Available online at www.sciencedirect.com

ScienceDirect

IFAC-PapersOnLine 48-30 (2015) 351–356

Closed-Loop Digital PWM Control using a Popular Power Electronics Platform

Cherian P. Mathews*   Bryson Y. Mitsui.**

**University of the Pacific, Stockton, CA 95219 USA (e-mail: cmathews@ pacific.edu)*
*** University of the Pacific, Stockton, CA 95219 USA (e-mail: b_mitsui@ u.pacific.edu)*

Abstract: This paper describes how a buck converter implemented on a power pole circuit board (a popular platform for study of DC-DC converters) can be digitally controlled using a Texas Instruments Piccolo kit. The control algorithm is implemented using block diagrams in Simulink, and automatically generated code is targeted onto the Piccolo processor. The power pole circuit board and the Piccolo kit are shown to provide an effective platform for the study of digital control algorithms. Various converters can be assembled quickly on the power pole board, and corresponding control algorithms can be rapidly deployed and tested on the Piccolo kit.

Keywords: Closed loops, digital control, converters, control education, computer simulation, bilinear transformations, microprocessor control, digital filters.

1. INTRODUCTION

The power pole circuit board (PPCB) is a platform that is widely used in academia for laboratory-based study of DC-DC converters (Robbins et. al, 2002). This paper describes an approach for closed-loop digital pulse-width-modulation (PWM) control of a buck converter that is constructed on the PPCB. The hardware platform on which the digital control algorithm is executed is the Texas Instruments (TI) “Piccolo” TMS320F28035 Experimenters Kit (hereafter referred to as Piccolo kit). The kit features a 32 bit Piccolo microcontroller that is designed for control applications. The software tools needed to implement the control algorithm are Simulink (a block diagram environment for model-based design), and Code Composer (the TI integrated development environment that supports the Piccolo). The control algorithm is implemented via block diagrams in Simulink, which in conjunction with Code Composer can automatically compile, download, and run the design on the Piccolo kit.

One of the objectives of the present work is to present a platform that can be used to teach concepts of digital control of power electronic converters without getting bogged down with the details of C programming of microcontrollers, or of converter hardware design. The platform (consisting of Simulink, the Piccolo kit and associated software, and the PPCB) can serve as an effective vehicle to teach digital control of power electronic converters. While the present work describes closed-loop control of a buck converter, the work could easily be extended to apply to boost, buck-boost, flyback, or forward converters. All of these converters can be implemented on the power pole board, and the control algorithms can be implemented on the Piccolo kit.

The ease of use of the approach presented here is what differentiates it from related work. Wu et al. (1999) discuss digital PWM control of an interleaved buck converter; the controller was implemented using the Verilog hardware description language, with hardware implementation on a XIlinix field-programmable-gate-array based chip. Prodic et al. (2001) provide comprehensive design details for digital control of a buck converter. The controller was implemented using an Analog Devices DSP processor with a separate dedicated PWM chip. The paper does not provide any software implementation details. The work of Choi and Saeedifard (2012) is closely related to the present work. The authors describe a power electronics laboratory that uses Simulink and the TI F28035 processor to produce gating signals for buck converters, boost converters, and inverters. All of the power electronic converters in this work are operated in open-loop; no feedback control is implemented. Another difference from the present work is that Choi and Saeedifard use dedicated hardware circuits for their converters, while the present work uses a single reconfigurable platform, the PPCB, to implement the converter.

2. THE BUCK CONVERTER CIRCUITRY

The schematic of the buck converter as implemented on the PPCB is depicted in Fig. 1. The MOSFET is an IRF640, the diode is an MUR2020, the inductance is $L = 100\mu$H, and the output filter capacitance is $C = 690\mu F$. The equivalent series resistance (ESR) of the capacitor is $r = 0.128\Omega$ (it is high due to the presence of a physical 0.1Ω resistor on the board that is used to probe the capacitor current waveform), and R is the load resistance, which is set at 20Ω.

Implementation of a buck converter on the power pole board is very quick and involves the following steps: (1) Connect a DC power supply to the board to provide the input voltage V_{in}. (2) Connect a separate 12V isolated DC power supply to provide power for the MOSFET gate drive circuitry (3) Flip a switch to deliver gating signals to the top MOSFET. (4) Screw in two wires such that the source of the top MOSFET connects to the cathode of the bottom diode, and that this junction connects to the inductor. Once the board is configured and powered up, a potentiometer allows the

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2015.12.403

switching frequency of the PWM signal to be altered. Another potentiometer allows the duty cycle D of the PWM signal to be varied. The output voltage V_o of a buck converter converter (assuming ideal devices) is $V_o = DV_{in}$. Varying the duty cycle thus allows the output voltage of the converter to be varied.

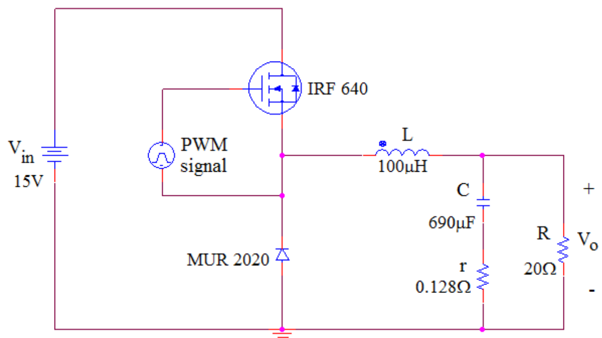

Fig. 1. The buck converter on the power pole circuit board

The PPCB allows for external PWM signals to drive the buck converter. To enable this, switch 2 of a selector bank must be set, and the external PWM signal must be injected via terminal J68 on the board. To enable external feedback control of the converter, the board provides a feedback signal $V_f = 0.2V_o$ that is brought out to pin 9 of connector J60. The gain of the feedback path in a closed-loop system is thus 0.2.

2. CONTROLLER DESIGN AND SYSTEM SIMULATION

The block diagram of the closed-loop buck converter system is depicted below. The portion of the block diagram that is boxed is implemented digitally on the Piccolo kit.

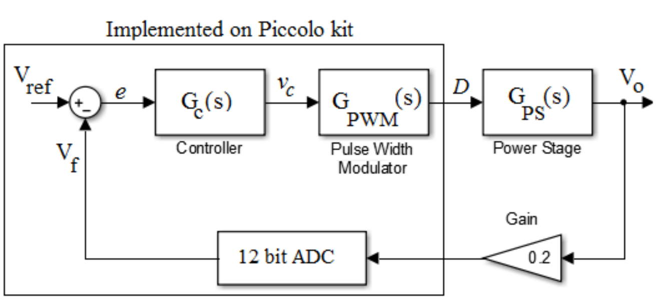

Fig 2. Block diagram of the buck converter control system

The Analog-to-Digital Converter (ADC) on the Piccolo is a 12 bit converter with an input voltage range 0-3.3V. The output of the ADC is an unsigned number in the range 0-4095. The ADC digitizes the feedback signal $V_f = 0.2V_o$ at a sampling rate of 100kHz. The reference input V_{ref} (which specifies the desired output voltage) is initialized via software, and the error signal e is obtained by subtracting V_f from it. The controller $G_c(s)$ operates on e and produces at its output the compare signal v_c for the pulse width modulator.

The pulse width modulator is programmed to produce a PWM signal at a switching frequency of 25kHz. The system clock on the DSP board has a frequency of 60MHz. To provide a switching frequency of 25kHz, the system clock must be divided down by a factor of 2400. The control signal v_c that determines the duty cycle D must thus lie in the range 0-2399. The pulse width modulator correspondingly can produce 2400 equally space duty cycles over the range $0 < D < 1$. The relationship between the compare signal v_c and duty cycle D is

$$D = \frac{v_c}{2400} \tag{1}$$

The small signal transfer function of the pulse width modulator is thus

$$G_{PWM}(s) = \frac{\delta D}{\delta v_c} = \frac{1}{2400} \tag{2}$$

The transfer function of the power stage of the buck converter is well known (Mohan, 2012) and is given below:

$$G_{PS}(s) = \frac{V_{in}r}{L} \frac{\left(s + \frac{1}{rC}\right)}{s^2\left(1 + \frac{r}{R}\right) + s\left(\frac{r}{L} + \frac{1}{RC}\right) + \frac{1}{LC}} \tag{3}$$

The loop transfer function without the controller is thus

$$G_L(s) = 0.2G_{PWM}(s)G_{PS}(s) \tag{4}$$

The Bode plots of the above loop transfer function can be obtained using the buck converter parameters: Input voltage $V_{in} = 15V$, load resistance $R = 20\Omega$, inductance $L = 100\mu H$, output capacitance $C = 690\mu F$, and capacitor ESR $r = 0.128\Omega$. Using the Bode plots, a Type 3 controller of the form

$$G_c(s) = \frac{k_c}{s} \frac{\left(1 + \frac{s}{\omega_z}\right)^2}{\left(1 + \frac{s}{\omega_p}\right)^2} \tag{5}$$

can be designed using the K-factor approach as described by Mohan (2012). The controller provides zero steady state error, and is designed to produce a phase margin of 60^oat a crossover frequency of 1kHz. This approach yields the following parameter values for the controller: zero frequency $\omega_z = 2212.659$ rad/sec, pole frequency, $\omega_p = 17842.072$ rad/sec, and $k_c = 1.0014956 \times 10^6$.

The controller transfer function can be discretized using the bilinear transform. The resulting transfer function in the z domain for a sampling rate of 100Hz is

$$G_c(z) = \frac{b_o + b_1z^{-1} + b_2z^{-2} + b_3z^{-3}}{1 + a_1z^{-1} + a_2z^{-2} + a_3z^{-3}} \tag{6}$$

where the coefficient vector $b = [b_o\ b_1\ b_2\ b_3]$ is

$$b = 100 \times [2.8055 \quad -2.6827 \quad -2.8042 \quad 2.6841] \tag{7}$$

and $a = [a_1\ a_2\ a_3]$ is

$$a = [-2.6724 \quad 2.3716 \quad -0.6992] \tag{8}$$

The closed-loop control system can be simulated in Simulink using the controller of (6). The Simulink block diagram is