ADVANCES IN PROTECTIVE RELAY SIMULATION AND TESTING

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Abstract– This paper discusses major advances in development of digital simulation environments and digital simulators for protective relay evaluation and testing. An overview of the world wide developments is given first. A discussion of the developments at Texas A&M University is given next. Practical consequences are discussed at the end.

Keywords: Digital Simulators, Protective Relaying, Relay Testing, Electromagnetic Transient Program, Relay Modeling, Simulation

INTRODUCTION

One of the first proposals for digital relaying dates back to the late sixties [1]. The first digital relay prototype using a mini–computer was installed in a substation at the beginning of the seventies [2]. Soon thereafter, microprocessors were invented and microprocessor–based digital relays were introduced in the early eighties [3]. In the mean time, a variety of digital algorithms and related relaying concepts were introduced. As a result, different digital protective relays and protective systems were developed [4,5]. Today, the field of digital relaying has matured with an established product line offered by all of the major relay manufacturers. As a sign of the maturity of the field, several excellent books have already been written on the subject [6,7,8].

As the field of digital relaying was developing, a need for evaluation of digital algorithms and testing of digital relays was recognized. Initial studies of digital algorithms have shown performance differences among various algorithms [9]. This issue has stimulated further developments of simulation methods for algorithm evaluation and digital simulators for relay testing [10,11]. Despite these initial efforts, the field of simulation environments and digital simulators was developing much slower than the field of digital relay and system designs. This discrepancy was quite noticeable in the late eighties which led to new developments of simulation environments and digital simulators to be initiated. As a result, some major advances in this field were recently made [12,13].

This paper first describes the meaning of the simulation environments and digital simulators. After that, historic developments of simulation environments and digital simulators are surveyed. At the end, some advanced developments undertaken in this field at Texas A&M University over the last 6 years are discussed. Finally, some practical uses of the new developments are outlined

TERMINOLOGY AND DEFINITIONS

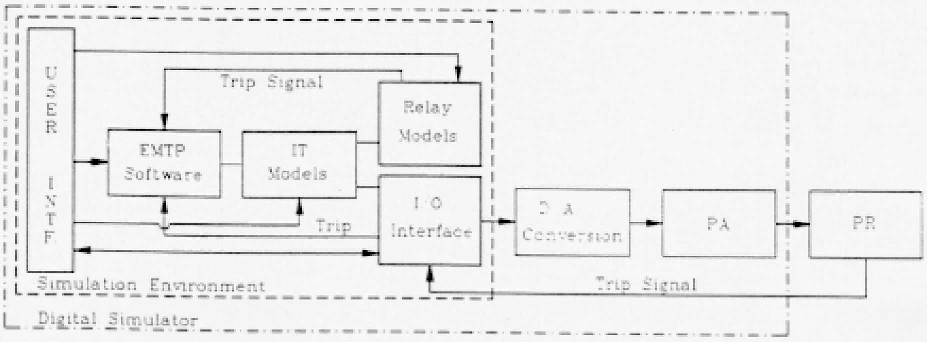
This section is aimed at explaining differences between the terms "simulation environments" and "digital simulators". Furthermore, definitions of real–time and open–loop evaluations of relay models and devices are outlined.

A simulation environment is meant to denote an all–software set–up where the power system and instrument transformers, as well as protection relays and protective systems are represented using software models. These types of environments can be implemented on a general purpose computer and may be used for different studies aimed at evaluating digital algorithms and final product designs for protective relaying. A typical procedure used for evaluation is to simulate power system faults using an electromagnetic transient program. As a result, fault waveforms of voltages and currents are obtained. These waveforms are fed into the instrument transformer models and the responses are simulated. The output waveforms correspond to the fault waveforms seen at the secondaries of actual instrument transformers. These waveforms are then taken as inputs to the models of digital relays. The relay algorithm and operation are simulated and a trip/no trip response is obtained. This response may be fed back into the power system model via operation of a switch corresponding to a circuit breaker tripping. This approach would allow for simulation of the interaction between the relay and the power system, as seen during autoreclosing sequences, for example. The main property of the simulation environments is digital implementation of the models, as well as digital representation of the analog waveforms of voltages and currents.

A digital simulator is meant to denote a combination of hardware and software aimed at generating analog waveforms that can be fed to a relay or relaying system for testing purposes. A digital simulator still has a simulation environment for generating fault waveforms and simulation of instrument transformer responses. However, the generated waveforms are converted via Digital-to-Analog (D/A) converter into analog waveforms. These waveforms are amplified using power amplifiers, and submitted to an outside protective device. In this case, an interaction between the relay and simulator may also be implemented to allow for emulation of the interaction observed in the actual power system. Figure 1 gives a combined representation of the simulator environments and digital simulators.

Another important concept in evaluating protective relays using digital simulation environments and simulators is the concept of open-loop and real-time interaction. These interactions are meant to indicate a type of feedback coming from the relay to the power system. This interaction is shown in Figure 1, both between the relay model and power system model, as well as between the physical relay and digital simulator.

The open-loop interaction is defined as the interaction where protective relay model, or physical device, are receiving fault waveforms, making decisions and issuing a trip signal. However, this trip signal is not used to cause an immediate reconfiguration of the power system model that results in a new set of waveforms generated by the new model. Instead, the power system model is not changed after the original fault is simulated. The real-time interaction, on the contrary, is defined as the one that causes immediate change in the power system model that reflects operation of a circuit breaker due to the relay tripping. As a result, a new set of waveforms is generated by the new model represented by the reconfigured power system network. Ideally, the "immediate" change is considered as the change that takes place within the same EMTP simulation time step relative to the occurrence of the relay trip signal.



IT–Instrument Transformers PA–Power Amplifiers PR–Protective Relays

Fig. 1. Simulation Environments and Digital Simulators

SIMULATION ENVIRONMENTS

The key ingredient of a digital simulation environment for protective relay studies is an electromagnetic transient program (EMTP) [14]. Since the time of the introduction of this concept, a variety of EMTPs were developed [15–20]. All of these programs are used to model power system components and simulate various power system events, including faults.

The next important component of a digital simulator environment is the instrument transformer. A variety of current and voltage transformers are presently used in the relaying field, so adequate models are needed. The most typical approach to modeling instrument transformers is by using related EMTP components. However, it is still a challenging problem to select proper components, appropriate equivalent network topology and related parameters to represent different instrument transformer characteristics [21,22]. A number of different current transformer (CT) models were introduced in the past, concentrating on proper representation of the iron core hysteresis, saturation, and remanent magnetism [23–25]. Likewise, various capacitor coupling voltage transformer models were introduced to reflect different topologies of the ferroresonance circuit, influence of the step-down transformer and stray capacitance effects [25–29].

The next item required to make a complete representation of the relaying set-up is the relay model itself. Modeling of protective relays spans from electromechanical to solid state and microprocessor based relays [30–32]. A number of different techniques were used to represent these relays [33,35].

Finally, an interaction between the power system model and a relay model needs to be represented and simulated. Again, a variety of approaches were taken in the past, ranging from an open-loop to real-time interaction [12,36,37].

A summary of various approaches used for relay modeling, together with related references, is shown in Table I.

Table I. Approaches to Relay Modeling

Modeling Approach	References
EMTP-TACS	[34]
ATP-Models	[9]
Fortran Code Embedded in EMTP	[36,37]
Independent "C" Code (High Level Language)	[12]
MATLAB	[35]

Table II. Real-Time Digital Simulators

Original Developer	Vendor	EMTP Software	Hardware Platform	References
TAMU	TLI, Inc.	RTS	IBM RISC 6000 Workstation	[44]
Manitoba Hydro	RTDS	EMTDC	Custom Designed Multiprocessor Platform	[45]
EdF	EdF	ARENE	HP Convex Multiprocessor Workstation	[46]

TAMU - Texas A&M University
EdF - Electricite de France
RTS - Real-Time System
ARENE - Real-Time EMTP
TLI, Inc. - Test Laboratories International, Inc., U.S.A
RTDS, Inc. - Manitoba, Canada

DIGITAL SIMULATORS

All of the initial digital simulators were open-loop designs. After the initial developments, several PC-based and workstation-based designs were introduced [38]. In the U.S.A., some of these designs were developed by utilities [39], some by vendors [40], and some were developed in a joint collaboration between universities and utilities [41-43].

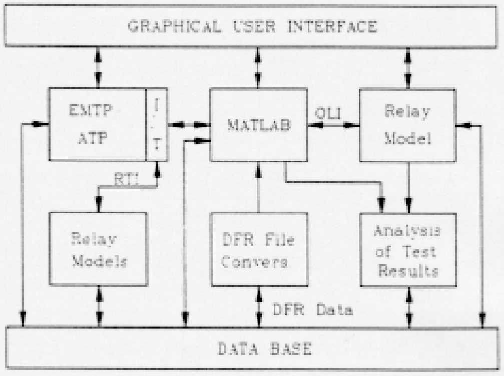
After the open-loop simulators became readily available, the development efforts have shifted into the direction of real-time simulator developments. A number of research and development efforts were involved in this area around the world [38]. As a result, several real-time digital simulator designs have been developed [44-46]. A summary of some of these developments that are commercial offered is given in Table II indicating different approaches undertaken in the selection of hardware/software characteristics.

SIMULATION ENVIRONMENTS AT TAMU

Developments of simulation environments at Texas A&M University (TAMU) date back to the late eighties [47]. Over the years, several enhancements were made to introduce a more complete simulation environment where digital fault recorder (DFR) files could be imported [48]. 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 [42,43,47,49,50]. In addition, a software for automated analysis of test results has been implemented [43]. Finally, a software facility for real-time interfacing between protective relay software models and ATP was recently realized [12]. A summary of the overall simulation environment is given in Figure 2.

DIGITAL SIMULATORS AT TAMU

Digital simulator developments at Texas A&M University (TAMU) were initiated in the late eighties and first digital simulator configuration was assembled in the early nineties [51]. After that, an elaborate open-loop simulator developments were undertaken under the sponsorship of EPRI [52]. These developments resulted in both a PC-based and workstation-based open-loop configuration [43]. The PC-based simulator was delivered to Florida Power and Light Company while the workstation-based one was delivered to Western Area



OLI - Open Loop Interaction
RTI - Real Time Interaction
IT - Instrument Transformers

Fig. 2. TAMU's Simulation Environment Features

Power Administration. Houston Lighting and Power Company and Pacific Gas and Electric were co-sponsors of these developments as well [52]. In parallel to these efforts, an advanced real-time digital simulator was developed for Western Area Power Administration [41, 44]. This development has been combined with an open-loop development to provide a digital simulator for the Commonwealth Edison Company of Chicago. This simulator was capable of both real-time and open-loop operation [42].

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 [53]. Such a concept provided an ability to select an optimal hardware/software solution to match the required cost/performance criteria [13]. As a result, TAMU's simulator technology has been commercialized by Test Laboratories International, Inc. (TLI).

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

Table III. Configuration Guide for TLI Simulators

Hardware/Software	**Open-Loop PC-Based**	**Open-Loop Workstation-Based**	**Real-Time Workstation-Based**
PC	X	-	-
IBM RISC 6000 (Low Performance)	-	X	-
IBM RISC 6000 (High Performance)	-	-	X
I/O Cabinet (TECHRON)	up to three terminals	up to three terminals	up to three terminals
EMTP/ATP	X	X	-
RTS-Real-Time System	-	-	X
GUI-Graphical User Interface	X	X	X
Signal Processing (MATLAB)	X	X	X
Instrument Transformer Models	X	X	X

PRACTICAL APPLICATIONS

The simulation environments have been used extensively by relay vendors for development of new digital algorithms and relays. Simplified versions of these environments were also used by the academic institutions as a tool for teaching advanced topics related to computer applications in protective relaying. The least spread use of the simulation environments is in the utilities. A simple explanation for such a situation is the lack of adequate power system and relay models as well as required modeling expertise and man-power. As the vendors of protection relays start making the relay models readily available, it is expected that some of the utilities will find it attractive to use the simulation methods to evaluate new relays and applications. The required man-power may be "released" by further automating the extensive routine testing of protective relays presently done at most of the utilities.

The simulators have been introduced to the market only recently. Their use is making its way into the utility practice [54]. A visible trend is that the PC-based open-loop simulators are being accepted faster due to their low cost and ability to be implemented on the existing portable test sets using software extensions. The workstation-based open-loop simulators are being accepted at a slower pace due to the higher cost and relatively unfamiliar UNIX environments. The real-time simulators are being purchased primarily by the relay vendors and research organizations due to the higher cost and expertise required to use them. However, the future acceptance of advanced digital simulators may not be dependent as much on the cost of the solutions as it may be driven by the change in the relaying testing and evaluation practice. As the technology becomes more understood by the utilities, it is expected that the simulator may become an indispensable tool for evaluating new relay techniques, studying new relay applications, and trouble-shooting relay misoperations [54].

CONCLUSIONS

This paper indicates that digital simulator environments and simulators are becoming readily available for utility use. Their features are enabling extensive evaluation of relays and relaying systems at both the model and physical device level. The technology used to implement the environments and simulators is very advanced and enables further enhancements as needed. The critical challenge for the utilities and vendors, as well as research organizations and academia, is to recognize the benefits of the use of these tools for relay evaluation and testing so that the existing practice in this field can be changed accordingly, making these tools indeed useful and required.

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