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A Versatile and Low-Cost Approach to Power Electronics Practical Training

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Abstract
Electrical machines, power electronics, and electric drives have permeated several industrial sectors with applications spanning across electrical and mechanical engineering, automotive, aerospace, renewable energy, etc. As such, there is an increasing demand for engineers with a skill set in power electronics, machines and drives. In electrical engineering education and specifically in the power electronics field, practical training is a key requirement to train a high-calibre power electronic engineer with skills that satisfies industry needs and employer expectations. In this work, a group from the University of Sheffield introduces a universal power electronics board that is versatile and compact. The proposed board is highly modular and emulates a graduate experience in industry settings. The board provides practical power electronics education resources to address industry needs and minimise cost to higher education institutions whilst enabling scalability in practical teaching, allowing more students to benefit from this type of training. The proposed system also addresses learning outcomes at levels 3, 4 and 5 for vocational qualifications, covering both the basics of power electronics and more advanced application-level concepts.

1. Introduction
With recent technological advancements such as electric vehicles, renewable assets integration and variable speed drives, power electronics (PE) are considered one of the most dominant industries. In the coming decades, all electric power applications will be processed through power electronics, from the milliwatt to megawatt level [1]-[4]. In the industry setting, employers find that graduates are well-equipped with theoretical knowledge but have some practical skill deficiencies [1], [5]. As such, bridging the gap between academic institutions and industry employers is crucial. The power electronics field can be characterised as multidisciplinary or interdisciplinary [3], [6]. Hence, teaching power electronics is a complex and more than often a challenging process, as it is highly interlinked with other disciplines such as circuit analysis, digital signal processing, automatic control, mathematics, physics, electromagnetics, and more [1], [3], [7].

Laboratory infrastructure plays a crucial role in teaching power electronics modules. Therefore, most engineering modules include instructional laboratories. Laboratory-based activities help students improve their practical skills and validate the phenomena or theoretical parts studied [8]. Practical hands-on exercises are the solution to successfully train high-quality power electronics engineers and narrow the gap between academic graduate level over industry expectations and demands [1], [3], [9], [10]. Additionally, realistic lab training provides soft and employability skills that industry employers require [1], [11]-[13]. Therefore, one of the targets in education and training is to provide learners with access to user-friendly and reconfigurable equipment, integration procedures, as well as knowledge on the application of techniques comparable to those they would encounter in the real industry [1], [2], [14], [15].

This paper introduces a versatile, low-cost power electronics hardware system suitable for large cohorts and remote access containing the necessary components to function like industrial hardware. The board allows remote accessibility whilst being compact, inexpensive, and highly scalable.

Remote accessibility seamlessly complements in-person practical training, allowing learners more flexibility and inclusivity whilst maintaining a high standard of teaching quality [10], [16]. Other approaches include simulation/virtual lab activities – which, albeit interactive, do not provide realistic lab experience.

To this end, Section 2 presents the design approach of the proposed hardware, detailing the evolution from an initial prototype to an improved design that optimises for cost, size, and ease of use. Section 3 introduces the versatility of the developed hardware, highlighting its modularity and the wide range of practical learning outcomes it enables. Section 4 presents a case study of the hardware being used in a laboratory setting, demonstrating how it can be employed to teach key power electronics concepts to students in engineering disciplines.

2. Design Approach
To facilitate practical teaching for large student cohorts undertaking power electronics (80+ students per session), the design approach was to optimise for cost-effectiveness, multi-functionality, ease of storage and handling, and ease of use. The hardware was designed to be compact, only containing the necessary components to emulate industrial hardware. The design follows two iterations of improvements.

2.1 Initial Hardware Design

Fig. 1 shows the legacy hardware of the University of Sheffield (UoS) designed to teach power electronics. This hardware consists of an isolated, adjustable magnitude 50 Hz power supply unit (PSU), a power electronics board, and load components. The PE board has six removable MOSFET switching devices that can be configured as required – the board is divided into 3 "legs", each of which can accommodate two MOSFET switches. Extra diodes and current sense components are used to separate learning outcomes (LOs), such as the Miller plateau, reverse recovery, etc. The PE board is controlled via a ribbon cable by a National Instruments myRIO connected to a PC running a LabVIEW interface.

The various auxiliary components on this PE board require a separate auxiliary DC power supply provided by a bench-top power supply unit (PSU). The myRIO also requires an extra auxiliary supply.

The board size is 350 mm x 200 mm, and the weight is 995g which has an impact on storage and handling capacity. This design approach resulted in a high failure rate due to the large number of components, separate power supplies and a large number of interconnections. The cost of the system is also high, especially when the FPGA-based myRIO is considered.

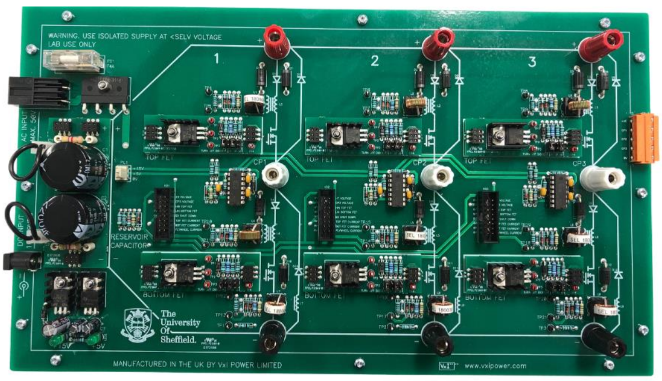

Fig. 1 First version of Switching PCB board.

2.2 Improved Design

To reduce the size, cost and increase the reliability of the system the hardware presented in this paper was developed, known as the Universal Switching PCB (USP, Fig. 2). This consists of a 3-phase full bridge built on a small, inexpensive printed circuit board (PCB). Specifications for the new design can be found in Table 1.

The MOSFETs that make up the 3-ph full bridge are each on their own small PCB, with pin headers for learners to add custom gate-drive resistors. The separate PCBs facilitate modularity, enabling different types of MOSFET or even other electronic switches like BJTs or IGBTs to be easily substituted. The developed hardware enables a diverse range of practical LOs to be achieved in the field of power electronics.

Many parts of the system have been designed to be easily accessible by learners, for example, allowing test equipment to be attached for example finding and correcting faults similar to large scale industrial systems.

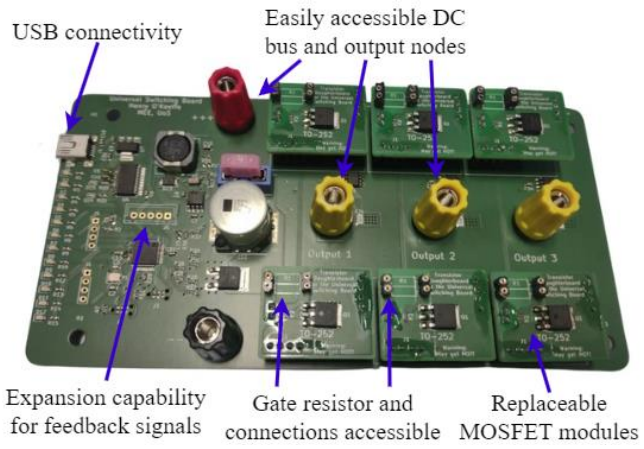

Fig. 2: Universal Switching PCB.

Table 1 USP Specifications

Bus voltage	≤ 48 V
Number of half-bridges	3
Maximum phase current	16.5 A_{pk}
Switches	Modular (replaceable)
Controller IC	dsPIC33CH512MP505
PCB Mass	125 g
PCB dimensions	180 mm × 85 mm

Control is achieved via a personal computer (PC) running the control software connected to the USP via a USB interface. A microcontroller on the USP runs firmware that allows the board to act as a 3-ph electrical machine controller, brushed DC machine controller, or three individually controllable half-bridges capable of operating at up to 100 kHz.

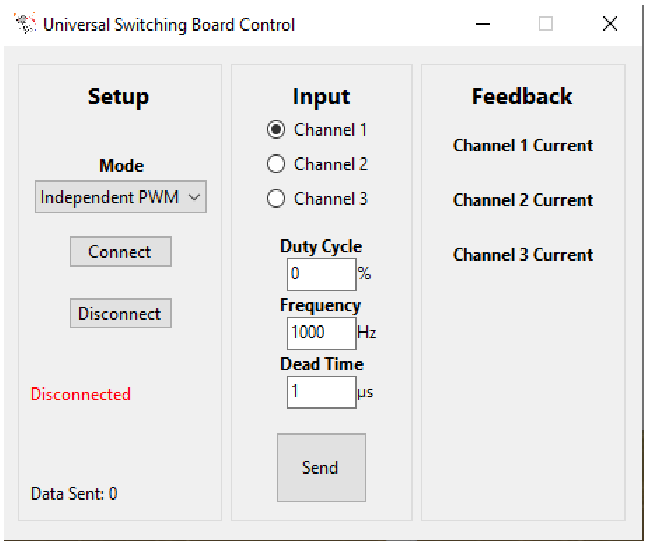

Fig. 3: Software front end (user interface).

The software front-end (Fig. 3) is used to command the hardware with simple UI elements (e.g., duty cycle, switching frequency, dead time, etc.); textboxes and buttons, to streamline the learning experience to focus on the lab activities rather than the process of setting them up, eliminating friction in the practical learning process.

3. Practical Teaching Agility and Versatility

A typical lab activity could involve three parts: a small amount of work for the learners to complete before the lab (a pre-lab activity), the lab activity itself, and a summative assessment, such as a quiz or report after the lab (post-lab activity). The pre-lab could be a simple familiarisation exercise where the students can read over background theory and complete a formative quiz, or it could be more involved, for example, requiring learners to perform a simulation of the upcoming lab activity.

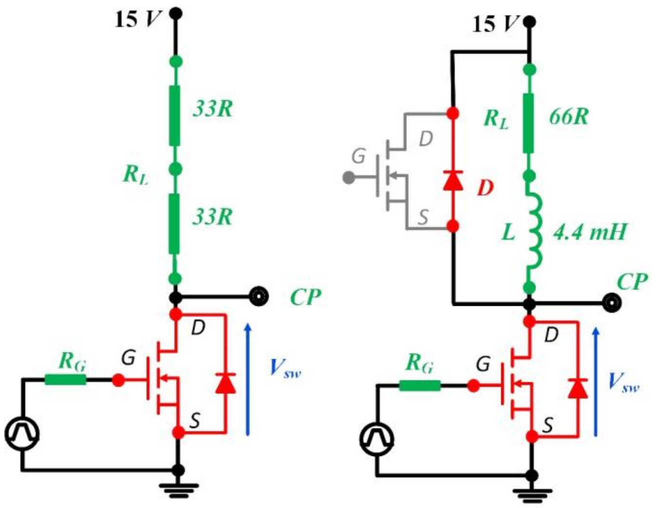

Fig. 4 Switching transistor circuit (a) resistive load and (b) inductive load.

An example of a power-electronics-based lab activity may involve connecting a resistor to the high side of one of the half-bridges and attaching a gate drive resistor to the low side only—the implementation of a simple low-side switch topology. A MOSFET PCB is left in place on the high side so the body diode can freewheel any inductive current during switching events (Fig. 4b).

Learners could simulate this system using MATLAB/Simulink as a pre-lab activity, comparing the simulation results to the data gathered in the lab activity. They can then suggest reasons for any differences, helping reinforce LOs centred around parasitic components and the limitations of the simulation model, as well as allowing learners to check that their lab setup is correct and working properly.

The modular nature of the USP allows many different power electronics components and their characteristics to be tested and explored (Fig. 5). These extend across multiple power conversion techniques (Fig. 6). In all these examples, multiple key circuit nodes are available as test points to attach measurement equipment. This enables investigation of key power electronic learning concepts ranging from the high level, e.g., illustrating how an electrical machine can be driven in 4 quadrants by a MOSFET bridge, to the low level, e.g., observing a minority-carrier device's tail-current.

Lab activities may involve the addition of loads like resistors (Fig. 4a) or inductors (Fig. 4b); a gate drive resistor could be added to the high-side MOSFET to illustrate active clamping, two half-bridges could be used together to make a full-bridge, all three legs could be used for driving 3-ph motors, other switches could be swapped in and compared, the fundamental differences between MOSFETs and BJTs could be explored. Fig. 6 illustrates the power conversion techniques and the applications of the universal switching PCB, which offers the ability to design a wide range of practical learning activities on the topic.

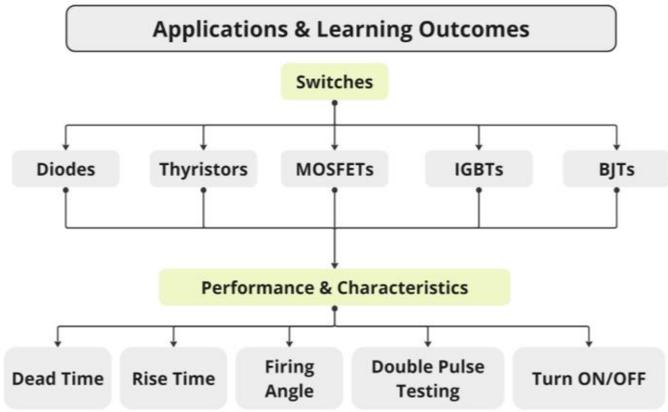

Fig. 5: Universal power electronic board applications.

The USP can facilitate remote lab accessibility. For instance, connections to an oscilloscope (with an interface to a PC) can be made, and the learner can interact with both the USP and the oscilloscope to take measurements and complete lab activities remotely. This feature allows the scaling of practical power electronics teaching beyond local cohort sizes. This scale expansion will help bring practical power electronics training to more learners, increasing accessibility and narrowing the skills gap in PEMD.

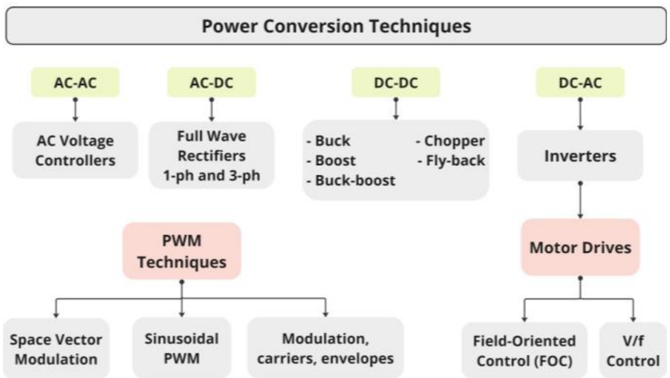

Fig. 6: Universal power electronic board power conversion techniques.

4. Case Study

The designed board can serve undergraduate and postgraduate modules up to the Master's level. Moreover, it suits core electrical and service modules such as aerospace, bioengineering, automatic control, mechanical disciplines, and undergraduate and postgraduate projects. This section will discuss a case study for a practical teaching activity offered to all the above disciplines.

The LOs of this lab are designed to follow on from a previous lab where learners are introduced to the concept of AC-DC conversion (rectification) by constructing a full-wave bridge rectifier. The LOs pertain to the construction of a switching circuit supplying variable power to a resistive or inductive load (i.e., DC-DC converter). The learners analyse how power delivered to the load can be controlled using a PC communicating to a microcontroller which performs Pulse Width Modulation (PWM).

The learners should achieve the following LOs as part of the described lab activity:

- Appreciate the voltage, current and power dissipation differences between inductive and resistive loads.
- Investigate the turn-on and turn-off characteristics of MOSFET switches.
- Understand how PWM can be used to switch transistors and vary the power supplied to electrical loads.

The lab script is available to the students via the virtual learning environment (VLE) platform before the lab session. The learners should complete a formative pre-lab quiz as a diagnostic test, preparing them for the actual lab session. Upon completion of the lab session, the learners undertake a summative post-lab activity.

For this lab activity, N-channel Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) have been chosen as the switching devices because they are widely used in industry, are capable of switching at very high speeds, can block large voltages when turned off and conduct large currents when turned on. They are particularly suitable for extra-low voltage applications used in the lab for safety. Fig. 7 shows a switching transistor circuit that switches current through a load, either a resistive load (*R*) or a resistive-inductive load (*R-L*).

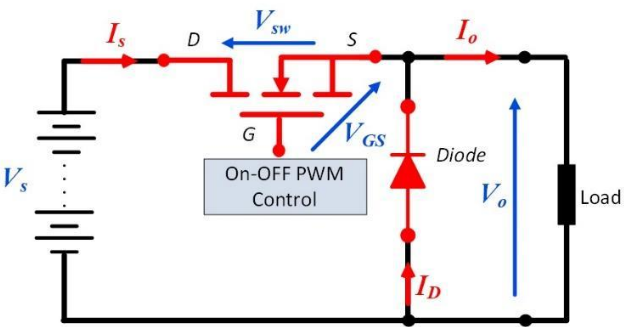

Fig. 7: A switching transistor circuit with MOSFET.

This circuit is used to illustrate to the learner that if V_{GS} is greater than the MOSFET threshold voltage ($V_{GS(th)}$), the transistor begins conducting and allows a current I_D to flow between the drain and the source. This current also flows through the resistive load R_L, which dissipates power. When there is no voltage applied to the gate (V_{GS}), or the voltage applied is less than the threshold ($V_{GS(th)}$), the MOSFET does not conduct and no current flows. Therefore, no power is delivered to the load.

The background theory includes details about the concept of pulse width modulation used in the lab and how to calculate the output voltage average and rms values of different current waveforms, as well as the hardware setup involved.

In the lab, students apply DC voltage to the USP, which is commanded to switch with pulse width modulation (PWM) with various duty cycles. With an oscilloscope, learners can monitor the voltage at the output node and the positive voltage rail in the time domain and observe the waveform.

The exposed gate-drive resistor also allows the learners to monitor the gate-drive waveform and observe the switching events on that node, helping reinforce key LOs such as understanding the cause and effects of MOSFET parasitic components, leading to phenomena such as the Miller plateau (Fig. 8).

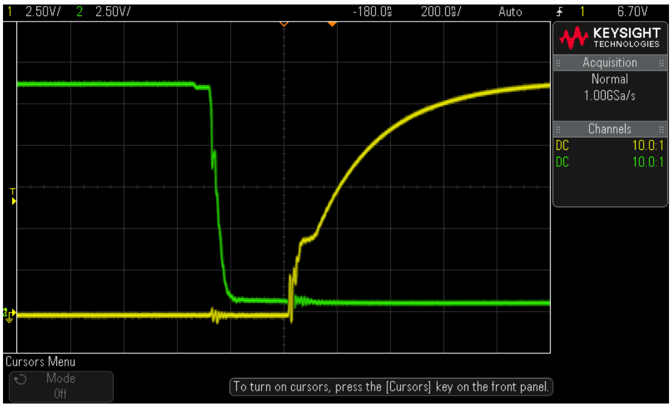

Fig. 8: Lab-acquired waveforms as observed by the learner, showing deadtime between the upper and lower MOSFET gate drive waveforms and the miller plateau.

Other key concepts that students can observe from these waveforms include the application of dead-time, and why it is important, the nature of pulse-width modulation and how it relates to power delivered to the load. The effects of the load (inductive or resistive) on the power delivered to the load, as well as energy stored in the inductor and the role of the freewheel diode, are also enabled by measurements taken from these waveforms, e.g. Fig. 9.

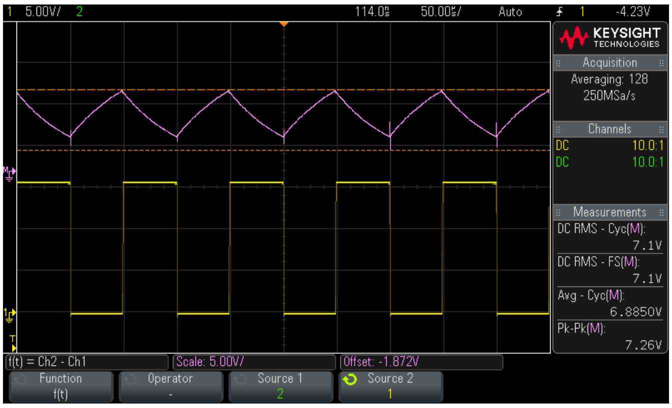

Fig. 9: Pulse-width modulation of an inductive load. The voltage at the MOSFET drain is yellow, and the load current is purple.

This experimental data is recorded, and the students obtain results similar to those presented in Fig. 8. Before implementing the switching circuit configurations illustrated in Fig. 4, the students simulate each circuit as an intermediate step between theory and practice. Throughout the lab script, the learners are prompted with questions that encourage them to critically consider and reflect upon the observed waveforms and measurements taken, reinforcing key concepts taught in the theory and beyond.

Once all experimental tasks have been completed, the students are gathered into groups, and with the assistance of the lab instructors, the USP is used to drive different types of electric machine, demonstrating the applicability of the lab to broader fields, as well as the high-level function of the hardware as an electric machine drive. It is important to note that the presented lab activity follows previous lab activities dedicated to the experimental characterisation of electrical machines, thus completing the practical teaching loop through the systems, hardware, and component level.

5. Conclusion

In this work, a versatile, low-cost power electronics hardware system was presented suitable for providing practical training to large student cohorts, including through remote access. The USP was designed to contain the necessary components to emulate industrial hardware while being compact, modular, and easy to use. The case study demonstrates how this approach enables a wide range of practical learning outcomes to be achieved, from low-level concepts like device switching characteristics to high-level applications like electric machine drives.

The modular and accessible design of the USP makes it ideal for teaching power electronics to students across electrical, mechanical, aerospace, and biomedical engineering disciplines. The USP features remote accessibility, complementing in-person labs and allowing practical training to be scaled up to reach more learners.

Future work will focus on developing additional laboratory activities that leverage the full capabilities of the USP, covering different power conversion techniques and circuit configurations. The learning outcomes of these activities will target multiple skill levels to provide a complete practical teaching experience from the component level to the system level. Additionally, a survey of student experience using the hardware will be conducted to assess the impact and effectiveness of the proposed teaching approach.

By providing a cost-effective, scalable solution for power electronics practical training designed to meet the needs of the industry, the presented approach can play an important role in narrowing the skills gap in the PEMD field. The combination of hands-on learning, remote accessibility, and alignment with real-world applications makes the USP a valuable tool for producing skilled power electronics engineers who are well-prepared to meet the needs of the industry and the demands of employers.

Acknowledgements

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