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Constant On-time Controlled Four-phase Buck Converter via Saw-tooth-wave Circuit and its Element Sensitivity

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Abstract. This paper proposes a four-phase DC-DC buck converter with constant on-time control, which can provide large output current with low voltage ripple. We describe here a method of saw-tooth-wave circuit, to achieve the four-phase converter. As a result, the saw-tooth-wave circuit well achieves the four-phase control, showing stable current balance and better transient response compared to the single-phase converter. Furthermore, the saw-tooth-wave method achieves high current level with stable current balance. As for its element sensitivity, the change of the current balance is measured within a certain component error range, showing that the current balance is sensitive to the on-time error of the main switch.

1. Introduction

Multi-phase DC-DC buck converter technology has been studied for a long time. For the operation of high-performance processors such as PCs and servers, markets demand for fast response and low ripple control of their power supplies [1]. In addition, whereas the operation voltage becomes lower, the output voltage accuracy and low ripple, as well as high speed load response are required [2].

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. On the other hand, 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 will change 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 [3]. On the basis of the two-phase converter technology [4] and the hysteretic control, this paper proposes an improved four-phase buck converter via saw-tooth-wave circuit. In this method, the four-phase PWM signals are produced by bleeder circuit, and its waveforms are simulated by SIMPLIS. The result shows good current balance, large load current capability and improvement in transient response compared to the single-phase converter. As for the element sensitivity, the change of current balance is measured within a certain component error range, resulting that the current balance requires extreme precision on the main switch turn-on time.

2. Control of Constant On-time

2.1 Circuit Configuration and Operation Principle

The configuration of the buck converter with the constant on-time control is shown in Fig.1. The operation principle waveforms thereof are shown in Fig.2. The circuit configuration of this system consists of the conventional power stage and the COT controller including an SR flip-flop. R_f, C_f are used, as a ripple injection circuit creates triangular wave and injects it into V_o, which results to V_r thereby. V_r and the reference voltage V_{ref} are directly compared by the comparator, and the output pulse is used to set the SR flip-flop, in which there is a T_{on} timer to achieve the constant on- time.

State1 t_0~t_1

At t_0, the ripple voltage V_r reaches to the V_{ref}, the comparator outputs a high level, so does Q port of the SR flip-flop, resulting into the turning on of switch SW. The on-time of SW is set to a constant time by the T_{on} timer. When the fixed on-time is over at t_1, the T_{on} timer outputs a high level to the R port, and Q becomes low level thereby, resulting in the turning off of the switch SW. Then V_r starts to decrease from peak, so does the inductor current I_L.

State2 t_1~t_2

From t_1, the SW keeps turning off until t_2, during which V_r and I_L continue decreasing. When it comes to t_2, V_r becomes lower than V_{ref} again, causing the high level output from the comparator. Then the SW turns on again in next cycle.

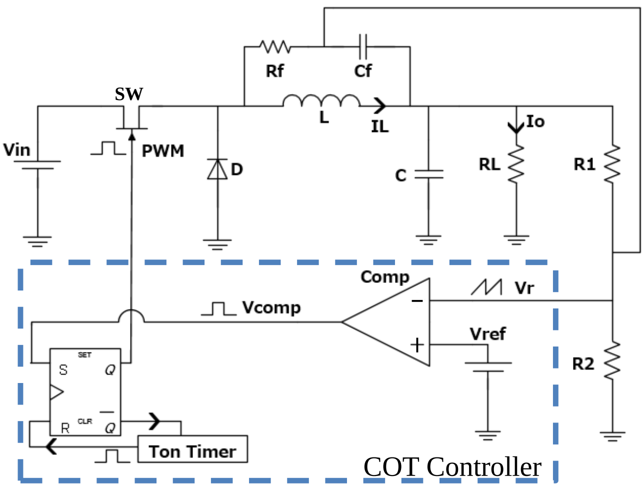

Fig.1 Buck converter with COT control

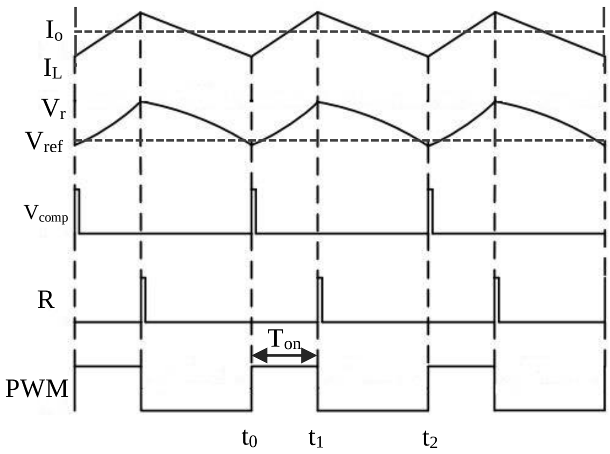

Fig.2 Waveforms during COT operation

2.2 Simulation Results

Fig. 3 shows the simulation results with the parameters in Table I. The operating frequency is 402 kHz and the on-time is 817.7 ns. The steady state simulation waveforms are consistent with the operation principle waveforms.

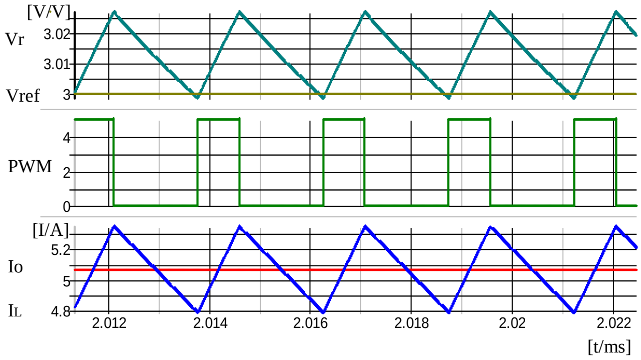

Fig.3 Simulated waveforms in steady state

Table I. Parameters of COT control

V_{in}	10 [V]
V_o	3 [V]
L	10 [uH]
C	200[uF]
R_f	220[K]
C_f	1 [nF]
R_1	3.9 [kΩ]
R_2	470[kΩ]
R_L	0.6 [Ω]

2.3 Four-phase Converter with COT Control

Fig.4 shows the configuration of the four-phase converter with COT control. Besides the main converter, there are three other sub-converters below. Each sub-converter receives the same input voltage V_{in} and includes the same components as the main converter, but they are controlled by different PWM signals whose phase positions differ by 90° from each other, so do their inductor currents I_{L2}, I_{L3}, I_{L4}. Fig.5 shows the waveforms of the four-phase PWM signals generated by the four-phase generator. The other three signals PWM2, PWM3, PWM4 are keeping their paces in the main signal PWM1, and keeping the phase difference of 90° exactly with each other.

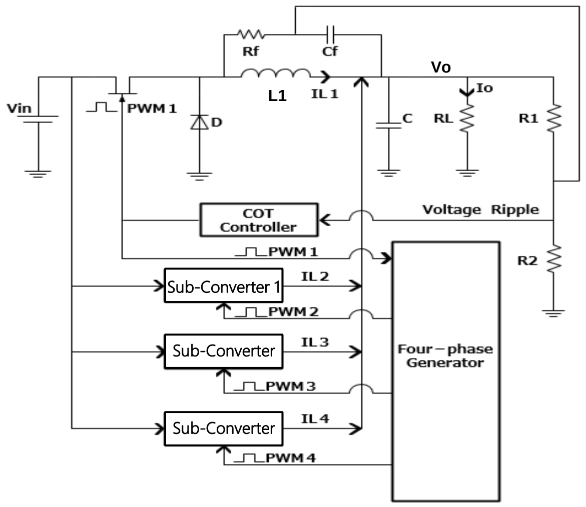

Fig.4 Four-phase converter with COT control

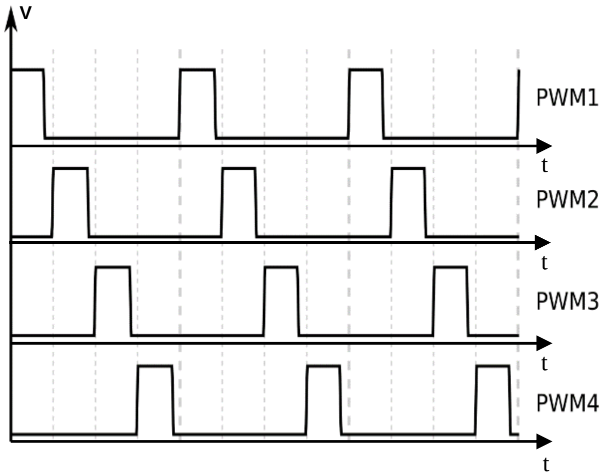

Fig.5 Four-phase PWM signals

3. Four-phase Converter via Saw-tooth-wave Circuit

3.1 Peak-hold Circuit of Saw-tooth-wave

The proposed peak-hold circuit is shown in Fig.6. V_{comp} in Fig.1 is picked up to generate the sampling pulse and a trigger pulse with little delay. The input voltage of the saw-tooth goes to the switch through a voltage follower which provides high input impedance and low output impedance, making the capacitor C segregated. When it is about to reach the peak voltage, the sampling pulse comes to make the switch turn on and the capacitor C is charged to the peak voltage thereby. Once the sampling pulse is over, the switch turns off immediately, and the voltage on the capacitor stays at the previous peak value, meanwhile the trigger pulse follows on to reset the saw-tooth-wave. The practical simulation result is shown in Fig.7.

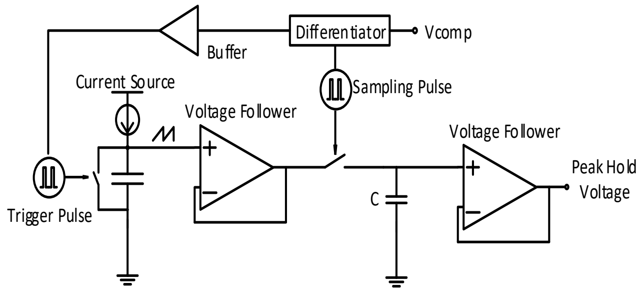

Fig.6 Configuration of the peak-hold circuit

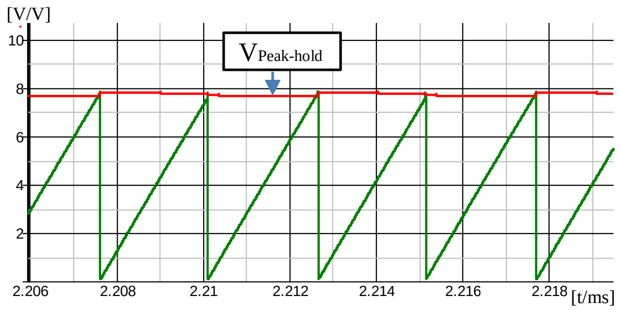

Fig.7 Simulation result of the peak-hold circuit

3.2 Voltage Divider for Generation of Four Phases

It is easy to know that the saw-tooth-wave made by V_{comp} has the same phase position as PWM1 in Fig.4. 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.9, and we can see that the generated three other pulses are following the main pulse, keeping the phase difference regularly.

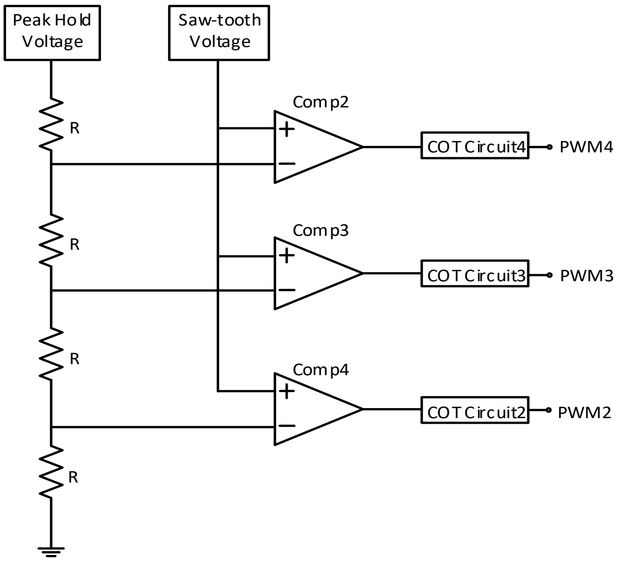

Fig.8 Four-phase pulse generator

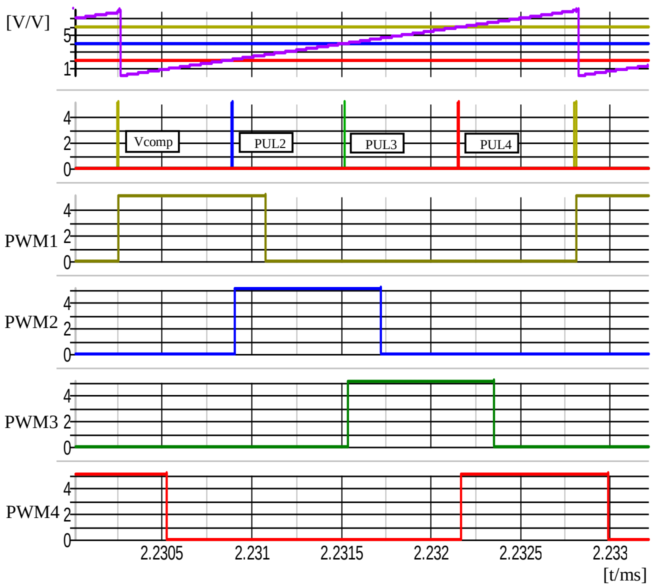

Fig.9 Simulation result of four-phase PWMs

4. Characteristics Simulation of Four-phase Converter via Saw-tooth-wave Method

4.1 Four-Phase Current Balance

As shown in Fig.10, in the case of Io =5.06A, the inductor currents in each phase are almost the same as 1.26A, which shows good current balance in the case of four-phase converter.

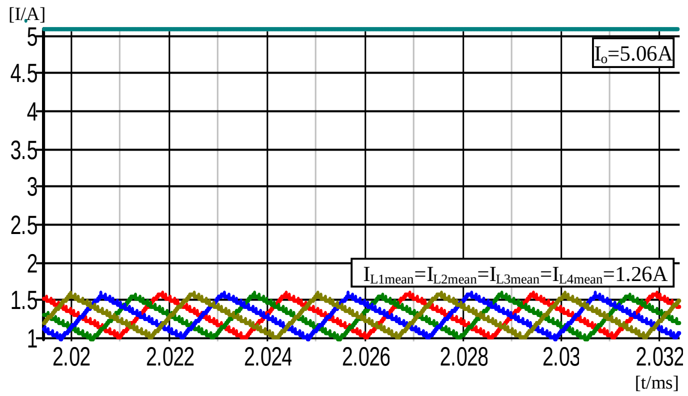

Fig.10 Currents of each phase in the four-phase converter

4.2 Comparison of Output Voltage Ripple and Transient Response between Single-phase and Four-phase Converters

As Fig.11 and Fig.12 show, the output voltage ripple of the four-phase converter decreased by 57% compared to that of the single-phase converter. As for the load fluctuation, when the load current changes by 10A, the four-phase converter decreases by 70% in overload and by 59% in under load, and the recovery time is just about one-fifth of the single-phase converter.

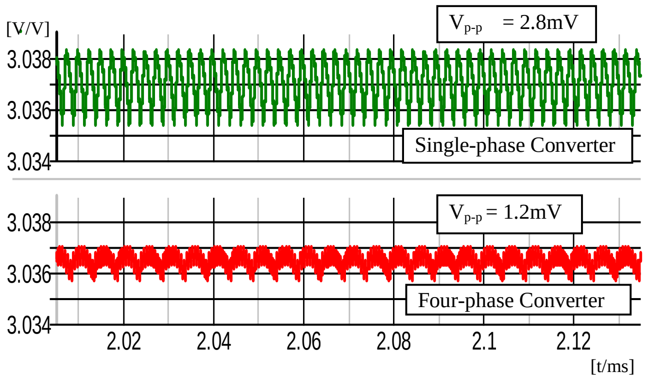

Fig.11 Comparison of the output voltage ripples

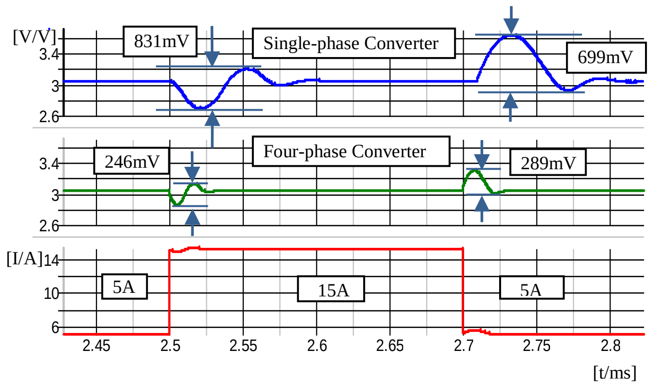

Fig.12 Comparison of the load fluctuations

4.3 Large Load Current Test

Fig.13 shows the simulation result of the large load current test. The load current successfully reaches to a high level of 55A, and the current balance among the current of the four phases remains stable.

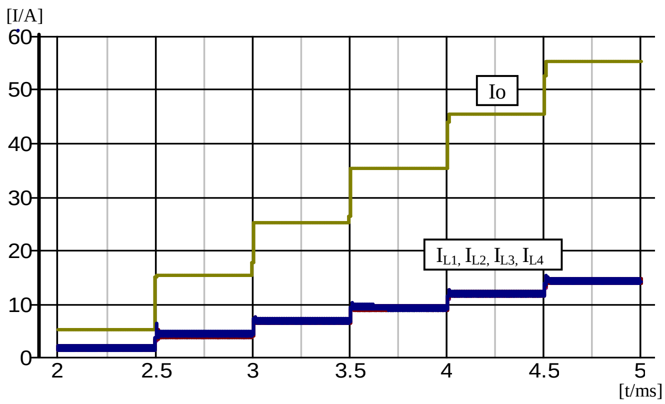

Fig.13 Simulation result of the large load current

5. Element Sensitivity for Current Balance

As shown in Fig. 14 and Fig. 15, the current balance changes with the error of various parameters, such as the on-time of PWM1 and the resistance of main inductor R_{L1}. In Fig.14, when the on-time of PWM1 increases by only 1%, I_{L1} increases by more than 100%, showing high sensitivity. As for sensitivity to R_{L1}, with the increase of R_{L1}, I_{L1} decreases linearly while I_{L2} I_{L3}, I_{L4} increases linearly. But the change is not obvious as a whole.

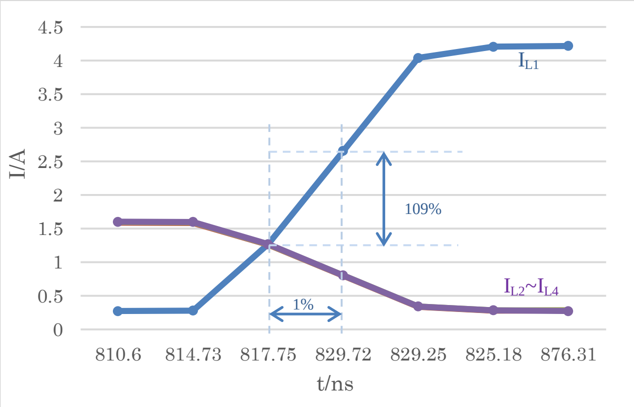

Fig. 14 Current balance via Ton of PWM1

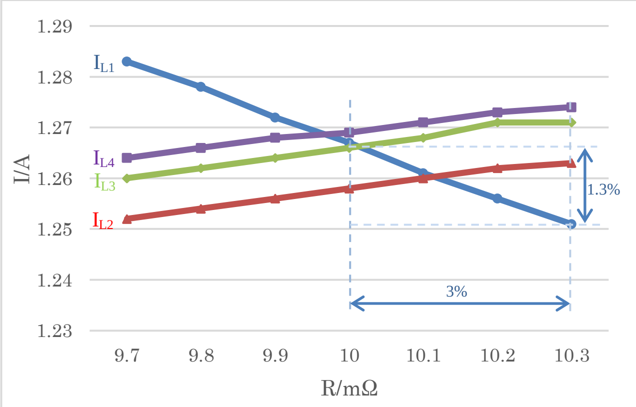

Fig.15 Current balance via R_{L1}

6. Conclusion

In this paper, we have proposed a constant on-time control and applied it to a four-phase buck converter via saw-tooth-wave circuit which does not need an external clock. The constant on-time control makes the frequency of the PWM signal fixed even when the load current changes, so that the four-phase buck converter is achieved without an external clock. The saw-tooth-wave circuit method obtains good current balance, and it also gets much improvement in the output voltage ripple and transient response compared to the case of the single-phase converter. It successfully achieves large load current with a stable current balance, reflecting practical application value. On the other hand, the test result of element sensitivity shows that the current balance is sensitive to the on-time of PWM1, meaning that the on-time of PWM1 must be set to 817.75 ns precisely to guarantee the steady operation of the four-phase buck converter.

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