PROTECTIVE RELAY WORKSTATION: APPLICATIONS OF A DIGITAL SIMULATOR

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I. Introduction

Interest in the application of digital simulators for the study and evaluation of protective relaying has been spurred by the availability of EMTP and by the development and application of digital fault recording (DFR) equipment. Using a digital simulator, a protective relay engineer can study and evaluate relay performance using the results of EMTP studies of planned or existing power system facilities for faults of varying type, location and initiation angle. DFR recordings of system disturbances with responses of relaying, communications, and breakers, can be applied to a digital simulator for detailed study of protective system performance evaluation in cases of incorrect or marginal responses. The digital simulator can be another tool, in addition to steady state and transient equipment currently available, for relay system test and evaluation for new or revised installations and for post-fault diagnostics.

EPRI and some of its member utilities have been following developments in this new technology for relay evaluation for some time. In concert with a member utility advisory group, a statement of work (SOW) was developed, for an EPRI contract for the Applications of a Digital Simulator in 1990. This SOW was based in part on an unsolicited proposal from Texas A&M University. At that time, Texas A&M University, with partial funding by Houston Lighting and Power Company, (HLP) had assembled and put in operation some of the elements of a digital simulator [1,2]. Bonneville Power Administration (BPA), one of the EPRI advisors, had also designed, constructed and applied a digital simulator. [3]

II. Objectives of The EPRI-Funded Study

The ongoing R&D effort, funded by an EPRI contract with added support from some of its member utilities, is scheduled for completion by about year-end 1991 and has the following objectives:

A. Guidelines for A Full-Scale Digital Simulator for Protective Relaying Studies

These guidelines are intended to provide to a utility information helpful for procuring a digital simulator either through in-house design and construction or by purchase from a supplier. Additionally, it can help a utility evaluate an offsite facility it may choose to use for relay studies -- a facility at some third party or at a relay supplier.

The guidelines are not intended as a design handbook but will be a compilation of key performance parameters along with a review of experience gained from digital simulator installations at utilities, Texas A&M and others. It will recognize that alternative technical approaches can be employed to provide digital simulation for relay studies and will aid a utility should it choose to build, buy or use an available facility.

B. Application of EMTP and DFR Files

1. EMTP for Relay Studies

As a part of the project, the level of Electromagnetic Transient Program (EMTP) complexity required for specific relay studies will be evaluated. EMTP programs, with reduced scope compared with programs run on a mainframe or mini-computer, are now available for use with desktop computers. Wherever these EMTP programs can be applied for relay studies, productivity can be improved. Key questions include the detail of representation of a transmission system under study, instrument transformer modeling for relay needs, etc. A full EMTP study represents the power system in great detail, perhaps hundreds of busses. More limited representation which provides inputs sufficiently accurate for relays studies will simplify the EMTP study. The need for frequency dependent modeling of power system elements for relaying studies will be evaluated. While frequency dependance can be significant for complex power system studies, it may not be required for evaluations of some types of relays. This may lead to additional simplification of some EMTP runs.

Digital models of relay inputs sources are required.for the development of EMTP files for relay studies. A review of available models for CTs, PTs and CVTs will be conducted to evaluate their suitability for relay studies. Particular attention will be paid to accurate representation of effects such as iron saturation which can cause waveform distortion which affect relay performance.

In addition, digital simulation for relaying requires a model of arcs in air -- line to ground and line to line. These are non-linear impedances which can affect the waveform of relay input quantities. This need was checked with EPRI-EMTP activities and found that arc representation to date is for short arcs only, such as in a circuit breakers. An extension of this model to the long arcs involved in faults on overhead transmission systems will be made available.

Other models available in EMTP, which also need review for relay evaluation studies, include protection for series capacitors.

2. DFR

Guidelines for the application of Digital Fault Recordings (DFR) files for digital relay studies are required. Some custom interfacing is required since at this point the format of DFR equipment is not standardized. Maximum use of the emerging IEEE standard for data exchange (COMTRADE) is planned. [4]

C. Test Cases

Another objective of the EPRI/TAMU effort is to provide a series of test cases which will help in the interchange in protective system studies between utilities and between utilities and suppliers. This is envisioned as detailed data, probably stored on disk, for typical faults for a number of power system configurations. Some of these test cases will be synthesized as representative of typical configurations; others will be actual, complex cases solicited from utilities.

As now planned for facility verification, test cases would be inputted to a digital simulator and output waveforms recorded with a specific burden representative of a typical relay configuration.. Comparison of the output waveform of the digital simulator to an analog representation of the input would be used to verify that digital simulator facilities are in agreement even though design details may differ.

III. Results-To-Date

The results obtained so far fall into four categories:

- Development of new software
- Completion of the DYNA-TEST simulator configuration
- Generation of library of test cases
- Production of simulator guidelines

A. Development of New Software

Development of new software includes the following packages:

- DFR and EMTP file conversion software
- Test file management software

1. DFR and EMTP File Conversion Software

At is well known, all of the Digital Fault Recorders (DFRs) available on the market have different file formats for their recorded data. These files are originally in a binary format with different arrangement of the data fields and bits.

Regarding Electromagnetic Transient Programs (EMTPs), the output data files may also be different going from one package to another. The EMTP output files are available in either binary or ASCII format. These files contain, besides the samples of the voltage and current signals, some modeling information relevant to the simulation at hand.

A software package has been developed to convert DFR and EMTP files into a common data format. There are two common data formats: binary format of the D/A converter driver used in the DYNA-TEST simulator design; ASCII format defined by the latest version of the COMTRADE standard draft [4].

The conversion software takes data from several different DFRs and EMTPs and produces a data file with a common data format. The software has several options that enable operators to perform selection of the channels as well as the number of the sample points that need to be converted per channel.

2. Test File Management Software

This software package is needed to prepare a test file. The conversion software is interfaced to this package.

The main functions of the package include file loading, editing, saving, plotting, processing, and formatting. These functions are implemented using a general purpose signal processing package [5].

File loading enables use of the files converted by the conversion software, or files generated by the file management software itself. File editing is related to selection of test signals out of the number of signals provided in the original DFR or EMTP file. Editing of test signals may also require truncation of the signal length. The files that are edited can be stored using the saving function or plotted using the plotting option. The selected test files can be processed using signal processing routines to perform signal decimation/interpolation. This is done in order to obtain a standard sampling rate used by the signal reconstruction subsystem of the simulator. Also, various signal parameter calculations can be performed to obtain symmetrical components or frequency spectrum of the signals. Finally, the test file formatting routine makes sure that the test signals are ordered in the sequence recognizable by the D/A driver software and that they are in the proper binary format used by the driver software.

B. Completion of the DYNA-TEST Simulator Configuration

The DYNA-TEST simulator developed at Texas A&M University has been designed and tested for its performance [1,2]. Some additional hardware needs to be added to provide for a full simulator configuration. The following activities are aimed at resolving this issue:

- Development of dedicated I/O hardware
- Study and selection of power amplifiers

1. Dedicated I/O Hardware Development

This hardware is related to high-precision test signal reconstruction. Digital files, generated by either DFR or EMTP, need to be converted to analog signals for relay testing.

The TAMU simulator will have a unique D/A conversion subsystem design with the following characteristics:

- 16-bit resolution
- serial interface
- compatibility with both UNIX and DOS machines
- galvanic isolation at the digital signal level
- variable output signal sampling frequency
- output signal filtering for smoothing

In addition, digital I/O interface will be provided to accommodate contact interfaces between a relay and the simulator.

At this time, dedicated I/O hardware has been designed and implementation is underway.

2. Power Amplifier Study and Selection
The TAMU simulator will be completed by adding dc-coupled power amplifiers. A study has been initiated to select power amplifiers. Power amplifier samples from different manufacturers are under study.

A part of the amplifier study is related to measurement of the amplifier characteristics. A test plan for power amplifier study has been developed. and the most important measurements are included in Table I.

Preliminary requirements for power amplifiers are defined. Table II is a summary of these requirements.

Development of the I/O hardware and the amplifier study are to be completed soon. It is expected that the full configuration of the TAMU simulator will be operational in the late summer of 1991.

Table I. Power Amplifier Tests

Basic Small Signal Parameter Measurements
1 - Output Offset Voltage/Current 2 - Output Noise 3 - Amplifier Gain 4 - Input Impedance 5 - Small Signal Frequency Response 6 - Output Impedance Vs. Frequency 7 - Rise Time 8 - Settling Time 9 - Slew Rate
Pass/Fail Tests and High Power Measurements
10 - Output Voltage Clipping Point 11 - Maximum Output Current/Current Limiting 12 - Transient Overload Recovery 13 - Stability vs. Load Variations
Application Specific Tests
14 - THD vs. Frequency, Level and Load Variations 15 - Intermodulation Distortion Level 16 - Frequency Response vs. Output Level and Load Variations 17 - Power Supply Induced Intermodulation Distortion

Table II. Preliminary Power Amplifier Requirements

PARAMETERS	VOLTAGE AMPLIFIERS	CURRENT AMPLIFIERS
1.1 OUTPUT OFFSET VOLTAGE	< 0.1% FSR	
1.2 OUTPUT OFFSET CURRENT		< 0.1% FSR
2. OUTPUT NOISE LEVEL	< 0.1% FSR	< 0.1% FSR
3. AMPLIFIER GAIN	15 < G < 300	5 < G < 200
4. INPUT IMPEDANCE	> 600 ohm OVER FREQUENCY R.	
5. SMALL SIGNAL FREQUENCY RESPONSE	DC - 7 kHz ± 1dB	
6. OUTPUT IMPEDANCE	< 1% of the LOWEST SPECIFIED LOAD IMPEDANCE	>100 TIMES HIGHEST SPEC. LOAD IMP.
7. RISE TIME	< 0.4 mS	< 0.4 mS
8. SETTLING TIME	< 0.6 mS	< 0.6 mS
9. SLEW RATE LIMIT	> 1.5 V/us	> 1A/us
10. OUTPUT VOLTAGE CLIPPING	> 150 V	> 30 V
11. MAXIMUM OUTPUT CURRENT	> ± 75mA $_{PIK}$	> ±100 A $_{PIK}$
12. TRANSIENT OVERLOAD RECOVERY	No significant delay should be introduced due to overload conditions. No instability should be encountered.	
13. STABILITY vs. LOAD VAR.	Amplifier should be unconditionally stable over the entire load and frequency range.	
14. THD LEVEL vs. FREQUENCY AND LOAD VARIATIONS	0.2 %	< 1%
15. SMPTE. INTERMODULATION D.	< 1%	< 5 %
16. FREQUENCY RESPONSE vs. FREQUENCY AND LOAD VAR.	No more than ± 2dB variations over the specified load range with full power bandwith broader than 0-1kHz (-3dB point)	
17. POWER SUPPLY INDUCED INTERMODULATION DIST.	< 0.1%	< 0.1% of the max. output current level

C. Generation of Library of Fault Cases

This activity is aimed at generating fault case files that may be used for extensive relay study. The test files are to be organized in a library. Sourcse for fault case are:

- EMTP simulated cases
- DFR fault records

1. EMTP Simulated Cases

The system shown in Figure 1 has been chosen to develop the techniques for building a library of fault cases for data exchange between digital simulator facilities. The library will include, typical transmission system configurations including parallel lines, three terminal lines, lines with series and shunt compensation, etc. In addition, there will be cases in the library developed from recordings and analyses of complex faults provided by the EPRI project advisors and others.

The system of Figure 1 contains two ideal voltage sources in series with coupled balanced source impedances. They are connected by a transmission line of length 120 miles with series capacitor compensation.

The following factors are varied to generate nine different fault cases for this simple system:

1. Fault location (switches SW1, SW2, SW3)
2. Fault incidence angle (0 and 90 degrees)
3. Series capacitor compensation together with its associated protection circuit (switch SW4).
4. Transmission line model (frequency dependent or constant parameter distributed line models). Table III describes the nine cases simulated. In all cases, the simulated faults are three-phase to ground solid shorts and they are cleared by the near end (right) relay in seven cycles and by the remote end (left) relay in five cycles. All relevant data are shown on the given diagram in Figure 1. The transmission line is modeled using frequency dependent (FD) and the constant parameter (CP) models.

2. DFR Fault Records

The cases for this part of the study come from utilities and include actual fault records obtained by DFRs.

The most difficult part of generating a library of DFR files is retrieval of all of the recording setup details relevant for the file reply. In particular, recorder antialiasing filter and A/D converter information is needed to determine the level of recording accuracy provided by the given file.

Table III. Description of Fault Cases

Case No:	Fault Switches SW1	SW2	SW3	Cap. Switch SW4	Fault Incidence Angle	Tr. Line Model
1	0	0	1	1	90	FD
2	0	1	0	0	90	FD
3	0	0	1	0	90	FD
4	1	0	0	1	90	FD
5	1	0	0	0	90	FD
6	0	1	0	0	90	CP
7	0	0	1	0	90	CP
8	0	0	1	1	0	FD
9	0	1	0	0	0	FD

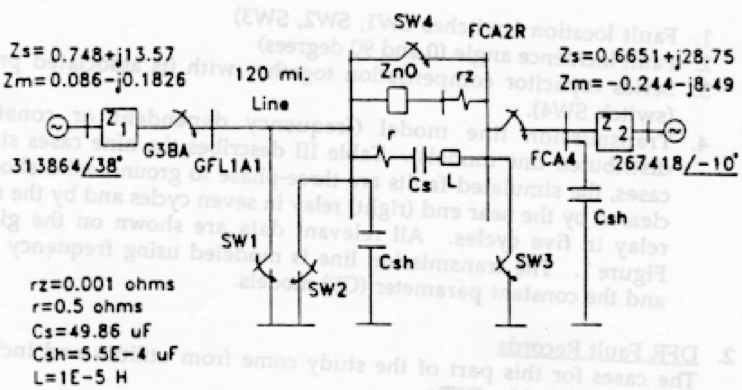

Fig. 1. Study System used for the Fault Cases

D. Production of Simulator Guidelines

One of the goals of this project is to generate simulator design guidelines that may be used by utilities for purchasing or designing a simulator facility. The guidelines can also be used to evaluate an existing simulator facility exists which may be employed by a utility to perform a relay study.

The following sets of guidelines are to be generated:

- Requirements Specification
- Accuracy Assessment
- System Modeling

1. Requirements Specification
These guidelines are to cover performance requirements of a simulator design. They are related to data file generation, signal reconstruction and signal amplification subsystems.

A data file generation subsystem includes EMTP and DFR facilities. Detailed performance requirements needed when generating a data file for relay testing will be specified. A typical example of the items to be included in the specification is given in Table IV for the EMTP system modeling.

Table IV. Requirements Specification for System Modeling

- Lines
  - Transposed
  - Untransposed
  - Cascaded Π.
  - Frequency Dependent
  - Constant Parameter
  - Mutually Coupled Circuits
  - Series and Shunt Compensated (with MOVs)
  - Underground Cables

- Source Equivalents
  - Constant Frequency
  - Frequency Dependent

- Transformers
  - Phase Shifting
  - Three-Phase Transformers with Saturation
  - Power Transformers with Different Connections
- MOVs, MOVs with Gaps, Gaps
- Shunt Reactors

- Grounding Banks
- Switches
- Sources/Loads
  - Synchronous Machines
  - Induction Machines
  - Constant Impedance Loads
  - Ideal Voltage Sources
- Instrument Transformers
  - Current Transformers
  - Capacitor Coupled Voltage Transformers
  - Potential Transformers

2. Accuracy Assessment

This document is to provide both methodology and test cases needed to assess accuracy of a simulator design. Such a set of guidelines can be used to evaluate a given simulator design by measuring the errors involved in producing relay test signals.

The guidelines will be generated for accuracy assessment of the simulator subsystems and the overall systems. The subsystems to be included are:

- Data File Generation Software
- Waveform Reconstruction Subsystem
- Power Amplifier Subsystem

The tests for the overall system will include the following:

- Frequency Response
- Harmonic Distortion
- Intermodulation Distortion
- Dynamic Range
- Phase Response
- Offset
- Gain

The set of guidelines for accuracy assessment will be used to quantify the accuracy of the TAMU simulator design.

3. System Modeling

Power system modeling for relay studies is done using the EMTP package [6]. This software is developed as a general simulation tool for various power system studies such as switching surges, insulation coordination, etc.

Guidelines will be developed to assist relay engineers when building power system models for relay studies. These guidelines will include instructions for setting up typical modeling problems such as:

- System Equivalencies
- Selection of Line Models
- Modeling of Autoreclosing Sequences
- Modeling Out-of-Step Conditions
- Control Sequences for Simulation of Various Faults

Guidelines for modeling important for relay studies are not fully developed in the EMTP package. One issue is modeling of instrument transformers such as current transformers (CTs), potential transformers (PTs) and capacitor coupling voltage transformers (CCVTs). To model instrument transformers, particularly CTs and CCVTs, it is necessary to include nonlinearities which are a consequence of iron core saturation. Generally analog simulators for protective relay evaluations have used analog models: scaled-down CTs and operational amplifier models for CCVTs.

Digital models reviewed to date fall into two categories. The first makes use of the excitation curve of a CT provided by the supplier. The steady-state (rms) excitation curve is translated into "instantaneous" format by means of software for use in a CT or CCVT digital model. The second category uses mathematical, digital representation of the B-H characteristics of the core iron of the particular instrument transformer in the CT or CCVT model. Each of the approaches involves approximations and analyses are beyond the scope of this paper. The area of digital modeling of instrument transformers requires further study by the industry for standardization and/or to establish equivalency among different models.

The models developed and applied to date in this project are described below:

The CT model may be implemented using the EMTP nonlinear elements (Type 98 or Type 96). In this case, the CT model may be represented by a circuit diagram shown in Figure 2.

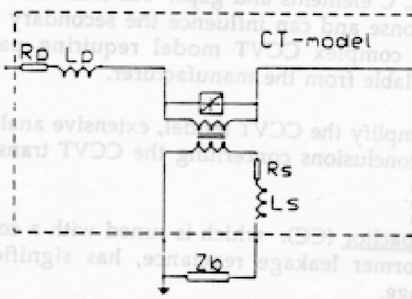

Figure 2. CT Model

The model parameters are as follows: ratio, rated burden (VA), winding resistance and leakage inductance, and core V-I characteristics. These values are commonly supplied by manufacturers. .

The CCVT model has a complex structure. As example, a particular CCVT type can be represented as shown in Figure 3.

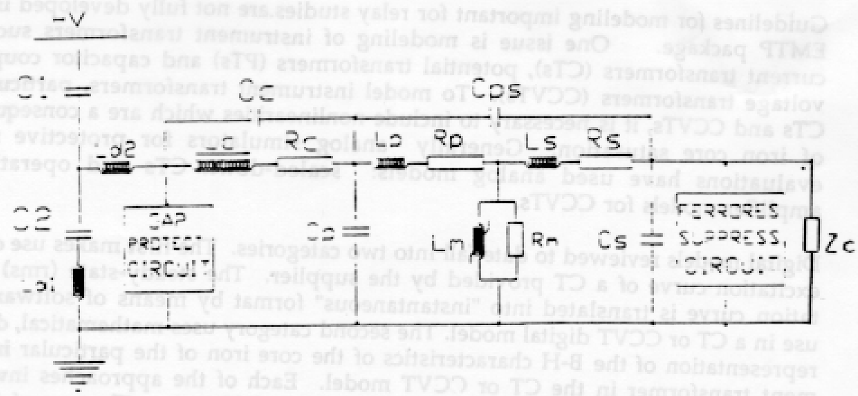

Figure 3. CCVT Model

The CCVT model consists of nonlinear elements such as: compensating reactor, step-down transformer, ferroresonance suppression circuit inductor, and many circuits with L, C elements and gaps. All these elements can influence the CCVT transient response and can influence the secondary signal. Their representation results in a complex CCVT model requiring parameter data which is not generally available from the manufacturer.

In order to simplify the CCVT model, extensive analysis has been done. Some of the relevant conclusions concerning the CCVT transient response are mentioned below.

<u>Coupling Capacitor</u> (CC): which is tuned with a compensating reactor and step-down transformer leakage reactance, has significant influence in the lower frequency range.

<u>Compensating Inductor</u> (CI): has been represented in the CVT with its stray capacitance. Investigations in frequency domain show that the influence of CI stray capacitance on CCVT frequency response is considerable at high frequencies.

Step-Down Transformer (SDT): impedances are measured with the windings short-circuited and open-circuited, respectively. The influence of SDT winding stray capacitances on frequency response shows that the influence of C_{ps} and C_3 on frequency response is small and can be neglected. Primary winding stray capacitance C_p is much higher than C_3. Its influence on frequency response is significant at higher frequencies (above 1kHz) and it is incorporated in the CCVT model. The TRANSFORMER model existing in EMTP has been used to represent the CCVT step-down transformer with saturation.

STD Iron Loss Resistance: also has considerable influence on frequency response and it should be included in the model.

As a final result, the system modeling guidelines will include instructions for building various types of instrument transformers. Further study will, therefore, include validation of the models already developed and development of some new models of additional types of transformers.

IV. Summary

The following is the summary of the project status:

- Most of the basic work for system modeling is completed. Future activities will concentrate on generation of modeling guidelines, fault cases for the library and appropriate CT, PT and CCVT models.
- The simulator facility at Texas A&M University will be completed by the late Summer 1991. Appropriate design of I/O hardware and software is to be implemented and the amplifiers are to be selected by that time.
- Added DFR cases and system fault studies will be collected and/or generated to enable specification of various test cases for simulator performance evaluation and relay studies.

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VI. References

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