Abstract--The traditional courses in electric machines and even in power electronics are attracting reduced number of students in USA and maybe soon in Europe. The paper will analyze why and suggest some remedies for revitalizing these courses. It is important to start with a course that is attractive. That is, it should in addition to power electronics or drives include aspects as theory for feedback control and a laboratory with an easy to program digital control. The goal of this paper is to open for some debate on these challenges.

Keywords--Education, Laboratory experiments, Power electronics, Electric drives.

I. INTRODUCTION

It is now important to discuss the way power electronics and electrical machines or electrical drives should be taught. Some of the arguments are:

- Power Electronics and Electric drives, PE&ED, are commodities
- There is few jobs in designing electric machines
- Few students apply for courses in PE&ED in USA, this may soon come to Scandinavia.
- At some universities in USA courses in electric machines are cancelled
- Some European universities introduce Master programs in electrical power engineering taught in English, to compensate for the reduction in their native student enrolment
- Students are clever; they see where the jobs are. With old fashion teaching the students see no applications and no jobs, enrolment is dropping.

II. NEED FOR CHANGES IN PE&ED EDUCATION AT UNIVERSITIES

How should universities cope with this need? We must prepare the students for jobs in industry. The description in this paper of the new courses in Power electronics and in Electric drives are based upon two papers presented at the IEEE PESC 2002 conference [3], [9].

Without doubt “More must be done in less time”.

The teaching should be a top-down approach with basis in applications. This is not new thoughts: it is stated: “Students are more interested in applications that convey a vision, such as environmental issues, energy saving, electro medicine or mobility. The systems aspects should be stressed instead of components.”

Sure, some fundamentals must be known in order to apply converters in systems. This means that there is only need for two fundamental courses in electrics machines and power electronics:

III. POWER ELECTRONICS

When teaching power electronics, as a summary some rules are presented:

- Start with appealing applications
- Use building block (two-port) approach. Thus the teaching of all power converters can be done in an efficient and non time consuming way
- Include control, illustrated by PSpice for simulation and dSPACE in lab
- Introduce magnetics design to provide a clear understanding of why switching frequency should increase and also as background for lab
- The concept of thermal design should be introduced
- The topics are taught in “just in time” or as needed basis
- An attractive lab is a part of the course, every week a new experiment is offered.
IV. ELECTRIC DRIVES

When teaching electric drives, it is important to:

- Start with appealing applications
- Courses in electric machines and in power electronics are not a prerequisite, an integrative approach should be used
- Necessary power electronics is taught by building block (two-port) approach
- Necessary electric machines theory is taught without including machine design related topics nor description of outdated machines
- Include control, illustrated by Simulink for simulation and dSPACE in lab
- An attractive lab is a part of the course, where the machines are controlled through dSPACE
- A well balanced textbook must be available.

V. COURSES IN POWER ELECTRONICS AND ELECTRIC DRIVES

There should not be too many power-engineering courses. In addition to the required courses, the students should be advised to attend courses in control, digital control, programming of DSPs (Digital Signal Processors) and FPGAs (Field Programmable Gate Arrays), environment issues, making web sites, economics to get the competence needed to work in small industry or even to start a company. These courses will also give good background for starting a PhD study.

PSpice® and Simulink® are the ideal simulation tools.

- Students know PSpice from electronics courses and Simulink is an easy to learn MATLAB based tool
- PSpice allows by the click of a button to obtain Bode-plots of transfer functions of for instance DC-DC converters in discontinuous mode

In the introductory courses in Power electronics and in Electric drives, the laboratory experiments are important. The approach described for teaching electric machines as electric drives has already paid off at some universities in USA where the student enrollment has tripled from one year to the next. This is by just changing the way the course is presented in the syallabus.

The new courses are based upon discussions between about 100 US professors at workshops supported by the National Science Foundation. Workshop # 5 was organized in Arizona in January of 2002, there will also be a workshop in January of 2003 [9].

Another basic course should be developed: Power Electronics in Power Systems. This course could be a bridge between power electronics and power systems. Topics like distributed generation and new renewable energy sources as wind and solar energy will make such a course attractive. Also here application should be the basis and students will see where the jobs are.

The use of dSPACE in lab for the basic courses in Electric Drives and Power Electronics is important. The students are able to build digital controlled motor drives by only spending a few hours in the lab. This gives a lot of motivation.

The dSPACE setup can of course also be used in advanced courses and research. In the introductory courses in Power electronics and in Electric drives, the laboratory experiments organized are important.

VI. A BUILDING-BLOCK-BASED POWER ELECTRONICS INSTRUCTIONAL LABORATORY

This part describes a new power electronics instructional laboratory based on the building block (switching pole) methodology. This methodology provides a common basis for describing all practical converter topologies and gives the student a unified top-down presentation of power electronic converters. The novel features of this laboratory include: a unifying building-block methodology (the Power Pole), tight coupling with lectures, use of low voltages (<50V) for enhanced safety, and ease of use and low cost. A key component of the laboratory is the use of a reconfigurable circuit board (the Power Pole board) which contains the Power Pole circuit as well as on-board isolated drive circuits, PWM generation, fault protection, output filter, and switched load. The detailed circuit board layout is described and several examples of its use are presented.

VII. BACKGROUND

NSF-funded educational projects [1,2] at the University of Minnesota have resulted in the development of new approaches to teaching power electronics and electric drives concisely in just two undergraduate courses. The adoption of these new approaches has resulted in tripling student enrollments in these first courses from their low point several years ago. A brief description of the first course in power electronics is given below. A similar description of the electric drives first course is described at the end of this paper, which discusses the electric drives portions of our integrated laboratory.
VIII. POWER ELECTRONICS FIRST COURSE DESCRIPTION

The first course in power electronics includes all the practical converter topologies, their control, and important design aspects. The course topics are organized into modules which can be sequenced appropriately to maintain interest. To reinforce theory, simulation software and hardware laboratories are tightly integrated into the modules. Table I shows a listing of the topical modules and associated laboratory sessions for a 15 week semester course with three lecture meetings per week.

IX. POWER POLE BUILDING BLOCK

The topics listed in Table I can be taught in a single semester course because the discussion is based on a building-block approach which brings cohesion to the various converter topologies and permits each to be discussed in a short period of time. The building block is the switching pole (power pole) [4,5] which consists of the bi-positional switch shown in Figure 1a whose position (up or down) is controlled by the PWM control signal.

![Switching pole building block](image)

**Fig. 1** Switching pole building block as a) bipositional switch and b) average model.

The power pole is a two-port: a voltage-port on one side across the capacitor and a current port on the other side due to the series inductance. An average representation of the switch is the ideal transformer shown in Fig. 1b whose turns ratio is controlled by the duty cycle.

<table>
<thead>
<tr>
<th>No.</th>
<th>Module Topic</th>
<th>Lect. (40 total)</th>
<th>Laboratory Experiments (One 2 hr session each)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction, Applications</td>
<td>3</td>
<td>1. Lab Safety, Familiarity with PSpice</td>
</tr>
<tr>
<td>3</td>
<td>Feedback Controller Design of DC-DC Converters</td>
<td>5</td>
<td>5. Voltage Mode Control of Buck Converter&lt;br&gt;6. Peak-Current Mode Control: Buck-Boost Converter in CCM</td>
</tr>
<tr>
<td>4</td>
<td>Power Quality, Power Factor Correction</td>
<td>3</td>
<td>7. Diode Rectifiers&lt;br&gt;8. Power Factor Correction Circuit</td>
</tr>
<tr>
<td>5</td>
<td>Magnetic Design</td>
<td>3</td>
<td>9. Inductors; High Freq. Transformers</td>
</tr>
<tr>
<td>6</td>
<td>Isolated Switch-Mode Power Supplies</td>
<td>3</td>
<td>10. Flyback Converter&lt;br&gt;11. Forward Converter</td>
</tr>
<tr>
<td>7</td>
<td>Inverters for DC and AC Drives, UPS</td>
<td>5</td>
<td>12. Inverters for DC Drives&lt;br&gt;13. Inverter for AC Drives</td>
</tr>
<tr>
<td>8</td>
<td>Soft Switching in DC-DC Converters</td>
<td>3</td>
<td>14. Full-Bridge PWM Converter&lt;br&gt;15. Soft Switching DC-DC Converters</td>
</tr>
<tr>
<td>9</td>
<td>High Freq. AC (CFL, Induction Heating)</td>
<td>1</td>
<td>Demo of Compact Fluorescent Light (CFL) Ballast</td>
</tr>
<tr>
<td>10</td>
<td>Thyristor Converters</td>
<td>4</td>
<td>Pspice-Based Simulations</td>
</tr>
<tr>
<td>11</td>
<td>Utility Applications of Power Electronics</td>
<td>1</td>
<td>None</td>
</tr>
</tbody>
</table>
In DC-DC converters, the power pole is configured to be a buck, boost, or buck-boost converter. Transformer-isolated converters (forward and flyback) are derived from the power pole. Three such power poles constitute a switch-mode inverter for three-phase AC motor drives. Thus all practical converter topologies are shown to have a common origin and the power pole needs to be analyzed only once and then the analysis used repeatedly. While the model shown in Fig. 1b strictly only applies to continuous conduction, it can be augmented with controlled voltage and current sources, both expressed conditionally, so that the model is also valid in discontinuous conduction. The average model has several benefits: it clearly provides an insight into how the desired output is synthesized by pulse-width modulating the switch between up and down positions, allows linearization for feedback controller design, and results in much faster simulation times for dynamic performance analysis.

X. POWER ELECTRONICS LABORATORY GOALS AND FORMAT

The fast pace and diversity of topics covered in the first power electronics course outlined in Table I makes it important to do everything possible to ensure that the concepts are grasped by the student. Software simulations such as Pspice-based exercises are helpful. But it is essential that students concurrently perform hardware-based laboratory experiments. It is a dangerous trend in many universities to move away from hardware to purely software-based laboratories - an approach that fails to excite students and does not prepare them for the “real world” where they will design, build, test, or use real hardware.

The salient features of this laboratory include:

- **Building-block methodology:** The majority of the experiments utilize a reconfigurable circuit board that implements the power pole. Students use the board to build converter circuits based on the power pole building block as discussed in lecture. Experiments which cannot conveniently use the Power Pole board (such as the power factor correction experiment, 9 in Table I) will use their own specifically designed board.
- **Tight coupling with lectures:** Experiments illustrate and reinforce basic concepts and are done concurrently with the discussion in lecture. Simulations and problems done either in the lecture course or as lab preparation are verified in the lab.
- **Safety:** Safety is of paramount importance and all experiments use voltages of 50V or less which provides relative electrical safety compared to traditional labs where voltages much in excess of 120V were common. Protective circuits on the power pole board shut down the converter if overvoltages or overcurrents occur. In addition all precautions normally practiced in conventional (higher voltage) laboratories will be carried out in this laboratory.
- **Ease of usage; Low cost:** Basic concepts can be illustrated at fairly low power levels which greatly simplifies interconnections and keeps equipment costs low. Hence power levels in all experiments will be kept less than 200 W. Isolated drive circuits for semiconductor switches and PWM generation circuits are included on the power pole board so that students do not waste valuable lab time re-constructing these circuits for every experiment.

The laboratory meets on a weekly basis for a two hour period with two students per workstation. Each workstation has the following complement of equipment:

- **Digital oscilloscope:** four channel, 100 MHz bandwidth, connection to computer.
- **Function generator, 10 MHz, 10V into 50Ω variable duty cycle.**
- **Main DC power supply:** 0-60V, 0-3A
- **DC power supply:** dual independent outputs, 0-20V, 0-0.5A for signal level circuits.
- **Digital multimeters (2):**
- **Differential voltage probe.**
- **Power Pole circuit board (described below).**
- **Computer with Dspace software and board, Matlab, Simulink, Pspice.**

XI. POWER POLE CIRCUIT BOARD

The re-configurable Power Pole circuit board is shown in the block diagram of Fig. 2 and a photograph of the board is shown in Fig. 3. The bi-positional switch is implemented as the half-bridge shown in the figure consisting of two series-connected power MOSFETs (500V-10A) and
Fig. 2  Power pole circuit board

- Isolated Drive Circuit
- PWM Generator
  - Selectable 100, 200, or 400 kHz
  - Duty cycle control via potentiometer setting - 15% to 90%
  - Select upper or lower FET
  - Select internal or external PWM

---

Fig. 3  Photograph of the Power Pole circuit board

- Fault Protection
  - Voltage - 60 V
  - Current - 7 A

- Power Supplies for drive and fault protection circuits
- Terminal strip for daughterboard

- LEM
- Filter
- 5 µF

- Key
  - Connection terminals
  - Power circuit

- Switched Load

- 10 µF
- 3 µF

- Signal from control section
discrete anti-parallel free-wheeling diodes (500V-10A). The gate and source terminals of the MOSFET are hard-wired to the on-board isolated drive circuits. One each of the MOSFET and diode terminals are uncommitted and this in combination with numerous uncommitted interconnection terminals makes the circuit board highly re-configurable. This board is a third generation design which incorporates the accumulated experience from previous designs.

The PWM generation section of the board has several features which could not be shown clearly in Figs. 2 and 3. These features, which provide important additional capabilities to the board include:

- **Ability to insert ac signals into the PWM generation circuit to provide small ac variations in the duty cycle about a steady-state value.** This enables the open-loop output-voltage/input-duty-cycle transfer function to be measured as a function of frequency.

- **Access to the PWM generation circuit via the daughterboard terminal strip for implementing closed loop control of converter outputs.**

### XII. EXAMPLES OF POWER POLE BOARD USAGE

We have used this board in our power electronics instructional laboratory. Several experiments listed in Table I have already been developed including (2), (3), (4), and (10). Figure 4a shows the board configured as a buck converter and Fig. 4b shows the board used for implementing a flyback converter. Experiments on snubbers, MOSFET characteristics, and diode characteristics have also been developed which use the Power Pole board.

The flexibility of the Power Pole board and comprehensive capabilities of the instrumentation at each workstation make a wide range of experimental measurements on converters practical. An instructor can specify the measurements which students are to make based upon the topical emphasis in the lecture course without being seriously constrained by limited laboratory capabilities. Measurements made by students at the University of Minnesota on several different converter topologies have included:

1. DC output voltage versus duty cycle.
2. Output ripple voltage versus frequency.
3. Load voltage versus load current at fixed duty cycle – CCM to DCM transition.
5. Converter operating waveforms.
6. Open-loop output-voltage/input-duty-cycle transfer function versus frequency.

![Fig. 4 Power Pole board configured as a buck converter (a) and a flyback converter (b).](image)

The external load is a 100W -200Ω potentiometer and the inductor is a 40 µH inductor.
More experiments which will utilize the Power Pole board are in the planning stage. The experiments will include (5), (6), (9), and (11) listed in Table I and will take advantage of the unique capabilities of the board. For example students can verify the simulations of the dynamic response of the closed loop converter control systems which they have designed by measuring the actual response using the switched load on the circuit board. The switched load provides a triggerable step change in the load which can be repeated at any desired rate.

XIII. SUMMARY POWER ELECTRONICS

We are developing a novel instructional laboratory that is tightly coupled to our first course in power electronics. The laboratory utilizes and reinforces the power pole building block approach used in the lecture course. The laboratory provides significant instructional flexibility and allows a seamless transition from a first course in power electronics to advanced courses in the same field or to a first course in electric drives as is described in a companion paper.

XIV. INSTRUCTIONAL LABORATORY FOR ELECTRIC DRIVES COURSES

This section describes the developments at the University of Minnesota of new approach in teaching of Electric drives, focusing on the associate state-of-the-art laboratory. The mission of these developments is to nationally revitalize courses in industrially and strategically vital fields of electric drives (and power electronics [10]). This is accomplished by making these courses appealing to students (undergraduate enrollments have significantly increased subsequent to adopting these approaches) where they receive a first-rate education in just one undergraduate course in a way that ensures a seamless continuity to advanced courses. The laboratory is based on a dSPACE development board and several custom designed power converter boards and electric motors, working on a 42V dc-bus voltage system.

XV. OVERVIEW OF THE LABORATORY

Developed by government funding in consultation with the consortium of nine universities and four government labs, the DSP-based electric drives laboratory is intended to serve as a model for adoption at other universities. Therefore, safety, transportability, ease of use and low cost are very important factors.

The laboratory is being developed with the following considerations:

- **Tight coupling with Lectures:** It is important that this laboratory illustrates and reinforces the basic concepts (more than what is possible with traditional laboratories) discussed in course lectures without putting students through pointless laborious exercises. Pre-lab simulations, for example using PSpice and Simulink, included in the course are actually verified in the lab sessions.

- **Safety:** Safety is of paramount importance and 42 V (although absolute care must still be exercise as explained in the next paragraph) provides electrical safety compared to traditional labs where voltage much in excess of 120 V are used. Moreover, there is a move to shift battery voltages in automobiles from 12/14V to 36/42V [6]. Therefore, 42-V is destined to become the new automotive voltage standard and also machines and semiconductor components for this voltage system will become prevalent. However, even with the intent of keeping voltages below 42V, it is very easy to get voltages in far excess of 42V (for example in a boost converter, where the output load is accidentally disconnected). Many levels of safety are built in to ensure in such cases the circuit operation will safely shut down. But there is always a finite chance that all these safety measures would fail. As a consequence all the precautions that are normally practiced in a conventional power electronics and a drives lab must be exercised.

- **Ease of usage:** The basic concepts can be illustrated at fairly low power that allows ease of connections and keeps equipment costs low. Towards this objective power is limited to less than 200 W in either laboratories.

- **Digital Control:** Many graduating engineers will be faced with system integration as their work assignment, which is made easier by means of digital control. Most commercial drives today use digital control, hence digital control is used in the Electric Drives Laboratory.

- **Use with other courses:** Such a laboratory should be useful with advanced courses in Power Electronics and Electric Drives as well as very basic courses, student projects and research in Electrical/Mechanical Engineering.
<table>
<thead>
<tr>
<th>No.</th>
<th>Lecture Topic</th>
<th>Lects.</th>
<th>Laboratory Sessions</th>
<th>Labs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction to Electric Drive Systems</td>
<td>1</td>
<td>Lab Safety, Familiarity with Simulink</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Understanding Mechanical System Needs</td>
<td>3</td>
<td>Mechanical System Modeling, Introduction to dSPACE</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>Review of Electric Circuits</td>
<td>1</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>Basic Understanding of Power Electronics</td>
<td>3</td>
<td>Switch Mode Converters for Drives</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>Magnetic Circuits</td>
<td>4</td>
<td>Line-Frequency Transformer</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>Basic principles of Electro.mechanical Energy Conversion</td>
<td>3</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>DC Motor Drives</td>
<td>5</td>
<td>DC Motors, DC-Motor Drives</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>Feedback Controller Design in Drives</td>
<td>3</td>
<td>Feedback Control of DC Drives</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>Introduction to AC Machines &amp; Space Vectors</td>
<td>5</td>
<td>Space Vectors in Simulink &amp; dSPACE</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>Sinusoidal PMAC Drives</td>
<td>4</td>
<td>PMAC Drives</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>Induction Machines: Steady State Analysis</td>
<td>5</td>
<td>Induction Machines</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>Adjustable Speed Induction Motor Drives</td>
<td>3</td>
<td>Adjustable Speed Induction Motor Drives</td>
<td>1</td>
</tr>
<tr>
<td>13</td>
<td>Reluctance Drives</td>
<td>1</td>
<td>Stepper Motor Drive</td>
<td>1</td>
</tr>
</tbody>
</table>

A. The Educational Impact of the Laboratory

In the teaching process, at the first level and without any “advanced” topics prerequisites, this laboratory represents a major breakthrough and an attraction for the students. In this respect, its salient features are:

- **Benefit of an open architecture design.** This means that it can run any control algorithm on any standard electric machine.
- **It can be used in both First and Advanced course in Electric Drives**
- **Can be used in other courses** such as: Power Electronics, Control Theory, and Digital Signal Processing etc.
- **Invaluable practical experience:** Its implementation at the undergraduate level form better prepared students for graduate and PhD research, as we'll as for the present industrial requirements.

The software advantages of this laboratory setup can be summarized as follows:

- **The laboratory is “software reconfigurable”**. Each type of motor or motor-load group can be driven in almost any imaginable control loop by simply modifying the block diagram in Simulink.
- **DOES NOT require any programming (C, assembly, etc.).** The control software relies on the ability of the user to build a functional Simulink model of the final control system. Simulink is a graphic-oriented modeler and simulator, extremely simple to learn and appropriate for applications that involve system-level process control.

  - **No discrete models or Z-transforms are needed.** To build the control algorithms, students work only in continuous domain and manipulate simple s-domain transfer functions.
  - **Automated DSP coding.** Compiling and downloading the object code into the DSP board is automated, totally transparent for the user.
  - **Reconfigurable graphical user interface.** DSPACE is providing the Control Desk, a software that allows drag-and-drop reconfiguration of the user interface.

![Fig.2 Block diagram of the DSP controlled electric drives laboratory](image-url)

The hardware advantages of the proposed laboratory are:

- **Compact, “all-in-one”, motor lab-kit.** The motors are custom designed to have similar electrical and mechanical characteristics. A performant flexible vibration or misalignment.
• **Two identical, general purpose, three-pole converters.** The power converter boards include current and voltage measurement capabilities, the drivers and low-voltage power supply circuits.

• **One dSPACE controller board.** The controller board is capable to run the control algorithm, execute data I/O transfer for closed-loop control or just for measurement, and generate the PWM pulses for each converter pole control.

**B. Laboratory’s Integrative vision**

Following the innovative concept of **integration** promoted in the conception of this First Course in Electric Drives, the laboratory not only implements the concept, but also highlights its advantages and enhances its outcome. The block diagram of the laboratory is shown in Fig. 5, where the bus voltage is chosen to be 42 V for safety reasons as well as recognizing the new automotive standards [6]. Since the load recycles power, only the losses in the overall system need to be supplied by a small DC power supply. 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. 6 are specially designed and built for this laboratory. The inverters for both machines and their interaction with dSPACE are illustrated in Fig. 7. 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 [7] are several: no knowledge of coding in C or assembly language is needed, the same simulation blocks used in Simulink are used in the hardware implementation, there is an easy-to-use graphical interface, which allows students real-time monitoring and parameter adjustments. The hardware setup in this electric drives laboratory is also intended to demonstrate converter operation for dc drives, three-phase ac drives and uninterruptible power supplies applications.

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 [12].

Among the multiple advantages offered, two of them are analyzed below.

a) **Use of digital control**

The use of digital control and dSPACE in describing fundamental concepts in electric drives is, in itself, a huge step forward. If, until recently, elaborating a digital control system was considered a master-thesis project or even a PhD research subject, with this system the transition from a theoretical model to its practical implementation is a simple “push of a button”.

The students don’t need any background in digital signal processing. They simply model a system in Simulink and verify its behavior in the hardware setup. The outcome is twofold:

- First, the gap between theoretical models and simulation is completely eliminated
- Second, the students are enticed to continue this path and take classes in other “hot” topics such as Advanced Control and DSP Systems.

---

![Fig. 3 Motor Lab Kit – 42 V motors with matching mechanical and electrical characteristics, special designed for the laboratory](image-url)
<table>
<thead>
<tr>
<th>No.</th>
<th>Experiments</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Familiarity with Simulink</td>
<td>Introduction of basic blocks, together with the important modeling and simulation parameter settings.</td>
</tr>
<tr>
<td>2</td>
<td>Mechanical Systems Modeling</td>
<td>Using the motion equations describing the rotational mechanics of a drive system, simulations using Simulink and Matlab.</td>
</tr>
<tr>
<td>3</td>
<td>Introduction to dSPACE</td>
<td>Some basic digital control principles will be presented, the Simulink interface blocks and their parameters will be introduced, and a basic example of generating different waveforms will be implemented.</td>
</tr>
<tr>
<td>4</td>
<td>Switch-mode Converters for DC Drives</td>
<td>Begin with modeling a Switch-mode converter in Simulink; use dSPACE to generate desired switching waveforms; observe the effects of different switching frequencies on an R-L load.</td>
</tr>
<tr>
<td>5</td>
<td>Switch-mode Converters for AC Drives</td>
<td>Using the model built in the previous lab, generate a three-phase sinusoidal pattern using signal generator blocks in Simulink. Observe how a three-phase sinusoidal voltage system can be generated at the output of the real converter using digital control of the switch-mode converter.</td>
</tr>
<tr>
<td>6</td>
<td>Experiment on Transformers</td>
<td>This experiment on a line-frequency transformer is intended to show the importance of its analysis to induction motors later on.</td>
</tr>
<tr>
<td>7</td>
<td>DC Motors</td>
<td>Determination of dc motor parameters using dSPACE.</td>
</tr>
<tr>
<td>8</td>
<td>DC Motor Drives</td>
<td>With the dc-motor characterized in the previous lab, an open loop system is developed and speed versus torque characteristics are measured at various input voltages.</td>
</tr>
<tr>
<td>9</td>
<td>Feedback control in Drives</td>
<td>A Simulink model for speed control of the dc-motor is built. The model is transferred to dSPACE system for hardware validation.</td>
</tr>
<tr>
<td>10</td>
<td>Space Vectors</td>
<td>This experiment consists of a graphical visualization of space vectors using Simulink.</td>
</tr>
<tr>
<td>11</td>
<td>Sinusoidal PMAC Drives</td>
<td>Operation of PMAC (brushless dc) machines and their closed-loop control.</td>
</tr>
<tr>
<td>12</td>
<td>Induction motor</td>
<td>Determination of induction motor parameters. Steady state performance at various torque loading.</td>
</tr>
<tr>
<td>13</td>
<td>Adjustable Speed Induction Motor Drives</td>
<td>A simple V/f algorithm is implemented in dSPACE for the induction motor drive.</td>
</tr>
<tr>
<td>14</td>
<td>Stepper motor drives</td>
<td>A control algorithm for a stepper motor is implemented in Simulink and transported to dSPACE for hardware validation.</td>
</tr>
</tbody>
</table>

Even though the impact with complex subjects may be overwhelming, this is only a first glance impression. In reality, the experiments are so easy and comprehensible that the students are immediately attract to the idea of being in the lab.

b) Topics covered in the Laboratory Experiments

The laboratory experiments must follow the lecture topics, attract students with simplicity and comprehensibility and, yet, to be enough powerful to demonstrate the basic concepts. A possible “line-up” for a full semester laboratory is described in Table III.

Quick Example

In this system, the students design the controller in Simulink by bringing various blocks together, and then dSPACE converts the code and downloads it in digital processor board for real-time control of electric drives.

An advantage of this reconfigurable system is that it uses Simulink, the same software used for modeling purposes. This way a 1:1 correspondence can be shown between the software simulation results and the hardware experimental results.

Integration of a software tool like Simulink and real-time digital control for applications of practical significance will appeal to a broader range of students than traditional machines and electric drives courses.

From physical and mathematical description of an electric drive to a full operational system only few steps have to be followed. Suppose the lab requirement is to design, simulate and operate an induction motor at variable frequency.

For such a purpose, in a “traditional” lab an expensive frequency converter needed to be purchased. Also, due to the inaccessibility of the converter logic, the only purpose of the lab was to visualize its operation without implementing any recently acquired concept.
In this case the concept of “black-box” is eliminated. Here is a quick look to the steps a student has to follow in this experiment:

**Step 1. The control algorithm is implemented in Simulink.** A model of the motor and the inverter are provided to the student. The simulation is performed with a fixed step of integration, of the same value of the sampling period, as it will be used in the real-time system. When the results are satisfactory (i.e. the controllers are well tuned), then go to: **Step 2. Preparation for real-time control.** In the Simulink model, the motor, the converter and all the outgoing controls and the incoming feedback signals are replaced with the I/O interface blocks provided by dSPACE (Fig5).

**Step 3. “Push-button” code generation.** Press the Build menu button to create the DSP code and automatically download it into the dSPACE board.

**Step 4. “Drag-and-drop” controls.** Using the tools provided by Control Desk, such as slider gains, buttons, switches, graphs, displays, the student creates its own user interface. To each control a variable name is assigned from the dSPACE Tool Window (Fig.7).

**Step 5. Run the experiment.** This process permits not only to visualize and analyze the results of one’s implementation, but also to dynamically change any parameter in the system defined in any of the Simulink model blocks.

**XVI. SUMMARY ELECTRIC DRIVES LABORATORY**

The laboratory proposed in this paper offer an unparalleled experience and is a great source of attracting students and exciting their interest. In this lab they will compare results of computer simulations with those of hardware experiments, providing them with an education that will be invaluable.
All experiment write-ups including the needed set up, suggested steps to be followed and the report expected from students will be posted on the Internet.

The University of Minnesota is planning to submit a CCLI ND-track proposal to NSF (proposal due date is June 6, 2002) to provide support to all universities that may adopt these new teaching approaches and the associated laboratories, and to encourage others to do so in the future. The University of Minnesota will propose to hold short courses and workshops at various locations to disseminate the NSF-funded developments. In between these short courses and workshops, net meetings using the Internet will be planned for which an equivalent of one faculty-day per week (from the University of Minnesota) will be proposed.

REFERENCES
