Soft-Switching Auxiliary Current Control for Improving Load Transient Response of Buck Converter

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ABSTRACT

A control technique for the auxiliary buck/boost converter is proposed herein to improve the load transient response of the buck converter. The proposed technique improves the system efficiency by enabling the soft switching operation of the auxiliary converter. The design guidelines for achieving capacitor charge balance for the output capacitor during the transient are also presented herein. The experimental results revealed that the output voltage undershoot and settling time during the load step-up transient were 40 mV and 14 μs, respectively, and the output voltage overshoot and settling time during the load step-down transient were 35 mV and 21 μs, respectively. The performance and effectiveness of the proposed technique were experimentally verified using a prototype buck converter with a 15-V input, 3.3-V output, and 200-kHz switching frequency.

1. Introduction

Various control techniques have previously been developed to improve the load transient response of the buck converter. The time-optimal control based on the capacitor charge balance (CCB) enables minimum output voltage fluctuation without the aid of auxiliary circuits[1]. Previous studies have emphasized the simple implementation and operation of resistive auxiliary circuits[2]-[3]. The auxiliary switched resistor attenuates the output voltage fluctuation, reduce the efficiency, and increase the electromagnetic interference (EMI) caused by the high di/dt of the switches[2]. The auxiliary inductor and bidirectional switches require complicated control circuits and impose a heavy computational burden on the digital integrated circuit (IC)[3]. Additionally, the resistance in the freewheeling path degrades the efficiency.

Control techniques employing nonresistive auxiliary circuits can also improve the dynamic response[4]-[6]. The auxiliary inductor exploits the resonance and soft switching[4], but the auxiliary switches must be controlled differently and according to whether the load is stepped up or down, which increases the controller complexity. The high-frequency switching controllers of the auxiliary circuit have been described in previous papers[5]-[6]. The average current of the auxiliary inductor has been controlled to a constant value to achieve CCB during the load transient[5]. Adaptive slope control has also been proposed to further improve the load transient response[6]. However, these control techniques require high-bandwidth sensors and high-speed digital ICs, which increase the controller complexity.

This paper proposed a technique for peak-current-controlling the auxiliary current in critical conduction mode (CRM). The technique minimizes the output voltage deviation during the load transient through cycle-by-cycle CCM, while the soft turn-on of the auxiliary switches suppresses the efficiency degradation and EMI generation. The remainder of this paper is organized as follows; Section 2 describes the circuit operation and design conducted via the proposed control scheme. The experimental results are presented in Section 3, and the conclusions are presented in Section 4.

2. Proposed Control Technique

2.1 Implementation of proposed control circuit

Fig. 1 shows the main converter (Q_1, Q_2, and L_1) and auxiliary buck/boost converter (Q_3, Q_4, and L_2) connected in parallel. The literals V_{in}, v_O, i_{L1}, i_{L2}, and i_O denote the input voltage, output voltage, main inductor current, auxiliary inductor current, and load current, respectively. The voltages v_{gsi} and v_{dsi} denote the gate-source and drain-source voltages of the metal-oxide-semiconductor field-effect transistor (MOSFET) Q_i, respectively. In the steady state, Q_3 and Q_4 are turned off, while Q_1 and Q_2 are operational via the conventional voltage mode controller (VMC). During the load transient, Q_3 and Q_4 operate along with Q_1 and Q_2 to control i_{L2} and improve the transient response.

The key waveform of the proposed auxiliary current control is shown in Fig. 2. The literals V_{ref} and ΔI_O are the target output voltage and magnitude of the i_O variation, respectively. During the transient period caused by stepping up i_O and t_1-t_5, Q_1 is fully turned on while Q_2 is

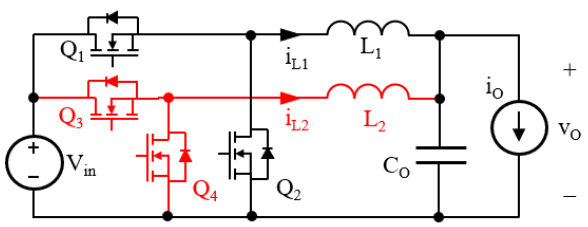

Fig. 1. Main buck converter (Q_1, Q_2, and L_1) and auxiliary buck/boost converter (Q_3, Q_4, and L_2) for applying proposed auxiliary current control.

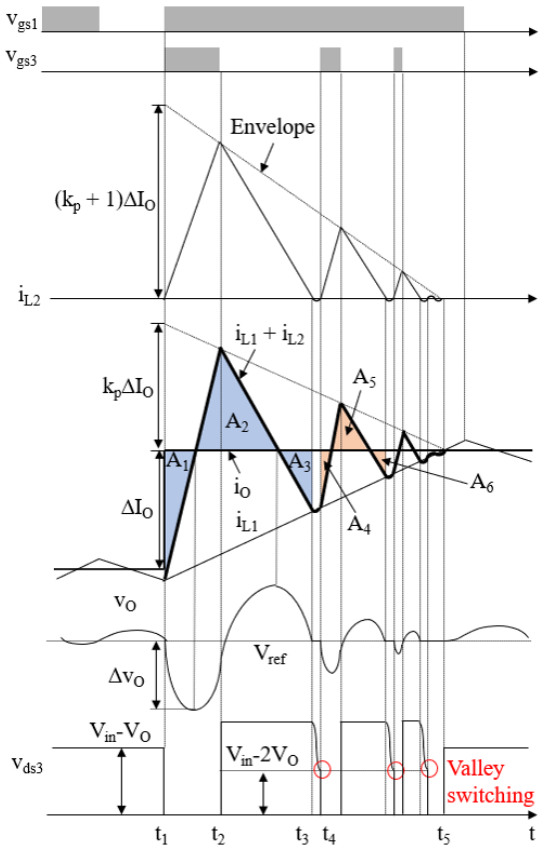

Fig. 2. Key waveforms of proposed auxiliary current control when i_O is stepped up (N=3).

fully turned off shown in Fig. 2. The auxiliary converter works as a peak-current-mode-controlled buck converter in the CRM. Switch Q_3 operates as the main switch of the auxiliary buck converter to produce the triangular wave shapes of i_{L2} under an envelope. The first switching period of the auxiliary converter comprises three switching states:

- State 1 [t_1-t_2]: Current i_O is stepped up at t_1; Q_3 turns on, and i_{L2} increases linearly.
- State 2 [t_2-t_3]: When i_{L2} reaches the envelope at t_2, Q_3 turns off, and i_{L2} decreases and freewheels through the body diode of Q_4. Switch Q_4 can be ON as a synchronous rectifier to reduce the conduction loss.
- State 3 [t_3-t_4]: When i_{L2} reaches zero at t_3, the output parasitic capacitances of Q_3 and Q_4 and L_2 resonate. Switch Q_3 turns on again at t_4, when v_{ds3} is minimum. During this state, the v_O variation is assumed to be negligible.

These states are repeated N times before the steady-state operation resumes and VMC regains control at t_5. The number N can be limited to avoid the risk of excessively high switching frequencies and power losses. The switching loss of Q_3 is minimized via valley switching, that is, by Q_3 turning on at the valley of v_{ds3}. Switch Q_3 may turn on with zero-voltage switching (ZVS) if $V_{in} \le 2v_O$.

Area A_n represents the amount of charge that is charged to or discharged from the output capacitor C_O, to which the v_O deviation is proportional. The coefficient k_p is set to

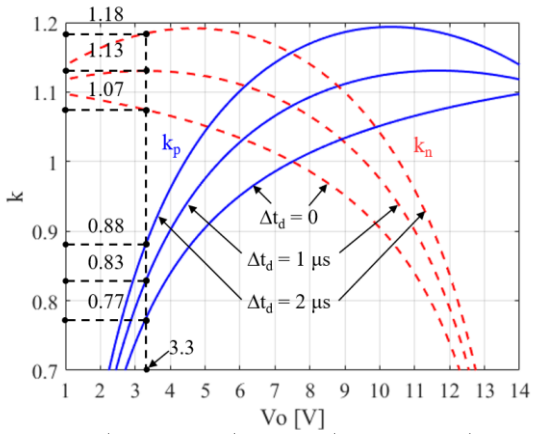

Fig. 3. k_p (solid curves) and k_n (dotted curves) versus v_O under conditions defined in Table 1.

Table 1. Circuit parameters of experiment.

Parameter	Description
V_{in}	15 V
v_O	3.3 V
i_O	4 A-15 A
Switching frequency of Q_1 and Q_2	200 kHz
L_1	10 uH
L_2	500 nH
C_O	220 uF

maintain the CCB of C_O in each switching cycle, as expressed in (1).

$$A_i + A_{i+2} = A_{i+1} \quad (i = 1,4,7,\cdots) \tag{1}$$

Section 2.2 presents the derivation of k_p in detail. The undershoot of v_O, Δv_O, is the function of voltages, inductances, and ΔI_O and is solely determined by A_1, as expressed in (2).

$$\Delta v_O = \frac{A_1}{C_O} = \frac{\Delta I_o^2 L_1 L_2}{2C_O(L_1+L_2)(V_{in}-V_O)} \tag{2}$$

When i_O is stepped down, the auxiliary converter operates as a peak-current-mode-controlled boost converter in CRM. Switch Q_4 acts as the main switch of the auxiliary boost converter and turns on with ZVS if $V_{in} > 2v_O$, while Q_1 is fully off and Q_2 is fully on.

2.2 Envelope for Capacitor-Charge-Balance

The magnitude of i_{L2} is controlled by the envelope of which height is $(k_p+1)\Delta I_O$ as shown in Fig. 2. The constant k_p is a function of V_{in}, V_O, L_1, and L_2 and is independent from ΔI_O, as expressed in (3).

$$k_p = \frac{L_1 V_O - L_2(V_{in}-2V_O)}{L_1 V_O + L_2(V_{in}-2V_O)} \tag{3}$$

The other constant k_n that determines the envelope when i_O is stepped down can be obtained using (4).

$$k_n = \frac{L_1(V_{in}-V_O)+L_2(V_{in}-2V_O)}{L_1(V_{in}-V_O)-L_2(V_{in}-2V_O)} \tag{4}$$

In practical implementation, the first turn-on of Q_3 may be delayed by the time Δt_d from the step change of i_O. Fig. 3 plots k_p and k_n versus v_O when V_{in}, L_1, L_2, and I_O are as presented in Table 1. The plots are symmetric with respect

to the $V_O = V_{in}/2$ line (7.5 V in this paper) when $\Delta t_d=0$, because the increasing and decreasing slope of $i_{L1}+i_{L2}$ are interchanged between the step-up and step-down cases of i_O. The nonzero Δt_d increases both k_p and k_n.

3. Experimental Verification

The prototype circuit shown in Fig. 1 was built; its parameters are listed in Table 1. The VMC control loop had a 78.6° phase margin at the 12-kHz cutoff frequency via a PIC type-3 compensator and the control circuit was configured by analog ICs only. Fig. 4 shows the experimental waveform of i_O (magenta trace), $i_{L1}+i_{L2}$ (red), v_O (blue), v_{ds3} and v_{ds4} (green) of the proposed control scheme when i_O was stepped up and down, respectively. The delay Δt_d was 1.2 μs at step-up and 0.5 μs at step-down. In Fig. 4(a), The measured undershoot voltage and settling time were 40 mV and 14 μs, respectively. As can be seen, Q_3 valley-switched to reduce the switching loss and noise. In Fig. 4(b), the measured overshoot voltage and settling time were 35 mV and 21 μs, respectively. The Q_4 was zero-voltage-switched, reducing switching loss and noise during the load step-down transient.

4. Conclusion

An auxiliary current control technique is proposed herein to improve the load transient response of buck converter. The proposed scheme controls the auxiliary buck/boost converter through the peak current mode in CRM. The proposed control scheme minimizes the output voltage deviation and power loss of the auxiliary circuit via soft-switching auxiliary switches. Experimental results by 15 V-3.3 V, 200-kHz buck converter demonstrated the improved dynamic response: the undershoot was 40 mV and the settling time was 14 μs when the output current was stepped from 4 A to 15 A, and the overshoot was 35 mV and settling time was 21 μs when the output current was stepped from 15 A to 4 A.

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References

[1] E. Meyer, Z. Zhang, and Y. F. Liu, "An optimal control method for buck converters using a practical capacitor charge balance technique," IEEE Trans. Power Electron., vol. 23, no. 4, pp. 1802-1812, Jul. 2008.

[2] S. Kapat, P. S. Shenoy, and P. T. Krein, "Near-null response to large-signal transients in an augmented buck converter: a geometric approach," IEEE Trans. Power Electron., vol. 27, no. 7, pp. 3319-3329, Jul. 2012.

[3] W. Lu, Z. Zhao, Y. Ruan, S. Li, and H. H. C. Iu, "Two-period frame transient switching control for buck converter using coupled-inductor auxiliary circuit," IEEE Trans. Ind. Electron., vol. 66, no. 10, pp. 8040-8050, Oct. 2019.

[4] Z. Shan, S. C. Tan, C. K. Tse, and J. Jatskevich, "Augmented buck converter design using resonant circuits for fast transient recovery," IEEE Trans. Power Electron., vol. 31, no. 8, pp. 5666-5679, Aug. 2016.

[5] E. Meyer, Z. Zhang, and Y. F. Liu, "Controlled auxiliary circuit to improve the unloading transient response of buck converters," IEEE Trans. Power Electron., vol. 25, no. 4, pp. 806-819, Apr. 2010.

[6] Y. Wen and O. Trescases, "DC-DC converter with digital adaptive slope control in auxiliary phase for optimal transient response and improved efficiency," IEEE Trans. Power Electron., vol. 27, no. 7, pp. 3396-3409, Jul. 2012.

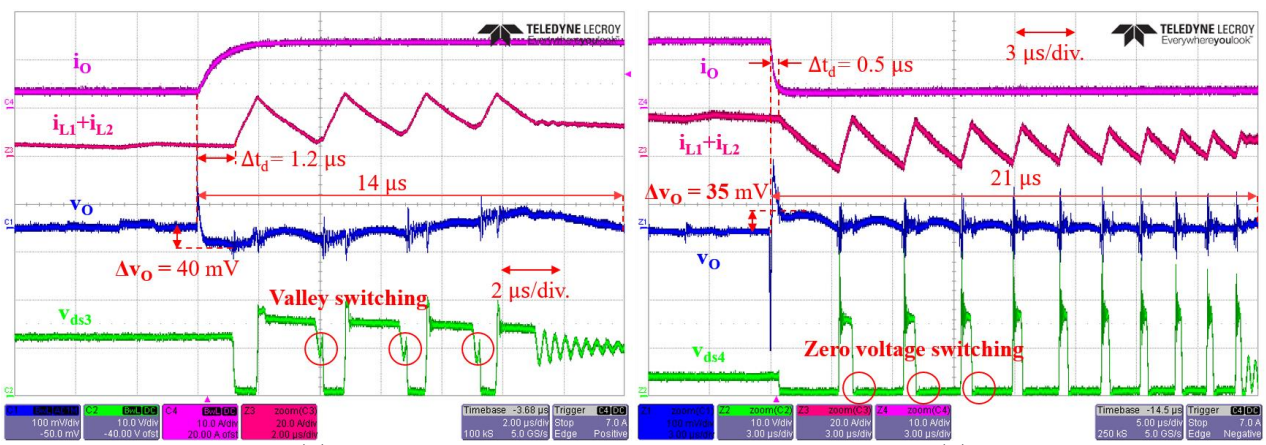

Fig. 4. Experimental waveforms of proposed control technique; trace i_0 (magenta) is in 10 A/div; trace i_{L1} + i_{L2} (red) is in 20 A/div; trace v_0 (blue) is in 100 mV/div. with AC coupling; trace v_{ds3} or v_{ds4} (green) are in 10 V/div. (a) When i_0 is stepped up from 4 to 15 A with N = 4; time scale is 2 µs/div. (b) When i_0 is stepped down from 15 to 4 A with N = 10; time scale is 3 µs/div.