

Electrical Circuits Virtual Lab

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Abstract

Most of our new generation students are experiential learners, whose understanding of engineering theories is enhanced by hands-on activities, simulation, and by using analytical tools to break down the problems. Using computational tools MATLAB helps to break down problems into steps and visualize the simulation results to develop their understanding abilities in order to help them in their future classes. MATLAB Live Editor®, Simulink® and Simscape® are used to create interactive documents and models, which combine formatted text, equations, codes, figures, and simulations to improve students' understanding of fundamental electric circuits analysis. Students are able to check their understanding by verifying the results, playing with the supplementary resources. The activities are good examples of pedagogical effectiveness for sophomore level engineering students. In this paper, students' performance are assessed whether the students have achieved the learning goals and measured the impacts of these changes on students' motivations and attitudes.

Keywords

Electrical Circuits, Virtual Labs, MATLAB, Critical Thinking, Engineering Education.

Introduction

Electric Circuit Analysis is the first course that the students take in Electrical and Computer Engineering and is a gateway course to upper division majors. Some other Engineering majors may also take the course. Electrical Circuit analysis is and has been a challenging course. The course is a way for students to experience electric circuits through simulation. With virtual labs, students are able to develop an understanding of electric circuits, validating their analysis and calculations, and it providing a way for students to develop an intuitive feel for electric circuit elements in the course and hands on lab experiments. In addition to virtual lab material, students may also have on campus laboratory experience.

There is a high failing rate in this course because students lose interest in the understanding of calculations, solving problems, and analyzing electrical circuits using textbook provided problems and pre-designed simulation software packages. MATLAB is one of the effective tools for solving electric circuits' problems quickly. Simple functions such as calculating the equivalent resistance or impedance of many types' connections of resistors, capacitors, and inductors; the conversion from Cartesian coordinates to polar coordinates or polar coordinates to Cartesian coordinates; the conversion from the wye configuration to delta configuration or delta configuration to wye configuration provide accurate answers quickly [2-3]. These simple functions can be part of the scripts that enable students to find solutions to typical circuit problems. Making plots as a function of any elements quickly in MATLAB assists the students in visualizing the effects of the changes made. Using MATLAB helps break down problems into

steps and creates a visualization of the simulation results, which help develop students understanding and development of skills to use in their future courses. MATLAB Live Editor®, Simulink® and Simscape® are used to create interactive documents and models, which are combined to formatted texts, equations, codes, images, and simulations to improve students' understanding of fundamental electric circuits and analysis.

Electrical circuits' modules were created in MATLAB for this purpose in collaboration with MathWorks Support engineers. Each module has a Live Scripts® file that includes learning objectives, description, solution methods, examples, and exercise problems [4-5]. Instructors may work on examples in the class and have students work on exercise problems individually or in group. Students go through the process of filling in the project templates created with Live Scripts® to demonstrate their understanding and results. MATLAB Live Scripts® included interactive elements such as numerical slider, in drop down or edit field menus so that students can change parameter values of a circuit and observe how the system response changes as indicated by the data on a graph. MATLAB Simulink Simscape® helps students verify the answer to the exercise problems and change the values of elements to analyze the circuit responses. Students can also modify the Simulink® models provided for the exercise problems for further exploration of the system. Students are able to check their understanding by verifying the results, playing with the supplementary resources, discussing the circuit response within a group and class or use the Live Scripts® as a basis for asking a question in a discussion group. Also, providing some online MATLAB Grader workout some quiz problems help students recognize and apprehend the subjects [6]. These simulation modules help students to use lab instruments, build the circuits, take measurements, and analyze the results effectively.

The activities are good examples of pedagogical effectiveness for sophomore level engineering students. In this paper, structure of each module content and example of a module are presented. Also students' performances are analyzed and assessed whether the students have achieved the learning goals or if there is an impact made, depending on the changes of the students' motivations and attitudes.

Organization of the Module Content

The plan is to improve learning by providing engaging interactive accessible resources for students, including narrative explanations, examples and embedded exercises with self-tests using MATLAB tools. These learning materials are available online [5]. We have consulted with MATLAB engineers for the application of these tools to have the best practices available in the format of critical materials, as well as the other components of the course modules.

Three or more examples are created for every module in MATLAB Live Script®. Each example in the modules contains a detailed narrative of how to approach the problem. This includes detailed derivation and solution of all relevant equations. Many times, students get lost on the simplest possible steps in the process of solving problems. The goal of these examples is to learn the problem-solving process step by step without spending time on the numerical calculations. Similarly, three or more exercise problems are created to provide students practice in applying the concept. These problems are flexible enough to accommodate a variety of learning styles as chosen by instructors. When a student fails to provide a correct answer, the program should be able to analyze the student's work and provide guidance until the student gets the correct answer.

The analysis of the student's answer should be able to locate the errors, to identify whether the student made simple mistakes in the algebra portion or made mistakes in setting up the equations. If the wrong answer is in the algebra portion, the program should be able to guide the student to correct the mistake. If the incorrect answer is in setting up the equations, the student is directed to the lecture materials and examples, or is given tips to correct the mistake.

Simulink® with Simscape® files are given for each example and exercise problems so that students can test and compare the results in the interactive problems. For each module, self-test problems have been created in MATLAB Grader®. These problems are similar to those in the quizzes, midterms, and final exams developed by professors teaching the course. The Grader provides feedback on each of the mistakes the student made along with the score. If a student does not get a satisfactory score, the student should be able to take as many times as needed until the score improves. In each subsequent test, the test questions are modified using random numbers and simple transposition of circuit elements.

The following modules has been created under MATLAB Live Scripts® simulations that contain background information, solution steps, examples and exercises with interactive tasks, and Simulink Simscape® files:

Module 1. Node Analysis: Use the node-voltage method to solve a circuit that containing resistors and independent and dependent current sources and voltage sources.

Module 2. Mesh Analysis: Use the mesh-current method to solve a circuit for an arbitrary network containing resistors and independent and dependent voltage and current sources

Module 3. Operational Amplifier Circuits: Analyze inverting, non-inverting, summing, and differencing operational amplifier circuits in the time domain.

Module 4. RC and RL circuits: Determine the natural and step response of both RL and RC circuits. Analyze circuits with sequential switching.

Module 5. RLC circuits: Determine the natural and the step response of RLC circuits.

Module 6. Op-Amp with a Capacitor: Analyze op amp circuits containing resistors and a single capacitor.

Module 7. Sinusoidal Steady State Analysis: Solve a circuit in the frequency domain

Module 8: Power Calculations: Calculate AC Power in a circuit Instantaneous power, Average (real) power, and Reactive power

The topics in these modules focus on fundamental electrical circuit analysis for engineering majors and developing a foundation for electrical and computer engineering majors in their upper division courses. They can be used in asynchronous or synchronous mode for electric circuits' classes and labs as homework, projects, and lab experiments. These modules can easily be used or modified for other engineering majors.

MATLAB Modules Design of Activities

During 2021, we explored the applications of MATLAB Live Script® and Simulink Simscape® to solve Electrical Circuits problems. In this project, we were able to provide many tools with MATLAB and Simulink® to the students who were taking the Electrical Circuits during the fall semester of 2021. Following paragraphs discuss the some examples of the documentation that has been created:

Figure 1 explains the steps to solve node analysis problems. Students expect to follow these steps when they do exercises.

Case 1 : All voltage sources are not connected between the nonreference node

We assume that all voltage sources are not connected between the nonreference node. If there is a voltage source in a circuit between two nonreference nodes whose voltages are unknown and we do not know the current through the voltage source, we call it a supernode and we will solve under **Supernode** section

Steps to Determine Node Voltages

1. Select a node as the ground node 0.
2. Assign V_1, V_2, \dots, V_{n-1} to remaining $n-1$ nodes, identifying any known voltages. The voltages are referenced with respect to the ground node.
3. Select a direction for the current passing through each resistor at the node with an unknown voltage and express the branch currents in terms of node voltages.
4. Apply KCL to each of the $n-1$ non-reference nodes.
5. Use Ohm's law to express the branch currents in terms of node voltage
6. Solve the resulting simultaneous equations to obtain the unknown node voltages.

Figure 1. Steps to determine Node Voltages

An example for Node Analysis is given in Figure 2. All component values are given and asked to find the node voltages, voltage across a resistor, and a current through a resistor.

Example 1. Node analysis with one terminal of voltage sources connected to reference node

Writing node analysis to find node voltages V_2, V_3 , voltage cross resistor R_3 , and current through R_5

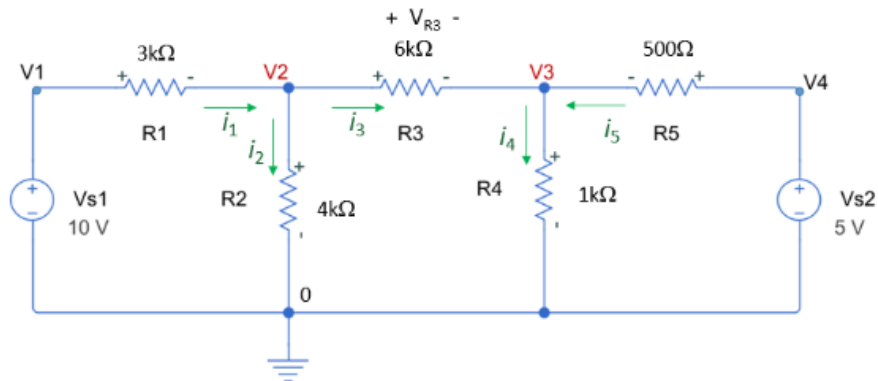


Figure 2. An example for Node analysis

Figure 3 shows the steps that need to be followed to find the node equation.

Solution

Steps 1, 2, and 3 is given in the figure above. We can look at the figure to find any of the nodes voltages are known.

$$V_1 = V_{s1} = 10V \quad \text{and} \quad V_4 = V_{s2} = 5V$$

4. Apply KCL at unknown nodes 2 and 3

$$i_1 - i_2 - i_3 = 0 \quad \text{and} \quad i_3 - i_4 + i_5 = 0$$

5. Let's write each of the branch currents in terms of node voltages. This is done using Ohm's Law (you have to be careful about the polarities).

$$i_1 = \frac{V_{s1} - V_2}{R_1} = \frac{12 - V_2}{3k\Omega}, \quad i_2 = \frac{V_2 - 0}{R_2} = \frac{V_2}{4k\Omega}, \quad i_3 = \frac{V_2 - V_3}{R_3} = \frac{V_2 - V_3}{6k\Omega},$$

$$i_4 = \frac{V_3}{R_4} = \frac{V_3}{1k\Omega}, \quad i_5 = \frac{V_{s2} - V_3}{R_5} = \frac{5 - V_3}{500\Omega}$$

6. Apply the branch currents equation to KCL equations at unknown nodes 2 and 3.

$$\text{At node 2} \quad \frac{V_{s1} - V_2}{R_1} - \frac{V_2}{R_2} - \frac{V_2 - V_3}{R_3} = 0 \quad \text{or} \quad \frac{10 - V_2}{3k\Omega} - \frac{V_2}{4k\Omega} - \frac{V_2 - V_3}{6k\Omega} = 0$$

$$\text{At Node 3} \quad \frac{V_2 - V_3}{R_3} - \frac{V_3}{R_4} + \frac{V_{s2} - V_3}{R_5} = 0 \quad \text{or} \quad \frac{V_2 - V_3}{6k\Omega} - \frac{V_3}{1k\Omega} + \frac{5 - V_3}{500\Omega} = 0$$

Figure 3. The steps to write node equations.

Figure 4 and 5 represent MATLAB Live Script® code to calculate unknowns' nodes voltages, where `symunit` is used to represent each unit.

There are two unknowns and two equations. Use MATLAB solve function to find unknown voltages V2 and V3 as follow.

```
u = symunit;

% Given Values
Vs1 = 10*u.V; Vs2 = 5*u.V;
R1 = 3*u.kOhm; R2 = 4*u.kOhm; R3 = 6*u.kOhm; R4 = 1*u.kOhm; R5 = 500*u.Ohm;

%Known node voltage V1 and V2
V1 = Vs1; V4 = Vs2;

%Unknown node voltage V2 and V3
syms V2 V3;
%Node equation and solution
[V2,V3] = solve ((V1-V2)/R1-V2/R2-(V2-V3)/R3==0, (V2-V3)/R3-V3/R4+(V4-V3)/R5==0);
V2 = rewrite(V2,u.V)
```

$$V2 = \frac{880}{169} \text{ V}$$

```
V3 = rewrite(V3,u.V)
```

$$V3 = \frac{580}{169} \text{ V}$$

Figure 4. MATLAB Live Script® codes for the example

```
% Find voltage cross resistor R3 and current i5 through resistor R5
i3 = (V2-V3)/R3;
VR3 = i3*R3

VR3 =
    300 V
    169

i5 = (V4-V3)/R5;
i5 = rewrite(i5,u.mA)

i5 =
    530 mA
    169
```

Figure 5. MATLAB Live Script® codes for the example

Using variable-precision floating-point arithmetic (VPA), each unit calculation can be evaluated to at least 5 significant digits as in Figure 6.

```
Display each values at least 5 significant digits.

V2 = vpa(V2,5)
V3 = vpa(V3,5)
VR3 = vpa(VR3,5)
i5 = vpa(i5,5)
```

Figure 6. Decimal representation of each units

Figure 7 represents the Simulink Simscape® file. The Simulink® file is linked to the Live Script® file so that students can download and make any changes or modifications.

Circuit simulation is given in the following MATLAB Simulink `./Simulink\Example_1.slx`

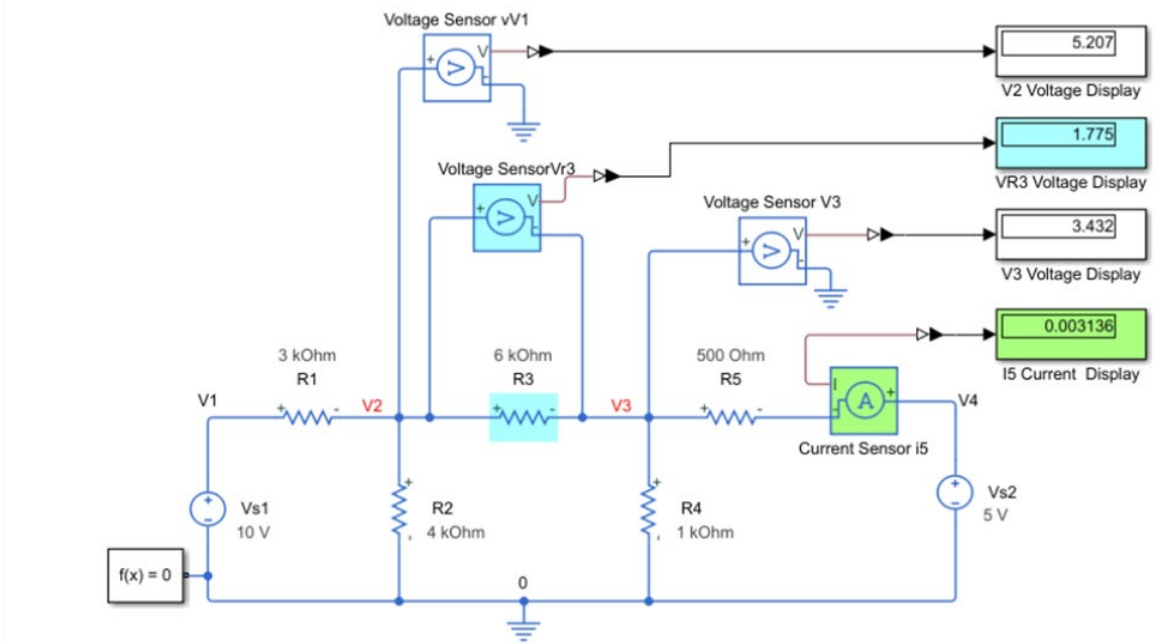


Figure 7. Example of Simulink Simscape® file

In the exercise, students work on given the steps in MATLAB Live Script® code as seen in Figure 8.

```

u = symunit;
% Given

% Known node voltage V1 and V2

% Unknown node voltage V2 and V3
% syms V2 V3;
% Node equation and solution
% [V2,V3] = solve(?? ,??);

% V2 = rewrite(V2,u.V)
% V3 = rewrite(V3,u.V)

% Find voltage VR5 cross resistor R5

% % Find Voltage VR5,an currents i3, i5

```

Figure 8. Example MATLAB Live Script® code

Each file content is compatible with MATLAB Online and Simulink®. To make the Live Script® files more interactive, Control Tools (Numeric Slide, Drop Down, Edit Field, etc.) can be used some examples. Students can change circuit parameters with control tools and see the effects on the time domain response.

Measures of Students' Performance and Attitudes

The modules have been tested on undergraduate programs of two different campuses. The students in Electrical and Computer Engineering (ECE) of the first campus have always struggle with the first core freshman level class ECE 1101 Electrical Circuit Analysis and its accompanying lab. Failure to grasp the basic concepts taught in this class have a deleterious ripple effect on a student's future success in our degree programs in ECE. Additionally, many of the students are the first in their family to attend college; they are unfamiliar with courses and lack basic skills for creating conceptual frameworks necessary for college learning.

MATLAB engaging interactive online resources are improve the students' interest and learning. The students' grade distribution is show some improvement. The grade distributions of the last three years taught by the same instructor are given in Figure 9. The class capacities had an average of 32 students. Only Fall 2021 students started to use the new MATLAB simulation tools. We observed the students who follow the new MATLAB tools, and have noticed the students with the average grade levels have improved, while the failing students have not had major changes. The lectures were given online and the failing students might have some difficulties in MATLAB coding. In addition to this, student-teacher evaluations increased by 23% in fall of 2021. This shows that students had overall appreciated using MATLAB simulation tools. The interactive exercises in simulation environments provide students with immediate feedback, assist in their learning, and make for an overall positive and fun experience. This helps students stay engaged and focused on the engineering material.

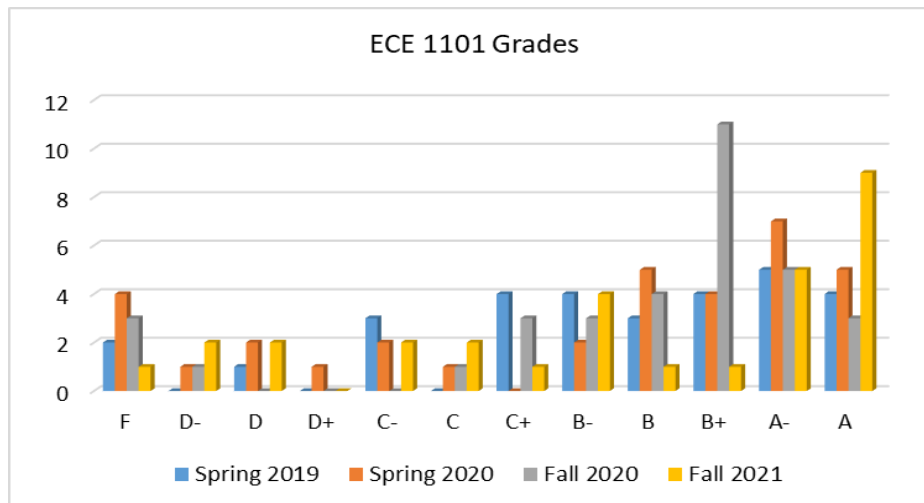


Figure 9. Electrical Circuit Analysis Grade distribution in the one of the campus Fall 2019 - 2021 comparison

The other campus applied MATLAB tools to Engr 17 Electrical Circuit Analysis in Electrical & Electronic Engineering department. It is a gateway course to upper division courses in Electrical and Computer Engineering and the course may also be taken by other engineering majors. The topics in the course are addressed on the Professional Engineering Licensing exam, Fundamentals of Engineering, FE, exam for Electrical Engineering. There is not a lab for this course material which makes the course material even more challenging.

Circuit Simulation and MATLAB are introduced to provide a “Virtual Lab” experience for the students. These tools allow the students to verify their hand calculations and explore circuit element behavior, to reinforce electrical circuit analysis. Figure 10 shows a comparison plot of two semesters taught by the same instructor. Spring 20 is typical without MATLAB and circuit simulation verification and Spring 21 grade distributions after introducing MATLAB and circuit simulation. We have noticed the students with the average grade levels have improved tremendously.

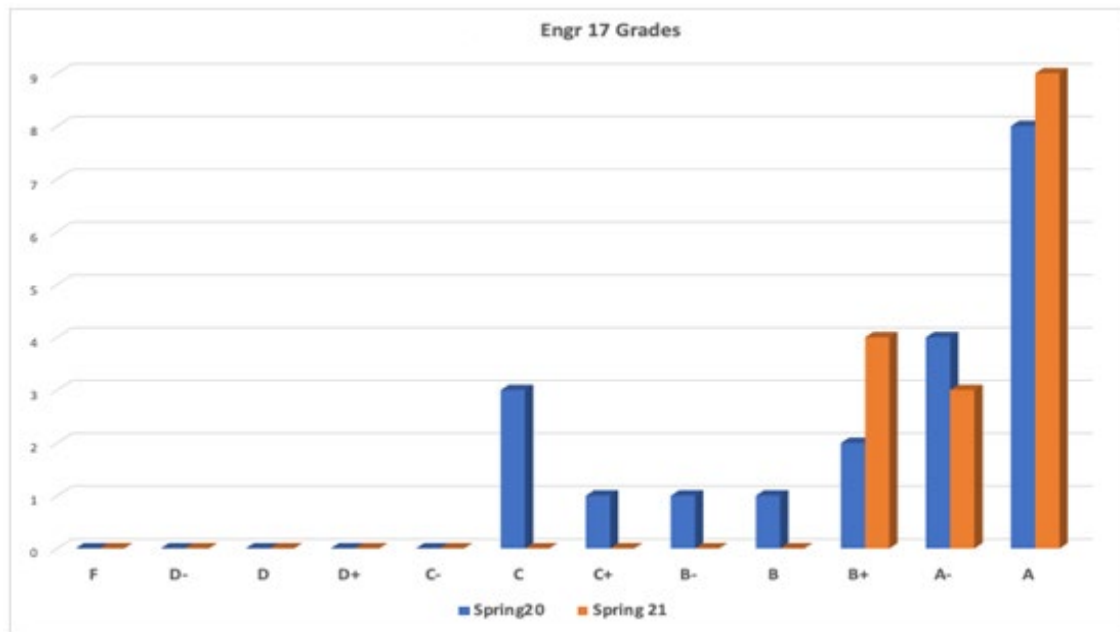


Figure 10. Engr 17 Electrical Circuit Analysis Grade distribution spring 2020 and 2021 comparison.

Discussion and Conclusions

By incorporating these virtual lab modules into our courses, we have had an impact on student learning of the material and a shift up the grading scale. Students now have a better intuitive “feel” understanding of electric circuits.

Using the material and approach on our respective courses on different campuses, we have seen the students’ grades improve. The C range grades improved to B+ grades, and B range grades improved to A range grades. Contrasting the semester before using the virtual lab modules to the semester after using the virtual lab modules, increasing the students’ interest. We have

experienced students who are more engaged with course material when they are able to take more of an engineering approach to electric circuit analysis. The students are not only able to analyze electric circuits but they are able to explore electric circuit elements behavior with MATLAB and virtual simulators. Students are able to verify their hand calculations by using these tools and exploring results that did not meet their expectations. This approach helps the students develop problem solving and critical thinking skills, and prepares them for an engineering career. The virtual labs and simulation tool environments are meant to assist and enhance the student learning experience and not to replace hands-on laboratory experience. They can also be helpful in situations where on campus laboratories are not available.

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