

Software Simulation to Reinforce Learning in a Power Systems Analysis Course

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Abstract- This paper describes software simulation exercises that were developed to reinforce learning in a power systems analysis course. The main purpose of these exercises was to supplement the classroom lectures with laboratory materials that correspond to the topics covered in the textbook. These topics include three phase power, transformers, transmission lines, power flows, faults, and system protection. The exercises ranged from writing simple MATLAB programs that perform computations and graph results to more complex and practical applications such as simulation of three-phase power circuits and synchronous generators using Simulink. Students also completed three simulation exercises using ETAP, an electrical analysis software package widely used in the commercial sector. This paper briefly describes the laboratory activities, show how students were exposed to a wide range of applications, and provide details about the Simulink and ETAP exercises, including schematic diagrams.

Introduction

Software simulation has become an integral component of a comprehensive learning experience in engineering and technology programs. Popular software packages include PSpice, LabVIEW, MATLAB/Simulink, and Multisim, [1-6]. This paper describes the use of software packages for developing several laboratory exercises that reinforce learning in a power systems analysis course. The course covers a range of topics including three phase power, transformers, transmission lines, power flows, faults, and system protection.

The main purpose of the exercises was to supplement the classroom lectures with laboratory materials that correspond to the topics covered in the textbook [7]. The overall goal was to enhance the students' critical thinking and problem-solving skills and train them to apply effective solutions by identifying alternative approaches, testing systems, and comparing results. The exercises ranged from writing simple MATLAB code that perform computations and graph results to more complex and practical applications such as simulation of three-phase power circuits and synchronous generators using Simulink. Simulink is a graphical programming environment that offers easy integration with the MATLAB environment to model, simulate, and analyze real-world systems and has been used to help in the design and simulation of power systems [8-12]. Students also completed three simulation exercises using ETAP. ETAP is an electrical analysis software widely used in the commercial and industrial sectors to model, design and simulate electrical power systems [13]. It is also suitable for monitoring, control, operator training, optimizing, and automating power systems.

Students prepared written reports that included a one to two-page conclusion where they described their designs, explained the operation of the systems, discussed results, mentioned problems they faced, stated what they have learned, and suggested ways to improve the laboratory assignments.

In this paper, we describe the laboratory activities, show how students were exposed to a wide range of applications, and provide details about the Simulink exercises, including schematic diagrams. Documentation for the Simulink blocks may be found on the MathWorks web site [14]. Additional resources, including simulation models for various circuits and systems, are also

available on Youtube and the MATLAB Central File Exchange web site [15]. When teaching the course again, Simulink would be further integrated into the course with additional improvements. Experiments would be expanded to include induction motors, smart grid, and renewable energy.

Laboratory Exercises

Throughout the semester, students completed a total of nine laboratory exercises in addition to a final project that required an oral presentation. Students submitted two-page laboratory reports that included a summary and conclusion where students were asked to include, as applicable, the following items (as applicable):

- a. State the learning objectives of the exercise.
- b. Describe any problems you experienced.
- c. Briefly comment on the theoretical and experimental results or values.
- d. Discuss any errors encountered and their sources.
- e. Briefly state what you have learned.
- f. Suggest ways to improve the exercise/assignment.

The following paragraphs provide information about each of the exercises.

Exercise 1: The purpose of this exercise was to have students review the basic MATLAB operations, create M-files that evaluate expressions, and practice matrix operations.

Exercise 2: The purpose of this exercise was to have students write M-files to solve a set of linear equations, experiment with loops, and use plot functions.

Exercise 3: In this exercise, students became familiar with Simulink and simulated a single-phase transformer circuit that include power measurements as shown in Figure 1. Specifications included an AC Voltage source with $V_{p-p} = 120$ V and 60 Hz connected to a single-phase transformer. The transformer has a turns ration $(N_1/N_2) = 4$. The secondary winding of the transformer is connected through a transmission line to an RLC load ($R = 4 \Omega$, $L = 10$ mH, and $C = 100 \mu\text{F}$). The transmission line has an impedance with $R = 2 \Omega$ and $L = 5$ mH. Students created a Simulink model to simulate this transformer circuit. In particular, they displayed (using scopes) the input voltage, the output voltage, and the active (P) and reactive (Q) powers supplied by the transformer. They also measured the RMS values of the transformer input current and the load current (RLC load).

Exercise 4: In this exercise, students used the Simulink toolboxes to simulate a three-phase power system that includes a transformer and several loads as shown in Figure 2. Specifications included: A balanced Y-connected source with $V_{\text{phase-to-phase}}$ voltage of $120 V_{\text{rms}}$, 60 Hz, connected to a three-phase transformer with a turns ration $n = 2$. The output of the transformer supplies power to two separate loads. The first load is a Δ -connected three-phase series RLC load of $P_L = 10$ kW, $Q_L = 200$ VARs, and $Q_C = 100$ VARs. The second load is a three-phase series RLC load with $P = 10$ kW, $Q_L = 200$ VARs, and $Q_C = 100$ VARs. Assuming the single

line impedance between the transformer and the load is given by an inductive reactance (RL branch) of $2+j2 \Omega$. Since the line impedance is given in Ohms, students needed to manually calculate the L and C values using $f = 60\text{Hz}$.

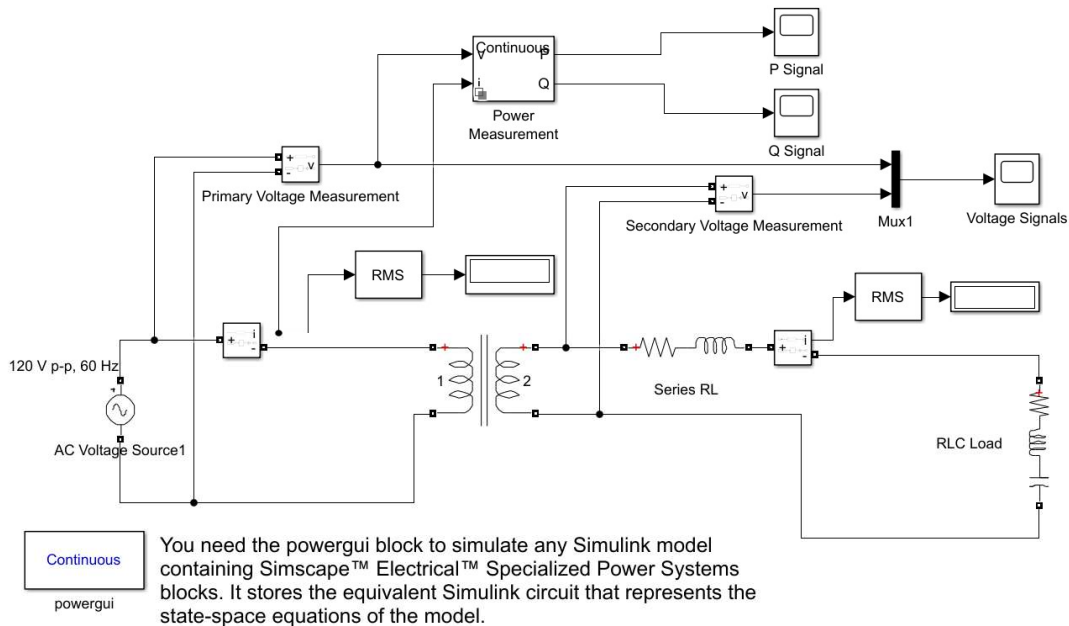


Figure 1. Circuit diagram for a single-phase transformer model

To perform a Simulink simulation, students were asked to do the following:

- Create a Simulink model that represents the system.
- Display the transformer Phase A/a voltages (primary and secondary of transformer) on the same scope. Confirm that the turns ratio (n) is equal to 2.
- Measure and display the 3 currents through the RLC line impedances and compare them (magnitude and phase angle).
- Measure and display the three-phase active and reactive powers of the Δ -connected RLC load.
- Measure and display the three-phase active and reactive powers of the Y-connected RLC load.

Exercise 5: In this exercise, students used the Simulink toolboxes to simulate a Power Transformer Short Circuit test as shown in Figure 3. Specifications included the use of a 60 HZ single phase AC voltage source of $240 V_{\text{rms}}$ and a transformer turns ratio of $240 V_{\text{rms}}/120 V_{\text{rms}}$. The AC source specifies a p-p voltage, so converting to V_{rms} manually is required in this case. Also, specifying a frequency of 60 HZ for all blocks is needed.

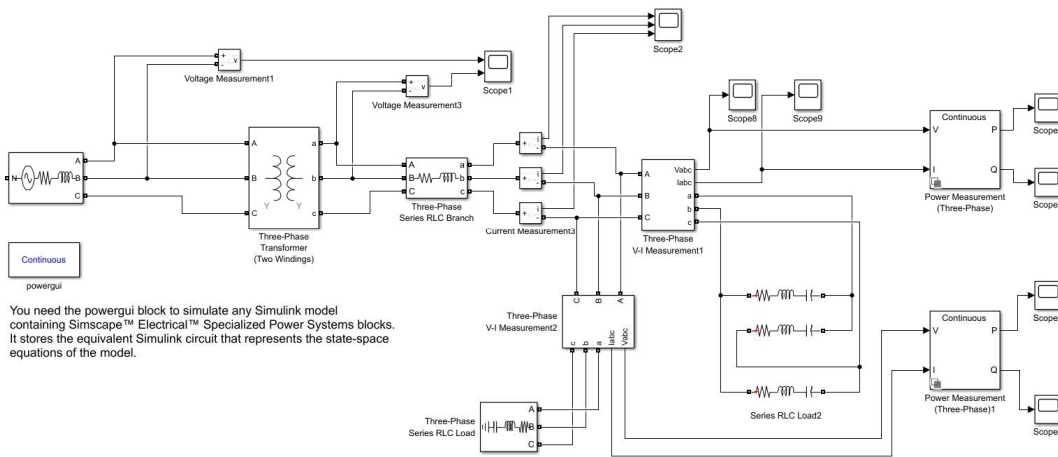


Figure 2. Three-phase power system diagram

Students were asked to do the following:

- (f) Create a Simulink model that represents a transformer short-circuit test.
- (g) Display the equivalent resistance referred to the primary (R_{eq}) and the equivalent reactance referred to the primary (X_{eq}) and record their values.
- (h) Change the value of the AC source to 120 V_{rms} and change the turns ratio to 120 $V_{rms}/240 V_{rms}$.
- (i) Run the model and record the new values of R_{eq} and X_{eq} . Compare results to those obtained in (g).

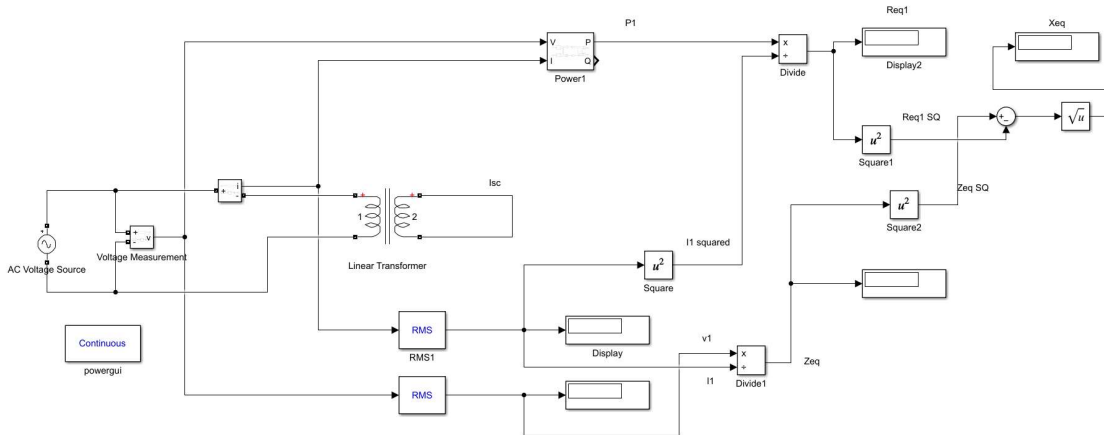


Figure 3. Diagram for the transformer short-circuit test

Exercise 6: This exercise uses the Simulink toolboxes to simulate a three-phase synchronous generator and examine its parameters. Students were asked to create a Simulink model similar to Figure 4 as follows.

1. Use the three-phase “synchronous machine “SI fundamental” block. Connect P_m and V_f to a constant block with value 1.
2. Connect the output of the generator to a three-phase Y connected parallel load with P (active power) = 10 kW, Q_L (Inductive reactive power) = 200, and Q_C (Capacitive reactive power) = 100 VAR.
3. Use scopes to display V_{abc} and I_{abc} . Are you getting balanced 3-phase signals?
4. Connect m of the generator to a “bus selector.” Click on the “bus selector” then select to display “Output active power,” “Output Reactive Power,” and the three stator currents (a, b, and c). Display P and Q on separate Scopes. Display all 3 currents on one scope.
5. Click on the generator and specify “swing” for the load flow.
6. Initialize the generator: Click on the “powergui” block. Click on “Tools.” Click on “Machine Initialization” Select “machine initialization” then select Swing Bus under “Bus Type.” Specify a terminal voltage of 13800 and an active power guess of 100. Click on “compute and apply” at the bottom right. Note that the inputs to the “ P_m ” and “ V_f ” inputs changed to correspond to the desired parameters. Did the constants connected to P_m and V_f change?

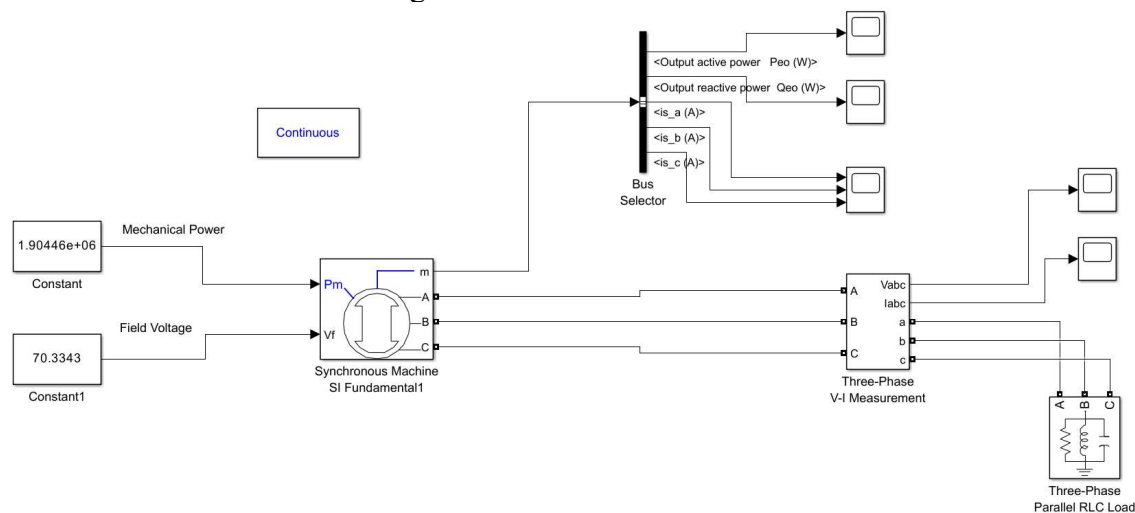


Figure 4. Diagram for a three-phase synchronous generator model

Exercises 7, 8, and 9: These exercises were based on ETAP. Exercise 7 was designed to familiarize students with ETAP by having them complete “how to get started - Learning ETAP in 5 Minutes [16]”.

Exercise 8 introduced a significant level of complexity to students’ educational experience by incorporating a real-life case study into the course. The modeling exercise is based on a physical 50 kVA microgrid testbed system in the PPL Power Laboratory on campus (Figure 5). The three-bus system has three 10 kVA synchronous generators, photovoltaic power sources, programmable DC power sources, bi-directional power converters, several motor loads, interconnecting lines, and a range of advanced programmable load systems. In addition, the cyber-physical system features advanced metering infrastructure (AMI), an integrated system of smart metering devices, network

communications, and PLCs for data management systems. These assets enable bidirectional interaction between providers and end users and devices. The assignment required ability to reduce the complex power system to a single-line diagram, approximation of the system to fit bus limitations of the ETAP modeling software, and the list of devices available in the software library. Furthermore, the work required the use of equipment manufacturer data, and approximations where data is not available.

Students were assisted by laboratory graduate assistants in scaling down model complexity, obtaining system data, and relating ETAP simulation results with experimental results from the laboratory.



Figure 5. PPL Electric Utilities Power Lab – Microgrid Testbed.

<https://sites.psu.edu/microgridtestbedpsh/lab/>.

In Exercise 9, students used the knowledge they gained in the earlier exercises to develop an ETAP model for a small industrial network and run power flows.

Students were given a single-line power system diagram and were asked to create an ETAP model similar to the one shown in Figure 6. Specifications for this part included:

Utility connection: 1500-MVA, 115-kV, X/R = 100. Short-circuit MVA of a utility connection (1500-MVA) is a value supplied by the utility company that makes it possible to represent the three-phase source of the external power system network (specifically the source impedance).

System base: 10-MVA, 115-kV at the Utility connection.

At the given utility bus voltage (115-kV), the corresponding source impedance:

$$X_{pu} = (\text{base MVA})/\text{fault availability in MVA}$$

$$R_{pu} = X_{pu}/(X/R \text{ ratio})$$

Motor reactance values are listed as follows:

M_1 : 0.2 pu

$M_2 - M_6$: 0.17 pu

$M_7 - M_8$: 0.20 pu

Motor VA ratings and voltage ratings were specified. Motor per-unit reactances are based on motor ratings. Motor VA ratings are indicated in the circles and voltage ratings are indicated on the connecting buses. Ignore system resistance values (do not represent the values of R).

Total line reactance:

Line C_1 : $X = 0.0574 \Omega$

Line C_2 : $X = 0.0645 \Omega$

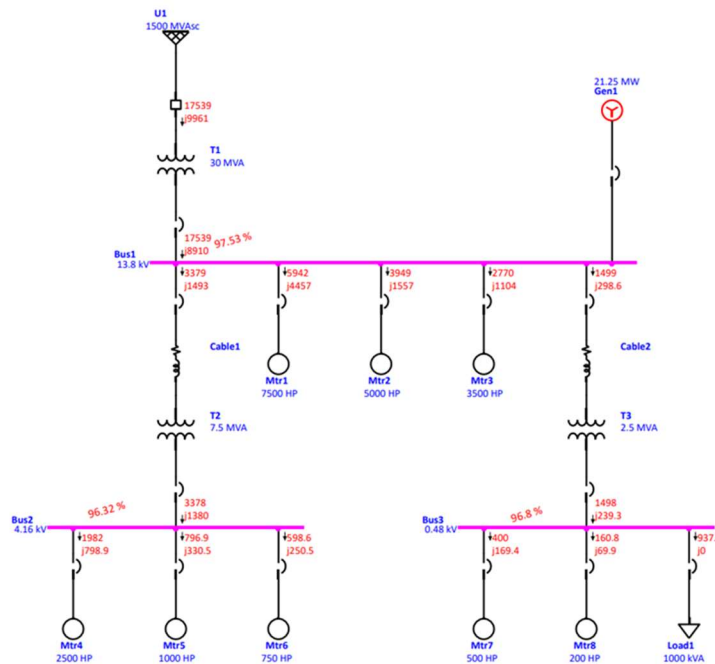


Figure 6. ETAP model for the industrial network

Final Project and Student Feedback

Students were expected to complete a final project either individually or in teams of two. Projects could be only software/simulation (MATLAB/Simulink, PowerWorld Simulator, etc.), only hardware, or a combination of both. Topics chosen by students included squirrel cage induction motor (Simulink), power flow analysis (ETAP), nuclear power generation (Simulink), microgrid power system (Simulink), commissioning box (ETAP), and induction heater (Simulink).

Students were encouraged to provide written feedback at the end of the semester as part of the final report and/or through the official course evaluation forms administered by the University.

Feedback was in general positive, but a number of students recommended more guided exercises. This feedback will be taken into consideration to improve the laboratory component of the course.

Conclusion

Software simulation has become an essential component of a comprehensive learning experience in engineering and engineering technology programs. This paper describes a set of software simulation exercises that were developed to complement the materials covered in a power systems analysis course. The exercises ranged from writing simple MATLAB programs that perform computations and graph results to more complex and practical applications. Feedback from students indicate that the exercises were successful in achieving the course objectives but there is room for improvement. Future plans include expanding the simulation exercises to include induction motors and the smart grid. The final project was well-received by students and is expected to continue to exist in a similar format.

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