Power Electronics Instruction: Topics, Curricula, and Trends

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Abstract

A review of the evolution of power electronics instruction in the US and Canada. Summary of surveys in the literature on structure and content of existing programs. The place power electronics occupies within curriculum with recommendations for improvement of that position. Outline of undergraduate power electronics courses, laboratories, and projects. Identification of trends that may affect power electronics instruction.

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] Such a demand requires engineers who understand the fundamentals of power electronics and has led to the rise of a number of programs to teach this subject.

In this paper, a look is taken at the evolution of power electronics programs and their existing place within the general curriculum. Results of surveys show that over 100 such programs exist, varying in depth from just a course or two to well-funded sequences including graduate courses and cutting-edge research. After presenting a summary of these surveys, the scope narrows to undergraduate curricula. While there is some common ground among most undergraduate programs, there is little agreement on any universal form or focus for a graduate program. For both established and new programs, a topic set for undergraduate instruction appears to be fairly common and will be shown in this paper, along with the content of supporting laboratories, examples of projects, and a list of 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 noted and explored.

General Curriculum

Power electronics instruction is ordinarily found within an energy conversion portion of the electrical engineering curriculum. Undergraduate course content is remarkably consistent from program to program, as will be shown in this section. Graduate instruction, on the other hand, tends to be focused in the research direction of the school at hand, as one might expect.

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 Figure 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 as many offer an introductory power electronics course, nearly all of which make it an optional part of the baccalaureate degree. Machines courses with power electronic content are about a dozen in number, of which 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, supporting primarily the research effort of the particular school at hand. [3]

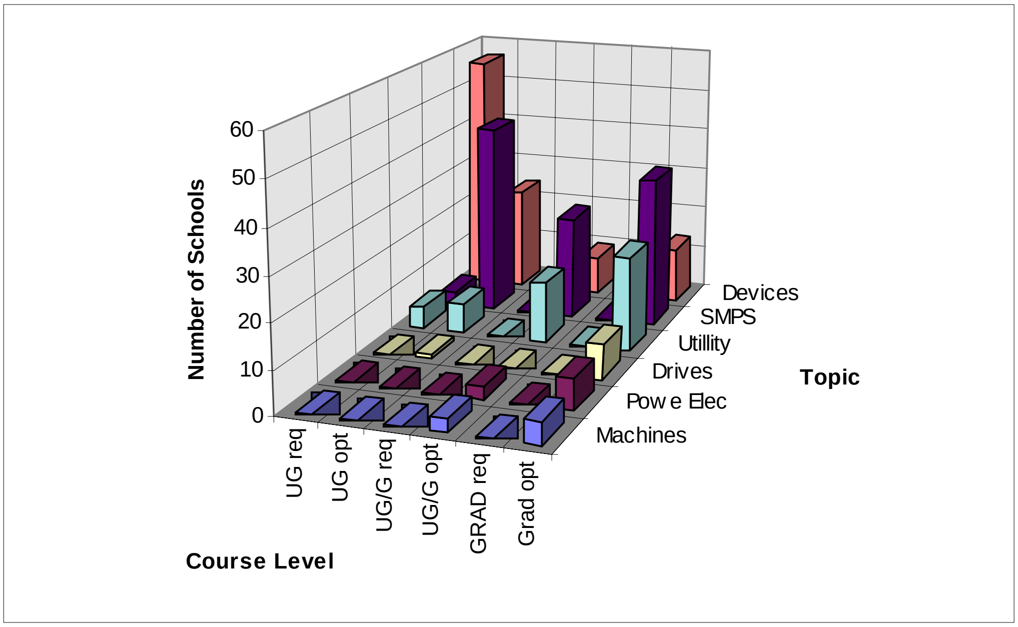

Figure 1
Course Offerings in Power Electronics In the US and Canada[3]

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] In an informal poll conducted in 1996, Professor Batarseh found graduate programs addressing more than three of the below listed topics in depth to be rare. He also found drives courses at the undergraduate level to be uncommon. His results are summarized the available courses in established programs as follows:[5]

Undergraduate courses
- Machines with lab
- Introductory Power Electronics with lab
- Drives with lab

Graduate Courses
- Second Power Electronics with lab
- Power Semiconductor Devices
- Switchmode Power Supplies
- Control and Stability of Electric Drives
- EMI Problems and Reduction Techniques
- Utility Applications
- Special and Advanced Topics

The machines courses consist of theory and analysis of electric machinery; a few teach some machine design. Texts such as A.E. Fitzgerald [6], M.S. Sarma[7], G. McPherson[8] and others outline courses of this nature in their prefaces. An example of a machines course with drives incorporated into the syllabus was presented at the ASEE Annual Conference in 1996.[9] Undergraduate courses focusing primarily on drives, as mentioned already, are still rare, 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] The balance of this paper will narrow the focus to power electronics instruction at the undergraduate level.

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 courses, however, usually do address the whole range of topics outlined later in this section, the location of depth and emphasis being the primary difference among such courses. 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, in some cases, become a course in fundamentals, 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 two quarters. Some form of graduate credit is typically allowed for graduate students who take this course.[4]

There exists no general agreement on the content nor 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 appropriate for the graduate program at hand.[4,5]

A typical introductory power converters course addresses the topics identified in the following outline.[5] This outline is similar to one compiled by Akagi in his survey of Japanese instruction in power electronics.[10].

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. Nonisolated 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

Absent from this outline are Silicon Controlled Rectifier (SCR) commutation circuits and cycloconverters, topics that once held a prominent place in most courses of this nature. Resonant converters and soft switching are beginning appear in courses at this level as an up-to-date means of teaching the circuit analysis techniques that the SCR commutation circuits once were.[13,14]

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 [38], Mohan[23], and Rashid[28]. References [15-42,80] are a bibliography of texts in print for Power Electronics as of approximately October 1996. Closely related to these texts are those texts that address Variable Speed Drives.[43-55] ISBN numbers are given with texts to aid in requesting copies through publishers.

Labs and Projects

Undergraduate laboratory instruction emphasizes the major application topics found in the introductory power electronics course. The literature documents such laboratory courses at Illinois[56], Wisconsin[57], New York[58], Pennsylvania (Penn State and Bucknell)[59,60], Toronto[61], Georgia Tech[62], Akron[11], and Missouri-Columbia[63]. There is general agreement throughout the literature on the specific topics so addressed, which are the following:

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: nonisolated 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[23] and Rashid[28] 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 rarely a problem. Other simulation laboratory work uses MATLAB and MathCAD.[65] Bass at Georgia Tech has developed a nice set of simulation laboratory exercises for SABER, a more expensive and specialized software package.[64]

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 [58]. 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.[66] 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.[67] The senior undergraduate project common to most ABET-accredited programs provides a convenient niche in the curriculum.

Electromechanical energy conversion provides fertile ground for projects also. Building a drive system for an electric motor is probably the most well known project. Loads include induction motors [68], permanent magnet motors and reluctance machines[54], and dc machines (Chapter 13 of [23]). Speed control of open loop drives is fairly straightforward; such an undergraduate project is described in detail in [68]. Recent research developments can now be incorporated into such projects. These include those suggested in [68] and sensorless induction motor control [47,67], field orientation[67,68], reduced torque ripple control of permanent magnet machines[54,67], random modulation of inverters[69], and voltage control of synchronous generators of various sizes[67]. Electromagnetic projectile launching also makes a challenging project.[70] Senior undergraduate students have completed these projects at various universities, demonstrating that such projects are within the reach of students at that level.

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, coordination with other disciplines such as mechanical and chemical engineering and schools of business, as well as large quantities of donated components and money. Regional and national competitions of various sorts give these projects a great deal of publicity.

Of the smaller vehicles, the most well-known are the micromouse projects, an annual event at the Applied Power Electronics Conference and elsewhere.[71] Even simple battery powered cars give the student much satisfaction despite fairly small resource requirements.

Photovoltaics adds interest to a project. Building a light-powered cannon, one of the newer competitions, is sponsored by the IEEE Power Electronics Society for their annual conference in June 1997.[72] 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.[73] These projects integrate, as do the vehicle projects, some interesting project areas: power supplies, photoelectric energy conversion and control, and electromechanical energy conversion.

Attracting Students

The final 1996 issue of IEEE Potentials advises students to select a discipline by three general criteria: whether employment exists there, whether they personally enjoy what engineers do there, and whether they personally understand its concepts readily—in other words, whether they perceive themselves as “good at it.” [74] The number of options they do consider is, of course, limited to their own experience and the experience of their close peer group. In that environment, perception can become distorted. If a student can be induced to consider power electronics, he or she often finds its wide range of opportunities and challenges much to their liking and suited to their talents. Power electronics possesses the capacity to attract undergraduate students in significant numbers, provided they are shown an accurate perception of what the discipline offers.

Electric power engineering education may have a public relations problem with students in general because it is perceived as a mature discipline, somehow lacking glamour or challenge. Because this mistaken perception is based on a shortage of facts, there are a number of means to dispel it. Publicity from projects and contests is an excellent way to gain attention. Students see other students doing exciting projects and competing with other groups and schools. They naturally inquire, gaining favorable information about power electronics. Giving students the opportunity means to talk one-on-one with the student designers and contestants is key to success here. For example, the micromouse contest attracts students who consider themselves to be digital designers, showing them that there is a place for their skills on a power electronics project and, by extrapolation, in related industry.[71]

Few underclassmen take the time to attend local senior design presentations. However, when the time comes to select a senior design project, students first consider projects of two categories: those similar to projects that they have already seen and those projects already defined by an instructor. A simple attendance incentive solves this problem and helps expand the student's database in the former category.[9]

Employment prospects and personal feedback from recent graduates attract students. Students need to see recent graduates who found employment in this industry returning for seminars and discussions. With the availability of videotape and videoconferencing, seminars or even brief comments are easier to bring to the students than in the past. Email gives students the means to verify quickly and privately what was said on tape. For example, at the University of Idaho, a survey of former graduates showed that nearly 80% of the last three graduating classes specified an electronic motor drive system for their employer within six months of graduating.[68] Recent graduates presented this fact in machines class and in sophomore seminar. After class, several students personally verified this perception with the speakers.

An active internship program is also helpful. Internship and coop programs are a common means of getting that first job. Many students actively seek such positions. Having employers in the power electronics industry available with internships increases interest among students, though interest is difficult to build overnight. It takes a combination of availability of industry positions (from local employers if possible), encouragement from faculty, and reinforcement from students who have had a favorable experience with these employers.[9,11,12]

Working carefully within the curriculum structure is also a productive means of creating interest in power electronics courses and topics. Typically, power electronics appears within the energy conversion portion of the electrical engineering curriculum, but nowhere else. Its location encourages many students to ignore it. This is both unfortunate and unnecessary 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.[75] Some of the electronics students who otherwise might not even consider the course may investigate it. For example, at MIT, the introductory power electronics course draws a majority of its students from circuit designers who want the breadth mandated by the curriculum.[79] Another approach is to structure the course to appeal to controls students.[77] 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.[14] The case for each of the above curriculum initiatives may be difficult to establish, but is not impossible. Indeed, to do so may be imperative.

Trends

The paper closes with a discussion of trends affecting the evolution of the power electronics curriculum, with emphasis on the undergraduate component. As mentioned and referenced 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.[1,2,9] The engineer who understands power electronics must have a broad knowledge base. Therefore, a market for engineers who understand power electronics will continue to exist and probably grow.[76]

Recent developments in power electronics have been governed by advances in semiconductor devices and in control techniques made applicable by advances in computation hardware. These are the limiting factors at present and appear to remain so for the foreseeable future. Nonetheless, a further development of a systems approach to design and fabrication (for example, "smart power") will also become quite significant.[76, 80]

These developments are expected to make the case for a more fundamental power electronics course for undergraduates, a "first principles" course that emphasized the basic concepts of the topics listed earlier in this paper.[12] From the 1960s, when the first power electronics courses appeared until recently, such courses 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 two years have followed that trend.

The next set of curriculum changes on the horizon may be more structural in nature. The interdisciplinary nature of power electronics indicates a capacity to appeal to a wide range of students. Keeping the power electronics course under a "power" umbrella may be neither wise nor, as in the new five-year curriculum at MIT, even possible.[77]

The new laboratories found in the literature tend to emphasize the topics given in the laboratory portion of this paper. Simulation for the power electronics lab is developing, particularly Mohan's and Rashid's use of PSPICE.[23,28,29] Students are usually already familiar with PSPICE, so learning can focus on learning power electronics and not on procedural details of the software.[81] The combination of cost, existing student expertise, libraries of circuit models, and textbook support, favors using PSPICE for undergraduate power electronics. The approach of Mahan and Rashid is a nice compromise between the inadequacy of 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. For graduate work requiring detailed device models, SABER may be a more appropriate place to start.[64,78]

Another trend that, at first glance, may seem to affect only graduate programs is the concentration of much of the available research funding in a few schools. A consortium model reinforces this situation: industry sponsors pay a regular fee and gain the benefits of a range of research results, usually in research programs already possessing substantial funding. The impact upon undergraduate programs is subtle: they tend to seek a common curriculum for their students to remain competitive for acceptance into the graduate programs.[11]

Conclusions

A number of schools offer instruction in power electronics. They have developed labs, hardware and software, and projects to augment classroom instruction. This paper lists the topics offered and reviews a wealth of experience gleaned from the literature and aids those seeking to establish this portion of a curriculum, as well as those seeking the state of the instructional art.

The most common curriculum consists of an undergraduate energy conversion course followed by a set of one or more energy conversion electives, one of which is an undergraduate power electronics course. If an attendant graduate power electronics program exists, courses such as electric machine drives or power electronics for utility applications that support that graduate program. There is loose agreement as to the content of an undergraduate power electronics course, though the nature of a particular school's research effort and industry support may encourage 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. Certain innovative ideas about attracting student interest in the courses have been presented. These ideas range from innovative projects and contests to structural options within the curriculum. 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.

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