Interfacing Protective Relays and Relay Models to Power System Modeling Software and Data Files

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***Abstract*--This paper addresses two important issues: how the relay models and physical relays may be interfaced to the models of power systems capable of simulating fault waveforms and related switching equipment status; how the data files containing recorded waveforms and equipment contacts generated by the actual faults and subsequent fault clearing may be utilized by the relays and relaying systems. The importance of the relay evaluation issue is linked to the capability to test the relays and relaying systems using very accurate representation of a fault event. This capability has not been used at its full extent in the past, yet a variety of options exist that have different performance potentials and implementation constraints. By discussing the options and pointing out the complexity of implementations, this paper sheds some practical light enabling users to better understand the issues involved and consequently make the best choices for their specific needs.**

***Index Terms*--Digital Fault Recorders, Digital Simulator, Electromagnetic Transients, Faults, Modeling, Protective Relaying, Simulation, Testing.**

I. Introduction

THIS This paper is focused on an important issue: how to better evaluate protective relays and relaying systems using advanced software and hardware tools. The evaluation approach is to test the relaying solution using inputs that resemble very closely the inputs the relays will see in an actual power system during faults. A number of practical uses of this approach utilizing affordable hardware and/or software options may be defined. One situation where such approach can be invaluable is in trouble-shooting relay missoperations [1]. Being able to recreate the conditions of the fault and associated relay operation(s) allows engineers to reconstruct the course of events very accurately. Further adjustments in the relays and relaying approaches used may be implemented to avoid similar misbehavior in the future. Yet another case is when a batch of new relays needs to be procured. Being able to test a sample from the batch using as inputs the signals that closely resemble actual events, one can check weather a given relay is suitable for the specific power system application at hand [2]. This approach has its distinct advantages over the approach where the purchasing decision is made solely based on the data provided in the relay manuals. In either case, the relay performance is better understood. This fact alone is pretty important since the knowledge about the relay behavior of the personnel involved in performing such tasks is enhanced.

To better understand the options for performing relay evaluations, one has to investigate the benefits and shortcomings of different approaches. First, the evaluation may be performed using software models as a representation of a physical relay. The flexibility of using relay models is unsurpassed if a complex relaying schemes or system solution involving multiple events and relays is to be evaluated. A typical example of such a case is a relay performance evaluation during cascade events. This approach has many advantages and disadvantages as discussed in a recent IEEE survey paper on the subject [3]. The bottom line of this approach is how good the relay model is. It is strongly recommended that the approach of evaluating relays using their software models be used to make some preliminary assessments and initial discoveries of the relay performance, while the final decisions should be reached only after the physical relays corresponding to the models are tested.

Another important issue is how the power system behavior can be represented most accurately for the purpose of evaluating the relay performance. Two major options have been used extensively in the past: a.) accurate simulation programs for generating the fault waveforms; b.) records of fault waveforms captured at the relay inputs. In either case, the fault waveforms are interfaced to the relays or relay models for further performance evaluation. The dynamic interactions between the relays and power system are the key to the evaluation; hence an important issue that needs to be addressed is how the implementation of the interaction using the available modeling and simulation means may be achieved.

This paper first gives a generic discussion of interfacing requirements and possible implementation options, and then a summary of the earlier attempts with a discussion of the specific approaches taken. Providing two practical interfacing examples, one for relay models and one for physical relays,

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the paper illustrates important design issues and some specific requirements related to the interfacing. Most important points about the interfacing are summarized in the conclusions.

II. Interfacing Requirements

A. Relay Interfacing

Before a relay model or a physical relay are interfaced to the power system model or a data file representing an actual event, one needs to define the interfacing requirements. Typically, a relay is interfaced to instrument transformer secondaries to obtain analog input waveforms such as voltages and current. In addition, the relay is interfaced to circuit breakers and other control devices to obtain an indication of their status represented by contacts. In some instances, such as the application of the transmission line distance relays, additional interfaces to the communication gear exist indicating the status of the control signals exchanged between the two relays located at two ends of a transmission line. Last, but not least, the user interfaces between the relay and an operator also need to be represented. In particular, any features that can facilitate user's understanding of the relay behavior during evaluation are highly desirable. All of the mentioned interfaces have to be well understood when specifying the requirements for their representation. As an example, if physical relays are used for evaluation, it is important to make sure that the simulators connected to the relays can faithfully reproduce the signals seen in the physical world. A discussion of this issue is elaborated on in a recent IEEE survey paper on digital simulator performance requirements [4].

B. Power System Interfacing

Interfacing between relays and power systems is done through instrument transformers. Most of the power system simulation packages will generate the analog waveforms that relate to the primary (network) level of voltage and current signals. The relays receive these signals after they are passed through instrument transformers. To make sure the relay inputs are properly specified during a given event, the representation of instrument transformers is very important. The issues and related requirements when using software models to represent instrument transformer behavior are discussed at length in a recent IEEE survey paper [5].

Yet another important part of the power system interfacing is the accurate representation of the contact changes associated with operation of circuit breaker and communication channel during the fault clearing sequences. The operation of circuit breaker contacts may need detailed investigation to determine how the switching taking place during the fault clearing may affect the power system behavior. Regarding the communication channels, if they are implemented using power line carrier, possible impacts of the faults on the channel behavior needs to be accurately represented.

The final decision about the contacts is the selection of the required number and the meaning when interfaced to the relays for the evaluation purposes.

C. Representing Dynamic Interactions

The most important part of the relay evaluation is to properly reflect dynamic interactions between the power system and relays during fault events as well as during normal operations that cause disturbances that may be misinterpreted as faults. A summary of the most relevant dynamic interactions that the interfacing has to capture is given in Table I. It is critical that the dynamic interactions are evaluated through some well-established benchmark means so that the complex interactions are properly represented.

Depending on the means of implementing the scenarios for relay evaluation, some interfaces will have inherent constraints regarding the representation. A good example is the real-time interaction during an autoreclosing action, which can not be readily represented in the open- loop modes of evaluation.

TABLE I
Summary of Dynamic Interaction Requirements

Event	Dynamic Interaction
Autoreclosing	Automatic change of power system model
Power swing	Power oscilations between the equivalent sources
Switching transients	Circuit breaker switching sequences
Line energizing to a "Hot" bus	Synchronizing and synchro-check

D. Field vs. Laboratory Evaluations

The final set of requirements is tied to the evaluation site. If the evaluations are done in a laboratory , then an assumption is made that the relays may be physically located next to each other irrespective of their actual location in the field. This simplifies connection between the relays and power system simulators. If the entire evaluation is done through modeling and simulation, an inherent assumption is that the evaluation is performed on a laboratory computer set-up.

Another option is to perform relay evaluations in the filed. In that case the interfacing options have to accommodate the need for generating physical signals at the required power level as well as the need to simultaneously generate relay inputs to the relays geographical dislocated at the transmission line terminals. The required power of the simulators that generate signals that need to be injected to the actual relays or relay panels has to be accordingly sized. The simultaneous injection of relay inputs at line terminals requires GPS synchronization of the instruments used for waveform replaying [6]. Providing high power relay inputs in the field (substations) for testing relays or relay panels still remains a challenge due to the present size of the power amplifiers required for such an interfacing.

III. Interfacing Options

A. *Interfacing Relay Models*

This section summarizes some of the options related to power network modeling, modeling of protective relays and interfacing between the power network models and relay models.

Interfacing options reported in recent papers are summarized in Table 2. Software packages used to model the networks are listed under “Network Programs”. The implementation languages for relay models are categorized as “Relay Programs”. References describing a particular interfacing approach are indicated in the cell that is at a cross point between the row indicating the network program used and a column indicating the language utilized for the model implementation. Additional references describe the network and relay modeling programs themselves.

Particularly powerful are the approaches, discussed below, that use MATLAB for relay modeling [28]. This general purpose signal processing package with its extensions Power Blockset and Simulink [29,30], provides a very flexible set-up for modeling relays and interfacing the models of the power network and relay.

Mahseredjian [31] presents a programmed link between MATLAB and EMTP. It is an interconnection where MATLAB functions can be called in from the EMTP Fortran code. The interconnection provides a user-defined modeling tool where the high-level computation facilities of MATLAB and its Toolboxes can be used in the general network simulator context of the EMTP.

Kezunovic [32] presents a new approach for interactive simulation between the power network protection and relaying system. In the new approach, power system transients are simulated using an EMTP/ATP, while protective relays can be modeled using any high-level language or commercially available software package, such as MATLAB. The interface between power systems and relays is implemented by using an "interaction buffer". Using this technique, the ATP/EMTP can be run in single-step, multiple-step or mixed mode.

Kezunovic also presents an approach where the network model is created in MATLAB/Power System Blockset and the relay model is developed in MATLAB/Simulink [33]. Five Simulink libraries are developed for modeling, design, optimization and testing the digital protective relays. Those are the following libraries: Relay Elements, Relays, Protection Systems, Input Signals and Tools [33]. The interfacing is achieved through MATLAB/Simulink [34].

Some papers present the relay models unrelated to any particular software used for network modeling. Sidhu [35] describes possibility of a generalized modeling technique for generating a software model for any microprocessor-based relay implemented using the general-purpose hardware. A modeling package based on MATLAB has been developed for generating models of relays. Further links with FORTRAN and C languages are possible. Saengsuwan [36] describes how to model the dynamic behavior of a quadrilateral or polarized MHO distance relay using MATLAB. As an example, it is demonstrated how the simulated distance relay can be tested using data generated by EMTP/ATP. Any transient power system simulator could also be used.

B. *Interfacing Physical Relays*

In order to interface physical relays one has to have a D/A system that will convert transient signals either simulated by digital programs or recorded by digital fault recorders. The main difference in the available options is the type of interaction allowed by the interface design between the network model and the relay. The interface options can be split into two main categories: open loop [37] or real-time [38,39,40].

Real-time interfaces are provided between network models and physical relay requiring a bi-directional link. The network models generate waveforms with a selected time-step. As the relay detects a fault, it sends a trip signal that is

TABLE II
Interfacing Options

		RELAY PROGRAMS				
		TACS [10]	MODELS [11]	FORTRAN	C++	EMTDC
NETWORK PROGRAMS	EMTP [7]	[12] [13] [14] [15] [16]		[15] [17]	[18] [19]	
	ATP [8]	[20] [21]	[22] [23] [24] [25]			
	EMTDC [9]					[26] [27]

interpreted by the network model through a change in the switching state of the related circuit breaker. As a consequence, the network model changes in the interval of a time-step, and the next iteration of the waveform computation is performed using the new network model. The open-loop interface allows a set of waveforms to be replayed into the relay, and the feedback is only captured for recording purposes.

IV. Example #1: Interfacing the Models

An example of an interface between MATLAB software package on one hand, and ATP and Power System Blockset (PSB) programs [28-30] on the other is described below [41].

A power network is modeled either in ATP or PSB and interfaced with the relay model and scenarios implemented in MATLAB. This setup can be used to initiate either open- or closed-loop relay simulation for defined scenarios. All selected fault or no-fault cases, specified by the user, are simulated automatically without any user intervention.

A. Model Interfacing

Even though both PSB and ATP simulation programs can be employed for solving power network transients, their usefulness depends on the case studied. For the case with simple power network (few buses) more convenient is modeling in PSB. PSB is fully integrated into MATLAB software package as its Toolbox. This integration enables easy control of all SIMULINK and consequently PSB simulations, by using MATLAB's commands. Relay models are realized either as SIMULINK blocks or MATLAB "m" files, and easily interact with power network model in PSB using SIMULINK built-in features. Using this approach closed loop simulations may be readily achieved.

For bigger power network (i.e. more than 5 busses), the simulation speed becomes very important issue, because PSB runs unacceptably slow and more useful simulation program is ATP. Also, ATP can be preferred tool if the network model contains specific network components only available in ATP. In this case the interface between ATP and MATLAB becomes more involved. Specially developed MATLAB program is needed for this purpose. The MATLAB program automatically controls ATP simulations for each of the desired scenarios and gets interactively simulation results for the relays and related recordings. Combining given approach with the one proposed earlier, where during simulation relay modeled in MATLAB acts if necessary and changes the network model in ATP [32], the closed-loop relay simulation for a large number of scenarios can be achieved (Fig. 1).

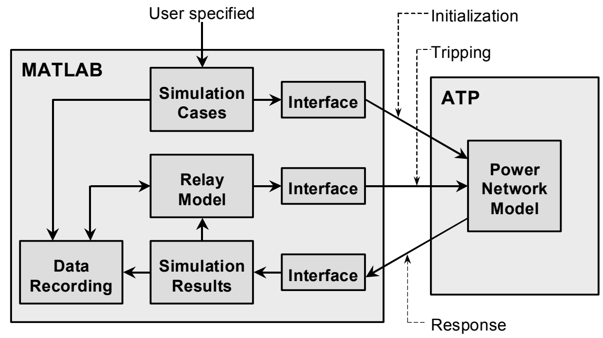

Fig. 1. Integrated simulation tools for protective relaying by using MATLAB and ATP

B. Generating Simulation Cases

The user can specify, through a MATLAB file, all the changes in the network topologies and parameters, as well as desired combinations of these changes for each simulation case. This includes variation of fault parameters (type, location, impedance and inception time), variation of source/load voltages, sequence of line switching, and many others. For most of scenarios this can be done in a systematic way where the user may specify few hundreds or thousands of scenarios through several simple steps. For each specified simulation case, the MATLAB program automatically updates the data (related to changed components) in the network model or file, and initiates simulation for each of those cases. This means that each specified change in the network is updated between consecutive simulations. After each simulation obtained results are in a complex form and program converts them into a data format understandable by MATLAB, and memorizes them for further processing.

As an example, Table 3 gives a listing of the fault and simulation parameters (that need to be specified for executing a large number of test cases) as well as functions of corresponding MATLAB's subroutines.

TABLE III
Available Fault and Simulation Parameters and Corresponding Subroutines for Updating the Network Model

User specification	Subroutine function
Fault type	Adjust opening and closing times for the switches used for fault realization
Fault inception time	
Fault location	Adjust line section lengths from the remote busses to the faulted point
Fault impedance	Adjust fault impedance
Integration step time	Ajdust ATP settings
Simulation end time	

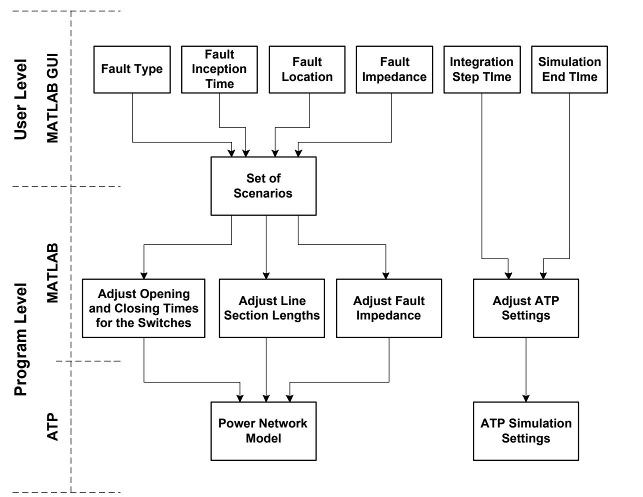

Fig. 2. The hierarchy between user and program levels

Fig. 2 shows the hierarchy between the user and program levels, where MATLAB GUI provides user access to create the scenarios and control the simulation settings, while MATLAB initiates network model updating and simulation.

V. EXAMPLE #2: INTERFACING THE RELAYS

Physical relays may be interfaced to the network models or recorded waveforms using digital simulators. Several important hardware and software features need to considered when using the simulators. This example illustrates how the hardware, software and interfacing interactions may be achieved if one is using and open-loop low cost solutions [43].

A. Hardware Interfacing

When specifying the interfacing hardware, it is important to consider the following specifications: burden of the relay, required power, number of relays to be simultaneously tested, number of contacts to/from the relay to be monitored and, the accuracy of the D/A conversion system.

The solution shown in Fig. 3 indicates the interfacing options regarding the D/A and amplifier system that may be used. This particular solution allows the use of low power commercial amplifiers, the standard test sets, or the high power commercial amplifiers. In the case the stand alone amplifier systems are used, a customized, high accuracy I/O interface is utilized. If the standard test sets are used, the output power and the number of test sets that can be used simultaneously are limited.

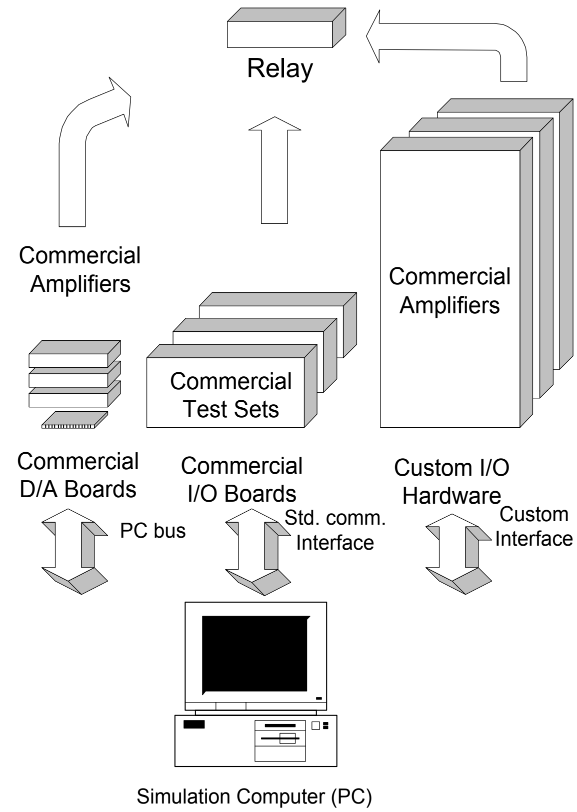

Fig. 3. Simulator hardware

B. Software Interfacing

Specialized software is needed to allow interfacing to both the recorded and simulated waveforms. Flow representation of such a software is given in Fig. 4 [44].

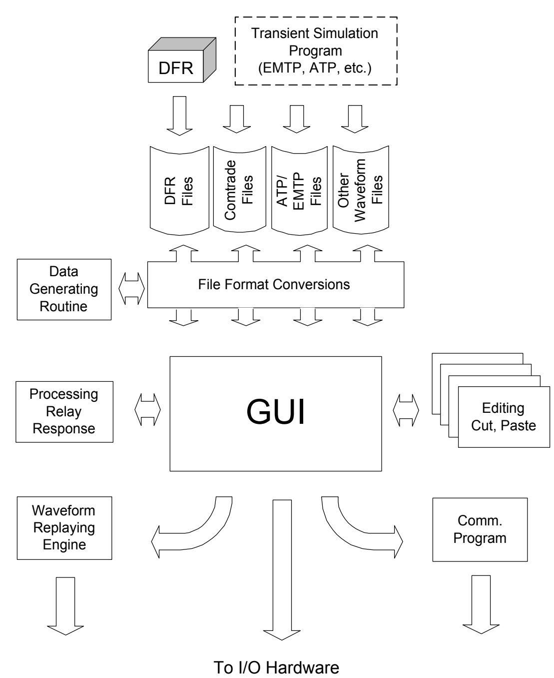

Fig. 4. Simulator software

The provisions required for interfacing recorded waveforms are: data file conversion programs for importing the recorded waveforms coming from different recording devices into a common format such as COMTRADE [45], waveform editing features allowing preparation of the recorded waveforms for replaying and, automated testing routines allowing replaying of large number of files without an operator intervention. Simple waveform importing capability is desirable for easy interfacing between the simulator and a recording device.

The desirable provisions for interfacing physical relays to the network simulation programs are: ability to generate a large number of simulation waveform cases using an automated batch processing routine; possibility of representing the contact waveforms corresponding to circuit breaker or relay communication channel; suitability for including models of instrument transformers as well as models of additional relays as a part of the power network being simulated.

C. *User Interfacing*

When interfacing physical relays to digital simulators the user interface provisions become very important since a variety of different actions may have to be performed by the operator to set-up the simulation software and hardware. As an example, Fig. 5 indicates how a batch of simulation cases may be generated using a custom software routine called BGEN [43]. This routine is invoked by the user and takes over execution of the ATP simulation runs after the user has specified the ranges of the simulation variables that need to be automatically adjusted in each simulation run. Typical examples of the simulation variables that may be adjusted in predetermined increments are: fault location, type of fault, fault resistance and, fault incidence angle. The BGEN and Relay Assistant are custom-developed software modules allowing the user interfacing, batch processing and waveform replaying [43].

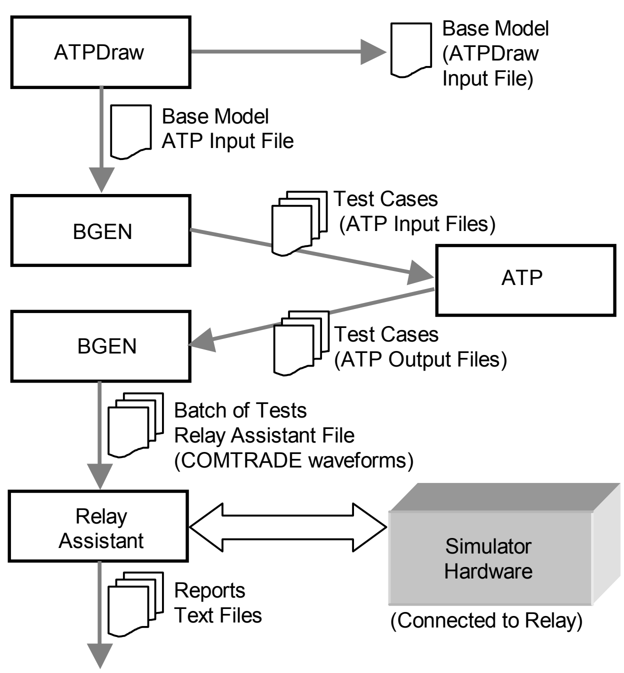

Fig. 5. BGEN interfacing

VI. Conclusion

The paper has given a survey of interfacing techniques that may be used for evaluating protective relays. Two examples of an advanced solution to interfacing are also discussed. The following are major conclusions that may be drawn related to the interfacing problem:

- In all mentioned cases, the power system network can be modeled very accurately using a software package for simulating electromagnetic transients.
- Behavior of instrument transformers is very important for relay evaluation and detailed models of instrument transformers need to be used.
- Relay models and physical relays can also be evaluated using waveforms recorded in the field at the low side of the instrument transformer. It should be understood that those waveforms already reflect the impact of the instrument transformer response.
- Relay models may be implemented using a variety of options. The final decision may driven by the convenience of interfacing with the simulation programs or recorded data files.
- Physical relays can readily be interfaced to the network models through D/A conversion modules and amplifiers. The level of power that needs to be delivered and geographical displacement of relays are very important considerations.
- Interfacing the relay models and physical relays to the network models can be readily achieved but the degree of flexibility in representing the dynamic interaction depend on the interfacing option.

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