 kHz	5 Hz – 40 kHz
Speed of simulations		N/A	Slow	Fast
Compact design		Yes	Yes	No
Power supply		1 – phase standard outlet	1 – phase standard outlet	3 – phase

Comparison: Package 1, Package 2 and Package 3

Package 1, Package 2 and Package 3 are used for network modeling and waveform simulations. Package 1 and Package 2 are software packages for network modeling and generating transient waveforms. They contain standard options to define simulation environment (sampling frequency, global network parameters, etc.). Results are obtained in ASCII format transferable to COMTRADE and suitable for further processing in other software packages. Speed of simulations is not critical for smaller networks. These programs are transient programs and they are not meant to be used on large-scale network models. Smaller portion of a power network is modeled in details, including network equivalents, and transient programs are supposed to run with such networks. For larger networks, simulations are slower. Speed of simulation decreases more rapidly with Package 2 then with Package 1. On the other hand, it is observed that Package 2 has more options for network components representation, such as library of relay components. Some simple protective relaying schemes can be created in Package 2, whereas Package 1 doesn’t provide such an option.

Package 3 is software designed to support short circuit studies and setting calculations for protective relays. Network models are created in Package 3 using database editor. Created database is a repository of network and protection data needed for analysis and record-keeping that may be useful when maintaining the protection. Package 3 can simulate traditional and user defined faults, as well as most of the types of network contingencies. Package 3 contains a large library of protective relay models. A network model can be created containing relay models and their settings assigned to all circuit breakers in a given network. A dynamic simulation can be performed, and waveforms could be recorded at assumed location of the relay under test. Those waveforms can be replayed to a real relay to evaluate its behavior under dynamic conditions. Simulation results are phasors of the pre-fault and fault currents and voltages. To create a COMTRADE file, two macros are available in Package 3. Waveforms in COMTRADE format can be replayed to an actual relay using compatible software such as Package 4. Since Package 3 doesn’t calculate transients, but phasor values of currents and voltages, speed of simulations is fast for large networks.

Short comparison of some characteristics of Package 1, Package 2 and Package 3 is given in Table XXIX.

Table XXIX. Requirements: software packages

Requirement	Package 1	Package 2	Package 3
Simplified and easy creation of data	Yes	Yes	Yes
Batch processing of fault simulations	Yes	No	No
Automated creating test results	Yes	Yes	Interactive procedure
Graphical representation of results and waveforms	Yes	Yes	Yes
Automated graphical representation of results and waveforms	No	Yes	No
Signal processing and editing	No	No	No
Relay elements	No	Yes	Yes
Relay models	No	No	Yes
Protection schemes	No	No	Yes
Creates phasors	Yes	Yes	Yes
Creates transients	Yes	Yes	No
Speed of simulation	Good	Satisfactory	Very good
Compatible with COMTRADE	Yes	Yes	Yes

Package 4 - software for automated testing

Package 4 is used in testing protective relays. It is capable of replaying waveform files that originate from variety of sources. The data format is the COMTRADE standard enabling the use of data captured by digital fault recorders. Also, it can replay the waveforms created in other software packages compatible with COMTRADE, such as Package 1, 2 and 3. Package 4 can also generate the waveforms using its own tools. It enables generation of the waveforms with desired harmonic and DC content. It contains the set of useful tools for signal processing, waveform editing, etc. The software automatically captures, processes and stores the relay response. Automated test reports can also be generated through Package 4. The above features make the software an excellent tool in testing practically all types of line relays: distance relays, overcurrent/ground fault relay. It is also suitable for differential relays testing for its capability for multi-terminal testing and creating desired harmonic content to check the 2nd and 5th harmonic restraint. Phasor testing could also be conducted through Package 4. Main features and benefits provided with Package 4 are given in Table XXX.

Table XXX. Main features of Package 4

Capability	Benefit
Testing relays using waveforms produced by Package 1, Package 2, Package 3 and other packages compatible with COMTRADE	Allows extensive relay evaluation for a large number of fault and operating conditions, utilizing advantages of different simulation software packages
Testing relays using field recorded waveforms captured by DFR’s	Provides evaluation of protective relay operation for waveforms recorded in the field, which may be very useful for troubleshooting relay misoperations
Automated testing process when large number of tests are performed	Makes the application test practical and affordable, a large number of tests can be performed without operator’s involvement
Creating analysis reports for relays being tested	Performs analysis of relay responses and related circuit breaker operations allows automated creation of test reports
Graphical representation of test results and test waveforms	Able to view the test conditions and results allowing for better understanding the relay performance under test
Signal processing and editing the waveform files before the tests are performed	Capable to alter waveforms and other test conditions
Drivers for various supported I/O hardware	Able to use different test sets and digital simulators through a single software platform

Conclusion

Application of the new methodology was demonstrated. Test results were obtained by using new methodology in transient testing. Two distance relays and two directional overcurrent relays were subject to tests. Scenarios and procedures that include standard faults and other fault events were successfully defined, modeled and used. New testing environment was created by combining two hardware tools for generating signals and three software packages for network modeling and simulations.

Software platform was used for relay testing. Relays were tested for large number of cases with repetitive tests for different fault inception angles. Sensitivity of protective relays and average tripping time were checked according to the new methodology. For each relay under test, it was concluded if it satisfies testing criteria. Out of four relays that were tested, three of them passed the tests and one of them failed because of unselective operation. This indicates that the new methodology, when utilized in evaluating relays, provides very useful results. Comparison of hardware and software components used to demonstrate the new methodology was given.

CHAPTER VI

CONCLUSION

Summary

Standard practice of relay testing in majority of electric utilities is to use conventional relay test sets to perform testing of protective relays by applying steady state fault currents and voltages. Such concept is widely applied in testing all types of protective relays: electromechanical, solid state and microprocessor relays.

Modern relays are mostly microprocessor-based. They use advanced processing of transient signals to extract steady state phasors and to reach the trip decision. In the real power system protective relays are exposed to transients. The latest trend in testing protective relays is to model power systems and faults in electromagnetic transient programs and to use digital simulators to apply the signals to the relay under test.

Standard approach to check the characteristic and tripping time of protective relays by applying phasors of currents and voltages is still the most common approach in testing numerical relays. Random nature of numerical relay's response cannot be analyzed in classical phasor tests. Transient tests need to be used to test selectivity and average tripping time of numerical relays. Although proved necessary, transient tests are still not widely used in relay testing practice. When used, they are usually conducted randomly and intuitively to achieve specific testing objectives. Methodological approach in transient testing is not yet established.

To meet the new requirements for advanced relay testing, new methodology was defined in this thesis to provide theoretical explanations why and when the advanced techniques in transient testing should be applied, to propose procedures how the transient tests should be conducted and what criteria for evaluating relays should be considered in transient tests.

Test procedures and scenarios proposed for the new methodology enabled detailed analysis of protective relay operation in various situations and operating conditions. Scenarios for testing protective relays and checking their functions were defined. The new methodology also defined how the test scenarios should be conducted and practically implemented. Test cases and scenarios were conducted for different fault inception angles and replayed in repetitive tests to check the random response of a relay under test. The main goal of transient testing, to test selectivity and average tripping time, was achieved successfully with the new methodology.

It was shown that different test equipment hardware need to be used to implement the new methodology. The new methodology should be applied with compact test sets in troubleshooting relay misoperations directly in the field. The new methodology should also be applied with high performance digital simulator in the laboratory for the purpose of testing new protective relays before procurement. It was demonstrated how to apply the new methodology with compact test sets and digital simulators.

It was shown that various test scenarios need to be applied to test selectivity and average tripping time of protective relays in transient tests. Test cases and scenarios were modeled and replayed by using available software packages. Representative network models were created in an attempt to cover variety of network conditions for a relay under test. Network models were defined in different modeling and simulation software packages, where each software package was used for specific applications.

Four types of microprocessor relays were subject to tests to demonstrate implementation of the new methodology. The results indicated the usefulness of the new methodology.

Contribution

In today's practice of relay testing, there is no methodology defined for transient testing of numerical relays. The main contribution of this thesis is that a new methodology is established. By defining and applying the new methodology, the following contributions were achieved:

- Defining purpose of transient testing: It was shown theoretically why the transient tests are necessary and when the transient tests are needed.

- Defining test procedures: It was proposed how the transient tests should be defined and conducted to check selectivity and average tripping time of transmission line protective relays.
- Using different test equipment hardware: It was proven that advanced testing could be conducted with digital simulators of high output power in the laboratory, as well as with compact test sets suitable for field application.
- Using variety of network models: It was demonstrated that relays could be tested on a large number of scenarios using a set of representative models.
- Using different modeling and simulation tools: By applying modeling and simulation tools in relay testing, it was shown how the advantages of different software tools can be utilized to achieve best possible conditions for testing applications.
- Testing different types of microprocessor relays: By testing various types of microprocessor relays, it was demonstrated how the new methodology can be practically implemented with modern numerical transmission line relays.

It is expected that this research and development effort contributes the following to the area of power systems engineering:

- Extensive utilization of the modeling and simulation technology
- The relay evaluation and testing in the future may be made more detailed and precise allowing for further improvements in the performance and reliability of protective relays and relaying systems

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