AN ADVANCED SIMULATION AND TESTING ENVIRONMENT FOR DESIGN, APPLICATION AND PERFORMANCE ASSESSMENT OF PROTECTION EQUIPMENT

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INTRODUCTION

Utilization of advanced technologies in developing new protective relaying equipment has resulted in a variety of microprocessor based designs, digital communication schemes and intelligent techniques being successfully applied for protective relaying today. This development has also led to a need for advanced tools for simulation and testing of the new solutions. An efficient assessment of the protection equipment design, application and performance became essential for acceptance and justification of the new technologies and solutions [1–3].

Development of the modeling environments for relay simulation and testing has resulted in a variety of hardware and software solutions [4]. A full ability for open loop and real–time relay evaluation has been achieved at both the simulation and actual device testing level [5,6]. At the same time, the cost of the required simulation tools has been significantly reduced when compared to the previous approaches [7].

This paper gives an overview of the requirements for performance assessment of protection equipment taking into account advances in the simulation technology and related tools. The basic features of the simulation and testing environments needed to meet the requirements are also discussed. Examples of different hardware and software developments of new simulation environments undertaken by the author and his research team are outlined. Some most relevant experiences are pointed out in the conclusions.

REQUIREMENTS

The performance assessment requirements can be summarized as given in Table I. The assessment requirements ask for an ability to verify the relay design and application performance.

The relay design assessment is needed when a new relay design is introduced. A vendor or utility may want to evaluate the relay design characteristics to make sure that its performance is as expected. Typically, this type of evaluation is performed using phasors representing prefault, fault and post fault waveforms. Once these waveforms are subjected to a relay, it is possible to get measurements of the corresponding relay operating characteristics. As a result, one can compare these characteristics with the theoretical ones that can be derived for a given design. Due to the flexibility of the existing relay designs, this performance evaluation is needed for characterizing the relay steady–state and dynamic operating characteristics, as well as its "expanding" properties resulting from the various polarizing schemes. An ability to perform these tests automatically and represent the results visually are the main requirements in this area.

TABLE I – Performance Assessment Requirements

Performance	Required Considerations
Design	Relay Operating Characteristic Phasor Concept
Application	Relay Selectivity Operation Times Transient Waveforms

The application performance assessment is related to the relay behavior under actual fault conditions in a given power system. This assessment is concerned with relay's ability to respond correctly under fault conditions, as well as its capability to achieve correct operation within a required time interval. In order to perform this evaluation, the relay has to be subjected to the transient waveforms that closely resemble actual fault events. The key requirement in this area is the ability to generate fault transients in a variety of ways, including reproducing recorded waveforms and generating waveforms through simulations. Automating the overall testing procedure and representing the test results in a user friendly fashion are also important requirements.

MODELING AND TESTING FEATURES

This section discusses various hardware and software features needed to perform simulation and testing. The reasons for requiring such features are also presented.

Protective System Modeling

The protective system consists of the power system, instrument transformers and protective relays.

Power system modeling is typically performed using an electromagnetic transient program (EMTP). A variety of such programs is in existence and almost all of them use a standard EMTP modeling approach [8]. However, it is important to note that the original EMTP developments were not aimed at protective relaying studies. As a result, modeling of faults on some apparatus, such as generators and power transformers, can not be implemented in a straight forward way and more work is needed in this area. Other outstanding issues include

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the network equivalencing rules, criteria for selection of the transmission line models and modeling of other disturbances, such as out-of-step conditions.

Another modeling issue is the instrument transformer. An accurate representation of the transient behavior, as well as nonlinear phenomena can be achieved, but this may require extensive field measurements and laboratory testing to determine needed model parameters [9,10].

The final modeling issues are the protective relays themselves. Advances in the modeling tools have been made recently allowing for a variety of approaches to be taken in modeling electromechanical, solid-state and microprocessor-based relays [3]. A part of the relay modeling task is representation of the relaying communication channels as well.

Test Waveform Generation

Relay testing requires generation of test waveforms. The main choices in this area are the following approaches: EMTP, recorded waveforms, general purpose waveform generators.

The EMTP is well known source of transient waveforms that correspond to actual fault events. Due to a large number of fault cases that need to be simulated in a typical relay evaluation study, it is very important to have a user-controlled feature for generation of test cases by automatically changing location of faults, incidence angle, fault type and fault resistance. It is also desirable to be able to replay a batch of test waveforms in a selected sequence automatically.

An ability to replay actual waveforms recorded in the field using digital fault recorders (DFRs) is also a highly desirable feature. This means that a software facility for converting various DFR file formats into a common format should be available. A variety of signal processing functions enabling preparation of a test file out of a DFR record are also needed [11]. A software capable of recognizing the recorded events automatically would also be useful when a new DFR file is to be used.

Finally, a software facility to synthesize any waveform using analytical expressions should be readily available. This feature is quite useful when a sensitivity of a given relay design to various signal components is being evaluated.

Waveform Replaying

Depending on the complexity of a given relay evaluation study, several different waveform replaying features may be required.

The most common approach to waveform replaying is an open-loop mode where the waveform is generated and submitted to the inputs of a relay or relay model. In this case, no feedback from the relay to the power system is taken into account. The feedback can be taken into account if multiple open-loop tests are performed in an interactive fashion. This approach may be quite tedious and time consuming when a multiple autoreclosing shots or other complex interactive phenomena are studied.

To facilitate simulation of the interaction between the simulator and relay, a real-time approach can be taken. This approach is available for representing an interaction between the power system model and relay model, as well as between the power system model and actual relays.

Another important feature related to waveform replaying is an ability to replay waveforms into several relays simultaneously. This is quite convenient when performance of several relays, under common fault conditions, is studied. Typical examples are behavior of the relays on a parallel line for a fault on the adjacent line. It is important that both the modeling environments and digital simulators allow for synchronized replaying of waveforms at multiple relaying locations.

Waveform Processing

As mentioned earlier, various protection system modeling and simulation, as well as waveform generation and replaying steps require different waveform processing features to be readily available.

A set of waveform processing features is related to file conversions. Besides the mentioned file format conversions for EMTP, DFR and custom software formats, it is also important to have decimation and interpolation features for converting the sample sets from one sampling frequency to another. This is needed to accommodate for different sampling rates used at the power system modeling level, relay modeling level and waveform digital-to-analog (D/A) conversion level.

The next set of waveform processing features is related to waveform modifications including filtering, cut-and-paste actions, extension of pre-fault data, editing of contacts, and alternating the signal polarity [12]. These features are needed when dealing with different testing actions requiring that specific waveform properties be changed or modified to investigate relay sensitivity under these circumstances.

One other important waveform processing feature is the fault analysis capability. The basic need, in the protective relaying studies, is to be able to represent test waveforms, both in the time and frequency domain. In addition, other types of transforms, such as wavelets, may have to be calculated for various considerations of the test waveform properties.

User Interface

Various features associated with user interfaces are listed in Table II.

The user interface features are very important for efficient simulation and testing studies and need to be implemented using the most advanced software concepts.

TABLE II – User Interface Features

Feature	Requirements
Graphical User Interface	One–line diagram of power system Automated generation of faults Automated system equivalencing
Data Bases	Interfaces to various programs Relational and object oriented data representation
Test Result Analysis	Automated comparison of actual versus expected relay performance
Displaying of Waveforms	Simultaneous waveform representation at various relaying points
Test Result Representation	Automated retrieval and reporting of test results
Test Sequence Control	Automated testing in open–loop and real–time modes
Protective Relay Modeling	Modeling facilities to build models of power systems, instrument transformers and relays

EXAMPLES OF RECENT DEVELOPMENTS

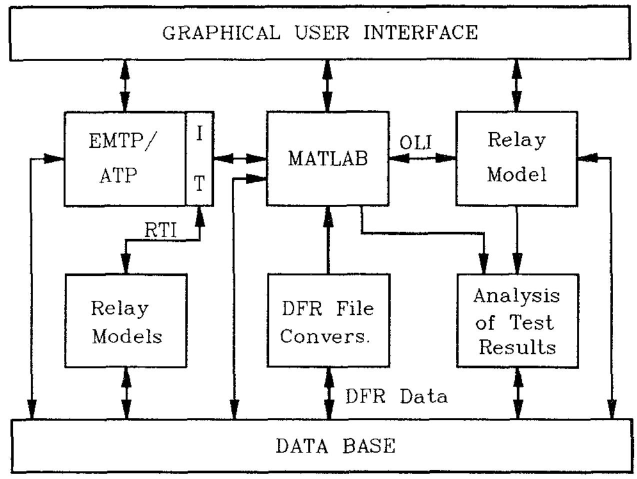
This section summarizes the recent development of modeling environments and digital simulators at Texas A&M University (TAMU). These developments are summarized in Table III.

TABLE III – Recent TAMU Developments

Development	Description
Modeling Environment	Modeling of power systems, instrument transformers and relays; open-loop and real-time interaction
PC-Based Digital Simulator	Open-loop design; extensive modeling, file conversion and signal processing features
Workstation-Based Digital Simulators	Open-loop and real-time designs Multi-terminal simulator configuration

Modeling Environment at TAMU

Developments of modeling environments at Texas A&M University (TAMU) date back to the late eighties. Over the years, several enhancements were made to introduce a more complete modeling environment where digital fault recorder (DFR) files could be imported [11]. These files allow for evaluation of relay models using fault data recorded in substations. Further enhancements were aimed at adding elaborate signal processing and analysis features using the MATLAB package, as well as extensive database and graphical user facilities [13]. In addition, a software for automated analysis of test results has been implemented [12]. Finally, a software facility for real–time interfacing between protective relay software models and ATP was recently realized [5]. A summary of the overall modeling environment is given in Figure 1. A real–time version of this environment is shown in detail in Figure 2.



OLI–Open–Loop Interaction; RTI–Real–Time Interaction IT–Instrument Transformers

Fig. 1. TAMU's Modeling Environment Features

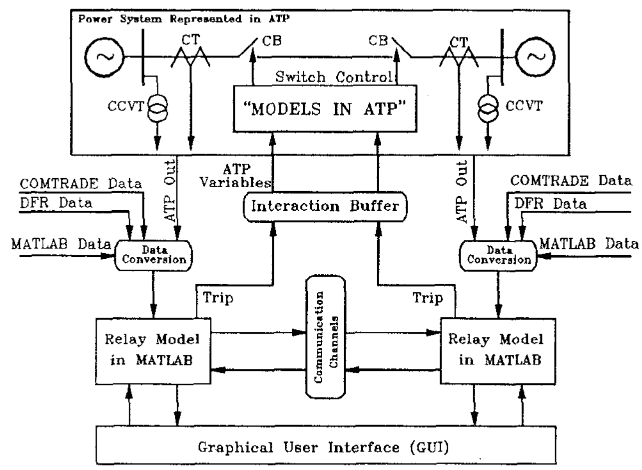


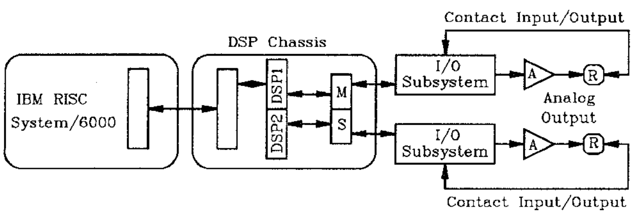
Fig. 2. Real–Time and Open–Loop Features

Digital Simulators at TAMU

Digital simulator developments at Texas A&M University (TAMU were initiated in the late eighties and the first digital simulator configuration was assembled in the early nineties. After that, elaborate open–loop simulator developments were undertaken under the sponsorship of EPRI [13]. These developments resulted in both a PC–based and workstation–based open–loop configuration. The PC–based simulator was delivered to Florida Power and Light Company while the workstation–based one was delivered to Western Area Power Administration. Houston Lighting and Power Company and Pacific Gas and Electric were co–sponsors of these developments as well. In parallel to these efforts, an advanced real–time digital simulator was developed for Western Area Power Administration [6]. This development has been combined with an open–loop development to provide a new digital simulator design for the Commonwealth Edison Company of Chicago. This simulator was capable of combined, user configurable, real–time and open–loop operation [14].

The most interesting feature of the simulator developments at TAMU is the use of commercial computers for the simulator implementation. This approach has enabled development of a modular concept for configuring various simulator options ranging from PC–based open–loop, to workstation open–loop, and workstation–based real–time configurations. Such a concept provided an ability to select an optimal hardware/software solution to match the required cost/performance criteria [7]. As a result, TAMU's simulator technology has been commercialized by Test Laboratories International, Inc. (TLI).

The basic hardware configuration of TLI's digital simulator designs is shown in Figure 3.



M – Master A – Amplifiers
S – Slave R – Relays

Fig. 3. Hardware Architecture

A summary of the simulator configuration options, as well as related hardware and software modules offered by TLI is given in Table IV.

TABLE IV – Configuration Guide for TLI Simulators

Hdwr/Sftw	Open-Loop PC-Based	Open-Loop Wrkst.-Based	Real-Time Wrkst.-Based
PC	X	–	–
IBM RISC 6000 (Low Perform.)	–	X	–
IBM RISC 6000 (High Perform.)	–	–	X
I/O Cabinet (TECHRON)	up to 3 terminals	up to 3 terminals	up to 3 terminals
EMTP/ATP	X	X	–
Real-Time Syst.	–	–	X
Graphical User Interface	X	X	X
Signal Processing (MATLAB)	X	X	X
Instrument Transformer Models	X	X	X

CONCLUSIONS

Based on the discussion given in this paper, the following conclusions are reached:

- Advanced simulation and testing environments are needed for efficient relay evaluation.
- Modern digital simulator designs provide an extensive relay testing environment at an affordable price.
- The latest developments at Texas A&M University, and other places, indicate that a variety of solutions can be realized using a modular design implemented with the latest hardware and software technology.

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