International Journal of Enhanced Research in Science Technology & Engineering, ISSN: 2319-7463
Vol. 2 Issue 7, July-2013, pp: (70-76), Available online at: www.erpublications.com

Synchronous buck converter with closed-loop voltage-mode controller

M.K.A. Ahamed khan[1], Mutaz Eltayeb Abd alla Hamd[2], S. Parasuraman[3], Irraivan Elamvazuthi[4], M. Amudha[5]

[1]Senior Lecturer, Faculty of Engineering, UNISEL, Malaysia
[2]Research scholar, UNISEL, Malaysia
[3]Senior Lecturer, Monash University, Malaysia
[4]Asso Prof, University Technology Petronas, Malaysia
[5]Lecturer, KLMU, Malaysia

Abstract: DC-DC Buck converters are used to step-down the voltages in some of the equipment's that we use in our daily life such as laptops, PDA's, mobile phones and also electric vehicles. These converters are a high frequency switching devices operating on PWM principle. This paper describes an advanced technique known as closed-loop voltage-mode control method in order to obtain a regulated output voltage of a synchronous buck converter. This method requires a comparison of a reference voltage and an output voltage. The differential of the compared value will be used to produce a pulse width modulation signal to control the switch in the buck converter. The real circuit of the power stage controller shall be constructed on the (Printed circuit board) PCB and the circuits shall be tested to confirm the result with the theoretical predictions. Experimental work was carried out with a circuit operated in continuous conduction mode with 12V output voltage, input voltage between 20V~30V and 50 kHz switching frequency. The test results showed that the proposed design can able to produce a 12V constant voltage.

Keywords: Pulse width modulation, buck converter, voltage mode controller.

Introduction

Direct current to direct current (DC-DC) converter is a power electronics circuit that convert's direct current (DC) voltage input from one level to another. This capability allows the converter to pass a low current when we want to use a device with low voltage level. DC-DC converters are also known as switching converters, switching power supplies. In some cases when a device is connected such as laptop or charger directly to the rectified supplied from the socket at home, the device might not be functioning properly or it might malfunction due to over current or overvoltage so in order to avoid unnecessary damage to the equipments and devices, one need to convert the voltage level to suitable voltage level for the equipments to function properly. The perfect solution to this dilemma is to use a buck converter for low power application due to the low voltage level at the output. The control method chosen to maintain a constant output voltage from of the buck converter was voltage-mode control. Voltage-mode control technique compares the actual output voltage with the reference voltage. The difference between both voltages will drive the control element to adjust the output voltage to a fix voltage level. This is called voltage regulation. Voltage regulation is very important in electronic circuit to ensure the load or the connected device can operate properly and to avoid damage to the equipment from overvoltage and over current.

Buck converters are very important in the modern life. But there is a problem in it which is that there is an unregulated output voltage being produced. Therefore, to obtain desired output voltage although input voltage is changing, a feedback control system for power supply control is needed to compare output voltages to a reference and convert the error to a duty ratio.

Synchronous Buck Converter Design Analysis

Figure 1.1 shows the basic configuration of a synchronous buck converter, as opposed to conventional buck converters, can achieve high efficiency in today's low-voltage, high-current applications because they replace the catch diode of buck converters with a MOSFET. As a result, the power they dissipate in the off-period is reduced significantly. Since there are two MOSFETs 'Q1' is called the high-side MOSFET and 'Q2' the low-side MOSFET. The low-side MOSFET is also referred to as the synchronous MOSFET while the high-side MOSFET is called the switching/control MOSFET.

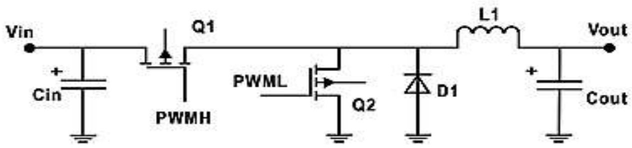

Figure 1.1: Synchronous buck converter power stage.

Assuming the desired output is 12V, the input is between 20~30V, the switch is operating under 50 KHz, the duty cycle will be 0.50, the capacitance is 100uF, and the inductor is assumed to be 100uH. The circuit parameters are showed in Table 1.1.

Table 1.1: Design specifications of buck converter with closed loop (VMC)

Parameter	Approximate value
Input Voltage (V_{in})	20~30 V
Output Voltage (V_O)	12 V
Switching Frequency (f_S)	50 kHz
Output Current	0 ~ 3A
PWM period (T)	20 µs
ON time (t_{on})	10 µs
OFF time (t_{off})	10 µs
Duty Cycle (D)	50%

Hardware Circuit Design

Group The buck regulator requires only one switch, and it has high efficiency greater than 90%. The di/dt of the load current is limited by inductor L. However, the input current is discontinuous and a smoothing input filter is normally required. It provides one polarity of output voltage and unidirectional output current. It requires a protection circuit in case of possible short circuit across the diode path.

The voltage across the inductor L is, in general,

$$e_L = L\frac{di}{dt} \tag{1.1}$$

Assuming that the inductor current rises linearly from I_1 to I_2 in time t_1,

$$V_s - V_a = L\frac{I_2 - I_1}{t_1} = L\frac{\Delta I}{t_1} \tag{1.2}$$

Or

$$t_1 = \frac{\Delta I \; L}{V_s - V_a} = 10us \tag{1.3}$$

And the inductor current falls linearly from I_2 to I_1 in time t_2,

$$-V_a = -L\frac{\Delta I \; L}{V_a} \tag{1.4}$$

Or

$$t_2 = \frac{\Delta I \; L}{V_a} = 10us \tag{1.5}$$

Where $\Delta I = I_2 - I_1$the peak-to-peak ripples current of the inductor L. Equating the value of ΔI in equation (1.1) and (1.3) gives:

$$\Delta I = \frac{(V_s - V_a)t_1}{L} = \frac{V_a t_2}{L} = 1.2{\sim}1.5 \tag{1.6}$$

Substituting $t_1 = kT$ and $t_2 = (1 - k)T$ yields the average output voltage as:

$$V_a = V_s \frac{t_1}{T} = kV_s = 0.50 * 30 = 15V \quad (1.7)$$

Assuming a lossless circuit, $V_s I_s = V_a I_a = kV_s I_a$ and the average input current:

$$I_s = kI_a \quad (1.8)$$

The switching period T can be expressed as:

$$T = \frac{1}{f} = t_1 + t_2 = \frac{\Delta I\ L}{V_s - V_a} + \frac{\Delta I\ L}{V_s} = \frac{\Delta I\ LV_s}{V_a(V_s - V_a)} = 20\mu s \quad (1.9)$$

This gives the peak-to-peak ripple current as:

$$\Delta I = \frac{V_a(V_s - V_a)}{fLV_s} = 1.2{\sim}1.5 \quad (1.10)$$

Or

$$\Delta I = \frac{V_s k(1-k)}{fL} = 1.2{\sim}1.5 \quad (1.11)$$

Using Kirchhoff's current law, the inductor current i_L can be written as:

$$i_L = i_c + i_o \quad (1.12)$$

If the load ripples current Δi_o is assumed to very small or negligible. $\Delta i_L = \Delta i_C$. The average capacitor current, which flows into for $\frac{t_1}{2} + \frac{t_2}{2} = \frac{T}{2}$, is:

$$I_C = \frac{\Delta I}{4} \quad (1.13)$$

The capacitor voltage is expressed as:

$$V_C = \frac{1}{C}\int i_C\, dt + v_C(t = 0) \quad (1.14)$$

And the peak-to-peak ripple voltage of the capacitor is:

$$\Delta V_C = v_C - v_C(t = 0) = \frac{1}{C}\int_0^{T/2} \frac{\Delta I}{4} dt = \frac{\Delta I\ T}{8C} = \frac{\Delta I}{8fC} \quad (1.15)$$

Substituting the value of ΔI from equation (1.9) or (1.10) in equation (1.14) yields:

$$\Delta V_C = \frac{V_a(V_s - V_a)}{8LCf^2 V_s} \quad (1.16)$$

Or

$$\Delta V_C = \frac{V_s k(1-k)}{8LCf^2} \quad (1.17)$$

This gives the critical value of the inductor L_c as:

$$L_c = L = \frac{(1-k)R}{2f} = 100uH \quad (1.18)$$

If V_C is the average capacitor voltage, then capacitor ripple voltage $\Delta V_C = 2V_a$. Using equations (1.6) and (1.16), we get:

$$\frac{V_s(1-k)k}{8LCf^2} = 2V_a = 2kV_s \quad (1.19)$$

International Journal of Enhanced Research in Science Technology & Engineering, ISSN: 2319-7463
Vol. 2 Issue 7, July-2013, pp: (70-76), Available online at: www.erpublications.com

This gives the critical value of the capacitor C_c as:

$$C_c = C = \frac{1-k}{16Lf^2} = 100uF \qquad (1.20)$$

Power Supply Circuit

The circuit is connected to (20~30) of DC source. Then, this voltage stepped down to 12V by a voltage regulator (LM 7812) to meet the rated voltage to supply the gate drive circuitry by 12V. then the voltage is stepped down from 12V to 5V by (LM 317) to meet the rated voltage required by the microcontroller (ATMEGA48). C2, C3 and C4 are filtering capacitors used to supply energy to the regulator and reduce the current spikes seen by the source. Also it filters the signal from the DC source till it reaches the microcontroller.

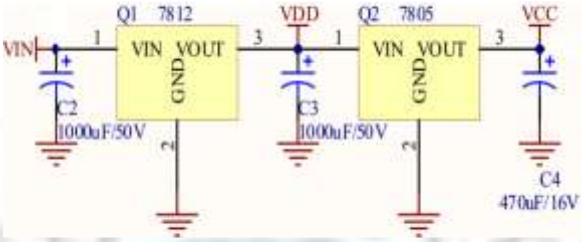

Figure 1.2: Schematic of a power supply circuit

Controller Circuit

A microcontroller (ATMEGA48) was selected to produce a set of pulse width modulation signal, because it is having a successive approximation analog to digital converter, comparator and pulse width modulation generator. Pulse width modulation signal with frequency 50 kHz can be generated when the microcontoller is driven by a 20 MHz clock cycle. The PWM signal generated has amplitude of 5V. The PWM signal then will be amplified (35V) by gate drive circuit to function the power circuit. The microcontroller is responsible for the stabilization of the output voltage at 12V point. This is done by setting the microcontroller at constant voltage mode; this is performed by certain commands inserted in the program-code structure. A reference voltage is set on the gate drive circuit, and basically the microcontroller check the reference voltage every 20us, (50kHz is the switching frequency) and if any changes happens in the output voltage due to the change of the load by withdrawing extra current, the microcontroller stabilize the situation by changing the duty cycle of the switching frequency. That is why it is called a close-loop controlling.

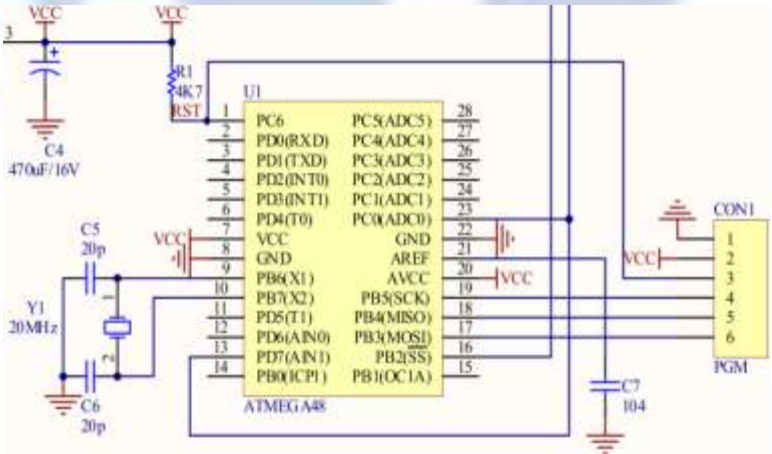

Figure 1.3: the overall construction of the microcontroller.

Gate Drive Circuit

In many applications especially in power supply applications, the simplest way of driving the gate of the main switching transistor is to utilize the gate drive output of the PWM controller as shown in Figure 3.4. A gate driver is used when a pulse-width-modulation (PWM) controller cannot provide the output current required to drive the gate capacitance of the associated MOSFET. Gate drivers may be implemented as dedicated ICs, discrete transistors, or transformers. A remarkable effect can be seen in both the turn-on and turn-off switching waveforms; the gate voltage exhibits a “step”, remaining at a constant level while the drain voltage rises or falls during switching. The voltage at which the gate voltage remains during switching is known as the Miller voltage, Vgm. In most applications, this voltage is around 4 to 6V, depending on the level of current being switched. This feature can be used to control the switching waveforms from the gate drive.

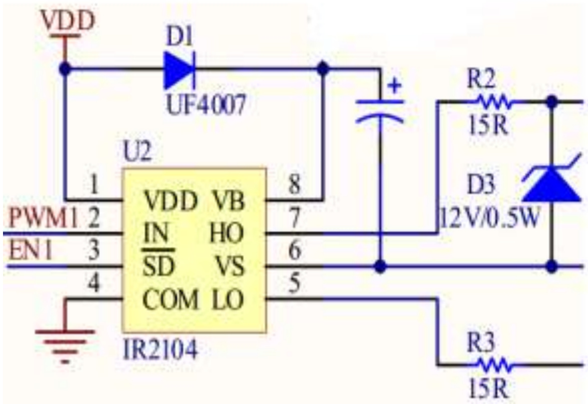

Figure 1.4: Gate drive circuit of the MOSFET (IRF540N)

Results and Discussion

The input and the output voltage of the buck converter closed-loop voltage mode controller are shown in Figure 4.1. The waveform from buck converter shows that DC output voltage V_o of 12 V does meet the expectation results, while the input voltage V_{in} is 22V, the range of the input voltage can be from 20~30V. Figure 4.3, shows the pulse width modulation directly from pin 16 (PB2) of the controller which has peak to peak voltage of 5V, then the pulses are stepped-up by the gate drive to 35V to trigger the MOSFET as shown in Figure 4.4.

Figure 4.5, shows the pulse width modulation from the MOSFET gate driver without load connected at the output of the converter. The duty cycle is 50% and the switching period near to 20us.

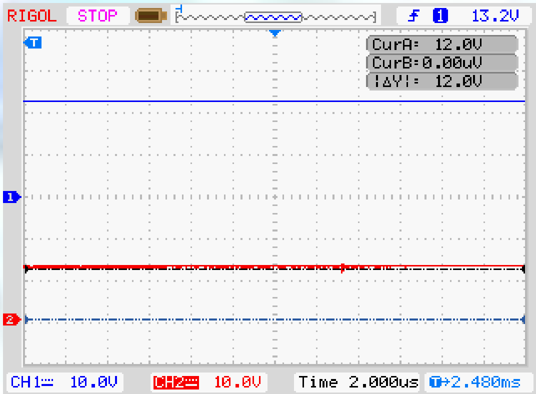

Figure 1.5: Input and output voltage.

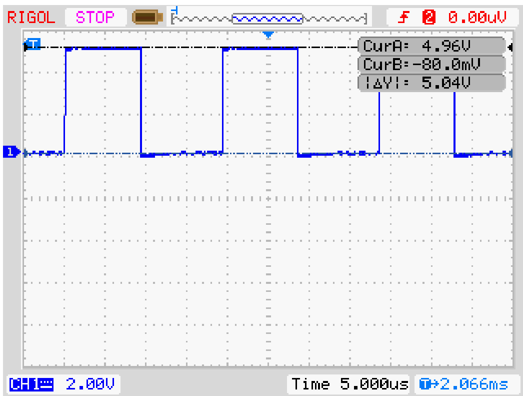

Figure 1.6: PWM output from control circuit (microcontroller).

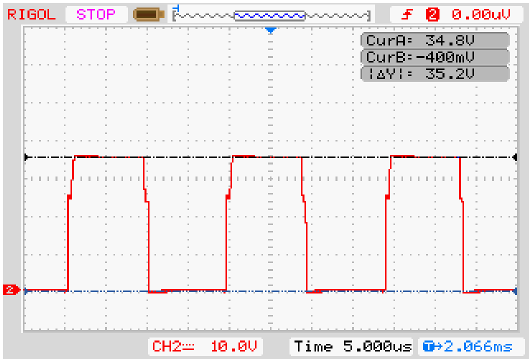

Figure 1.7: PWM output from gate driver circuit.

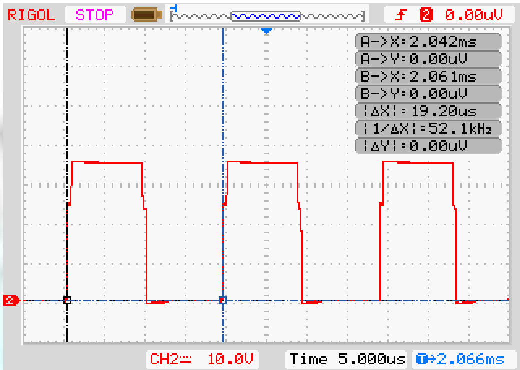

Figure 1.8: PWM output without load with 50% duty cycle

Summary

As conclusion, this work had successfully achieved its main objective which is to develop a closed-loop voltage-mode control of a synchronous buck converter. The closed-loop circuit simplifies the tedious work of controlling the output by automatically adjusting the duty cycle to regulate the output voltage at a particular level. DC-DC converters and their design remain an interesting topic and new control schemes to achieve better regulation is continually developed. Step down switching regulators are the backbone of electronic equipment's that employ IC's running at supply voltages lower than 5V. A key challenge to design switching regulators is to maintain almost constant output voltage within acceptable regulation. Even though voltage-mode control sense the changes in output and input signal to regulate the voltage at specific level, it still can be expanded by adding other method such as peak-current control. However, this will add complexity to the design. Thus further research and studies are required for such expansion. Voltage-mode control is chosen for this work since its design process is not very complex and not to mention, cheap. The controlling method is also easy to understand since it detects the voltage change through sense network and feed the signal back to the controller circuit for regulation process.

References

[1]. Varely Vodovozof & Ventus publishing Aps ISBN 978-87-7681-625-4 Introduction to power electronics 2010.

[2]. Robert L. Boleystad, Louis Nashelsky; Electronic Devices and Circuit Theory, Eighth Edition; 2002; Prentice Hall International, Inc., Upper Saddle River, New Jersey.

[3]. Designing With the TL5001 PWM Controller; Application Report; Texas Instrument.

[4]. M.S. Jamil Asghar, Power Electronics, Eastern Economy edition, Prentice-Hall of India, New Delhi, 2004.

[5]. Bellur, D.M. and Kazimierczuk, M.K., "DC-DC Converters for Electric Vehicle Applications", IEEE, Electrical Insulation Conference and Electrical Manufacturing Expo, 2007, pp. 286 – 293.

[6]. Steigerwald, R.L., "Power Electronic Converter Technology", Proceedings of the IEEE, Vol. 89, Issue: 6, 2001, pp. 890-897.

[7]. Chang, C., "Mixed Voltage/Current Mode Control of PWM Synchronous Buck Converter", Power Electronics and Motion Control Conference, 2004. IPEMC 2004. The 4th International, Publication Date: 14-16 Aug. 2004, Volume: 3, On page(s): 1136-1139 Vol.3.

[8]. Doug Mattingly, "Designing Stable Compensation Networks for Single Phase Voltage Mode Buck Regulators", Intersil, Technical Brief December 2003. Available at:http://www.intersil.com/data/tb/tb417.pdf

[9]. B. Lynch, "Current-Mode vs. Voltage-Mode Control in Synchronous Buck Converters," in Analog Zone, http://www.analogzone.com/pwrt0407.pdf.

[10]. A.M. Rahimi, P. Part, P. Asadi, "Compensator Design Procedure for Buck Converter with Voltage-Mode Error-Amplifier," AN-1162, International Rectifier.

[11]. Chang, C., "Mixed Voltage/Current Mode Control of PWM Synchronous Buck Converter", Power Electronics and Motion Control Conference, 2004. IPEMC 2004. The 4th International, Publication Date: 14-16 Aug. 2004, Volume: 3, On page(s): 1136- 1139 Vol.3.

[12]. K. Wan, J. Liao, and M. Ferdowsi , "Control methods in dc-dc power conversion– comparative study," in Proc. IEEE Power El electronics Specialists Conference, Jun.2007, pp. 921-926.

[13]. Data Sheet "NCP1570 Low Voltage Synchronous Buck Controller", ON Semiconductor, 2002.

[14]. B. Lynch, "Current-Mode Vs. Voltage-Mode Control In Synchronous Buck Converters," in Analog Zone, http://www.analogzone.com/pwrt0407.pdf.

[15]. M. Hartman, "Inside Current-Mode Control," in Power Designer, no. 106, pp. 1-7, 2005.

[16]. C. P. Basso, Switch-Mode Power Supply Spice Cookbook. New York: McGraw-Hill Companies, Inc., 2001.

[17]. D.Mattingly, "Designing Stable Compensation Networks for Single Phase Voltage Mode Buck Regulators," TB417.1, Intersil, 2003.

[18]. A.M. Rahimi, P. Part, P. Asadi, "Compensator Design Procedure for Buck Converter with Voltage-Mode".