

AC 2007-1330: BUILDING A MODERN POWER ELECTRONICS AND ELECTRIC MACHINES LABORATORY

Ke Chen, Cleveland State University

Ke Chen received BS degree from Tsinghua University, Beijing, China. He is currently a master student in Electrical and Computer Engineering Department at Cleveland State University.

Ana Stankovic, Cleveland State University

Dr. Ana V. Stankovic received BS, MS and PhD degrees from the University of Belgrade, Serbia and University of Wisconsin-Madison. She is currently an Associate Professor in Electrical and Computer Engineering Department at Cleveland State University. Her expertise is power electronics and electric machines and drives.

Building a Modern Power Electronics and Electric Machines Laboratory

Abstract

This paper presents the development of the state of the art Power Electronics and Electric Machines Laboratory at Cleveland State University. This laboratory was designed as a part of newly developed power program that consists of three required courses in the undergraduate electrical engineering curriculum. Typically, Electromechanical Energy Conversion is the only one required power course in electrical engineering curriculum. To support the need of local industry in North East Ohio, two power courses, Power Electronics I and Electric Machines and Power Electronics Laboratory, have been added as required courses to undergraduate electrical engineering curriculum. With these changes, a new state of the art laboratory was designed and implemented, providing students with experiments related to all topics covered in two prerequisite courses, Electromechanical Energy Conversion and Power Electronics I.

The laboratory experiments represent the unique blend of traditional and contemporary approach to learning electric machines and power electronics. Modular Lab-Volt equipment has been used for experiments related to steady state analysis of Electric Machines and transformers. In addition, modern software and hardware technology (DSPACE) has been used for experiments related to real time control of different types of electric machines. In addition, several experiments related to power-pole approach and average models designed for power electronics converters have been adopted from the University of Minnesota and incorporated into the laboratory course material.

The new laboratory has been working flawlessly since its inception in fall of 2004. This paper describes the set of laboratory experiments, assessment method as well as the survey from students who took the laboratory course.

Introduction

In 2001, Power Electronics and Electric Machines program was fully developed in electrical and computer engineering department at Cleveland State University. To support newly developed curriculum, state of the art Power Electronics and Electric Machines Laboratory has been established. The old Electric Machines Laboratory that consisted of line-fed motor generator sets has been completely dismantled and replaced with seven modern test benches.

This paper presents the construction of the newly developed laboratory along with the structure of the Power Electronics and Electric Machines program. It has been shown in literature that number of power electronics and electric machines laboratories use either modular Lab-Volt equipment [1] or integrative approach [2], [3], [4], [5] and [6]. Unlike the majority of power electronics and electric machines laboratories that have recently been renovated, the laboratory at Cleveland State University has been designed to take the advantage of both traditional as well as contemporary approach to teaching power electronics and electric machines. To support this idea, several experiments have been developed with modular Lab-Volt equipment as well as DSPACE equipment and have been combined with experiments adopted from the University of

Minnesota. This unique combination of Lab-Volt, Power-Pole and DSPACE test benches helped us apply both contemporary as well as traditional method in teaching power electronics and electric machines. In addition, assessment method as well as student feedback is presented.

Power Electronics and Electric Machines Program

Typically, Electromechanical Energy Conversion is the only one required power course in electrical engineering curriculum. To support the need of local industry in North East Ohio, two power courses, Power Electronics I and Power Electronics and Electric Machines Laboratory, have been added as required courses to undergraduate electrical engineering curriculum. Figure 1 shows the structure of Power program in Electrical Engineering Department at Cleveland State University. All courses but the Power Electronics and Electric Machines Laboratory are four credit-hour courses and offered once a year. The Laboratory course is a two credit hour course.

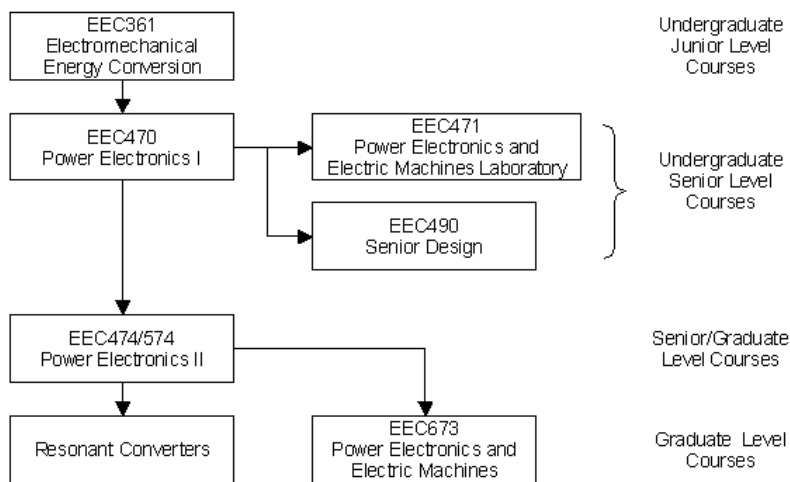


Figure1. Structure of the Power Electronics and Electric Machines Program

Topics covered in Electromechanical Energy Conversion (EEC 361) and Power Electronics I (EEC 470) are shown in Tables I and II. These courses are prerequisites for Power Electronics and Electric Machines Laboratory (EEC 470) and Senior Design (EEC 490).

Table I. Course structure of Electromechanical Energy Conversion

| No. | Topics | Lecture (hours) |
|-----|---|-----------------|
| 1 | Review of basic single/three-phase circuits | 3 |
| 2 | Review of rotational motion and magnetic field; The linear DC machine | 6 |
| 3 | Transformers: Ideal transformer; Real single-phase transformer | 6 |
| 4 | Introduction to AC machinery fundamentals | 6 |
| 5 | Synchronous generators: The speed of rotation; Internal generated voltage; Equivalent circuit; Phasor diagram; Power and torque | 6 |
| 6 | Synchronous motors: Basic principles of operation | 6 |
| 7 | Induction motors: Basic concepts; Equivalent circuit; Power and torque; Torque-speed characteristics | 6 |
| 8 | Introduction to DC machinery fundamentals | 6 |

Table II. Course structure of Power Electronics I

| No. | Topics | Lecture (hours) |
|-----|--|-----------------|
| 1 | Introduction to Power Electronics | 1 |
| 2 | Semiconductor devices | 2 |
| 3 | Review of basic electrical concepts | 4 |
| 4 | Line-frequency Diode Rectifiers | 5 |
| 5 | Line-frequency Phase Controlled Rectifiers and Inverters | 4 |
| 6 | DC-DC Switch-mode Converters | 4 |
| 7 | PWM with bipolar and unipolar switching | 4 |
| 8 | Switch-mode DC-AC Inverters | 4 |
| 9 | Power Supply Applications | 4 |
| 10 | Motor Drive Applications | 4 |
| 11 | Computer Lab | 9 |

A newly developed Power Electronics and Electric Machines Laboratory is strongly coupled with the power program requirements of Figure 1 and course structure of Table I and Table II. With the help of three modern facilities, Modular Lab-Volt equipment, Power-pole board, and DSPACE, all topics in the two prerequisite courses are covered in the Laboratory course as an efficient utilization and combination of these three totally different methods. The structure of Power Electronics and Electric Machines Laboratory is shown in Table III.

Table III. Structure of Power Electronics and Electric Machines Laboratory

| No. | Topics | Description | Equipment |
|-----|-----------------------------------|--|------------------------|
| 1 | Transformers | Determination of transformer parameters by performing no load and short circuit test. Voltage Regulation and Efficiency. | Lab-Volt |
| 2 | AC/DC Rectifiers | Operation of Single-phase and Three-phase Diode/Thyristor rectifiers; | Lab-Volt Power-Pole |
| 3 | DC/DC Choppers | Introduction to DC/DC choppers: Buck, Boost, Buck-Boost choppers; Verification of output voltage versus duty ratio; The effect of switching control signal frequency; Measurement of the output power versus input power. | Lab-volt Power-pole |
| 4 | DC/AC Inverters | Variable voltage, variable frequency single –phase switch-mode single-phase and three-phase inverters. | Lab-Volt Power-Pole |
| 5 | Synchronous Motors and Generators | The effect of load changes on a synchronous motor; The effect of field current changes on a synchronous motor; The effect of load changes on a synchronous generator operating alone. | Lab-Volt |
| 6 | Introduction to DSPACE | Mechanical systems modeling. Example of building a real-time system through simulink and DSPACE. Operation and control of DC machines by using DSPACE. | DSPACE |
| 7 | Induction Motors | Determination of induction motor parameters. Steady state performance at various torque loadings. Control of induction machines | Lab-Volt DSPACE |

New Laboratory Workstations

Power Laboratory at Cleveland State University consists of three Lab-Volt test benches, four Power Board test benches and four DSPACE test benches.

Lab-Volt Test Benches

The Lab-Volt Power Electronics Training System is a versatile, flexible, modular, and complete teaching system [1]. It consists of all different types of modules including power supplies, power electronics circuits and variable-speed drive modules, AC and DC machines and transformers, wiring cables, control panels, power meters and various measuring instruments [2]. Lab-Volt test bench is shown on Fig.2.



Figure2. Lab-Volt Test Bench

Power-pole board Test Benches

The Power-pole boards shown on Fig.3 is a building-block-based power electronics reconfigurable circuit board which contains power-pole circuit as well as on-board isolated drive circuits, PWM generation, fault protection, output filter, and switched load [3]. The main feature of the Power-pole Board is the reconfigurable power-pole consisting of two MOSFETs and two diodes. The drive circuits for the MOSFETs are incorporated on the board, and so are the various

protection circuits for over current and over voltage. PWM signals to control the MOSFETs can be generated onboard or supplied from an external source. The power-pole can be configured to work in various topologies using three magnetic boards which plug into the Power-pole board. In addition, there is an option of doing frequency analysis of each topology by injecting a small-signal sinusoidal control voltage. The board can also be operated in voltage/current feedback mode using an external control circuit mounted on a daughter board which plugs into the Power-pole board [4].

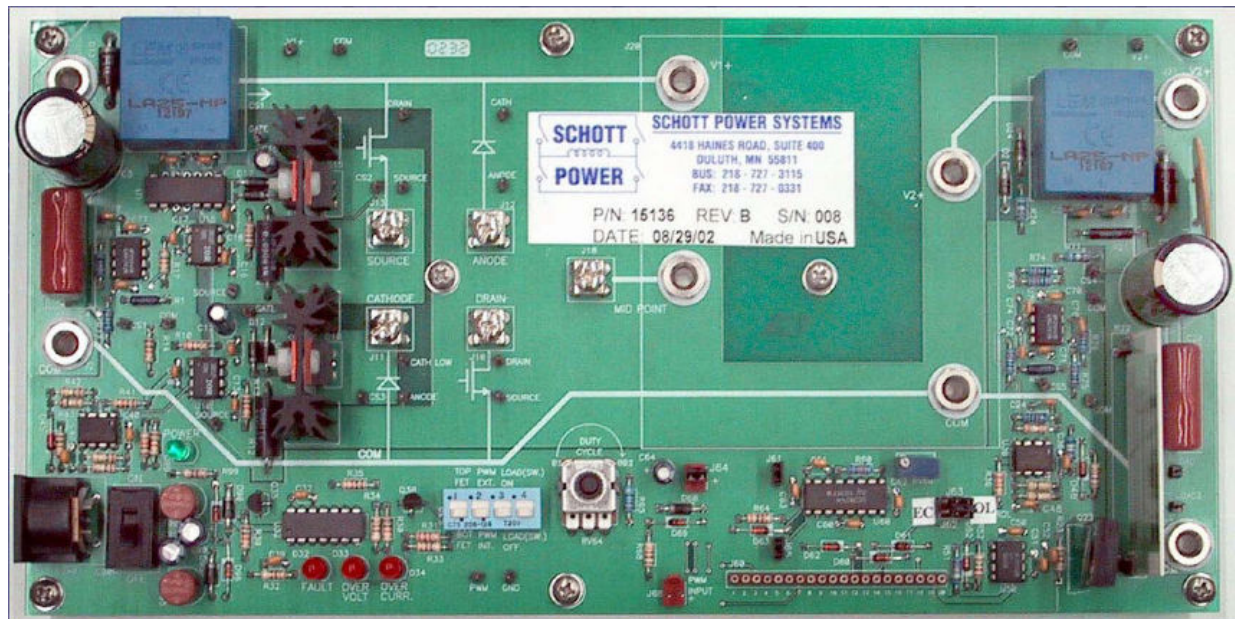


Figure3. Power-Pole Board

DSPACE Test Benches

DSPACE DSP controller board shown on Fig.4 is an interface between the host computer, the driving circuit, and the motor drive system, including PWM inverters, transducers, serial interfaces, sensors, etc. One of the best features of the DSPACE package is the ease of building real-time applications [5]. DSPACE has a software interface to the controller board based on MATLAB-SIMULINK. Since SIMULINK is a block-oriented, graphical interface based simulation package that works within MATLAB environment, students do not have to write a code at all [6]. Once the model in SIMULINK is completed, DSPACE software can convert it into real-time DSP code. Then it downloads the code to the controller board, and execute the hardware in real-time. DSPACE software also has tools to display, store data, and change parameters.

In addition all test benches are equipped with Tektronix oscilloscopes, voltage and current probes, power supplies, digital meters etc.

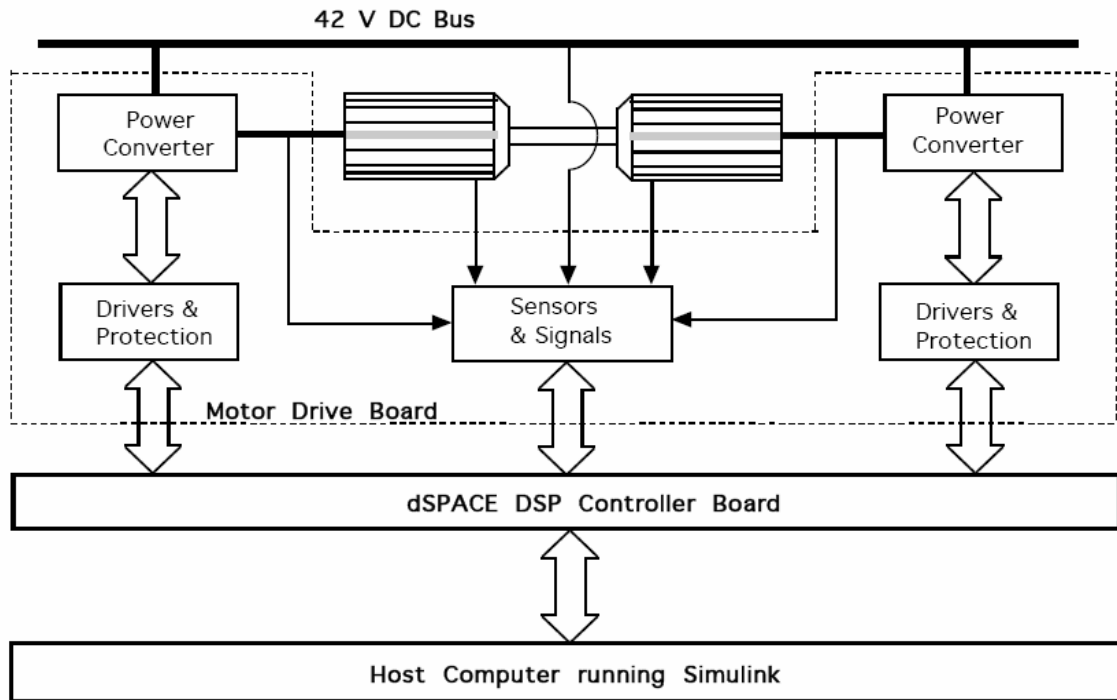


Figure4. DSPACE Structure

Modular Lab-Volt Equipment which has been used for training purposes on number of industrial sites helps students understand the operation of each power electronics module but it does not expose them to actual industrial set-up. Therefore, it has been combined with Power-pole boards. By using such well-designed and more industrial-style Power-pole board, students avoid many unnecessary difficulties in getting familiar with practical devices. In addition, traditional approach in teaching electric machines and drives should not be completely eliminated. Therefore, Lab-Volt equipment has been used as an introduction to steady state operation of different electric machines and transformers. Once students get familiar with steady state operation of electric machines and drives, they get exposed to contemporary approach by using DSPACE. After the procedure of getting acquainted with SIMULINK, students can build and operate a real-time motor drive system. DSPACE related experiments will allow students to observe and comprehend the operation adjustable speed drives.

According to TABLE III, Lab-Volt equipment and industrial Power-pole board are used for experiments 2, 3 and 4. Experiments related to DC/DC converters by using Power-pole board have been adopted from the University of Minnesota whereas the experiments related to AC/DC converters by using the Pwer-ole board have been developed at Cleveland State University.

According to TABLE III, Lab-Volt equipment and DSPACE test benches are used for experiments 5, 6 and 7. Experiment 6 is adopted from the University of Minnesota whereas experiment 7 has been developed at Cleveland State University.

The experiments related to DC/DC choppers in the laboratory course are partially adopted from those developed at the University of Minnesota.

Teaching Method

The three-hour lab session starts with a 15 minute lecture followed by a 15minute quiz related to experiments covered that week. Students are given handouts in advance in order to prepare for quizzes and laboratory experiments.

Students have to submit written laboratory report every week. An instructor evaluates laboratory reports for technical accuracy. In addition, two of the reports are selected for a more comprehensive evaluation with numerical scores applied to content and writing skills. The University Writing Center evaluates writing skills. The form that has been used for laboratory report evaluation is shown on TABLE IV.

TABLE IV. Laboratory Report Evaluation Form
 FENN COLLEGE OF ENGINEERING
 EEC 471 - SPRING 2006 SEMESTER
WRITTEN LABORATORY REPORT EVALUATION

Prepared By:
 Team Members:

| Max Pts. | Title | Poor | | | | | Excellent | | | | | 60 | 70 | 80 | 90 | 100 | |
|----------|--|------|--|--|--|---|-----------|--|--|--|---|-----------------------|----|----|----|-----|-----|
| | | | | | | | | | | | | | | | | | |
| 5 | Title 5 Describes lab content concisely, adequately, appropriately | | | | | X | | | | | | 5.0 | | | | | |
| 15 | Abstract 10 Provides summary of purpose, procedure, overall results, and conclusions 5 Conveys a sense of the full report concisely and effectively | | | | | X | | | | | X | 15.0 | | | | | |
| 15 | Introduction 5 Establishes the context (concept/lab procedure) of the lab 10 Effectively presents the objectives and purpose of the lab | | | | | X | | | | | X | 15.0 | | | | | |
| 15 | Apparatus and Procedure 5 Identifies specifications of equipment and how it was used in experiment 10 Gives concise details of experiment procedure so others could repeat it | | | | | X | | | | | X | 15.0 | | | | | |
| 15 | Results 3 Opens with 1 or 2 sentence(s) describing main finding of lab 2 Presents visuals clearly and accurately 5 Presents verbal findings clearly and with sufficient support 5 Successfully integrates verbal and visual representations | | | | | X | | | | | X | 15.0 | | | | | |
| 10 | Discussion 3 Opens with explanation of how findings link to the context of lab 2 Addresses questions & issues related to the lab & discusses the answers 5 Sufficiently addresses other issues pertinent to lab | | | | | X | | | | | X | 10.0 | | | | | |
| 15 | Conclusion 10 Convincingly describes what has been learned in the lab 5 Relates results to objectives and purpose as discussed in Introduction | | | | | X | | | | | X | 15.0 | | | | | |
| 6 | Presentation 2 References tables and figures effectively to text 2 Prepared tables and figures in correct format 2 Used scientific writing style - clear and concise | | | | | X | | | | | X | 6.0 | | | | | |
| 4 | Overall aims of the report: the student... 2 Successfully learned what the lab is designed to teach 2 Accurately analyzed data for lab findings | | | | | X | | | | | X | 4.0 | | | | | |
| 100 | | | | | | | | | | | | Points Earned | | | | | |
| | | | | | | | | | | | | Total Possible Points | | | | | 100 |

In addition, students take a mid-term and final bench exam. All bench exams have been video-taped. During the mid-term and final bench exam, demonstrations evaluation form, as shown in Table V, has been used to assess students' performance. It has been shown that the form was extremely useful and easy to use. Instructor can easily grade a bench exam by simply deducting points from each category such as: knowledge of fundamentals, use of bench equipment etc.

TABLE V. Demonstrations Evaluation Form

| Fenn College of Engineering - ECE Department LABORATORY BENCH DEMONSTRATIONS EEC 471 - SPRING 2006 - DR. STANKOVIC | | | | | | | | | | |
|--|-------------------|---|----|----|---------------------|----|----|-----------|----|----|
| Student: | | | | | Total Score: | | | Date: | | |
| | | | | | | | | | | |
| EVALUATION AREAS | | POOR | | | AVERAGE | | | EXCELLENT | | |
| Knowledge of Fundamentals | | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| Evidence Of Preparation | | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| Use of Bench Equipment | | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| Audience Focus | | | | 8 | 9 | 10 | 11 | 12 | | |
| Style/Enthusiasm | | | | 8 | 9 | 10 | 11 | 12 | | |
| Voice Projection/Control | | | | 8 | 9 | 10 | 11 | 12 | | |
| Composure/Eye Contact | | | | 8 | 9 | 10 | 11 | 12 | | |
| Effective | Needs Work | PRESENTATION TECHNIQUES | | | | | | | | |
| Knowledge of Fundamentals | | | | | | | | | | |
| <input checked="" type="checkbox"/> | | Demonstrated knowledge of electrical engineering fundamentals | | | | | | | | |
| <input checked="" type="checkbox"/> | | Gave convincing delivery of information | | | | | | | | |
| Evidence Of Preparation | | | | | | | | | | |
| <input checked="" type="checkbox"/> | | Demonstrated a logical approach in laboratory procedure | | | | | | | | |
| <input checked="" type="checkbox"/> | | Appeared to have a general knowledge of laboratory experiment | | | | | | | | |
| Use of Bench Equipment | | | | | | | | | | |
| <input checked="" type="checkbox"/> | | Demonstrated how to connect equipment and conduct experiment | | | | | | | | |
| <input checked="" type="checkbox"/> | | Explained purpose of bench equipment and use of instrumentation | | | | | | | | |
| Audience Focus | | | | | | | | | | |
| <input checked="" type="checkbox"/> | | Discussed circuit and equipment with audience | | | | | | | | |
| <input checked="" type="checkbox"/> | | Demonstrated an effective interaction with audience | | | | | | | | |
| Style and Enthusiasm | | | | | | | | | | |
| <input checked="" type="checkbox"/> | | Demonstrated a creative and energetic style | | | | | | | | |
| <input checked="" type="checkbox"/> | | Used gestures to emphasize major points | | | | | | | | |
| Voice Projection and Control | | | | | | | | | | |
| <input checked="" type="checkbox"/> | | Projected voice to entire audience | | | | | | | | |
| <input checked="" type="checkbox"/> | | Demonstrated a steady and clear voice and used some variations | | | | | | | | |
| Composure/Eye Contact | | | | | | | | | | |
| <input checked="" type="checkbox"/> | | Control of nervousness and body movement | | | | | | | | |
| <input checked="" type="checkbox"/> | | Eye contact with audience | | | | | | | | |
| GENERAL COMMENTS | | | | | | | | | | |
| | | | | | | | | | | |

Student Feedback

Students have responded very well to the new laboratory. Results obtained from laboratory course evaluations are shown on Fig.5. Lab-Volt equipment helps students understand the input output characteristics of each power electronics module without going into details how each module was actually designed. Once students get familiar with each module, and its input-output characteristic, they get introduced to Power-pole boards. Power-pole boards help students understand details of actual industrial design of power electronics converters. Likewise, students get introduced to the steady state operation of electric machines and drives by using Lab-Volt equipment prior to using it in combination with digital controllers and power electronics converters in DSPACE related experiments.

DSPACE related experiments that used for digital control of electric machines turned out to be very interesting but yet abstract. Students complained that it took them a long time to learn how to use DSPACE before they applied it in the actual experiment.

Assessment methods used in this course have proved to be very efficient, especially mid-term and final bench exams. Students had to practice and review material related to assigned laboratory experiments. During their presentations, demonstrations evaluation form was used for grading different skills. Some students were uncomfortable during the mid-term exam but most of them improved by the time they took the final.

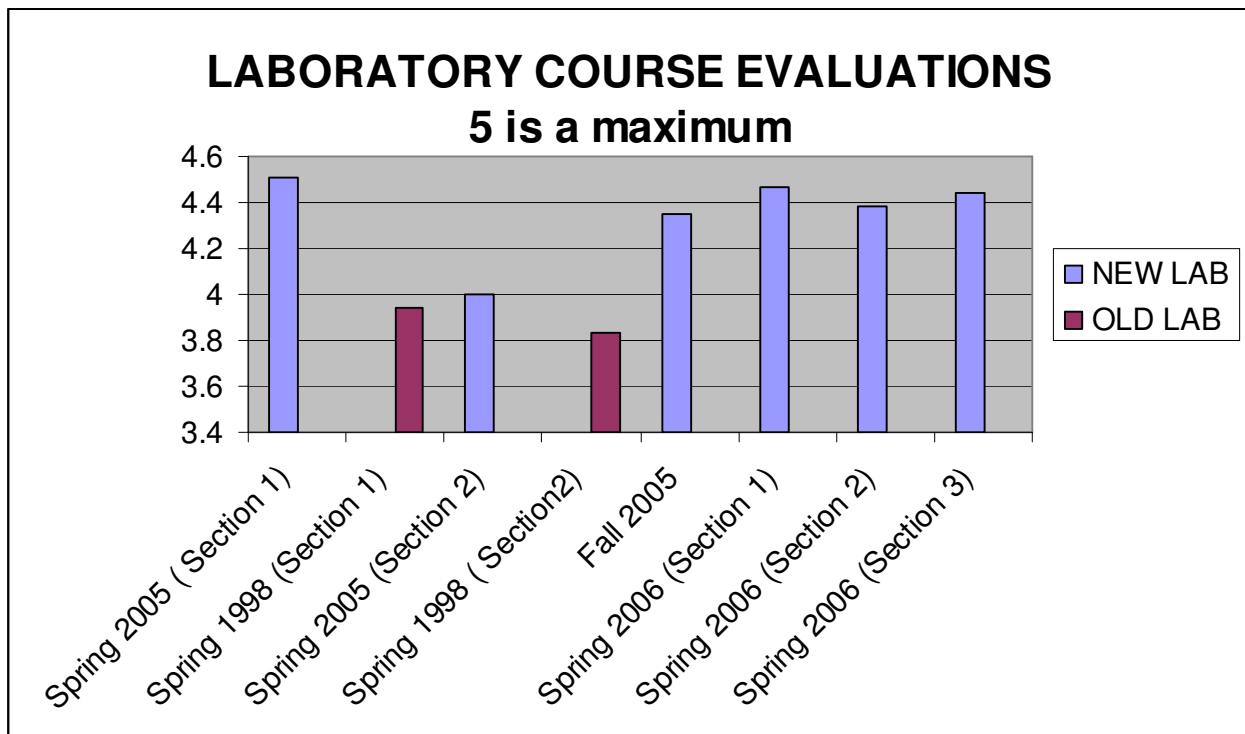


Figure 5. Laboratory course evaluations

Conclusion

The state of the art Power Electronics and Electric Machines Laboratory that has recently been developed provides an excellent opportunity for our students to learn Power Electronic and Electric Machines by using modern equipment. The unique approach to teaching the laboratory course by using traditional as well as contemporary approach resulted in enthusiastic and efficient learning process. The assessment methods stimulated the majority of students to efficiently apply their knowledge obtained in two prerequisite courses and greatly improve their writing and speaking skills.

Acknowledgment

Authors would like to thank NSF (award # 0410912), Nasa Glen Research Center and Fenn College of Engineering for supporting this project.

References

- [1] Lab-Volt Systems, Inc., < <http://www.labvolt.com>>
- [2] Youakim Al Kalaani and Abul K M Azad, "Teaching Electric Machines and Power electronics: Emphasis and challenges," *Proceedings, 2002 ASEE Annual Conference & Exposition*, 2002.
- [3] William Robbins and Ned Mohan, "A Building-Block-Based Power Electronics Instructional Laboratory," in *Proc. IEEE power electron. Spec. Conf.*, vol. 2, Cairns, Australia, 2002, pp. 467-472.
- [4] Department of Electrical and Computer Engineering University of Minnesota, "Power Electronics Laboratory user manual," July. 2004.
- [5] Shuhui Li, "Laboratory Restructuring and Development for the Course of Electric Machinery Using Software and Hardware IT tools," *Proceedings, 2005 ASEE Annual Conference & Exposition*, 2005.
- [6] Ahmed Rubaai, James H. Johnson, Jr. and Donatus Cobbinah, "The New Motors and Controls Laboratory at Howard University," *Proceedings, 2005 ASEE Annual Conference & Exposition*, 2005.