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4 authors, including:

Xi Zhang
Southwest Jiaotong University

Jianping Xu
Southwest Jiaotong University

Guohua Zhou
Southwest Jiaotong University

Capacitor Current Fixed Off-Time Control for Buck Converter with Fast Response and Output Capacitor ESR Independence

Xi Zhang, Jianping Xu, *Member*, *IEEE*, Guohua Zhou, *Senior Member*, *IEEE*, Yiming Chen
School of Electrical Engineering
Southwest Jiaotong University
Chengdu, Sichuan, China
zhangxi.98@163.com, jpxu-swjtu@163.com, ghzhou-swjtu@163.com, chen90sky@163.com

***Abstract*—Fixed off-time (FOT) control technique has been widely used in various industry applications due to its fast transient response. However, when output capacitor with small equivalent series resistance (ESR) is used, output capacitor voltage phase lagging behind inductor current phase can cause instability in FOT controlled buck converter. Although using large output capacitor ESR can ensure stable operation, which will cause large output voltage ripple. To eliminate the instability in FOT control switching dc-dc converter with small output capacitor ESR, a capacitor current FOT (CC-FOT) control is proposed in this paper. The operational principle of CC-FOT controlled buck converter is elaborated. By the describing function method, the control-to-output voltage transfer function of CC-FOT controlled buck converter is derived and its stability is studied. The study results indicated that CC-FOT control has a better control performance than that of FOT control, and its stability is independent of output capacitor ESR, which are verified by PSIM simulation results.**

Keywords—Buck converter, capacitor current (CC), fixed off-time (FOT) control, stability

I. Introduction

Similar to constant on-time (COT) control technique, fixed off-time (FOT) control, a variable-frequency ripple-based control technique, has advantages of fast load transient response and simple control loop, which are attractive for powering microprocessor of portable electronics devices [1]. COT control is a valley-ripple-based control technique and its switching frequency changes proportionally with the load in discontinuous conduction mode (DCM), which is optimal for improving light load efficiency; however, its output voltage ripple increases with the decrease of load [2]. Compared with COT control, FOT control is a peak-ripple-based control technique and its switching frequency increases with the decrease of load in DCM, supplying a small output voltage ripple at light load [3]. Besides, the light load efficiency of FOT controlled buck converter can be improved by introducing additional operation mode, such as idle mode [4].

For COT or FOT control, the output voltage ripple, which includes the current information sensed by equivalent series resistance (ESR) of output capacitor, is directly used to modulate the duty-cycle. However, when output capacitor with small ESR is used, output capacitor voltage phase lagging behind inductor current phase can cause the subharmonic oscillations [1, 2] or the pulse bursting phenomenon [5, 6] in COT or FOT controlled buck converter. To ensure normal stable operation of FOT controlled buck converter, large output capacitor with large ESR is required, however, which will cause large output voltage ripple [1, 2, 5].

To improve stability of COT or FOT control switching dc-dc converter with small output capacitor ESR, an internal or external compensation ramp is often introduced in control loop [1, 7, 8]. However, the introduction of ramp compensation can deteriorate the load transient response of the converter [8] and complicates the control loop. Moreover, the dc regulation accuracy of FOT control is inadequate [1, 9], and a high dc-gain error amplifier is often introduced in control loop [1], for example, V^2-FOT control. However, the stability of V^2-FOT controlled buck converter is still affected by the output capacitor ESR [6].

For buck converter, capacitor current equals the inductor current minus load current and reflects the variations of inductor current and load current [10]. When load current perturbation or inductor current perturbation occurs, the capacitor current can respond to it promptly. Thus, using the sensed capacitor current as modulation ramp can provide fast transient response. Besides, due to there is no output capacitor ripple in modulation ramp, the instability related to output capacitor voltage phase lagging behind inductor current phase is avoided. In this paper, a CC-FOT control technique for switching converters is proposed, and its control performances are studied.

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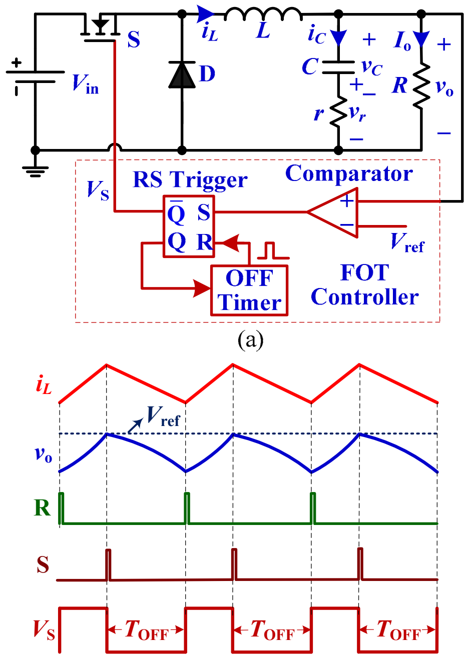

Fig. 1 FOT controlled buck converter. (a) Schematic diagram. (b) Steady-state waveforms.

II. Review of FOT Controlled Buck Converter

A. FOT Controlled Buck Converter

The schematic diagram of the FOT controlled buck converter and its steady-state waveforms are depicted in Fig. 1 [6], where the power stage circuit is composed of input voltage source V_{in}, switch S, diode D, inductor L, output capacitor with capacitance C and ESR r, and load resistor R; FOT controller consists of comparator, RS trigger and OFF Timer.

From Fig. 1(b), when output voltage v_o reaches the reference voltage V_{ref}, the RS trigger is set by comparator and the switch S is turned off, and v_o begins to decrease. After fixed off-time T_{OFF}, the RS trigger is reset by the OFF Timer and the switch S is turned on, and v_o begins to increase. When v_o reaches the reference voltage again, a new switching cycle begins.

B. Instability in FOT Controlled Buck Converter

Based on the PSIM software, using circuit parameters as listed in Table I, the simulation results of FOT controlled buck converter under different output capacitor ESRs are shown in Fig. 2. From Table I, the critical ESR can be calculated as $r_{critical}$ = 12.5 mΩ [6]. When r = 20 mΩ > $r_{critical}$, FOT controlled buck converter operates in stable state with smaller output voltage ripple, as shown in Fig. 2(a); while when r = 5 mΩ < $r_{critical}$, the converter operates in subharmonic oscillations with pulse bursting, causing larger output voltage ripple, as shown in Fig. 2(b). Additionally, from Fig. 2(a), it is found that there exists steady-state error in FOT controlled buck converter.

Table I Circuit Parameters for FOT Controlled Buck Converter

Parameters	Significations	Values
E	Input voltage	3.3 V
V_{ref}	Reference voltage	1.8 V
L	Inductance	5 μH
C	Capacitance	100 μF
R	Load resistance	1 Ω
T_{OFF}	Fixed off-time	2.5 μs

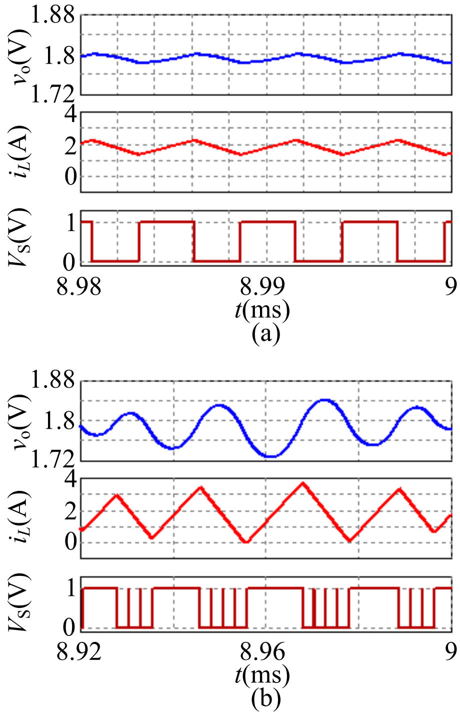

Fig. 2 Simulation results for different ESRs. (a) r = 20 mΩ. (b) r = 5 mΩ.

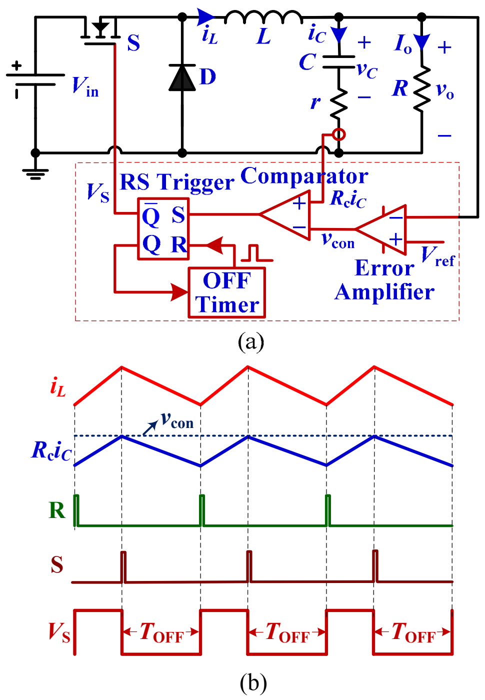

Fig. 3 *CC*-FOT controlled buck converter. (a) Schematic diagram. (b) Steady-state waveforms.

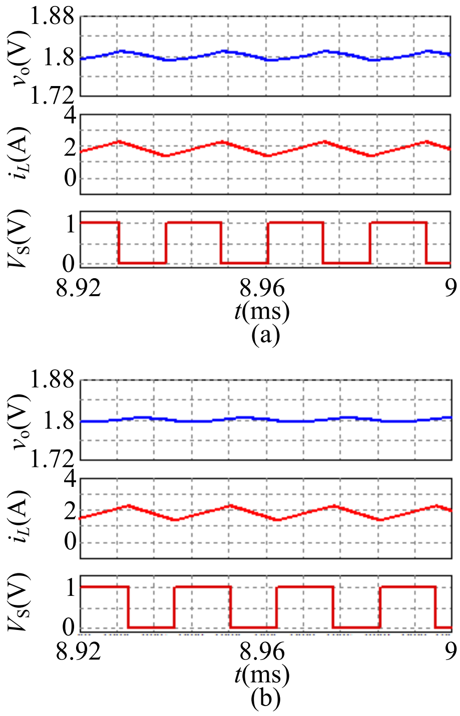

Fig. 4 Simulation results of the *CC*-FOT controlled buck converter. (a) $r = 20$ mΩ. (b) $r = 5$ mΩ.

III. Proposed Control Method: CC-FOT Control

A. CC-FOT Controlled Buck Converter

CC-FOT controlled buck converter and its steady-state waveforms are shown in Fig. 3. From Fig. 3(a), it can be found that compared with FOT controller, the controller of CC-FOT control uses error amplifier and its compensator as outer control loop and use the sensed capacitor current $R_c i_C$ as internal control loop, where R_c is sensed resistance. From Fig. 3(b), when $R_c i_C$ reaches the control signal v_{con}, the switch S is turned off and the sensed capacitor current decreases. After fixed off-time T_{OFF}, the switch S is turned on and the sensed capacitor current increases. When $R_c i_C$ reaches v_{con} again, the converter enters the next switching cycle.

Using the circuit parameters listed in Table I, the simulation results of the CC-FOT controlled buck converter with $K_P = 20$ and $K_I = 50000$ under different ESRs are shown in Fig. 4, from which CC-FOT controlled buck converter is always in stable operation and independent of output capacitor ESR. Thus, the output voltage ripple can be minimized by using smaller output capacitor ESR. Compared Fig. 4 with Fig. 2(a), it is found that the steady-state error is eliminated in CC-FOT controlled buck converter.

B. Stability Analysis

To analyze the stability of CC-FOT controlled buck converter, its control-to-output voltage transfer function is derived based on describing function method [7].

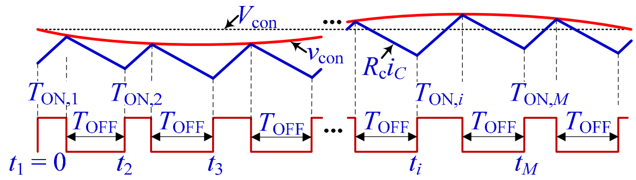

Fig. 5 Perturbed waveforms for *CC*-FOT control

As shown in Fig. 5, a small sinusoidal perturbation is added to the control signal, and the perturbed control signal is expressed as

$$v_{con} = V_{con} + \hat{v}\sin(2\pi f_m t + \theta), \quad \hat{v} \ll V_{con} \tag{1}$$

where V_{con} is the steady-state dc value of control signal, and $\hat{v}$, f_m and θ are the magnitude, frequency and initial angle of the small sinusoidal perturbation, respectively. To employ the describing function method, it is necessary to make the assumption that the perturbation frequency f_m is in the same order with the switching frequency f_s, i.e. $M \cdot f_m = N \cdot f_s$, where M and N are both positive integers.

Due to the off-time T_{OFF} is constant, the on-time is modulated by the perturbed signal. In the perturbed i-th switching cycle, the perturbed on-time $T_{ON,i}$ can be expressed as $T_{ON,i} = T_{ON} + \Delta T_{ON,i}$, where T_{ON} is the steady-state on-time and $\Delta T_{ON,i}$ is the on-time perturbation. Thus, the beginning of the perturbed i-th switching cycle t_i can be written as

$$t_i = (i-1)(T_{ON} + T_{OFF}) + \sum_{k=1}^{i-1} \Delta T_{ON,i} \tag{2}$$

Fourier analysis is implemented on the capacitor current, and the Fourier coefficient $c_m(i_C)$ of capacitor current at the perturbed frequency f_m can be obtained as

$$\begin{aligned} c_m(i_C) &= \frac{j2\pi f_m}{N\pi}\int_0^{t_i + T_{ON,i} + T_{OFF}} \left(i_L - \frac{V_o}{R}\right) e^{-j2\pi f_m t}\,\mathrm{d}t \\ &= \frac{\hat{v}e^{-j\theta} f_s V_{in}}{j2\pi f_m K V_o}\left(1 - e^{-j2\pi f_m T_{OFF}}\right) \end{aligned} \tag{3}$$

The Fourier coefficient of perturbed control signal at the perturbation frequency f_m is $c_m(v_{con}) = \hat{v} \cdot e^{-j\theta}$; thus, the control-to-capacitor current transfer function can be derived by

$$\frac{i_C(s)}{v_{con}(s)} = \frac{f_s V_{in}}{s R_c V_o} \bullet \left(1 - e^{-sT_{OFF}}\right) \tag{4}$$

By using the Padé approximation, the exponential term $e^{-sT_{OFF}}$ can be simplified to

$$e^{-sT_{OFF}} = 1 - \frac{sT_{OFF}}{1 + \frac{s}{\omega_1 Q_1} + \frac{s^2}{\omega_1^2}} \tag{5}$$

where $\omega_1 = \pi / T_{OFF}$ and $Q_1 = 2/\pi$. According to (5), (4) can be simplified as

$$\frac{i_C(s)}{v_{con}(s)} \approx \frac{T_{OFF}}{R_c T_{ON}} \bullet \frac{1}{1 + \frac{s}{\omega_1 Q_1} + \frac{s^2}{\omega_1^2}} \tag{6}$$

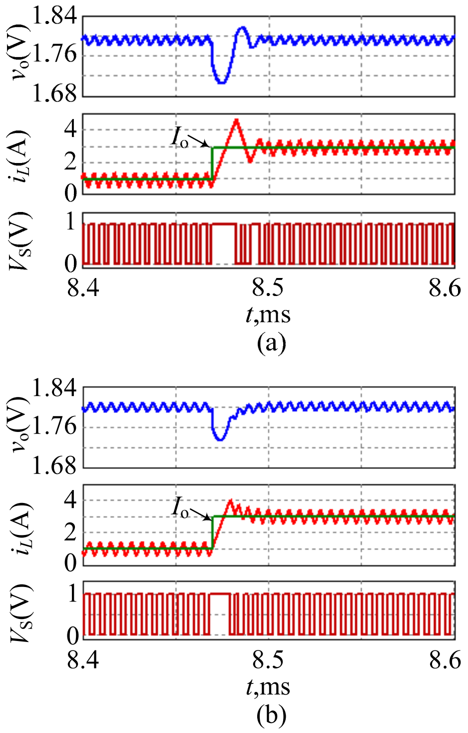

Fig. 6 Transient response for Load step from 1 A to 3 A at $r = 20$ mΩ (a) FOT controlled buck converter. (b) CC-FOT controlled buck converter.

Furthermore, the control-to-output voltage transfer function is obtained as

$$\frac{v_o(s)}{v_{con}(s)} \approx \frac{T_{OFF}}{R_c T_{ON}} \cdot \frac{1}{1+\frac{s}{\omega_1 Q_1}+\frac{s^2}{\omega_1^2}} \cdot \frac{1+sRC}{sC} \qquad (7)$$

From the transfer function, the double poles at half of the switching frequency always locate in left half-plane and are not related to the parameters of output capacitor, indicating that the stability of CC-FOT control is independent of the output capacitor ESR. The transient response waveforms of the buck converter with FOT control and CC-FOT control are shown in Fig. 6, from which CC-FOT control shows the faster transient response than that of FOT control.

IV. Conclusion

When output capacitor with small ESR, output capacitor voltage phase lagging behind inductor current phase can cause instability in FOT controlled buck converter. To eliminate the instability, a CC-FOT control technique is proposed in this paper. By the describing function method, the control-to-output transfer function is derived, on which the stability of CC-FOT controlled buck converter is studied. The study results show that compared to FOT control, CC-FOT control shows a better transient response and high dc regulation accuracy, and its stability is independent of output capacitor ESR, which can provide smaller output voltage ripple by using output capacitor with smaller ESR.

V. References

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