Power Electronics and Motion Control Laboratory

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1.   Introduction

The Power Electronics and Motion Control Laboratory (PE&MC) of the School of Engineering, San Francisco State University serves three senior electrical engineering courses: ENGR 455 Power Electronics, ENGR 447 Control Systems, and ENGR 306 Electromechanical Systems. There are many projects configured for these three courses, using various apparatus. Some of devices and systems are purchased and some of them are made in house, taking advantage of a Printed Circuit Board prototype machine, which was acquired through a NSF-ILI grant. We will introduce a few projects that demonstrate our design philosophy in setting up this Power Electronics and Motion Control (PE&MC) Laboratory: Hands on Experience and System Approach.

Hands-on Experience:

One of the most important objectives for the PE&MC Laboratory is for students to acquire as much hands-on experience in power electronics as possible. We believe the best way to re-enforce any engineering theory is to do it yourself in the laboratory. This is especially true in power electronics because many circuits are inherently high voltage and high current analog electronics. This is quite different from the low voltage digital and analog circuits most EE students are accustomed to. The focuses of the Hands-on experience we would like to introduce to students in the PE&MC Laboratory are experimental techniques and special precautions, which should be taken seriously for anybody interested in doing power electronics related works.

System Approach:

Another common deficiency for courses on control theory and electromechanical system is that students concentrate too much on control subsystem and/or rotating machine subsystems individually so a global system view of the complete motion control applications is not fully developed and appreciated. This task is quite challenging. Our approach is to present students with different viable engineering solutions for a given specification. Take a constant speed conveyor belt industrial application as an example: A DC motor can be used to configure a system that can meet the specification. To achieve the objective of the speed control, either a Pulse Width Modulated full bridge DC to DC converter [1] or a controlled rectifier circuit can be used to drive the DC motor. By choosing different circuits, students need to understand what other peripherals associated with the chosen circuits are needed in order to make the whole

system work. With this type of training, we try to plant a seed in students' analytical mind so they can develop the global system view for the motion control system.

2.   Basic Training on Instrumentation

To accomplish these two objectives of the PE&MC laboratory (<u>Hands on Experience</u> and <u>System Approach</u>), the first part of the laboratory projects is to train students how to use modern instruments that are essential in the field of power electronics: digital oscilloscope, spectrum analyzer, voltage and current transducers, and curve tracer. We have a Tektronix 754C digital oscilloscope, Nicolet 420 oscilloscope, Hewlett Packard 3582A Spectrum Analyzer, Tektronix 370 Curve Tracer, and various voltage and current transducers available for students to use in the laboratory projects. The following concepts are emphasized:

*   Digital sampling theory: Students need to know the impact of using different sampling frequencies on the captured experimental data. They also have to develop a sense of guessing on what to anticipate in the laboratory before they adjust various knobs of the oscilloscope.
*   Post-processing of the captured experimental data: Students need to know how to capture experimental data and save it on floppy disks for future analysis. Once they master this skill, they can perform many advanced data analyses such as Fast Fourier Transform (FFT) of periodical waveform.

The project setup for the basic training is shown in Figure 1. A HP function generator is used to generate a square wave signal of adjustable frequency, which ranges from 1 kHz to 50 kHz. A Nicolet 420 oscilloscope is used to capture and display the generated square wave. The sampling frequency of the Nicolet Oscilloscope can be adjusted to the maximum of 1 MHz with a 12-bit resolution. The HP 3582A Spectrum Analyzer is used to show the spectrum of the generated square wave signal up to 50 kHz, since the maximum sampling frequency for it is 100 kHz. We ask students to do the following:

*   Generate a square of 10 kHz using the function generator. Use the HP spectrum analyzer to record the harmonic spectrum of the generated square wave. Adjust the sampling frequency of Nicolet Oscilloscope to 1 MHz and capture and store the square wave signal.
*   Using either Matlab or Excel to analyze the harmonic spectrum of the captured waveform from the Nicolet Oscilloscope and compare them to those from HP spectrum analyzer.
*   Generate a square wave of 100 kHz and repeat previous two steps. Given the maximum sampling frequency of HP spectrum analyzer and Nicolet Oscilloscope is 1 MHz and 100 kHz respectively, students need to analyze and comment on all experimental results.

With this proposed exercise, students can learn the basic operation of a digital oscilloscope and spectrum analyzer. They also understand the importance of sampling frequency on the integrity of digitized waveform.

3.   **DC to DC Converter Laboratory Project**

Students in the power electronics course need to form a group of either 2 or 3 persons and each group must select one DC to DC converter circuit to be their semester long project.

Students must design, build, and test the selected circuit module to satisfy the project requirement. In the meantime, the following modules are available for students to use and play with in the power electronics laboratory during the semester:

- Basic MOSFET Switching Circuit Module
- Buck (Step Down) DC to DC Converter
- Boost (Step Up) DC to DC Converter
- Buck and Boost DC to DC Converter
- Cuk DC to DC Converter
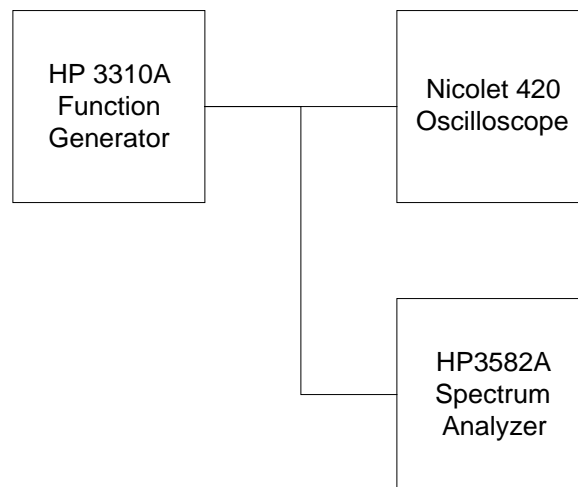- Full Bridge DC to DC Converter

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+-----------------+          +-----------------+
|  HP 3310A       |          |  Nicolet 420    |
|  Function       |----------|  Oscilloscope   |
|  Generator      |          |                 |
+-----------------+          +-----------------+
                  |
                  |          +-----------------+
                  |          |  HP3582A        |
                  |----------|  Spectrum       |
                             |  Analyzer       |
                             +-----------------+
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Figure 1: Block Diagram for the Instrumentation Project

All the power electronics modules are actually designed, built, and tested by students under supervision of faculty from previous semesters. Students, using PCBoard software from MicroSim and a prototype PCB manufacturing machine from LPKF, make the printed circuit board (PCB) for each module. All inductors and transformers that are used in these modules are also designed and built by the students. These modules are the results of semester long design projects previous students finish as a required assignment for power electronics course. Obviously, students must demonstrate innovative design in their project assignment from the modules available in the laboratory in order to get appropriate grade. Figure 2 shows the schematics of the Buck and Boost DC to DC Converter. The control gate voltage and current waveforms for the inductor L for both continuous and discontinuous current operating modes are shown in Figure 3.

Hands-on experience is the objective for these laboratory projects. Students need to study the schematics of these DC to DC Converter circuit modules in advance. They also have to observe various waveforms in the laboratory sessions to enhance their understanding of various DC to DC Converters. Since to design, build, and test a DC to DC Converter is one of the assignments, these modules provide students with plenty of suggestions on their own design. Which MOSFET driver should be used? How can an inductor of 200 µH at 100 kHz be designed? Which controller IC chip is convenient to use? Which MOSFET shall be used? How

can a heatsink be selected? How to accomplish the PCB layout of a circuit, which has power and control signals at close proximity? Based on our experience, these DC to DC Converter modules are right size of semester long project for students. They have enough opportunities for students to explore and at the same time, these projects are not so complicated such that students can complete the whole project in one semester time to give them a sense of accomplishment.
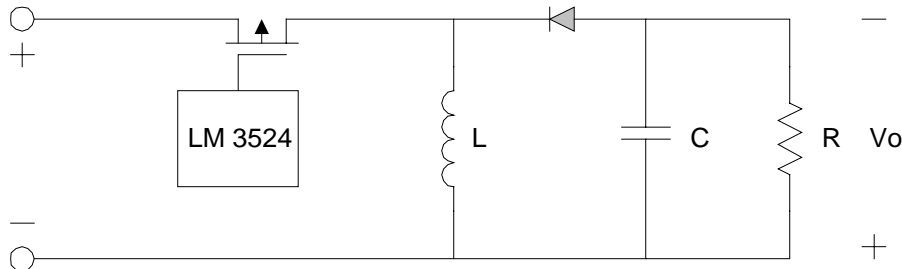

Figure 2: A Simple Buck and Boost DC to DC Converter

4.   Pulse Width Modulation for DC Motor Drive

To illustrate how a power electronic circuit, rotating machine, and control algorithm can be used together to configure a complete motion control application, we use the circuit shown in Figure 4 as the laboratory project. The LM18200 full bridge DC to DC converter from National Semiconductors is used to drive a DC motor, Matsushita GMX-6MP009A, using the Pulse Width Modulated scheme. Three control signals, *PWM*, *Direction*, and *Brake*, are needed to control the LM18200 module. These signals can be generated from a PWM controller IC or any other digital means to control the output of the LM18200 [2]. In Figure 4, we used a dedicated Unirode 3524 PWM controller IC to generate a PWM signal whose frequency and duty cycle can be adjusted through two potentiometers. A duty cycle can vary between 0.1 to 0.9 and the frequency can change from about 100 Hz to 100 kHz. A built-in current transducer from LEM can allow current waveform to be observed. The output of LM18200 drives the Matsushita GMX-6MP009A DC motor with a gear-head and 1250-pulse encoder output. Figure 5 shows the voltage of the DC motor, current through the DC motor, and encoder output waveforms. This converter can also receive three control signals - *PWM*, *Direction*, and *Brake* - from any digital outputs such as the data acquisition board controlled by a LabView® Virtual Instrument (VI) [3], simply by turning on a control switch S1. With this experimental system, the following tasks can be accomplished:
- Demonstrate the working principles of a full-bridge DC to DC converter.
- Demonstrate the Pulse Width Modulated control scheme of a DC Motor.
- Demonstrate the working principle of an optical encoder, which is essential for most motion control application.
- Demonstrate how the encoder output can be integrated into the DC motor controller to implement a speed control loop for the DC motor using PWM control scheme.
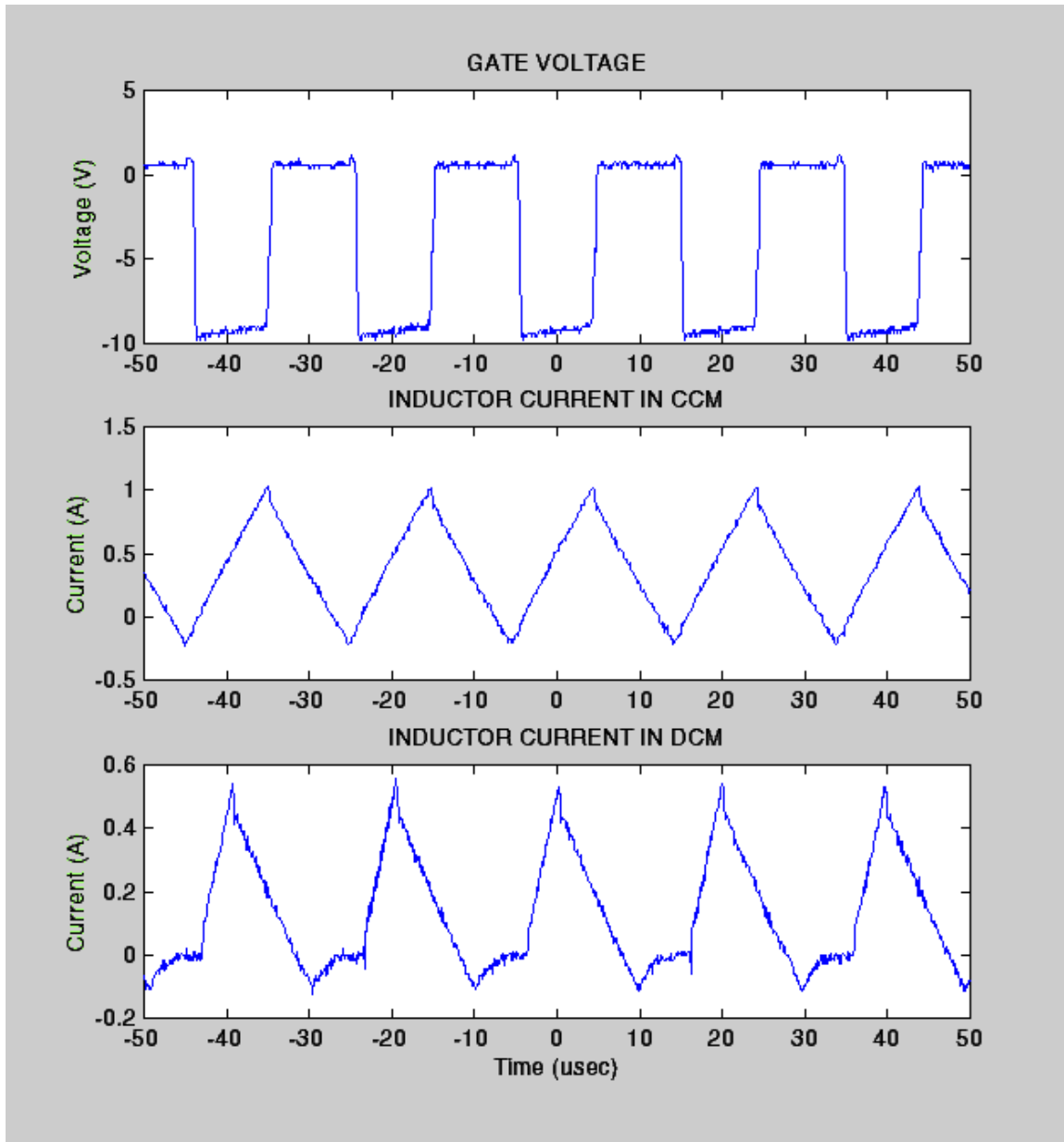
Figure 3: The Control Voltage and Inductor current for Continuous and Discontinuous Current Operating Mode

We use LabView's VI to implement a speed control loop for the DC motor. LabView's VI is a powerful tool that can seamlessly integrate hardware control and software algorithm for this project. A VI program can be written to convert the encoder output to a signal that is proportional to the actual speed of the DC motor. This actual speed can be compared to the commanded speed to generate the error signal. Then a PI, PD, or PID controller can be implemented easily using LabView's VI programming capability to generate a control signal that controls the duty cycle of the LM18200. Torque control can be incorporated easily, using the current limiting feature of the LM18200 [3]. With this experimental setup, a DC motor speed control loop can be demonstrated to students, using commonly available components and

devices. The same principle can be applied in profile control loops if desired. With this simple experimental setup, students can study how power electronics, rotating machine, and control algorithms are integrated into a complete system to achieve specific objective of motion control.

We can also ask students to write their own LabView® VI programs for the speed control loop and various control algorithms such as PI, PD, and PID controllers. This experimental setup is simple enough so students can understand the basic building blocks of DC motor speed control application. It also allows students ample opportunities to explore further if they desire.
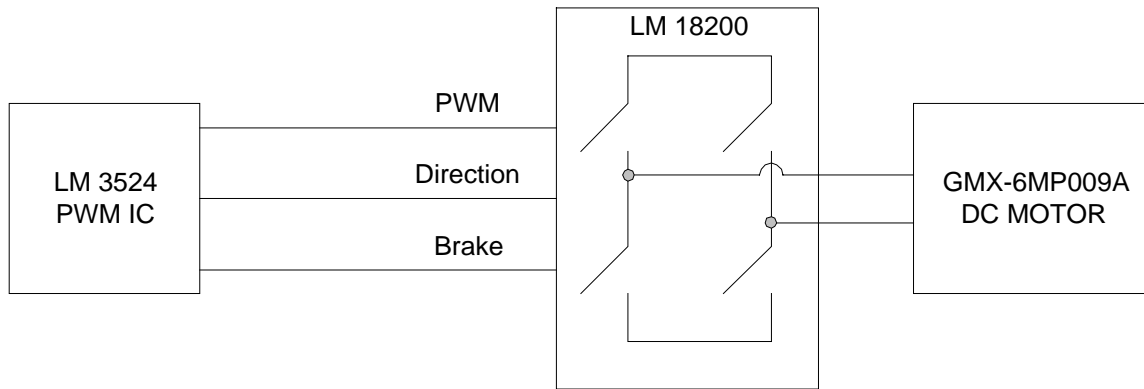

Figure 4: Pulse Width Modulation DC to DC Converter using LM18200
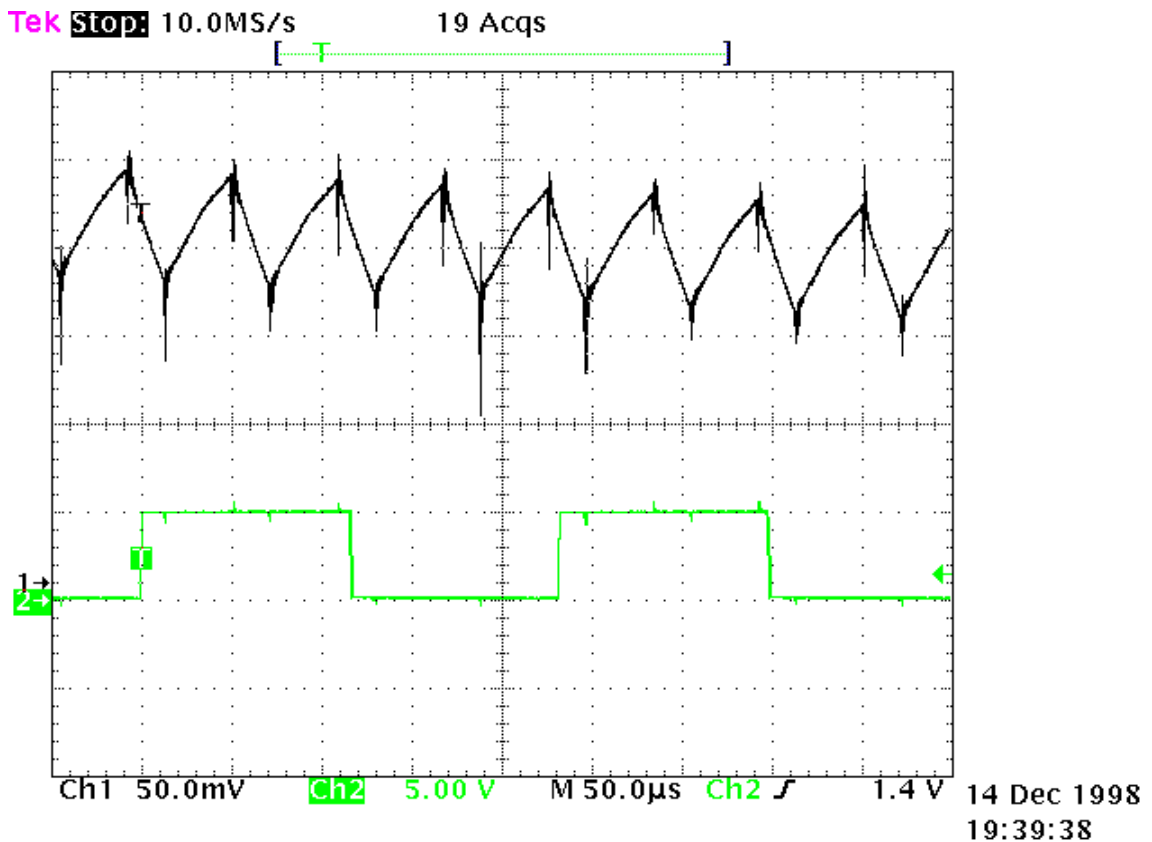

Figure 5: The Armature Current and Optical Encoder Output for DC Motor

5.   Implementation of Control Algorithms for DC Motor using LabView's VI

We also set up an experiment to demonstrate general principles of control algorithms used in motion control application. The experimental setup is shown in Figure 6. An HP AC/DC source 6813A is used to generate a voltage source whose magnitude could be controlled through the IEEE 488 protocol which in turn controls a LESSON 1-hp permanent magnet DC motor. A Magtrol HD-710-8 dynamometer with 5240 controller is used to simulate various load cycles for the permanent magnet DC motor. This dynamometer can also receive commands from computer to set specific load torque at any speed. It can also send the actual torque and speed information back to the computer via IEEE-488 protocol.
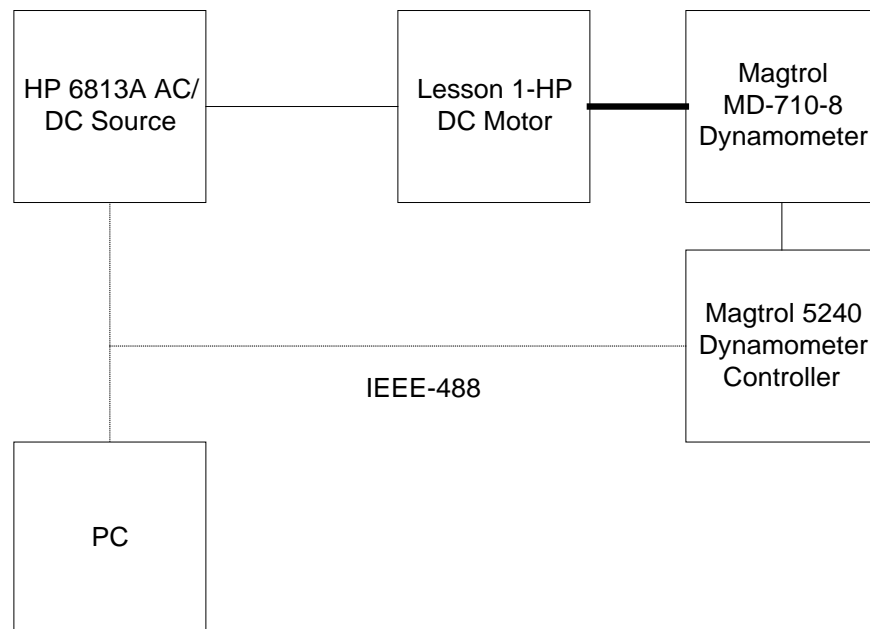

Figure 6: Block Diagram for Control Algorithm Laboratory Project

The purpose of this experimental setup is to simulate how to implement various motion control algorithms using an almost ideal voltage source, HP AC/DC source 6813A. We are trying to complement the lecture with an experimental project to demonstrate the basic control concepts without using abstract mathematical tools such as transfer functions. For example, in the control theory class, it is mentioned that in order to control the speed of DC motor, there shall be a torque control loop inside the speed control loop. How can a torque control loop be implemented? For DC motor, you have to control the armature current. How did you control the armature current of a DC motor? Use a voltage source whose magnitude can be adjusted based on actual speed of DC motor. Thus, we try to introduce the basic concept first without lots of mathematical burdens. Once students understand the basic physical concepts using the ideal source, then they can realize how control should be implemented for a PWM DC motor controller.

They can concentrate on how to implement a speed control loop using the measured actual speed from the Magtrol Dynamometer. The following concepts are emphasized:

- How is a speed control loop is implemented based upon the most basic physical concepts? What information do they need to have in order to implement a speed control loop?
- How to write a simple control algorithm using LabView's VI programming capability with simple *add*, *subtract*, and/or *gain* functions?
- How to incorporate actual constraints into the implementation phase, such as maximum voltage and/or maximum current the source can provide?
- How to implement P, PI, PD, and PID controllers, using basic physical concepts and simple LabView's VI capability?
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Figure 7 shows armature voltage, armature current, output torque, and speed of the permanent magnet DC motor. The voltage waveform closely correlates the speed of the motor, as expected. Also, the armature current has the same waveshape as that of the motor torque. The LabView's VI program is shown in Figure 8. It can be seen that the speed control loop is very simple. The actual speed is compared with the control speed. The difference of them is sent to a simple gain K1. The output of the gain K1 is the commanded current (torque). This commanded current is compared to the actual current and the error signal is sent through another gain box K2. This value is added to the actual armature voltage to generate the updated armature voltage, which in turn is sent to the DC motor to control its speed. This is a simple conceptual speed control loop. Students understand this approach extremely well since we leave out many unnecessary details at the beginning. After this simple conceptual loop is introduced, more detailed and practical control algorithms can be presented to students to enhance their understanding of the abstract concept of control theory. We just finished this experimental setup and we don't have any opportunity to show it to students in the control theory class yet. Once we have feedback from students, we will report our findings on this topic in the future ASEE conference.

6.   Conclusions and Future Suggestions

We have started the task of establishing a Power Electronics and Motion Control (PE&MC) Laboratory in the School of Engineering at San Francisco State University. Hands-on Experience and System Approach of the Motion Control Applications are the two objectives for this PE&MC laboratory. The methodology we use in trying to achieve these two objectives is presented in this paper. The initial impression from students is unanimously good. They like the idea of building the circuits themselves especially using the PCB circuit board prototyping machine. They also enjoy the PWM DC Motor speed control experiment and the LabView's VI programming. They have a better understanding of how a speed control or any other control loops are implemented using actual power electronic circuits. Based on students' responses, we believe the PE&MC is on the right track to achieve those two objectives: hand-on experience and system approach of motion control application.

The limited number of projects we presented is not meant to be inclusive at all. As a matter a fact, we are currently working on many other experimental projects that utilize other types of motors and DSP-based controllers. We have various sizes of switched reluctance motor and controller, brushless DC motor, stepper motor, and induction motor in the PE&MC laboratory. We also acquired a DSP-based board using Texas Instrument's TMS320C6201 DSP

chip running up to 120 MHz that could be used as the controller for any motion control application. We will report new development on experimental projects in a later ASEE paper.

Bibliography
[1]   Ned Mohan, Tore Underland, and William Robbins, *Power Electronics, Converters, Applications, and Design*, John Wiley and Sons, 2nd edition, page 100, 1995.
[2]   Application Note for LM18200 Full Bridge Motor Driver, National Semiconductors, Inc.
[3]   LabView® Instruction Manual, National Instrument, Inc.

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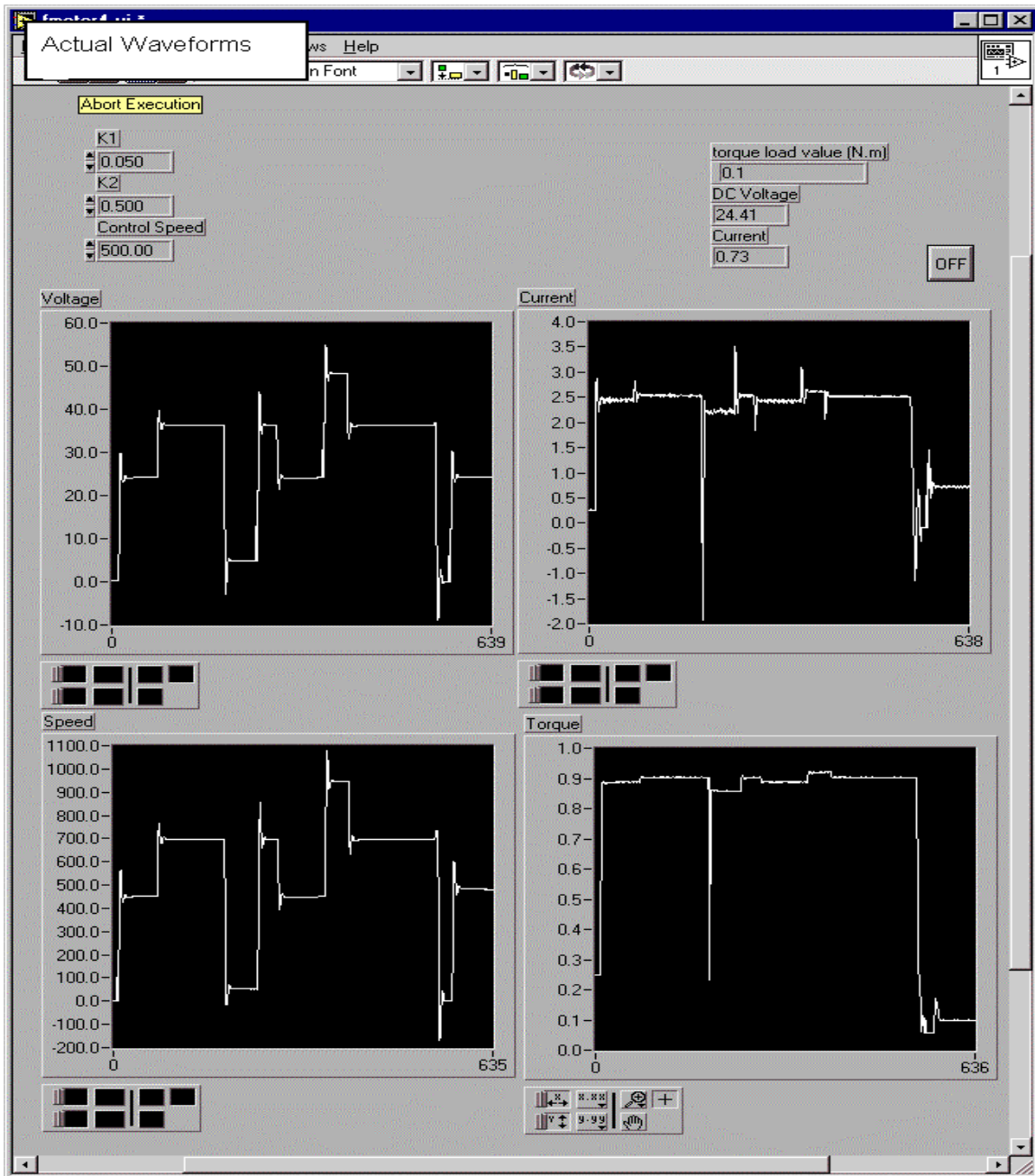
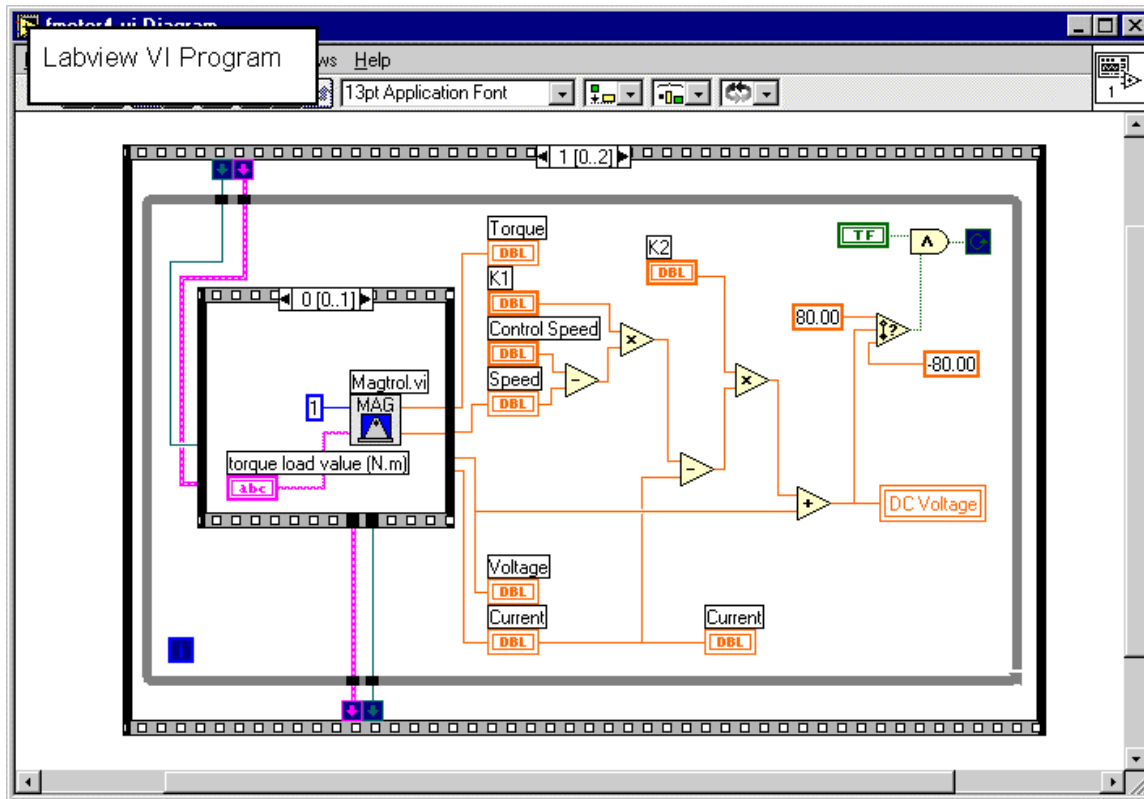**Figure 7: The Voltage, Current, Speed, and Torque Waveforms of DC Motor**

Figure 8: Labview® Programming for the Simple Control Loop