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Four-phase Ripple Controlled Switching Converter with EMI Noise Reduction Circuit

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Abstract. This paper describes a four-phase switching converter using a ripple control without a stable clock pulse. By dividing the peak hold voltage by four which is supplied from the saw-tooth signal of the main converter, four phase clocks are generated. In our converter, the output voltage ripple is reduced by 10% and the settling time is decreased to one-fifth. Good current balance is obtained for the large load current of 105 A. Moreover, the EMI noise of the PWM spectrum is reduced by 15 dB using the phase-modulating of main control signal.

1. Introduction

Multi-phase DC-DC buck converter technology has been studied since a long time ago. For the operation of high-performance processors such as PCs and servers, markets demand for fast response and low output voltage ripple control of their power supplies [1]. The ripple-controlled four-phase converter is a kind of four-phase converter that can achieve high-speed response. The conventional multi-phase method in switching power supply uses an external clock, and the four-phase PWM signals are generated by the frequency division of the clock. However, there is no fixed frequency clock in the ripple control converter, so it is difficult to obtain accurate four-phase PWM signals. In the case of the clock-less power supply, since there is no fixed clock signal, it is necessary for the remaining three-phase power supply circuits to operate synchronizing with the reference power supply. As for the control method of the multi-phase converter, the hysteresis control is simple enough to satisfy the demand for high speed load response. However, the switching frequency is changed by the load current transient.

Attempting to alleviate this problem, another method called constant on-time control (COT) is considered; it makes the switch on-time constant, as well as the operating frequency in the steady state, regardless of the load current change [2]. In this method, the four-phase PWM signals are produced by bleeder circuit. We have simulated the investigated circuit using SIMPLIS. The result shows good current balance, large load current capability and fast transient response compared to the single-phase converter. Also the authors propose a scheme of the EMI noise reduction.

2. Control of constant on-time ripple controlled converter

2.1 Circuit configuration and operation principle

The configuration of the buck converter with the constant on-time control is shown in Fig.1. Fig.2 shows the configuration of the four-phase converter with COT control. The circuit configuration of this system consists of the conventional power stage and the COT controller including an SR flip-flop. Rf, Cf are used, as a ripple injection circuit creates triangular wave and injects it into the output voltage Vo, which results to the feedback voltage Vr thereby. Vr and the reference voltage Vref are directly compared by the comparator, and the output pulse is used to set the SR flip-flop, and a Ton timer achieves the constant on- time [3].

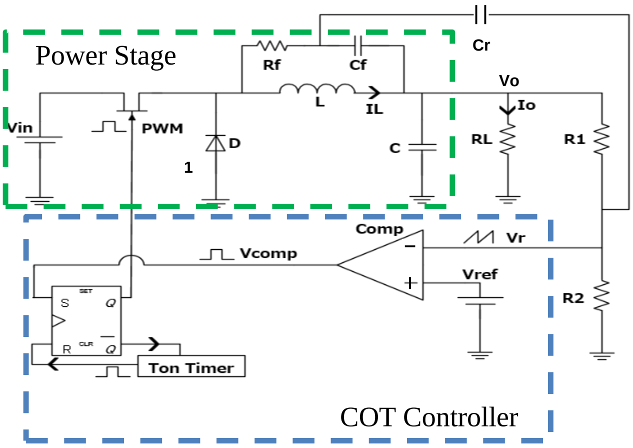


Fig.1 Buck converter with COT control

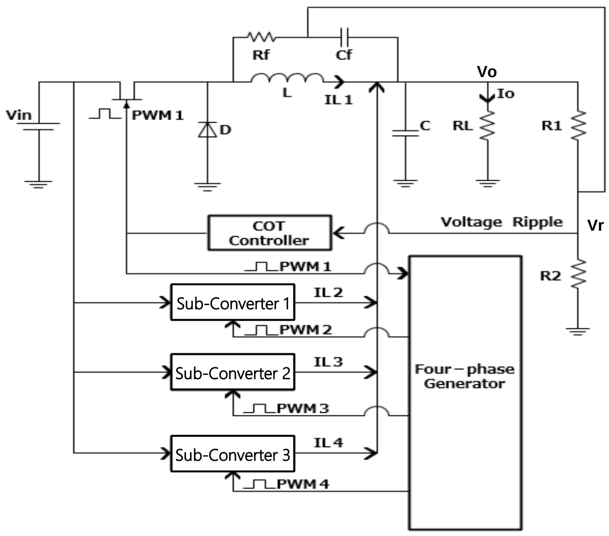


Fig.2 Four-phase converter with COT control

2.2 Simulation results

Fig. 3 shows the simulation results with the parameters in Table 1. The operating frequency is 320 kHz and the on-time is 1.01 μs. The steady state simulation waveforms are consistent with the operation principle waveforms. “Pulse” in Fig. 3 is a key signal inside the COT controller.

Table 1 Parameters in COT control circuit

V_{in}	10V
V_o	3V
L	10uH
C	200uF
R_f	220K
C_f	1nF
R_1	3.9kΩ
R_2	470kΩ

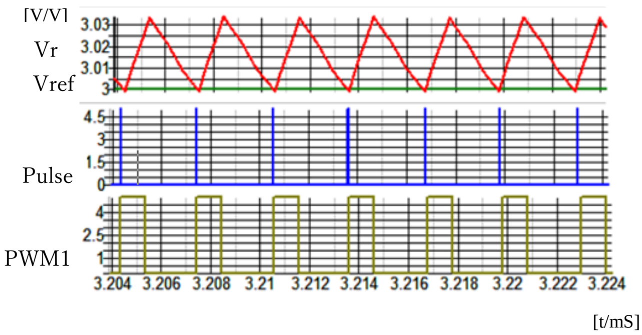


Fig. 3 Simulated waveforms in steady state.

3. Four-phase converter with ripple control

3.1 Conventional system

The saw-tooth-wave made by Vcomp has the same phase position as PWM1 in Fig. 2. There we use a voltage divider to divide the peak voltage of the saw-tooth into quartered four parts, and through the comparison between each divided voltage and the peak-hold voltage, the other three pulses are generated. The simulation result is shown in Fig. 4, and we can see that the generated three other pulses are following the main pulse, keeping the phase difference regularly.

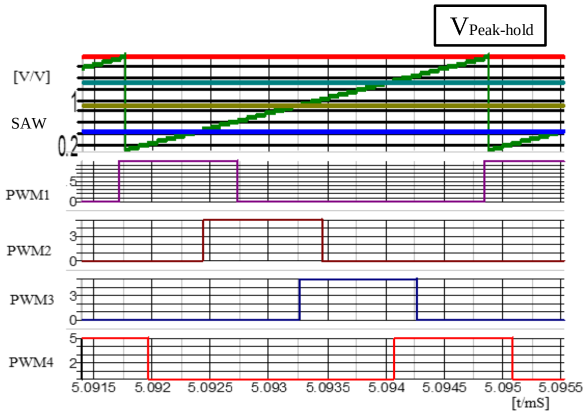


Fig. 4 Simulation result of four-phase PWMs.

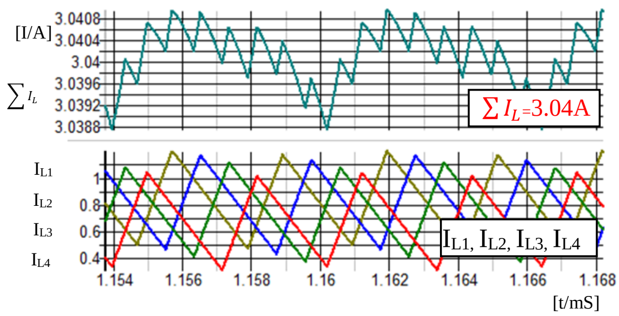


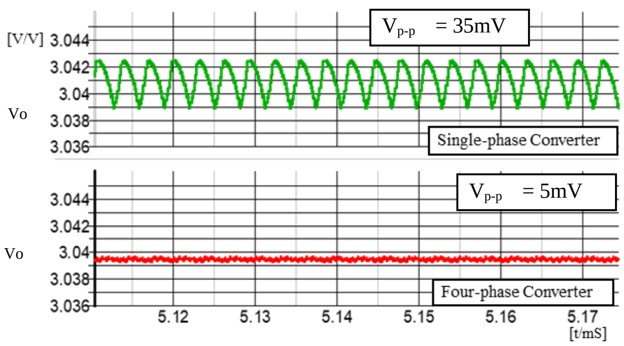
Fig. 5 Simulated waveforms of four-phase converter.

3.2 Proposed four-phase current balance

As shown in Fig. 5, in the case of $\sum I_L$=3.04 A, the inductor currents in each phase are from 0.67 A to 0.84 A, obtaining few offset (±0.09 A) by only 11.8% which shows good current balance in the case of four-phase converter. The means of the inductor currents are 0.67 A, 0.74 A, 0.80 A and 0.84 A.

3.3 Static and dynamic characteristics

As Fig. 6 and Fig. 7 show, the output voltage ripple of the four-phase converter decreases by 86% (from 35mV to 5 mV) compared to that of the single-phase converter at Io=0.5 A. As for the load fluctuation, when the load current changes by 10 A, the four-phase converter decreases by 70% in overload and by 59% in underload, and the recovery time is just about one-fifth of that of the single-phase converter.



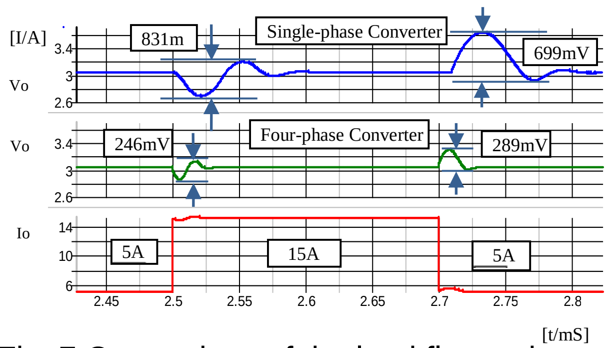


Fig. 6 Comparison of the output voltage ripples. Fig. 7 Comparison of the load fluctuations.

3.4 Large load current simulation

Fig. 8 shows the simulation result of the large load current test. The load current successfully reaches a high level of 105A, and the current balance among the currents of the four phases remains stable.

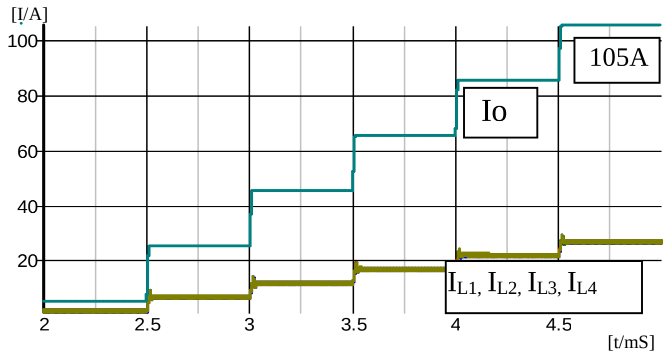


Fig. 8 Simulation result for large load current.

4. EMI reduction in four-phase converter

In multiphase power supplies, there is a concern about the influence of electromagnetic noise (Electro Magnetic Interference (EMI)) in which large current switching is scattered. Since the ON time of the switch is fixed in the COT system, the operating frequency does not fluctuate much depending on the load current, and frequency modulation and phase modulation of the PWM signal are considered as EMI countermeasures.

4.1 EMI reduction for four-phase converter

The proposed pulse phase modulation circuit is shown as Fig. 9. The phase is randomly changed while maintaining the on time fixed for each clock. As shown in Fig. 9, this system is realized by inserting a modulation circuit for phase-modulating the pulse in front of the COT circuit in the four-phase ripple control power supply. A saw-tooth wave whose frequency is synchronous with Vcomp is generated. By superimposing the triangular wave signal on the saw-tooth wave voltage, phase modulated pulse is obtained, applying to the COT pulse generator. On the Pos edge of Comp, the COT of the next stage operates. On the Neg edge, there is no modulation effect. That is, the effect of modulation appears at the trailing edge of the pulse.

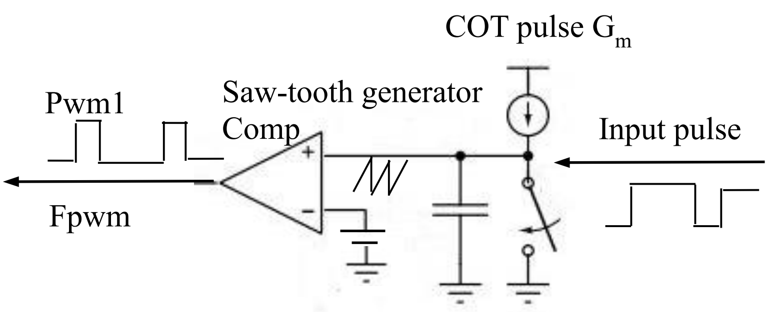
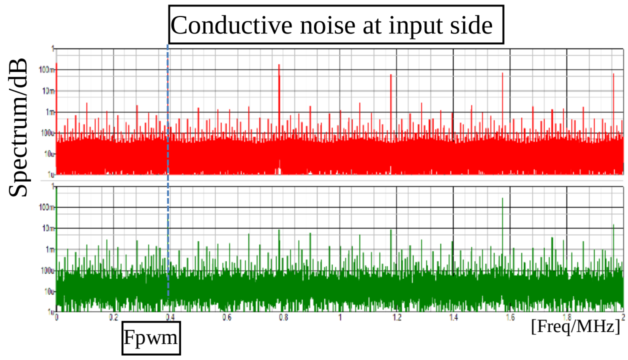
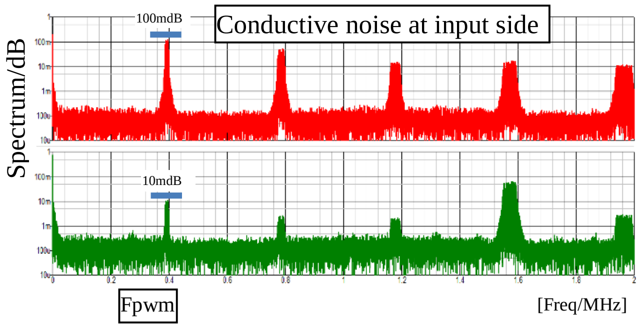


Fig. 9 Proposed COT phase modulation circuit.





Top: Single phase, Bottom: Four-phase
Fig. 10 Spectrum without EMI reduction.

Top: Single phase, Bottom: Four-phase
Fig. 11 Spectrum with EMI reduction.

Fig. 10 shows the spectrum of the conductive noise (input current) without the EMI reduction and Fig. 11 shows that with the EMI reduction. Where the top spectrum is of the single phase converter and the bottom one is of the four phase converter, which is modified by the triangular signal of 2.0 V amplitude and 1.0 kHz frequency. In the single phase converter, the spectrum level at the clock frequency (Fpwm=390kHz) is reduced from 300 mV to 100 mV, which is 9.5 dB reduction. In the four phase converter, the spectrum level at the four-fold frequency of the clock frequency is reduced from 240 mV to 60 mV, which is 12 dB reduction.

4.2 Relationship between conductive noise and reference voltage Vref of COT pulse width

Fig. 12 shows the relationship between the conductive noise and the reference voltage for the COT pulse. As the reference voltage changes, the turn-on time of the switch changes, and the component of the input current noise at the PWM frequency also changes. The level of the conductive noise, which is the input current, means the spectrum level at the clock frequency in the four phase converter. When the phase difference of each sub-converter is just divided into 90 degrees, there is no spectrum at the clock frequency. As shown in Fig 12, the minimum level of the conductive noise is -30 dB, theoretically this level will be less level at Vref=0.9848 V.

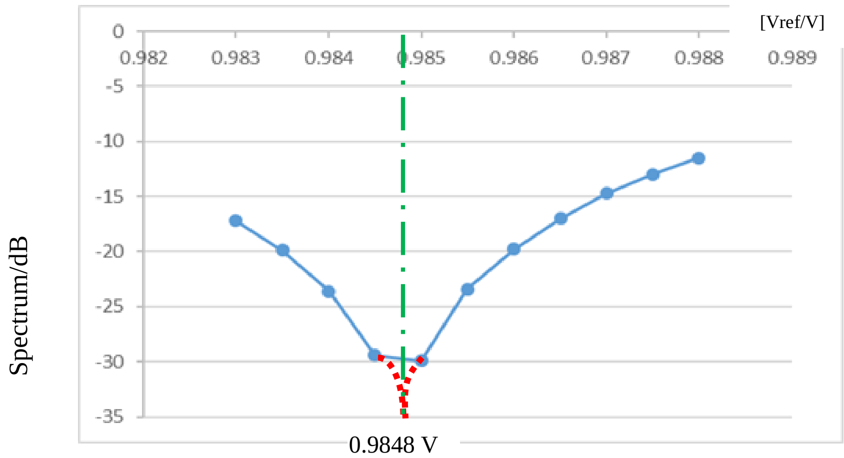


Fig. 12 Relationship between Vref of COT pulse and
converter output spectrum level of conductive noise at Fpwm

5. Conclusion

A four-phase ripple controlled converter with the EMI reduction is proposed. The peak level of the spectrum at the 4Fpwm is reduced by 15 dB with phase modulation of the main PWM signal. Moreover, in the four-phase converter, the output voltage ripple is decreased by 86% and the over/undershoot at the current step 10 A is decreased by 70%/59% and its settling time is decreased to one-fifth. Current balance is very good at large output current Io=105A.

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