2006-1957: SIMULATION LEARNING EXPERIENCES IN ENERGY CONVERSION WITH SIMULINK AND SIM POWER SYSTEMS

David McDonald, Lake Superior State University

David McDonald has over thirty years of teaching experience in electrical engineering and engineering technology. Recent teaching has been in electrical machines, signal processing, and control systems.

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Abstract

The paper discusses introducing simulation into an introductory the introduction of physical modeling in an electrical machinery course using Simulink and the SimPowerSystems software. The paper provides a brief overview of the software with basic examples, and discusses faculty considerations for integrating the software in a class or laboratory. The integration of simulation is a work in progress, and the paper outlines initial outcomes assessment and future plans.

Introduction

Engineering professionals in education and industry are concerned about enhancing the effectiveness and productivity of the design process through the use of simulation software. The high cost of engineering development activities in industry has fostered an interest in model-based design approaches that use computer-based modeling, simulation and model validation tools. The high initial and maintenance cost of laboratory equipment is also a concern for both industry and education, and limited equipment can be augmented by including simulation and model validation learning experiences that help to prepare students for modern industry.

The traditional instruction in electrical device modeling in typical energy conversion courses can be enhanced using modern software tools to enhance student learning and motivation while providing simulation experiences that many students will encounter in industry. MATLAB, Simulink and SimPowerSystems software products by MathWorks Inc. provide high-level model development, simulation and model validation capability. This software allows the engineer to build physical models of electrical circuits and electro-mechanical devices, and has a library of models for power conversion components such as single and three-phase circuits and loads, power electronics, transformers, motors, generators, motor drives and instrumentation accessories.

The remainder of the paper will discuss the initial introduction of simulation activities using physical modeling software into an electrical machinery course. It will briefly discuss the need for Simulation in Energy Conversion Engineering, provide Overview of SimPowerSystems software, provide a few specific Examples of SimPowerSystems that could be used for homework or laboratory problems, discuss Instructional Considerations, and review the Outcomes Assessment and Future Plans for using simulation activities. The discussion is based upon the introduction of simple simulation exercises within an introductory level course in electro-mechanical energy conversion.

Simulation in Energy Conversion Engineering

The demands of modern engineering have created a need for a design process that emphasizes simulation and model validation. This approach provides a corresponding reduction in timely prototype development and testing. The use of an integrated environment for simulation and model validation simplifies the design process, thus reducing time and costs. As a specific example, Alstrom Transport reduced product development time by 50% by changing from separate modeling and prototyping to an integrated software environment which included SimPowerSystems. The company used a model-based design approach that simplified the design, simulation and model validation process. The unified environment reduced documentation time, design changes and other aspects, which enhanced productivity [1].

Engineering design and development costs can be reduced by appropriate use of model-development, simulation and model validation. The automotive industry has been using this approach for brake controllers and other vehicle components. The integrated environment provides the strengths of model development, simulation, and validation as well as assistance in the development of production systems.

The electrical engineering community has known for years that the traditional energy conversion course needed to be re-engineered and tailored to students who will use the technology as opposed to those who will design it [2,3]. Traditional energy-conversion education has a rich heritage of model development, and that strength can be easily expanded with modern physical modeling and simulation tools. The same integrated environment that has enabled industry to improve the efficiency of engineering design can be used to strengthen engineering education by enhancing student interest and motivation while providing students with the tools they will encounter in industry. It is relatively easy to integrate a computer-assisted teaching methodology into an energy conversion course using MATLAB and Simulink [4]. These simulation tools are readily available, reasonably easy to use, and their use builds on and can strengthen the student's basic engineering and programming skills.

If model simulation and validation are important in energy conversion education, then what specific topics should be considered? The information listed below is the result of a survey of introductory electrical engineering courses in energy conversion at BSEE programs in eight universities in Michigan. The course descriptions included the following topics:

- Magnetic circuits (7/8),
- Three Phase (3/8),
- Transformers (7/8),
- Energy Conversion (8/8)
- DC & AC Machines (8/8), and
- Motor Drives (4/8).

This small sample reflects the traditional cross section of an introductory course in the area of energy conversion in electrical engineering. The heart of transformer and motor instruction involves developing an electrical circuit model, and then using the model to perform loading analysis. Fortunately, the topic areas listed above are suitable for computer-based modeling, simulation, and model validation.

The School of Engineering and Technology at Lake Superior State University is working to enhance students' motivation and interest in energy-related studies while building their understanding of energy conversion systems. Activities have included strengthening energy conversion instruction through curricular changes and laboratory development. These activities have been supported by grants from industry and the National Science Foundation. The activity has impacted the electrical and mechanical engineering programs with new laboratory equipment and instrumentation in the areas of thermo-fluids, electrical machines, and machine controls. Simulation using physical modeling software is currently being integrated into the electrical engineering course in energy conversion for electrical engineering majors as well as the electrical engineering applications course for mechanical engineering majors.

Overview of SimPowerSystems

This section will provide a general introduction to the software, while the following section will present a few basic examples. Physical modeling in the Simulink environment requires the use of one or more of the following: SimPowerSystems for electrical systems, SimMechanics for mechanical systems, and SimDriveSystems for drive train systems. This paper presents the introduction of simulation activities using Simulink with SimPowerSystems.

SimPowerSystems is used for the physical modeling of power electrical systems within the Simulink environment by allowing the designer to create a physical model of the circuit or system, and then analyze the performance of the model. The modeling can include transient solutions, steady-state solutions, phasor analysis, and load flow capability along with both SI and Per-Unit unit capability. The software includes libraries of models of electrical sources, transformers, transmission lines, motors and drives, and power electronics devices. The validity of classical machine models has been refined by the Power Systems Testing and Simulation Laboratory of Hydro-Quebec, Ecode de Technologie superieure and Universie Laval.

Simulink is a block diagram modeling environment. SimPowerSystems operates within Simulink using pre-defined models. To construct the physical model the user begins by constructing a block diagram using pre-defined blocks from the Simulink library and the SimPowerSystems powerlib library. The drawing must contain at least one measurement block (i.e. current measurement block, voltage measurement block, etc.) Once the circuit diagram is constructed and the simulation started, Simulink gets the parameters of the blocks, sorts them into linear and non-linear blocks, and numbers the electrical nodes. Next the State-Space Model (A, B, C, & D matrices) of the linear part of the circuit is computed, and steady-state calculations and initializations are performed.

If a discrete solution has been requested, then the discrete state-space model is computed from the continuous state-space model. If a phasor solution method has been requested, the state-space model is replaced with the complex transfer matrix H|(jaw)| relating inputs and outputs (voltage and current phasors) at the specified frequency. This matrix defines the network algebraic equations. Simulink then builds the simulation equivalent circuit, links between the circuit and the measurement blocks, and starts the simulation. Waveforms can be observed on scopes connected to the block diagram circuit.

Powergui, a graphical user interface that is available in the Library, can be used to provide access to the transfer functions between input and output signals or an FFT analysis of recorded signals. It also enables the user to set initial conditions, specify the desired frequency range, visualize impedance curves, and store results in the workspace.

There are three solution methods: continuous solution using Simulink variable step solvers, discrete solution with fixed time steps, or phasor solution. The choice of solution method is selected within the Powergui block. Continuous solution uses variable-step integration algorithms, and can be more accurate for some applications. Discrete solutions use fixed-step integration. The phasor solution replaces the differential equations with algebraic equations, and provides information on the magnitudes and phases of all voltages and currents. Data from the Simulink model can be copied to the MATLAB Workspace and saved or used from plotting.

Examples of SimPowerSystems

SimPowerSystems is a comprehensive software tool with an extensive assortment of device models. The following simple examples do not illustrate the capability of the software, but have been selected to illustrate that simple activities can be included in introductory classes.

Example 1: Simulink Model vs. SimPowerSystems Model

Simulink is a block diagram programming environment where the blocks represent a state-space model, and are organized as a transfer function. The top portion of the diagram in Figure 1 shows a traditional Simulink model of an R-C circuit that uses a transfer function of the circuit.

The bottom portion of the diagram in Figure 1 represents a physical model using components from the library of SimPowerSystems. The measurement blocks are necessary to obtain data from the physical model, and all SimPowerSystems models require at least one measurement block.

The waveforms in Figure 2 represent the scope data from Figure 1. The scope measurements for both solutions were saved to the MATLAB Workspace, and then plotted using the graphics plotting tool in MATLAB. The top waveforms represent the input and output waveforms of the transfer function solution, and the bottom portion represents the input and output waveforms of the physical model.

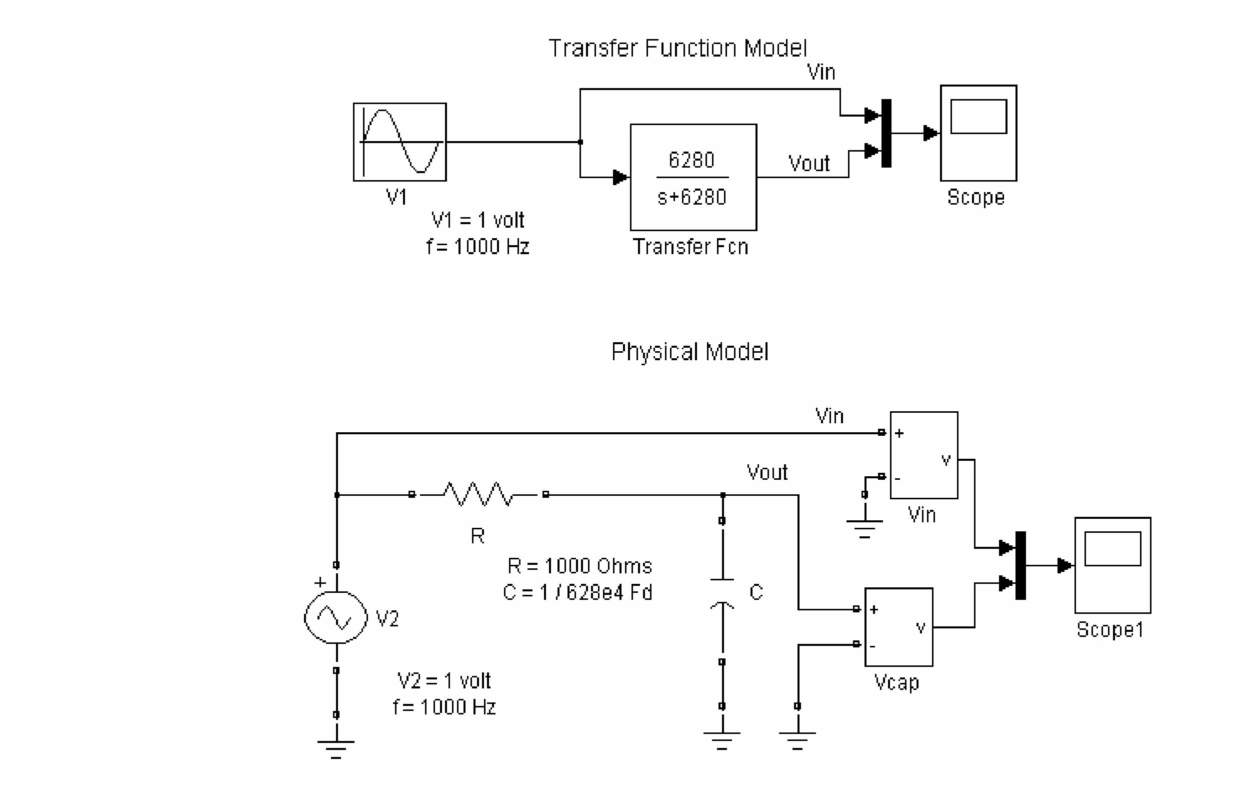


Figure 1: Simulation of an RC circuit with block diagram model in Simulink and physical model using SimPowerSystems components.

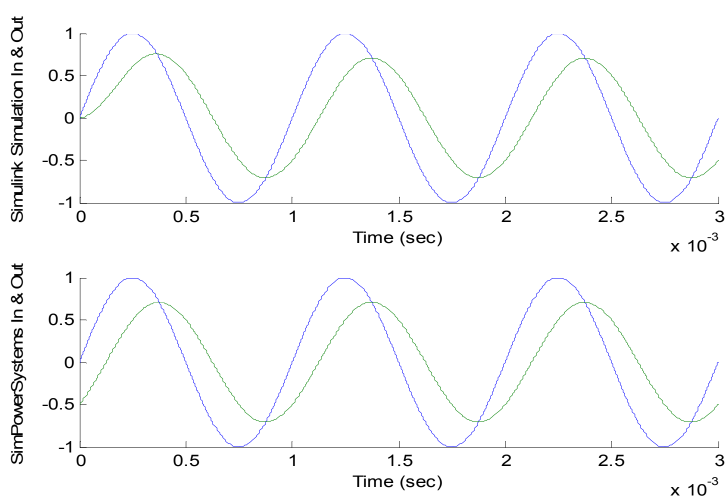
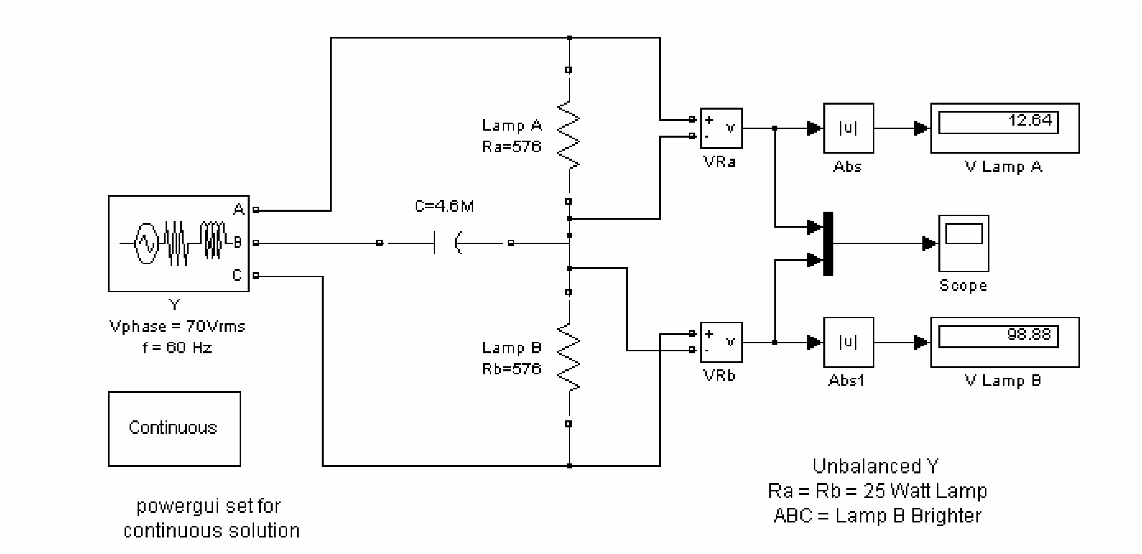


Figure 2: Waveforms for the model shown above in Figure 1.

Example 2: Unbalanced Three Phase Load – Phase Sequence Indication

A simple circuit that indicates the phase sequence of three-phase voltages can be constructed using two light bulbs and a reactive element, either a capacitor or inductor. One lamp will be brighter than the other depending upon the type of reactive element, either capacitance or inductance, and the phase sequence, either ABC or ACB.

The example shown below in Figure 2 is easy to develop, and shows both the lamp voltages and the waveforms. The scope was used for viewing the waveforms in Simulink, but the graphs were obtained by saving the data to the MATLAB Workspace and then plotted using the graphical plotting tool. This example can be a basic homework exercise or part of a laboratory activity.



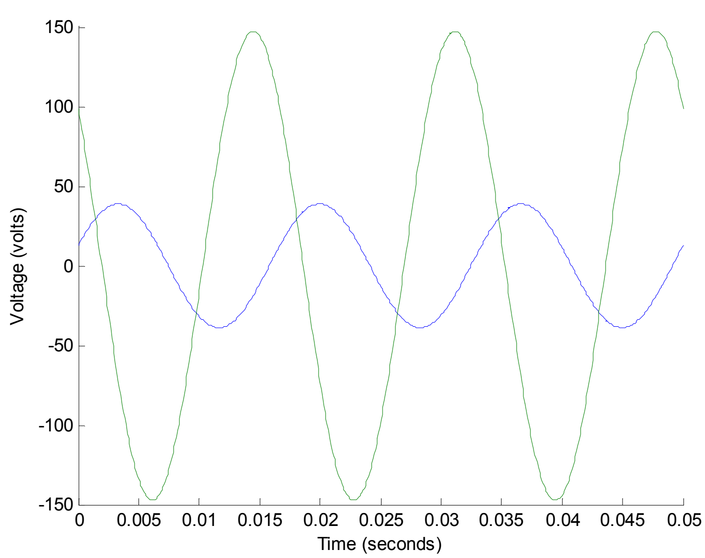


Figure 2: Unbalanced Three-Phase Loads and Lamp Voltage Waveforms

Example 3: Three Phase AC Load

The three-phase circuit shown below in Figure 3 is a Wye connected R-L load in parallel with a Wye connected C load. This example could be used to the reinforce power factor correction topics in a circuit analysis or electrical machinery course.

The loads can be defined in the model using either P-Q load values or R-L-C component values. A three phase measurement block is used to obtain the line current (rms) and time plots of the three-phase voltages and currents. This model was developed in a short amount of time, and could augment a homework or laboratory activity.

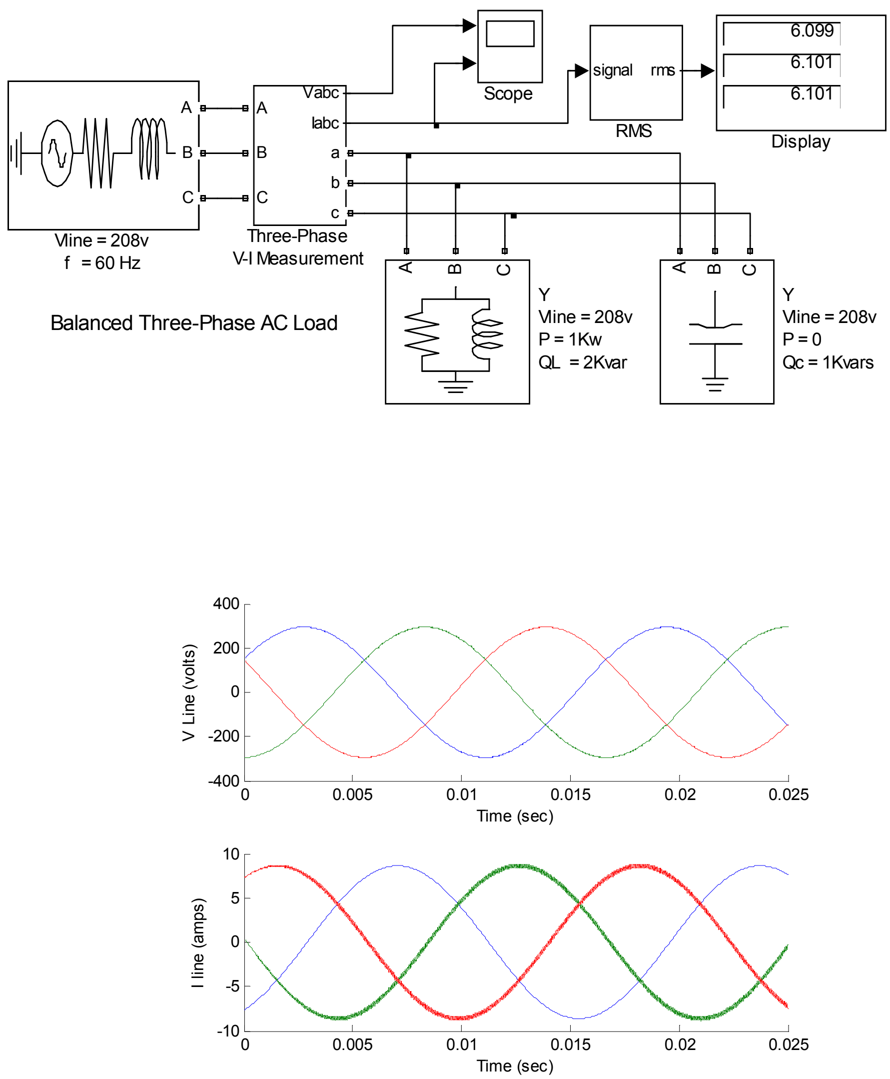


Figure 3: Three Phase Loads and Waveforms

Example 4: DC Motor Starter

The starting or in-rush current of a DC motor is very high unless special starting techniques or components are used. The starting current depends upon the applied voltage, the series resistance, and the counter or back emf that is developed inside the motor. One starting method is to insert additional resistance in series with the motor, and then gradually remove the resistance in steps as the motor speed and resulting back voltage increase.

The example shown below in Figure 4 represents a resistance motor starter. The DC motor is a standard SimPowerSystems library item, and represents a state-space model for the motor. The motor state data is de-multiplexed, and the speed is multiplied by a constant to represent the mechanical shaft load on the motor. The scopes provide viewing of the motor's current, voltage and speed. The scope data was copied to the MATLAB Workspace and then graphed as shown in Figure 6.

Subsystems in Simulink are a reusable sub-model, and similar to subroutines or functions in a text-based programming environment. The Subsystem block labeled Motor Starter in Figure 4 is expanded in Figure 5 with the connections In 1 and Out 2. The Subsystem is a three-step resistance starter where the three resistors are bypassed at 2.8, 4.8, and 6.8 seconds as the motor comes up to speed. This example is a modified Demo from the software, and illustrates that existing Demos that accompany the software can be easily modified for specific applications.

The design of the motor starter is a common problem in DC motor instruction because it integrates several fundamental motor concepts and equations. The simulation can help students check their work.

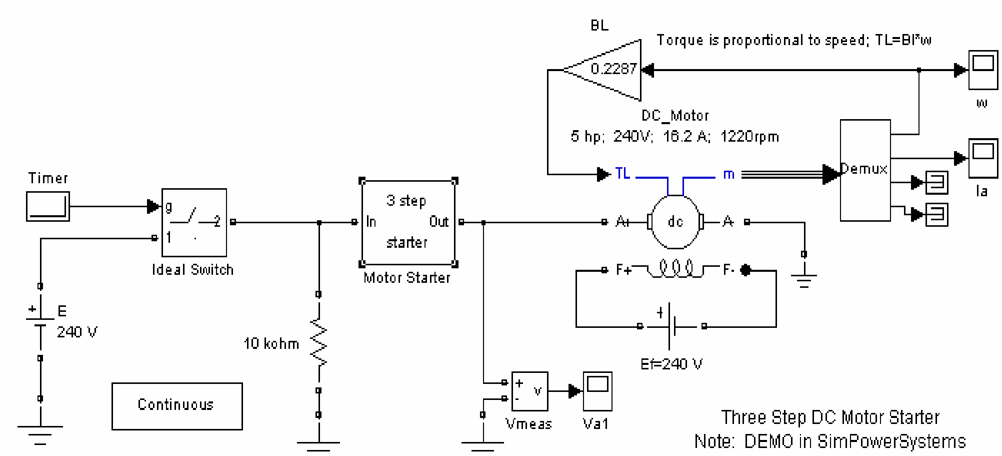


Figure 4: DC Motor Starter Model

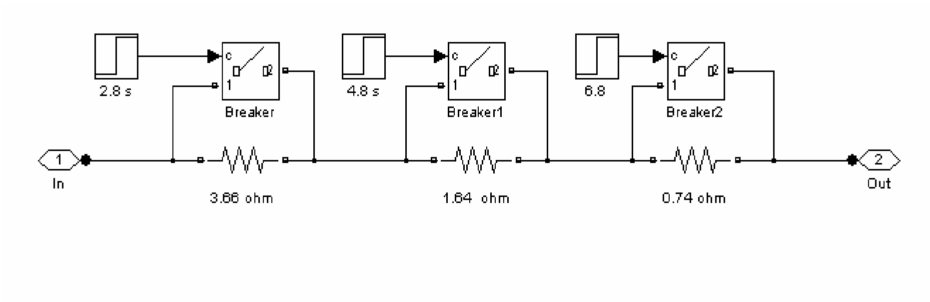


Figure 5: DC Motor Starter Subsystem

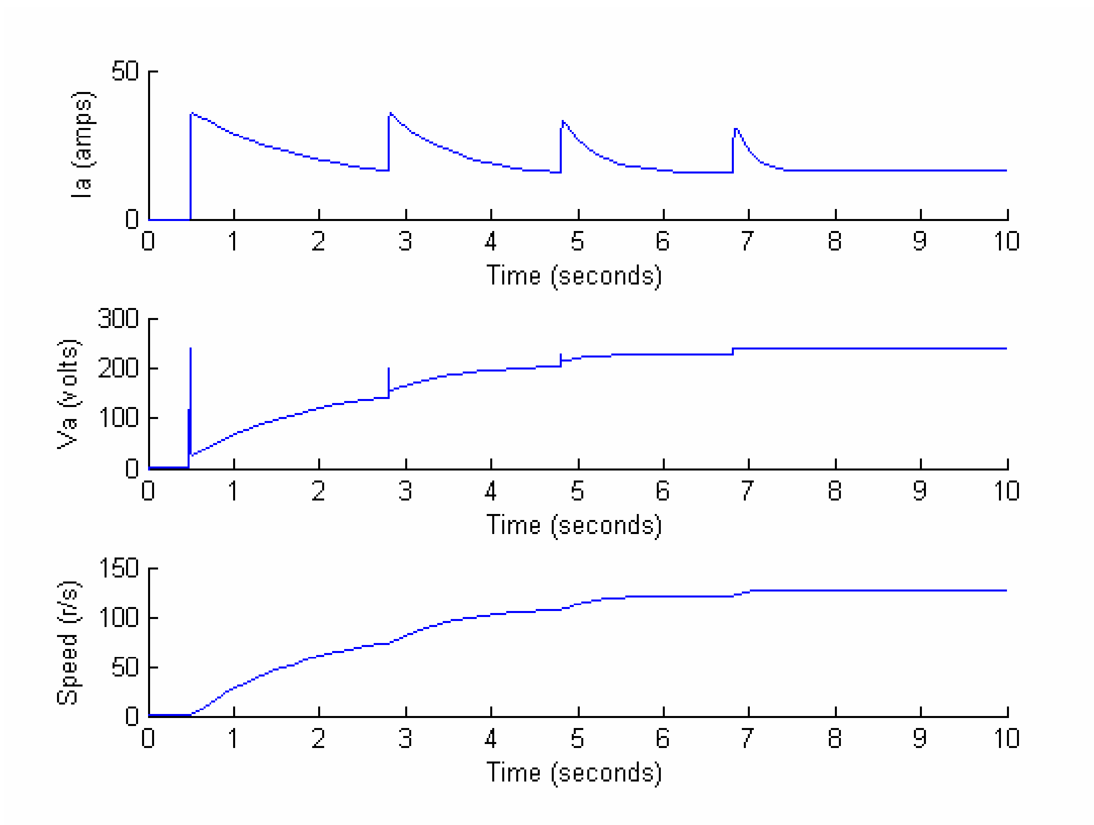


Figure 6: DC Motor Current, Voltage, and Speed Waveforms

Example 5: Phase-Controlled Converter

The example in Figure 7 and resulting waveforms in Figure 8 represent a single-phase, phase-controlled converter with an SCR firing delay angle of 45 degrees. The current in a phase-controlled converter becomes continuous with an appropriate inductance to resistance ratio.

A typical homework problem would assume a continuous current condition, and then ask the students to calculate the average current as the average voltage divided by the resistance. The theoretical load voltage waveforms for the continuous case can be easily plotted using a MATLAB script as illustrated in the text used for the course [5].

The simulation using the physical model allows the student to visualize both the transient and steady-state conditions of the circuit. The results of the simulation are available on the scope, and can be copied to the MATLAB Workspace. The average current could be measured within the model with appropriate measurement blocks, or calculated using the data in the Workspace.

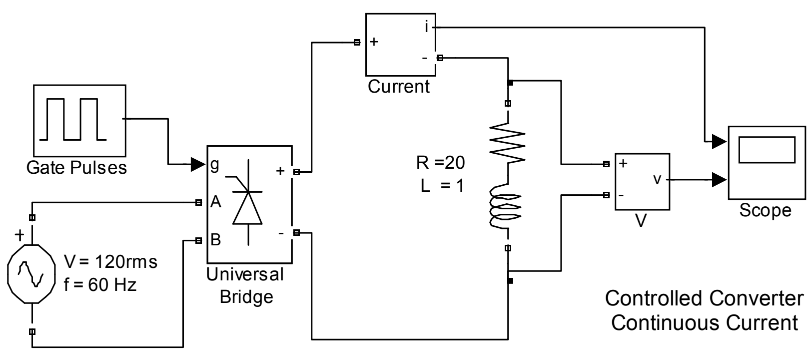


Figure 7: Phase Controlled Converter

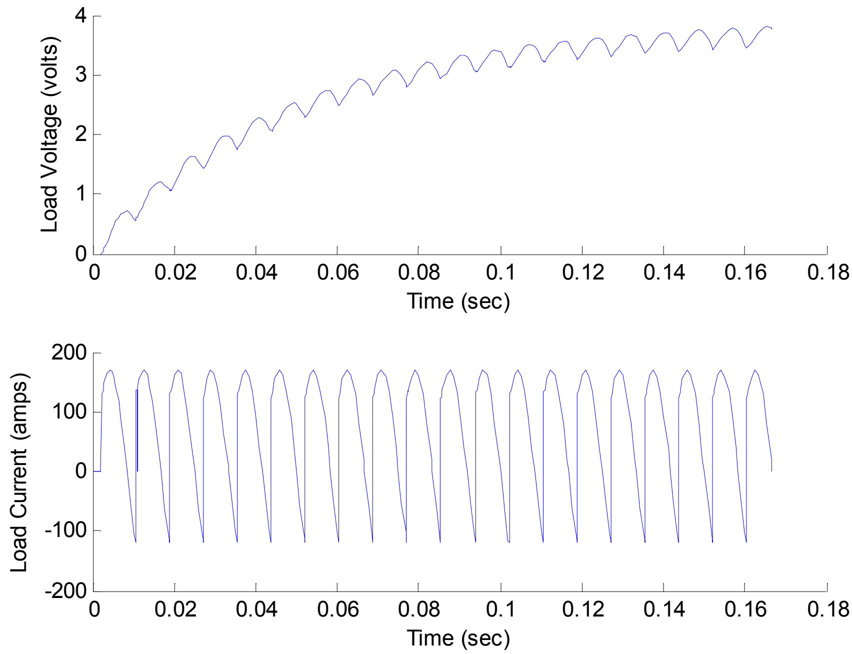


Figure 8: Phase Controlled Converter - Continuous Load Current

Model Validation

The previous examples indicate the simulation of systems using physical models instead of block diagrams. The validity of the simulation depends upon the validity of the model. Model validation involves acquiring data from an actual system, comparing the actual system responses with the computer model, and making appropriate adjustments in the computer model.

Model validation has not yet been included in the electrical machines course; however, a laboratory for this activity is being integrated into the electrical engineering applications course for non-majors. This laboratory uses the MATLAB Data Acquisition Toolbox with a National Instruments Data Acquisition Board to acquire model input and output data. The students then use the optimization capability of the Parameter Estimation option in Simulink to determine values for the parameters based and adjust the model accordingly.

Instruction Considerations

The integration of simulation using physical modeling into a course requires consideration of the educational objectives, student preparation, and software resources. The instructor needs to determine the appropriate instructional goals and integrate the software accordingly.

Simulation activities can enhance student motivation by shifting the focus from some of the theory topics, such as winding details, to applications of the technology. As discussed by Li and Challoo[4], this shift in focus is particularly true in an electrical machinery course which doesn't have the same student appeal as some other technical areas. Engineering education needs to connect with today's video generation[7]. While simulation software applications may help address the learning styles of incoming students who have spent many hours playing computer games, they still need a laboratory with hands-on activities.

Simulation activities could be used to empower the student to investigate applications of electrical machines without the costs and safety considerations of a laboratory environment. Introducing the concepts of physical modeling will provide students with tools that they are likely to encounter in future employment. Finally, the use of these tools helps students to visualize both the transient and steady-state performance of electrical systems.

Most students will need some initial instructional support in order to become productive with the software. Students who take an introductory energy conversion course will normally have experience using MATLAB; however, a smaller number will have previous experience with Simulink. There various introductory tutorials available online, and the software has an efficient Help capability with Demo examples.

Students will need access to computers, MATLAB, Simulink and SimPowerSystems software to complete models like the examples in this paper. SimPowerSystems is a comprehensive, professional-level, physical modeling environment. However, educational pricing for instructional use helps to reduce the cost of the software.

Outcomes Assessment and Future Plans

Integration of simulation activities is a work in progress. Initial assessment results are based upon student oral and written comments during the formal course assessment, and informal assessment methods including student journals, student discussions and the instructor's observations. The results are also based on a relatively small number of students.

Course Background

The following items provide an overview of the course and instructional environment, and provide a context for the student feedback and course assessment.

- Course assessment outcomes are from a four-credit electrical machinery course, with laboratory, that covers the following topics: three-phase, magnetic circuits, transformers, ac single and three-phase motors, dc generators and motors, motor drives, and controlled converters. The course prerequisites include a four-credit DC/AC circuit analysis course with laboratory, and a 1-credit course that covers engineering applications of calculus using MathCAD and MATLAB.

- Students who took the course were either electrical engineering majors who were fulfilling a BSEE degree requirement, or computer engineering students who were completing a minor in electrical engineering.

- Students did not have previous experience using Simulink. Some of the students had completed courses in control systems or network analysis that introduced transfer function or block diagram approaches to modeling physical systems.

- The students were accustomed to and comfortable with providing assessment feedback. Typically a class period during the last week of instruction is devoted to formal course assessment and teacher evaluation. The assessment involves a written assessment instrument as well as an open, oral discussion of the course outcomes.

- Instruction occurred in an informal atmosphere where students and faculty know each other well. In addition, the instructor had previously taught the students in one or more courses, and the students were very open regarding their thoughts and recommendations.

- The course included several informal writing assignments in the form of journals where the students explaining technical topics. Most students also use the journal as a forum to express their thoughts regarding any aspect of the lecture or laboratory activities.

Student Feedback

Initial student feedback has been positive and helpful, and focuses primarily on the mechanics of integrating the software into the course. The initial assessment yielded the following information.

- Students were receptive to the use of the software, and interested in expanding their skills applying it.

- Students encouraged using the software to expand, but not replace, laboratory activities.

- Students were cautious regarding their competence in physical modeling using the software.

- Students recommended setting aside a portion of class or laboratory time to assist students with the simulations, and suggested having the modeling represent a designated portion of the laboratory activity.

- Students recommended having access to the software both during the laboratory and outside of scheduled course times.

- Students liked that the course activities represented real-world applications of theory, and viewed that as an important aspect of the course.

Students' reception of the software is consistent with general observations regarding the learning preferences of the 'video generation,' [7] and their use of Help tools and confidence with software.

The comment regarding real-world examples is encouraging and consistent with the intent to capture students' interest and enhance their motivation and ownership of the course activities.

Instructor Feedback

Feedback or 'lessons learned' from the instructor's viewpoint focus mainly on the mechanics of implementation, competence with the software, and student and faculty interest.

- The software needs to be more carefully integrated in a step fashion to develop students' skills and confidence with its use.
- Limited student access to the software during scheduled laboratory sessions was a clear constraint to integrating the use of the software.
- Although the software has Help capability and Demos, there are limited or no additional student-focused, instructional materials. Specifically, there are few student-focused texts that address Simulink, and the author knows of no student-focused items for SimPowerSystems. The Mathworks Inc. website does have tutorials for MATLAB and Simulink, and provides references to free resources offered by other sources.
- Initial introduction o f the software in the course incurred created some frustrations related to lack of familiarity with the software.
- Adding the software was a refreshing and positive experience for the instructor even given the difficulties associated with the initial start-up of this integration.
- The instructor has observed that some students have taken the initiative to apply it in other courses.
- The instructor has observed that the motivation level of some students to use Simulink has increased because they anticipate using the software after graduation.

Although the author has used Simulink for years, the initial implementation of this software demonstrated that his competence using this software is a work in progress. Simulink and SimPowerSystems are very powerful and comprehensive software packages. One can become productive with the software quickly, but the software has many useful features that can be helpful. The initial use of simulation was largely a case of trying to determine how to use the software and what worked and what didn't in terms of student use.

Future Plans

The future plans focus on instructional goals, mechanics of integration, and assessment tools as outlined below.

- The previous 2-hour laboratory has been increased to a 3-hours laboratory. This will provide additional time for the simulation and provide for a more comprehensive laboratory experience.

- Steps have been taken to ensure that students will have access to the software concurrently with the use of the electrical machinery trainer equipment.

- Instruction in the use of Simulink and SimPowerSystems will be included within the initial laboratory activities. This was done in a later electrical applications course for non-majors with good results.

- Simulation activities will include adding it to some homework activities to validate their design or to demonstrate special outcomes such as transient characteristics.

- Data acquisition and model validation will be included in at least one laboratory activity to introduce students to this important concept.

- The course instructional goals will be reviewed with regard to integration of simulation activities within the other course objectives.

- In addition to the formal course assessment instrument, a separate assessment instrument will be used evaluate students' impressions on use of the software to support instructional goals, integration of the software, and impact of the software on the students' interest and motivation with regard to the course topics.

Conclusion

Instructors of energy conversion courses can effectively enhance homework and laboratory activities with physical modeling using MATLAB, Simulink, and SimPowerSystems. Careful integration of the software enables the expansion of traditional modeling activities to investigate transient response or other items. Learning experiences of this type help to enhance student motivation and interest in energy conversion courses while providing the student with valuable physical modeling experiences. Finally, instructors need to evaluate the reason for adding simulation activities into the course, make adequate provision for its use, and acquire proper feedback to provide for continuous improvement of the overall learning experience.

Acknowledgement

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