New Software Tools for Teaching Power System Relaying Utilizing Modeling and Simulation

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Abstract—**This paper presents new MATLAB software aimed at facilitating teaching of power system protection courses by means of modeling and simulation. The operating conditions and functions of modern protective relays are described. The resulting requirements for efficient teaching of the subject are given followed by the description of the developed software. Simulation examples are given and the summary of already completed teaching rounds is included.**

Keywords: modeling and simulation, power engineering education, protective relaying, MATLAB, MERIT2000.

I. Introduction

The term "power system protection" stands for a number of protective relays (special controllers) that supervise components of the power system such as transmission lines, transformers, generators, motors, busbars, etc. The relays disconnect the supervised (protected) elements from the rest of the system in the case of abnormal conditions by opening appropriate circuit breakers. The abnormal conditions include primarily internal short-circuits while the operation must be fast (milliseconds) and selective (the circuit breakers should be tripped only when actually needed but always when called upon).

Majority of contemporary relays are built using the microprocessor technology. The numerical relays sample their input signals (currents and/or voltages associated with a protected element), process them by calculating certain features of the signals and compare the signal features to the tresholds in order to decide whether or not to issue a tripping command. From this standpoint a relay is an on-off controller or an automated decision-making device.

In both teaching of this subject and actual designing of the relays a number of operating principles, algorithms and hardware configurations need to be investigated. Each of the aforementioned categories includes several standard solutions. Numerous novel approaches are possible utilizing various concepts from the digital signal processing and automated decision making areas. For example, the operating principles include the overcurrent, distance and differential; the algorithms include pre-filtering, Fourier and Walsh measuring algorithms for the magnitudes, differential equation methods for measuring the impedance, etc.

Certainly, teaching protective relaying courses would benefit from having generic models of typical software and hardware components of protective relays [1].

This paper presents new SIMULINK [2] libraries developed for modeling, testing and evaluating protective relays. These libraries include [3]: **Relay Elements** (models of generic components of digital relays enabling one to set-up a detailed model of a given microprocessor based relay); **Relays** (models of protective relays such as overcurrent, impedance and differential); **Protection Systems** (models of complete protection terminals); **Input Signals** (specialized signal generators and file converters); **Tools** (specialized displays).

Also, this paper shows how to use the developed software in teaching including the undergraduate, graduate and continuous education levels.

The described research/education activities in the protective relaying field take place within the NSF sponsored project — Multi-disciplinary Education Using Curriculum Re-engineering, Industry Partnership and Simulation Technology — **MERIT**. This concept is being now realized and its deliverables are to be made available in the year 2000, hence, the project designation **MERIT 2000**.

II. Effective Teaching by Simulation

The Merit2000 Project Summary

The main objectives of the **MERIT 2000** project are to:

- Create a working example of a new re-engineered curriculum for undergraduate and graduate power engineering education.
- Involve various segments of the utility and manufacturing industry, as well as the consulting and engineering services in the process of defining multi-disciplinary needs and practical examples for the educational process.
- Exploit unique expertise of the university teams and industry advisors to explore the simulation technology and related benefits in implementing efficient methodologies for classroom and laboratory teaching.

Industry and University Partnership

The main philosophy behind the partnership in the **MERIT 2000** approach is to follow the existing trends in the partnership seen between various industries, as well as between industries and their customers. It is understood that a major advancement in the power engineering education cannot be easily achieved by one school, or without the industry input. Hence, the approach taken was to make a team of two universities, four utilities and four vendors that jointly participate in this project from the stage of the proposal writing to the stage of the final curriculum implementation.

Multi-disciplinary Approach

The basic idea is to enhance the existing fundamental power engineering topics with the additional themes such as customer relationship (marketing, public relations), advanced technology (communications, intelligent systems), economic considerations (cost analysis, pricing) and new applications (FACTS, renewable energy sources).

Simulation Technology

Simulation environments offer an advanced technology and a powerful methodology to be extensively used in teaching. Each of the fundamental power system topics are being re-examined in order to decide how the required modeling and related simulation can be utilized to enhance understanding of both the fundamental phenomena and practical solutions.

Innovative Teaching Methodology

The main ingredient of the innovative teaching methodology is a comprehensive use of digital simulators in the teaching process. This allows for redistribution of the teaching-load in the classroom where the time required for presenting and understanding of theories and concepts is reduced due to a well prepared set of visual demonstrations. Furthermore, detailed considerations and practical examples are shown in the laboratory environment which is turned into additional teaching time and self-learning experience.

III. Requirements for Effective Protective Relaying Teaching Using Simulation

Operating Environment for Protective Relays

In order to teach operating principles for protective relays, exercise some design activities, set and test protective relays one needs to simulate the operating environment for the relays. This includes the power system with its transients as well as communication channels used by the relays to exchange information. Often, both the power system and its relays must be simulated interactively (closed-loop simulation) in order to study relay coordination.

Requirements for Effective Teaching

From the above, we specified the following requirements for the simulation tool facilitating effective teaching of power system protection courses:

- libraries of blocks modeling the basic components of a digital relay must be developed and made available for the students to build (design) their own relays,
- pre-defined models of typical protective relays must be built to illustrate the basic concepts and help students in their design work,
- software facilitating connecting the relay models with the operating environment must be available (this includes modeling power system transients and converting transient data files),
- certain display and analysis tools must be provided to facilitate both the teaching and students' design activities.

IV. MATLAB in Teaching

Taking the above into consideration, MATLAB has been selected as a development shell for the new educational software in the project [3].

MATLAB, a high-performance language for technical computation, integrates calculation, visualization and programming in an easy-to-use environment.

Particular factors that support the choice of MATLAB in the project are:

(a) MATLAB is a standard that already dominates the university environment and is more and more recognized in industry including the power engineering field. Due to the high-volume distribution, the package is readily available for all the targeted audiences of the project.

(b) Flexible software structure of MATLAB comprising of libraries, models and programs enables one to integrate different educational components in one package conveniently.

(c) MATLAB and its time domain solver, SIMULINK, create a friendly and open system. New models and libraries may be just added to the package without a deep knowledge nor modification of the existing parts. This is very useful if the user is involved in further development of the software (modifications, extensions or customization). This is particularly a case during successive rounds of teaching when new students may be assigned, as a part of their education, to develop new or improve existing elements of the package.

(d) Fast-development with MATLAB using powerful calculation and visualization means of the package enables one to expand the software quickly and efficiently without developing any extra programming tools.

(e) A wide selection of TOOLBOXes - comprehensive collections of pre-defined functions for solving application-specific problems - is already available with MATLAB and seems it will be growing even faster in the future. The examples of toolboxes relevant for the protective relaying application include the signal processing, optimization, neural network and wavelet toolboxes.

(f) Power System Blockset, one of the latest extensions of MATLAB enabling one to model the basic components of power systems, provides a vital alternative to Electromagnetic Transient Program (EMTP/ATP [4]) particularly by permitting modeling of both the power system and its controls in the same environment facilitating closed-loop simulation.

V. THE NEW MATLAB SOFTWARE

The elements of the new software are:

- short-circuit program as introduction to symmetrical components and networks enabling the students to simulate and investigate power system faults represented as unsymmetrical steady-states,
- models of power system elements including instrument transformers enabling the students to simulate and investigate power system transients,
- models of protective relays components enabling the students to investigate the basic relay design components and build more complex structures such as complete relays and protection systems,
- pre-set models of protective equipment and sample power systems illustrating certain relaying design and application principles,
- specialized tools facilitating simulation automation and visualization processes.

Both the software and teaching material are organized in seven major categories.

<u>Input Signals</u>

This class relates to generating the relay input signals. This includes transient modeling of the power system for closed-loop simulation (ATP and MATLAB's Power System Blockset) as well as steady-state analysis of the power system (short-circuit program). Also, the analytical way of generating the signals is provided as well as file format conversion from major transient file formats.

Table I provides a brief summary of this class.

<u>Relaying Principles</u>

This class contains examples related to the protective relaying principles. Three major principles are considered: overcurrent, impedance and differential. The emphasis is put on understanding the theory but certain design and setting issues are also addressed.

This class contains pre-defined SIMULINK models of both the power system and simplified protective relays.

<u>Design Principles</u>

This class incorporates examples illustrating the fundamental design issues for digital protective relays. This covers analog filtering and sampling, digital estimation of signal parameters, post-filtering, tripping logic, etc.

This class contains pre-defined SIMULINK models of certain elements of a digital relay.

TABLE I. SUMMARY OF THE *INPUT SIGNALS* CLASS

Sub-Category	Elements	Structure
Signal Generators	General signal specification generator, limited frequency spectrum generator, phasor to waveform converters, etc.	Library
File Converters	ATP to MATLAB, COMTRADE [5] to MATLAB, DFR to MATLAB	Programs
Power System Transient Model	Power System Blockset, Instrument Transformers, internal fault models	Libraries
Power System Steady-State Model	Symmetrical components and networks	Models
	Short-Circuit Program	Program

<u>Relay Elements</u>

This class includes models of the basic hardware and software components of a digital relay such as data acquisition board, digital filters, Fourier algorithm, comparators, etc.

This class is a collection of blocks (MATLAB library) enabling the students to design complete relays by selecting and connecting appropriate elements from the library and setting their parameters.

Table II shows the most important elements of this class.

<u>Relays</u>

This class contains pre-set models of complete digital relays such as overcurrent, impedance and differential relays. The models of the relays are composed from the elements of the *Relay Elements* library and the general SIMULINK libraries. Some of the relays emulate actual relays to the extend possible using the publicly available design details.

This class is a SIMULINK library.

<u>Protection Systems</u>

This class is similar to the previous one but contains models for the entire protection systems including communication and elements of integrated protection and control.

<u>Tools</u>

This class contains elements that facilitate analysis and testing procedures. Examples include specialized displays such as the phasor display or the impedance plane, timers, test sequence controls, etc.

This class is also a SIMULINK library.

VI. TEACHING EXAMPLE

Fig.1 presents the pre-defined SIMULINK model for the topic of analog filtering, signal conditioning and sampling within the class *Design Principles*. This model consists of the Data Acquisition Block (DAB - see Table II) and few auxiliary elements.

The student assignments for this example include:

- Simulation and explanation of the frequency aliasing phenomenon in both the time and frequency domains.
- Selection of an analog filter. Investigation of its effects on both the noise and information.

TABLE II. SUMMARY OF THE *RELAY ELEMENTS* CLASS

Element	Description
Data Acquisition Block (DAB)	An analog signal is filtered, 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 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 any 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 signal and a threshold, signal and time or the two signals. The direction of comparison may be alternated and all 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 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.

- Selection of the sampling frequency.
- Simulation and explanation of the phenomenon of vertical resolution of the A/D converter.
- Testing the complete front-end part of a digital relay with analytical and EMTP-generated signals.

This example was successfully utilized in the short-course activities at Texas A&M University in the form of computer-assisted lecture and a supervised hands-on laboratory exercise.

VII. CONCLUSIONS

The MATLAB-based educational software package for teaching protective relaying courses within the concept of **MERIT 2000** has been presented.

Both the software and the written teaching material are under extensive development. They have been or will be tested soon in various teaching activities such as undergraduate and graduate courses as well as in continuing education. The students have been exposed to both the usage of the ready-to-use elements of the package (undergraduate) and development of the new elements (graduate). The students' response is encouraging.

VIII. ACKNOWLEDGMENTS

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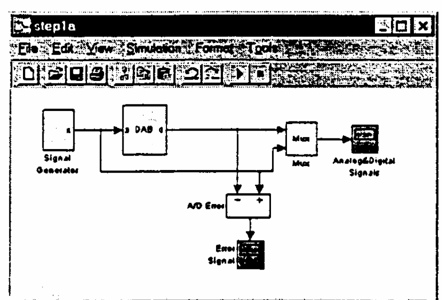

Fig.1. Teaching example for analog filtering and sampling.