

# Real Time Implementation of a Digital Controlled Boost Converter

İrfan YAZICI<sup>1</sup>, Ayhan ÖZDEMİR<sup>2</sup>, Zekiye ERDEM<sup>3</sup>

<sup>1,2,3</sup>Sakarya University, Electrical&Electronics Eng. Dep.  
Sakarya, Turkey

<sup>1</sup>iyazici@sakarya.edu.tr, <sup>2</sup>aozdemir@sakarya.edu.tr, <sup>3</sup>zekiye@sakarya.edu.tr

## Abstract

**This paper presents real time implementation of a digital controlled conventional boost converter works on the fixed frequency driven by the duty cycle control techniques. The digital controller, implemented using ADUC841 microcontroller, monitors the output voltage and calculate the error to determine the next duty cycle value. Simulation and experimental results indicates that the constructed PI controlled boost converter have good transient response as well as stable and accurate steady-state response during the drastically changes occur in input voltage and output load.**

## 1. Introduction

The switching mode dc-dc converters are a class of power electronic circuits that convert one level of DC voltage into another level by switching action [1]. DC-DC converters may also provide voltage isolation through the utilization of a small high frequency transformer besides the controllable DC voltage conversion [2]. Due to their advantageous features in terms of size, efficiency and reliable operation they have been used in widespread applications such as personal computers, battery charging, DC motor drive and welding machine.

The main task of the controller established in a switching mode power converter is to drive the main switching device (IGBT or MOSFET) with a duty cycle, the ratio on-time/switching-period, such that the dc component of the output voltage is equal to its reference [3]. For reliable operation, this regulation should be maintained in despite of variations in input voltage and output load, that frequently occurs in normal operating condition.

As the name suggests the switching mode dc-dc converters periodically entails different modes of operation, each with its own associated linear continuous-time dynamics. This is the main adversity in controlling of the converter. Moreover, hard constraint is also present on the input variable (duty cycle) and output current [3,4].

Traditionally, regulation of the output voltage of DC-DC converters has been achieved through the use of analog controller implemented by analog circuits [3]. However, change in controller gains or algorithms in an analog controller can only be done by hardware modification which is time consuming and expensive solution. In addition, the implementation of newly developed advanced control algorithms by analog circuits is nearly impossible [5]. On the other hand digital controller implemented by digital processor such as microcontroller, digital signal processing (DSP) and personal computer has many advantages over analog controller, including programmability, adaptability, reduced susceptibility to environmental variations and ability to implement complicated control algorithms and etc. And also, technological

advances have yielded microcontrollers and DSPs with the necessary on-board features, such as analog-to-digital converter (ADC), pulse width modulation (PWM), to allow implementation of a digital controller for a DC-DC converter using a single chip with a few extra component.

In digital implementation of switching mode power converters the main drawback is the limited switching frequency caused by sampling time delay and processing time of the control algorithm to calculate the new duty cycle [6]. Nevertheless, using the high speed DSPs a power converter working an admissible switching frequency may be implemented.

In this study, a digital proportional-integral (PI) controlled boost converter was implemented using a ADUC841 microcontroller from Analog Devices. This microcontroller owing to on board features such as three 16-bit general purpose timers, 2 PWM channels and a 12-bit, 8-channel ADC which facilitates to implementation of boost converter operates at 20 MIPS with an instruction cycle time of 50 ns. Both the sampling frequency and switching frequency were selected to be 15 kHz for this study. The digital controller acquires a sample once every sampling period and calculate the new duty cycle through PI algorithm and updates the duty cycle at the start of the next switching period.

Simulation results and experimental studies verifies effectiveness of the designed digital PI controlled boost converter both in steady state and dynamic conditions while the input voltage and output load changes in wide range.

## 2. Modeling of Boost Converter

The conventional boost converter circuit is shown in Fig. 1a. The boost converter, operating in the continuous conduction mode (CCM), depending on the position of the switch S has two operating mode as shown in Fig. 1b and 1c.

The mathematical model for simulation studies can be easily derived by applying Kirchhoff's voltage law, including the parasitic elements  $R_L$  and  $R_C$ , for these two operating modes as given below [1].

When the switch is on position, Fig. 1b, the dynamics of the circuit are,

$$\frac{dI_L(t)}{dt} = \frac{1}{L} (V_i - I_L(t)R_L) \quad (1a)$$

$$\frac{dV_C(t)}{dt} = -\frac{V_o}{CR_o} \quad (1b)$$

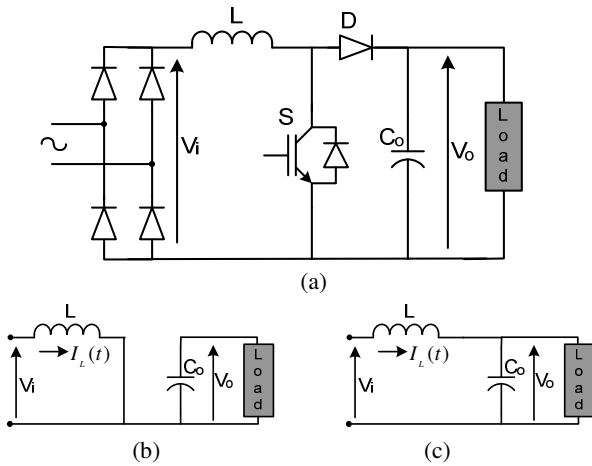
When the switch is off position, Fig. 1c, the dynamics of the circuit are,

$$\frac{dI_L(t)}{dt} = \frac{1}{L}(V_i - I_L(t)R_L - V_o) \quad (2a)$$

$$\frac{dV_c(t)}{dt} = \frac{1}{C}\left(I_L(t) - \frac{V_o}{R_o}\right) \quad (2b)$$

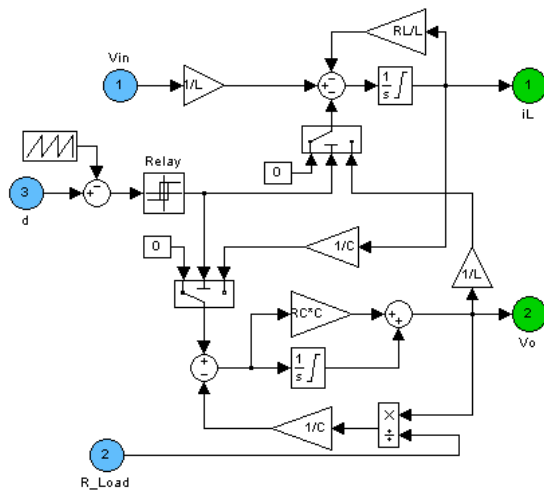
In both cases, capacitor voltage  $V_c(t)$  and output voltage  $V_o(t)$  are related via the following equation:

$$V_o(t) = R_c C \frac{dV_c(t)}{dt} + V_c(t) \quad (3)$$



**Fig. 1.** (a) Conventional boost converter topology, (b) switch is on and (c) switch is off

Simulink model of the boost converter, using Eq. (1) ... Eq(4), was created for simulation studies as shown in Fig. 2.



**Fig. 2.** The boost converter block diagram constructed in Simulink.

Due to inherent switching operation, dc-dc converters periodically switch between the subsystems, each subsystem described by the separate set of equations as given above.

Therefore, it is difficult to obtain accurate model of the converters for the transient analysis and control design. The technique called average-value model, wherein the effects of fast switching are neglected, provides a solution to this problem [2]. In [7], based on [8], authors claims that asymptotical stability of the average value model and detailed switching circuit are equivalent. Therefore, transfer function obtained from small signal model around the nominal operating point may be used to design the controllers [7]. The simplified transfer function of the boost converter used to design PI controller is obtained below.

When the switch is on position, dynamics of the inductance current is,

$$\frac{dI_L(t)}{dt} = \frac{V_i}{L} - \frac{R_L I_L(t)}{L} \quad (4)$$

and its Laplace form is,

$$I_L(s) = \frac{V_i(s)}{sL + R_L} \quad (5)$$

The average value of the inductance current for the switch is off position,

$$I_{Lave}(t) = \frac{T_{off}}{T} I_L(t) = \frac{T(1-d)}{T} I_L(t) = (1-d)I_L(t) \quad (6)$$

$$I_{Lave}(t) = (1-d) \frac{V_i(s)}{sL + R_L} \quad (7)$$

The output voltage  $V_o(t)$  is,

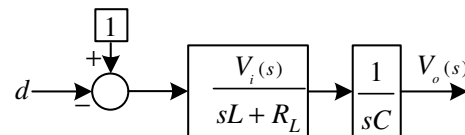
$$V_o(t) = \frac{1}{C} \int I_{Lave}(t) dt \quad (8)$$

$$V_o(s) = \frac{1}{sC} I_{Lave}(s) \quad (9)$$

When the Eq.(7) written in Eq. (9) the transfer function of the system can be derived as below.

$$G(s) = \frac{V_o(s)}{(1-d)} = \frac{V_i(s)}{sC(sL + R_L)} \quad (10)$$

The open-loop block diagram of the system may be shown as below.



Transfer function of the discrete PI controller is [9],

$$G_{PI}(z) = K_p + K_i \frac{z}{z-1} = (K_p + K_i) \frac{z - \frac{K_p}{K_p + K_i}}{z-1} \quad (11)$$

The controller parameters,  $K_p$  and  $K_i$ , can be calculate in many different ways. In this study we calculate these parameters as  $K_p=5.3$  and  $K_i=0.37$  by discrete characteristic equation given in Eq. (12), while design criterias were damping ratio is  $\xi=0.8$  and settling time is  $t_s=0.02s$ .

$$1 + G_{PI}(z)G(z) = 0 \quad (12)$$

### 3. Simulation

The simulation studies are performed in Simulink with the following specifications  $V_i=30V$ ,  $V_o=40V$ ,  $C_o = 660 \mu F$ ,  $L = 570 \mu H$ , and  $R_o = 50 \Omega$  (load resistance) using the model given in Fig. 2. In order to clarify the effectiveness of the designed PI controller the converter was tested with and without controller when output load and input voltage changes drastically. The simulink block diagram of the controlled boost converter was given in Fig. 3. and the simulation waveforms are shown in Figs. 4 and 5.

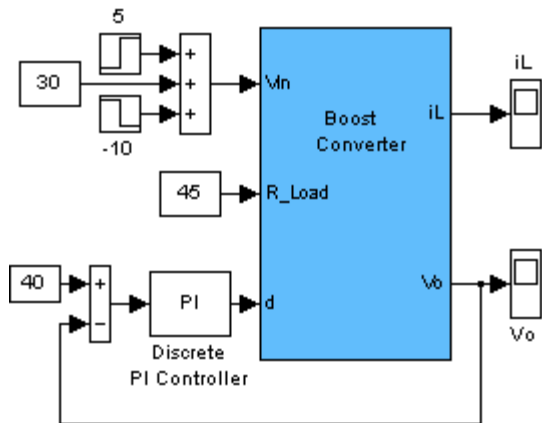


Fig. 3. Simulink model of the controlled boost converter

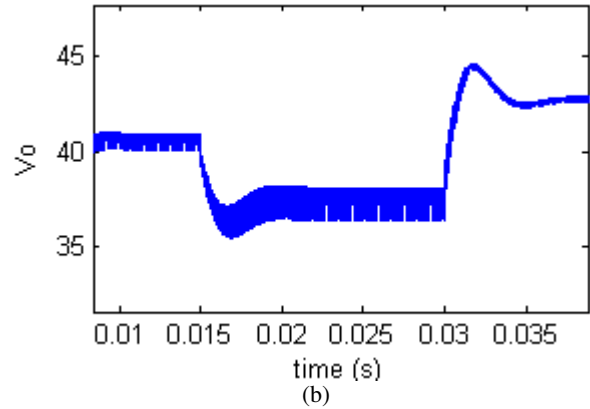
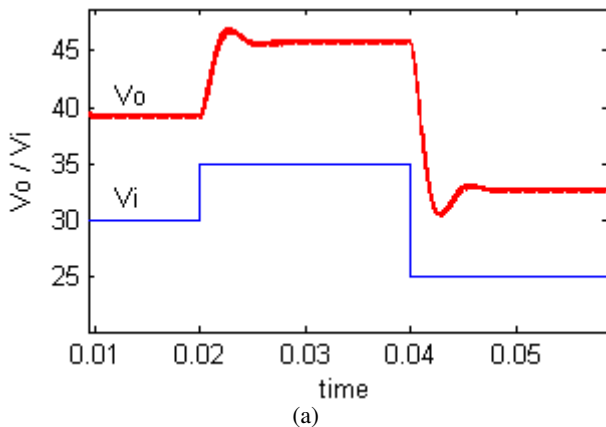


Fig. 4. Simulation results for open-loop response of the boost converter: (a) input voltage variation (b) load variation.

It is clear from Fig. 3 that the output voltage of the open loop converter is significantly deviate from nominal value when step changes occur at load and input voltage while the Fig. 5. verifies the effectiveness of the designed PI controller.

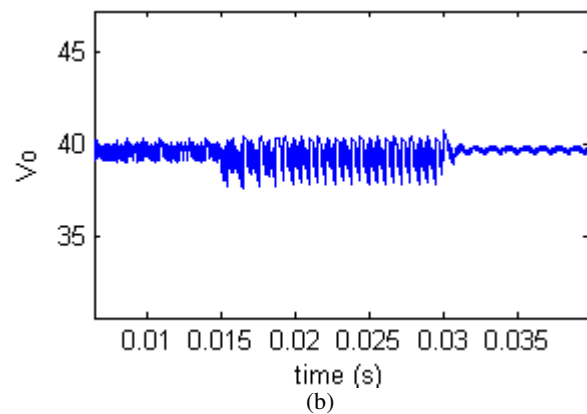
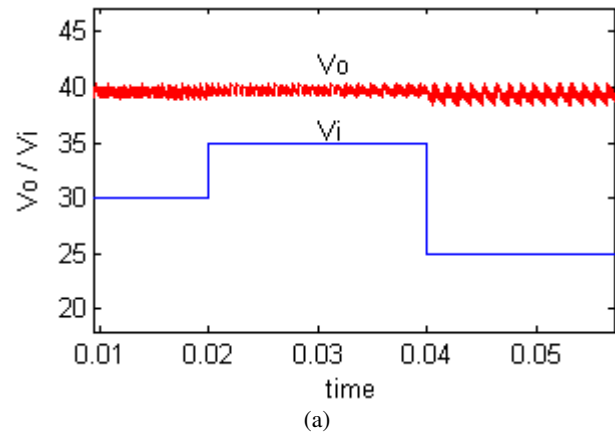


Fig. 5. Simulation results for the PI controlled boost converter: (a) input voltage variation (b) load variation.

## 4. Real Time Implementation

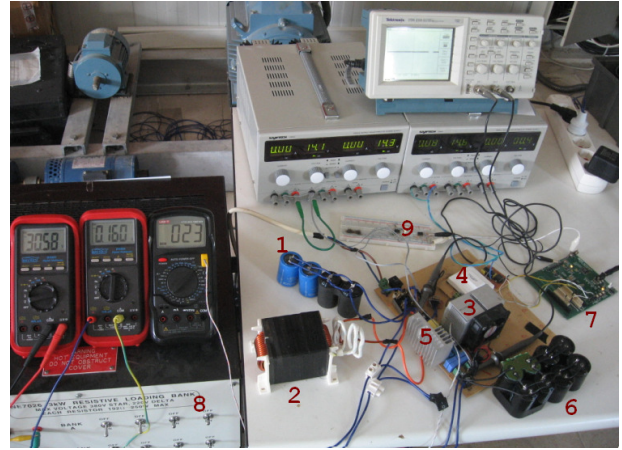
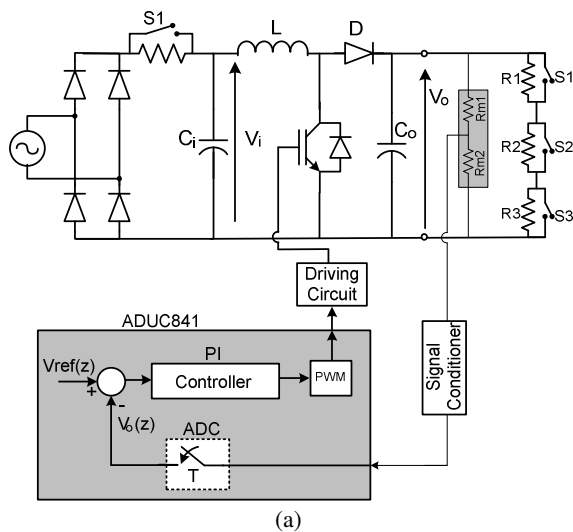
When the real time implementation of PI controlled boost converter is considered the output voltage needs to be sampled. However, the switching action of the semiconductor devices in a converter will produce high frequency switching noise in the converter output voltage. If the output voltage is sampled at the switching instant, the ADC may capture the switching noise. This would result in an erroneous input to the controller and hence it would be difficult to maintain system in agreeable operation [10]. Therefore, sampling instant of the output voltage has crucial importance over the controller performance and hence great importance should be given to determination of the sampling instant.

### 4.1. Determination of the sampling instant

A high peak and succeeding oscillations, due to  $dv(t)/dt$  and  $di(t)/dt$ , appears at the switching point is inherent to the operation of the boost converter. The best solution to eliminate affect of the switching noise over the controller performance is to adjust the sampling point sufficiently away from the switching point. In literature [11], to solve this problem, rising-edge-sampling (RES) and falling-edge-sampling (FES) techniques were offered. Depending on the value of the on-time of the switch S, RES or FES may be used as the sampling instant. If the  $on-time > off-time$  RES is chosen otherwise FES is chosen [12]. In this study this technique is used to determine the sampling instant for output voltage.

### 4.2. Experimental Results

A prototype boost converter, given in Fig. 6, was designed and constructed to produce an output voltage of 40 V from an input voltage of 30V. The circuit parameters for the boost converter were  $C_o = 660 \mu\text{F}$ ,  $L = 570 \mu\text{H}$ , and  $R = 45 \Omega$  (load resistance). The switching frequency for the boost converter and the sampling frequency for the digital PI controller was chose as 15 kHz. The digital PI controller was implemented using ADUC841 microcontroller that has the necessary on-board features such as timer, ADC, PWM and etc. The scheme of the realized system and its hardware implementation in laboratory are shown in Fig. 6.

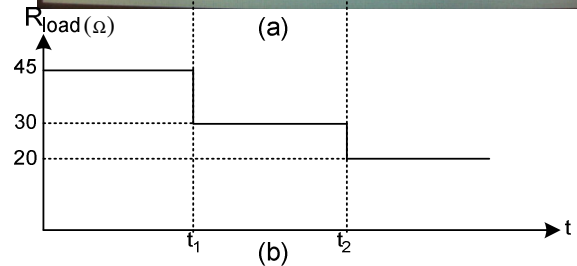
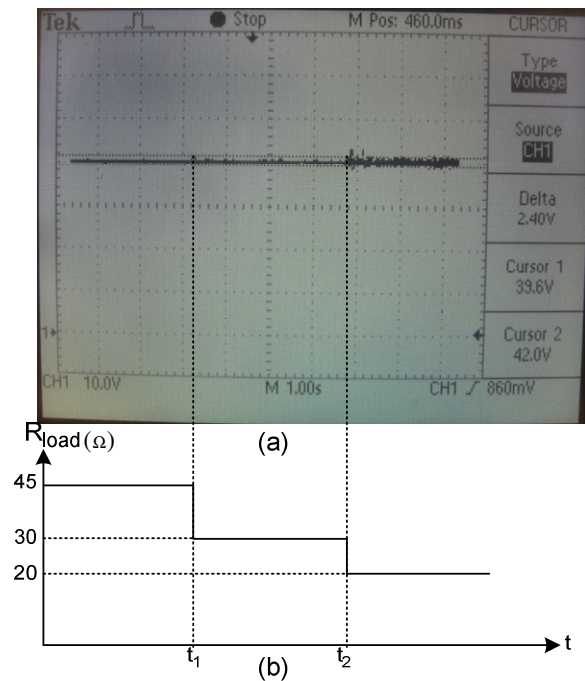


1)  $C_i$ , 2)  $L$ , 3) IGBT, 4) Driving circuit, 5) Diode, 6)  $C_o$ , 7) ADUC841, 8) Load bank 9) Signal Conditioner

(b)

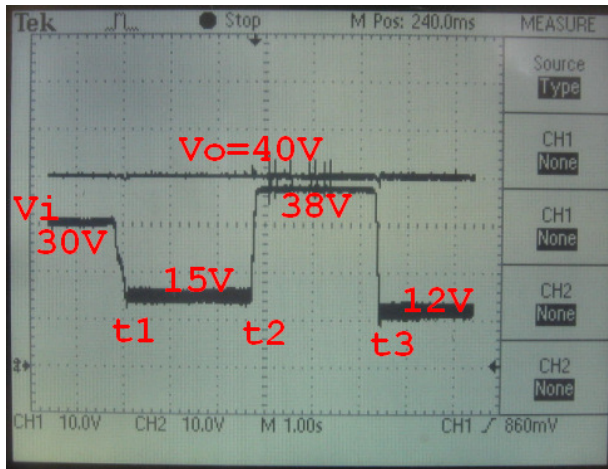
**Fig. 6.** (a) Circuit scheme and (b) hardware implementation of the PI controlled boost converter.

The performance of the design controller is verified by studying the effect of sudden changes in load and input voltage  $V_i$ . The PI controller was designed to regulate the output voltage at 40V by adjusting the duty cycle with the following parameters:  $K_p=5.3$  and  $K_i=0.37$ . The converter initially operates in a steady-state with a  $45\Omega$  resistor connected to the output. Then, as a first experiment, the load is changed to  $30\Omega$ , and  $20\Omega$  at  $t=t_1$  and  $t=t_2$  respectively while the input voltage kept constant at  $V_i=30\text{V}$ . Fig. 7 shows the output voltage in this circumstance.



**Fig. 7.** (a) Output voltage (b) during load variation in real time applicaiton.

As a second experiment the input voltage  $V_i$  is changed to  $V_i=15V$ ,  $V_i=38V$  and  $V_i=12V$  at  $t=t_1$ ,  $t=t_2$  and  $t=t_3$ , respectively, through an auto transformer. The real time oscilloscope screen of this experiment is given in Fig. 8.



**Fig. 8.** Output voltage during input voltage variation in real time implementation.

The experimental results given in Figs. 7 and 8 are confirmed that the designed PI controlled boost converter is insensitive to wide changes in load and input voltage. While the input voltage and load changed up to 60% percent the output voltage of the boost converter keep in nominal value thanks to designed PI controller.

## 5. Conclusions

In this study, a digital PI controlled boost converters was designed and implemented in real time using a ADUC841 microcontroller at 15 kHz operating frequency. The results obtained from simulation studies and real time experiments indicate that a good steady-state performance and transient response can be achieved with developed PI controller during the input voltage and output load changes in wide range.

## 6. Acknowledgment

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