DIGITAL SIMULATOR PERFORMANCE REQUIREMENTS FOR RELAY TESTING

Prepared by Working Group F–8 of the Relay Input Sources
Subcommittee of the IEEE Power System Relaying Committee

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Abstract– Working Group F–8 “Digital Simulator Performance Requirements for Relay Testing” of the Relay Input Sources Subcommittee, Power System Relaying Committee, was formed in 1992 with the following assignment:

> “Investigate performance characteristics of digital simulators when generating Electromagnetic Transient Program (EMTP) and Digital Fault Recorder (DFR) based relay test waveforms. Write performance requirements specifications and prepare a paper describing the importance of the simulator performance characteristics.”

This paper presents the work accomplished by the working group in fulfilling its assignment.

INTRODUCTION

Over the past half century relay testing has evolved from quasi–steady state to real–time system transient simulation methods as the need for faster and more reliable relay performance has become more important. The conventional approach has been to devise low voltage, low current electrical models (analogs) of the primary high power system, scaled to provide normal inputs to the relays. Electrical models of alternators, transformers, transmission lines, capacitor banks, reactors, and circuit breakers were developed and interconnected to comprise Model Power Systems (MPS). Control and measuring systems were added to facilitate better simulation of system faults and to record accurately the model and relay responses. These analog model power systems have become very effective development tools even though they do have some inherent limitations.

Within the past two decades, there has been extensive application of the techniques pioneered by Dommel [1], in developing EMTP, the Electromagnetic Transients Program. This work has applied the computational power of the digital computer to the solution of the differential equations describing the behavior of power system networks. The method uses numerical integration techniques to obtain time incremented solutions for the network voltages and currents. In EMTP, there have been developed mathematical models of power system apparatus which accurately model nonlinear behavior, frequency dependent effects, and distributed parameters. EMTP can be used to model quite large networks having hundreds of elements. The accuracy of the analysis has been confirmed by comparison with field measurements in numerous cases. It is widely accepted as a valuable tool for power system transient analysis.

As a result of EMTP developments, it was obvious that digital simulators of power systems can be developed for testing protective relays by implementing an interface between simulation computers and relays to be tested. The advent of digital fault recorders (DFRs) and digital relays have also provided an opportunity for testing relay performance to actual realy faults by replaying recorded events.

Digital simulators for relay testing were introduced in the early 80’s [2,3]. A number of open–loop designs have been developed to date [4–7]. Recently, several developments of the real–time simulators have been reported [8–14].

This paper summarizes performance requirements for digital simulators when used for relay testing. After giving brief simulator definitions, requirements related to the following issues are discussed: relay testing, relay input characteristics, simulation computer, I/O subsystem, and power amplifier subsystem.

SIMULATOR DEFINITIONS

For the purposes of this paper, a “simulator” may be defined as 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. These waveforms are used to drive the relays under test.

A primary distinction between different simulators is the speed at which the computer performs the computations to generate each data point of the waveforms. If the time required for computation of each data point is less than or equal to the time step, the computation is defined as occurring in real time. When the computation

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time is greater than the simulation time step, the waveforms are generated off line, stored and reproduced in real time by playback apparatus. The distinction between real *time simulation* and playback simulation will affect how the results of the simulation are used to test equipment such as relays. The device to be tested with the playback waveforms is tested "open loop" since there is no way of feeding information from the device under test into the simulation process. The combination of the computer running the simulation and the playback apparatus would be called a "Playback Digital Simulator", or "Open Loop Simulator." If the computer runs the simulation in real time, then "closed loop" testing of apparatus is possible. To close the loop, it is necessary that the simulator be able to accept input information from the apparatus under test and to incorporate this information into the ongoing simulation run. This combination of the computer and interface apparatus can be called a "Real-time Digital Simulator", or a "Closed Loop Simulator."

A typical digital simulator configuration is shown in Figure 1.

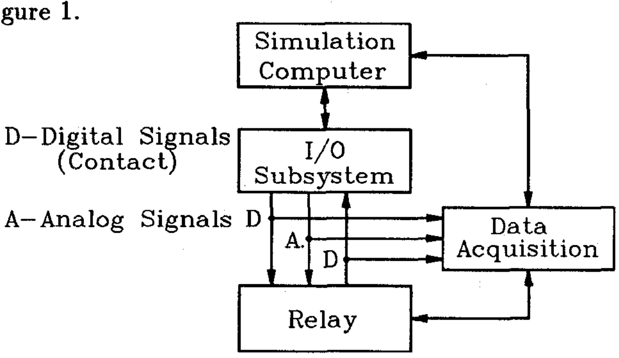

Figure 1. Typical Digital Simulator Configuration

The minimum interface requirement between the simulator and the relay under test is for the simulator to be able to supply analog voltage and/or current signals at suitable levels to operate the relay equipment. Real-time digital simulators could also have a digital input and output interface, where the output would supply status information of breakers and switches from the simulation and the input would accept the status information (trip or close signals to breakers) from the relay equipment under test. In addition, there is a need to record both the signals coming out of the simulator and various signals generated by the relays. This recording may be performed by the digital simulator interface equipment or by a stand-alone data acquisition system. The minimum requirements considered in this paper are related to the set-up shown in Figure 1 where an outside data acquisition system is used for full recording.

RELAY TEST REQUIREMENTS

The preferred approach, i.e., using an open loop simulator or a closed loop simulator, is suggested by the nature of the relay tests. Relay tests could be conducted with an open loop simulator, which involves playback of signals generated with off line digital simulation or previously recorded field signals. However, in some situations as cited below, the use of a closed loop simulator will improve the efficiency with which the tests can be conducted.

Interaction of the Relay With the Power System

Most relays may be tested in the open loop mode such that the response of the relay does not need to be fed back to the modeled system. This applies in cases where it can be assumed that the timing of the tripping action of a relay, in response to fault detection, does not influence the relay's response to subsequent changes in the power system. For example, consider a transmission line relay in three-pole tripping applications with slow reclosure (typically 5 seconds). In this case, it can be assumed that the timing of the tripping action generated by the relay will not influence the conditions that the relay has to contend with on reclosing of the line. This is because both the power system and the relay have settled to their new steady state conditions by the time the reclosure takes place. Hence, the tests for tripping action and for reclosure can be performed separately in open loop mode. Relays for protection of most other major power system apparatus, i.e., generator protections, transformer protections, and bus protections, can be tested in this type of open loop mode. However, there are exceptions which include:

(a) transmission line relays in applications with fast reclosing of transmission lines (typically 0.5 seconds)
(b) relays for out-of-step protection
(c) relays for frequency protection
(d) transmission line relays in single-pole autoreclose applications
(e) relays with reclosure for distribution feeders.

The above list is not necessarily complete, but the mentioned relay types serve as examples for the purposes of this discussion.

In cases (a)–(c), the action of the relays create dynamic conditions in the power system which are dependent on timing of the relay actions. In (a), a transmission line relay will, on reclosing, need to contend with a dynamic power system and possibly with dynamics within the relay, which are dependent on the timing of the initial response and action of the relay. That is, the initial conditions for testing the response of the relay on reclosure is relay and power system specific. In (b) and (c), the relays perform measurements with the power system in a dynamic condition. The dynamics with which the power system progresses beyond the relay's initial corrective action is governed by the timing of the initial response of the relay. Again, the initial conditions for tests subsequent to the initial test, are relay and power system specific.

In (d), the relay will open a single pole on a phase-ground fault. This creates an unbalanced condition to the relay which, in a dynamic power system, can be influenced by the initial response of the relay. The recloser is usually an integral part of the protection package in this application. Therefore, various time settings in the reclosure could have been designed to properly coordinate with the protection response. Hence, the initial response of the protection could have an influence on the response of the reclosure. This latter point also applies in (e), which refers to distribution feeder protection with a reclosing feature. Verification of the response of the relay to its own actions is accomplished in a most straight-forward manner with a closed loop testing approach. The open loop approach can also be used. However, it could require a number of iterations to determine the initial conditions that are needed for subsequent tests. For closed loop testing, the trip outputs of the relay need to be interfaced to operate the appropriate breakers in the simulation.

Testing Requiring Long Simulation Times

Open loop simulation approaches may have certain limitations in the length of data files that can be played back for a particular test. In some implementations, the limit is as low as 15 cycles of 60 Hz data. Such a limit would make the open loop approach unworkable in, for example,

(a) tests on an out–of–step protection in which the required simulation time could be several seconds
(b) tests on protection equipment with respect to Geomagnetic Induced Currents in which the required simulation time could be tens of seconds
(c) tests on protection equipment for prevention of voltage collapse in which the required simulation time could be several minutes

The above may not only pose a difficulty for most open loop systems, but also be unwieldy in terms of the execution time of the simulation and storage requirements for the resulting files.

Interaction With the User

The use of a closed loop simulation system may be preferred where

(a) the test program is investigative, as in the evaluation of a relay for a particular or general application, requiring many tests that are suggested by the results of previous tests
(b) the number of test cases is large, with variations in fault type, location, and point–on–wave switching, requiring extensive execution time
(c) the simulated power system is complex, requiring extensive verification of the correctness of the simulated system

In all of the above, real–time simulation will reduce the time required to execute the test program.

RELAY INPUT CHARACTERISTICS

Nominal Currents and Voltages

Protective relays are used to protect a wide variety of power system elements; and thus vary greatly in design. The relay hardware may range from electro–mechanical to microprocessor. The current and voltage signals used in simulation testing must, therefore, be capable of wide range of magnitude, frequency, and power level.

In general, the nominal voltage and current ratings of a relay will fall in the following range:

Voltage:	100 to 120 V_{rms} phase to phase
	(57 to 69 V_{rms} phase to neutral)
Current:	1 or 5 Amperes
Frequency:	50 or 60 Hz

Operational Currents and Voltages

The dynamic operational range of the input signals will vary greatly from the nominal ratings, depending upon the type of relay being considered. In order to illustrate this, some examples of typical relays are shown in Table I where the required dynamic range is evident from the setting range.

It is important to realize that the manufacturers burden is quoted on average or rms measured values, but that the voltage across the relay burden is often non–sinusoidal because of the saturating nature of the relay input inductance. When considering the amplifier compliance voltage required to drive a relay at multiples of relay tap setting, empirical results suggest that the peak voltage compliance more nearly approximates the tap value peak voltage (from the tap value burden) multiplied by the tap multiple [15].

An additional variable on some relays is the addition of surge capacitors to the current and voltage inputs. These surge capacitors are often required to meet the applicable Surge Withstand tests. On low burden relays, the impedance of the capacitor may become a major component in the relay burden; and may, in some cases, cause the burden to become capacitive. This will affect the amplifier requirements.

As can be seen by the above relays, a simulation system must be capable of supplying a wide range of current and voltage signals to a protective relay. For single function relays (time over current, etc.), it may be easy to establish a range of inputs based on a particular setting. A distance relay, on the other hand, is very dependent upon its application in the power system to establish the range of currents and voltages which will be seen in service. For a relay system which typically will include many individual relay elements, it is extremely difficult to develop a limited set of currents and voltages.

Effect on Amplifier Requirements

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 a higher compliance voltage are needed than if only solid state/digital systems are to be tested.

SIMULATION COMPUTER

Digital simulator performance can significantly be affected by the choices of functions, hardware, software, and user interfaces. The following discussion is related to the requirements of the 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, MORGAT, MICROTRAN, NETOMAC [6,10,16–20]. However, the 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 DFR files for replaying. Study of the influence of the instrument transformers is yet another example of the signal analysis needs.

Signal replaying may be done by a dedicated controller, separate from the simulation computer, in an open–loop simulator 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, which again only requires a floppy drive capability.

Relay testing in real–time 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 [21].

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 it may be done by the simulation computer 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,

Table I. Examples of Typical Relay Characteristics

Relay Type	Rated Current	Rated Voltage	Setting Range	Burden at Rated Conditions
Induction Disk Time Over Current Relay	5	NA	0.5–16A	Min Tap 21Ω @ 0.26 pf Max Tap 0.35Ω @ 0.29 pf
Induction Disk Time Over Voltage Relay	NA	67–345	10–40%	Min Tap 35VA @ 0.35 pf Max Tap 15 VA @ 0.95 pf
Plunger Type Instantaneous Over Current Relay	25 1.5	NA NA	40–160A 0.5–2.0A	0.025 VA @ 0.33 pf 165 VA @ 0.40 pf
Plunger Type Instantaneous Over Voltage Relay	NA	115–460	60–140%	9 VA @ 0.5 pf
Transformer Percentage	5	NA	2.9–8.7A	2.9 A Tap Op: 0.128Ω Rest: 0.052Ω 8.7 A Tap Op: 0.028Ω Rest: 0.020Ω
Current Differential Relay	5	NA		1 X PU : 58Ω 25 X PU : 5.4Ω
Solid State Frequency Relay	NA	120	44–61 Hz	AC Powered: 11.7 VA @ 0.85 pf DC Powered: 1.3 VA @ 0.98 pf
High Impedance Bus Differential Relay (Voltage)	5	150	75–500V	Current Burden @ 5 A 1678Ω @ -24°
Cup Type Distance Relay	5	120	0.75–30Ω	I : 0.3Ω @ 0.98 pf V : 340Ω @ 0.99 pf
Solid State (Hybrid Analog–Digital) Distance Scheme	5	120	0.10–50Ω	I : 0.03Ω @ 5° V : 0.2 VA @ 50°
Numeric Digital Relay	5	120	0.10–50Ω	I : 0.02Ω @ 5° V : 0.15 VA @ 50°

the case if a graphical user interface is used for interaction with several application programs in a multi–tasking, multi–user environment.

Hardware

The simulation computer may have a number of different configurations. It could be a workstation dedicated to EMTP simulations and user interfaces. In this case, it is not used for direct replaying of the waveforms. The waveforms are only 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 EMTP 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 main difference in the selection of the simulator hardware is related to the price/performance characteristics. The performance requirements are determined by the I/O requirements for signal replaying and signal acquisition as well as the number crunching requirements for EMTP simulation and signal analysis. User interfaces also place a requirement for a particular type of the graphical interface standards. The other considerations are the memory space, both for the hard disk and for the working memory. More elaborate system and application software may require quite demanding memory specifications.

Software

The software requirement can be divided into two categories: system software and application 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 EMTP package and signal processing package. Software tools for development of graphical user interfaces are also a part of this consideration. A choice of a database management also 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.

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, in turn, 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 application. A typical choice may include: EMTP, a sig-

Table II. Typical I/O System Specifications

Input Capabilities		
1	Number of Digital Inputs*	16
2	Digital Input Specifications**	optically coupled, 50 – 150 V dc. / 10 mA
Output Capabilities		
3	Number of Digital Outputs*	16
4	Digital Output Rating**	optically coupled, 5 – 150 V dc. / 200 mA
5	Number of Analog Outputs*	8
6	Analog Output Specifications	± 10Vpk / 20 mApk
AC Performance		
7	Resolution	16 bits
8	Sample Rate	20 kHz (per channel)
9	Frequency Response	dc – 3 kHz /± 0.25 dB
10	Group Delay	50 μs
11	Group Delay Variations (0–3kHz)	± 1 μs
12	Stop Band Attenuation (f > fs/2)	> 60 dB
13	Time Skew Between Channels	< 500 ns
14	Output Impedance (0 – 3 kHz)	0.1 Ω
15	Output Offset (relative to FSR***)	< 0.1%
16	THD+N (relative to FSR***)	< 0.1%
17	IMD (relative to FSR***)	< 0.1%
18	Compensated Gain Error	< 0.2%
Environmental		
19	Operating Temperature	10 – 40 C^o
20	Output Offset Drift @ 20 C^o	< 0.05% FSR /C^o
21	Power Consumption	150 VA

* Per protection terminal
** Individually isolated on each input or output channel
*** Full Scale Range (FSR)

nal processing package, a database management package, and a graphical user interface package. A number of customized software routines may have to be developed to allow for conversion of various data formats so that data from different DFRs and EMTPs may readily be used [22].

A special category are real–time simulators that may have custom EMTP implementation and I/O interactions to support the real–time capability.

Graphical user interfaces are an essential feature of an easy to use operator interface. Typical features of such an interface should include data entry using an editing window on a network diagram, 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.

The graphical interface tools are quite important for development of the interfaces and do require selection of a particular standard in this field. A typical choice might include: MSWindows and data representation managers for PCs as well as OSF/MOTIF and Open Look for workstations.

I/O SUBSYSTEM

The I/O, or 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 subsystem is responsible for converting the digital data into low level analog signals (± 10 to ± 20 volts peak) required by the main amplifier system, filtering those signals to remove unwanted high frequency components (interpolation), 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 characteristics of the main system amplifiers. A set of typical I/O subsystem specifications is given in Table II. Explanation of most of the terms used in Table II is given in [23].

As can be seen, some of the parameters in Table II are interrelated. For example, the actual sample rate used by a given system may vary as long as the frequency response at the system output is flat within the 0 to 3 kHz frequency

Table III. Typical Power Amplifier Specifications

		Voltage Amplifiers	Current Amplifiers
Input Characteristics			
1	Input Impedance	>10 k Ω	>10 k Ω
2	Input Range	±10 Vpk	±10 Vpk
3	Common–mode Input Range	±10 Vpk	±10 Vpk
4	CMRR	60 dB	60 dB
5	Gain	30 V/V	10 A/V
Output Capabilities			
6	Maximum Output Voltage	±300 Vpk	±50 Vpk
7	Maximum Output Current	±1 Apk	±100 Apk
8	Continuous Output Power	150 VA	2500 VA
AC Performance			
9	Frequency Response	0 – 10 kHz	0 – 10 kHz
10	Accuracy (|Gain*V_{in} − V_{out}|)	<1% error, dc–1kHz <3% error, 1kHz–3kHz <5% error above 3kHz	
11	Group Delay	<50 μs	<50 μs
12	Group Delay Variation (0 – 3 kHz)	±1μs	±1μs
13	Slew Rate	$> 10V/\mu s$	$> 2.5V/\mu s$
14	Power Bandwidth	0 – 10 kHz	0 – 10 kHz
15	Output Impedance (0 - 3 kHz)	< 0.5Ω	> 250Ω
16	Output Offset	<0.1 V	<0.05 A
17	THD+N	<0.1%	<0.1%
18	IMD	<0.1%	<0.1%
Load Constraints			
19	Worst Case Load Impedance	70 Ω – inf. *	0 – 5 kΩ **
Environmental			
20	Operating Temperature	10 – 40 C^o	10 – 40 C^o
21	Output Offset Drift @ 20 C^o	<0.05% / C^o	<0.05% / C^o
22	Power Consumption	600 VA	10 kVA

* Voltage amplifier load constraints are determined by the maximum output current handling capabilities. Voltage amplifiers must be protected against accidental short circuit, and should remain stable with a capacitive load of up to 220 nF.

** Current amplifier should remain stable with its output open. The actual burden constraints will be determined by the available compliance voltage, output impedance, offset and noise specifications.

range, and all frequency components above one half of the sampling frequency are properly attenuated (60db). The group delay should be virtually constant (linear phase), with minimum variations among different channels. The absolute value of this delay however will be irrelevant for most replaying based systems and may range anywhere from 10μs to 5 ms depending on the interpolation filter design.

The specifications imply that the D/A converter part of the I/O subsystem is followed by an interpolation filter (analog or combined analog+digital), making it impossible to use standard D/A converter terminology (settling time, accuracy) to fully describe the overall system behavior. The combined specifications describing output signal accuracy are given instead: Total Harmonic Distortion + Noise (THD+N), Intermodulation Distortion (IMD), Stop Band Attenuation etc.

It is important to note that the numbers given in Table II represent typical values. The actual range will often be broader, as in the case of digital input and output channel specifications. In a typical system, the digital inputs will most often be used to monitor contact closures from either relays under test or other auxiliary hardware. The digital inputs may therefore be required to accept typical industrial wetting voltages (24 to 250 V_{dc}), or to provide wetting voltage for dry contacts. The same voltage range would be applicable to digital outputs, with output current handling capabilities increased up to 1A.

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 perform perfectly and the power system model is incredibly detailed and accurate, improper amplifier performance will invalidate any test results.

A set of typical power amplifier subsystem specifications is given in Table III. Explanation of of the terms used in Table III is given in [23]. All values were derived by assuming $5A_{rms}$ as a per unit current, and $115/\sqrt{3}\ V_{rms}$ as per unit Voltage levels, and must be scaled accordingly in systems where different per unit values are used.

Interfacing the I/O subsystem with the high power amplifiers requires special attention. In general, the amplifier inputs and outputs should be constructed in such a manner as to avoid all possible interactions between them. In practice this means that the inputs and outputs should not share the same electrical reference, and should preferably be floating with respect to each other. Depending on the actual system implementation, it may even be appropriate to provide galvanic isolation as an integral part of the I/O subsystem analog output circuitry. Properly implemented galvanic isolation not only helps avoid the potentially disastrous feedback across amplifier terminals, but it also allows the user to configure the amplifier outputs and relay connections to better match the connections that will be used in the field.

CONCLUSIONS

This paper summarizes basic digital simulator performance requirements for relay testing. It has been concluded that the following issues need to be considered when the requirements are to be specified:

- Relay test procedures, including the choice of open-loop or real-time interactions between the relay and the power system
- Relay input characteristics, including characteristics of the relay burden
- 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, as well as AC performance, load constraints, and environmental impacts.

REFERENCES

[1] H. W. Dommel, "Digital Computer Solution of Electromagnetic Transients in Single and Multiphase Networks," *IEEE Trans. on Power Apparatus and Systems*, Vol. PAS-88, No. 4, pp. 388–399, April 1969.

[2] A. Williams, R. H. J. Warren, "Method of Using Data From Computer Simulations to Test Protection Equipment," *IEE Proceedings*, Vol. 131, Pt. C, No. 7, 1984.

[3] J. Esztergalyos, et. al., "Digital Model Power system," *IEEE Computer Applications in Power*, Vol. 3, 1990.

[4] M. Kezunović, et. al., "Dyna–Test Simulator for Relay Testing – Part I: Design Characteristics," *IEEE Trans. on Power Delivery*, Vol. 6, No. 4, 1991

[5] M. Kezunović, "Protective Relay Workstation – Application of Digital Simulator for Protective Relay Studies," *Electric Power Research Institute RP 3192-1, Phase I Final Report, EPRI TR-102781*, Palo Alto, California October, 1993.

[6] P. Bornard, et. al., "MORGAT: A Data Processing Program for Testing Transmission Line Protective Relays," *IEEE Trans. on Power Delivery*, Vol. 3, No. 4, 1988.

[7] M. A. Redfern, et. al., "A Personal Computer Based System for the Laboratory Evaluation of High Performance Power System Protection Relays, *IEEE Trans. on Power Delivery*, Vol. 6, No. 4, 1991.

[8] P. G. McLaren, et. al., "A Real Time Digital Simulator for Testing Relays," *IEEE Trans. on Power Delivery*, Vol. 7, No. 1, 1992.

[9] J. R. Marti and L. R. Linares, "Real Time EMTP–Based Transients Simulation," *IEEE Trans. on Power Systems*, Vol. 9, No. 3, August 1994.

[10] D. Jakominich, et. al., "Real–Time Digital Power System Simulator – Design Considerations and Relay Performance Evaluation," *Proceedings of ICDS '95*, College Station, April 1995.

[11] R. J. Marttila, et. al., "Closed Loop Testing with the Real–Time Digital Power System Simulator," *Proceedings of ICDS '95*, College Station, April 1995.

[12] M. Jerosolimski, et. al., "A Real Time Digital Transient Network Analysis for Testing Equipment on a General Purpose Computer," *Proceedings of ICDS '95*, College Station, April 1995.

[13] M. Kezunović, et. al., "Transients Computation for Relay Testing in Real–Time," *IEEE Transactions on Power Delivery*, Vol. 9, No. 3, pp. 1298–1307, July 1994.

[14] M. Kezunović, et. al., "Design, Implementation and Validation of a Real–Time Digital Simulator for Protection Relay Testing," *IEEE Transactions on Power Delivery*, Vol. 11, No. 1, January 1996.

[15] J. A. Jodice, et.al., "Understanding Conditioning Amplifier Response," *Proceedings of ICDS '95*, College Station, Texas April 1995.

[16] *Electromagnetic Transient Program (EMTP) Rule Book*, Bonneville Power Administration.

[17] *Electromagnetic Transient Program (EMTP) Rule Book EPRI EL-6421-I*, Vol. 1, 2, Research Project 2149-4, June 1989.

[18] *Alternative Transient Program (ATP)*, Canadian/American EMTP User Group and European EMTP User Organization LEC.

[19] O. B. Nayak, et. al., "A Totally Graphical User Interface for Electromagnetic Transients Programs," *IEEE Computer Applications in Power*, Vol. 8, No. 1, January 1995.

[20] *Transient Analysis Program for Personal Computers*, Microtran Power System Analysis Corporation, Vancouver, B. C., Canada, 1988.

[21] *Proceedings of the First International Confrence on Digital Power system Simulators – ICDS '95*, IEEE Catalog No. 95TH8172, College Station, Texas, April 1995.

[22] *IEEE C37.111-1996*, "IEEE Standard Format for Transient Data Exchange (COMTRADE) for Power Systems," IEEE, 1996.

[23] *ANSI 54.51-1991*, "AES Standard Method for Digital Audi Engineering–Measurement of Digital Audio Equipment," Audio Engineering Society, Inc., New York, 1991.