Int. J. Engng Ed. Vol. 14, No. 4, p. 282–288, 1998
Printed in Great Britain.
0949-149X/91 $3.00+0.00

Power Electronics Instruction in the USA and Canada: Topics, Curricula and Trends*

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A review of the evolution of power electronics instruction at universities in the USA and Canada is presented. Recent surveys in the literature on structure and content of existing programs are summarized. Undergraduate power electronics courses, laboratories, and projects are outlined. The place power electronics occupies within curricula is given with recommendations for improvement. Trends that may affect power electronics instruction are identified.

INTRODUCTION

BY THE YEAR 2000, about 60% of all electric energy consumed in the US and Canada, will be processed through at least one power electronic stage [1, 2]. Such a demand requires engineers who understand the fundamentals of power electronics and has led to the rise of a number of programs teaching this subject.

This paper presents a review of power electronics programs in the United States and Canada. Results of surveys show that over 100 such programs exist, varying in depth from just a single undergraduate course or two to well-funded, established programs that include graduate courses and cutting-edge research. Though there is little agreement on any universal form or focus for a graduate program, some common ground among most undergraduate programs exists. After presenting a summary of the surveys, the scope of this paper narrows to undergraduate curricula and issues. A common set of topics for undergraduate instruction is presented, along with supporting laboratories, projects, and textbooks. The place in the curriculum occupied by power electronics is then described and ideas for improving that place are proposed. Finally, some trends that may influence power electronics instruction are identified.

GENERAL CURRICULUM

Power electronics instruction is ordinarily found within an energy conversion portion of the electrical engineering curriculum. The undergraduate curriculum structure is remarkably consistent from program to program. Graduate instruction, on the other hand, tends to be focused in the research direction of the school at hand.

Survey of courses at US and Canadian universities

Professor Mohan conducted a survey in 1995 to determine the state of power electronics instruction in the US and Canada [3]. He polled all colleges and universities through their department chairs, a mailing list that is easy to get from the ABET or NEEDHA directories. From 119 responses, he assembled courses under six categories: machines, power electronics, drives, utility applications, switchmode power supplies, and power semiconductor devices. For undergraduates, courses appeared in each of the first four categories. As shown in Fig. 1, machines courses with no power electronics are the most numerous with 85 schools offering a machines course, of which 57 require it for an electrical engineering baccalaureate degree. About half offer an introductory power electronics course and nearly all of those make it an optional part of the baccalaureate degree. Machines courses with power electronics content number about a dozen, but those courses that have drives as the primary focus at the undergraduate level can be counted on one hand. Graduate courses cover the range of opportunities, but tend to support the local research effort [3]. There is substantial agreement between Mohan's poll and that of the IEEE Power Engineering Society, though the latter lists the courses in somewhat more detail [4].

Topics for complete courses within a power electronics curriculum

In an informal poll conducted in 1996, Professor Batarseh found graduate programs addressing more than three of the topics listed in Table 1 to be rare. He also found undergraduate drives

* Accepted 15 July 1998.

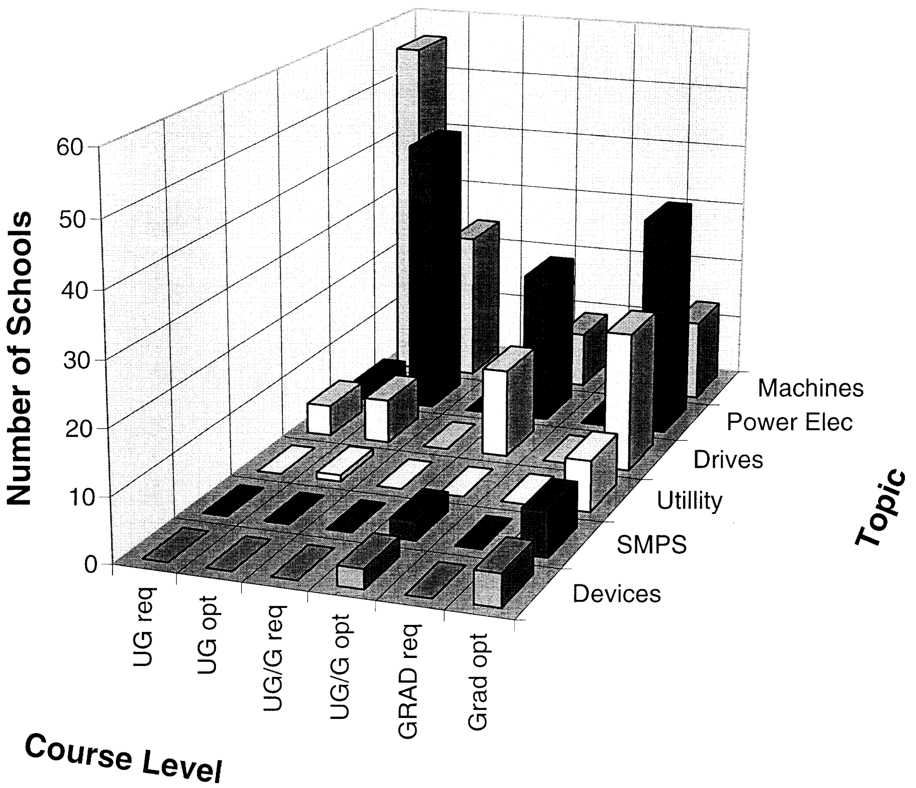

Fig. 1. Course offerings in power electronics in the US and Canada [3].

courses to be uncommon. Poll results are shown in Table 1 [5, 6].

Machines courses consist of theory and analysis of electric machinery. A few teach some machine design. Texts by A. E. Fitzgerald [7], M. S. Sarma [8], G. McPherson [9] and most others outline courses of this nature in their prefaces. An example of an undergraduate machines course with drives incorporated into the syllabus was presented at the ASEE Annual Conference in 1996 [10]. Undergraduate courses focusing primarily on drives are few and exist mostly in schools with a research focus in that area. Examples are found at the universities of Wisconsin, Minnesota, and Akron (Ohio) [4, 5, 11]. For the balance of this paper, the focus narrows to undergraduate power electronics instruction.

Table 1. Power electronics course topics

Undergraduate courses	Graduate Courses
Machines*	Second Power Electronics
Introductory Power Electronics*	Power Semiconductor Devices
	Switchmode Power Supplies
Drives*	Control and Stability of Electric Drives
	EMI Problems and Reduction Techniques
	Utility Applications
	Special and Advanced Topics

* Often has concurrent lab.

Note: No individual US or Canadian university offers complete courses on all of these topics.

INTRODUCTORY POWER CONVERTERS COURSE

There is general agreement as to the content of an introductory undergraduate power converters course, though the general focus of a particular school's research effort and industry support may lead to emphasis on a particular subset of topics and relatively lighter coverage of others [5]. Such a course usually does address the whole range of topics outlined later in this section, but the location of depth and emphasis varies. This is a compromise between introducing a core set of topics universally considered necessary to understanding the subject and the mere impracticality of addressing every topic in depth [5]. The course has become a course in fundamentals in many cases, a first principles approach with instruction and a few examples on how to apply these principles [11, 12]. Those institutions offering such a course usually do so at the senior undergraduate level. Duration is ordinarily one semester or one or two quarters. Some form of graduate credit is typically allowed for graduate students who take this course [4].

Typical undergraduate introductory power electronics course topics

A typical introductory power converters course addresses the topics identified in the outline shown in Table 2 [5]. This outline is similar to one compiled by Akagi in his survey of Japanese instruction in power electronics [13]. Absent from

Table 2. Outline of topics found in a typical introductory power electronics course

I. Introduction
  A. Overview
  B. Applications of Power Electronics

II. Review Material
  A. Modern Switching Semiconductor Devices
  B. Switching Characteristics
  C. The Ideal Switch
  D. Switching Functions
  E. Magnetics
  F. Transformers
  G. Three-phase Systems

III. Diode Circuits and Rectifiers (AC to DC Conversion)
  A. Rectifier Concepts
  B. Single Phase Half and Full Wave Diode Rectifiers with
    1. Resistive Load
    2. Inductive Load
    3. Capacitive Load
  C. Three Phase Full-wave Rectifiers

IV. Phase Controlled Rectifiers (AC to DC Conversion)
  A. Natural and Forced Commutation
  B. Principle of Phase Controlled Converters
  C. Single Phase Full Wave Converters
  D. Three Phase Half Wave Converters

V. DC to DC Switchmode Converters
  A. Concept of Source Conversion: source vs. load
  B. Linear Regulators
  C. Switchmode Converters
    1. Non-isolated Switchmode Converters
      a. (Buck, Boost, Buck-Boost, Cuk)
      b. Continuous and Discontinuous Conduction Modes
    2. Isolated Switchmode Power Converters
      a. Single-ended Isolated Forward Converter
      b. Flyback Converter

VI. Switchmode DC to AC Converters
  A. Principles of Operation
  B. Single Phase Inverters
  C. Three Phase Inverters

this outline are silicon controlled rectifier (SCR) commutation circuits and cycloconverters, topics that once held a prominent place in many courses of this nature. Resonant converters and soft switching are beginning to appear in courses at this level as a means of teaching circuit analysis techniques once done with SCR commutation circuits [14].

Textbooks

A survey of 119 schools in the US and Canada [3] revealed that the three most popular texts for an introductory power converters course are those by Kassakkian [40], Mohan [23], and Rashid [32]. References [15–43] are a bibliography of texts in print for Power Electronics as of approximately October 1996. Closely related to these texts are texts that address variable speed drives [44–56].

A second (graduate) course

As noted earlier in this paper, there exists no general agreement on the content or structure for a second power electronics course, one that has the introductory power converters course as a prerequisite. Such second courses are invariably graduate courses intended to prepare the student for research for the associated graduate program [4, 5].

UNDERGRADUATE LABS

Undergraduate laboratory instruction emphasizes the major application topics found in the introductory power electronics course. The literature documents such laboratory courses at Illinois [57], Wisconsin [58], New York [59], Pennsylvania (Penn State and Bucknell) [60, 61], Toronto [62], Georgia Tech [63], Akron [11], and Missouri-Columbia [64]. There is general agreement throughout the literature on the specific topics so addressed:

- Modern switching semiconductor devices, components, and their characteristics
- Magnetics, including inductors and transformers
- Diode circuits and rectifiers (AC to DC conversion)
- Phase controlled rectifiers (AC to DC conversion)
- DC to DC switchmode converters: non-isolated and isolated
- Switchmode DC to AC converters

Simulation is an important aspect of power electronics laboratory instruction. The perception that software is specialized and expensive need not be true. Mohan [22] and Rashid [32] have PSPICE simulations that complement their texts. Students already understand PSPICE by the time they enter a power electronics course, so the software learning curve is not a problem. Other simulation laboratory work uses MATLAB and MathCAD [65]. A nice set of simulation laboratory exercises for SABER, a more expensive and specialized software package, has been developed by Bass at Georgia Tech [66].

PROJECTS

Power electronics projects require a much wider range of student expertise than initially may be expected. To be successful, students must effectively use concepts from electromechanics, heat generation and transfer, circuit design and layout, analog and digital signal processing and control, filtering, electromagnetics, circuit protection, and microprocessor application. Therefore, the interdisciplinary nature of power electronics presents a wealth of project possibilities.

A number of projects follow from the laboratory topics list given above. Several of these possibilities are listed in [59]. Because students see an immediate use for a good power supply, designing and building the same is a popular project. Fortunately, such a project follows nicely from the laboratory projects listed at the beginning of this section and is well within the capability of individual senior undergraduates. Small linear power supplies are still a simple and popular project among beginning students; most linear regulator data books and applications notes have sufficient information to enable the student to build these [67]. However, switchmode power supplies are more challenging and appropriate projects for students who have completed a power electronics lab. Recent research developments that can be incorporated at a fairly low level include high power factor rectifier concepts, resonant converters, static var compensation, and various forms of modulation and acoustic noise reduction [68]. The senior undergraduate project that most ABET-accredited programs offer provides a convenient niche in the curriculum for such projects.

Electromechanical energy conversion provides fertile ground for projects also. Building a drive system for various motors is probably the most well-known project; loads include induction motors [69], permanent magnet motors and reluctance machines [55], and DC machines (Chapter 13 of [23]). Speed control of open loop drives is probably most straightforward; an undergraduate project is described in detail in [69]. Recent research developments, can now be incorporated into such projects. These include those suggested in [69] and sensorless induction motor control [47, 68], field orientation [68, 69], reduced torque ripple control of permanent magnet machines [55, 68], random modulation of inverters [70], and voltage control of synchronous generators of various sizes [68]. Electromagnetic projectile launching also makes a challenging project [71]. These projects have been completed by senior undergraduate students at various universities and hence are within the reach of students doing group capstone design projects.

Electric vehicles, large or small, are widely advertised projects for power electronics students. Included among these are all-electric (battery-powered) vehicles, hybrid electric vehicles (HEV), and solar-powered vehicles. These are full-size cars intended to be roadworthy and, as such, involve a substantial effort in faculty and student time, co-ordination with other disciplines such as mechanical and chemical engineering and schools of business, as well as large quantities of donated components and money. Competitions, regional and national, of various sorts give these projects a great deal of publicity.

Of the small vehicles, the most well-known project is the Micromouse, an annual event at the Applied Power Electronics Conference as well as other conferences and competitions [72]. Simpler battery powered cars give the student much satisfaction while keeping the resource requirements fairly small.

Photovoltaics adds interest to a project also. Building a light-powered cannon is one of the newer competitions sponsored by the IEEE Power Electronics Society and was held at their annual conference in June 1997 [73]. At the University of Idaho, students have built an entire photoelectric energy conversion system with generator and battery storage, installing it in a wilderness location [74]. These projects integrate, as do the vehicle ones, some interesting topic areas: power supplies, photoelectric energy conversion and control, and electromechanical energy conversion.

TRENDS

Certain trends affect the evolution of the power electronics curriculum, particularly the undergraduate component. As stated in the opening sentence of this paper, by the year 2000, about 60% of electric power consumed will be processed by at least one power electronic stage. That fraction is expected to grow as further power-electronic-based advancements appear in such industries as portable electronics, motor drives, advanced electronic ballasts, resonant converters, electric transit, electric utilities, power quality, custom power, smart power, motion control, automation, process control, and a host of others [1, 2, 10]. The engineer who understands power electronics must be a multidisciplinary person. Therefore, a market for engineers who understand power electronics will continue to exist and probably grow [75].

Trends in course technical content

Advances in semiconductor devices and progress in the control techniques made available by more powerful computation hardware have led to many recent developments in power electronics. Devices and control techniques appear to be the limiting factors for the foreseeable future [76]. Nonetheless, development of a systems approach to design and fabrication (for example, 'smart power' and 'power electronic building blocks') may also become significant [75, 77].

These developments are expected to make the case for a more fundamental power electronics course for undergraduates, a 'first principles' course that emphasizes the basic concepts of the topics listed earlier in this paper [12]. Until recently, such courses often lacked uniformity of content from one place to another. However, there has been a loose convergence to a power electronics course that applies fundamental principles of circuit transients and switching devices to a fairly small number of basic converter topologies [3]. The most popular texts of the last few years have followed that trend [23, 32].

Structural trends in the curriculum

The next set of curriculum changes on the horizon may be more structural in nature. Typically, power electronics appears within the energy conversion portion of an electrical engineering curriculum, but nowhere else. Its location encourages many students to ignore it. This is unfortunate due to its interdisciplinary nature. If a power electronics course focuses strongly in a particular direction, then it may be possible to get it included as an option within another discipline, for example, including power electronics as an elective within the electronics curriculum as well [78]. Some of the electronics students who might otherwise not even consider the course may investigate it. Indeed, the introductory power electronics course at MIT draws a majority of its students from circuit designers who want the breadth [79]. Another approach is to structure the course to appeal to students studying automatic control theory [80]. If device behavior is a strong focus in a particular introductory power electronics course, then it may be possible to include the course as an option for the electronic devices curriculum [78]. The case for each of the above curricula initiatives may be difficult to establish, but is not impossible. Keeping the introductory power electronics course under a 'power' umbrella may be neither wise nor, as in the new five-year curriculum at MIT, even possible [79].

Trends in laboratories—simulation

The new laboratories found in the literature tend to emphasize the topics given in Table 3; further specialization usually supports the local research effort [57–66]. Simulation for the power electronics lab is evolving, particularly Mohan's and Rashid's use of PSPICE [23, 24, 32, 33]. Students are usually already familiar with PSPICE, so learning can focus on power electronics, not programming details. The combination of cost, existing student expertise, libraries of circuit models, and textbook support, favors using PSPICE for undergraduate power electronics. The approach of Mohan and Rashid is a nice compromise between the inadequacy of simply modeling switches as ideal, a practice conveniently compatible with the use of general math packages such as MATLAB, Mathematica, and MathCAD, and the more expensive and specialized alternatives such as SABER. On the other hand, for graduate work requiring detailed device models, SABER may be a more appropriate place to start [66, 81].

CONCLUSIONS

A number of schools offer instruction in power electronics. Their faculty members have proposed, both in discussions and in the literature, the topics they offer. They also have built labs, hardware and software, and projects to augment classroom instruction. This paper reviews this wealth of experience and is appropriate both for those seeking to establish this portion of a curriculum, as well as those who seek to know the state of the instructional art.

The most common curriculum consists of a general energy conversion course followed by a set of one or more electives in energy conversion topics. These electives usually include an undergraduate power converters course and, if an attendant graduate program exists, courses such as drives or power utility topics that support that graduate program. There is loose agreement as to the content of such an undergraduate power converters course, though the general focus of a particular school's research effort and industry support may generate emphasis on a particular subset of topics. Several supporting laboratory programs that appear in the literature have been identified and discussed. Appropriate project ideas, proven in other schools, were also noted. Finally, the trend appears to be to move toward a fairly common undergraduate program, with or without labs and simulation, and some structural innovations and projects that build on the interdisciplinary nature of power electronics.

Acknowledgments—Professor Issa Batarseh arranged the National Science Foundation Workshop on Developing Power Electronics Curriculum: Courses, Hardware, and Software Laboratories at which many of the ideas in this paper were discussed. The author also thanks Professor Batarseh for his assistance in preparing this paper.

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