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Board 68: Work in Progress: LabSim: An Ancillary Simulation Environment for Teaching Power Electronics Fundamentals

Mr. Mohamed Khaled Elshazly, University of Toronto

Mohamed Elshazly is a PhD student at the University of Toronto's Edward S. Rogers Sr. Department of Electrical & Computer Engineering (ECE). He is currently engaged in developing support simulations for teaching introductory power electronics to undergraduate ECE students, as well as providing technical support. Mohamed's main research interests are numerical simulations and computational energy materials, focusing on quantum mechanical modelling of electrochemical energy storage devices.

Dr. Hamid S Timorabadi P.Eng., University of Toronto

Hamid Timorabadi received his B.Sc, M.A.Sc, and Ph.D. degrees in Electrical Engineering from the University of Toronto. He has worked as a project, design, and test engineer as well as a consultant to industry. His research interests include the application of digital signal processing in power systems.

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Abstract

Switch-mode power conversion is one of the most crucial topics in a modern undergraduate electrical energy systems curriculum. The importance and ubiquity of switch-mode power converters, however, are matched by their complexity. Students are expected to have developed a rigorous understanding of electrical circuits, semiconductor physics, signal processing, control theory, digital logic, and wave mathematics before being introduced to power electronics. Students at our institution are introduced to fundamental concepts in lectures then they put them into practice in hands-on labs, which are limited to three-hour-long experiments conducted in a strictly controlled environment due to safety concerns. This leaves little room for exploration and independent trial-and-error. We have developed LabSim, an out-of-the-box functional software implementation of the switch-mode converters studied in class, in order to provide students with the opportunity to practically explore power electronics fundamentals and experiment at their own pace. LabSim is implemented in Simulink using visual PLECS blocks, an approach that ensures students do not have to spend significant time learning new software or navigating complex mathematical models. A pilot run of LabSim was conducted over the course of a semester, with students being provided the models in pace with the relevant lecture and lab material. We present a detailed description of the LabSim implementation and the specific shortcomings it aims to address within our introductory power electronics course. We also present and analyze the positive results of the LabSim pilot project as indicated by a student survey emphasising learning impact and workload management.

Introduction

Due to their ubiquity and technological importance, switch-mode power converters are one of the most crucial components of a modern electrical engineering curriculum. The importance and ubiquity of power electronics, however, are matched by their complexity. Students are typically introduced to power electronics when they have developed a rigorous understanding of electrical circuits, semiconductor physics, signal processing, elementary control theory, digital logic, and wave mathematics. The interplay between these concepts in practical circuits can be difficult for inexperienced students to grasp.

Third-year undergraduate students at our university are introduced to power electronics in Fundamentals of Electrical Energy Systems (FEES). The course covers basic concepts in energy systems such as (DC/DC, DC/AC) converters, magnetic circuits, and electric machines. These concepts are presented in lectures and then put into practice during hands-on labs. Students' enquiries and feedback reveal two shortcomings for this approach. The first of which is that during the lectures, power electronics are taught by providing a step-by-step analysis of converter circuits. For instance, current waveforms are drawn in a step-by-step fashion on the blackboard during the lecture. If a student misses or misunderstands a single step, they are left with a final snap-shot of the waveform and cannot comprehend how that waveform is reached. The second shortcoming is that labs are limited to three-hour-long experiments conducted in a strictly controlled environment due to safety concerns, leaving little room for exploration and independent trial-and-error.

One attractive complement to the lecture/lab approach is simulations. Simulation software allows students to operate realistic power electronics circuits on their own time, and hence gain a more thorough understanding of the concepts they are exposed to in lectures at their own pace.

There have been multiple reports of simulations being successfully used to augment teaching in engineering courses. Butterfield and coworkers developed browser-based simulations for a first-year-level chemical engineering laboratory course covering diverse concepts such as reaction dynamics, heat transfer, and RC electrical circuits. The simulations resulted in a 24% improvement in student performance, as evaluated through pre- and post-course tests [1] [2]. Xie and coworkers developed Energy3D, a graphical simulation and artificial intelligence software for the CAD of energy efficient buildings, which resulted in improved design skills for students developing rooftop solar energy systems as part of their coursework [3]. Altuger-Genc conducted a pilot project testing interactive simulation software for a sophomore-level fluid mechanics course, with 80% of students reportedly preferring the interactive learning approach and 90% preferring the addition of simulations to the lecture materials [4]. Chyung and coworkers developed MATLAB-based graphical simulation tools for a multivariable and vector calculus class, with examples illustrating concepts such as divergence, line integrals and directional derivatives. Through a series of surveys, 74% of 117 students enrolled in that class rated the value of these simulations as moderate or high [5]. Akkoyun reported very positive student feedback to a Visual Basic software tool developed for mining engineering students in order to simulate the operation of raw stone processing plants; accounting for variables such as cost calculation, machine components, and waste recovery [6]. Abramovitz reported excellent student reception for an industrial electronics course that involved state-space-averaged PSPICE models of power electronic converters and active power factor correction (APFC) circuits [7].

The operation of power electronic circuits presents some unique challenges in terms of simulation development. The first of which is that switching frequencies in practical converters are in the 10-100 kHz order of magnitude. This corresponds to a required sampling time of less than 100-10 μs, which can be computationally demanding. Another challenge lies in the modelling of the circuits' switched states, which can cause numerical instability or excessively long simulation time depending on the underlying switch models [7] [8]. These challenges are typically addressed through the use of state-space averaged models. These models, while highly useful in research, require advanced understanding of power electronics state-space representation and would be challenging for an introductory-level student to understand and modify. Moreover, averaged models typically exclude the switching ripples in the resulting voltage and current waveforms, which is undesirable for students learning about the limitations of power electronic circuits at the introductory level [9].

In light of the many promising reports of simulation-augmented classrooms, we developed LabSim in order to address FEES' shortcomings by providing an out-of-the-box functional implementation of the power electronics converters discussed in the course. LabSim is implemented in Simulink [10] using visual PLECS blocks [11], an intuitive approach that ensures students do not have to spend significant time navigating obscure software or modifying abstract mathematical models. It also mitigates the aforementioned challenges of simulating fully-switched power electronic circuits through integrating basic Simulink control blocks with piecewise-linear models of the circuit components [8], ensuring students are exposed to the full switching operation of the circuits they learn in a graphical interface that is easy to modify.

We conducted a pilot test of LabSim over the course of a semester, with students being provided the models in pace with the relevant lecture and lab material. We present a detailed description of the LabSim implementation and the specific shortcomings it aims to address within FEES. We also present and analyze the results of the LabSim pilot project as indicated by a student survey, with emphasis on learning impact and workload management.

Overview of FEES & LabSim

While FEES covers various core concepts in energy systems engineering, there is particular emphasis on open-loop switch-mode power conversion. Students spend the majority of lecture and tutorial time practicing the steady-state analysis of DC/DC and DC/AC converters, covering key ideas such as switch realization, continuous/discontinuous conduction modes (CCM/DCM), harmonic analysis, and pulse-width modulation (PWM).

Like lectures and tutorials, laboratory experiments are mostly focused on the analysis of circuits involving power converters. Figure 1 shows two examples of the power converter circuits students operate and analyze in the lab. As the figure shows, students are expected to understand the interplay between switching control, (two-way) power flow, and proper instrumentation mere weeks after learning about a converter's isolated operation for the first time. Moreover, as shown in Figure 1, the experiments are conducted at the full grid voltage levels (~110 – 120 V) with power flows close to the 1 kW order of magnitude. This requires the use of bulky high-power equipment under strict safety rules, so students seldom have the opportunity to deviate from the standard lab procedures.

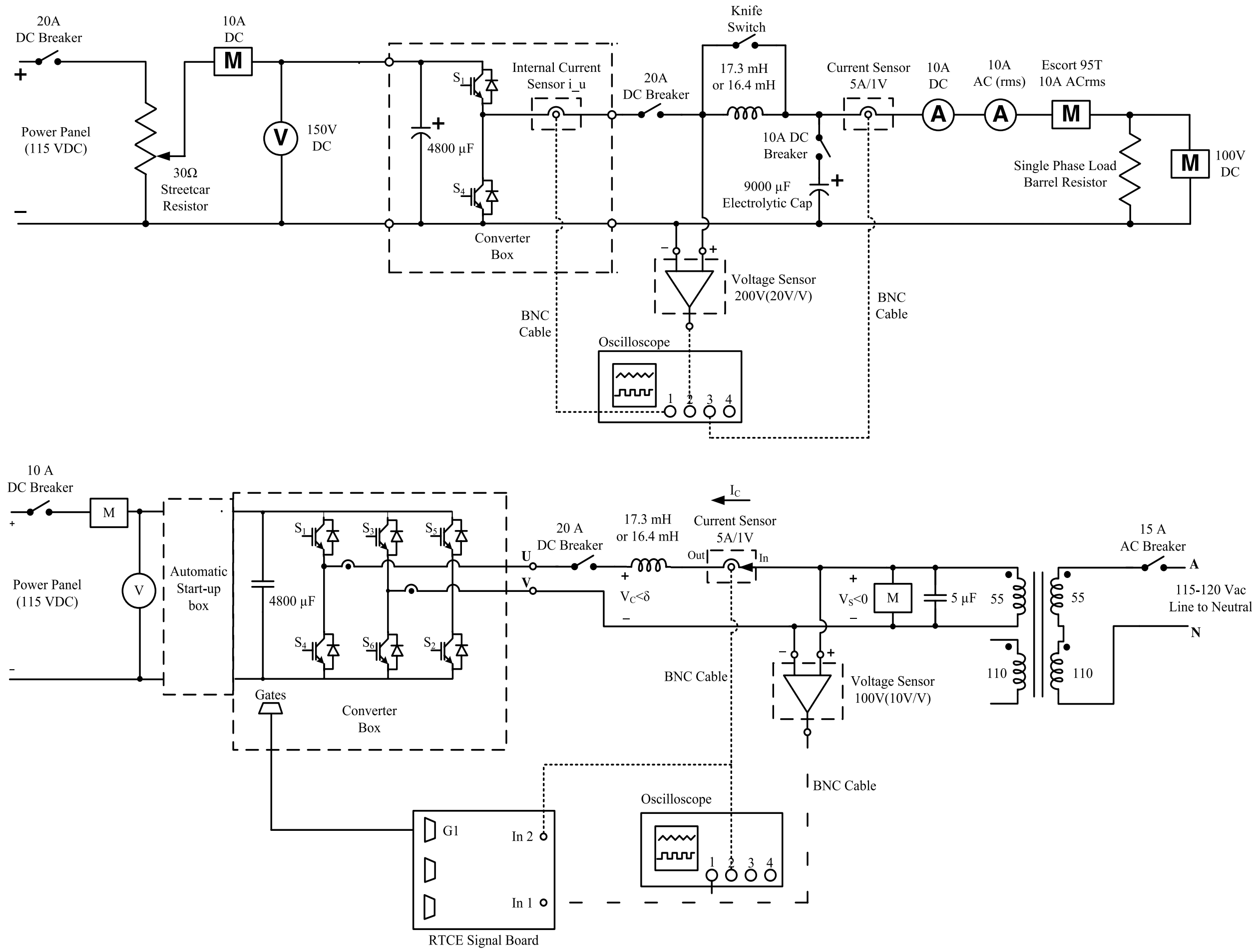


Figure 1 - Two samples of the circuits that students are expected to operate and analyze in FEES labs. The top circuit is a buck converter with a resistive load and the bottom circuit is a grid-connected DC/AC Converter with two-way power flow.

LabSim was designed to bridge this gap by providing students with the opportunity to experiment on isolated converters. Figure 2 shows the three basic building blocks of all LabSim models: Control Inputs, Converter Circuit, and Instrumentation. Control Inputs typically include the input DC voltage setting and the gating signal sent to the switches, which are implemented using Simulink control blocks. The Converter Circuit is the PLECS model containing all the power components. This includes the DC power supply, switches, filters, sensors, and load. The Instrumentation blocks utilize standard Simulink components to simulate the equipment students use in the lab, typically limited to oscilloscopes, harmonic analyzers, or a combination of the two.

The circuit elements and sub-blocks comprising each of these components depend on the type of converter. We provided students with five models for this pilot project: DC/DC converters (buck, boost, buck-boost), a single-phase full bridge inverter, and a three-phase inverter. For the purpose of this paper, we present two sample models: the buck converter and the single-phase inverter.

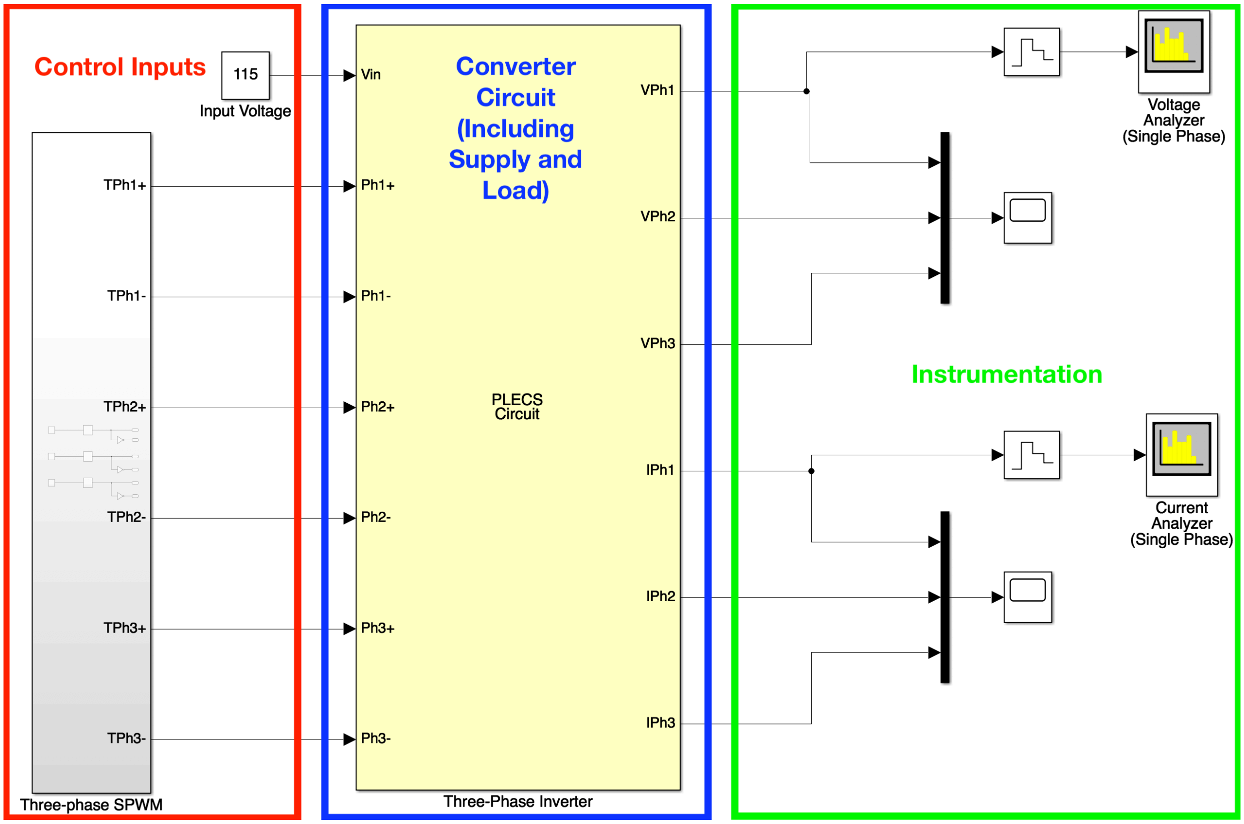


Figure 2 - Main components of the LabSim models.

The circuit model and control inputs for the buck converter are shown in Figure 3. The switching signal is generated using a constant reference between 0 and 1, corresponding to the duty cycle, passed to the PWM generator provided in the PLECS library. Students can modify the values of load and filter components very simply by double clicking the corresponding element in the PLECS circuit. Modifying the switching frequency and the duty cycle is done by modifying the value of the carrier frequency in the PWM block properties and the constant value in the reference block properties, respectively.

The buck converter is typically the first converter students are taught due to its simplicity. Providing students with an equally simple model enables them to experiment with a fully-functioning switching converter, validate theoretical predictions, and learn the influence of each component on the circuit operation at an early stage. It is possible, for instance, to investigate the influence of switching frequency on the output voltage ripple at a certain filter size and duty cycle, as shown in Figure 4.

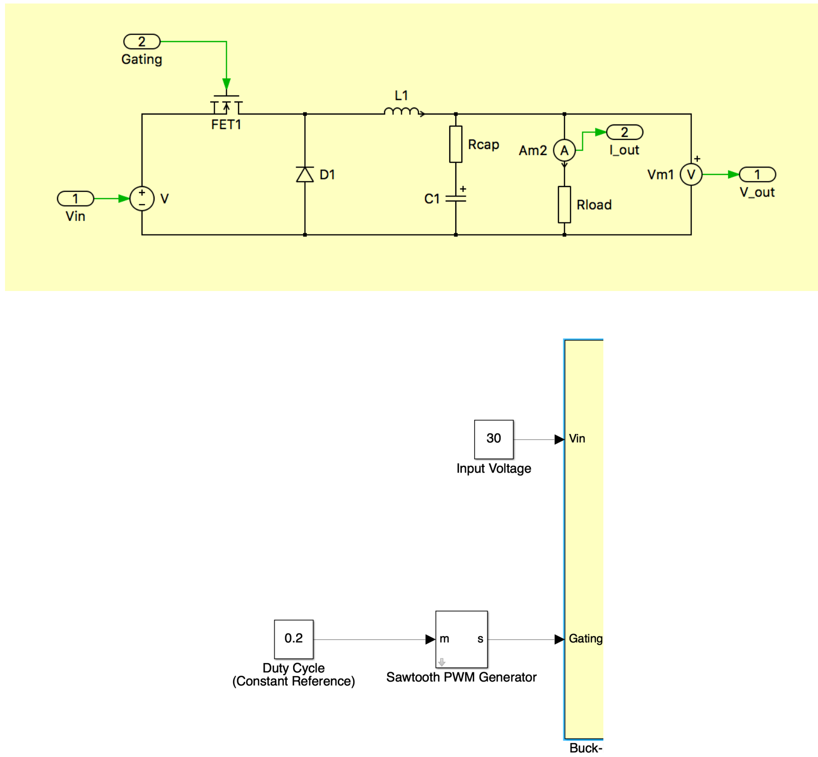


Figure 3 - PLECS circuit for buck converter (top) and its Simulink circuit inputs (bottom).

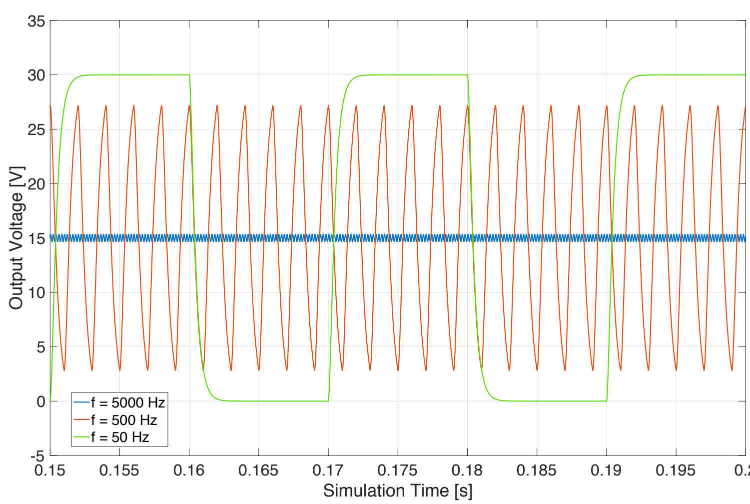


Figure 4 - Example application for the LabSim buck converter model at an input voltage of 30 V and a duty cycle of 50% and constant filter values. The plot shows a comparison of the model's output voltage waveform at 3 different frequencies to investigate the influence of switching frequency on output voltage ripple.

For more advanced capabilities, we turn to the second sample model. The circuit model and control inputs for the single-phase inverter are shown in Figure 5. For the inverter model, the students are given three different PWM generators for the gating signal with three different reference waves: square, bipolar sine, and unipolar sine. The Simulink implementations for the control inputs are shown in Appendix A.

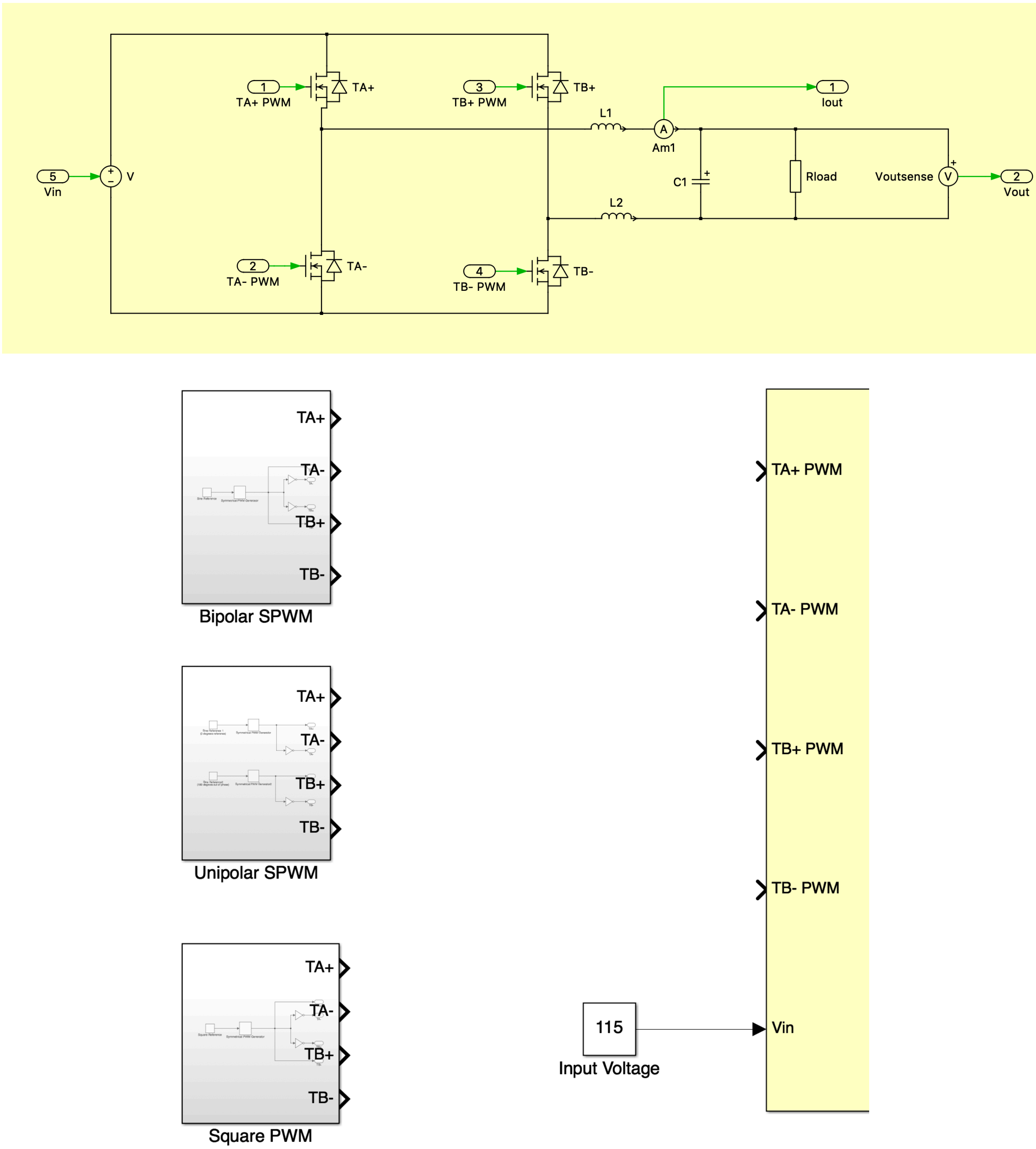


Figure 5 - PLECS circuit for the single-phase inverter (top) and its Simulink circuit inputs (bottom).

At that stage of FEES (week 7 of the semester), students are familiar with more advanced analysis techniques and concepts such as Fourier decomposition and total harmonic distortion (THD). LabSim provides students with harmonic analyzers in the instrumentation (Figure 2) in order to compare how different PWM schemes and frequencies influence the quality of the output wave. Figure 6 shows the output of Simulink's harmonic analyzer for a square wave PWM at 500 Hz carrier frequency. Harmonic analyzers are also used in FEES laboratories for inverter experiments, so LabSim gives students an opportunity for better preparation by practicing harmonic analysis before the lab session.

In addition to Fourier analysis, students can also visualize the output voltage and current waveforms resulting from the different PWM switching schemes. Figure 7 compares the output voltage waveforms for the three PWM implementations at a carrier frequency of 1 kHz. This visualization can help students internalize the physical meaning of harmonic analysis and understand the importance of waveform quality when designing power electronic circuits. Students can also probe any of the power conversion stages to understand them better, such as investigating the impact of filters in the converter circuit or visualizing how the PWM pulses relate to the input reference signals.

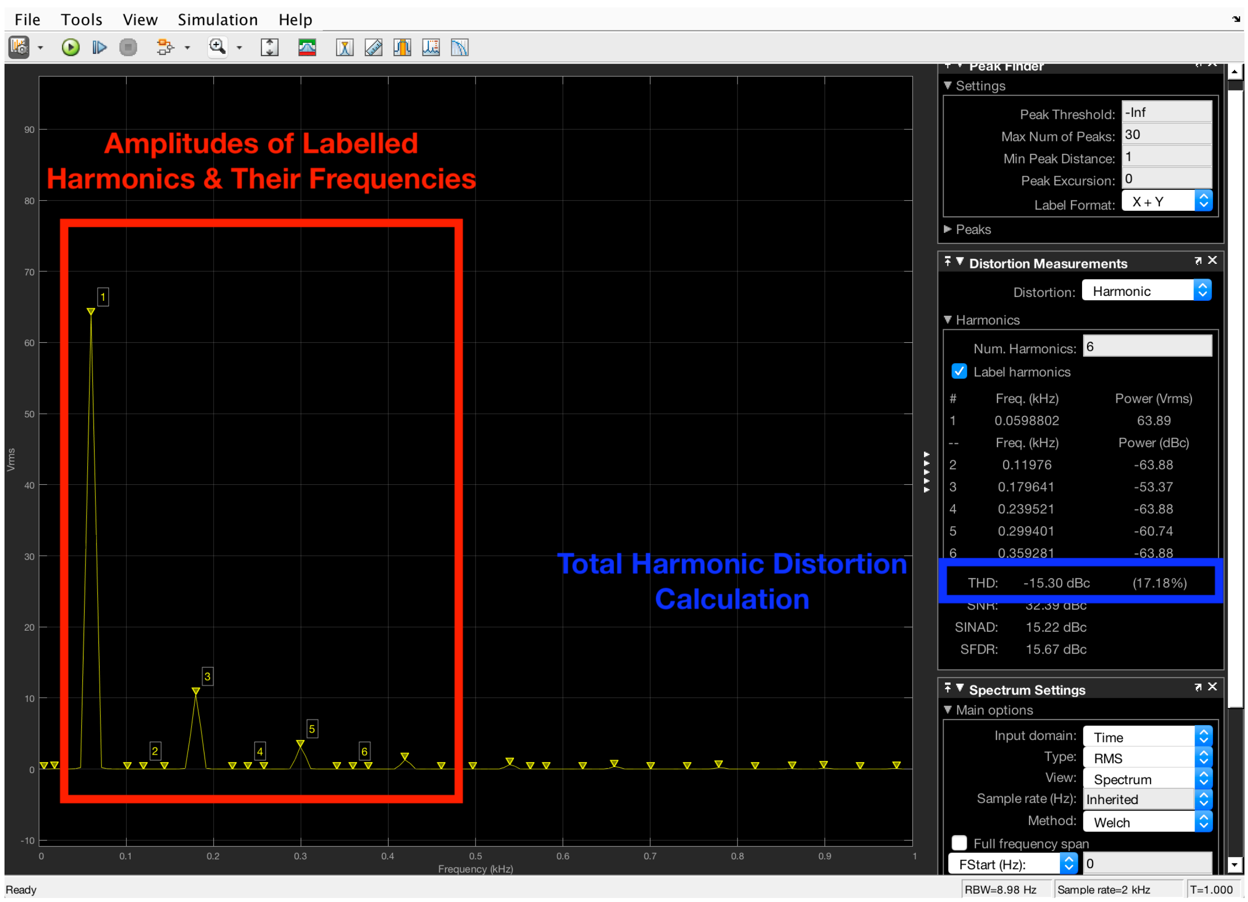


Figure 6 - Screenshot of Simulink’s harmonic analyzer for the single-phase inverter operating with square wave PWM at a carrier frequency of 500 Hz. The analysis shows significant odd harmonics in the voltage waveform, demonstrating the limitations of square wave inverters.

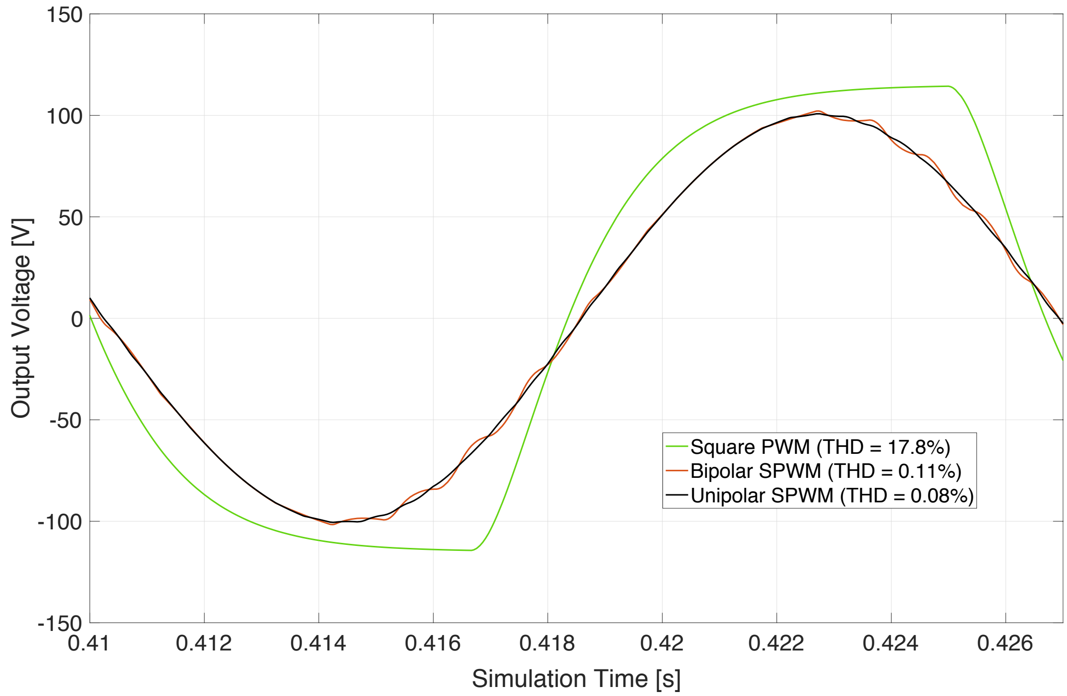


Figure 7 - 60 Hz output voltage wave forms for square wave PWM, bipolar SPWM, and unipolar SPWM at a carrier frequency of 1 kHz.

Student Reception

At the start of term, students of FEES were introduced to the LabSim pilot project and provided with license keys for PLECS and installation instructions for MATLAB/Simulink, both of which are available free of charge for engineering students at our university. The students were then provided with the LabSim models in pace with their progress within the course. Typically, the model is uploaded to FEES' online portal a week or two before the relevant lab sessions are scheduled to take place.

Since the pilot project emphasizes both learning support and workload management, usage of LabSim was not mandatory so that students can utilize it when they need to without the added stress of losing marks. In accordance with this strategy, student guidance for LabSim also emphasized student independence through a "hands-off" approach. Each model was uploaded with a detailed user guide explaining the various components and how they can be used and modified, including example circuits that they can test. The course also included a dedicated TA for technical support through email and office hours. There was, however, no direct instruction relating to LabSim in lectures, tutorials, or assigned problems beyond a one-hour demo at the beginning of term. Students were encouraged to try and modify the provided LabSim models to run the basic circuits they see in lectures and understand their operation before dealing with the more involved lab experiments. Students were also encouraged to contact the dedicated TA with questions or discussions at any time.

To assess the efficacy of the LabSim pilot project, an anonymous online survey was conducted between the 10th and 13th weeks of the semester. The survey was conducted on the course's online portal through Canvas [12] to ensure it is only available to FEES and have a reliable measure of participation. 52 out of the 59 registered students completed the survey, corresponding to a participation rate of 88.1%.

The survey consisted of 23 five-point Likert items grouped into three scales:

- *Educational Outcome*, which measures the relevance of LabSim to the course material and the impact it had on improving the students' understanding of the circuits they operated.
- *Workload*, which measures the impact of LabSim on the overall course workload and whether students see any perceived worth in this workload.
- *Technical,* which assesses the ease of installation, use, and modification of LabSim models and related software.

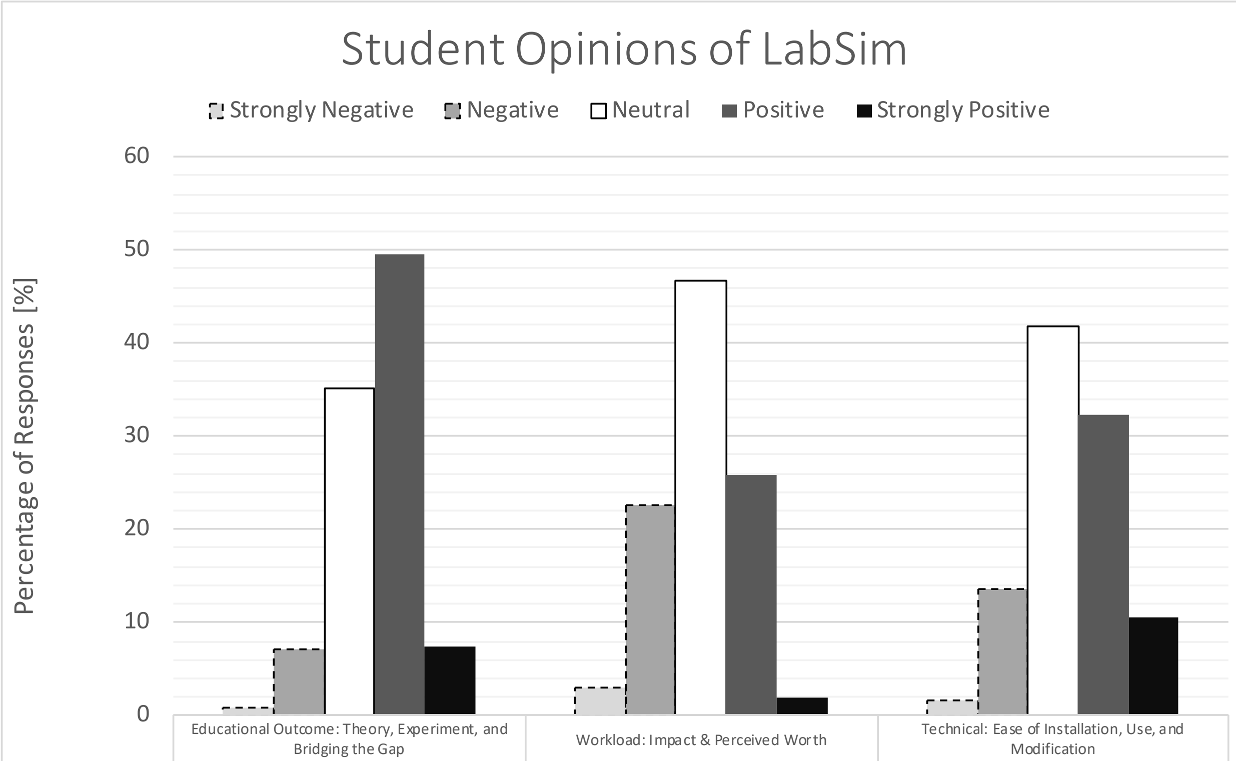
Students were also provided with three open-ended text fields where they can provide comments and suggestions relating to each of the aforementioned metrics.

Each survey item is a statement to which students can provide one of five responses, ranging from "strongly disagree" to "strongly agree". All survey items were phrased consistently such that any (strong) agreement would correspond to a (strongly) positive opinion and any (strong) disagreement would correspond to a (strongly) negative opinion of the item being assessed. Figure 8 summarizes the responses of survey participants for each of the three performance metrics. As Table 1 shows, a Cronbach's Alpha range of 0.8 – 0.88 shows good internal consistency for every question group [13] [14]. The detailed questionnaire and student responses are provided in Appendix B, and provide further insight into the success of the pilot project.

Table 1 – Values of Cronbach's Alpha for each question group in the survey.

Metric	Number of Items	Cronbach's Alpha
Educational Outcome	7	0.809
Workload	7	0.823
Technical	9	0.875

Students provided the most positive responses to the educational outcome group of questions. 71% agreed or strongly agreed that LabSim was relevant to the lecture material and 73% agreed or strongly agreed it was relevant to the laboratory experiments. 50% agreed that LabSim helped them understand the lecture material better and 62% agreed or strongly agreed it helped them understand lab experiments better. Most importantly, 57% agreed or strongly agreed that LabSim helped them connect the theory they learn in class to the laboratory experiments.



	Educational Outcome: Theory, Experiment, and Bridging the Gap	Workload: Impact & Perceived Worth	Technical: Ease of Installation, Use, and Modification
Strongly Negative	0.82	3.02	1.71
Negative	7.14	22.53	13.68
Neutral	35.16	46.7	41.88
Positive	49.45	25.82	32.26
Strongly Positive	7.42	1.92	10.47

Figure 8 - Student opinions of LabSim for the three performance metrics.

Students provided helpful feedback regarding LabSim's place and function in FEES. There is general agreement among students who provided comments that LabSim needs to be more directly involved in their coursework to encourage usage and further elucidate the connection between theory and experiment. Specifically, students suggested it can be incorporated into the lectures for illustration and into the lab preparation assignments as simulation problems. This is indeed a promising course of action for future iterations of the project, and it is our view that it would be more productive to involve LabSim directly into coursework as extra credit. This would encourage participation without penalizing students who choose not to use LabSim. Another possible strategy would be to add a simulation component to the most basic of required homework problems in addition to extra-credit problems that require more advanced use of LabSim. This would encourage students to get familiar with LabSim's basic functionality without a significant addition to their workload.

Student attitudes towards workload issues were more divided. Only 25% agreed or strongly agreed they had time to use it and only 29% agreed or strongly agreed it was not a significant addition to their workload. Most students also do not feel that LabSim helped them reduce the workload associated with understanding lecture material and lab experiments. Interestingly, however, 50% agreed or strongly agreed that the additional workload is justified by the skills they gained using Simulink and PLECS. This highlights the importance of using industry-standard simulation software since students see intrinsic value in practicing it for their own development.

Students' feedback regarding workload generally addresses two issues: (1) the length of the lab preparation assignments making it difficult to invest time into using LabSim and (2) the learning curve associated with using the Simulink/PLECS interface. While students were provided with user guides for each model, some students feel that a more hands-on approach such as tutorial exercises would be more helpful, particularly in the early stages of the course. This can certainly be explored within the practical time constraints of tutorial sessions.

Students' attitudes towards the technical aspects of LabSim were generally neutral to positive, with 60% agreeing or strongly agreeing they were able to run it on their personal computers without problems and 52% agreeing or strongly agreeing that the circuit models were easy to relate to the lab experiments and schematics they use in class. 48% agreed or strongly agreed that the Simulink instrumentation helped them understand the operation of the circuit and 38% agreed or strongly agreed that the control inputs were easy to understand.

Finally, 46% of students agree or strongly agree that the installation of MATLAB and PLECS was straightforward. However, it is important to highlight that 28% disagreed or strongly disagreed with that statement due to the "lengthy and cumbersome" installation and activation process for PLECS, as was evident in student feedback. While students were provided with license keys in the first week of term, some of them had to wait days to receive their activation files via email. Students also reported compatibility issues when running LabSim on university computers with older versions of MATLAB. While the former issue is largely beyond our control, the latter can be addressed through more extensive testing and updating of LabSim in future iterations. The problem can also be mitigated by installing LabSim on campus-hosted virtual machines and providing online access to students.

Conclusions and Future Work

We have developed LabSim, a set of models for basic power electronic converters, in order to bridge the gap between lectures and laboratory experiments in an introductory energy systems course. The simulations were designed with flexibility and intrinsic value in mind, utilizing an integrated Simulink-PLECS user interface that provides full switching functionality at a viable computational cost using industry-standard software. LabSim's key novelty is that it emphasizes simplicity of implementation and usage so students do not need to tackle complex mathematical models on top of their already heavy workload. Using or modifying LabSim only involves changing input parameters and component values of a converter circuit in a graphical user interface that matches the circuit schematics, control schemes, and instrumentation they use in laboratory experiments.

LabSim received positive reception from students, with the most positive attitudes towards its impact in improving their understanding of course material and bridging the gap between theory and practice. Attitudes were also mostly positive towards the technical aspects of LabSim. Based on students' feedback, the most urgent improvement required for LabSim is increased teaching involvement at the early stages of the course to reduce the workload associated with learning the software. Another future improvement would be to directly involve LabSim in the students' coursework for extra credit, which would motivate more active participation. The results of this pilot project, however, agree with previous reports of simulation-augmented classrooms contributing to a more positive learning experience. We, therefore, believe LabSim is a step in the right direction for teaching power electronics fundamentals.

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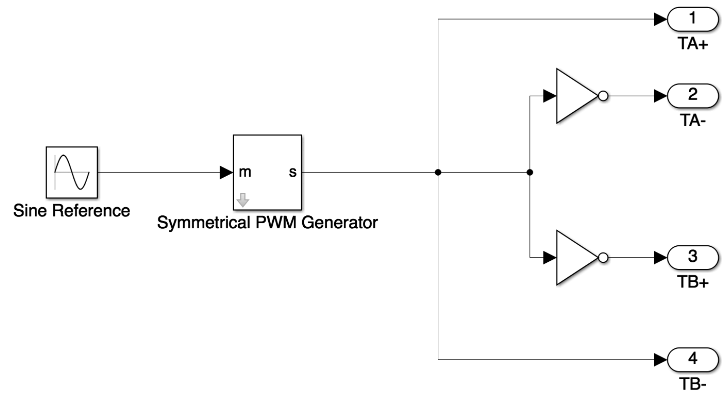
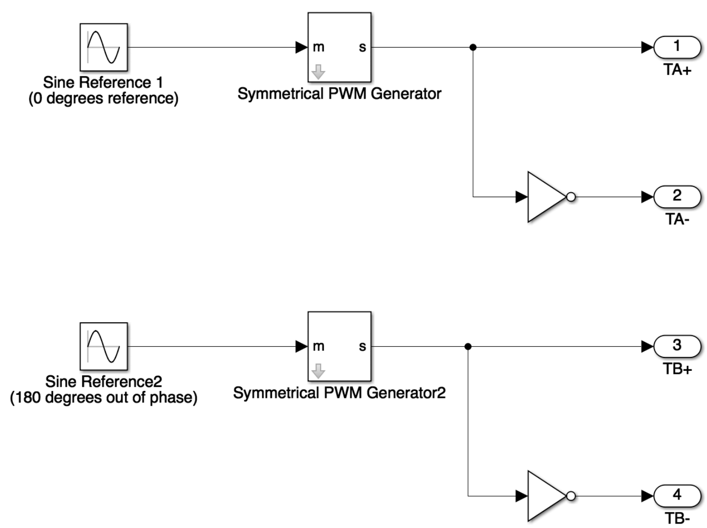
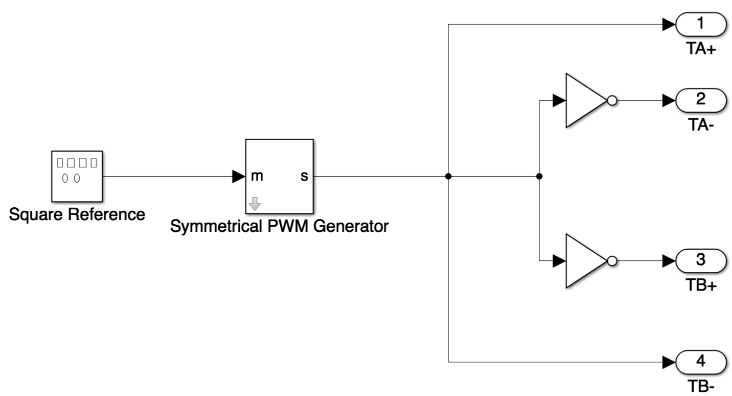
Appendix A– Detailed Implementation of LabSim Control Inputs for Bipolar Sinusoidal PWM (top), Unipolar Sinusoidal PWM (middle) and Square PWM (bottom)







Appendix B– Detailed LabSim Survey Responses (Number of Students per Response)

Educational Outcome	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
LabSim models are relevant to the lecture material.	1	0	14	32	5
LabSim models helped me understand lecture material better.	1	3	22	26	0
LabSim models are relevant to the lab experiments.	0	0	14	32	6
LabSim models helped me understand lab experiments better.	0	3	17	25	7
LabSim helped me connect the concepts and circuits I learned in class to the lab experiments.	0	2	20	27	3
LabSim helped me solve, understand and/or visualize problem sets or past exams.	0	13	21	15	3
LabSim helped me solve, understand, and/or visualize lab preparation questions.	1	5	20	23	3
Total	**3**	**26**	**128**	**180**	**27**

Workload	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
I had time to use LabSim for simulating the circuits and/or experiments that are covered in the course material.	0	15	24	12	1
The time and effort I invested into learning how to use LabSim did not significantly add to the course's workload.	1	15	21	14	1
LabSim helped me reduce the workload associated with understanding lecture/tutorial material.	3	12	28	9	0
LabSim helped me reduce the workload associated with	2	14	25	11	0

understanding and/or preparing for lab experiments.					
The time and effort I put into learning and using LabSim is justified by its impact in reducing other course workload.	2	12	25	12	1
The time and effort I put into learning and using LabSim is justified by its impact on improving my grades or understanding of the course material.	2	10	26	11	3
The time and effort I put into learning and using LabSim is justified by the experience I gained in using industry-standard simulation software (Simulink/PLECS).	1	4	21	25	1
Total	**11**	**82**	**170**	**94**	**7**

Technical	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
The installation and activation process for MATLAB and/or PLECS is simple and straightforward.	2	12	14	16	8
I was able to run LabSim on my personal computer without problems.	1	7	13	22	9
I was able to run LabSim on university computers without problems.	3	3	30	11	5
I found the Simulink/PLECS software interface simple and intuitive.	1	7	25	15	4
The PLECS interface (i.e. circuit model) was easy to relate to the circuit schematics and components used in the lectures and labs, respectively.	0	4	21	23	4

The Simulink implementation of switching signals (i.e. circuit inputs) was easy to understand.	0	7	25	15	5
The Simulink instrumentation (i.e. oscilloscopes and harmonic analyzers) helped me understand the operation of the circuits.	0	4	23	20	5
I found it simple to modify the provided models by changing circuit components (e.g. remove inductor, change capacitor value) or operation parameters (e.g. switching frequency).	0	4	24	17	7
I was able to simulate circuits other than the ones provided by the TA using the LabSim interface.	1	16	21	12	2
Total	**8**	**64**	**196**	**151**	**49**