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A Laboratory-Supported Power Electronics and Related Technologies Undergraduate Curriculum for Aerospace Engineering Students*

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Power electronics technologies will play a vital role in the aerospace industry in the years to come and all emerging technologies are already an important part of the industry either at R&D or in many cases production level. It is recognised that aerospace engineering and avionics students need to be aware of these technologies and in a position to work as a team member with development of power electronics technologies addressing specific needs. The paper discusses pioneering initiatives undertaken and the newly introduced course of power electronics and related technologies into the undergraduate aerospace engineering curriculum at the University of Glasgow, UK. The various components of the course are described in detail, along with the laboratory programme, which is based on a "closed-loop" approach for the understanding of the various concepts. The pre-laboratory/post-laboratory questions and the course assessment are given. A sample final exam question is also provided to introduce the industry relevance requirement component of the course. The views of the students regarding their experiences, especially in the laboratory environment, are critically discussed.

INTRODUCTION

THE POWER ELECTRONICS (r)evolution is mainly due to the developments in solid-state and other technologies and has been making its way in numerous fields where traditionally other technologies, such as mechanical switches, have been employed [1].

One of the many fields where power electronics promises to make significant changes is in aerospace systems. Specifically, the aerospace industry requires the replacement of mechanical complexity with electronics [2–5]. Electrical systems can offer significant reductions in system complexity, redundancy, weight and associated cost. Moreover, the power requirements within the cabin of a civil aircraft keep increasing due to customer demands. Manufacturers, in order to offer such flexibility without adding extra weight and cost, look at "more" electric technology for engine operation and at the aircraft level. Power electronics technologies with new topologies such as matrix converters, and reduced enclosures with "clever" thermal management can offer the solutions that the industry requires. Power density and problems associated with the temperature operation of both semiconductor devices and passive elements such as capacitors remain a challenge.

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Power electronics technologies have already been studied and in many cases modified to address the specific needs of the industry [6–11]. Future technologies that are likely to have an impact on aerospace technologies, such as wide band-gap semiconductors, have been considered elsewhere [11]. The miniaturisation of power electronics has also played an important role in the development of this technology [12].

From the point of view of education, the power electronics curriculum is expanding, even in traditional electrical and electronic engineering courses, but in the last decade this has made its way into other disciplines, such as mechanical engineering, through the mechatronics curriculum. For instance, [13] describes a new course in mechatronics at the School of Electrical and Computer Engineering at Georgia Tech, USA, including its goals, lecture plan and laboratory programme.

On the other hand, numerous modern approaches have been documented in order to improve the curriculum of power electronics offered for electrical and electronic engineering students [14–27]. Significant steps have been taken in the teaching of converter technology, through restructuring of the curriculum or by employing a building block approach [16], new laboratory experiments [18, 19, 26] and methods based on the use of technology [23–26]. It is also important to note the many initiatives that use the web and java technology to illustrate power electronics concepts and circuit operation as well as to help the design process [23–24]. The natural expansion of the power electronics programme into the utility applications and power systems has been described in [20] and [22]. Curriculum development based on application-specific power electronics education has been discussed in [27].

Philosophically, many power electronics related technologies and systems are "falling from the space" as fuel cells, photovoltaics and power conditioning technology have been used in space missions since the 1960s. It is therefore not unusual to ensure that such technologies are embedded in the modern aerospace engineering curriculum. This would address the current and future needs of the industry for many challenging projects associated with "all-electric" aircraft for civil and military applications or unmanned aircrafts.

So far, however, there has been no documented initiative to introduce the power electronics subject into the undergraduate curriculum of an aerospace engineering programme. The objective of an earlier paper [28] was to report on initiatives taken since 2000 and the now successful introduction of power electronics and related technologies into the aerospace engineering undergraduate curriculum for students at the University of Glasgow, Scotland, UK. However, this gave only limited information on the way the experiments and the laboratory are organised. The objective of this paper is to provide detailed information on the laboratory experiments, including the pre- and post-laboratory questions and relevant checklists. A sample exam question is also provided, so that the reader can appreciate the way the link is made between the theory and industrial applications.

The paper is organised as follows. First the objectives of the course are presented, followed by a general description of the lectures, tutorials and the laboratory programme. The various sections of each laboratory are then described in greater detail and the formal feedback received from students is discussed, followed by a summary of the conclusions.

COURSE OBJECTIVES

This is a second-year course in the aerospace engineering curriculum. The course attracts approximately 100 students from the Aerospace Engineering department annually. However, the course is also offered to students from the Mechanical Engineering Department, which attracts another 100 students, making it the largest course in the Department of Electronics and Electrical Engineering at the University of Glasgow, UK. The objectives of the course can be summarised as follows.

Understanding

- Architecture of products and systems that include electrical and/or electronic components and sub-systems

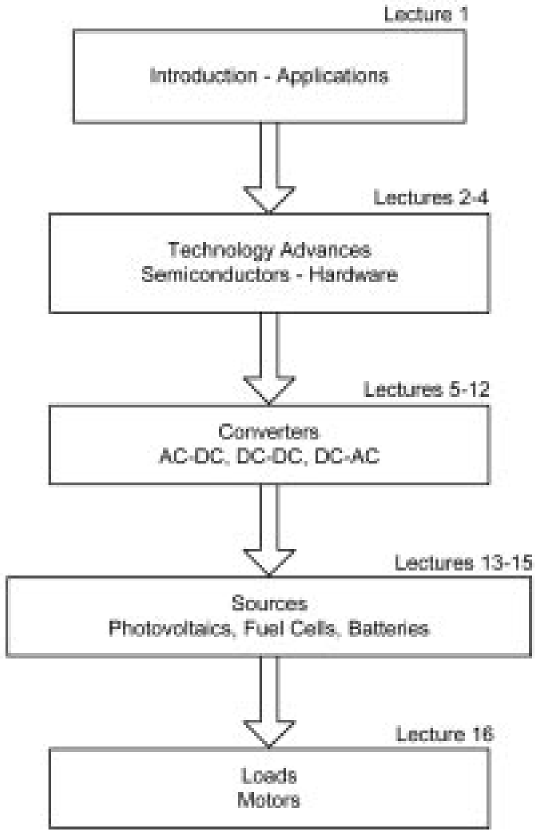

Fig. 1. Diagram of the lecture schedule of the course.

- Operation of basic DC-DC power electronic converters with voltage control by PWM, and DC-AC conversion by PWM inverter
- Structure of adjustable speed electric motor drives based on a block diagram approach

Knowledge

- Function, design, and characteristics of the most widely used key electrical and electronic components
- Semiconductor devices and their use as switches
- Principles of thermal management, power losses, converter hardware, packaging and integration of electrical and electronic components
- Current trends on power systems in automobile and aircraft systems

Course organisation

The course is organised in the traditional way, with lectures, tutorials and laboratory experiments, and is well supported with documentation for each activity. The total contact time is 24 hours and there are 16 formal lectures as part of the course (Fig. 1). The rest of the time is spent on tutorials, revising and dealing with exam papers, open sessions for questioning, etc. There are also four laboratory sessions lasting three hours each (Fig. 2).

Lectures, tutorials

An outline of topics covered in each lecture follows.

Lecture 1: Introduction to power electronics systems; Applications and new emerging technol-

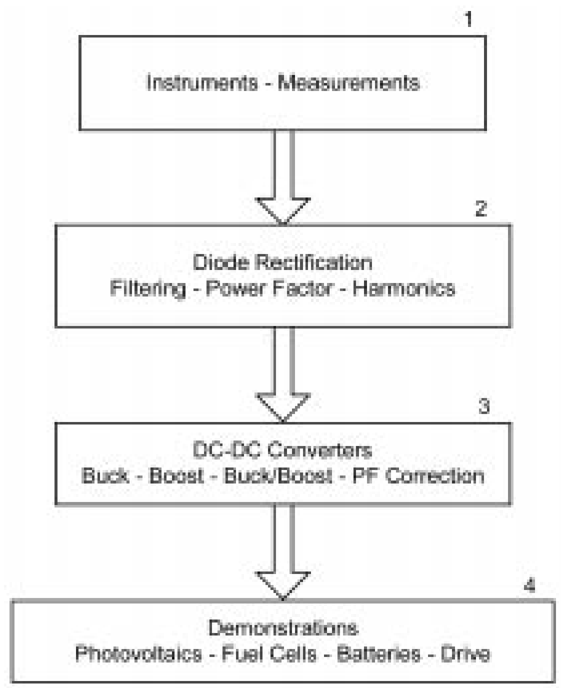

Fig. 2. Diagram of the laboratory schedule of the course.

ogies; Aerospace industry and space applications; Mechatronics and mechanical engineering applications; Other related applications.

Lecture 2: Recent advances and market expansion; Linear electronic systems; Power electronics systems—block diagrams; Comparison between linear power supply and power electronic converter based solutions; Circuit-based block diagrams of typical power electronics systems and applications; Function of various power electronic converters.

Lecture 3: Overview of power semiconductor devices; Classification with respect to degree of controllability; Diode, MOSFET, IGBT and others; Switching performance characteristics; Evaluation and comparison; Applications in automotive and other space-related systems.

Lecture 4: Desirable characteristics of fully controlled semiconductor switches; Switching converter basic design rules; Switching losses in semiconductor devices; Simplified inductive switching circuit operation and switching waveforms; Power loss calculation (turn-on, turn-off, conduction); Converter hardware components; Heat transfer mechanisms and heat sinks; Converter hardware examples.

Lecture 5: Simulation of power electronic converters and systems; Device level, circuit level, system level simulation; Introduction to PSPICE, MATLAB and other software packages; Rectification; Types of rectifier circuits and topologies; Diode rectification; Half-wave diode rectifier with resistive load; Circuit analysis and waveforms; Definition of rectifier performance parameters; Harmonic distortion and Fourier series analysis; Ideal rectifier performance parameters.

Lecture 6: Capacitor charging and discharging; Half-wave diode rectifier with resistive load and capacitive filtering, circuit waveforms and analysis; Full-wave diode rectifier with resistive load, circuit waveforms and analysis; Full-wave diode rectifier with resistive load and capacitive filtering, circuit waveforms and analysis.

Lecture 7: DC-DC converters and applications; Step-down (buck) DC-DC converter; Continuous and discontinuous conduction modes of operation; Circuit analysis, steady-state waveforms and equivalent circuits for continuous conduction mode only; Steady-state analysis and input/output DC transfer function.

Lecture 8: Step-up (boost) DC-DC converter; Continuous and discontinuous conduction modes of operation; Circuit analysis, steady-state waveforms and equivalent circuits for continuous conduction mode only; Steady-state analysis and input/output DC transfer function.

Lecture 9: Step-down/up (buck/boost) DC-DC converter; Continuous and discontinuous conduction modes of operation; Circuit analysis, steady-state waveforms and equivalent circuits for continuous conduction only; Steady-state analysis and input/output DC transfer function.

Lecture 10: Inverters and applications; Topologies with respect to input (namely, voltage and current source type); Topologies with respect to output (namely, single and three-phase); Control (namely, square-wave, modified square-wave and pulse-width modulation (PWM)).

Lecture 11: PWM inverters; Bipolar and unipolar switching; Harmonics and filtering; Drawbacks of PWM inverters; Comparison of PWM against square-wave inverters.

Lecture 12: Diode rectifier circuits, harmonics and power factor (review); Why we need and in fact use power factor correction (PFC) circuits; Basic power circuit topologies for power factor correction; Fixed pulse duty cycle control and PWM control; Boost DC-DC converter example for PFC system; Diode rectifier with capacitive filter; Diode rectifier with capacitive filter and fixed width (duty-cycle) boost active power factor correction.

Lecture 13: Photovoltaic cells, technology and operation principles; Solar panels and arrays; Maximum Power Point Tracking (MPPT) systems (electrical tracking system); Maximum area exposed to the sun at all times (mechanical tracking system); Power electronic converter based conditioning; Applications for satellites and the international space power station; Solar racing car, integrating technologies from previous lectures.

Lecture 14: Fuel cell technology and operation principles; Types of fuel cells (namely, Proton Exchange Membrane (PEM) FC, Alkaline (AFC), Molten Carbonate (MCFC), Solid Oxide (SOFC), Phosphoric Acid (PAFC)); Power electronic converter based conditioning; Applications for space and automotive systems.

Lecture 15: Battery technology; Operational principles of primary cells and secondary cells; Voltage-current characteristics and battery capacity; Open-circuit and closed-circuit voltages; Battery state of charge; Closed-circuit voltage and load effect; Types of batteries; Battery-charging methods; Applications in uninterruptible power supply (UPS) systems and hybrid electric vehicles.

Lecture 16: Introduction to motors/generators; DC motor and AC induction motor; Brushless motor; Stepper motor; Operation principles and characteristics; Speed control via voltage control; Applications of motor drives.

Lectures 17–24: Tutorials, review, discussion, past exam papers and other questions, laboratory Q&A sessions, introduction of research topics such as the "all-electric aircraft", drive by wire, fly-by-wire, and matrix converter technology.

Extra reading material: The students are also given numerous technical articles drawn from current literature, such as the IEEE Spectrum or IEE publications that target a general engineering audience, in order to be exposed to the latest information on the subjects covered in the course.

Laboratory experiments

There are three sessions lasting three hours each where the students perform experiments. These are organised as follows:

Laboratory 1: Familiarisation with basic signals and their measurements with laboratory electrical and electronic instruments

Laboratory 2: Half- and full-wave diode rectifier circuits with and without capacitive filtering

Laboratory 3: Experimental study of basic DC-DC power electronics converters: buck (step-down), boost (step-up) buck/boost (step down/up)

Laboratory demonstrations

There is also a fourth session, where the students are shown advanced equipment and systems. A wide range of advanced equipment is demonstrated in the laboratory without the students doing work but rather observing and questioning. A document that describes the equipment is provided to the students to enhance documentation and encourage questioning. The equipment includes: a vector-controlled drive attached to a small three-phase induction motor, run from a single-phase (Fig. 8); fuel cells; photovoltaics; various electrical and electronic equipment, such as capacitors, resistors, inductors, heat sinks and other hardware-related items.

Laboratory-customised equipment

For each laboratory, customised equipment has been designed and manufactured. In order to meet safety requirements, a specialised power supply has been developed. The front panel for this equipment is shown in Fig. 3. It allows the connection of a wattmeter in special points in order to make measurements.

In most experiments, the load is resistive and the intensity of a light bulb is used to show how the converter and filtering affects the value of the output voltage and currents. The students are asked to observe the intensity and feel the variation of the parameters, rather than relying on "dry" measurements only. For this purpose, a special load bank has been developed and its front panel is shown in Fig. 4.

For voltage and current measurements, a specia-

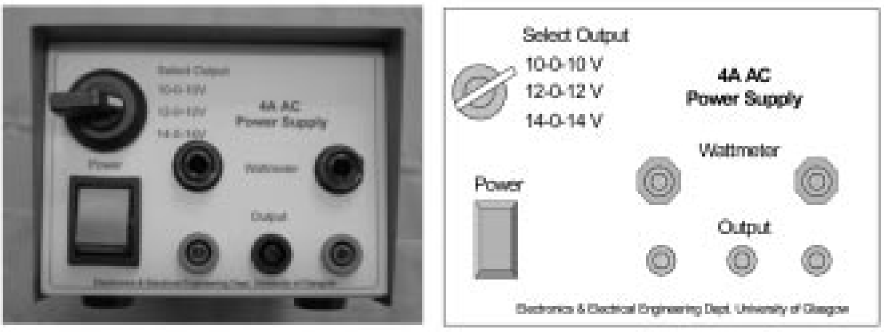

Fig. 3. The front panel of the custom-made 4A AC power supply.

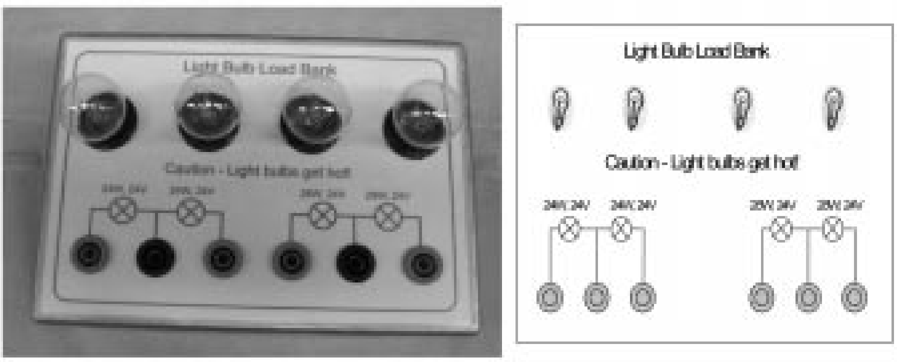

Fig. 4. Load bank with light bulbs.

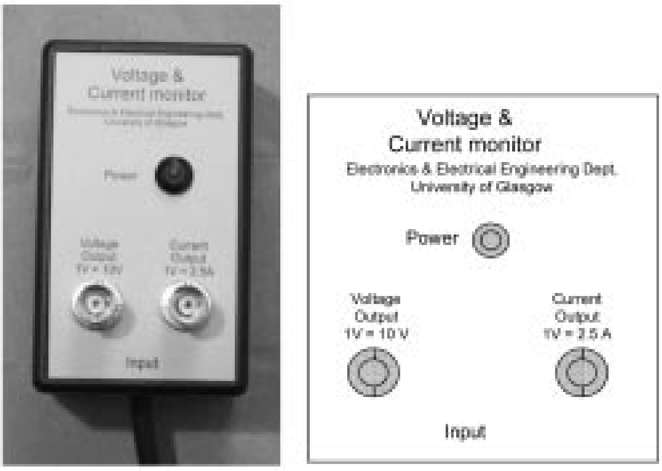

Fig. 5. Voltage and current monitoring equipment.

lised circuit has been built in order to act as a current sensor combined with a voltage sensor, so that a direct connection to an oscilloscope channel can be done. This is shown in Fig. 5.

Customised equipment to accommodate the diode rectification experiments along with filtering has been built and its front panel is shown in Fig. 6. It has been designed as a block system as well, so that, in another session, students can use it as a block and connect a boost converter following the diode rectifier in order to see and study the effect of power factor correction. They can also compare it directly with results from the previous session.

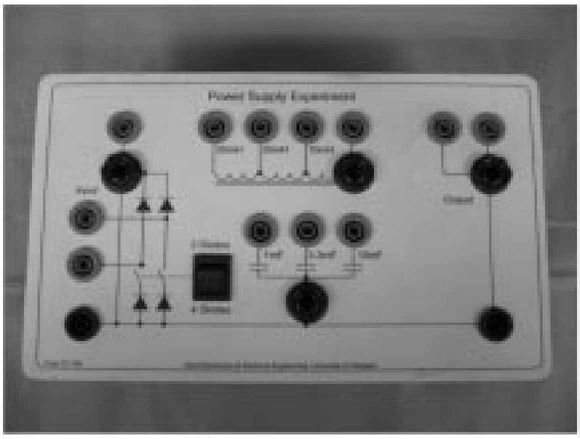

Fig. 6 Power supply experiment apparatus.

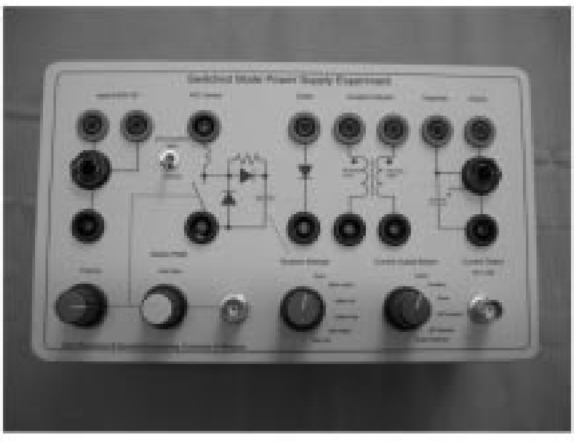

Fig. 7. Front panel of the custom-made DC-DC power electronic converter apparatus.

Finally, the DC-DC converters can be studied with another custom-made apparatus, shown in Fig. 7. Snubber selection is also built into the system, to study aspects associated with the implementation of a given converter. Duty cycle control is offered through a selector and the current in various circuit components can also be monitored through a selector. Fig. 8 shows the compact motor-drive system used in the laboratory demonstrations.

Laboratory description

Each laboratory experiment is organised with pre-laboratory and post-laboratory questions. A number of reflective questions are also included in the latter section. In this section, key questions are presented, so that the reader can better understand the way the laboratory is organised. The pre-laboratory questions are answered before the experimental work starts. This ensures that all students have a basic understanding of what the laboratory is all about.

Fig. 8. The set-up of the drive system.

Laboratory 1

The objectives of the first laboratory session can be summarised as follows:

- To present some basic signals and provide information associated with them; i.e. AC (effective or RMS value) and DC (average value).
- To discuss electronic and electrical measurements and associated issues.
- To introduce some basic electronic equipment; namely, the analogue and digital oscilloscope, the function generator, the analogue and digital multimeter.
- To become familiar with some basic controls and functions of the above-named instruments.
- To use the function generator to generate basic signals, display them on the oscilloscope screen, and perform measurements with the multimeters.

Pre-laboratory questions:

- What is a periodic signal?
- How are the period and the frequency of a periodic signal related?
- Consider the signal given in Fig. 9(a) and assume that the DC-GND-AC switch of the oscilloscope is set to DC. Draw in the oscilloscope screen provided in Fig. 9(b) the signal when the DC-GND-AC switch is changed to the AC position. ***Note: Please do not forget to indicate the reference point for the drawn waveform.***

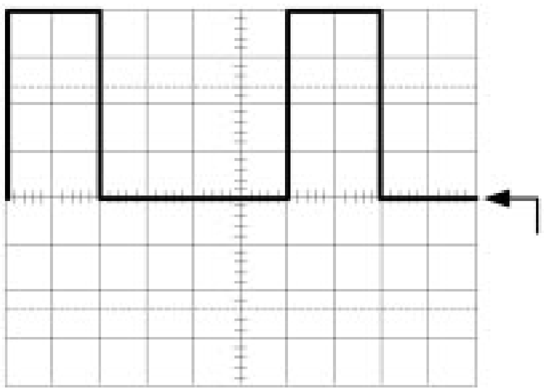

Fig. 9a.

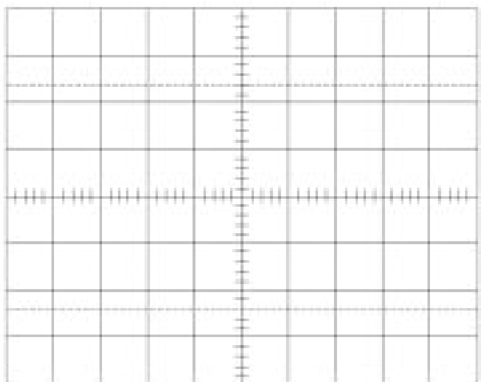

Fig. 9b.

- Do you think that the voltage signal of a wall socket in any home or office is generally a periodic signal? If yes, what is the frequency of such a signal? If no, explain why.
- What is the frequency of the signal provided by a battery?
- What are the average (DC) and effective (*RMS*) values of the function: $v(t) = V_0 \sin(\omega t)$.
- What is the relationship between the DC (average) value and the effective (*RMS*) value of the two signals depicted in Fig. 10. ***Please note the different frequency of the two signals.***
- What is the average and effective (*RMS*) value of the sinusoidal signal shown in Fig. 11(a).
- Repeat for the sinusoidal with the DC offset of 2 Volts shown in Fig. 11(b).
- What is the average and effective (*RMS*) value of the triangular signal shown in Fig. 12(a). Repeat for the triangular with the DC offset of 3 Volts shown in Fig. 12(b).

Post-laboratory questions:

- Write down, in point format, what you learned from this laboratory session.
- Did you encounter any difficulties in performing or understanding the laboratory work? If yes, please write down why this is the case. (For example, if you missed a lecture or your preparation was not sufficient, or the material has not been presented clearly enough, or any other reason.)
- Can you use the analogue and/or the digital multimeter to measure the voltage signal of a wall socket in your house? If yes, on which setting?
- What kind of instrument from the ones that you have been introduced to so far would you use to measure a 5 Volts 250 kHz signal?

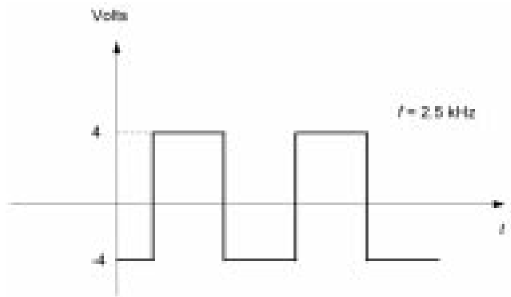

Fig. 10a.

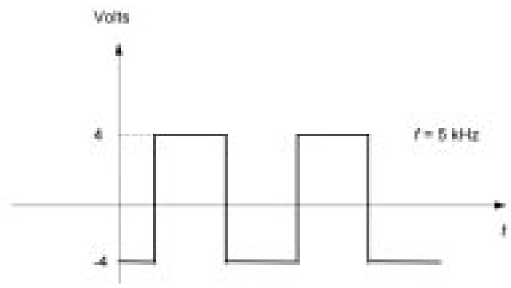

Fig. 10. Square-wave signals with 50% duty cycle.

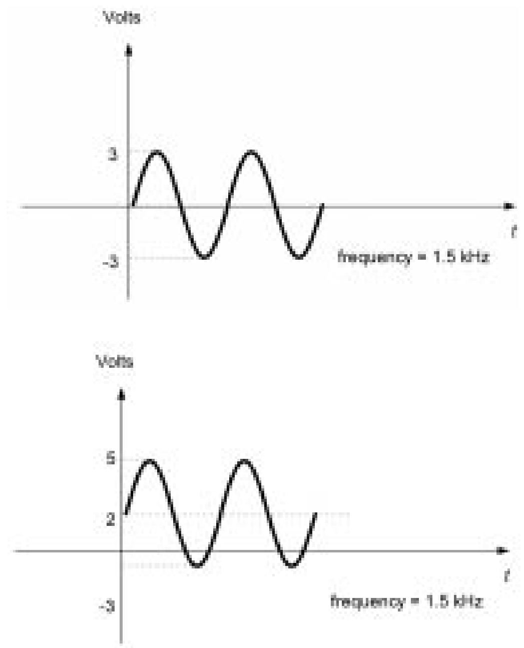

Fig 11. Sinusoidal signals (a) without and (b) with DC offset.

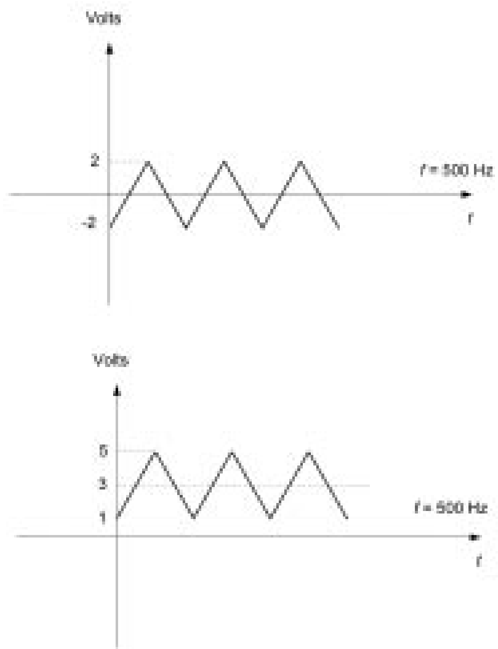

Fig. 12. Triangular signals (a) without and (b) with DC offset.

- You are told that the total *RMS* (true *RMS*) value of a signal is 15 Volts and the average value is 13 Volts. What is the *RMS* value of the pure AC component of the signal?
- You are required to measure a very weak sinusoidal signal (in the range of mVolts) at frequencies higher than 20 MHz. What instrument are you going to use and why?
- What is the average and *RMS* value of the signal shown in Fig. 13? What is the duty cycle of the signal?

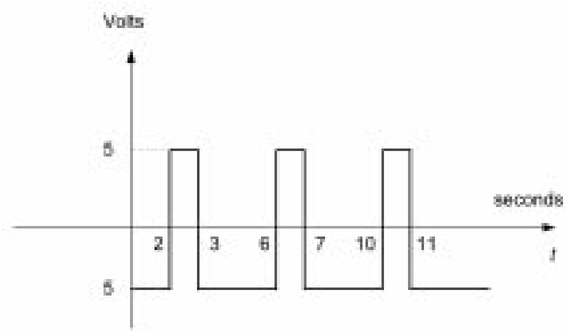

Fig. 13.

In this session, a number of questions to confirm that learning and understanding have occurred are also given (see Table 1). These are taken from the laboratory manual.

Laboratory 2

The objectives of the second laboratory session can be summarised as follows:

- To study experimentally the operation of the half-wave diode rectifier circuit with a resistive load.
- To extend that study to a full-wave diode rectifier circuit also with a resistive load.
- To investigate the effects of a capacitive filtering on the performance of both circuits with respect to both input (AC side; i.e. source) and output (DC side; i.e. load).
- To compare the performance of the two rectifier circuits against one another.

Pre-laboratory questions:
(Half-wave diode rectifier with resistive load)

- Assume a 12V AC sinusoidal voltage waveform applied to the input of a half-wave diode rectifier with resistive load and no filtering. Calculate the average value and the *RMS* value of the half-wave-rectified (output) voltage waveform.

Table 1.

Questions	Yes	No
Have you realised that instruments have limitations and certain ranges that operate accurately?		
Did you learn what the "bandwidth" is for a given instrument?		
Have you realised that the frequency of a periodic signal does not affect its *RMS* or effective value?		
Have you learnt that the 50% duty cycle square wave has average and *RMS* values that are zero and peak voltage respectively?		
Have you realised that the *RMS* value of a triangular signal is not given by the same formula as in the case of a sinusoidal signal?		

Table 2.

Frequency (Harmonic per unit)	Amplitude (Peak)	*RMS* value
0		
1		
2		
4		
6		

Table 3.

Frequency (Harmonic per unit)	Amplitude (Peak)	*RMS* value
0		
2		
4		
6		

- Use the analytical expressions provided in the previous section to calculate and record the expected values of the various voltages in the table below.

(Full-wave diode rectifier with resistive load)

- Assume a 12V AC sinusoidal voltage waveform applied to the input of a full-wave diode rectifier with resistive load and no filtering. Calculate the average value and the *RMS* value of the full-wave rectified voltage waveform.
- Use the analytical expressions provided in the previous section to calculate and record the expected values of the various voltages in the table (Table 3).
- What is the relationship between the DC (average) value of the two sets of signals depicted in Fig. 14?

A list of questions given to students in this session is provided in Table 4.

Post-laboratory questions:

- The previously mentioned reflective questions are asked once again, followed by the questions: What is the output frequency of a half-wave rectifier when the input frequency is 400 Hz? What happens to the output frequency when the same input frequency is used but the rectification is obtained through a full-wave configuration?
- A checklist of the learning and understanding that has occurred is given in Table 5.

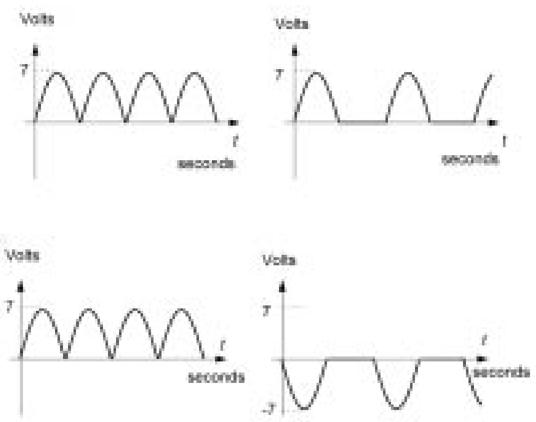

Fig. 14.

Laboratory 3

The objectives of the third laboratory session can be summarised as follows:

- To study experimentally the operation of the basic DC-DC power electronics converters; namely, the buck, the boost and the buck/boost converters for continuous conduction mode.
- To investigate the effects of the duty cycle control on the converter output voltage.
- To confirm that the switching frequency variation does not affect the converter output voltage a great deal but rather the ripple and the mode of operation (being either continuous or discontinuous), since the inductor value remains constant.

Pre-laboratory questions:
(Buck DC-DC converter)

- Assume a 16 Volt DC voltage applied at the input of a buck DC-DC converter operating in continuous conduction mode. The converter operates at 40% duty cycle. Calculate the converter output voltage. Assume that the converter operates at 3kHz switching frequency.
- Now assume that the converter switching frequency changes to 4kHz. What is the converter output voltage, assuming that the duty cycle remains unchanged?
- The duty cycle now changes to 60% and the frequency remains unchanged at 4kHz. What is the converter output voltage?

(Boost DC-DC converter)

- Assume a 16 Volt DC voltage applied at the input of a boost DC-DC converter operating in

Table 4.

Question	True	False
1. The average value of the output voltage waveform in half-wave diode rectifier circuits is increased when a capacitive filter is included.		
2. The higher the capacitor values in diode rectifier circuits, the higher the AC ripple of the output voltage waveform.		
3. The industry-acceptable power factor of equipment connected to the AC mains is any value between 0.86 and unity. The closer to unity, of course, the better.		
4. The average value of the half-wave diode rectifier without filtering is V_p/π.		
5. The maximum theoretical value of the average value of the half-wave diode rectifier when a very large (infinite value) capacitor filter is included is V_p.		
6. The frequency of the AC ripple in the case of a half-wave diode rectifier with or without a capacitor is twice the input frequency.		
7. The period of the output-rectified voltage waveform in the case of the full-wave diode rectifier is half the period of the input voltage waveform.		
8. The unfiltered average value of the full-wave-rectified voltage waveform is V_p/π.		
9. The average value of the output voltage of the half-wave rectifier without filter is equal to the average value of the output voltage of the full-wave rectifier.		
10. When a capacitor filter is used at the DC side of the diode rectifier circuits, the AC line power factor is reduced (gets worse) when compared with the unfiltered case.		
11. The full-wave diode rectifier is better than the half-wave diode rectifier with or without a filter and for all purposes.		
12. The half-wave diode rectifier is not a practical circuit, mainly due to the DC current that draws from the AC line, which is unacceptable.		

Table 5.

Questions	Yes	No
Have you realised that the average value of a rectifier is increased when we go from a half-wave topology to a full-wave one?		
Have you realised that the capacitor filtering improves the performance of a rectifier with respect to the AC ripple and the average value voltage (DC side)?		
Have you realised that the higher the capacitor filter values the worst the rectifier from the input point of view; i.e. for the line?		
Have you learnt that the design of a rectifier involves conflicting interests between the load and the source, and when improving the output performance the input performance is compromised?		
Are you confident now that between the half-wave and the full-wave rectifier the one to use from a practical point of view is the latter and you are fully aware of the reasoning behind such a selection?		

continuous conduction mode. The converter operates at 50% duty cycle. Calculate the converter output voltage. Assume that the converter operates at 3kHz switching frequency.

- What is the time width of the switch control signal when the switch is ON?
- What is the time width of the switch control signal when the switch is OFF?

(Buck/boost DC-DC converter)

- Assume a 16 Volt DC voltage applied at the input of a buck/boost DC-DC converter operating in continuous conduction mode. The converter operates at 40% duty cycle. Calculate the converter output voltage. Assume that the converter operates at 3kHz switching frequency.
- What is the converter output voltage, assuming that the duty cycle changes to 50%? Assume that the switching frequency remains unchanged.
- What is the converter output voltage, assuming that the duty cycle changes to 60%? Assume that the switching frequency remains unchanged.

Assessment

The assessment of the course is based on the laboratory work and the final exam performance. Feedback for performance in the laboratory is given during the laboratory session. There is no formal submission. The laboratory manual serves as a workbook as well. The post-laboratory questions are worked on in the class at the end of the experimental work.

Exam type of questions

The exam questions incorporate the material presented in the class but have a link to the profession, so that students can see the relevance of the topics taught and how the various concepts are used in the industrial examples. An example follows so that the reader can appreciate the approach as a matter of reference. The question below is worth 7% of the final mark and the exam length is a two-hour closed book session.

The electrical power system for the International Space Station consists of power generation, energy storage and power management and distribution. The system

Table 6.

Questions	Yes	No
Have you realised that, for the continuous conduction mode, the only parameter affecting the converter performance with respect to the output voltage is the duty cycle D value for all three basic DC-DC converters?		
Is it clear that there are only two converter blocks (namely, the buck and the boost) and that the third one is the cascaded connection of the two?		
Have you learned that the switching frequency controls the mode of operation of the converter (i.e. continuous and discontinuous) and that any variation does not affect the converter performance with respect to the output voltage?		
Have you realised that all three basic DC-DC converters use the same number of components (i.e. a switch, a diode, an inductor and a capacitor) to function?		
Have you noticed that the polarity of the output voltage in the buck/boost converter is reversed with respect to that of the input voltage?		

provides 78 kW which is obtained from four photovoltaic (PV) Array Modules. Each module consists of two flexible deployable array wings of silicon solar cells supported by an extendible mast. The station orbits the earth every 95 min. spending approximately 2/3 of the time in sunlight 1/3 in eclipse. Power is provided during sunlight by the PV Arrays. During the eclipse the 78 kW of station power is provided by Nickel-Hydrogen batteries which are charged during the sunlit part of the orbit. The power management and distribution subsystem distributes the power at 160 Volts DC around the station through a series of continuous duty, DC contactor switchgear. The switchgear has built-in microprocessors, controlled by software and connected to a data bus running throughout the station. DC-DC converter units step down and condition the voltage from 160 to 120 Volts DC to form a secondary power system to service the loads through solid-state switchgear. The converters also provide isolation of the secondary from the primary system and maintain uniform power quality throughout the station. Assume that these converters operate at 5kHz, that all devices are ideal and that the converters operate in the continuous conduction mode.

i. Calculate the duty cycle of each converter.
ii. What is the width of the ON time of the switch?
iii. What happens to the output voltage if the duty cycle remains unchanged and the switching frequency is doubled?

DISCUSSION

This course has been running for three years now. Formal evaluation has been done in all three years. It is quite challenging to teach electronics and electrical engineering concepts to a large group of students who have had little exposure to such matters. The students have given the highest appraisal to the hardest component of the course; i.e. the laboratory experiments. They find them very useful in understanding the course material and rightly so. It is very encouraging, at a time when, at many institutions and for many reasons, hardware systems have been abandoned and replaced by computer software experiments, that the students appreciate the "hands-on" approach.

The back-to-basics approach used in this course, along with very good organisation, has been given positive feedback. This can be summarised in a simple sentence. No matter how modern one wishes to be, students studying engineering remain strongly committed and interested in building systems and "playing" with them, and this course has been no exception.

The laboratory manual has been designed in a way to incorporate the "closed loop" approach, with minimum intervention by the teaching assistants or the lecturer. Simply explained, the students are asked to study and analyse the circuits in advance with the same voltage/current levels and predict the various circuit parameters which will be measured in the laboratory. They build the circuits and make measurements, which have to be recorded and compared with the expected ones. If there is any discrepancy, they have to investigate the reason. The circuits and measurements are confirmed by other means and therefore any mistake has to do either with their analysis being wrong or their measurements being wrong. The chance of both the predicted and measured outcomes being the same but wrong is also eliminated by double measurement using a different instrument and this redundancy ensures that all students will understand and complete the laboratory feeling that they have achieved the objectives. They have commented that the "closed loop" approach is very powerful in making sure that they themselves do the experiments and understand their work, without relying on others. The manual serves as a report as well; therefore, their time in the lab is used more effectively. Each laboratory has post-laboratory questions, to confirm that understanding has taken place. There are also reflective questions to help students build up their own confidence in the electronics field.

CONCLUSION

A new course based on power electronics technologies has been successfully introduced in the undergraduate curriculum of the Aerospace Engineering undergraduate programme at the University of Glasgow, Scotland, UK. The course not only involves the latest technologies in power electronics but also sources fuel cells and photovoltaics along with batteries. A laboratory component forms an integral part of the course. The complete programme is described in this paper, along with the equipment used for teaching in the laboratory. Information from the laboratory manual that includes pre-laboratory and post-laboratory questions to stimulate critical thinking is given in this paper. Linking the material to applications in the aerospace industry is considered important and examples are provided to illustrate such an approach in the final exam paper context. The course has been running successfully for the last four years and is considered a key initiative to attract more students into the power electronics field. Power electronics is an enabling technology and many new areas of growth, including the aerospace industry, must be addressed at the educational level. It is believed that this course has addressed this need.

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