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Development of Versatile Buck Converter Module for Laboratory Experiment in Power Electronic Course

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Abstract

Buck converter is a type of power electronic circuit commonly found in consumer electronics and many other electrical systems. It is widely used due to its ability to match voltage level of the power source to a lower voltage level at the user side. It is therefore important to prepare future electrical engineers with the necessary knowledge and skill in Buck converter. This paper presents the development of a new Buck converter module that allows students to conduct laboratory experiments to study the operation and performance of a Buck converter. The custom-made laboratory module was designed for ease of use and versatility, enabling students to perform tests that will otherwise be challenging to perform with any commercially available manufacturer's evaluation board. The module was the result of a collaborative work between Monolithic Power Systems (MPS) and Cal Poly State University, with MPS fully supporting the design and construction of several units of the lab module. One experiment has been developed using the new Buck module for the introductory course in power electronics as part of the Advanced Power Systems Initiatives initiated by the electrical engineering department at Cal Poly to modernize the power curriculum for the rapidly changing power industry. Learning outcomes are formulated based on the desirable skills students should attain utilizing the lab module. Further detailed description of the experiment using the new Buck module along with its initial assessment will be presented in this paper. Initial results from the lab experiment that uses the new Buck module will also be described, along with challenges and lessons learned.

Introduction

Power electronics as an enabling technology has become crucial in today's society where energy-efficient intensive-computing electrical systems such as portable consumer electronics are increasingly popular and prevalent[1,2]. In addition, any applications requiring conversion of electrical energy from one form to another form such as those commonly found in renewable energy applications[3,4] will require power electronics. Within power electronics, dc-dc converters comprise the majority of power electronic circuits, with the non-isolated step-down or generally known as the Buck converter being the most prevalent topology. The popularity of Buck converter is largely due to its ability in stepping down a voltage from one level to another regulated level. This is the condition that is commonly encountered in real world. For example, charging a cell-phone from a wall outlet will require to convert from the voltage level of the outlet which is typically larger than 100V to a low voltage around 4V. Furthermore, a portable electronic device operates from a single battery, and so the Buck converter is also needed here to distribute the power from the battery to the numerous integrated circuits at even lower voltage levels[5,6].

For these reasons, it is therefore important to prepare future electrical engineers with the necessary knowledge and desired skills in power electronics, which should include the topic of Buck converter.

At Cal Poly State University, the electrical engineering department has been offering power electronic courses for their electrical engineering students to prepare them for the ever increasing demand from the power electronic industry. There are currently four well established power electronic courses that have been regularly taught as technical electives at Cal Poly State University. These are:

- EE 410: Power Electronics I with Lab
- EE 411: Power Electronics II with Lab
- EE 433: Introduction to Magnetic Design with Lab
- EE 527: Advanced Power Electronics

As listed above, EE410 is the first technical elective course in the power electronic sequence where students get introduced to the fundamental concepts in power electronics, which includes dc-dc converter topics and thus Buck converter. Moreover, the course has laboratory component where students get the opportunity to enhance their hands-on skill and apply theoretical concepts through conducting laboratory experiments using commonly used power electronics and industry standard laboratory equipment.

For the Buck converter experiment in EE410, a custom made Buck converter module had been used for years to allow students to achieve the following learning outcomes:

- Students are able to conduct laboratory measurements on steady-state performance of Buck converter which includes duty cycle, switching frequency, line and load regulations, peak to peak output voltage ripple, and efficiency.

The old Buck module worked well in fulfilling the learning outcomes as stated above[7]; however, as the technology advances the experiment needs to be aligned with current industry practices. To this extent and for even a broader scope, the electrical engineering department launched the Advanced Power System Initiatives to modernize the power program. Included in this effort is updating and redesigning laboratory experiments in power courses to be more relevant to today's power industry. For the Buck converter experiment, a new lab module has been designed and constructed to enable students to gain understanding of the basic concept and technologies incorporated in modern Buck converter.

The New Buck Module and Experiment

As part of the Advanced Power System Initiatives, the power electronic laboratory at Cal Poly State University has undergone several updates. One lab experiment that has been revamped is the Buck converter experiment. As stated previously, the experiment used a lab module that was able to meet the previous learning outcomes which covered the basic operation and performance of a Buck converter. However, the module lacked the ability to allow students to perform further analysis and gain deeper understanding of the Buck converter. Therefore, a new Buck module was designed and built to meet these additional features and to enhance student's learning experience, knowledge, and skills in power electronics in general and Buck converter in particular. The learning outcomes of the new Buck laboratory experiment are as follows:

- Students are able to conduct laboratory measurements on steady-state performance of Buck converter which includes duty cycle, switching frequency, line and load regulations, peak to peak output voltage ripple, and efficiency.
- Students are able to inspect and analyze the effect of switching frequency to overall efficiency and output voltage peak to peak ripple of Buck converter
- Students are able to inspect and analyze the effect of output voltage to overall efficiency of Buck converter
- Students are able to observe inductor current waveform and calculate the inductance value used in the Buck converter module
- Students are able to inspect steady-state performance of Buck converter under Pulse Width Modulation and Pulse Frequency Modulation modes.

As listed above, the new learning outcomes cover more learning objectives which were established based on the feedback from companies who regularly visit Cal Poly's campus during career fair.

Figure 1 shows the new Buck module. A total of 12 modules were designed and constructed with the full support from Monolithic Power Systems[8] (MPS) in San Jose. The module is a versatile Buck converter module with several features that did not exist in the previous module. These features as listed below are also provided to aid in student's learning:

- The provision of a wire loop for placing a current probe to allow students to observe inductor current waveform. Such ability is important since inductor current waveform contains information on the operation of a Buck converter, and thus serves a great tool for learning the steady-state operation of Buck converter.
- The ability to choose the switching frequency of the Buck converter at 500 kHz or 1 MHz by the use of a simple slide switch. This feature enables students to conduct performance test and analysis of the impact of operating the Buck converter at different frequencies.
- The ability to adjust the output voltage of the Buck converter to either be at 1.8 V or 3.3 V, again by using a simple slide switch. With this feature, students will be able to perform efficiency measurement and analysis of the effect of the different output voltage to the operation of the Buck converter.
- The ability to utilize a simple slide switch to choose from two different switching techniques for the Buck converter: Pulse-Width-Modulation (PWM) or Pulse-Frequency-Modulation (PFM). This feature allows students to gain understanding of the different steady state and transient characteristics of the Buck converter when operated under either technique.

Figure 1: The new Buck laboratory module

A new Buck lab experiment has been developed to utilize the new Buck module for the EE410 course. Since the course covers introductory topics in power electronics, only a couple of features such as the wire loop and output voltage adjustment of the module will be used in the new experiment. The remaining features will be exposed to students in another lab experiment in the follow up course EE411, which covers advanced topics in power electronics.

The new lab experiment consists of two parts: pre-lab calculation and hardware experimentation. In the pre-lab, students must calculate the ideal duty cycle values when input voltage is 9 V, 10 V, 11 V, 12 V, 13 V, 14 V, and 15 V while the Buck converter operates with the PWM technique and output voltage of 3.3 V. The hardware portion of the lab involves two laboratory test setups that students have to construct, as shown in Figures 2 and 3. The two setups serve to emphasize the importance of having the proper test setup before testing and measurements take place. Later in the lab exercise, students are being asked based on their results and analysis as to which setup is the correct one. In each setup the new Buck module is being used where students conduct standard dc-dc performance measurements including efficiency, line regulation, load regulation, and peak to peak output voltage ripple. Additionally, students also conduct measurement of duty cycles to compare with the pre-lab results.

The following is the list of several items that students must include in their lab report:

- In one plot, Duty Cycle vs. Input Voltage from Prelab and Setup #2
- Duty Cycle vs. Load
- Efficiency obtained from setup #1 and setup #2 (when input voltage is 12 V)
- Efficiency for input voltages 9 V, 12 V, and 15 V obtained from setup #2
- Calculate the percent error of the percent line regulation
- Calculate the percent error of the percent load regulation

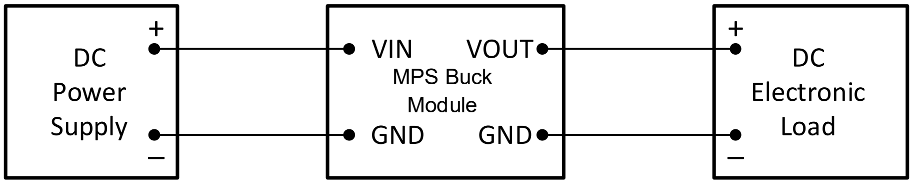

Figure 2: Laboratory test setup #1

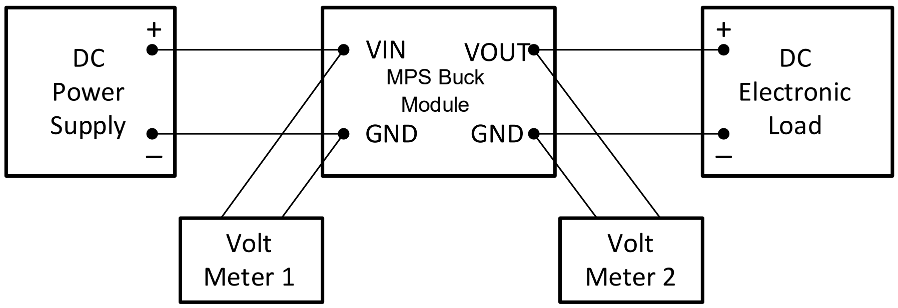

Figure 3: Laboratory test setup #2

Initial Assessment

The new Buck experiment was launched in EE410 for the first time in Fall 2018. The class had 68 students, and in the lab portion of the course students formed groups of 2 or 3 people. Students had approximately 3 hours to complete the lab and submit their reports. The new experiment with the new Buck module went very well with no major issues except for one dysfunctional module. Initial student assessment took place during the lab by instructor verifying circuit and supervising from a distance as well as post lab questions included at the end of experiment to reinforce important concepts. To complete the lab, students must submit answers to the post lab questions. Additionally, each group was asked verbally to respond to the effectiveness and clarity of the new lab module and experiment.

Initial student feedback regarding the experiments was positive. After performing the new Buck experiment, every group commented that the new Buck module is simple to use and to connect to external laboratory equipment since the module has easy to access test points (turrets) with clearly marked labels. Many groups also felt that they did not come across any issues in using the new lab module to perform performance tests (as listed in the outcomes) of the Buck converter. Rather, they commented that the problem mainly arose from determining the right settings of their lab equipment, especially the electronic load. This was expected since this was the first time students get to use an electronic load in their lab experiment. Many comments also indicated that the new lab module is effective in demonstrating the concepts students needed to learn from the experiment. This was further verified by their answers to the post-lab questions which were graded and returned to them. These post-lab questions consisted of 5 short answer type questions, and the average score for the four lab sections was 8.85/10.

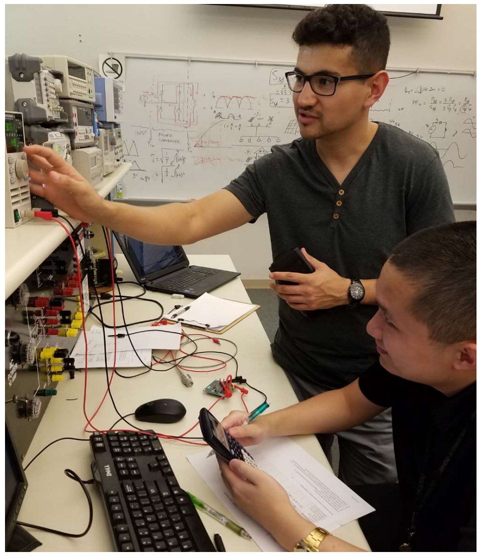

Figure 4: Students working on the new Buck experiment

As in any other labs, having a well-written and well-organized lab manual with clear instructions on the steps used in the experiment is important. For the new Buck module, the lab manual has been revised based on the feedback from students. The lab experiment overall went well in all 4 lab sections of the course. However, there is always room for improvement. The Buck module could be modified to make it more robust for use by students in lab setting. For example, some type of protection device could be added for inverse polarity at the input terminal in case students do not pay attention to the labels despite being clearly marked on the module. We plan to address this problem by adding a small circuit board that will be attached to the input terminal to incorporate the protection device.

Conclusion

A new laboratory experiment utilizing a new Buck converter module has been developed to improve students' learning experience and skills in power electronics. The new lab module was constructed with the full support from Monolithic Power Systems, and it was designed to accommodate new learning outcomes. Initial assessment of the new Buck experiment indicated that the new Buck converter is able to effectively fulfill the new learning outcomes. A more formalized survey is currently under plan to assess the effectiveness of the new lab module in helping students achieve the learning outcomes.

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