Transient Response Improvement of DC-DC Buck Converter With Adjustable Sawtooth Signal

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1. Introduction

Transient response performance is very important in DC-DC converters. It measures how steady the output voltage is maintained when the load changes suddenly. For single inductor dual output (SIDO) converters (1)~(4) that work in continuous conduction mode (CCM), the transient response affects cross-regulation: if the load of one sub-converter changes, the output voltage of the other sub-converter is affected.

The conventional control strategy in switching power supplies is to use output voltage or inductor current feedback. Although feedback control can stabilize the system, its effectiveness is limited by control loop delay and by the increased cost of using a large capacitor to stabilize the output voltage. Since feed-forward control does not introduce control delay, combining conventional feedback control with an additional feed-forward controller is one way to improve transient response. Load current feed-forward control methods (5)(6) have been proposed for output voltage regulation. Although these improve transient response, the performance improvement is limited in large load current transient conditions as the duty cycle saturates to 100%. Digital non-linear control methods have been also proposed (7)(8). The main drawback of such approaches is difficulty of non-linear calculation, especially for SIDO converters.

This paper proposes to use an adjustable sawtooth signal to realize a simple feed-forward controller for DC-DC buck converters. This approach employs sawtooth signal modulation based on charge balance of output capacitor. The adjustable sawtooth signal is compared with the error signal to provide the PWM drive signal. The proposed controller—whether used in single inductor single output (SISO) or SIDO converters—has the advantage of transient response improvement, and also it does not require complex and precise calculations that are required for digital controllers.

2. Proposed Adjustable Sawtooth Signal and Feed-forward Control

〈2・1〉 Conventional control method

The typical control method is that the error signal between output voltage and reference voltage is compared with a sawtooth signal to generate PWM drive signal. In voltage control mode (VCM), the sawtooth signal operates at fixed frequency and peak value, and it is supplied by external circuit. In current control mode (CCM), the sawtooth signal is synchronized with inductor current. This sawtooth signal has fixed-frequency but its peak value is the error signal. Unlike voltage control mode, the sawtooth signal in CCM has some relationships with output current. Therefore transient response of CCM is faster than VCM. However, whether VCM or CCM is employed, they are feedback control scheme based on error signal, so that control delay cannot be eliminated. There is no regulation until the error signal changes when the load is changed stepwise.

〈2・2〉 Proposed adjustable sawtooth signal

The sawtooth signal in this paper operates also at fixed-frequency while the peak value depends on the current of output capacitor. Under steady state, the average current of output capacitor should be zero, and the output current is equal to the average current of inductor in a buck converter. This is called charge balance of the output capacitor. If the load is changed suddenly, then capacitor must supply or store more charge because the inductor current cannot change stepwise. Therefore the charge balance is disrupted, and capacitor voltage (output voltage) is affected. The average current of the output capacitor is directly related to the load change. Since the peak value modulation of the sawtooth signal by the capacitor average is independent of the error signal, it works as a feed-forward control. There is not control delay when load is changed, so that the transient response will be improved.

3. System Configuration and Circuit

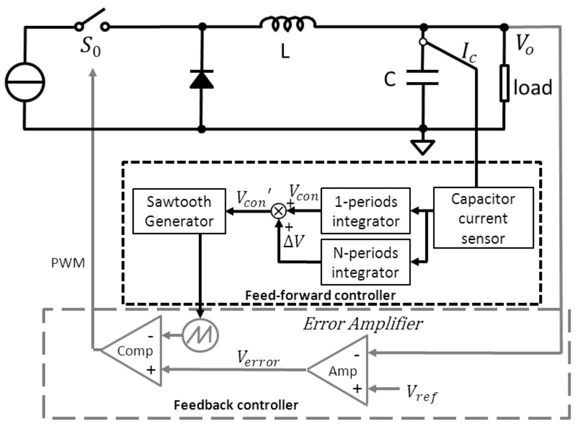


Fig.1 Buck converter with proposed controller.

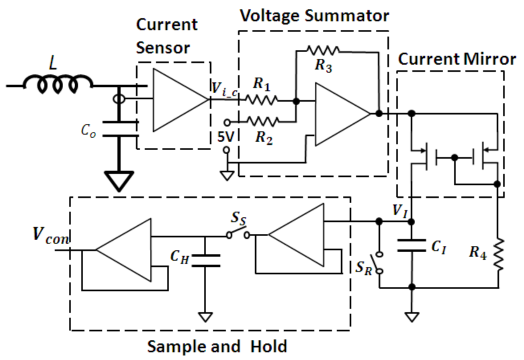
Fig.1 shows the proposed control scheme of an SISO DC-DC buck converter that includes a normal output voltage feedback control loop and the proposed adjustable sawtooth generator. The current in the output capacitor is measured and integrated. By integrating this current, it is possible to determine the charge balance approximately. The integrated result is used to control the sawtooth generator and modulate the duty cycle of the PWM signal before any error signal change is detected. Compared with feedback control, feed-forward control can respond to load-change disturbances faster and better to regulate the system.

〈3·1〉 Capacitor current integration

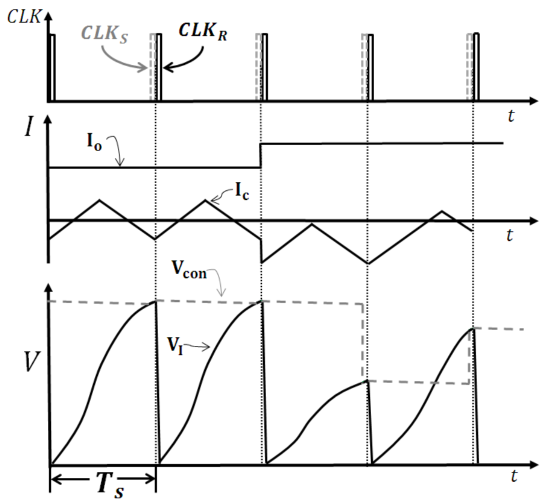
Fig.2 shows the integrator circuit and its timing chart. First the current in the output capacitor is converted to voltage V_{i_c} by a current sensor, and then this voltage signal is carried with a 5V DC bias. The integral capacitor C_I is charged by a current mirror whose current value is determined by the sum of V_{i_c} and 5V. Switch S_R driven by CLK_R is used to reset C_I every period. If the transfer ratio of the current sensor is set as R_{cs} and $R_1 = R_2 = R_3$, the peak value of integral capacitor voltage V_{I_peak} can be expressed as:

$$V_{I\_peak} = \frac{1}{R_4 C_I}\int_0^{T_s}(R_{cs}I_c(t) + 5)dt$$

where T_s is the switching period. As Fig.2 (b) shows, when the load increases suddenly, the peak voltage of V_I drops. Accordingly, when the load decreases, the peak voltage rises. The information about the load change can be expressed by the peak value, so the peak value is sampled by sampling switch S_S, which is controlled by CLK_S, and is held by a sample and hold capacitor C_H. The result V_{con} is used as the control variable to modulate the sawtooth generator.



(a) Circuit Diagram



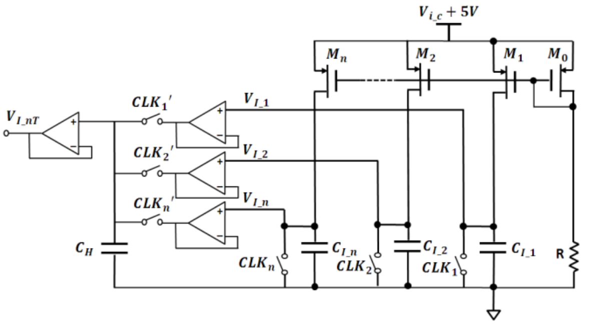
(b) Timing Chart

Fig.2 Integrated capacitor current.

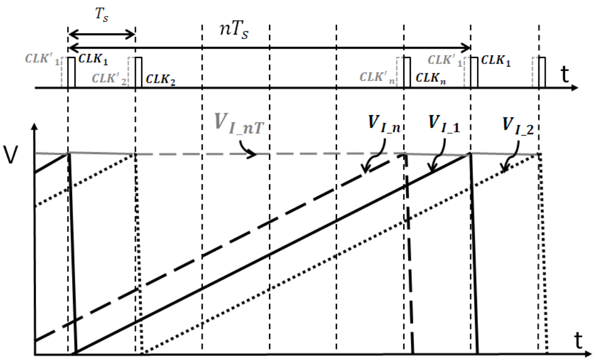
〈3·2〉 Control variable compensation

Notice that the integrator circuit shown in Fig. 2 uses only a single period of integration (only one period of charge balance is considered). Such an integrator is sensitive to a stepwise change, however, so—for transient response—capacitor charge balance over several periods must be considered, thus multi-periods integration is required in practice. Although the multi-period integrator is not sensitive to a stepwise change, it can be used to compensate the control variable and regulate the output voltage once the transient ends. The circuit in Fig.3 is similar to the design shown in Fig.2, except that n-periods of capacitor current are integrated. Output signal V_{I_nT} is also updated every period, but the information reflects the charge balance state of the output capacitor during the previous n periods. This information is used to determine the compensation for the control variable, as shown in Fig.4.

The output signal V_{I_nT} of the n-period integrator is compared with threshold values. When it is within a threshold range, there is no need to compensate the control variable V_{con}' that was obtained from the single period integrator. On the other hand, if V_{I_nT} exceeds the threshold, it means charge and discharge during the previous n periods did not balance, and the voltage signal is compensated by altering the single period integration control variable. By using this compensation scheme, even though single-period charge is balanced, the information provided by the previous n periods is used by the feed-forward controller to regulate the output after integration is complete.



(a) N-period integrator circuit.



(b) Timing chart of n-period integrator.

Fig.3 N-period integration.

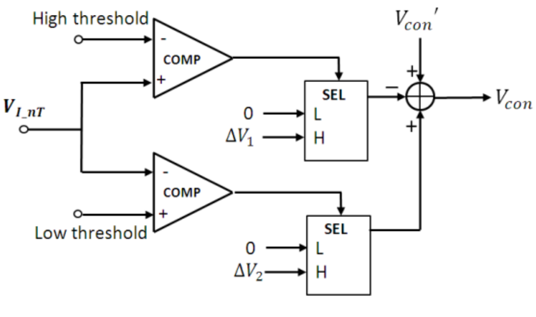


Fig.4 N-period integration compensation.

〈3･3〉 Sawtooth signal generator

The sawtooth generator circuit is shown in Fig. 5. Capacitor C_s is charged by a current mirror which is controlled by control variable−V_{con}. As previously stated, V_{con} is updated by the single-period integrator at the end of every period, and stays constant during the next period. V_{con} determines the current mirror, which acts as a controlled linear resistor. Switch S_{R_S} is reset by a switching pulse. The control variable is carefully set to generate an appropriate sawtooth signal by adjusting the parameters of the integrator. The sawtooth generator should not be over-sensitive to load, to avoid oscillation. However, it also should not be overly insensitive to load changes. Therefore, not only should the integrator be well-designed, but the sawtooth generator should also be properly adjusted.

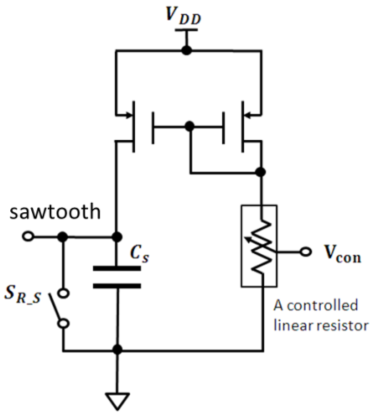


Fig.5 Sawtooth generator.

4. Simulation

The performance improvement of the proposed adjustable sawtooth control method has been tested through simulation using SIMetrix. Fig.6 shows the simulation result of SISO buck converter and Fig. 7 for SIDO buck converter. The converter parameters are set as shown in Table.1

In Fig.6, the black curves are the simulation results with the proposed adjustable sawtooth method, the gray curves show when only feed-back control with fixed sawtooth signal is used. (1) is load current, (2) and (3) are inductor current, (4) and (5) are output voltage, (6) is PWM signal, (7) is sawtooth signal. When there is a load current step change from 0.5A to 1A, the PWM signal is high for two periods since the sawtooth signal is modulated. Therefore the inductor and capacitor are continuously charged by the input voltage source. The buck converter is compensated before large errors are caused. The output drops by only 5mV, whereas it would drop by 11mV if the converter were regulated by feedback control alone. Transient response time is shortened from

Table.1 Simulation Conditions.

SISO		SIDO	
V_{in}	12V	V_{in}	12V
V_{out}	6V	V_{out1}	6V
		V_{out2}	4V
L	20μH	L	20μH
C	500μF	C_{o1}, C_{o2}	500μF
f_{switch}	500kHz	f_{switch}	500kHz

500μs to 8μs.

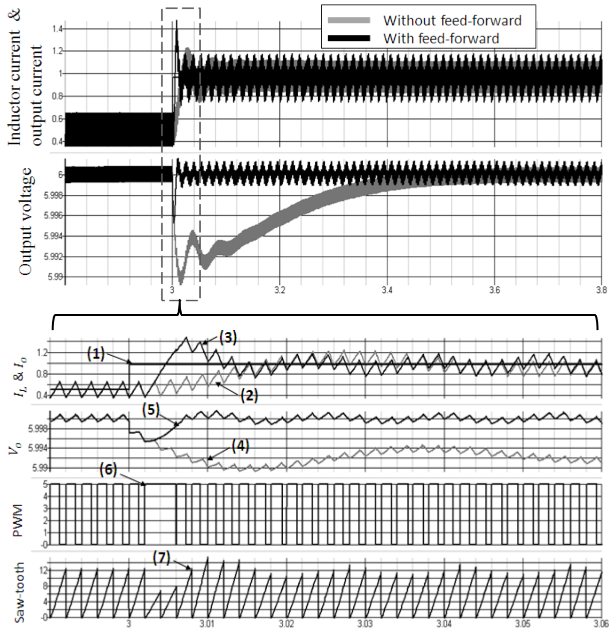


Fig.6. Simulation result (load current step change 0.5A→1A), (1) Load current, (2) Inductor current without FF, (3) Inductor current with FF, (4) Output voltage without FF, (5) Output voltage with FF, (6) PWM signal with FF, (7) Saw-tooth signal with FF

Fig.7 shows the simulation results of the SIDO buck converter. The load current of sub-converter 2 keeps at 0.5A, while at 3ms load current of sub-converter 1 step changes from 0.5A to 0.96A. The SEL signal decides to which sub-converter should be supplied with energy. Similar to the SISO simulation, the saw-tooth is modulated. Since the transient response of the load changed converter is improved, the cross-regulation is also improved. This figure shows that cross regulation can be practically negligible.

5. Summary

This paper proposed a new and simple feed-forward control method which is realized by an adjustable sawtooth signal generator. Compared with digital feed-forward controller, this method does not require complicated calculation and digital signal processing. The saw-tooth signal is modulated based on the information of output capacitor current. Since this method has almost no control delay, the transient response is significantly improved. This performance improvement is helpful to improve the cross-regulation in SIDO buck converter.

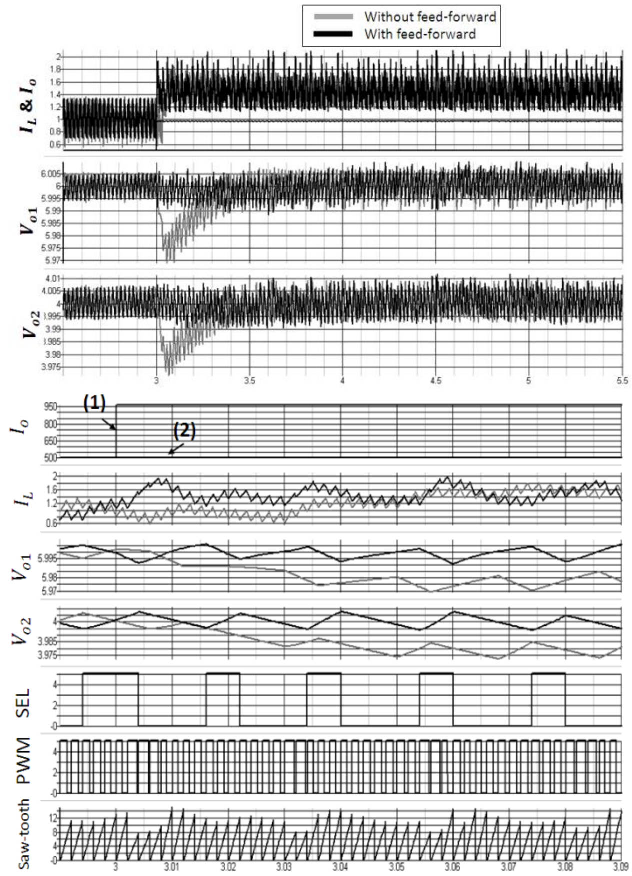


Fig.7. Simulation result (I_{o1}: 0.5A→0.96A, I_{o2}: 0.5A), (1) Load current of sub-converter1, (2) Load current of sub-converter 2

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