Development of modular and accessible teaching labs, incorporating modelling and practical experimentation

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Abstract

Practical laboratory experimentation has always been a crucial part of engineering education and its effectiveness in facilitating learning is universally acknowledged. Huge advances in computer science, coupled with significant increases in the cost of ever more complex and sophisticated laboratory set-ups, have led to engineering schools' adopting computer models and simulation software. Although simulation-based laboratory work does enhance the learning experience, it plays a more effective role *alongside* practical experimentation rather than as a replacement. This case study presents the results and experience gained from an enquiry-based learning of power-converter development laboratory work to support a power electronic converter module at the University of Greenwich. The approach taken allows students to learn the basics of the module through a combination of modelling, simulation and practical experimentation. The modular and portable nature of the laboratory set-ups afforded the students more time and opportunity to explore the subject matter and integrate the laboratory experience with the concepts covered in the lectures. The feedback from students, which was gathered from the students through the university's EVASYS system, strongly indicated that the approach led to a sustained improvement in students' learning experience and satisfaction with the module.

Keywords:

enquiry-based learning, power electronics, modular

Introduction

Given that the main goal of engineering education is to enable students to become practising engineers, instructional laboratories have always been an essential part of engineering programmes in higher education institutions (HEIs). In each laboratory activity that learners engage with, they explore the relationship between mathematical models and the natural phenomena that these models represent. This process in turn allows them to study the limitations of the models while developing the skills necessary to deal with real-world problems and gain hands-on expertise (Feisel *et al.*, 2005).

Before engineering became part of the mainstream education system, the subject was taught practically – broadly based on the British apprenticeship model, where learners had to design, build, test and analyse their own products. Although a tension between practice and theory evolved as the subject was delivered more formally at HEIs, engineering learning still occurs in the laboratory as much as it does in formal lectures (Grayson, 2003).

While there is a broad consensus about the value to learning of practical laboratory experimentation in engineering subjects (Chen, 2010; Schweingruber, 2006), it is also clear that the high cost associated with complex equipment, space and maintenance (technician time) as well as safety concerns have forced institutions to look for cheaper and simpler alternatives (Gomes and Bogosyan, 2009). The huge advances in technology that have made it possible to measure and manipulate complex parameters have also resulted in complex systems requiring highly trained technicians who are difficult to hire and command high salaries (Feisel, 2005). This has led to a decline in the provision of practical laboratories and a consequent significant development in software-based modelling and simulation packages. A recent addition to this endeavour is the concept (and some application) of virtual laboratories that attempt to leverage the huge advances in IT technology in order to bring to learners the traditional practical laboratory experience (Gustavsson *et al*., 2006).

Power electronics, which is largely application driven, is a complex subject, drawing concepts from electronics, embedded systems, electrical power, instrumentation, digital/analogue control theory and thermodynamics. Power electronics-based applications are also wide-ranging and include power supply for electronic devices, vehicular propulsion systems, industrial motor drives, electromechanical motion control, and grid integration of renewable energy resources (Emadi *et al*., 2008). The subject area of power electronics is multi-disciplinary and spans a variety of subjects, including circuits, signal analysis, electronics, digital control systems and semiconductor switching applications. Consequently, the subject is perceived as been difficult to tackle, owing to the variety of concepts involved (Emadi *et al*., 2008; Torrey, 1994). As grasping these disparate concepts is challenging for students, laboratory experimentation plays a huge role in assisting students to deal with the complexity involved (Balog, 2015).

Experimental laboratory activities, an important element of active learning, are widely used to support the theoretical concepts of power electronics and other complex topics in the field. Unfortunately, the usual lab equipment used in this field tends to be quite specialist in nature and consequently very expensive. Not only is its availability limited, but it is also mainly subject to input/output measurements (‘black box’-type testing imposed by safety concerns) and this does limit the range of experiences the students can gain. The trend has increasingly been to adopt electronic simulations in place of physical experiments.

Unfortunately, laboratory provision for power electronics modules has also been affected by the persistent trend of rising cost that is prevalent in the wider engineering discipline. While many institutions still provide some practical experiments, the trend has been a move more towards software simulation packages (Matlab/Simulink, Spice etc.), web-based instructional tools such as Java applets, and virtual labs (sometimes referred to as remote labs).

Although there is a broad consensus that traditional lectures/tutorials supported by some laboratory experimentation (regardless of whether this is practical, simulated or virtual/remote) leads to improved learning, conducting controlled studies to determine whether practical or simulation-based laboratory leads to better learning experiences is problematic. Some studies have focused on educational objectives while others have prioritised different objectives and reached different conclusions (Ma *et al*., 2006; Finkelstein *et al*., 2005; Corter *et al*., 2007). A study conducted by Steger *et al*. (2020), which claims to have conducted controlled tests, reached the conclusion that practical laboratories resulted in statistically significant improvement in outcomes compared to simulation-based laboratories, though admittedly with some inevitable limitations.

Even when practical laboratories are used in power electronics education, there is a tendency – either on account of safety concerns or to deal with the complexity involved – to adopt a black-box approach, in which students put together pre-built modules to make a system. The weakness of this approach is that this limits students' understanding of what is involved in making these modules and systems (Balog and Chapman, 2012). A 'blue-box' approach, where the boxes are transparent, is sometimes used to enable students get some appreciation of the inner workings of the modules (Drofenik and Kolar, 2002).

More recently, project-based learning (PBL) has been shown to be very effective, especially for multi-disciplinary subjects such as power electronics (Medeiros *et al*., 2019). Although this approach seems to be used in advanced modules that follow other modules with similar content (as may be the case in integrated masters programmes), aspects of PBL may be mixed with instructional labs to enhance the experience of students undertaking traditional one-year MSc programmes. PBL, when implemented well, is particularly suited for enhancing students' creativity and engaging them in deep learning (Dym, 2005).

Thus, in this case study, I consider an approach that leverages the intrinsic advantages of a simplified and modular practical laboratory experimentation while maximising the advantages of modelling and simulation that use industrial-level embedded systems.

This case study presents the development of power electronics laboratory for an MSc module. The main objectives of the laboratory work were to:

(i) support students' understanding of fundamental concepts relevant to the subject by using experimental work to link theory to applications;
(ii) engage students in practical design of power-electronic circuits and thereby provide students with active learning experience;
(iii) familiarise students with industry-standard simulation and design software that seamlessly link with practical testing through embedded electronics;
(iv) make the laboratory kits more portable and give students, with progressive independence, more opportunities to use the kits to go through the process of design, implementation and testing.

The module and participants

'Power Electronic Converters' is a fifteen-credit level 7 module. In this case study, the participants were mainly international students from different undergraduate programmes and with limited practical laboratory work experience. When the module was initially developed, the laboratory work consisted mainly of simulations using Matlab/Simulink and Spice and of a couple of practical labs using two set-ups that used the black-box approach. The feedback from the students clearly indicated that they would have very much appreciated having more hands-on laboratory work in the module. About twenty-five students were taking the module (a number which has recently increased significantly).

Implementation

The module was delivered over a twelve-week term in the winter/spring. Delivery was based on a two-hour lecture followed by two-hour laboratory/tutorial sessions on a weekly basis. For the purposes of the laboratory work, students were provided with a box of components needed to build the circuits, along with the list of names of the components. Four instruction sheets were also placed in the module shell in Moodle. Students were provided with access to two software packages: Matlab/Simulink, used for modelling/simulation studies, and Proteus, used for simulation and also to design electronic boards.

Each lab activity had two stages. The first stage was to model the circuits using the Matlab/Simulink platform. Once the students were happy with the analysis of the simulated results, they then proceeded to the next stage to design and test the circuits in Proteus, using manufacturer-specific products as provided in the instruction sheets and Arduino code. The Proteus files were then sent to the technicians, who produced the printed circuit boards (PCBs); the students populated these with components and completed the required soldering. Finally, practical testing was conducted using the Arduino micro controller and the populated PCB and circuit performance were demonstrated in front of instructors. The designs were deliberately kept low power to deal with low voltages, so that the lab activities could be implemented by students independently as take-home kits.

As the module was designed for MSc students, who came from different nations with varying levels of prior exposure to practical laboratory work, the tutorial/lab sessions in the first three weeks were used to train students in how to use basic laboratory tools safely and how to build models and simulate circuits using the available software. In the fourth week, they started engaging with the lab instruction sheets. In the first lab, the students tested (in simulation) different pulse width modulation (PWM) techniques in the Proteus software environment to switch the power semi-conductor devices. Afterwards, they directly generated the executable codes and loaded them on to the Arduino micro-controller. The students then, in week five, generated results and performed relevant analysis using digital oscilloscopes. As the students were given a mixture of power-electronic components in addition to the Arduino platform, they got involved in the detailed process of design and implementation, using appropriate component selection and analysis of various power electronic converters. This was very different and much more engaging for the students than the traditional black-box-based lab activities where the students passively observed input/output values. This was also the most likely scenario that the students would face in industry.

The module was delivered in such a way that the theoretical coverage was reinforced by corresponding modelling/simulation and practical lab activities. That the students were given pre-lab work through the instruction sheets and tutorial sessions helped them prepare for the lab as well as make the link between theory and lab activities. The following design/modelling/simulation work, based on Matlab/Simulink and Proteus, the students performed in their own time, with support from the instructor. Once they had completed these tasks, they proceeded to build and test the converters by making appropriate selection of components. Students' practical work was then demonstrated in formal lab sessions in weeks five, seven, nine and eleven. These weeks coincided with the completion of each lab sheet (used to give students feedback on their work). Although the students were encouraged to document their work and reflect regularly upon both it and the feedback from instructors, week twelve was also used to finalise their write-up and submit their logbooks. As such, the general pedagogical objectives of the module were laid out to follow an inquiry-based learning process that supported different learning styles (Venkataramanan, 2004), such as those proposed by Kolb (1984). This was reinforced by the fact that the outcome of the activities in the labs fed into the next topic's lesson plan. For instance, one of the earlier activities was to programme the micro-controller to generate pulse width modulation (PWM) signal which controls a metal oxide semiconductor field effect transistor (MOSFET). The PWM signal and the MOSFET were then used to drive a buck converter, which was the topic of the following lesson plan.

Evaluation and analysis

Student feedback about this new arrangement was very positive: they commented favourably on the opportunities they were getting – enabling them to do more with the take-home kits they were being given – as well as on the visual representation of some of the concepts, which they said was enhancing their understanding of the subject. However, they also said that making the licence for the design software available would have helped them to explore more aspects of the topics. This was taken on board and a student version of the licence was made available to the next cohort for them to instal in their machines.

The educational approach adopted in designing these laboratory activities provides additional hands-on experiences to motivate students and help contextualise the module material, while creating opportunities to explore the topics in greater depth. This pedagogical aspect, in conjunction with the visualisation capabilities of the laboratory tools, motivates student-oriented learning and provides significant opportunities for active learning of power electronics. Since the students received copies of relevant software and required components at the beginning of term, they had much more time to work on the lab activities; this facilitated deeper learning to take place while giving them the flexibility to fit the activities around other responsibilities. This in turn led to much better student engagement, both in terms of students' completing tasks, usually ahead of schedule, and also of their being much more proactive in making suggestions about what else they might be able to do with the kits they had. Another signature aspect of the laboratory set-up is that the skills students gain from engaging in the various tasks are very relevant to other modules, such as electrical machines and drives, helping students retain knowledge across multiple modules. In this study, many students also were motivated by the positive experience they had with the module and went on to generate project proposals for their individual research project.

Although the students provided positive feedback informally, the data collected by EVASYS was used to gauge students' perception of the module following the changes in the laboratory activities over several years. Figure 1, which shows the EVASYS average score for available data, clearly shows that there was sustained improvement in students' satisfaction with the module. The slight dip this year may have been caused by the prevailing pandemic, especially as many of the students were not in the United Kingdom (UK) and did not have the benefit of being able to engage with the practical labs. The labs were not also delivered in the normal way as a significant part of the term passed before we returned to campus-based mode of delivery.

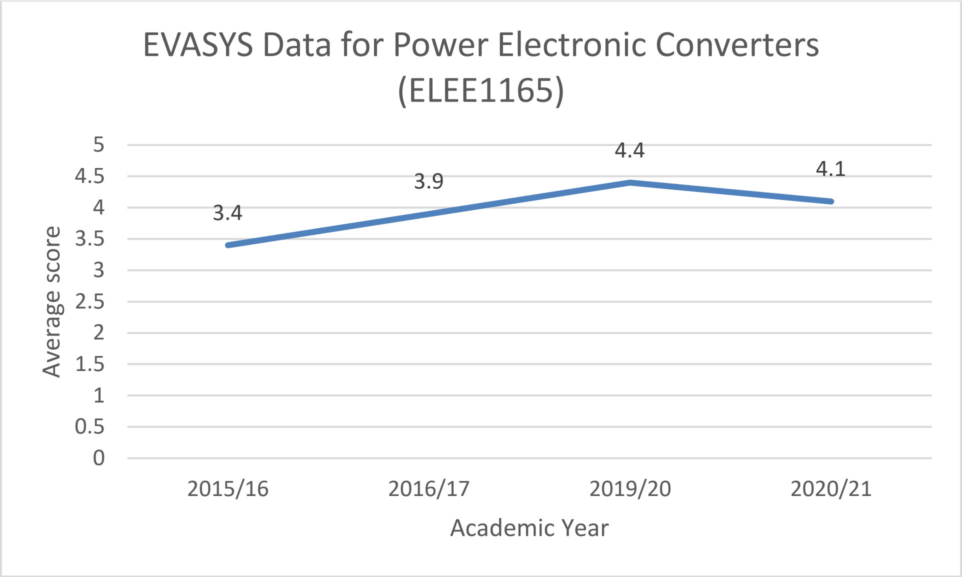

Figure 1. Students' response to the EVASYS survey

Although students do not generally seem very keen to write feedback in the EVASYS system, there were some positive comments in relation to the way the module was organised – including the labs. Here are a few comments taken from the EVASYS reports:

- "[My tutor] is a strict but fair lecturer. He provided us with all the necessary support and materials. This course's Moodle page was well organized."
- "It's good to have new experience in learning. There are labs with lectures to support learning."
- "Well organized module as expected, learnt more things about converters compare to my bachelor studies."

Limitations and conclusions

The work for this case study was motivated by feedback from students who took the module in previous years. The students felt that there were not enough laboratory opportunities for them to experience the impact of what they were learning in real-world applications or in a way that explicitly demonstrated what components or systems were involved in the circuits. The laboratory activities were redesigned and expanded so that students could take a design from first principles to circuit-testing, using discrete components while avoiding the black-box approach. The labs were integrated with the lectures and tutorial sessions in a way that facilitated an inquiry-based pedagogic process to occur. This approach seemed to have resulted in positive experiences and improved outcomes, as evidenced from informal feedback from students and from the feedback gathered through the University's formal EVASYS system.

Although the fact that the labs were designed so that students could take the equipment and software away and work independently (which was very popular with the students), this approach is only feasible in situations where the labs could be made portable and conducted safely by the students. Another limitation might also arise from the fact that the EVASYS system was designed to capture students' feedback on their overall experience of the module rather than just the laboratory side of the operation. That aside, there were comments from students within the EVASYS feedback that alluded to how learning/understanding was enhanced by the way the lab exercises were conducted, as evidenced in some of the student comment samples highlighted above. With the benefit of hindsight, it would have been much better and more instructive if separate and targeted feedback had been sought from the students as part of the study.

In conclusion, the study demonstrates how the benefits of project-based approach could be used to make traditional instruction-based laboratory activities more effective while making the whole set-up much more accessible to students. Many engineering disciplines and other areas that rely on expensive or bulky laboratory equipment for instructional lab exercises could benefit from adopting aspects of this study.

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