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Multi-Phase Clock-less Switching Converter with EMI Noise Reduction

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Abstract. This paper describes multiphase implementation in clock-less power supply such as ripple control method. In the ripple control power supply, four phase sub control pulses are generated by changing main control pulse. The peak voltage of the saw-tooth-wave signal generated from the main control pulse is held and this peak voltage is equally divided to produce a multiphase control pulse. Also EMI noise is reduced by spectrum spreading by phase-modulating this main control signal. These are verified with simulation.

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 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. In the past, the authors proposed a multi - phase power supply in the clock - less ripple control system and report on the transfer function characteristics and the EMI noise reduction scheme.

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 which is injected into V_o, resulting 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.

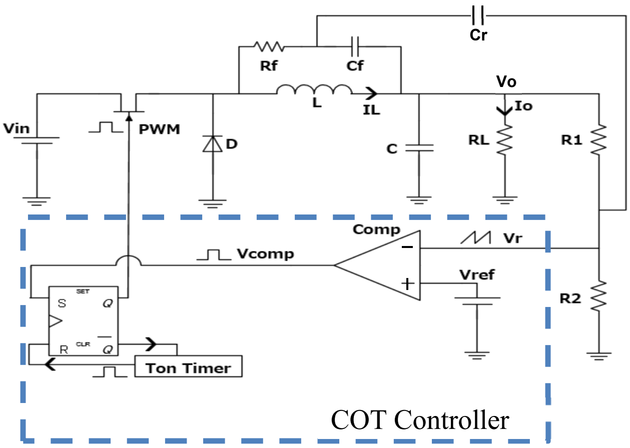

Fig.1 Buck converter with COT control

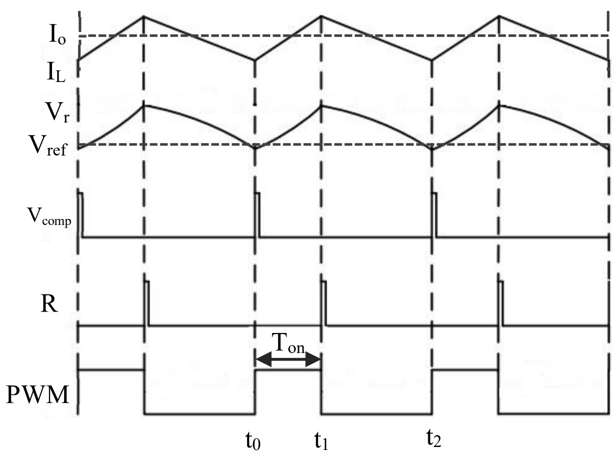

Fig.2 Waveforms during COT operation

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.

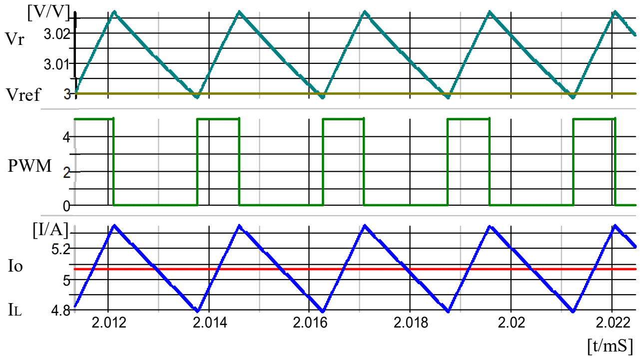

Fig.3 Simulated waveforms in steady state

Table I. Parameters of COT control

V_{in}	10 [V]
V_o	3 [V]
L	10 [uH]
C	200[uF]
R_f	10[kΩ]
C_f	1 [nF]
R_1	3.9 [kΩ]
R_2	470[kΩ]
R_L	1.5 [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.

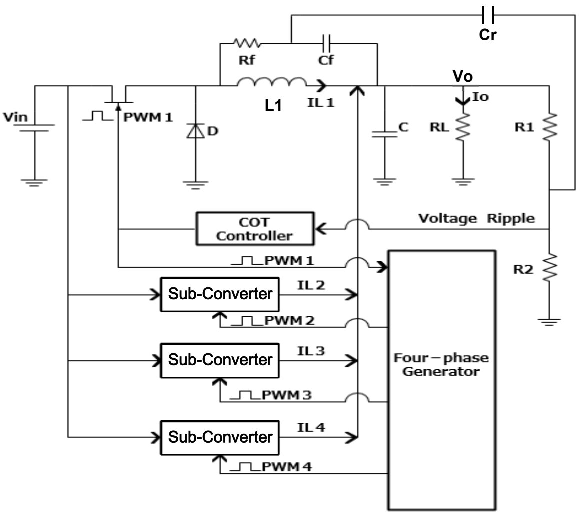

Fig.4 Four-phase converter with COT control

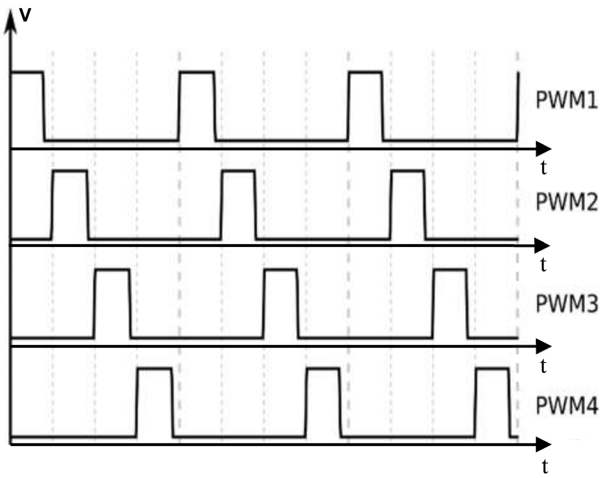

Fig.5 Four-phase PWM signals

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.

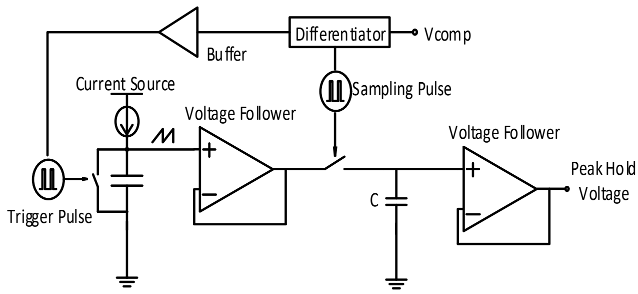

Fig.6 Configuration of the peak-hold circuit

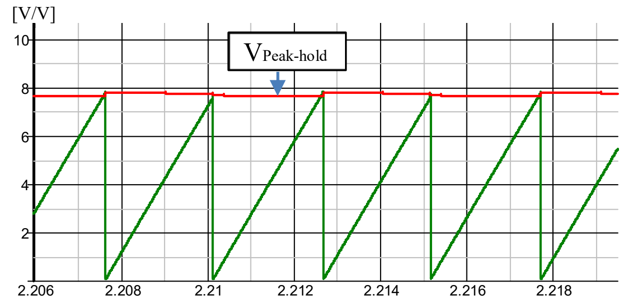

Fig.7 Simulation result of the peak-hold circuit

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.

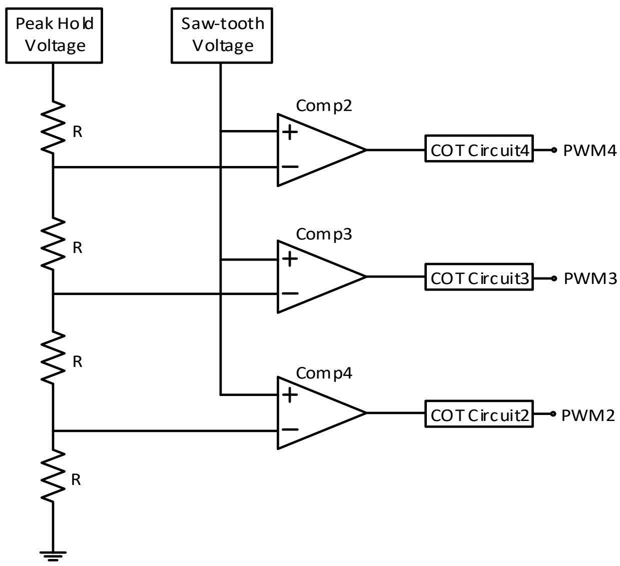

Fig.8 Four-phase pulse generator

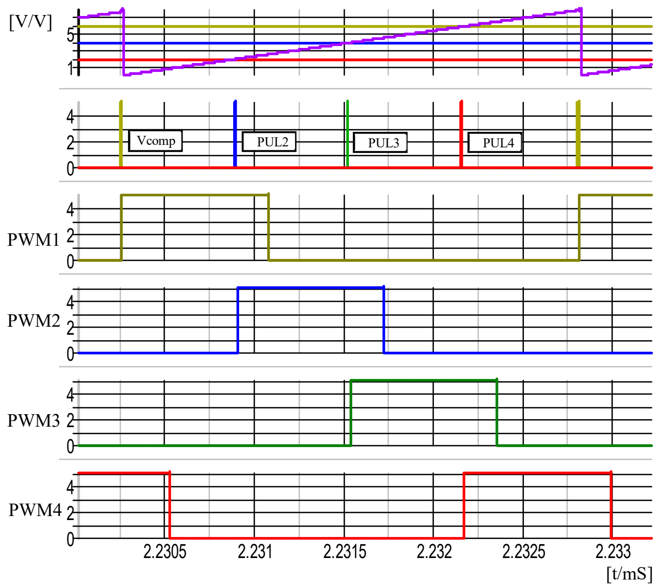

Fig.9 Simulation result of four-phase PWMs

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

4.1 Four-Phase Current Balance and Large Load Current Test

As shown in Fig.10, in the case of I_o =5.06A, the inductor currents in each phase are almost the same as 1.26A, obtaining few offset by only 0.39% which shows good current balance in the case of four-phase converter in Fig.11 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 current of the four phases remains stable.

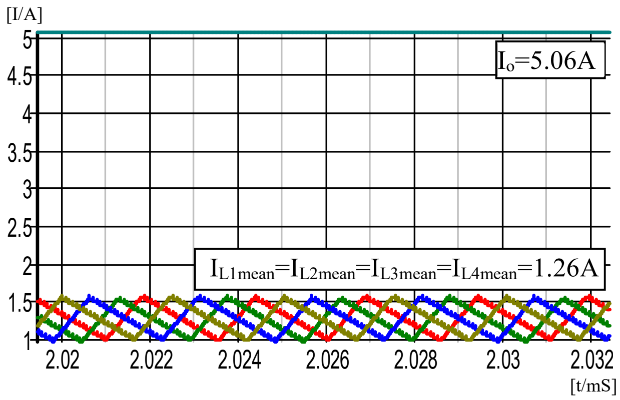

Fig.10 Currents of each phase in the four-phase converter

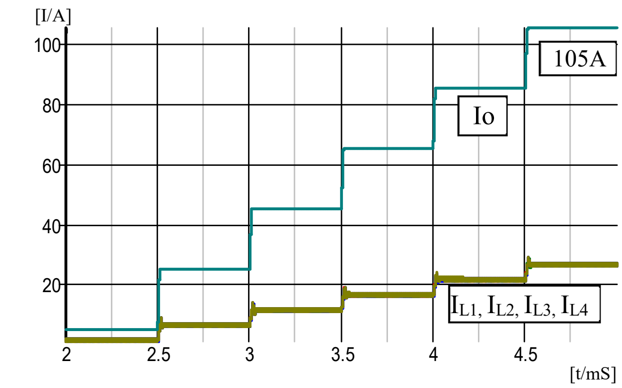

Fig.11 Simulation result of the large load current

4.2 Static and Dynamic Characteristics

As Fig.12 and Fig.13 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 underload, and the recovery time is just about one-fifth of that of the single-phase converter.

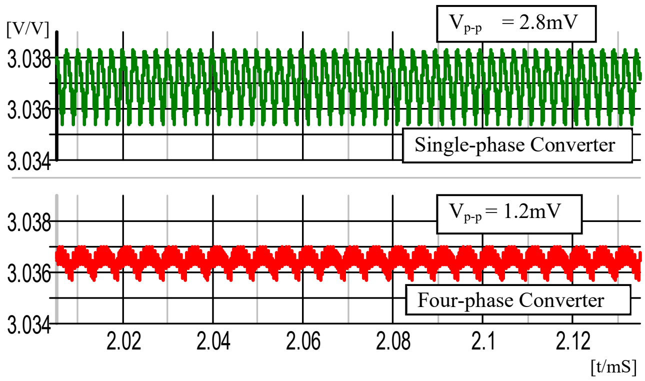

Fig.12 Comparison of the output voltage ripples

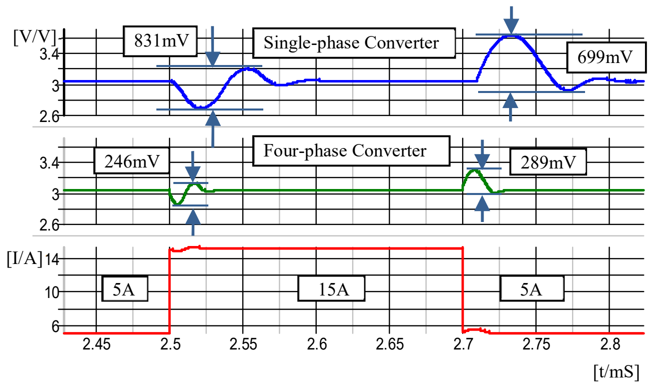

Fig.13 Comparison of the load fluctuations

4.3 Loop Transfer Function Characteristics

The open loop transfer function of a single-phase converter and a four-phase converter are shown in Fig 14. In the single-phase gain characteristic, the inclination of -40 dB/dec is higher in the high-frequency range than the superposition by LC, but it is immediately -20 dB/dec due to the influence of the zero point. The frequency of LC resonance peak is F_{o1}= 3.1 kHz, and the phase margin is P_{m1}= 38°. On the other hand, the gain characteristic of the four phases has almost the same slope as the gain characteristic of the single phase, and the phase margin is stable as P_{m2} = 60°. The frequency of the LC resonance peak is F_{o2} = 5.6kHz, which is twice that of the single phase. The inductance is connected in parallel by four-phase conversion, and it can be thought of as follows.

The LC resonance frequency single-phase converter is expressed by the following equation (2).

$$F_1 = \frac{1}{2\pi\sqrt{LC}} \tag{2}$$

In the four-phase power supply, four power stages are connected in parallel, and the resonance frequency is expressed by the following equation (3).

$$F_2 = \frac{1}{2\pi\sqrt{\frac{1}{4}LC}} = \frac{1}{\pi\sqrt{LC}} = 2F_1 \tag{3}$$

As a result, faster response is possible with the four-phase power supply.

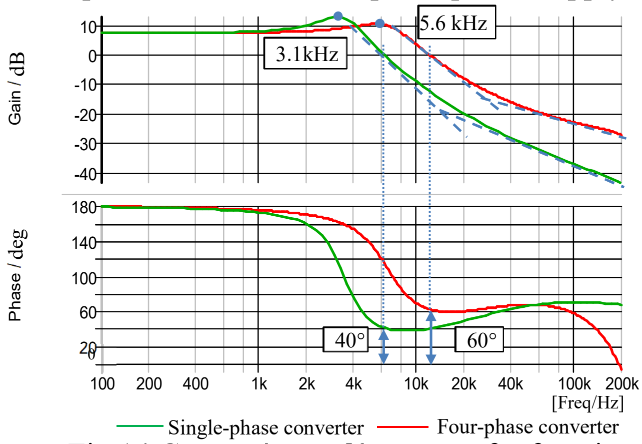

Fig.14 Comparison of loop transfer function

5. Clock-less Four-phase converter EMI Reduction Solution

In multiphase power supplies, there is 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.

5.1 Outline of EMI Reduction

In switching power supplies, PWM (Pulse Width Modulation) control method that modulates pulse width with a constant period clock is usually used. On the other hand, frequency spreading PFM (Pulse Frequency Modulation) and PPM (Pulse Phase Modulation) of the clock are available for spectrum spreading.

(1) Pulse frequency modulation method: As shown in Fig.15, the modulation method is that the period is slightly changed randomly while the pulse width and the phase of rising edge are kept constant.

(2) Pulse phase modulation method: As shown in Fig.16, the phase of rising edge of a pulse is modulated while the pulse period and width are kept constant.

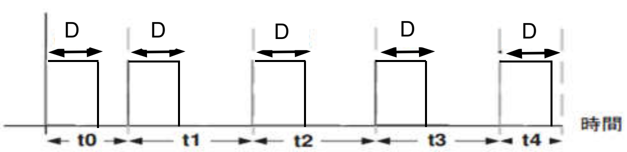

Fig.15 Pulse frequency modulation

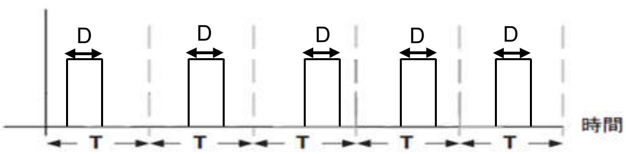

Fig.16 Pulse phase modulation

(3) The proposed pulse phase modulation circuit is shown as Fig.17. The phase is randomly changed while maintaining the on time fixed for each clock. As shown in Fig.18, 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 V_{comp} 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.

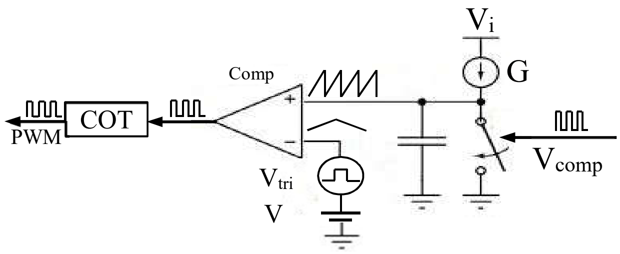

Fig.17 Proposed pulse phase modulation circuit

The spectrum of the PWM1 is tested while the simulation parameters are set as below: F_{PWM} = 381kHz, F_{tri} = 1kHz, the amplitude voltage of triangle wave V_{tri} = 2.0 V, the reference voltage V = 2.5 V. As shown in Fig 18. The peak level of the clock noise is reduced and diffused to surroundings. Generally, the diffusion width of the clock frequency is set by the amplitude level of the modulation signal. In the case of the four-phase COT control power supply, when the spectrum of PWM1 is diffused, the other three PWM signal are also phase-modulated in the same manner, it can be seen that the spectrum is synchronized as shown in Fig. 19.

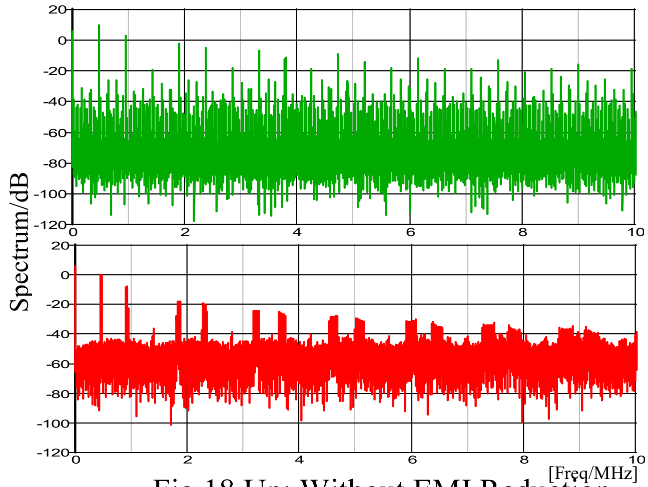

Fig.18 Up: Without EMI Reduction
Down: With EMI Reduction

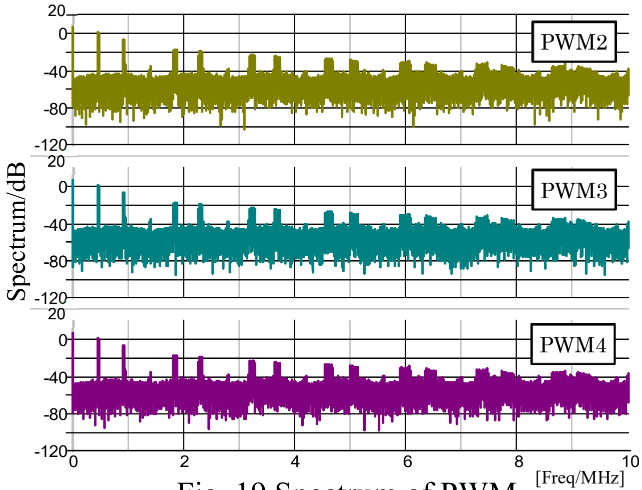

Fig. 19 Spectrum of PWM of four-phase converter

5.2 Spectrum of Conductive Noise

In Fig. 20, we can also see the reduction of conductive noise in the main power stage.

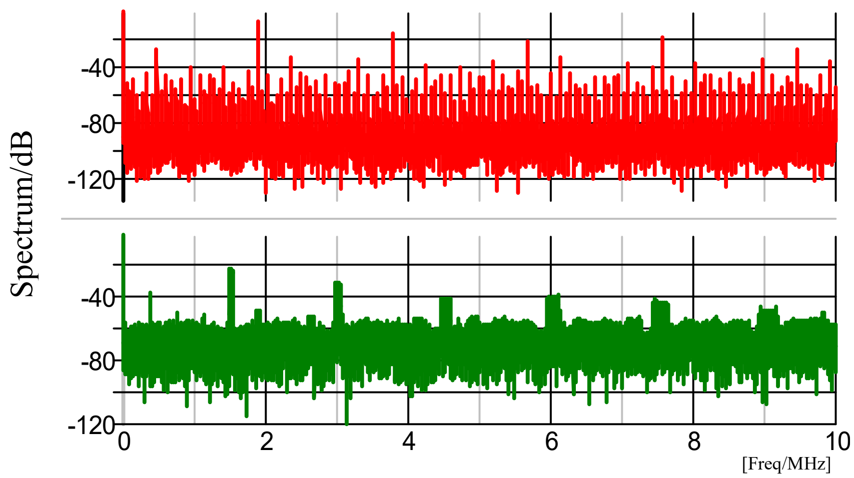

Fig. 20 Up: Without EMI Reduction Down: With EMI Reduction

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 and the load fluctuation is greatly improved. By comparing the open loop transfer function, we can see that the four-phase converter get more phase margin and it is possible to realize high speed response according to the gain board diagram. Moreover, it realized EMI reduction of the four-phase power supply. When spectrum spreading of PWM1 is carried out, it turned out that the spectrum state of the four-phase PWM becomes synchronous.

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