

# New educational MATLAB software for teaching protective relaying courses

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**Abstract**—This paper presents an extensive use of the simulation technology exerting MATLAB to enhance student's understanding of the fundamentals as well as practical solutions of power system protective relaying, while making this approach quite effective in reducing overall classroom teaching time. This is achieved by efficiently presenting and explaining the analytical and practical aspects of related phenomena through simulation, as well as by redistributing some of the teaching to the laboratory environment. This approach makes an additional time in the curriculum available for introduction of new topics reflecting the advancements in power system protection, monitoring and control as well as the multidisciplinary issues created by the changing environment.

**Keywords:** power engineering education, protective relaying, modeling and simulation, MATLAB, MERIT 2000.

## I. INTRODUCTION

The curriculum of the prevalent power engineering education provides a solid background of traditional power system problems and classifies issues according to the historical utility organization. The industry, however, has been driven by continuing de-regulation and increasing competition into a new paradigm of operation where the customer becomes the focus. This approach not only redefines who the customer is, but what the customer wants and what the options in achieving the goals of satisfying the customer are. An obvious consequence of this process is a need for a new profile of an engineer that can fit the new paradigm.

There is a wide consensus that the existing power engineering education does not offer the desired solution [1]. The new profile of an engineer requires a new paradigm for power engineer education where the "customer focus" concept becomes a driving force for the education process as well.

The above diagnosis is an underlying assumption for the new concept in power engineering education — 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 designa-

tion **MERIT 2000** [2].

Introducing briefly the **MERIT 2000** project (Sec.II), this paper focuses on one of the project scopes — protective relaying, monitoring and local control. The choice of the MATLAB [3] software environment for modeling and simulation is discussed in Section III. Protective relay testing as an educational instrument is introduced in Section IV. The new approach to teaching protective relaying courses using MATLAB is presented (Sec.V) and supported by the teaching examples (Sec.VI).

## II. MERIT 2000 PROJECT SUMMARY

### A. Research objectives and significance

The main objectives of the **MERIT 2000** project are to [2]:

- 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.

### B. 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 [2].

### C. New educational concept

The new concept is based on three pivotal components:

#### 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.

The project uses the existing packages created in the university environment [4], certain commercial tools as well as the new software.

### Innovative Teaching Methodology

The main ingredient of the innovative teaching methodology is an 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.

#### D. Curriculum issues

The curriculum includes the fundamental power engineering issues, namely:

- Energy sources and conversion,
- Power system design, analysis and control,
- Protective relaying, monitoring and local control,
- Advanced technologies for power system automation and control,
- Power quality design and assessment,
- Distribution systems and automation,

as well as additional topics associated with de-regulation and new technologies:

- Deregulation and market competition,
- Standardization, industry recommendations and quality assurance,
- Social, environmental and economic impacts,
- Communication skills, team work and marketing strategies.

The focus of MERIT 2000 is to maintain a structure similar to the traditional power system education while adding the new elements to the curriculum.

### III. MATLAB IN TEACHING BY MODELING AND SIMULATION

MATLAB has been selected as a development shell for the new educational software in the MERIT 2000 project.

MATLAB, a high-performance language for technical computation, integrates calculation, visualization and programming in an easy-to-use environment. In the university environment, MATLAB becomes a standard instructional tool for introductory and advanced courses in mathematics, engineering and science. In industry, MATLAB is a tool of choice for high-productivity research, development and analysis.

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 low-price distribution, the package is practically available for all the targeted audiences of the MERIT 2000 project.

- (b) Flexible software structure of MATLAB comprising 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 EMTP/ATP [5] particularly by permitting modeling of both the power system and its controls in the same environment facilitating closed-loop simulation.

### IV. PROTECTIVE RELAYING DESIGN AND APPLICATION TESTING

#### A. Relay testing as a teaching tool

Testing protective relays is considered in the MERIT 2000 project an important educational instrument. Generally, the performance assessment for protective relaying devices can be summarized as given in Table I [6]. The assessment requirements ask for an ability to verify both the relay design and application performance.

The relay design assessment is needed when a new relay design is introduced. In industry, a vendor or utility may want to evaluate the relay design characteristics to make sure that its performance is as expected. In education, students learn by emulating an algorithm of a given relay (modeling) and testing it (simulation).

Typically, this type of evaluation is performed using pha-

TABLE I. RELAY PERFORMANCE ASSESSMENT

Performance	Considerations
Design testing	Relay operating characteristics Phasor concept
Application testing	Relay selectivity Operating times Transient waveforms

sors representing pre-fault, 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.

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 waveform that closely resemble actual fault events.

### *B. Modeling and testing*

#### Protective system modeling

By a protective system we mean the power system, instrument transformers and protective relays.

Traditionally, an EMTP-type program is used for power system modeling. This includes EMTP, ATP, EMTDC, MORGAT, MicroTran, NETOMAC, ARENE [7] and recently introduced educationally oriented MATLAB's Power System Blockset [3]. These packages have been developed for general transient studies, and as a rule, they do not include ready-to-use internal fault models of the power system components. In some cases, such as transmission lines or busbars, modeling of internal faults is quite straightforward. In another cases, however, such as generators, motors or transformers, accurate modeling of internal faults is a research subject in itself.

Modeling of instrument transformers, particularly in conjunction with testing of ultra high speed relays, requires extensive field measurements in order to verify the adopted models and acquire values of their parameters.

An increasing interest and progress is observed with respect to modeling protective relays themselves [8]. Since the power system simulation packages usually are not intended to model control devices in an easy and efficient way, separate environments are used for modeling the power system and relays. This may create extra problems in implementing closed-loop testing.

#### Test waveform generation

Relay design and application testing requires generation of test waveforms. The main choices in this area are the following approaches:

- EMTP-type simulation,
- Recorded waveforms,
- Universal waveform generators (test sets and others).

#### Test waveform replaying

Depending on the complexity of a given relay evaluation study, the following waveform replaying features may be required:

- Open-loop replaying (the tripping signal from the relay is not fed back to the power system model), closed-loop replaying (the relay opens the circuit breakers in the power system model) or pseudo closed-loop replaying (multiple test runs in the open-loop mode to mimic the closed-loop mode [9]),

- On-line (actual relays tested) or off-line (relay models tested) replaying,
- Single or multiple relay testing.

#### Waveform processing

The waveform processing functions include three major categories:

- File format conversion from output files of variety of simulation programs and Digital Fault Recorders (DFRs). This may include decimation and interpolation.
- Waveform editing including cut-and-paste, extensions, editing contact signals, alternating polarity, etc.
- Fault waveform analysis capability in both the time and frequency domains.

#### User interface

An efficient user interface is a very important component of a good relay testing tool. Its major elements include:

- Graphical User Interface (GUI) with such functions as one-line diagram of power system, automated generation of faults, and automated power system equivalencing,
- Data bases to interface with different programs,
- Tools for analyzing, reporting and displaying test results,
- Test sequence control.

### **V. TEACHING APPROACH USING MATLAB**

The requirements, options and components of relay testing tools mentioned in the previous section are implemented in the educational package using MATLAB. The commercial tools will be used in the new curriculum as well following the introductory and theoretical MATLAB-based part.

From the educational perspective the software classes are:

- simple 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 and design and application principles,
- specialized tools facilitating simulation automation and visualization processes.

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

#### *A. Input signals*

This class relates to generating the relay input signals. This includes transient modeling of 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

TABLE II. SUMMARY OF THE *INPUT SIGNALS* CLASS

Sub-Category	Elements	Structure
Signal Generators	General specification generator, limited frequency spectrum generator, phasor to waveform converters, etc.	Library
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
Power System Steady-State Model	Symmetrical components and networks	Models
	Short-Circuit Program	Program

signals is provided as well as file format conversion from major transient file formats into COMTRADE [10].

Table II provides a brief summary of this class.

This class contains MATLAB programs (file converters), SIMULINK libraries (such as the Power System Blockset or models of instrument transformers) and SIMULINK models (such as introduction to symmetrical components and networks).

### B. Relaying principles

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.

### C. Design principles

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.

### D. Relay elements

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 III shows the most important elements of this class.

### E. Relays

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.

TABLE III. 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.

### F. Protection systems

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.

### G. Tools

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 EXAMPLES

Having the package developed and capable of performing emulation of both the power system and related controllers, its usage in education and training needs to be carefully designed and planned.

This section presents teaching examples of different complexity levels and different perspectives.

### A. Symmetrical components and networks

Fig.1 presents the pre-defined SIMULINK model for the topic of symmetrical components and networks within the class *Input Signals*. In this model:

1. The three-phase one-machine power system is set-up using the Power System Blockset.
2. Three-symmetrical networks are created and connected to reflect the type and location of a fault occurring in the three-phase system.
3. Measuring devices are placed in both the original system and symmetrical networks to facilitate comparison between the signals from the three-phase system and symmetrical networks. This includes ideal voltage transformers, a converter from the phase values to symmetrical components, and displays.

The configuration and parameters of the entire model may be changed by cut-and-paste and drag-and-drop manipulations with the icons.

The student assignments for this example include:

- Selecting the three-phase system in terms of parameters and connections (especially the way of grounding the neutral points); changing the type, parameters and location of the fault and observing the values and relations between the symmetrical components (studying the power system in unsymmetrical post-fault states).
- Editing the original three-phase system, changing the fault type and parameters and editing the symmetrical component networks in terms of parameters and connections to reflect the changes of the original system. Comparing the results from the original system and its symmetrical-network-based "solver" (learning how to use symmetrical networks).

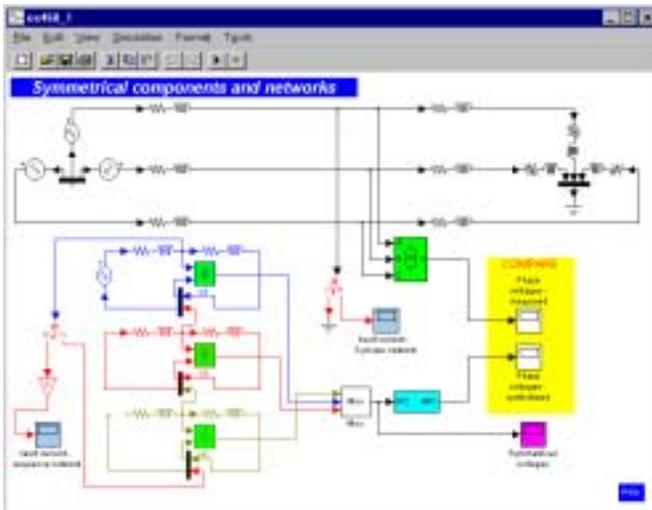


Fig.1. Teaching example for symmetrical components and networks.

By this example the students learn:

- (a) The relation between the type and parameters of a fault and values of symmetrical components.
- (b) The rules of using the symmetrical component networks for analysis of three-phase systems.

### B. Impedance relaying principle

Fig.2 introduces the pre-defined SIMULINK model for the topic of impedance relaying principle within the class *Relaying Principles*. The model consists of:

1. Single-phase model of a two-machine three-line power system with models of the fault and instrument transformers.
2. Measuring blocks estimating the voltage and current phasors as well as impedance components.
3. Zone comparators checking the impedance location against three impedance zones.
4. Displaying elements.

The student assignments for this example include:

- Placing faults at different locations and observing the value of the impedance. The ideas of a *relaying point*, a *protected line* and *impedance seen* by the relay are introduced.
- Simulating faults at the far end busbar with non-zero fault resistance and different pre-fault power flows. Explanation of the in- and out-feed effects. Recommendations for relay settings.
- Simulating faults at the relaying point. Recommendations for relay settings. The need of a directional element.
- Setting the first zone of the relay. Testing the relay. Introduction of the *sensitivity* and *selectivity* concepts.
- Simulating external faults. The idea of a *back-up protection*. Setting the second and reverse zones.

By this example the students learn:

- (a) The basics of the impedance relaying principle.
- (b) Certain relay design issues.
- (c) Basics of impedance relay setting.

The two examples were successfully utilized in the undergraduate course *ELEN460—Electric Power Systems II* at

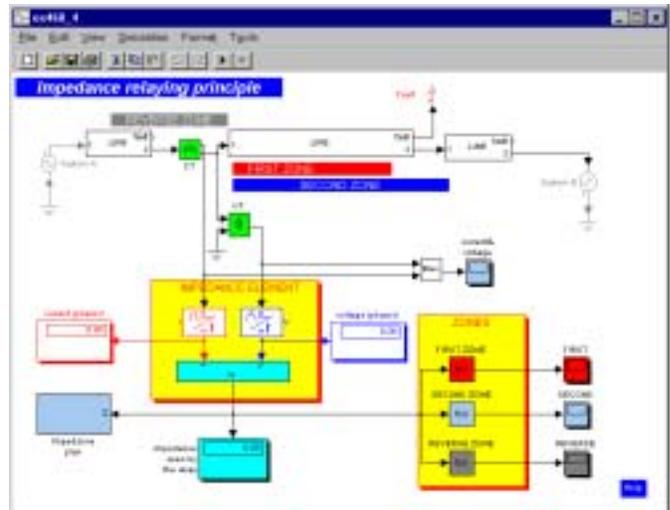


Fig.2. Teaching example for impedance relaying principle.

Texas A&M University in the form of a two-hour supervised laboratory exercises and take-home assignments.

### C. Analog filtering and sampling

Fig.3 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 III) 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.
- 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 MERIT 2000 concept of re-engineering power engineering curriculum to meet the needs of future employers has been presented. The MATLAB-based educational software package for teaching protective relaying courses within the frames of MERIT 2000 has been introduced.

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 usage of the ready-to-use elements of the package (undergraduate) and development of the new elements (graduate). The students' response is encouraging.

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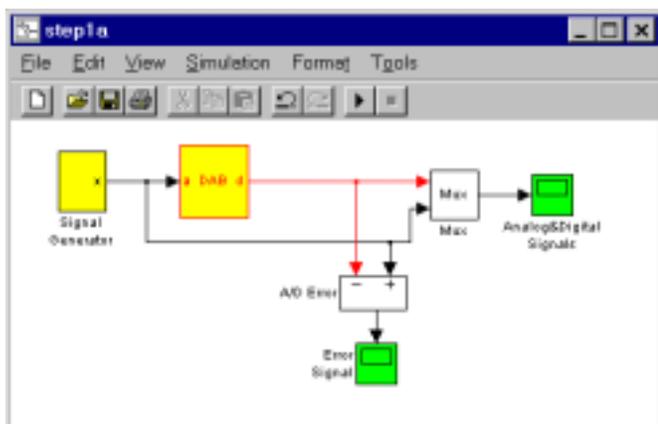


Fig.3. Teaching example for analog filtering and sampling.

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## BIOGRAPHIES

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**Bogdan Kasztenny** (M'95, SM'98) received his M.Sc. (89) and Ph.D. (92) degrees (both with honors) from Wroclaw University of Technology, Poland, where he is a faculty member of the Department of Electrical Engineering since 1989. In 1994 he was with Southern Illinois University at Carbondale as a Visiting Professor. During the academic year 1997/98 Dr.Kasztenny was with Texas A&M University as a Senior Fulbright Fellow. His research interests include protective relaying, digital signal processing, real-time computer application in power systems and artificial intelligence methods in power system protection. Currently he is with Texas A&M University as a Visiting Scholar.