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NSF-Sponsored Faculty Workshops on Teaching of Power Electronics and Electric Drives

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ABSTRACT

This paper describes the restructuring of power electronics and electric drives courses, sponsored by NSF, EPRI, NASA and the local utilities, which has significantly increased student enthusiasm, and the undergraduate enrollment in these courses at the University of Minnesota has tripled since 1997 The developed teaching approaches have been the subject of NSF-sponsored faculty workshops in 1994, 1997, 1998, 2002, and 2003

In power electronics, the power-pole based building-block approach unifies analysis and control aspects of all converters. PSpice-based simulations aid in analysis and design, supported by a hardware laboratory. For electric drives, an integrative approach addressing all three aspects of electric drives – machines, power converters and control is being used Space vectors, introduced on a physical basis rather than purely mathematical abstractions, are used for analysis of ac machines This leads to a more physical understanding of machine operation and also makes it easier to address control aspects in the advanced course. The lecture materials are supported by a DSP-based laboratory.

Keywords: Teaching, Education, Instructional laboratory

1. Introduction

Declining student enrollments in spite of increased opportunities in the fields of power electronics and electric drives have made it imperative to restructure courses in these fields This restructuring effort at the University of Minnesota has been sponsored by NSF, EPRI, NASA, and the local utilities The developed teaching approaches have been the subject of NSF sponsored faculty workshops held in 1994, 1997, 1998, and 2002 Another workshop will be held in January 2003[1].

This restructuring has resulted in significant increase in student enrollments in recent years (Fig. 1).

This paper presents the highlights of the restructured courses Fundamental principles have been identified that unify analysis and controls aspects of these courses The power-pole building-block for power electronics converters is a prime instance of this PSpice-based simulations as an aid in analysis and design of power electronics circuits have been adopted. A hardware power electronics laboratory based on the building-block approach has also been developed. For electric drives an integrative approach addressing all three aspects of electric drives – machines, power converters and control is being used. Space vectors, introduced on a physical basis rather than as purely mathematical abstractions, are used for analysis of ac machines.

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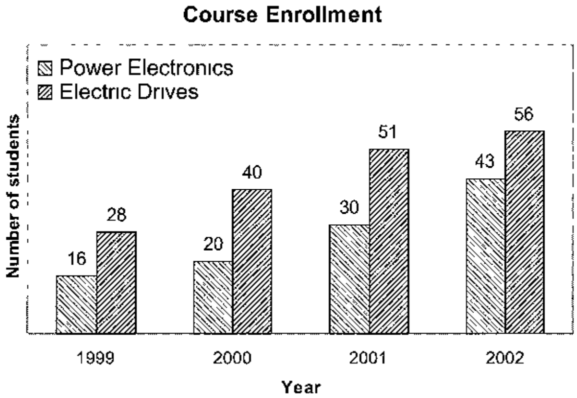


Fig 1 Increasing student enrollment trends at the University of Minnesota

This proves effective in giving a more physical understanding of machine operation and also makes it easier to address control aspects in the advanced course. The hardware laboratory developed for the electric drives course is described briefly

2. Problems and Response

2.1 Looming Crisis and the Promise of Power Electronics and Electric Drives

There is looming crisis in the undergraduate education of power electronics and electric drives, which if not addressed, will result in very few engineers to take advantage of the new opportunities described below As an instance, in a survey of 120 Electrical Engineering programs in the United States and Canada[2] only about half of the universities have machines courses as a requirement and even there, they are in danger of being made optional due to pressure from other courses. Also, declining student enrollment in these courses is a result of the fact that courses in these fields have not been changed over the years and therefore fail to convey the excitement which is otherwise possible For example, in a traditional machines course only line-fed operation of induction motors is discussed, when in reality most of these machines are used for speed or position control applications with sophisticated control algorithms implemented using power electronic converters and embedded controllers

Power electronics as an enabling technology has an estimated worldwide market of approximately $50 billion per year The applications range from switch-mode dc power supplies in all electronic equipment to controlling power flow on the utility grid. Electric vehicles, grid connection of distributed generation sources such as wind, solar or fuel cells, and FACTS devices are some of the promising applications requiring power electronics engineers Variable speed electric drives have the potential for resulting in enormous energy savings in flow control applications, enhanced factory automation, and energy conservation in hybrid electric vehicles

2.2 Restructuring of Courses in Power Electronics and Electric Drives

To address this problem, the University of Minnesota, received funding from NSF in 1997 to develop lecture materials and laboratories for course restructuring that will serve as a model for adoption in universities nationwide This restructuring has several objectives The undergraduate course should prepare students for industry as well as for advanced courses and for research and development careers They should be appealing and exciting so that students are drawn to them These courses should provide the requisite information about power electronics and electric drives in a way that provides motivation and allows time to take related courses in areas such as digital signal processing applications, programmable logic, and digital control. An important aspect of this effort is the dissemination of the developed approaches

The courses have been designed using a top-down approach where topology and control are described in the context of applications Each course is divided into modules, which are sequenced to maintain interest and to allow practicing engineers the flexibility to choose the requisite ones In analysis, utilizing the common underlying principles for topology and control not only saves valuable course time but also provides a deep understanding that is otherwise not possible To reinforce theory, simulation software and hardware laboratories are tightly integrated. Fig. 2 shows the course offerings at the University of Minnesota, including a recently organized course on Energy, Environment and Society The first courses are meant for undergraduates, but can also be taken for credit by graduate students The converse is true for the advanced courses.

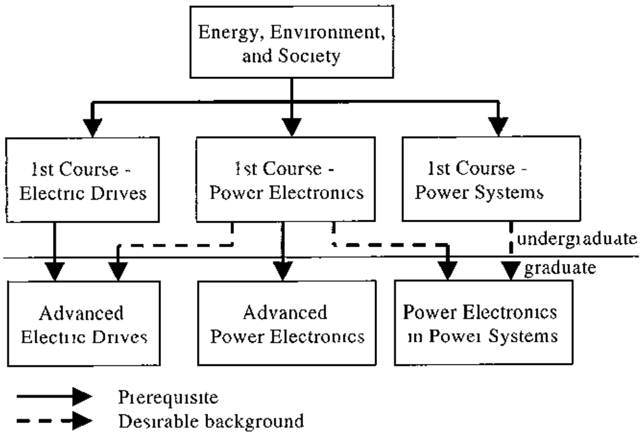


Fig 2 Course offering at the University of Minnesota

3. First Power Electronics Course

The first course in power electronics is divided into the modules shown in Table 1

Table 1 Modules in the first power electronics course

Module	No of Lectures
Introduction	4
DC-DC Converters	8
Control in DC-DC Converters	5
Power Quality; Power Factor Correction	3
Magnetic Design	3
Switched Mode Power Supplies (Isolated)	3
DC Drives, AC Drives, UPS	5
Soft-Switching	3
High frequency AC applications	1
Thyristor converters	4
Utility Applications	1

3.1 The Building-Block approach

An innovative concept in the teaching of power electronics has been to use a building-block approach [3][4], which brings cohesion to various converter topologies.

Fig. 3(a) shows this building block as a power-pole consisting of a bi-positional switch in a two-port a voltage port (*vp*) across the capacitor and a current port (*cp*) on the other side due to the series inductor. This power-pole is a part of buck, boost, buck-boost, and converters from motor drives (see Fig 4(a)) The transformer-isolated topologies are derived from the buck and buck-boost converters Thus, all practical converter topologies can be explained using the power-pole.

A power-pole in Continuous Conduction Mode (CCM) can be represented using an ideal transformer with a controllable turns-ratio as shown in Fig 3(b) This results in the average representations of converters as shown in Fig. 4(b). For Discontinuous Conduction Mode (DCM), encountered in single-quadrant converters, the model in Fig. 3(b) can be easily augmented with dependent sources so that the composite model is valid for both DCM and CCM[5]. This average modeling has three distinct benefits

- Easy explanation and analysis of converter operation
- Linearization for feedback controller design
- Fast simulation of dynamic response under large disturbances

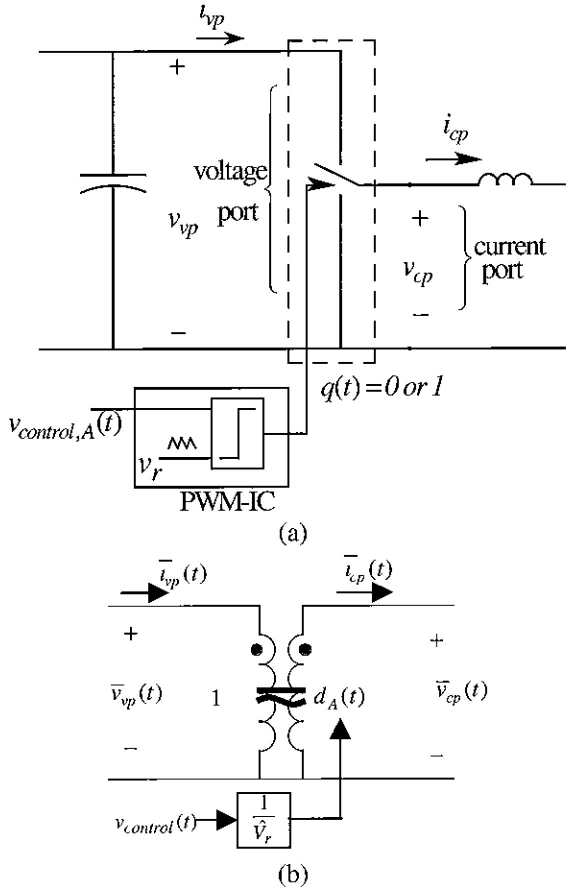
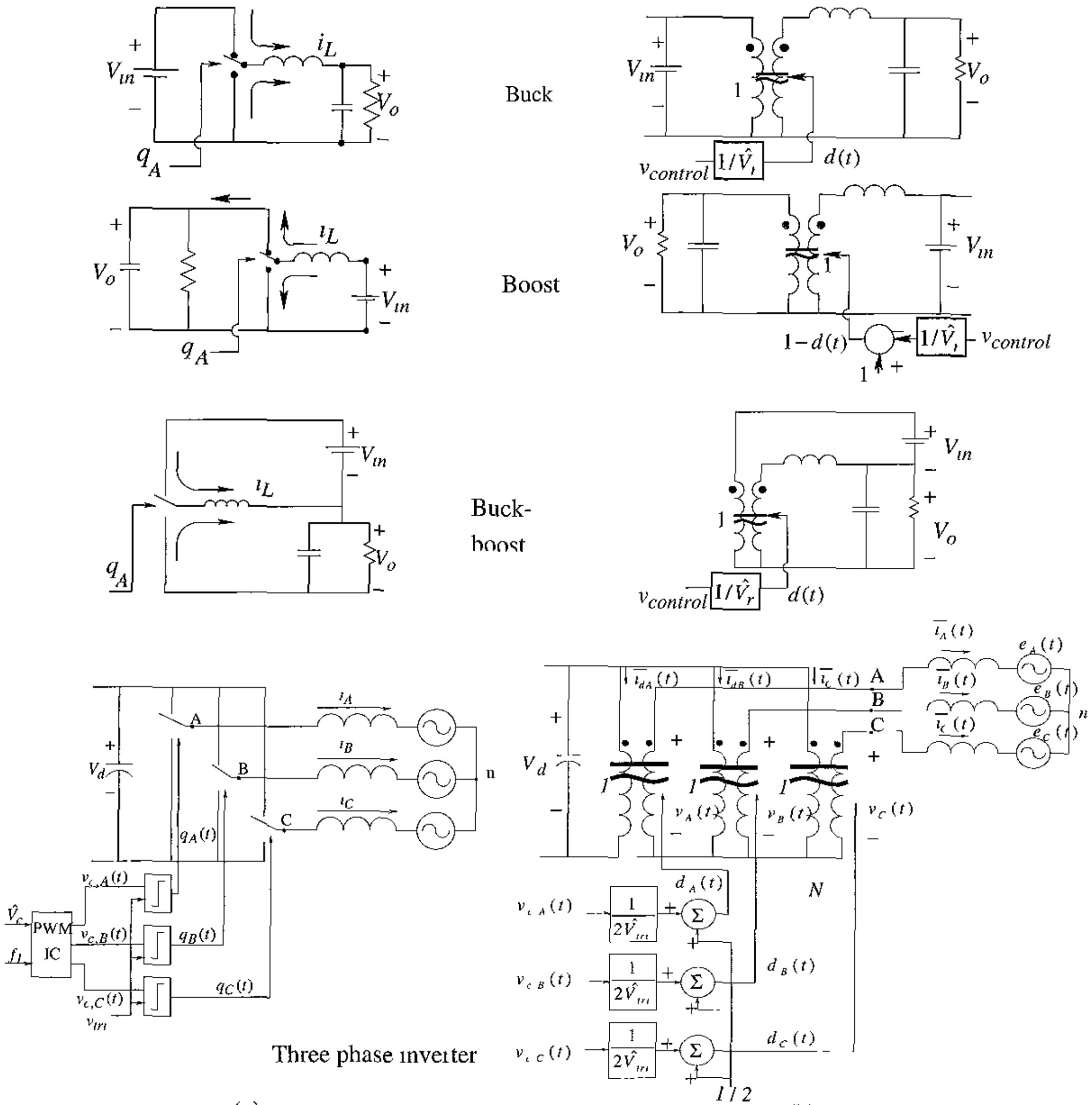


Fig 3 (a) Power-pole as a building-block synthesis by PWM, (b) average representation



(a) (b)

Fig 4 Basic power electronic converters and their average representations

3.2 PSpice Based Simulations

Simulations based in PSpice for analyzing converter operation is emphasized throughout the course Using the average model described above, PSpice can be used for linearization about different operating points to obtain bode plots for feedback controller design. Fig 5 shows the example of a boost converter. The average model shown in Fig 5(a) is valid for both discontinuous and continuous conduction modes

3.3 Building-Block-Based Instructional Laboratory

A hardware laboratory tightly coupled to the lecture modules is developed. The experiment list for this laboratory is shown in Table 2 A power-pole board based on the building block principle has been developed which can be configured to operate as different converters - buck, buck-boost, boost, flyback and forward[6]. For safety purposes voltages have been kept below 42V and power levels are restricted to below 100W

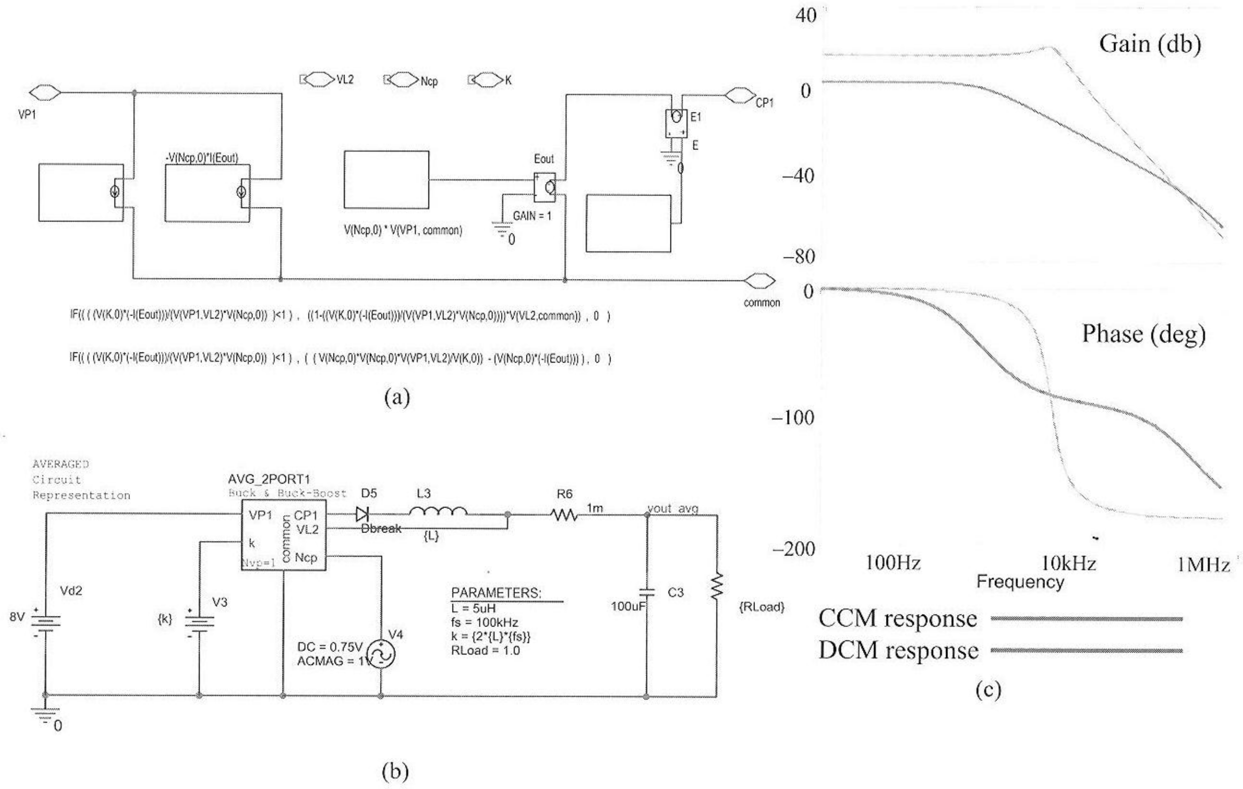


Fig. 5. Use of average model for obtaining bode plots in Pspice: (a) average model incorporating both CCM and DCM operation; (b) average representation of a Boost converter; (c) Bode plots of duty ratio to output voltage.

Table 2. List of Experiments for the Power Electronics Laboratory.

1	Familiarity with Pspice
2	Switching Characteristics of Power MOSFETs and Diodes
3	Buck Converter in Continuous and Discontinuous Conduction Modes (CCM & DCM)
4	Boost and Buck-Boost Converters
5	Voltage-Mode Control of a Buck Converter
6	Peak Current Mode Control of a Buck-Boost Converter
7	Diode Rectifiers, Power Factor Correction Circuit
8	Inductors, High Frequency Transformers
9	Flyback Converter
10	Forward Converter
11	Converters for DC Drives
12	Converters for AC Drives
13	Full-Bridge, Transformer-isolated PWM DC-DC Converter (hard switched)
14	Full-Bridge, Phase-Shift-Modulated DC-DC Converter (soft switched)

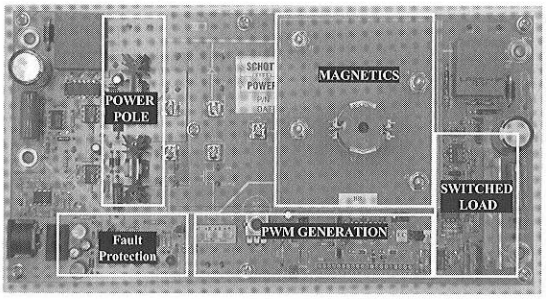


Fig. 6. Photograph of the power pole board being used for the power electronics laboratory.

Fig. 6 shows the photograph of the power-pole board. Experiments for DC motor drives and AC inverters are performed using the platforms for the electric drives laboratory described in Section 4.

4. First Electric Drives Course

In contrast to the traditional first courses, which deal with line-fed uncontrolled machines, an integrated approach is adopted to address all three subsystems of an electric drive – power electronic converters, electric machines, and feedback controllers – in a single semester (Fig. 7). An outline of the course along with the hardware lab is detailed in Table 3.

Electrical machines, without assuming any prior knowledge of them, are described using fundamental principles of electromagnetic force production, $f_{em} = Bli$ on a current carrying conductor and induced emf $e = Blu$ in a conductor cutting flux lines This approach shows the common principle on which all electric machines operate

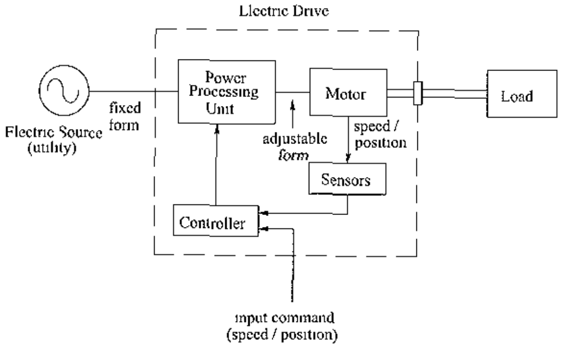


Fig. 7. Three main subsystems in the first course on electric drives

and how they ought to be controlled for optimum performance

Power electronic converters are described concisely in terms of their functionality by means of controllable turns-ratio ideal transformers as mentioned earlier. Feedback control system design is introduced in this first course by selecting a dc-motor drive, as an example, where torque, speed and position are controlled in a typical cascade connection Each control loop is designed using the bandwidth and phase margin considerations similar to that discussed in switched mode dc power converters This discussion of controller design provides a seamless continuity to designing vector-controllers or direct-torque controller (DTC) in ac motor drives in the advanced course

4.1 Use of Space Vectors

Space vectors for the analysis of ac machines provide a physical understanding and lead smoothly to speed andposition control Space vectors are introduced on a very physical basis as shown in Fig 8, where sinusoidal flux-density distribution created by three sinusoidally-distributed phase windings at a time t as shown in

Table 3 Topics in Electric Drives Course and Associated Lab Sessions

No	Topic	Lects (41)	Laboratory Sessions	Labs (14)
1	Introduction to Electric Drive Systems	1	Lab Safety, Familiarity with Simulink	1
2	Understanding Mech System Requirements	3	Mechanical System Modeling, Intro to dSPACE	2
3	Review of Electric Circuits	1	-	0
4	Basic Understanding of Power Electronics	3	Switch-Mode Converters for Drives	2
5	Magnetic Circuits	4	Line-Frequency Transformer	1
6	Basic principles of Electro-Mechanical Energy Conversion	3	-	0
7	DC Motor Drives	5	DC Motors, DC-Motor Drives	2
8	Feedback Controller Design in Drives	3	Feedback Control of DC Drives	1
9	Intro to AC Machines & Space Vectors	5	Space Vectors in Simulink & DSPACE	1
10	Sinusoidal PMAC Drives & Synchrounous Machines	4	PMAC Drives	1
11	Induction Machines: Steady State Analysis	5	Induction Machines	1
12	Adjustable Speed Induction Motor Drives	3	Adjustable Speed Induction Motor Drives	1
13	Reluctance Drives	1	Stepper-Motor Drives	1

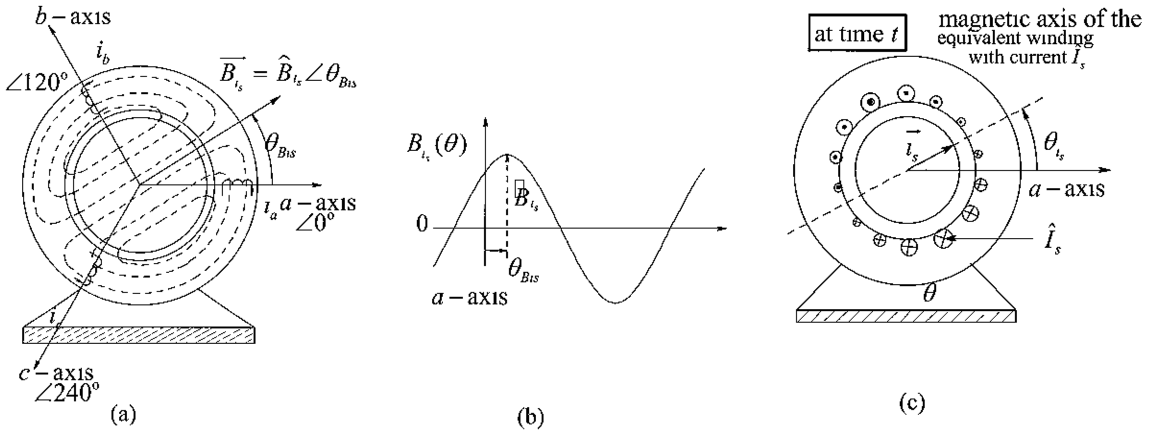


Fig 8 Space vector representation of sinusoidal flux density distribution

Fig 8(a) (plotted as a function of θ in Fig. 8 (b)) is represented by a space vector $\vec{B}_{i_s}$ The orientation of $\vec{B}_{i_s}$ is along the axis where the flux-density distribution peaks and the length of this vector represents the magnitude of the flux-density distribution. Terminal quantities like current can be represented by space vectors defined mathematically as,

$$\vec{i}_s = i_a\angle 0^\circ + i_b\angle 120^\circ + i_c\angle 240^\circ = \hat{I}_s\angle\theta_{i_s} \qquad (1)$$

This can be interpreted physically as follows. current $\hat{I}_s$ flowing through a hypothetical sinusoidally-distributed winding with its axis oriented at an angle of θ_{i_s} produces the same flux-density distribution as that produced by the three phase windings together with their respective currents The space vector approach allows easy physical-principles based explanation of torque production as shown in the equivalent winding diagram of Fig 9 for a permanent magnet ac motor

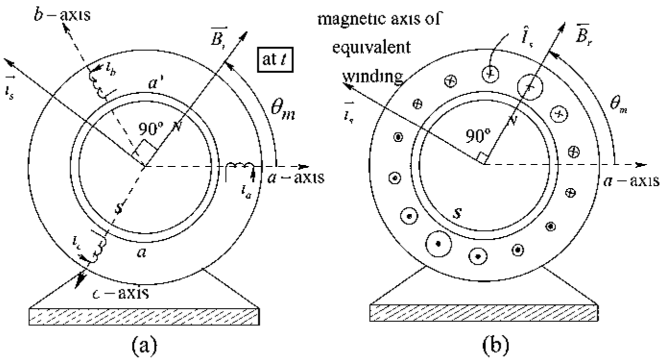


Fig 9 Stator current space vector and rotor field space vector in a PMAC drive

Such a discussion[8][9] clearly shows that dc as well as ac machines have a voltage constant equal to their torque constant.

4.2 Electric Drives Laboratory with first course

A hardware laboratory for the electric drives course has been developed using a rapid prototyping system, a specially designed set of machines rated for 42V, and a power electronics board

Fig 10 shows a block diagram of the laboratory setup The load is actively controllable in all four quadrants, opening up possibilities for experiments that cannot be done in traditional machine labs Small motors shown in Fig 11 are specially designed and built for this laboratory.

For experiments, from very simple to very sophisticated, the controller is designed in Simulink and then downloaded into a DSP, which provides switching signals to the power electronics drive board The advantages of such a high-level rapid prototyping tool from dSPACE[10] are several:

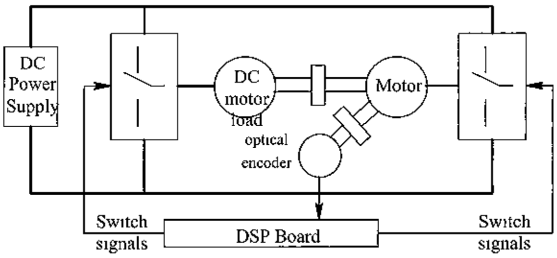


Fig 10 Block diagram of the DSP controlled electric drives laboratory

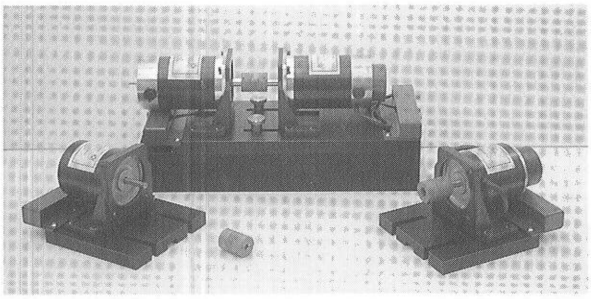


Fig. 11. Specially designed 42V machines for the electric drives laboratory.

- No knowledge of coding in C or assembly language is needed
- The same blocks used for simulation in Simulink are used in the hardware implementation, and
- There is an easy-to-use graphical interface that allows students real-time monitoring of variables and continuous adjustment of inputs and parameters.

Table 3 shows the list of experiments corresponding to the lectures. This hardware setup is also intended for demonstration of some converter operations in the power electronics lab. In the advanced course in electric drives where simulations are essential, having introduced Simulink in the first course (which has a very short learning curve) is very helpful. The proposed laboratory will be invaluable to show the correspondence between simulation results and their verification experimentally in topics such as field-oriented control and direct torque control of induction motor drives[11].

5. Summary

This paper presents a brief description of the revitalization methods being used for Power Electronics and Electric Drives courses. The new teaching approaches emphasize underlying unifying principles for both power electronics and electric drives. A building-block based approach that unifies analysis of various power converter topologies has been presented. PSpice-based simulations are shown to have advantages both for understanding of operation and for control loop design of power converters. A hardware power electronics laboratory, also based on the building-block approach, is developed to complement the lectures. The power-pole board has already been adopted by several universities for use in their curriculum.

In the electric drives course, an integrated approach allows the first course to cover all the three aspects of drives – machines, power converters and control. Experience at the University of Minnesota has shown that the use of space vectors in the first course has proved effective in giving a more physical understanding of machine operation and also made it easier to address control aspects. A hardware laboratory for the electric drives course is also being developed using a rapid prototyping system, and a specially designed set of electric machines. Already 68 universities have shown interest in adopting the hardware laboratories. These laboratories will be further demonstrated in the next NSF-sponsored workshop to be held in January 2003[1].

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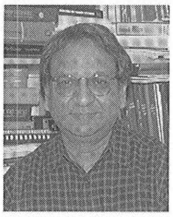

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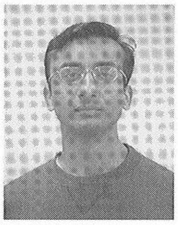
Ned Mohan is a Fellow of the IEEE and a proud recipient of the Distinguished Teaching Award presented by the Institute of Technology, University of Minnesota.



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