ADVANCED SOFTWARE ENVIRONMENT FOR EVALUATING THE PROTECTION PERFORMANCE USING MODELING AND SIMULATION

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ABSTRACT

In this paper a new interactive simulation environment is proposed for protective algorithm design and evaluation as well as for protective relay testing. Dedicated software packages for simulation of particular events in power system, MATLAB's Power System Blockset (PSB), Alternative Transient Program (ATP), EUROSTAG, NETOMAC and PSS/E, can be used for detailed modeling of network components and simulating specific events. Simple protection algorithms can be implemented in these programs. For complex algorithms, more efficient tool, such as MATLAB may be used. In this study, MATLAB is selected as the main software environment for evaluating the protection. In that sense other programs are connected with MATLAB and used for simulation of power system faults.

1. INTRODUCTION

Protective relay evaluation and testing require modeling of the power network and protective relays, and their interactive simulation for a variety of the events in power system. These events encompass many scenarios, including various faults and normal operating states, and correspond to specific time scales.

Modeling and simulation of complex power networks require availability of diverse simulation tools. The use of electromagnetic transient programs EMTP [1] and ATP [2] for power system simulation, which create power system voltage and current transient waveforms, has been known for a long time. More recently, general purpose modeling and simulation tool MATLAB with its toolbox Power System Blockset has been used for the power network modeling [3,4]

Protective relay simulation has also been of great interest to researchers for more than decade [5-8]. The relay models may be implemented in either EMTP/ATP or in standard programming languages. Existing modeling approaches in EMTP/ATP do not facilitate interfacing complex relay models to the power network models. Proposed closed-loop simulation approaches require relay models to be embedded into EMTP/ATP facilities by using either TACS or MODELS [1,2,9]. It is still rather difficult to implement sophisticated and detailed relay models, due to the lacks of complex mathematical tools and appropriate graphical user interfaces for modeling. Moreover, difficulty in automatically simulating a large number of scenarios is a limiting factor as well. The relays can be more accurately and more efficiently modeled by using either C language or a commercial software package with pre-defined libraries implemented in MATLAB's SIMULINK [10]. In recent years, few new approaches have been proposed to connect the electromagnetic transient programs with MATLAB [11-13].

The software environment presented in this paper uses MATLAB as the main engineering tool for performing modeling and simulation of power systems and relays as well as for interfacing the user and simulation programs. Through one interface the operator is able to select and set models of the appropriate power systems and relays, to interface the relay models to the models of the power system, to define power system disturbance scenarios and to initiate various simulations corresponding to specific time intervals of the disturbance.

The paper is organized as follows. Section II introduces a short background of protection evaluation for cascading events. An overview of power system fault events and normal operating states, as well as the selected model of an actual power network are given in

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section III. Section IV provides insight into recently developed relay modeling and simulation tools. Section V defines a new simulation environment for protective relaying algorithm design and evaluation. The conclusions are given at the end.

2. BACKGROUND

The traditional relaying schemes have been in service for many years and have performed rather well in the past. The instances when the schemes did miss-operate were often attributed to the inherent limitations of the existing relaying principles. It is well known that occasionally the power systems go into a cascading failure mode that can cause major blackouts. The cascading operation is quite often initiated by the relays tripping various adjacent transmission lines and by doing so eventually bringing the entire network down. The subsequent analysis of the events may designate these operations as correct if the relays operated correctly according to the selected settings. The fact that the settings were selected based on the prevailing conditions that did not incorporate the particular event in question is not considered a disadvantage of the conventional relaying concept but as an inherent limitation instead. Hence, the term “correct” instead of the term “incorrect” is used to designate the relay operation. In other words, the relays are recognized as operating correctly, even though the entire system may be brought down for the initial event being just a single fault.

Existing relaying principles are based on the notion that the relay settings are computed ahead of time based on some well-known and easily anticipated fault conditions. In addition, the settings are determined in such a way that the relay does not operate under the normal conditions. It is well known from the protective relaying practice that the settings are determined in a conservative way by performing the worst-case simulation studies. This approach always leaves an uncertainty as to what is the best balance between the security and dependability. As a consequence, the final solutions are biased towards either dependability or security to make sure that the one or the other type of operation can be guaranteed. In an ideal case, the trade off is to be avoided and the scheme should be both dependable and secure. In the existing approaches this may be a conflicting requirement due to the way the settings are computed.

The protective relays "see" a variety of operating conditions: normal loading, fast electromagnetic transients during the initial phases of the fault, post fault unbalanced steady state operation, fast and slow stability oscillations. In the modern power system analysis, the mentioned power system states are modeled using a variety of software tools such as Load Flow, EMTP, Short Circuits, and Stability programs. These software package use power system models that correspond to the level of details and the time scale relevant for simulating the particular disturbances. Using advanced digital simulators, the relay behavior may be assessed for a specific moment of time after occurrence of a fault. This technique is quite powerful when dealing with the individual relay or a small number of relays. The protection evaluation for cascading disturbances requires a more complex software environment.

The MATLAB software tool has the required user interfaces to allow different simulations to be setup and controlled using the powerful set of programming tools. The unique feature is also the capability of implementing the models of the controllers (relays) using the programming tools provided in MATLAB. Extensive libraries of complete relays and relay elements have been developed in MATLAB [14]. The environment allows for evaluation of both individual relays as well as the interactions among relays incorporated into a protective relaying system. The evaluation may be performed under a variety of power system operating conditions including cascading failures.

3. POWER SYSTEM MODELING AND SIMULATION

The evaluation of a relay design for the protection of power system transmission line requires a model of the corresponding power system. The model should represent the real power network in great detail and be flexible to meet the specific evaluation requirements. It means that transmission lines should be modeled carefully and with the required detail.

The specially developed power network model of actual power system section, selected as an example in this paper, is the Reliant Energy (RE) HL&P Stp-Sky, nine-bus model shown in Fig. 1. This model was implemented using calculations based on short-circuit data available from RE HL&P company. The simulation accuracy is “calibrated” using recordings captured during actual fault events in the system.

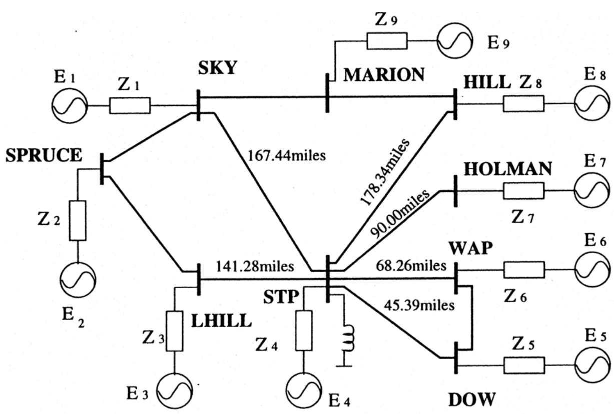

Figure 1. RE HL&P Stp-Sky Power System Model

This model represents a typical 345kV power system, containing both short and long transmission lines. This system has some very long lines (190 miles) with heavy mutual coupling along 80-90% of the line. Mutual coupling may affect relay operation and settings in a way that is sometimes not very easy to predict.

RE HL&P Stp-Sky model has been implemented in Power System Blockset (PSB) and ATP, appropriate for simulation of short-term transient phenomena. PSB, one of the latest extensions of MATLAB, enabling one to model the basic components of power systems, provides a convenient alternative to EMTP/ATP [4].

This power network model of actual power system section needs to be capable of simulating various fault events and operating states. The testing and evaluation of either existing or any new protection algorithm must cover a variety of power system conditions and events, because reliable and fast execution of all relay functions is expected in all cases. Many scenarios including faults and no-fault events should be investigated, and they are given in Table 1.

Table 1. General Scenarios for Power Network Protective Relaying

Group of events	Specific event
General fault events	All types of fault; Fault location variation; Fault impedance variation; Fault inception angle variation; Infeed/outfeed;
Special fault events (Dependability)	Faults in reverse direction; Evolving faults; Cross-country faults; Unsymmetrical faults; Time variant fault impedance; The parallel line out of service or faulted; Sympathetic trip on parallel lines;
Events in the normal state (Security)	Source voltage variation; Load variation; Line switching; Line parameters variation; System frequency variation; Power swings; Inaccuracies in measurement system.

4. RELAY MODELING AND SIMULATION

The main modeling and simulation tool used in this paper to illustrate the implementation of the relay models is MATLAB with its toolbox SIMULINK, developed as special GUI for the time domain simulations [10]. PSB is fully integrated in this environment, and user may construct and add his/her own blocks and functions.

The new MATLAB-based software, capable of modeling digital relays by providing detailed models of the common components of contemporary digital relays, has been used in recent years [14]. The most important part of this software are SIMULINK libraries developed for modeling, optimizing, setting and testing digital protective relays. These libraries include relay elements (models of generic components of digital relays), relays (model of complete protective relays such as overcurrent, impedance and differential), protection systems (models of complete protection terminals including communications and elements of integrated protection and control) and utilities for input signals generation and file format conversion.

The developed blocks facilitate setting-up models of protective relays using generic representation of various hardware and software elements of actual relays. Their basic description is given in Table 2 and they are shown in Fig. 2. This library enables designing complete relays by selecting and connecting models of appropriate elements from the library and setting their parameters. As a result, protective relay modeling can be implemented independently from the network modeling. Table 3 outlines a brief summary of the Input Signals Library.

Table 2. Summary of the Relay Elements Library

Element	Description
Data Acquisition Board (DAB)	An analog input signal is filtered for antialiasing, conditioned, sampled and forwarded as a data window of signal samples. The options include analog filtering and A/D vertical resolution enable/disable switches; type, order and cut-off frequency of the analog filter; range and number of bits of the A/D converter; conditioning gain and the length of the output data window.
Digital Filter (DF)	An input signal is filtered digitally. The pre-defined filters include Infinite Impulse Response (IIR) low-pass, high-pass, band-pass and band-stop filters of Butterworth, Bessel and Chebyshev approximation as well as Walsh and Fourier Finite Impulse Filters (FIR). "Free-expression" digital filter can also be set.
Digital Fourier Transform (DFT)	An input data window is captured and the phasors of up to five harmonics are calculated using the DFT technique. The options include selection of the frequency of the reference (first) harmonic and other requested harmonics.
Basic Measurement (BM)	The voltage and current phasors are captured and the amplitudes, impedance components and power are calculated. The post-filtering may be applied using either mean or median filters (individually for each output quantity).
Differential Equation based Impedance Measurement (DEIM)	The block measures the impedance based on the differential equation approach. The pre-filtering using either Walsh or Fourier filters of selectable window length may be applied. The post-filtering using either mean or median filters may be applied. Either Euler or trapezoidal method of numerical differentiation may be used.
Universal Comparator (UC)	The block is fed by two signals and does a comparison between either the signal and a threshold, the signal and time or the two signals. The direction of comparison may be alternated and the standard time characteristics are included.
Zone Comparator (ZC)	The block is fed by the resistance and reactance values and emulates four forward and one reverse impedance zones. Either the mho or "free-expression" shapes may be set.
Triggering element (TR)	The block is fed by the data window of a signal and acts as a transient detector. The implemented methods include sample-to-sample, cycle-to-cycle and value-to-threshold checking.
Symmetrical Components (SC)	The block is fed by three phase signals and produces three symmetrical components signals. Either phasors or instantaneous values are utilized.
Vector Group Compensator for two-winding transformers (VG-2)	The block captures instantaneous values of six phase currents of a three-phase two-winding transformer and computes the differential and restraining currents. The parameters include the CT ratios, transformer rated voltages, connection type and vector group.
VG-3	Similar to VG-2, but for three-winding transformers.
Bias Characteristic (BC)	The block is fed by the operating and restraining signal and applies a "free-expression" (point by point defined) bias characteristic.

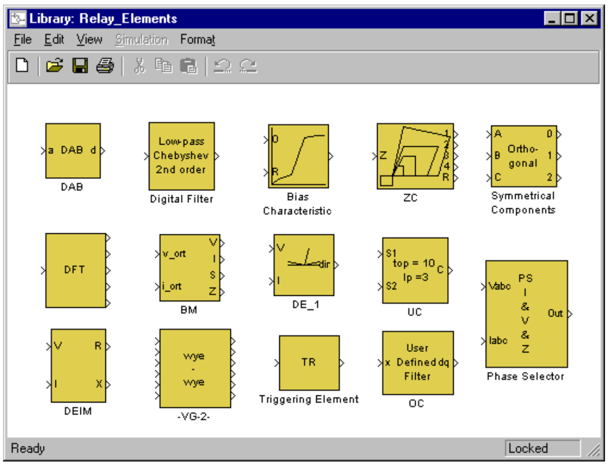

Figure 2: The library of relay elements

Table 3. Summary of the Input Signals Library

Sub-Category	Elements	Structure
Signal Generators	General specification generator, limited frequency spectrum generator, phasor generators, etc.	Library
Data File Converters	ATP to MATLAB, COMTRADE to MATLAB, DFR to MATLAB	Programs
Power System Transient Model	Power System Blockset, Instrument Transformers, Internal fault models	Libraries

5. INTERACTIVE SIMULATION ENVIRONMENT

MATLAB based simulation environment that interacts with widely used power system simulation tools has been developed. In this environment various scenarios may be implemented and different simulation time scales considered. Both, open-loop and closed-loop simulation features are available. MATLAB interaction with ATP and PSB programs has been completely established. Interfacing some other programs (EUROSTAG, NETOMAC, PSS/E) will be investigated during future research.

By using MATLAB, a suite of standard modeling and simulation tools is brought into one simulation environment (Fig. 3). The standard programs such as ATP for electromagnetic transient simulation, PSS/E for load flow and short circuit study, EUROSTAG for simulating the network stability dynamics, and NETOMAC for simulating electromagnetic and electromechanical phenomena, may be interfaced to the MATLAB environment. Providing interfaces to power network modeling and simulation programs such as ATP, PSS/E, EUROSTAG and NETOMAC, enhances the MATLAB simulation tools and enables different aspects of the network behavior depending on the time-scale of interest to be considered. This approach allows the simulations to be split into the time domains of interest: prefault, immediately after the fault, a few cycles after the fault, several hundreds of milliseconds or several seconds after the fault. These time scales correspond to the well-known power system conditions: load flow, fast electromagnetic transients, steady state unbalanced operation, and fast and slow stability dynamics. This approach allows different controllers to be subjected to different waveforms coming from the network simulations at various time intervals.

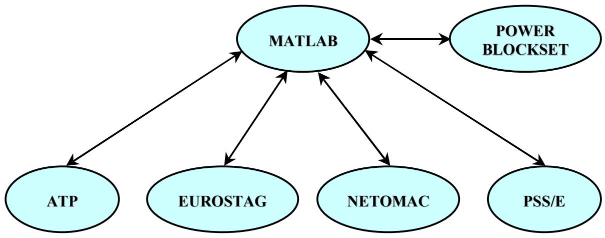

Figure 3. MATLAB as the Main Software Environment for Interfacing other Software Packages

In the new simulation environment open-loop and closed-loop simulation features are needed to demonstrate interaction between power system and selected protective relays. In open-loop testing, there is no interaction between relay trip signal and power system model. In closed-loop testing, a feedback between the relay trip signal and the power system simulation exists. Thus, the relay tripping or reclosing can be implemented in the model of the power system network. There are many cases where closed-loop testing is the preferred approach, and it is a requirement for proper determining the relay responses. Some of these include simultaneous, system-wide, multi-terminal relay interactions in a particular network. Aim of these simulations is to establish optimal setting for single relay as well as proper interaction between relay operations.

Power network model represented in ATP and PSB interacts with the relay and scenario models implemented in MATLAB. Both programs, ATP and PSB, offer their specific advantages and disadvantages and their comparative characteristics are given in Table 4. This setup can be used to apply different scenarios and events by changing network topologies and parameters. This is done by initiating either open-loop or closed-loop relay simulation for defined scenarios and extracting simulation output data for further processing. All selected fault cases, specified by the user in the MATLAB file are simulated automatically without any user action.

Table 4. Comparative Characteristics of ATP and PSB

Category	ATP	PSB
Power network modeling capabilities	Great, libraries contain diverse elements	Limited, library contains only basic elements
Protective relay modeling capabilities	Strictly limited, include only TACS and MODELS statements	Great, include all inherent and user-defined MATLAB functions and SIMULINK blocks
Interface with MATLAB	Complex, include data conversion programs	Simple, compatible and fully integrated
Simulation speed	Fast	Very slow
Recommended use	Complex networks and components	Simple networks with standard components

Existing problems in both programs can be eliminated in two different ways, depending on the case studied. For the case with simple power network (several buses) and standard components, network is modeled in

PSB. Specially developed MATLAB program interface enables running simulations for a large number of cases. The user can specify all the changes in the network topologies and parameters. The program automatically performs data rewriting in the PSB model and initiates simulation for each of those cases. Relay models are realized as SIMULINK blocks and interact with power network model during simulation. After each simulation, the program memorizes simulation results for further processing.

In other case, with complex power network (several tens of buses) or simple network with complex components, the network is modeled in ATP. As in the previous case, a specially developed MATLAB program can be used, but now significantly more complex. ATP writes graphically edited model into specific file. MATLAB program initiates data rewriting in that file, and initiates ATP simulation for each of the desired scenarios. Combining this approach with the one proposed in [11], the closed-loop relay simulation for a large number of scenarios can be achieved. Obtained simulation results are in a complex form and program converts them into form understandable by MATLAB. An example of this interaction is given in Fig. 4.

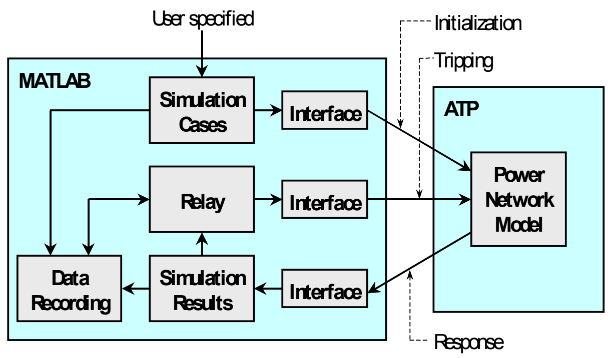

Figure 4. An Example of Integrated Simulation Tools for Protective Relaying by Using MATLAB and ATP

6. CONCLUSION

This paper presents advanced approach to evaluation and testing of protective relays. A novel interactive simulation environment has been proposed, implemented, and demonstrated. Diverse modeling and simulation tools are combined into one simulation environment. This unique simulation environment enables use of various software modules specialized for particular power system operating conditions, protective relaying solutions, and required interacting. The power network model is used to simulate a variety of fault events and operating states. Protective relay modeling can be implemented independently from the network modeling. This provides additional flexibility in selecting and combining the most appropriate simulation tools resulting in improved accuracy of modeling and simulation. The new utility for simulating a large number of scenarios automatically has also been developed. Open-loop and closed-loop evaluation of relays is enabled in PSB and ATP programs. Proposed interaction between dedicated programs and MATLAB leads to better design implementation and performance evaluation of the protection algorithm and relays for many real situations in power networks. This approach allows evaluation of multi-terminal, coordinated relaying systems and their operation during complex cascading events.

7. ACKNOWLEDGEMENTS

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