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DYNA-TEST SIMULATOR: PROTECTIVE RELAYING TEACHING TOOL

M. Kezunovic, Senior Member, IEEE
Texas A&M University
College Station, TX 77843-3128

Abstract - This paper is concerned with teaching aspects in the protective relaying field. Present practice in this field is to teach fault analysis and protection methods based on the steady-state concept of unbalanced power systems. Teaching of the protection relay design issues requires analysis of the fault transients associated with power apparatus and instrument transformers. Appropriate tools to simulate dynamic behavior of a power system are needed in this case. A Dynamic Testing (DYNA- TEST) Simulator concept, to be used as a teaching tool, is proposed in this paper.

INTRODUCTION

Some new developments in the area of digital protection relay design and fault transients simulation have posed exciting challenges to the Power Program educators. The traditional field of protective relaying may now be taught in a more attractive way by exploring some new theoretical and advanced teaching tool concepts.

Even though some basic methods and teaching tools for protective relaying have been known for several decades, the main implementation technologies were not giving a wide opportunity for major advances in the protective relaying educational area. Very limited capabilities in obtaining an efficient and inexpensive way of simulating fault transients, as well as limitations in the relay design simulations have narrowed down the options for teaching topics and methods. As a result, the Transient Network Analyzers were not widely used to teach the fault transients and not very many schools have ventured into teaching relay design topics for electromechanical and solid state relays. The traditional way of teaching protective relaying was to focus on the steady-state unbalanced power system considerations including short-circuit and relay setting coordination studies [1-5]. The major emphasis was on the relaying methods [1,3,4], while relay design issues were mostly discussed from the application standpoint, addressing different schemes available from different manufacturers [5-8].

The major developments introduced by application of digital computer technology to the design of digital relays, and simulation of fast electromagnetic transients had opened the new teaching possibilities [10,11].

The field of computer relaying has been characterized by introduction of a number of different digital algorithms for signal processing required for implementation of various relays [10,12,13]. The relay design issues have become much more attractive and understandable as the microprocessors become the major technology base [10]. Availability of well presented textbook material on the subject has provided an interesting opportunity for teaching the new topics in relaying such as computer relaying algorithms and designs [10,12,14].

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Another important area of development is application of digital computers to electromagnetic transient modeling [11]. This has led to the quite efficient and flexible way of simulating fault transients using standard minicomputer facilities [15,16]. Digital simulation of the relaying system was also made possible by introducing digital models of relays and related equipment [17,18].

These developments suggested that some powerful teaching tools may be implemented using mentioned approaches. This paper gives discussion of a digital DYNA-TEST Simulator concept that may be used as an inexpensive and very flexible teaching tool for protective relaying. The protective relaying study requirements are discussed first to indicate the expected simulator characteristics and benefits. The DYNA-TEST Simulator environment is described next. The last section provides examples of using the simulator concept to teach some relay algorithm design issues as they apply to transmission line distance relaying.

PROTECTIVE RELAYING STUDY REQUIREMENTS

The following discussion points out the major differences between the steady-state and the transient analysis of the fault phenomena in a power system. Different teaching tools requirements for the two approaches are also indicated.

Phasor Representation of The Fault Phenomena

The most fundamental approach to protective relaying study is to teach first the unbalanced power system analysis using symmetrical components. This has been a classical topic of almost any introductory course on protective relaying. Availability of a number of nicely written textbooks have facilitated the teaching process [1,2,4]. Some of the recent textbooks even provide, as a supplement, the problems handbook with personal computer software for calculation of symmetrical component quantities [19].

Another logical extension of the unbalanced system analysis is a study of short circuit quantities related to different types of faults. This subject is also well covered by the existing textbooks [2,4,20], and several computer programs are available to perform the required calculations. It is important that this issue is well understood by the students since it represents a basis for the relay setting coordination study. Some well documented computer programs for the relay setting coordination study have lately become available [21].

It may be concluded that fault studies based on the phasor representation are sufficient introductory material to teach the basic protective relaying methods and the art of implementing different relaying schemes. A number of mentioned textbooks are excellent teaching material for this subject providing a range of different levels of details regarding the treatment of relaying application problems [1,4,22].

Transient Analysis of Faults and Relay Designs

This subject area has not been traditionally a topic of the university courses on protective relaying. Implementation of computer-based relays and simulators have provided the necessary tools to introduce these topics in advanced university courses on protective relaying.

One interesting subject is the analysis of the fast electromagnetic transients of the power system. This issue becomes crucial when computer relaying algorithm and design topics are taught. Transients associated with both system disturbances and faults should be understood in order to appreciate performance requirement of different signal processing algorithms for relaying functions. An Electromagnetic Transient Program (EMTP) is quite capable of reproducing accurate transients for different power systems. Availability of these programs suggests that an inexpensive and extensively documented EMTP may be used for teaching purposes [23,24]. It should be noted that this program was not designed to be used as a teaching tool for protective relaying, and hence, several extensions may be required for teaching the advanced protective relaying topics. A definite improvement is needed in the user interface area which requires more efficient methods for setting the study cases and interpreting the results [25,26]. Another area of concern is EMTP's capability to represent instrument transformer transients in sufficient detail required for protective relaying studies. Digital models to facilitate these enhancements and some related software have been developed to simulate the response of relaying transformers quite accurately [15,17,27,28]. Further EMTP enhancements are required for automatic reclosing sequences [29], and circuit breaker operations [30]. Even though one can stretch the imagination as to what the EMTP enhancements may possibly be used for teaching purposes, the present version of the EMTP, readily available at low cost, is an acceptable teaching tool for most of the basic protective relaying problems.

Another exciting area is a study of the recorded fault data obtained from the actual faults in a power system. The use of this data to study some of the relaying situations, that may not be possible to simulate, can be considered as a benefit of this method. A typical example is the study of High Impedance Faults Detection Methods for distribution system applications [31]. An exposure of the students to the tools available to analyze these waveforms is quite justified since all of the facilities are readily available. Some recent efforts within the IEEE Power Engineering Society Relaying Committee are concentrated on standardization of the output formats of the recorded fault data for file exchange purposes. This would enable anyone interested to obtain standardized files produced by digital recorders, or even produced by an EMTP.

Finally, the most complex and intriguing teaching area is simulation and testing of the entire relaying system. This includes simulation of the power system signals, instrument tranformers, and relays. Some efforts in simulating these systems have been undertaken in the past [17,18,32], but the software packages are not readily available. However, some of these programs may be generated during an advanced protective relaying course as design projects carried out by the students.

DYNA-TEST SIMULATOR CONCEPT

The DYNA-TEST Simulator can be implemented using almost any common mainframe computer. The required supplemental hardware and software is readily available and may be purchased at moderate cost. However, some advanced features may require a more expensive environment based around a dedicated computer workstation configuration. On the other hand, a quite inexpensive environment may be implemented using a personal computer, but in this case some performance limitations must be recognized. The most attractive approach is to develop some of the required hardware and software through different project activities undertaken by the students enrolled in the protective relaying courses.

The following is a description of the most advanced DYNA-TEST Simulator environment that is based on a dedicated computer workstation (COW) configuration. It should be noted that such a configuration is not yet operational at Texas A&M University, but a number of the features required have been developed. This section points out how different features developed independently may be combined and used as a very powerful protective relaying teaching tool.

DYNA-TEST Simulator Software

The DYNA-TEST Simulator software functional block diagram is given in Figure 1. As it may be observed, a number of simulation configurations are possible. The simplest simulation is associated with analysis of the power system disturbance and fault transients. In that case only an EMTP may be used [23,24]. This is indicated in Figure 1 by the block sequence (1),(2),(3). A number of different levels of sophistication are possible even at this stage. The first issue is how detailed one wants to be in representing the fault transients. If the goal is to teach instrument transformer transient response problems, then a special purpose program needs to be developed [27,28]. The same is true if some automatic reclosing sequences and breaker operation are to be included [29,30]. Another level of sophistication may be added to the EMTP output file processing. Besides the standard output files for plotting and CRT displays, one can envision a number of complex graphic terminal displays. These may include one-line diagram of a power system together with the tables and plots associated with power system fault parameters and transients. In this case special attention should be paid to the design of the user interface software. This software is a major enhancement needed in the existing EMTP packages, if this environment is to be used as a teaching tool [25,26]. A similar environment may be implemented for analysis of the field recorded fault transients. In this case the block sequence (1),(4),(5) should be used, as indicated in Figure 1. A number of signal processing techniques may be utilized to perform both time and frequency analysis of these waveforms [31].

Another type of study may be related to the analysis and design of protective relaying devices. This study would require implementation of the block sequence (1),(2),(3),(5),(6),(8) or block sequence (1),(4),(5),(6),(8), as indicated in Figure 1. It is important to note that in this case models of different electromechanical [33], solid state [18], and computer relays [32] have to be developed and implemented as software packages. Even though these packages are not readily available, they may be easily developed for some of the well known relay principles.

Finally, a simulation environment may also be defined to create test signals for actual relay designs. In this case some D/A converters and power amplifiers are needed to "replay" the transient data files into relays to be tested. The software block sequence (1),(2),(3),(5),(7),(9) or (1),(4),(5),(7),(9) is required. Some very advanced software packages for this purpose are also available at a moderate cost under a university licensing agreement [15].

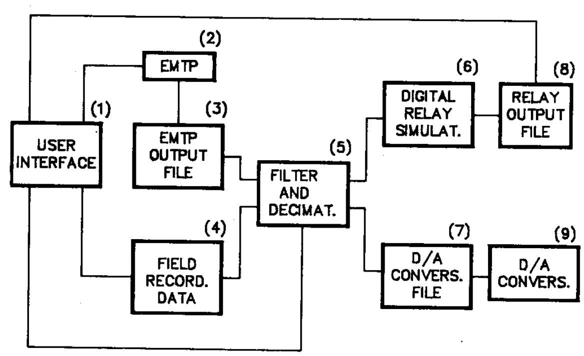

Figure 1. Software Functional Block Diagram

DYNA-TEST Simulator Hardware

The simplest approach is to use a general purpose mainframe computer which is usually accessible by the students at almost any university. The only specific requirement is that a relatively large memory space is allocated for the EMTP configuration and execution. If the program is already in the executable form, the memory space requirement is then moderate. Another convenient feature would be a plotter to be used to display the transient response signals. However, this is not a limiting factor since the EMTP output files may be organized for a CRT representation as well.

Another version of the simulator may be developed using an advanced, dedicated computer configuration as given in Figure 2. In this case two computer workstations (COWs) are used to separate different simulator tasks. The COW1 is used for EMTP and relay simulations. It is also used for input data routines for simulation set-up. The COW2 is used for analysis of the EMTP simulation results as well as for processing of the field recorded fault signals. A high resolution graphics terminal and a plotter are used for interaction between an operator and the signal data files. This computer also controls the D/A converter boards. The two computers are interconnected in a local area network. This provides for the required interaction between the two computers and for future expansion of adding more users. A common data base may be utilized using a large memory space within the COW1. In this case the COW1 will act as a system server to COW2. The COW2 would not then require a large disk space.

As indicated in Figure 2, some additional hardware may be attached to this simulator. A Transient Recorder, either analog or digital, may be directly connected to supply the field recorded signals. This data may also be transferred by using disk or tape medium.

Other external attachments are the power amplifiers. They are used to output either EMTP simulated or field-recorded transients in an analog form. These signals have a power level required for testing of relay devices. Hence this feature may be used to evaluate different relay designs at different stages of implementation.

CASE STUDY: DIGITAL ALGORITHMS FOR DISTANCE RELAYING

This subject may be considered as the most illustrative of all computer-based relay design issues. It is probably the most complex problem design-wise, and there is also the largest number of different algorithms proposed for implementation [10,12].

A number of different simulation arrangements may be used for distance relay design study. One approach discussed here is based on the software organization indicated in Figure 3 [32].

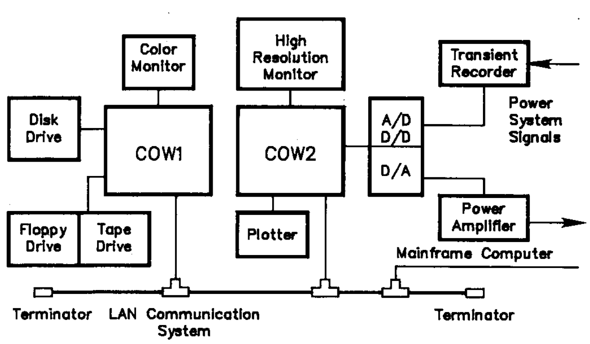

Figure 2. Hardware Block Diagram

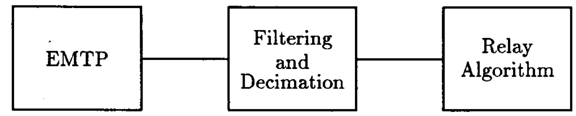

Figure 3. EMTP – Based Digital Algorithm Simulation

The EMTP is used to generate fault transients. The filtering and decimation package is used to adjust the EMTP sampling rate to a rate required by different distance relaying algorithms, and to perform the required filtering of relay input signals. The relay algorithm package may be developed with different levels of relay design features represented. As it is well known [10,12], a number of hardware and software aspects of the distance relay are quite important. The required signal processing includes Fault Detection, Fault Classification, Impedance Measurement, Fault Verification, and Tripping routines. An example discussed here is focusing on teaching different approaches to the design of the Impedance Measurement algorithms. Some theoretical considerations of these algorithms are needed in order to illustrate the benefits of the experimental method.

Theoretical Background

The first issue is the different forms of possible algorithms. Published references related to algorithm analysis indicate that there are over twenty signal processing schemes proposed for impedance measurement in distance relaying [10,12,14,32]. The students should be exposed to most of these approaches in order to appreciate the variety of methods and ideas that may be used for implementation. An important step is to introduce a classification of the existing algorithms. This would help the students to understand that there may be several algorithms that belong to the same class, and therefore, there might not be as many distinct algorithms as it may appear from reading the related references. The challenging part is to demonstrate that each of the distinct classes has unique performance characteristics which are inherent in the assumptions made for algorithm definition. This issue may well be supported by some simulations. The following is a discussion of some of the interesting simulations considered to be quite useful as a teaching demonstration. This example is related only to the algorithms based on measurements of the fundamental frequency signals with a narrow band of other harmonics and transients present. The traveling wave algorithms are not considered in this example.

The main algorithm classification is based on the approach for impedance calculation. As it is well known, the impedance of a transmission line may be defined in one of the two following ways:

$$Z = R + jwL \tag{1}$$

$$Z = \frac{V}{I} \tag{2}$$

Therefore, one class of algorithms is related to calculation of R and L based on the voltage and current measurements. In this case a differential equation model is needed as given below:

$$u(t) = Ri(t) + L\frac{di(t)}{dt} + e(t) \tag{3}$$

where: R, L - line parameters
$e(t)$ - the noise term.

An algorithm classification scheme related to the model given by equation (3) can be defined, as given in Table A in the Appendix. These algorithms are designated as Class I algorithms. The classification is based on the two basic steps needed to determine parameters R and L. One step is to treat the di/dt term, and the other step is to treat the $e(t)$ term. The important observation is that various algorithms defined to perform these two steps may have quite different properties.

Table I. Summary of an Algorithm Property Analysis

Algorithm Design Assumptions and Characteristic		Class I				Class II				
		Treatment di/dt term		Treatment of the e(t) term		No optimization		Optimization		
		Via Samples	Via Integration	Two eq.	More eq.	First harmonic	Other comp. in the signal	Least-square fit	Linear estimation	Kalman filtering
Signal content	Fundamental harmonic	Theoretically do not influence the results				Some alg. are not sens.	Could be sensitive			Very sens.
	Higher harmonic and transients					Sensitive	Hard to generalize	Not sensitive under the assumption		
	Noise term	Sensitive	Sensitivity may be reduced		Sensitivity is reduced	Sensitive	Sensitivity may be reduced			
Signal Measurement	Analog signal Processing	Imp. resp. the same for current and voltage				System function the same for w_0				
		Postpones the results								
	Signal sampling	Synchronization required				Synchronization is not required if sample rotation is applied				
		Optimal sampling freq. likely to exist	No conclusion about optimal sampling frequency		Optimal sampling frequency likely to exist		No conclusion about optimal sampling frequency			
Major alg. parameters	Data window	Can be: fixed, selected in an optimal way, determined by the fixed number of samples and the sampling frequency, free to be selected				Fixed	The same four choices			
	Number of Samples	Either depends on the sampling frequency or is not determined by any particular requirement				Fixed	The same two choices			

The other class of algorithms, designated as Class II, can be defined by the following model:

$$u(t) = Vcos(w_o t + \phi) + \sum_k C_k^u f_k^u + n_u(t)$$
$$i(t) = Icos(w_o t + \psi) + \sum_k C_k^i f_k^i + n_i(t) \qquad (4)$$

where: C_k^u, C_k^i – unknown coefficients
$f_k^u(t), f_k^i(t)$ – known functions representing higher harmonics and transients
$n_v(t), n_i(t)$ – noise terms

Typical estimation approach in this class usually consists of the following two steps: estimation of the first harmonic (direct and quadrature components, or amplitude and phase components); calculation of impedance as a quotient of the voltage and current phasors. This is indicated by equation (2). Again, a number of methods may be implemented to perform mentioned estimations. They primarily depend on an assumption about the complexity of the waveforms described by equation (4). Some basic methods are indicated in Table A given in the Appendix.

An extensive theoretical study of the algorithm properties indicates that mentioned classes of algorithms will perform differently under different algorithm design assumptions and characteristics. Summary of the typical algorithm theoretical study results is given in Table I. It should be noted that several of the algorithm property qualifications given in this table are not conclusive. On the other hand, some algorithm behavior may be quite well predicted by a theoretical study. An interesting teaching exercise would be to use experimental results to explain and complement the theoretical considerations.

Teaching Experiments

Example 1 – Frequency Sensitivity. The first experiment is used to illustrate algorithm sensitivity to the change of the power system frequency. If Table I is analyzed, it may be observed that the theoretical considerations indicate that class I algorithms should not be sensitive to the frequency change. This may be concluded from the model given by equation (3), which is the basis for development of class I algorithms. In this model no assumptions are made about the fundamental frequency, and hence the derived algorithms should not be sensitive to the change of fundamental frequency.

On the other hand, class II algorithms are based on the assumption about the fundamental frequency signal. This is obvious from the model given by equation (4), that is used as a basis for development of algorithms in this class. Hence, this class of algorithms could be sensitive to the frequency change. A more detailed theoretical analysis reveals that different algorithms in this group would perform with different level of sensitivity. This conclusion is noted in Table I. The subclass of algorithms, based on the no-optimization techniques with the signal model containing only the fundamental harmonic, is partially insensitive to frequency variation. This may be observed from expressions for R and L as given below [36]:

$$R = \frac{2u_{k-1}i_{k-1} - u_k i_{k-2} - u_{k-2} i_k}{2(i_{k-1}^2 - i_k \cdot i_{k-2})} \qquad (5)$$

$$X = \frac{u_{k-1}i_k - u_k i_{k-1}}{i_k^2 - i_k \cdot i_{k-2}} sin(w \cdot \triangle T) \qquad (6)$$

The expression for R does not include the frequency term, and hence, is not sensitive to frequency change. The expression for X may be approximated, for small values of angle, as:

Table II. Sensitivity to the System Frequency Change

Algorithm Class/Subclass	Ref.	f=60 Hz		f=63 Hz		f=57 Hz	
		R	X	R	X	R	X
Class I, integration, two equations	[34]	70.13	67.52	70.57	67.40	69.75	67.68
Class II, no optimization, first harmonic only	[35]	69.88	68.47	70.28	68.60	69.51	68.37
The same as above, but different algorithm	[36]	70.02	68.44	70.53	68.59	69.57	68.35
Class II, no optimization, other components	[37]	62.14	57.93	62.95	65.74	62.94	51.43
Class II, optimization, Kalman filtering	[38]	-5.85	72.72	227.68	70.62	-224.93	65.75

$$L \cong \frac{u_{k-1}i_k - u_k i_{k-1}}{i_k^2 - i_k \cdot i_{k-2}} \cdot \Delta T \quad (7)$$

In this case, equation (7) indicates that the expression for L becomes less sensitive to the frequency change. This is particularly true for the case when sampling frequency is high enough to make the term ΔT small enough.

Another subclass of the class II algorithms contains the ones that may be sensitive to the frequency change. The level of sensitivity, in this case, has to be determined by some simulations. The Kalman filtering algorithm may be observed as being very sensitive to the frequency change. This is caused by the fact that the frequency w_o appears in the measurement model, through the Kalman gain matrix.

Finally, the above theoretical considerations may be demonstrated by the simulations [32]. One typical output of an EMTP-based simulation is given in Table II. The correct value for R and X is 70. The results are in full agreement with the predicted theoretical behavior. This is illustrated by the results for the algorithms belonging to the different classes and subclasses, as given in our previous discussion. Table II also contains an indication of a reference where a full discussion of the related algorithm is given.

Example 2 - Sampling Rate Sensitivity. This example is related to determination of an optimal sampling rate for voltage and current signals. Results of the theoretical analysis, given in Table I, suggest that it is not easy to determine an optimal sampling rate based on theoretical analysis only. The sampling rate is usually chosen based on the sampling theorem. However, the sampling theorem requirement is a necessary condition for the signal reconstruction. But, it is not clear if it is the necessary and sufficient condition for reconstruction of parameters R and L, based on samples of voltage and current.

Based on the given consideration, the optimal sampling rate problem should be analyzed regarding the specific properties of an algorithm subclass at hand. For example, for some of the class I algorithms, an optimal frequency is likely to exists. The algorithm subclass that deals with approximation of the di/dt term via samples, and is based on more then two equations to deal with the noise term, requires a compromise for the selection of ΔT term. The approximation of the derivative term depends on the interval ΔT, but the noise term treatment is also related to the same interval. Therefore, sampling rate should be determined to compromise for the required accuracy. Another example are algorithms of class II, belonging to a subclass that assumes the signal representation to be the fundamental harmonic only. In this case, if interval ΔT is too small, sampled values are almost the same and,hence,a poorly conditioned matrix problem exists. If interval ΔT is too large, the results will be sensitive to the system frequency change, as indicated in the previous example. As indicated in Table I, a conclusion about optimal sampling frequency for other algorithm subclasses can not be drawn based on the theoretical study alone.

The EMTP based simulation can be used to perform some experiments that illustrate the given sampling rate problem. Table III gives MEAN and standard deviation (STD) values calculated for different algorithms, by varying sampling rate over the range from 4 s/c to 96 s/c [32]. The nominal value of estimated impedance is 61.27%. The MEAN values in the range between 60.2% and 62.2% are underlined in Table III. The minimum values of STD are also underlined in Table III.

Table III. MEAN and STD Sensitivity vs. Sampling Rate

Algorithm Class/Subclass	Ref.		Sampling Rate						
			s=96	s=32	s=24	s=16	s=12	s=8	s=4
Class I, sample approximation, more than 2 eq.	[39]	MEAN	60.80	60.83	61.06	62.00	63.61	69.04	113.53
		STD	0.63	1.08	1.69	3.06	4.63	8.59	46.17
Class I, integration, two equations	[40]	MEAN	61.14	60.92	60.78	60.35	59.75	58.03	48.45
		STD	2.99	0.99	0.96	0.99	1.04	1.22	3.27
Class II, no optimization, first harmonic only	[36]	MEAN	61.06	61.05	61.05	61.05	61.04	61.03	61.02
		STD	1.51	0.92	0.91	0.91	0.91	0.89	0.86
Class II, no optimization, other components	[41]	MEAN	61.31	61.31	61.31	61.31	61.30	61.27	61.10
		STD	4.42	4.42	4.42	4.43	4.44	4.49	4.77
Class II, optimization, Kalman filtering	[38]	MEAN	70.65	67.32	65.03	63.31	63.16	61.25	61.88
		STD	1.31	1.01	0.82	0.70	0.74	0.88	1.61

In order to determine the optimal sampling rate,both MEAN and STD values must be analyzed. However, the most accurate MEAN and the smallest STD do not always occur at the same sampling rate. Therefore, this example illustrates that for some algorithms, there may be no optimal sampling rate. This example also suggests that the experimental study may be the only way to deal with this problem.

CONCLUSIONS

The field of protective relaying can benefit from introducing more advanced methods for teaching. Some interesting protection relay design issues need to be studied using transient analysis of the fault phenomena. Digital dynamic testing simulators can provide a quite flexible and yet inexpensive teaching tool for analysis of power systems, instrument transformers, and relay design transient behavior. Several power system simulation software packages already exist, but further developments are needed for simulation of the related equipment and protection relay designs. The use of the field recorded fault signals, for study of the protective relaying problems, should also be explored. Implementation of stand alone digital dynamic simulators, interfaced to the D/A controllers and signal amplifiers, would provide for a very powerful testing environment for teaching the overall relay design methodology.

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Appendix

Table A. Classification Scheme for Digital Distance Relaying Algorithms

ALGORITHMS OF CLASS I

Treatment of di/dt term		Treatment of e(t) term	
Approximation of the derivative using samples	Elimination of the derivative via integrat.	Two equations	More than two equations
$u(t_k)=Ri(t_k)+Li'(t_k)+e(t_k)$ i'(t)-derivative approx.	$\int_{t_1}^{t_2} u(t)dt=R\int_{t_1}^{t_2} i(t)dt+L[i(t_2)-i(t_1)]+\int_{t_1}^{t_2} e(t)dt$	$e(t)=0$ Two algebraic equations are needed for solution of R and L: $AR+BL=C$ $DR+EL=F$	$e\neq 0$ Two algebraic equations may be obtained: $A_kR+B_kL=C_k$ $D_kR+E_kL=F_k$
1. $i'(t_k)=\frac{i(t_k)-i(t_{k-1})}{\Delta t}$ 2. $i'(t_k)=\frac{i(t_{k+1})-i(t_k)}{\Delta t}$ 3. $i'(t_k)=\frac{i(t_{k+1})-i(t_{k-1})}{2\Delta t}$	1. $\int_{t_1}^{t_2} x(t)dt=\sum_{k=n-N}^{n-1} x_k\Delta t$ $t_2=n\Delta t;\ t_1=(n-N)\Delta t$ 2. $\int_{t_1}^{t_2} x(t)=\sum_{k=n-N}^{n-1}\frac{(x_k+x_{k+1})}{2}\Delta t$ $x_k=x(k\Delta t)$	Coefficient A,B,C,D,E and F are obtained by using one of the two methods mentioned for treatment of the di/dt term.	by using the minimum square error criterion: $\frac{\partial J}{\partial R}=0,\frac{\partial J}{\partial L}=0,J=\int_{t_{k-T}}^{t_k} e^2(t)dt$

ALGORITHMS OF CLASS II

No Optimization			Optimization
	Other components in the signal		
First harmonic only	Correlation	Convolution	
The signal models are: $u(t)=V\cos(w_ot+\phi)$ $i(t)=I\cos(w_ot+\psi)$	The signal models are: $u(t)=V\cos(w_ot+\phi)+\sum_k C_k^u F_k^u$ $i(t)=I\cos(w_ot+\psi)+\sum_k C_k^i F_k^i$		The signal models are: $u(t)=V\cos(w_ot+\phi)+\sum_k C_k^u F_k^u+n_u(t)$ $i(t)=I\cos(w_ot+\psi)+\sum_k C_k^i F_k^i+n_i(t)$
The signal models are plugged into the equation: $u(t)=Ri(t)+L\frac{di(t)}{dt}$ The two equations to solve for R and L are obtained by taking two time instances t_k and t_{k+1}. The corresponding terms multiplying $\cos w_o$ and $\sin w_o$ from the left and right hand side are equated to obtain the two equations.	The signal is multiplied with a time dependent weight function and integrated in a data window. The following approaches are possible: -Full Cycle Fourier Analysis -Half Cycle Fourier Analysis -Fourier Analysis with a Non-Fundamental Harmonic -Current and voltage are the weight functions	The signal is multiplied with a weight function "moving" with the data window. The following approaches for the weight functions are possible: -fundamental harmonic -Walsh functions SAL(t) and CAL(t)	The following methods for optimal signal parameter estimation can be used: -Minimum least square fit -Linear estimation -Kalman filtering

Mladen Kezunovic, (S '77, M '80, SM '85) received his Dipl. Ing. degree from University of Sarajevo, Yugoslavia, the M. Sc. and Ph.D. degrees from University of Kansas, all in electrical engineering in 1974, 1977, and 1980, respectively.

Dr. Kezunovic's industrial experience is with Westinghouse Electric Corporation, and the Energoinvest Company in Yugoslavia. He was responsible for the development of an integrated microprocessor- based substation control and protection system at the Energoinvest Company during 1980-1986 time period. He also worked at University of Sarajevo, Yugoslavia. He was a Visiting Associate Professor at Washington State University and at Texas A&M University, for the 1986-1987 and 1987-1989 academic years, respectively.

Dr. Kezunovic's current research interest is in the areas of digital algorithms for relaying and control, and advanced automation product development. He is a corresponding member of the CIGRE W.G. 34-01 (Digital Protection Techniques and Substation Functions).

Discussion

R. Fischl and **E. Stagliano** (Drexel University, Philadelphia, PA): The author is to be commended for his very clear and timely article regarding the teaching of protective relaying. There are however, some areas that require additional discussion.

The first area is in the modeling of electromechanical relays, especially those used for transmission line protection, commonly called distance relays. While it is true that one can develop an appropriate algorithm for a particular manufacturer's relay; and test the validity of the algorithm on a model power system. It is also true that the developed algorithm may only apply to a very limited number of relays bearing the same catalog number. In some cases, this may be attributed to differences in the magnetic circuit (due to the work hardening of the laminations, variations in the allowable tolerances of air gaps, etc.) Other factors, that may be difficult to model, or even ignored, are the day to day variations of the transient performance when the fault is near the relay location.

Another area that must be addressed is the non predictable harmonic content of the inrush current to three phase power banks as described in a paper presented to the Georgia Institute of Technology Protective Relay Conference in May 1976 entitled "A Dissertation on Power Transformer Excitation and Inrush Characteristics."

As the author has noted the EMT programs are not designed for relay teaching and do require extensive modification for teaching advanced protective relaying.

While we agree that digital dynamic testing simulators can aid in the teaching of advanced relaying courses, we also believe that both the students and the instructors must be aware that the results should be regarded as average at best until there are sufficient numbers of "proven" cases demonstrated on well designed model power systems. This implies performing sensitivity studies not only with respect to the model parameters, but also such unknowns as temperature.

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M. KEZUNOVIC: The author would like to thank the discussers for their comments. The author agrees with observations made by the discussers and would like to expand on some of the subjects.

As it was noted in the paper as well as in the discussers' observations, the problem of modeling the power system and relay components in a transient state is quite a complex problem. However, the main question is what is the level of modeling complexity (or simplicity) that can be considered sufficient and at the same time accurate enough for practical use in relaying studies. The discussers are pointing out particular nonlinear behavior of a magnetic circuit and its implications in developing models to represent transient response of such a circuit used in quite different applications such as the electromechanical relays and the three phase power transformer banks. This observation can also be extended to some other magnetic circuits that are critical when protection relay performance is evaluated. The examples are instrument transformers and the relay auxiliary transformers.

In order to provide an answer to the question raised, it should be recognized that the DYNA-TEST Simulator concept enables one to implement a unique methodology of using both the simulated data and the field data for analysis and testing purposes. This methodology can be used to verify different modeling techniques used to model both the power system and the relay system components. It is believed that this process is educational in itself and significantly improves understanding of the complexity of evaluating the protection relay transient performance. On the other hand the limitations of the present analysis of the relay performance using the steady state approach become even more obvious when the mentioned methodology is used.

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