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Use of a Popular Power Electronics Platform in a Control Systems Laboratory

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Use of a Popular Power Electronics Platform in a Control Systems Laboratory

Abstract

The "power-pole board", developed at the University of Minnesota (UMN), and commercialized by Hirel Systems, is widely used in U.S. universities for power electronics laboratory experiments. The board can be configured as a buck-converter, boost converter, buck-boost converter, flyback converter, or forward converter. A lab manual developed at UMN for use with the power-pole board is available in the public domain. The manual also includes experiments on closed-loop control of the buck converter; closed loop control allows the output voltage of the converter to be regulated and remain immune to variations in the input voltage or converter load. Design of the controller in the UMN lab manual is based on the the K-factor approach (a frequency domain technique that involves a number of derivations and calculations pertaining to achievement of a desired phase margin).

University of the Pacific was a member of an 82 university consortium (led by the University of Minnesota) that was supported by a Department of Energy grant to "revitalize electric power engineering education by state-of-the-art laboratories". This paper describes how the grant enabled University of the Pacific to implement a new power electronics course and lab using the power pole board and publicly available UMN developed materials. The paper also describes how the power pole board was used to support the laboratory experience in a control systems course without any additional expense for lab equipment. It describes how Proportional + Integral (PI) controllers can be designed for the power pole board buck converter. The design approach (using Matlab to design the controller) is simpler than the K-factor method, and provides instantaneous information on the transient response of the closed-loop system. The paper also shows how PI controllers can be implemented on the power pole board (this information is not available in the UMN lab manual, and could prove useful to the community of power pole board users).

The power pole board (a relatively low cost investment of about $1250 per board) has enabled University of the Pacific to provide meaningful lab experience in power electronics and control systems. Student feedback on the lab experience in these two courses has been positive and is presented.

Introduction

The University of Minnesota (UMN) was the lead institution that was awarded a Department of Energy (DOE) grant[1] over the 2010-2013 period to create "A nationwide consortium of universities to revitalize electric power engineering education by state-of-the-art laboratories." The consortium consisted of 82 universities that used UMN developed laboratory hardware and software resources to set up laboratories in their home institutions. Besides developing new laboratories, one of the objectives of the grant was for institutions to modify or create new experiments to meet local needs. Under this grant, University of the Pacific acquired 5 lab stations containing the "power-pole board" (PPB) and associated equipment to support teaching of power electronics. The PPB, which can support lab experiments for a number of power electronic converters[2], was developed at UMN with support from a National Science Foundation (NSF) grant. The board is now available for purchase from Hirel Systems[3] at a cost of $1250 (discounts are available for purchases involving more than one board).

UMN developed materials available to consortium members to support development of the power electronics course include a PSPICE simulation lab manual and a hardware lab manual to accompany the power-pole board. Both these resources are available at no cost to anyone who wishes to use them[4]. These resources were extremely helpful in the development of a new course by a faculty member whose primary expertise was not in the area of power electronics. The laboratory component of the course includes some of the simulation labs and hardware labs based on UMN materials that have been customized for the local context. The power electronics course has been offered three times (Fall 2011, Spring 2013, and Spring 2015) and has a number of graduates who are working in power and energy related careers. Student course evaluation data shows that the power electronics laboratory was effective in developing lab skills and facilitating understanding of power electronics concepts.

The author also had the opportunity to develop and teach a control systems course in Spring 2014 and Fall 2015. The control systems course does not have a dedicated laboratory period, but has about an hour per week on average for simulation-based lab exercises and for one culminating hardware experiment. The power-pole board was used for the hardware experiment: closed-loop voltage mode control of a buck converter. The UMN lab manual has an experiment on voltage mode control of a buck converter (it uses the K-factor approach[5,6] to design a controller to provide a 60º phase margin). For the control systems course, pole-zero placement using the Matlab GUI *sisotool* was used to design a PI controller. Use of Matlab tools for controller design is something the control systems students were already exposed to, and this circumvented the lengthy derivations and formulas associated with the K-factor approach. The power-pole board is widely used for power electronics education (in addition to the 82 universities participating in the DOE grant, several published papers[7-14] document use of the power-pole board at universities). The approach for using the PPB for closed-loop control as documented in this paper provides a low cost option for hardware experimentation in control systems courses.

The Power Pole Board

The UMN hardware lab manual[4] describes how the PPB can be used to experiment with Buck converters, Boost converters, Buck-Boost converters, closed-loop voltage mode control of a Buck converter based on the K-factor approach, peak current mode control of a Buck converter, flyback converters, and forward converters. Configuring the board to implement any of the converter circuits just involves flipping selection switches on the board, connecting a couple of wires between appropriate screw terminals, plugging in the appropriate magnetics board, and connecting external power and loads. Fig. 1 (taken from the UMN lab manual) depicts the wiring (shown with thicker lines) needed to configure the PPB as a buck converter. The DC input voltage to be stepped down is connected to the left side of the board via banana cables. The external load resistance is connected similarly at the right end of the board. A couple of wires between screw terminals connect the left power pole (Mosfet and diode combination) to the inductor (which is located on the inductor board that plugs into the PPB). The inductor board (depicted with a double lined border) supports all experiments except the flyback and forward converters, for which different magnetics boards are needed. The PPB contains probe points to view relevant input, output, switching, and other pertinent signals on an oscilloscope. The current sensors (marked LEM in Fig. 1) allow the input and output current waveforms to be viewed on an oscilloscope.

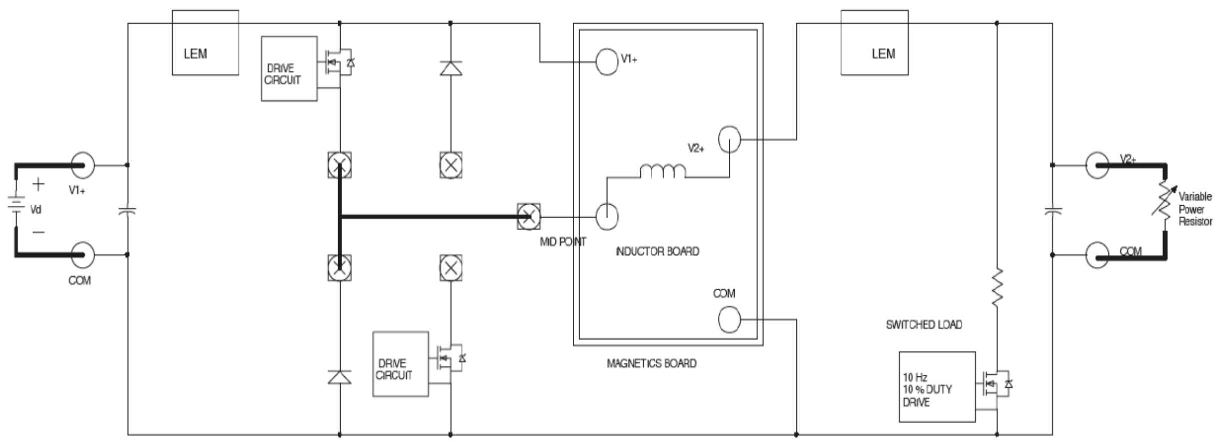

Fig 1: Interconnections to configure the PPB as a buck converter

Fig. 2 (taken from the UMN lab manual) shows the switches, jumpers, and potentiometers on the PPB. The leftmost switch when turned on delivers the pulse-width-modulated (PWM) switching signal to the MOSFET. The next block is a switch bank consisting of four switches; for configuration as a buck converter, the leftmost switch is put in the up position to deliver the PWM signal to the top MOSFET (corresponding to the left power pole of Fig. 1). The duty cycle potentiometer when rotated adjusts the duty cycle of the PWM signal, and thus the output voltage of the buck converter. The switching frequency potentiometer can be used to adjust the switching frequency of the PWM signal from about 14kHz to 114kHz. The jumpers at the right end of the figure can be used to configure the board for open-loop operation (jumper positions as in Fig. 2), or for external feedback control (jumper positions as in Fig. 3).

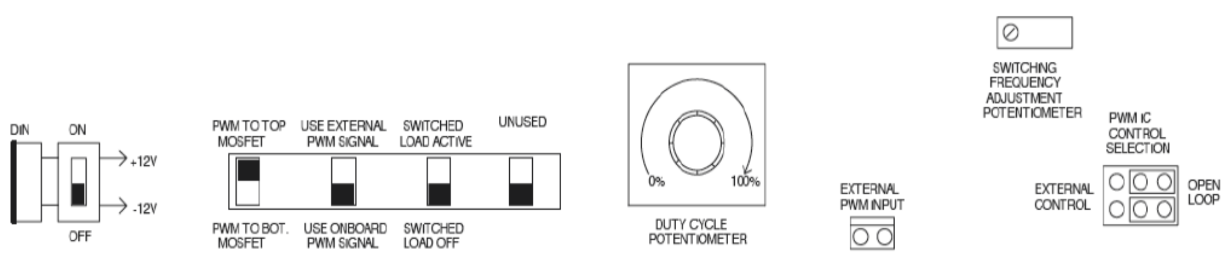

Fig 2: Switches, potentiometers, and jumpers to configure the PPB

Use of the power pole board in a Control Systems course

The control systems course at University of the Pacific does not have a separate 3 hour lab period. Instead, about 1 hour per week of the 4 unit course is devoted to lab exercises, most of which are simulation-based using Matlab and Simulink. In light of the limited time available for lab work, the PPB was a perfect platform for performing a hardware lab experiment on closed-loop control. All that is needed to implement closed loop buck controller control on the PPB is to make the wiring connections shown in Fig. 1, and the feedback controller connections depicted on the breadboard in Fig. 10. Low hardware setup time allows the hardware lab to be completed in a one hour time frame.

The block diagram of the buck converter control system is depicted in Fig. 3 along with the jumper settings needed to put the board into external control mode (the top jumper J63 is moved to the left, while the bottom jumper J62 is left unchanged).

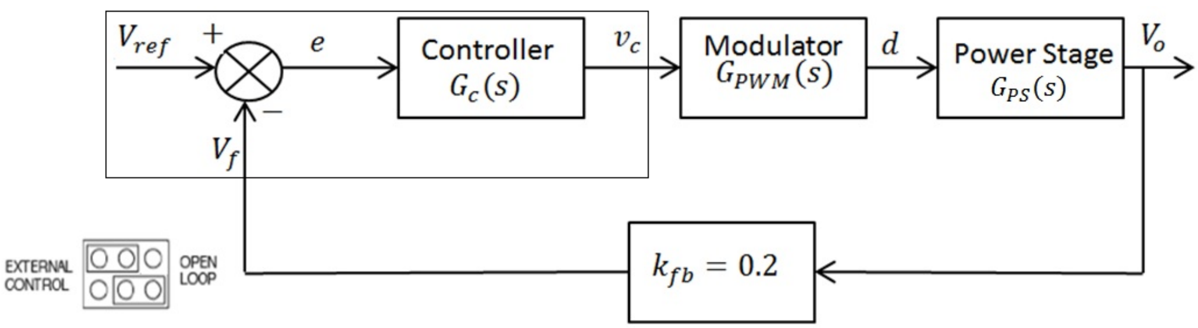

Fig. 3: Block diagram of the buck converter control system

In external control mode, the reference voltage V_{ref} is set by the duty cycle potentiometer of Fig. 2. On the PPB, the feedback signal is produced by scaling the converter output voltage V_o by a gain factor $k_{fb} = 0.2$; the feedback signal is thus $V_f = 0.2V_o$. The controller $G_c(s)$ operates on the error signal e and produces the output control voltage v_c. The modulator $G_{PWM}(s)$ compares the control voltage against a ramp signal to produce the PWM signal of duty cycle d that drives the MOSFET in the power stage. In response, the buck converter produces the output voltage $V_o \approx dV_{in}$, where V_{in} is the DC supply voltage of the converter.

The companion textbook[5] that complements the UMN developed lab materials shows that the transfer function of the pulse width modulator on the power pole board is

$$G_{PWM}(s) = 0.556 \tag{1}$$

The derivation of the power stage transfer function in the textbook[5] is lengthy and includes an approximation. The exact transfer function of the buck converter power stage can be derived in a simpler fashion as follows. The buck converter power stage schematic is depicted in Fig. 4. The switching frequency of the PWM switching signal is set at $F_s = 100\text{kHz}$ with variable duty cycle d. The converter supply voltage is set at $V_{in} = 20\text{V}$, the inductance is $L = 100\mu\text{H}$, the capacitance is $C = 690\mu\text{F}$, and the equivalent series resistance of the capacitor at the 100kHz switching frequency is $r = 0.128\Omega$ (it is high due to the presence of a physical 0.1Ω resistance in series with the capacitor to probe the capacitor current waveform). The load resistance is set to $R = 10\Omega$.

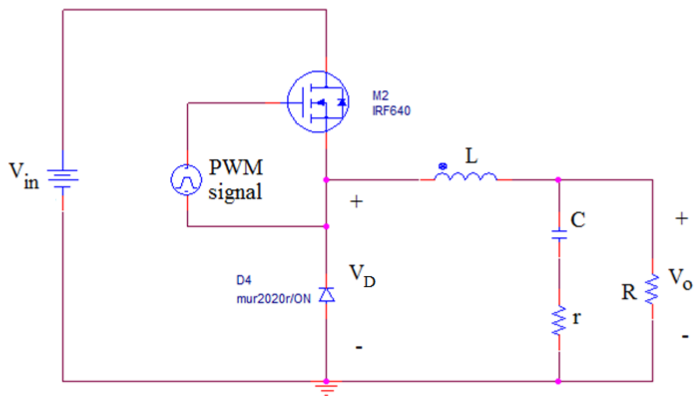

Fig. 4: Buck Converter Schematic

The small signal transfer function of the power stage is $G_{PS}(s) = \frac{\tilde{V}_o}{\tilde{d}}$, where $\tilde{d}$ is a small change in the switching signal duty cycle, and $\tilde{V}_o$ is the corresponding change in the average output voltage. Simple s domain analysis shows that the transfer function of the output filter is

$$\frac{\tilde{V}_o}{\tilde{V}_D} = \frac{r}{L}\frac{\left(s + \frac{1}{rC}\right)}{s^2\left(1 + \frac{r}{R}\right) + s\left(\frac{r}{L} + \frac{1}{RC}\right) + \frac{1}{LC}}$$

It is well known that the change in average diode voltage $\tilde{V}_D$ due to a duty cycle change $\tilde{d}$ is $\tilde{V}_D = \tilde{d}V_{in}$. Making this substitution in the above equation yields

$$G_{PS}(s) = \frac{\tilde{V}_o}{\tilde{d}} = \frac{V_{in}r}{L}\frac{\left(s + \frac{1}{rC}\right)}{s^2\left(1 + \frac{r}{R}\right) + s\left(\frac{r}{L} + \frac{1}{RC}\right) + \frac{1}{LC}} \qquad (2)$$

The forward path transfer function excluding the controller in the block diagram of Fig. 3 is $G(s) = G_{PWM}(s)G_{PS}(s)$. Using $G_{PWM}(s) = 0.556$ from (1) and substituting the power pole board component values specified earlier into (2) we get

$$G(s) = \frac{14233.6(s + 11208.75)}{1.0128s^2 + 1423.47s + 14.347 \times 10^6}$$

We now proceed to describe the design of the controller $G_c(s)$. The most appropriate controller for this application is a proportional + integral (PI) controller. A PID controller is not appropriate because the output voltage of the converter contains high frequency ripple which is amplified by the derivative operation. The PI controller provides zero steady state error and can be tuned to provide good dynamic response. The Matlab GUI *sisotool* is used to design the PI controller $G_C(s)$. The tool is launched by typing in *sisotool* at the Matlab command prompt. In the *Architecture* tab, select *System Data* and enter in the transfer function G and feedback path gain $H = 0.2$ as seen in Fig. 5.

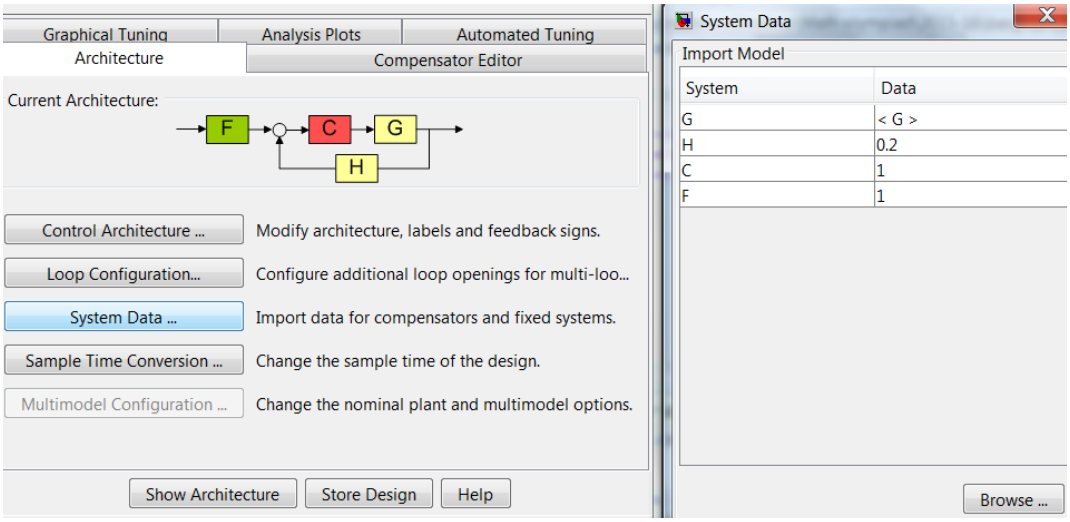

Fig. 5: Sisotool screen showing system architecture

Under the Graphical Tuning tab, selecting Root locus and Open loop Bode plots brings up a window showing these two plots, as in Fig. 7. The design can be interactively done, for example, by grabbing a pink dot on the root locus with the mouse and dragging it. This changes the controller gain, and the corresponding changes in Bode plots and phase margin are automatically updated.

A PI controller has a pole at $s = 0$ and an additional zero. Automated tuning of the controller (via the automated tuning tab in Fig. 5) does not work well for this problem: since $G(s)$ already has a zero, automated tuning results in a controller that consists only of an integrator (1/s) term. The PI controller is therefore designed manually: clicking on the red x at the top left of the window of Fig. 7 brings up a controller pole which can be placed on the negative real axis in the root locus window. The pole location can be edited by clicking on the Compensator Editor tab seen in Fig. 6: the pole location is set to $s = 0$ in the location field. A zero is similarly placed on the negative real axis by clicking on the red 'o' at the top left of the window of Fig. 7. The zero location and compensator gain are varied and the phase margin and step response examined. A zero placed at $s = -1000$ and a gain scale factor of 8000 is found to provide good system response. Fig. 6 shows the Compensator Editor window with the pole and zero frequencies and the compensator gain. Examining the compensator C in Fig. 6, we see that the compensator designed is

$$G_c(s) = 8 + \frac{8000}{s} \tag{3}$$

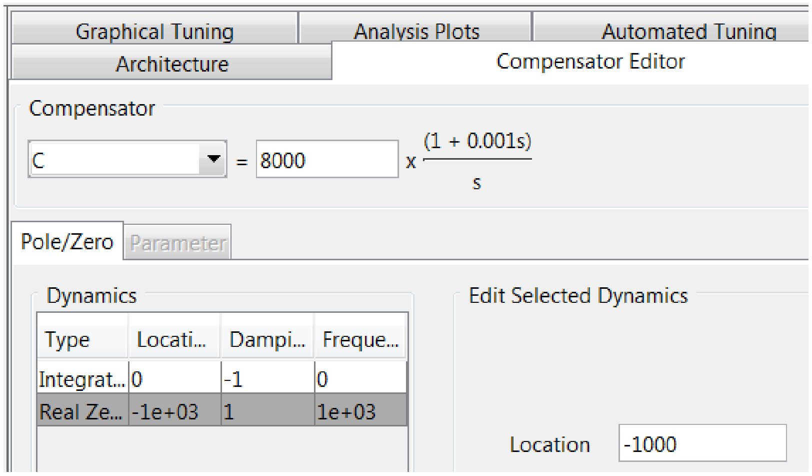

Fig. 6: Compensator editor window showing pole and zero locations and transfer function

Fig. 7 shows the root locus and Bode plots with this compensator $G_C(s)$ in the loop. It shows that the phase margin is 67°at a crossover frequency of 25.2 krad/sec. The system unit step response of Fig. 8 (obtained via the *Analysis Plots* tab) shows that the system has 16.3% overshoot, and a settling time of 1.09ms. With an input reference voltage $V_{ref} = 1V$, the expected output of the buck converter in steady state is $V_o = 5V$ (this makes the feedback signal $V_f = 0.2V_o = 1V$, resulting in steady state error $e = 0$ as expected with a PI controller). Fig. 8 shows that the final output of the buck converter is $V_o = 5V$ as expected.

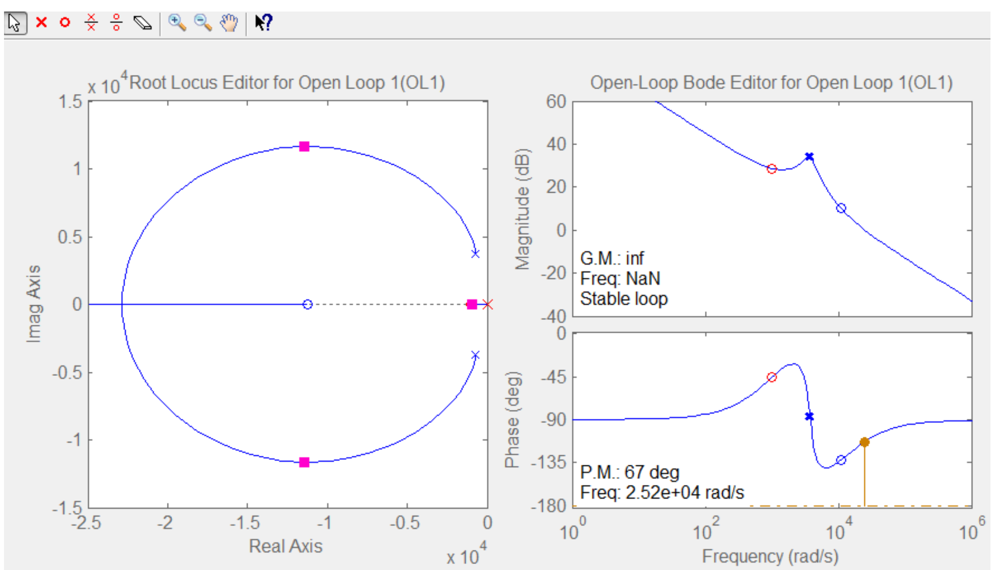

Fig. 7: Graphical tuning design window in sisotool showing design results

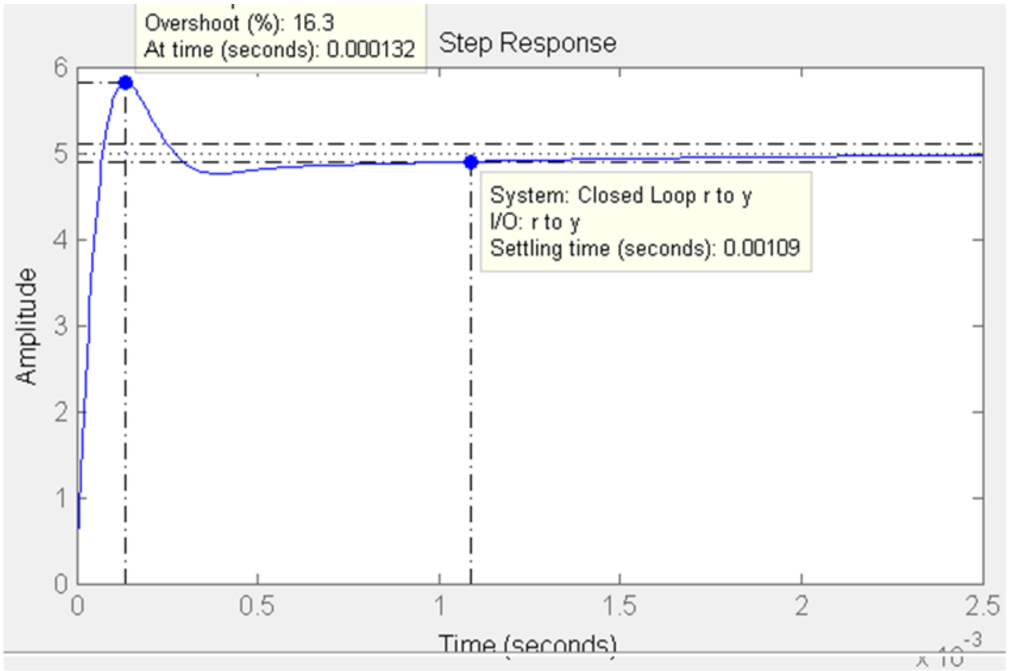

Fig. 8: Unit step response of the buck converter system

Controller implementation on the power pole board

Consider the boxed portion of the block diagram of Fig. 3. Let $\tilde{V}_{ref}$, $\tilde{V}_f$, $\tilde{e}$, and $\tilde{v}_c$ be small variations from the steady state operating points of the corresponding variables. The reference input V_{ref} is typically constant since we want a fixed converter output voltage. We thus have $\tilde{V}_{ref} = 0$, due to which $\tilde{e} = -\tilde{V}_f$. The small signal controller transfer function is thus

$$G_c(s) = \frac{\tilde{v}_c}{\tilde{e}} = -\frac{\tilde{v}_c}{\tilde{V}_f} \tag{4}$$

Fig. 9 depicts the hardware implementation of the controller on the power pole board. Pulse width modulation on the power pole board is performed by the Texas Instruments UC3824 IC. This chip contains a wide bandwidth error amplifier that is used to implement the controller. Moving the top jumper J63 to the external control position as depicted in Fig. 3 connects the black potentiometer (which used to control duty cycle in open loop) to the + input of the op-amp; the black potentiometer thus provides the reference input voltage V_{ref}. The feedback signal V_f, the – input of the op-amp, and the output v_c of the op-amp are available at pins 9, 12, and 13 respectively of a header (daughter board connector J60) on the power pole board. The impedances $Z_1$and Z_2 are placed on an external breadboard and connected to the op-amp circuit via pins 9, 12, and 13 of the header. Performing small signal analysis of the op-amp circuit, the + terminal is essentially grounded, since $\tilde{V}_{ref} = 0$. The circuit thus acts as an inverting amplifier, and its small signal transfer function is

$$\frac{\tilde{v}_c}{\tilde{V}_f} = -\frac{Z_2}{Z_1}$$

Substituting this result into (4) shows that the controller transfer function is

$$G_c(s) = \frac{Z_2}{Z_1} \tag{5}$$

Selecting Z_1 to be a single resistor R_1, and Z_2 to be a resistor R_2 in series with a capacitor C yields the impedances $Z_1 = R_1$, and $Z_2 = R_2 + 1/(sC)$. Substituting these values into (5) yields the controller transfer function

$$G_c(s) = \frac{R_2}{R_1} + \frac{1}{sR_1C} \tag{6}$$

The controller of (3) designed using sisotool can thus be implemented by choosing $\frac{R_2}{R_1} = 8$ and $\frac{1}{R_1C} = 8000$. Component values $R_1 = 2.5k\Omega, R_2 = 20k\Omega$, and $C = 0.05\mu F$ thus implement the desired controller.

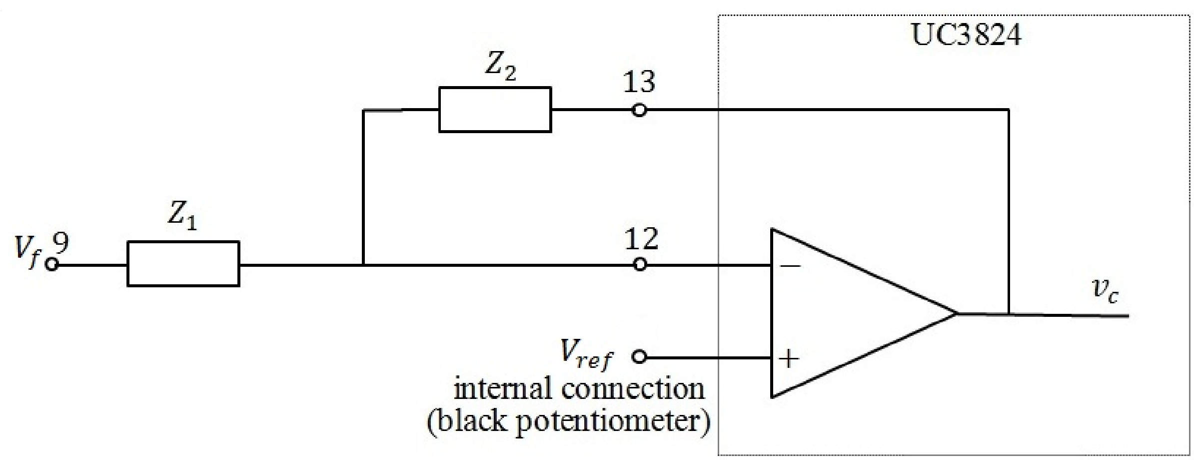

Fig. 9: Hardware implementation of the controller on the power pole board

Experimental Results

A photograph of the power pole board configured for external control is seen in Fig. 10. Three wires connect pins 9, 12, and 13 from the header J60 on the board to an external breadboard. The resistor R_1 (corresponding to Z_1 of Fig. 9) is connected between the red and yellow wires, while R_2 and C connected in series (corresponding to Z_2 of Fig. 9) lie between the yellow and black wires. The reference voltage V_{ref} is set to 2V using the potentiometer indicated in Fig. 10. The multimeter shows that the load voltage (across the 10Ω load resistance) is 10V, corresponding to zero steady state error.

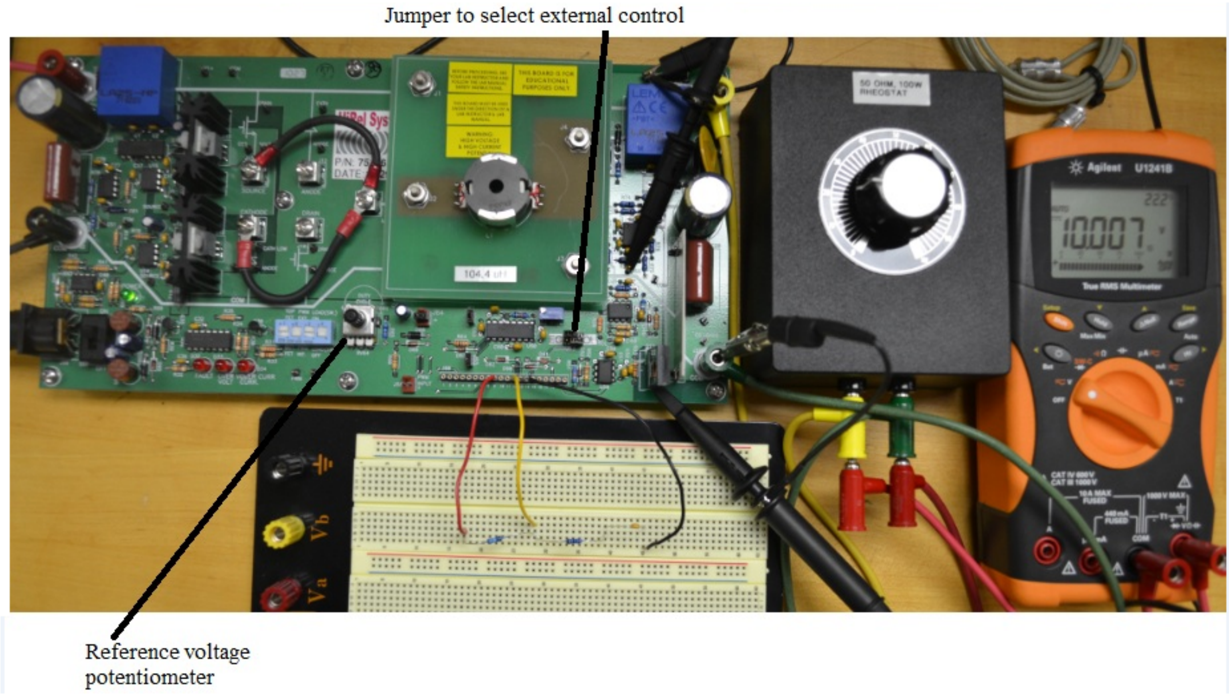

Fig. 10: Experimental setup showing PI controller implementation on the power pole board

The power pole board has a switched load that can be used to investigate dynamic behavior of the control system. The switched load can be activated by setting switch 3 in the switch bank of Fig. 2 to the up position. The switched load is a 20Ω load that is switched into the circuit (in parallel with the load resistance) at a duty cycle of 10% with a switching frequency of 10Hz. The net load resistance thus drops from 10Ω to $10||20 = 6.67\Omega$ when the switched load is active. This causes an increase in load current, which causes the converter output voltage to drop before the control system automatically adjusts the duty cycle to restore the set output voltage of 10V. Fig. 11 shows the dynamic response of the control system. The lower trace (channel 2, blue color, 10V/div) shows the switching signal; the 20Ω load is switched in to the circuit when the switching signal goes high in the middle of the screen. The upper trace (channel 1, yellow color, 50mV/div) shows the converter output voltage waveform, AC coupled, so the small changes superimposed on the 10V output voltage can be seen (this trace thus effectively displays the output voltage error). Fig. 11shows that the output voltage V_o drops by about 70mV at the instant the load is switched in. The controller acts to subsequently reduce the error to close to zero within the 0.5ms that is visible after the switched load turns on. The top trace (channel 1) is obtained using averaging to smooth out the noise that is visible at the scale sensitivity of 50mv/div.

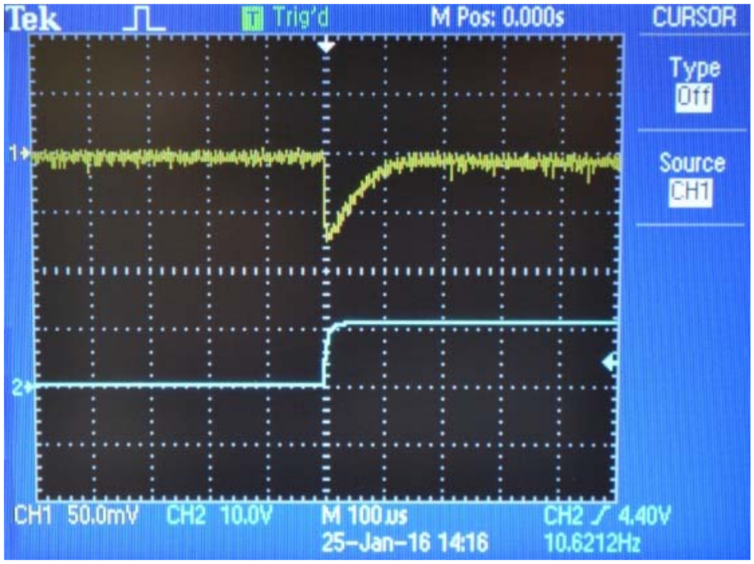

Fig. 11: Output voltage error waveform upon addition of switched load

The theoretical load current of the buck converter is $I = \frac{10V}{10\Omega} = 1A$ without the switched load, and $I = \frac{10V}{6.66\Omega} = 1.5A$ when the extra switched load is connected in parallel. Fig. 12 shows the buck converter inductor current waveform (top trace, channel 1, yellow color, 200mV/div) and the switching signal (bottom trace). The current sensor on the PPB has a scale factor of 0.5V per Amp. Cursor 1 (488mV) thus corresponds to an initial load current of $0.488 \times 2 = 0.976$A, and cursor 2 (728mV) thus corresponds to a final load current of 1.456A. The steady state current values are thus close to the theoretical predictions of 1A and 1.5A, respectively. The inductor current waveform exhibits some overshoot, while overshoot is not really visible in the output voltage waveform.

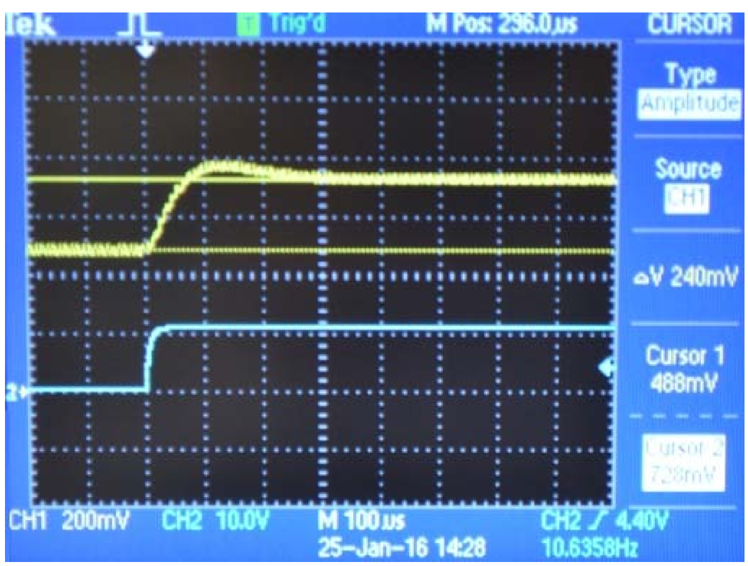

Fig. 12: Buck converter inductor current waveform

Assessing the efficacy of the power electronics and control systems labs

As has been mentioned, the PPB and power electronics laboratory materials developed at University of Minnesota are used by at least 82 universities. Such widespread use already testifies to the value of the hardware platform and curricular materials. Evaluation of the effectiveness of the power electronics lab at University of the Pacific was based on student course evaluations. The evaluation of the laboratory component of the course is via student responses to six statements that seek student input on the effectiveness or relevance of the lab in several categories (the categories are listed in the first column of Table 1). Students respond to each statement with an integer score that can range from 1 to 5. A score of 1 indicates low or poor effectiveness or relevance, while a score of 5 indicates high or outstanding effectiveness or relevance. The range of ratings from 1 to 5 allows student perceptions to be quantified between the lower limit of poor effectiveness and the upper limit of outstanding effectiveness.

Statement pertaining to lab effectiveness	**Average student rating**
Effectiveness of lab experiments in promoting understanding	4.8
Effectiveness of lab experiments in developing lab and data analysis skills	4.8
Effectiveness of lab experiments in developing teamwork skills	4.7
Effectiveness of lab manuals and other supportive materials	4.7
Effectiveness of lab equipment, resources or supplies	4.6
Relevance of lab to course objectives	4.9

Table 1: Student evaluation of effectiveness of the power electronics laboratory

Thirty one students took the power electronics course in three offerings (Fall 2011, Spring 2013, Spring 2015) and twenty three of them responded to the evaluation instrument. Table 1 lists the average student rating in each of the effectiveness categories. All categories receive scores above 4.6 out of a maximum of 5. The student rating of 4.8 for effectiveness of the lab experiments in promoting understanding provides strong justification for the effectiveness of the power pole board in promoting understanding of power electronic circuits and concepts.

The control systems course was offered twice (Spring 14 and Fall 15), and consisted of Matlab and Simulink-based simulation experiments with a concluding experiment on PI control of the buck converter using the PPB. Table 2 summarizes the student evaluation data for the control systems lab. Thirty two students took the course, and twenty two students responded to the question on effectiveness of lab experiments in promoting understanding. The average score of the respondents to this question was 4.7 on 5. Students therefore lean towards the outstanding rating for the effectiveness of the labs in promoting understanding of control system concepts.

With such small numbers of students and relatively infrequent offerings (both the power electronics and control systems courses are electives), it was not practical to do a controlled study to evaluate the effectiveness of the PPB-based laboratory experiments on student learning outcomes. Nevertheless, the positive feedback from student course evaluations supports the inference that the PPB-based labs help promote understanding of power electronics and control systems concepts.

Statement pertaining to lab effectiveness	**Average student rating**
Effectiveness of lab experiments in promoting understanding	4.7
Effectiveness of lab experiments in developing lab and data analysis skills	4.9
Effectiveness of lab experiments in developing teamwork skills	4.9
Effectiveness of lab manuals and other supportive materials	4.6
Effectiveness of lab equipment, resources or supplies	4.9
Relevance of lab to course objectives	4.9

Table 2: Student evaluation of effectiveness of the control systems laboratory

Thirty three students who have taken the power electronics and/or control systems courses to date have graduated. It is gratifying that fifteen of these graduates are known to be working in fields related to power electronics, power systems, and control systems. The DOE grant[1] has significantly impacted the curriculum at University of the Pacific and the marketability of its graduates[15].

Conclusions

Power pole boards (PPB) acquired in conjunction with a Department of Energy curricular grant have been successfully deployed in power electronics and control systems courses at University of the Pacific. Student evaluations and alumni placements show that the PPB is an effective platform for teaching power electronics and control systems concepts. The PPB has been shown to provide a low cost solution for introducing hardware labs experiments in control systems. Methods for designing and implementing PI controllers on the PPB for use in a control systems lab have been presented. These methods augment the curricular resources for the PPB that are available in the public domain[4] and can be useful to universities wishing to use the PPB in control systems courses.

Acknowledgments

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