A Study on Feed-forward Control for SIDO Buck Converter

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This paper presents usage of feed-forward control to improve the cross-regulation of Single-Inductor-Dual-Output (SIDO) DC-DC buck converters with pulse-width-modulation (PWM). Duty cycle should be modulated directly by the detected load current. This method reduces control delay, so that the regulation process can be completed as soon as possible and cross-regulation is improved. We have validated the proposed method with simulation.

Keyword: Single-inductor-dual-output (SIDO), DC-DC converter, Feed-forward control, Pulse-width-modulation (PWM), Cross-regulation, Control delay.

1. Introduction

In a portable device, such as cellular phones and notebook computers, some different DC supply voltages are required for different function modules. Multiple-supply implementations are required for getting high performance and reducing power loss. Among existing techniques, single-inductor dual-output switching converters are cost-effective solution. These converters require only one off-chip inductor and fewer on-chip power switches that help reducing system volume and saving chip area[(1) ~ (4)]. However, the converters are independently regulated if they work at continuous conduction mode (CCM), which leads to cross-regulation problem. (For SIDO converters which work at CCM, if the load of one sub-converter changes, the other sub-converter should be affected. This phenomenon is called cross-regulation.)

In recent years, some techniques of improving cross-regulation have been proposed. The reference [(5)] employs time multiplexing (TM) control. Sub-converters are isolated by a zero current period. However this converter has large current ripple, particularly when the load is heavy. Since the inductor current should be zero at the end of each cycle, a pseudo-continuous conduction mode is proposed in the reference [(6)]. This mode integrates the advantages of both CCM and DCM. When the load is light, the converter works at DCM. If load increases, a freewheel switching control keeps the inductor current above zero as CCM, but sub-converters are isolated by a DC level. However if the load is large enough, the converter may turn to CCM.

This paper tries to improve the cross-regulation based on control theory. Theoretical analysis of PWM feedback control in buck converter is given in section 2. A Feed-forward controller is employed in section 3, to shorten the control delay in feedback loop. In section 4, simulation results are presented. Section 5 provides a conclusion.

2. Control Theory in Buck Converter

〈2・1〉 Volt-Second Law and Converter Duty Cycle

We describe a steady state in switching converter by the inductor equation:

$$V_L = L \cdot dI_L/dt \quad (1)$$

Here V_L means the inductor voltage, I_L denotes the inductor current. In steady state, the product of the voltage applied across the inductor, multiplied by the duration, must be equal to the voltage that appears across the inductor during the off-time, multiplied by the duration the last for.

For a buck converter, we get the following:

$$\Delta I_L = (V_{in} - V_{out}) \cdot t_{on}/L = V_{out} \cdot t_{off}/L \quad (2)$$

It follows from (2) the relationship between input and output as:

$$V_{out} = V_{in} \cdot t_{on}/(t_{on} + t_{off}) = V_{in} \cdot D \quad (3)$$

Here D denotes the converter duty cycle. If converter operates in CCM, then $t_{off} = (1 - D)T_{switch}$.

〈2・2〉 PWM Feedback Control

A typical implementation for PWM control is shown as in Fig.1.

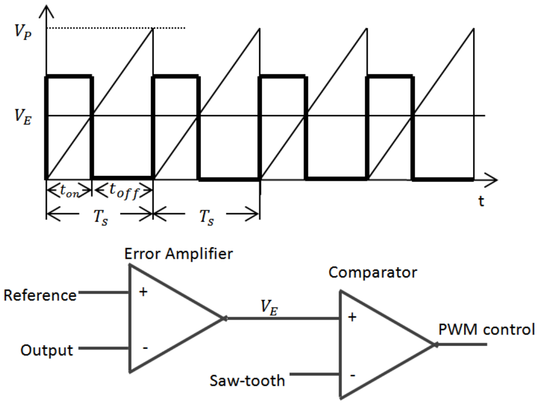


Fig. 1. Typical PWM control implementation.

Duty cycle is proportional to the amplified error and inversely proportional to the peak voltage of the saw-tooth. Then we obtain the following:

$D = V_E / V_P$ ……………………………………………………(4)

From the output voltage, we obtain error, and then we obtain PWM signal by comparing between the error and a saw-tooth reference signal. Finally the PWM controls the output by changing the duty cycle. All of them constitute a feedback control loop.

3. Load Regulation and Feed-forward Control

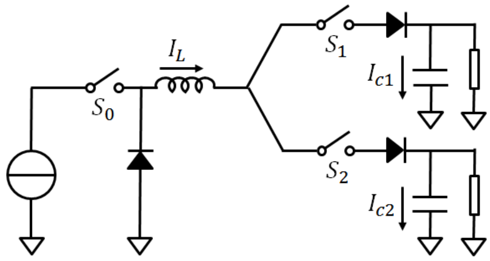
In a power supply the line and load variations are common. Line variation means that the input ripple should affect the output. Load variation always means a sudden change of output current. Since input voltage and output current both are not in the feedback loop, they are referred to as 'external disturbances' for a feedback control. The basic purpose of feedback is to reduce the effect of these disturbances on the output. However feedback is a control scheme based on error, so that control delay cannot be eliminated. While feed-forward scheme is based on prediction, it can provide quick regulation for the system.

For input ripple, if peak voltage of saw-tooth is made proportional to input, input-to-output voltage regulation can be achieved without change in V_E. This is a feed-forward controller for line change.

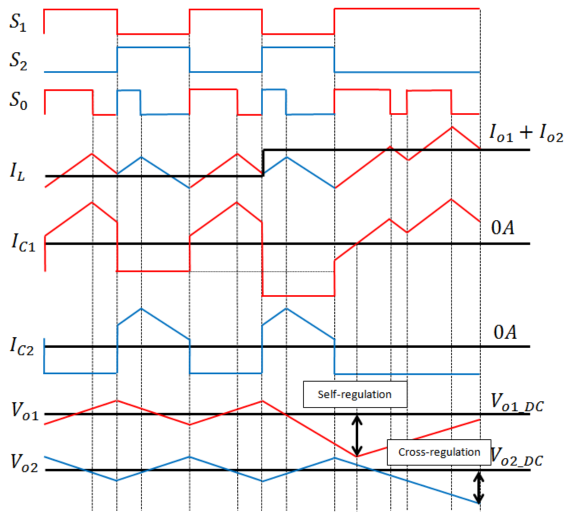
〈3･1〉 Load Regulation

Let us first consider the load regulation in a single-inductor single-output (SISO) buck converter. Output current is equal to the average current of the inductor in the buck converter. Suppose that load suddenly increases by ΔI_o, and then original balance is broken. Inductor current must be increased to get new balance. However inductor current cannot change in a step manner. According to the volt-second law, the increment of inductor current during on-time must be bigger than the decrement during off-time. In the other words, the duty cycle should be increased. By a feedback controller, it can be enforced only after the error increases. Down-shoot occurs at the output when load suddenly increases, on the other hand, over-shoot occurs when load decreases.

Load regulation in SIDO converter is more complicated. A SIDO buck converter proposed in reference [7] as showed in Fig.2 (a) is employed as discussion object.



(a)



(b)

Fig. 2. (a) SIDO buck converter in reference [7]. (b) Timing diagram of the converter.

In this SIDO converter, which sub-converter is served is decided by the error comparison at the beginning of every period. Timing diagram is shown as Fig. 2 (b). Suppose that the load of converter 1 suddenly increases, the balance of filter capacitor current whose average value is zero in steady state is broken, and then output voltage drops. As the load regulation in SISO converter, feedback controller adjusts duty cycle based on the amplified error, and we get a new balance. However, the other sub-converter is impacted during adjusting period. For example, as shown in the timing diagram, the period which should serve converter 2 is used to serve converter

1, therefore a voltage drop also occur at output2. Converter 2 is not served until the error of converter1 is reduced smaller than it. Sub-converters are alternately and interactively adjusted to reach a new steady state. This phenomenon is well known as the cross-regulation. If large load changes occur simultaneously at both outputs the converter may fail to be regulated.

〈3･2〉 Feed-forward Control

As above theoretical analysis the duty cycle is adjusted to make system reach a new steady state. According to equation (4), this adjusting can be carried out by changing error voltage or the peak voltage of saw-tooth. Since we hope that the error does not change, so that two choices are available. One is adding an additional voltage to amplified error voltage; the other one is regulating saw-tooth peak. Supposing load change by ΔI_o in a SISO buck converter, we get regulating value for feed-forward as:

$\Delta I_o = [(V_{in} - V_{out})D'T_s - V_{out}(1 - D')T_s]/L$……………..(5)

Here D' denotes adjusted duty cycle, and then we get

$\Delta V_E = V_P L \Delta I_o / (V_{in} T_s)$……………………………………..(6)

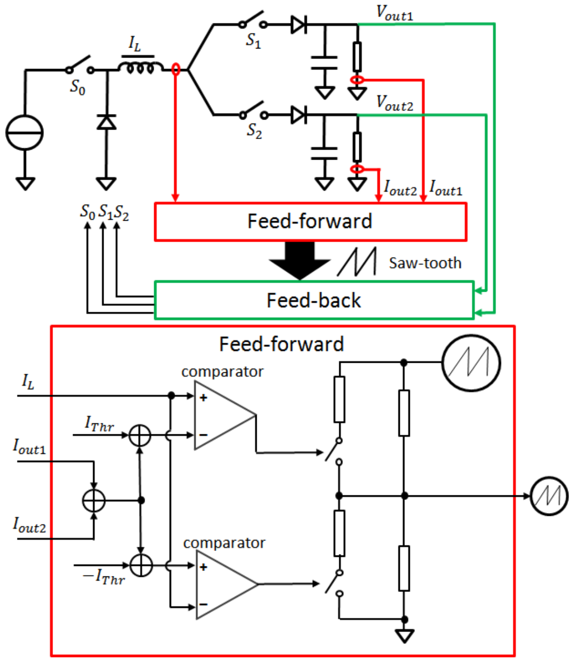
$\Delta V_P = V_E V_{in} L \Delta I_o / [V_{out}(L \Delta I_o + V_{out} T_s)]$…………………..(7)

From (6) and (7) we know that is hard to get an accurate regulation unless employing an additional compute unit. Observably it is not cost-effective. In addition, since $0 \le D' \le 1$ the load change is limited in a range. Otherwise can't complete regulate operation in one cycle. It leads to a more complex calculation. Above inference is based on SISO converter, it is complex, but much less than SIDO converter.

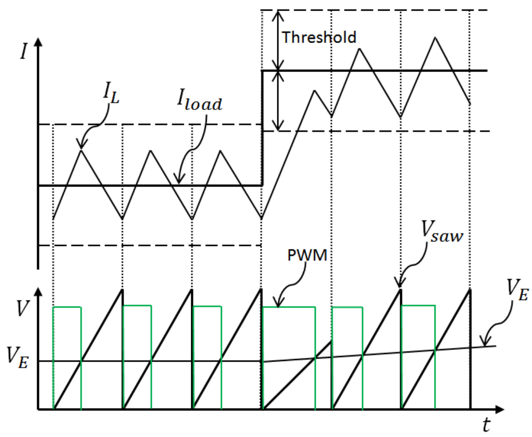
Here we propose to adopt a rough and fuzzy feed-forward strategy to simplify the system. Load current and inductor current are detected. Set threshold for load current. Setting principle of the threshold is enough wide to ensure that cover the ripple of inductor current at steady state. Therefore when inductor current is lower than the threshold, it means load increase. Saw-tooth peak voltage is reduced for increase of duty cycle by the same error voltage. It is similar while load decreases. Fig.3. shows the block diagram and regulation process of proposed feed-forward controller for SIDO buck converter. Since the regulation action is based on the same output error, we do not need wait until the error changes as in feedback control, so that it has quicker load response.

4. Simulation

In this section, some simulations are presented to validate the features of load regulation optimization of feed-forward. Let us begin with a simple SISO buck converter. Simulation conditions are shown in Table1.



(a)



(b)

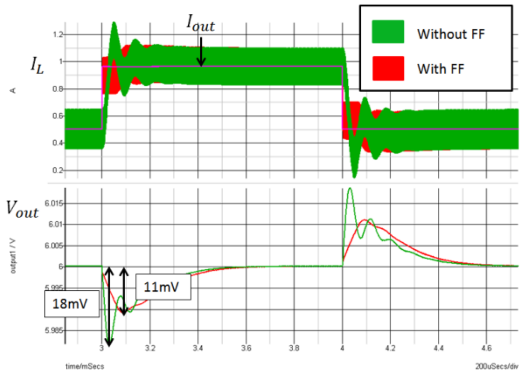
Fig. 3. Proposed feed-forward controller. (a) block diagram (b) regulation process

Table 1. Specifications of SISO buck converter.

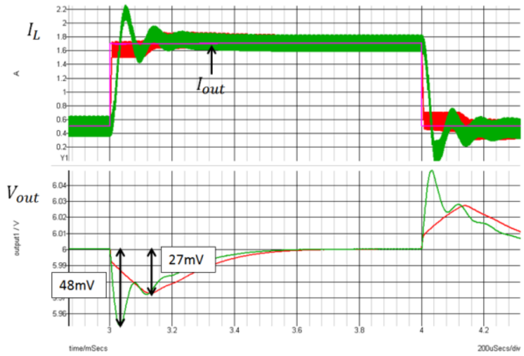
Parameter Name	Value	Parameter Name	Value
V_{in}	12V	V_{out}	6V
L	20 μ	f_{switch}	500kHz
C	500 μ		

Fig. 4 shows the simulation result; the red one is with feed-forward, green one means without feed-forward. In Fig. 4(a), load changes between 0.5A and 1A. Load regulation is reduced 7mV by feed-forward. While load changes between 0.5 A and

2A in Fig. 4(b), 21mV load regulation is improved.



(a)



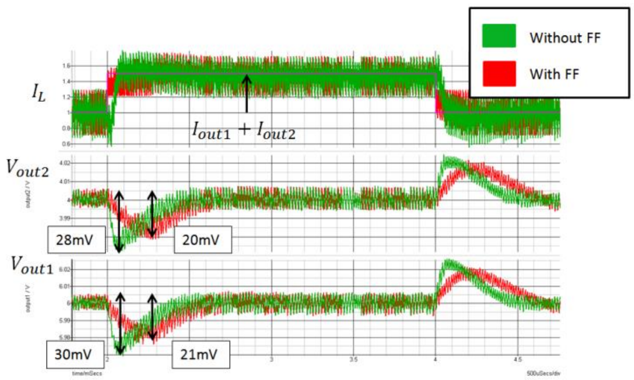
(b)

Fig. 4. Load regulation of a SISO buck converter with and without feed-forward (a)$I_{out} = 0.5A/1A$(b) $I_{out} = 0.5A/2A$

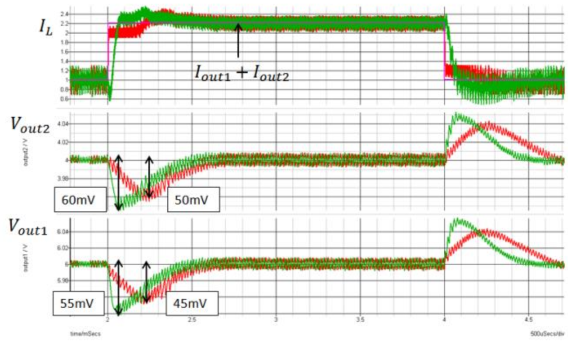
The next simulation object is a SIDO buck converter. Simulation conditions are shown in Table 2.

Table 2. Specifications of SIDO buck converter.

Parameter Name	Value	Parameter Name	Value
V_{in}	12V	V_{out1}	6V
L	20 μ	V_{out2}	4V
C_1, C_2	500 μ	f_{switch}	500kHz



(a)



(b)

Fig. 5. Load regulation of a SIDO buck converter with and without feed-forward (a)$I_{out1} = 0.5A/1A$. (a)$I_{out1} = 0.5A/2A$

In this simulation, the load of converter1 changes, while the load of converter2 keeps 0.5A. When load1 change between 0.5A and 1A, as shown in Fig. 5.(a), load regulation of converter1 is reduced about 9mV by feed-forward. At the same time, cross-regulation of converter2 is decreased about 8mV. With a larger load changes, as in Fig. 5.(b), load1 changes between 0.5A and 2A. Both of sub-converters have about 10mV reduction in load regulation by feed-forward control. Although the suppressing effect for SIDO converter is not distinct as in SISO converter, it is enough to prove that feed-forward control can optimize load regulation for switching power supplies.

4. Conclusion

After theoretical analysis about load regulation, we find that using feed-forward control to optimize load regulation for SIDO buck converter is possible in theory (though the mathematical derivation is depressing). Designing an accurate feed-forward control for SIDO converter is complicated and not cost-effective. Therefore a simple design is proposed. Although this rough and fussy feed-forward control cannot eliminate the load regulation completely, it can improve the load regulation effectively.

Only an incondite threshold is available criterion for control action, and the feature of open loop of feed-forward make it cannot be accurate as feedback control. Therefore more action criterion is necessary as the future work.

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