

An Intelligent Software Tutor for Scaffolding Solving DC-DC Converter Circuits

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Abstract

Power electronics is an enabling technology for the smart power grid. However, students often struggle in the Power Electronics course because it requires mastery and simultaneous application of concepts from several earlier courses. To address this educational challenge, based on this NSF-supported project, we have designed and developed a software tutor to help students in this course by providing a scaffold to translate visual information (circuit diagrams) to written information (equations) and analyze a power electronic converter circuit. The developed web-based software tool uses scaffolding as an interactive well-established pedagogical approach to improve students' learning and problem solving skills. Scaffolding provides students with a template and dynamic feedback to assist them in their early stages of learning. In our case, the developed software tutor assists students by scaffolding (i) creating circuit diagrams, (ii) translating circuit diagrams into equations, and (iii) solving the resulting equations. In each step, the tutor checks the accuracy of the student's work and provides constructive and formative feedback. Constructive feedback means that it takes note of student's mistakes and suggests ways to alleviate them. Formative feedback means that the tool advises students of their mistakes immediately after the mistake is made. The feedback messages provide the answer to three major questions: "where am I going?" (feed up), "how am I going?" (feed back), and "where to go next?" (feed forward). A feedback message describes (i) the issue, (ii) the cause of the issue, and (iii) the suggested solution.

Introduction

Power electronics is an enabling technology for the smart power system, the smart grid [1]. Power electronics studies efficient conversion of electric power from one form to another (e.g., DC to AC). It has applications in a wide-range of areas, from the tiny battery charger in a cell phone to the small inverter in a solar renewable system [2] to the enormous converters in an HVDC converter station. Therefore, it is imperative for students who seek employment in the power industry to understand the underlying concepts of power electronics. However, students often struggle in understanding power electronics concepts. Increasing this understanding is what this work addresses.

Power electronics is typically taught as a senior-level course (EE 486 at WSU). It is a multidisciplinary course and requires simultaneous application of concepts from several earlier courses, such as circuits, electromagnetics, electronics, signals and systems, power systems, physical electronics, electric machines, and control systems [3]. In our experience, confirmed by the literature [4], a major challenge for power electronics students is problem solving. This is ironic as problem solving is expected to be among the strong suits of engineering graduates [4]. Students have difficulty in solving multidisciplinary problems even when they have a reasonable command of each individual discipline [5]–[8]. These observations confirm an educational challenge that we plan to address through “scaffolding.” Educational scaffolding provides a problem solving template to assist students during early stages of learning.

Several commercial software tools exist for simulation of power electronics circuits. However, certain features that are preferred for a professional audience decrease their educational value. For example, they include a comprehensive set of facilities, but this can overwhelm students. Moreover, they perform calculations in the background, but it is precisely learning how these calculations are done that is essential in learning engineering. Efforts for developing educational simulators have been made [9], [10], but there is no tool yet available that guides students through steps of problem solving. This gap is addressed in this work guided by the following research question: To what extent will scaffolding via a software tool and a flexible hardware kit improve students’ understanding of and interest in power electronics?

Pedagogical Approach

Power electronics is an early exposure of undergraduate students to multidisciplinary courses. As Fig. 1 shows, power electronics includes concepts from several earlier courses, such as electric circuits, power systems, electromagnetics, electric machines, signals and systems, electronics, physical electronics, and control systems [3]. We have observed that students often have difficulty putting these concepts together to solve power electronics problems. Although the succession of courses in a curriculum normally do draw from the knowledge gained in the previous courses, in case of power electronics, two factors increase the challenge that students face: (i) the need to simultaneous multidisciplinary knowledge to solve problems and (ii) the multitude of explicit and implicit prerequisite courses. This situation is more pronounced in our higher education system as students can complete a course with a passing grade, but not necessarily a full grade. Thus, it is very likely that a student may proceed to higher-level courses without fully understanding all the prerequisite concepts. Such conceptual difficulties tend to accumulate and present themselves clearly in a multidisciplinary context, where mastery of several courses is required to successfully analyze problems. Moreover, they can lead to misconceptions that can undermine understanding of the new topics [11]–[14]. Our developed tool seeks to alleviate these difficulties.

Based on the literature [5]–[8], which is confirmed by our observation of EE 486 course work, these conceptual difficulties include

- Circuit simplification (Thévenin and Norton equivalent circuits);
- KCL and KVL in power electronics circuits with time-varying topology;

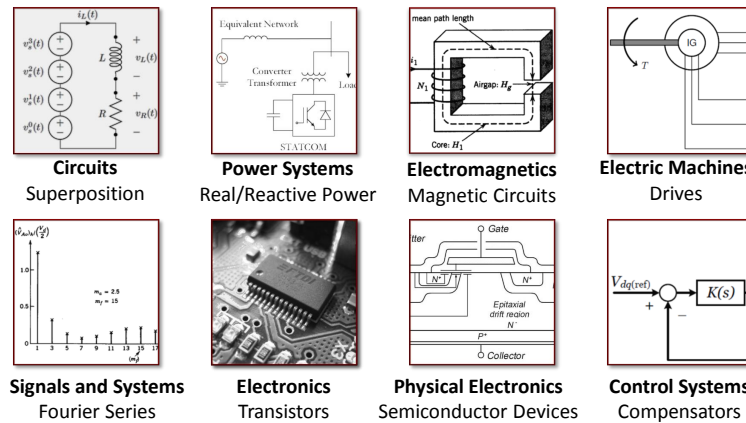


Figure 1. Multidisciplinary nature of power electronics.

- Passive reference convention for voltage and current in power electronics circuits;
- Harmonic analysis of circuits (simultaneous application of superposition and Fourier series);
- Existence of voltages higher than the source’s in power electronics system;
- Possibility of power delivery to a node with a higher voltage magnitude (unlike a DC system).

These difficulties tend to prevent students from approaching problems in a methodical way.

Implementation

Due to lack of formative feedback, commercial simulation tools are not suitable for educational applications. Our objective is to design a tutor that enables students to explore different power electronic converter topologies and receive immediate and formative feedback on the validity of their topology and developed equations as they put the circuit elements together. We focus on the DC-DC converters as they are the cornerstone of power electronics converters—other converters can be conceptually thought of as their generalizations.

Fig. 2 shows a screenshot of the developed intelligent tutor [15]–[17]. A beta version is available at <http://perks.eecs.wsu.edu>. The tutor scaffolds solving power electronics circuits for students by providing step-by-step and formative feedback on the correctness of the circuit, its equations, and the voltage and current diagrams. If the circuit is not a valid converter circuit, the student will receive a message outlining the error, its likely cause, and the possible remedy. The students will also receive feedback on the time spent on the different aspects of their solution. The tutor is currently being tested with students in EE 486 Power Electronics at WSU. Students are asked to solved several converters using this software and additionally provide feedback on its usability, features, and ease of use. It will be tested with partner universities as well.

The tutor is intentionally limited to avoid overwhelming students [11, Ch. 2]. In early stages of learning, students need only a limited “palette” consisting of basic electrical components

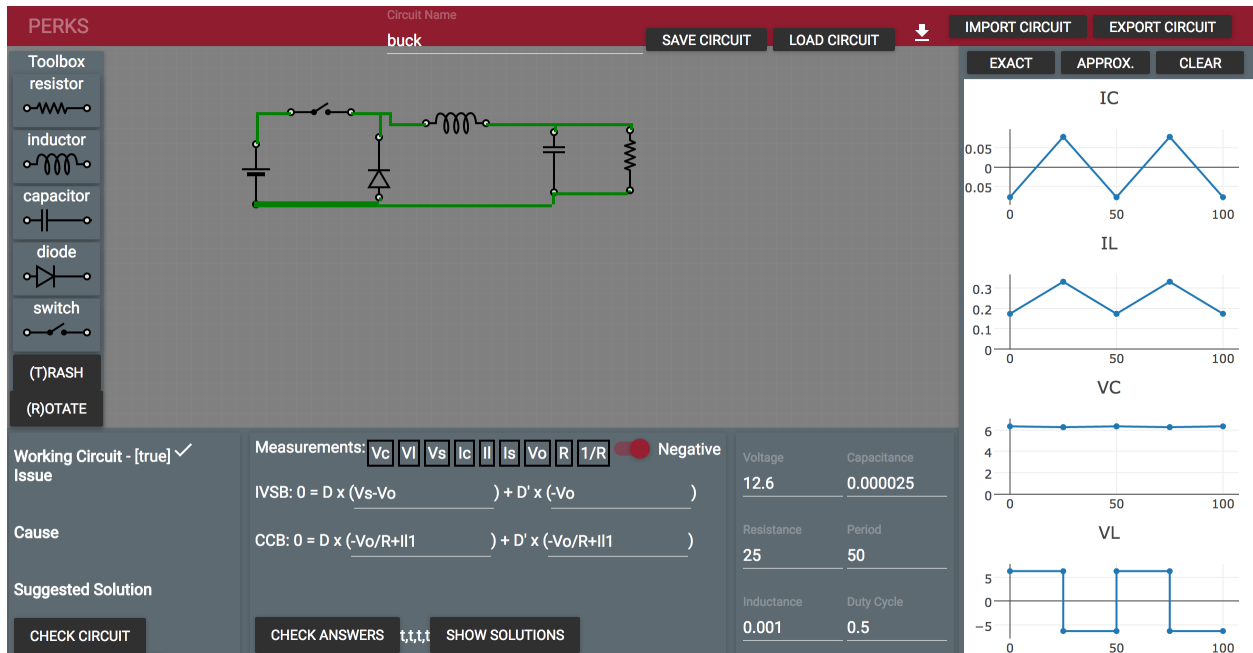


Figure 2. Screenshot of the designed power electronics tutor.

including resistor, inductor, capacitor, single-pole single-throw (SPST) switch, and voltage source. Students can drag and drop these components to the canvas and change the values of the circuit parameters and study their effect. This software assists students by scaffolding the following steps: (i) creating circuit diagrams, (ii) translating circuit diagrams into equations, and (iii) solving the resulting equations. In each step, the tutor will check the accuracy of the student's work and provide constructive and formative feedback. Constructive feedback means that it takes note of students mistakes and suggests ways to alleviate them. Formative feedback means that the tool advises students of their mistakes immediately after the mistake is made. We expect that this formative feedback will have a higher educational value than the summative feedback that is provided by commercial tools only after the user attempts to “run” the simulation case [18]. The feedback messages will provide the answer to the three major questions identified in [18]: “where am I going?” (feed up), “how am I going?” (feed back), and “where to next?” (feed forward). As Fig. 2 shows, a feedback message will describe (i) the issue, (ii) the cause of the issue, and (iii) the suggested solution. In line with scaffolding theory [19]–[21], we aim to maintain a balance in creating this tool: we want to assist students to master problem solving, but we do not want them to be so dependent on the scaffold that they cannot transition to independent problem solving.

To provide meaningful feedback messages, we use a rule-base guided by the students' approach to problem solving. The rule-base is essentially a database of common mistake-solution pairs, including the following:

- In the steady state, the average voltage across an inductor should be zero (conservation of energy);
- In the steady state, the average current flow in a capacitor should be zero (conservation of

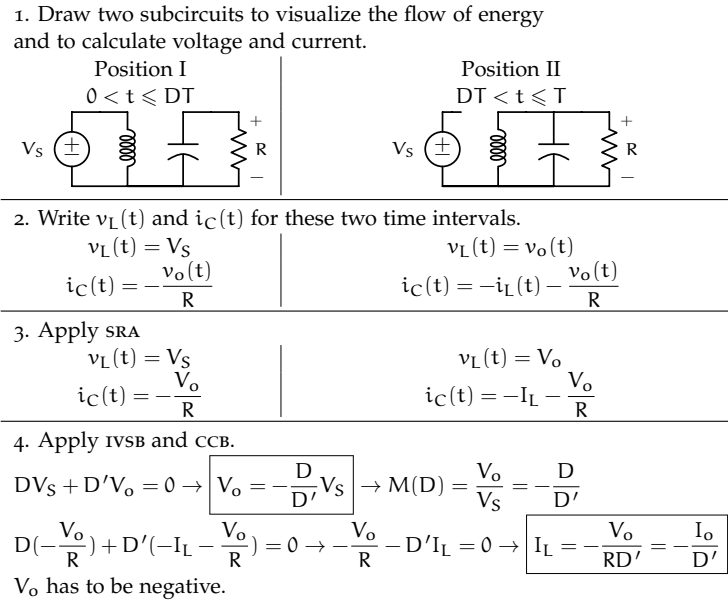


Figure 3. Governing equations of a buck-boost converter.

mass);

- Opening a switch should not interrupt the current of an inductor (KCL); and
- Closing a switch should not short circuit the voltage of a capacitor (KVL).

After the topology of the circuit is validated by the tutor, the student can start writing the circuit equations. Fig. 3 shows an example for a buck-boost converter. Producing the equations for the average inductor current (IVSB) and average capacitor voltage (CCB) is among the most difficult steps for students; therefore, the tutor scaffolds this task by enabling students to drag and drop elements to the equation editor, Fig. 2. The drag-and-drop functionality has two benefits: (i) limit the elements in equations and reduce mistakes, and (ii) reinforce the relationship between the circuit variables and equations. In these equations, only voltages of the source V_s and capacitors V_c and currents of the inductors I_L can be used.

After correct equations are produced, the tutor shows the circuit voltage and current waveforms obtained from these equations side-by-side with the exact circuit solution. The exact solution is obtained by solving the differential equations using EMTP-type algorithms on a modification of Y_{bus} [22], [23]. The approximate solution is obtained directly from the validated equations. Comparison of the approximate and exact solutions is performed to demonstrate two points:

- Power electronics circuits, similar to any other circuit, can be analyzed using differential equations obtained from KCL and KVL; and
- For well-designed converters, the results obtained from power electronics circuit analysis techniques (IVSB, CCB, and SRA) are very close to the exact results.

Comparison of the approximate and exact solutions demonstrates two points: (i) Power electronics circuits, similar to any other circuit, can be analyzed using differential equations based

on KCL and KVL; and (ii) for well-designed converters, the results obtained from power electronics circuit analysis techniques (IVSB, CCB, and SRA) are very close to the exact results. In line with scaffolding theory, we have maintained a balance in creating this tool: we want to assist students to master problem solving, but we do not want them to be so dependent on the scaffold that they cannot transition to independent problem solving.

Conclusions

This paper discusses the motivation behind and design/development of an intelligent tutor tool for scaffolding solving power electronics-based DC-DC converters. The software walks students through different stages of solving such converter circuits. Based on the initial feedback of students in WSU's EE 486, we expect that this tool increases their understanding of the energy conversion process underlying the operation of DC-DC converters. Additionally, we expect the software to help students appreciate the convenience and accuracy of engineering methods (in this case, IVSB and CCB), as compared to the full-fledged mathematical analysis, in handling properly designed converters.

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