令和元年度　修　士　論　文

多相リップル制御を備えた DC-DC スイッチング 降圧コンバータの解析と改善

指導教員　　小林　春夫　教授

群馬大学大学院理工学府 理工学専攻
電子情報・数理教育プログラム

李　晶

ANALYSIS AND IMPROVEMENT FOR DC-DC SWITCHING BUCK CONVERTER WITH MULTI-PHASE RIPPLE CONTROL

JING LI

群馬大学
GUNMA UNIVERSITY

Master Dissertation

DIVISION OF ELECTRONICS & INFORMATICS
GRADUATE SCHOOL OF SCIENCE & TECHNOLOGY

GUNMA UNIVERSITY

JAPAN

September 2019

Analysis and Improvement for DC-DC Switching Buck Converter with Multi-Phase Ripple Control

DISSERTATION
Submitted by

JING LI

In partial fulfillment of the requirements for the award of the Degree of

MASTER IN
ELECTRONICS & INFORMATICS ENGINEERING

Under the guidance of

PROFESSOR HARUO KOBAYASHI, Ph. D. Eng.

DIVISION OF ELECTRONICS & INFORMATICS
GRADUATE SCHOOL OF SCIENCE & TECHNOLOGY
GUNMA UNIVERSITY
JAPAN

September 2019

Acknowledgement

The formation of this dissertation, although it is extremely immature, but I personally have a sense of accomplishment. And all of this is thanks to my teachers' guidance. Special thanks to my supervisor Professor Dr. Haruo KOBAYASHI for his tutelage and encouragement. I would like to express appreciate to Professor Yasunori KOBORI for his great guidance and advice. I would also like to thank professors Toshiki TAKAHASHI, Anna KUWANA for valuable discussions. I am not their best student, but they will always be my best teachers. I would also like to thank my review committee members, professors Tadashi ITO and Yasushi YUMINAKA.

I am thankful to the members of our laboratory. Thanks to Yifei SUN for her useful discussions and help in my Japanese communication. I would also like to thank Yukiko SHIBASAKI, as my Japanese tutor, she has helped me a lot in my study abroad life.

Furthermore, I would like to thank Dr. Chi ZHOU who is my elder cousin at Illinois Institute of Technology. My current major is polymer material and engineering, but under her influence, I gradually started to interest in electrical engineering and made me I am today

Thanks also to zzx, who taught me to grow up.

Finally, I hope this dissertation will not be the end of my academic thinking. I hope that the previous sentence is not just a hope.

Declaration

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person, nor material which has been accepted for the award of any other degree of the university or other institute of higher learning, except where due acknowledgement has been made in the text.

Signature:

Name: JING LI

Student No.: t171a100

Date:

Table of Contents

Abstract

With the rapid development of power electronics technology, power electronic equipment is increasingly closely related to people's work and life, and electronic equipment is inseparable from reliable power supplies. A power circuit inside the electronic device is defined as any circuit used to carry electricity that operates a load. There are two types of power supplies existed, AC and DC power supplies. Based on the electrical device's electric specifications it may use AC power or DC power.

The purpose of this dissertation is improving the performance for switching converter. Recently, we can see that the high demand for output current and slew rate of the power supply of process. So ripple control and multi-phase are considered as an approach to meet the demand of high speed response and the large load current.

Chapter 1 reviews the basic circuit and basic operation of the switching power supply. The buck converter, boost converter and buck-boost converter are introduced. Multi-phase implementation of the ripple control power supply circuit is analyzed in Chapter 2. Besides the main converter, there is another sub-converter below. Each sub-converter receives the same input voltage Vin and includes the same components as the main converter, but they are controlled by different PWM signals whose phase positions differ from each other. As for the dual-phase generator, a saw-tooth signal tracking with PWM1 is generated by SAW generator. The peak hold circuit holds up the peak voltage of the saw tooth wave. The peak voltage is divided into two parts by voltage divider and compared to the tracking saw tooth wave. The compared result is a set of pulse. Then we can obtain the dual-phase PWMs whose phase positions differ from each other, those results to the dual-phase PWMs. Automatic correction technology for balance of element variation is introduced in Chapter 3. This kind of converter solves the problem of the current imbalance due to inductance and capacitance element variations for the large load current.

In Chapter 4, the technology of multi-phase power supply is also applied in EMI noise reduction.

CHAPTER I
INTRODUCTION

The switched-mode power supply is called SMPS for short, which is based on the basic principle of energy storage of inductors, thereby achieving efficient and energy-saving power conversion. SMPS represents the development direction of stabilized voltage supply, and it has become an important product of stabilized voltage supply. We use the basic principle of a SMPS to convert one kind of voltage into another or a few kinds of voltage. This type of power supply is called a switching regulator.

SMPS has the advantages of high efficiency, low power consumption, small size, light weight, etc. Its power efficiency can reach more than 80%, which is about double the traditional linear regulated power supply. SMPS is used in a wide range of applications, including instrumentation, measurement and control systems, and power supply systems within the computer, as well as a variety of consumer electronics. At present, SPMS is developing in the direction of integration, intelligence and modularization [1-5].

1.1 SWITCHING REGULATOR

Switching regulators are highly efficient and available as modular chips which are compact and reliable. The basic configuration of switching regulator is shown in Fig.1.1. Power is supplied from the input to the output by turning ON a switch (MOSFET) until the desired voltage is reached. Once the output voltage reaches the predetermined value the switch element is turned OFF and no input power is consumed. Repeating this operation at high speeds makes it possible to supply voltage efficiently and with less heat generation.

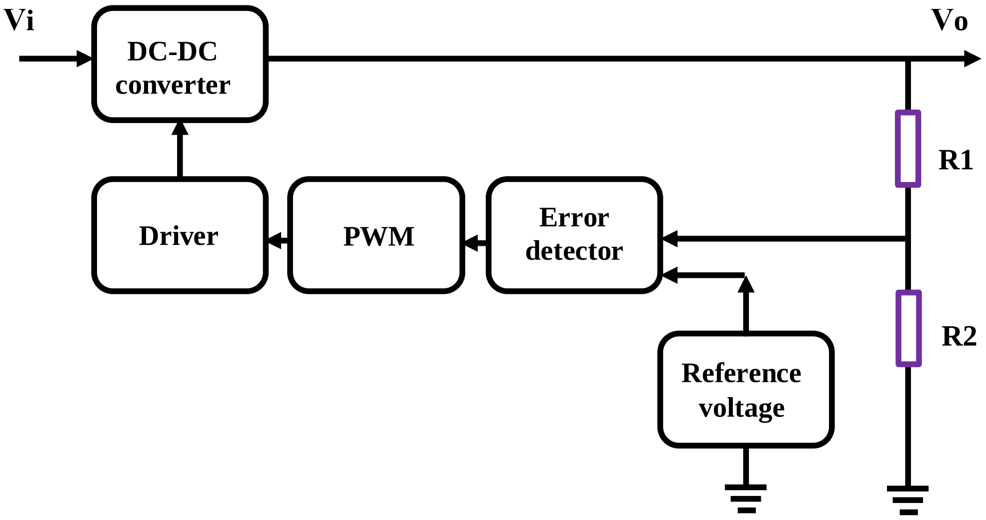


Fig. 1.1 Configuration of switching regulator

1.2 BASIC OF DC-DC BUCK CONVERTER

1.2.1 Topological structure of DC-DC buck converter

The topological structure of the DC/DC buck converter is shown in Fig.1.2. In the Fig.1.2, U_I is the DC input voltage, VT is the power switch, VD is the freewheeling diode, L is the output filter inductor, C is the output filter capacitor, Uo is the DC output voltage, and R_L is the external load resistor. The PWM is used to control the turn-on and turn-off of the power switch VT, which is the most important part of the converter.

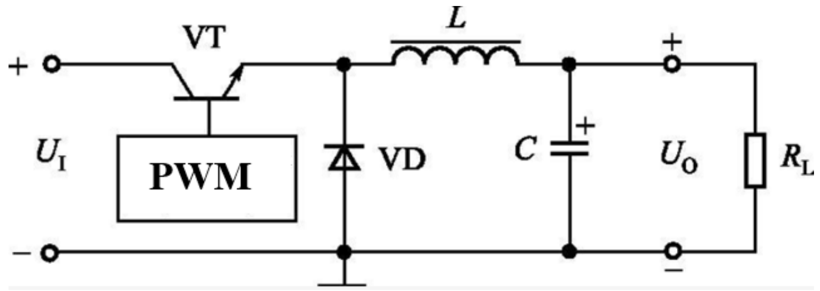


Fig. 1.2 Topological structure of buck converter

1.2.2 Operation of DC-DC buck converter

When the switch VT is switched on, current will flow from the inductor L. Current flowing through the load is being restricted by the inductor and a surplus amount of energy will be stored in the inductor. Circuit diagram of a buck converter is shown in the Fig.1.3 given below when the transistor is switched on.

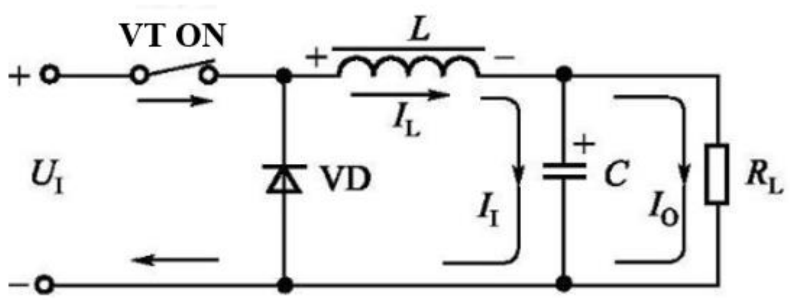


Fig. 1.3 Current path when VT is on

The diode which is reverse biased won't take part in the operation of the buck converter as there is large positive voltage appear to the cathode part of the diode. When the switch is closed the voltage across inductor will be

$$V(\text{Inductor}) = U_I - U_O \quad (1.1)$$

The capacitor using in this circuit diagram will continuously charge up to the maximum value and releases its energy when the transistor switches to off condition.

When the VT is off, the diode available in the buck converter turns to forward biased, making its cathode negative and anode side positive. Circuit diagram of the buck converter is shown in the Fig.1.4 given below when transistor is switched off.

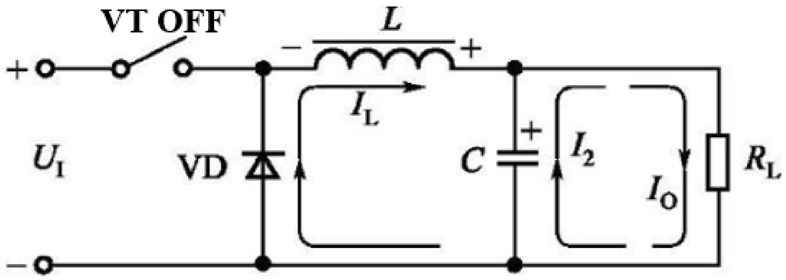


Fig. 1.4 Current path when VT is off

When transistor is switched off, the inductor will automatically change its polarity with respect to the polarity given in transistor on condition. Now, the voltage across the inductor is also called back electromotive force and it will give its energy back to the circuit during off condition. When the switch is switched off the voltage across inductor can be obtained as the following equation.

$$V(\text{Inductor}) = -U_0 \quad (1.2)$$

1.2.3 Operation waveform of DC-DC buck converter

The operation waveform of DC-DC buck converter is shown in the Fig.1.5. PWM represents the pulse width modulation waveform, Ton is a time duration of the cycle when the transistor is on and T is the total time of the cycle. T is equal to Ton plus Toff. The ratio of Ton to T is called the duty, duty is denoted by D, and D is expressed by the following equation

$$D = Ton/T \quad (1.3)$$

Since the duty ratio D is less than 1, this kind of converter is called a buck converter. The output voltage can be changed by controlling the value of the duty ratio D.

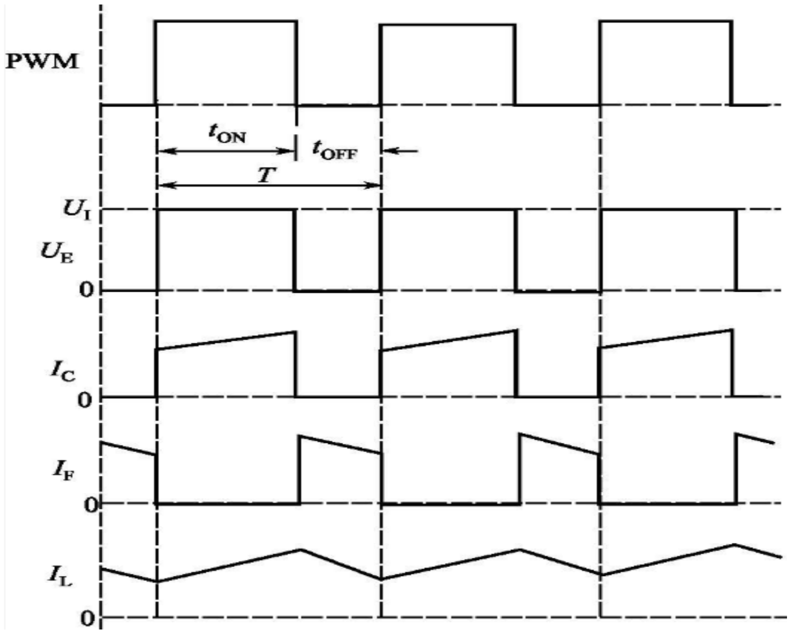


Fig. 1.5 Operation waveform of buck converter

The U_E is the emitter voltage waveform of the switch VT, and the I_C is the current waveform of the collector of the VT. I_F is the waveform of the current of the diode VD. IL is the current waveform of the inductor. During whole cycle input current will be much less than the output current, resulting in stepping down the voltage at the output.

However, getting perfect circuit is not possible in reality due to some energy losses. Maximum efficiency that practical buck converters exhibit is about 85%.

1.3 APPLICATIONS OF BUCK CONVERTERS

The buck converter is a ubiquitous DC-DC converter that efficiently converts a high voltage to a low voltage efficiently. Efficient power conversion extends battery life, reduces heat, and allows for smaller gadgets to be built. The buck converter converters exhibit a wide range of application. Some of its main applications are given below.

1.3.1 USB On-the-GO

The main purpose of buck converter using in USB is to draw power from the USB and delivers it to the smartphone. Hence, it is handled using a synchronous buck converter that can transfer power in both directions.

When some mouse or keyboard is connected to the smartphone, the buck converter runs in a reverse order and draws power from the lithium battery and delivers it to the keyboard or mouse connected to the smartphone.

1.3.2 POL converter for PCs and laptops

A Point-Of-Load Converter, or POL, also known as a voltage regulator, is a non-isolated buck converter that is widely used in laptops and desktop computers. It is very especially helpful in operating the motherboards.

1.3.3 Solar chargers

There are lots of buck converter products for solar chargers. They often come with a built-in microcontroller which allows the buck converter to draw the maximum amount of power and helps in charging the battery in shortest time possible.

1.4 BASIC OF DC-DC BOOST CONVERTER

1.4.1 Topological structure of DC-DC boost converter

The topological structure of the DC-DC boost converter is shown in Fig.1.6.

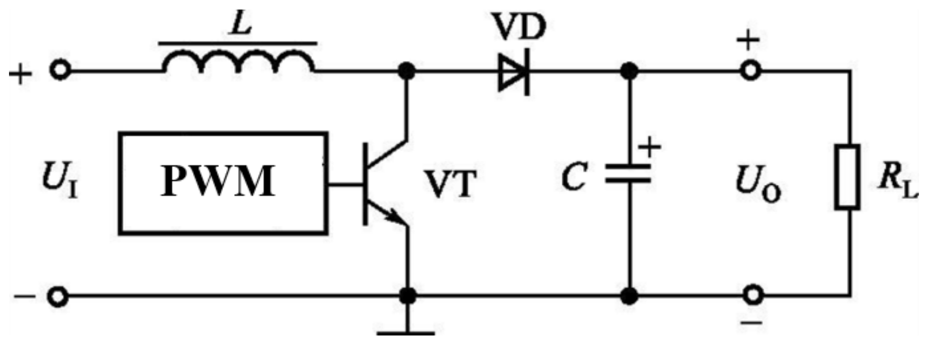


Fig. 1.6 Topological structure of boost converter

1.4.2 Operation of DC-DC boost converter

When VT is turned on, the input voltage UI is directly applied to both ends of the storage inductor L, and no current flows through the freewheeling diode D. Since L is applied with the voltage of UI, the current I_L increases linearly, and the energy stored by the inductor also increases.

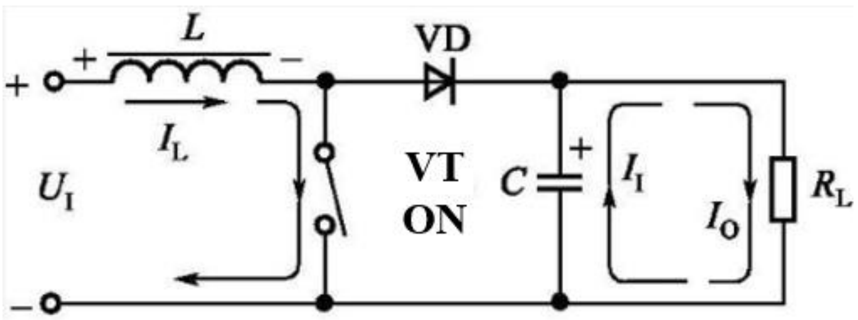


Fig. 1.7 Current path when VT is on

When VT is off, the diode is on because the inductor current is continuous. The voltage (U_I-U_O) is applied to the inductor L1 in the opposite direction to the on state, and the reactor flux is reset.

$$V(\text{Inductor}) = U_I - U_O \tag{1.4}$$

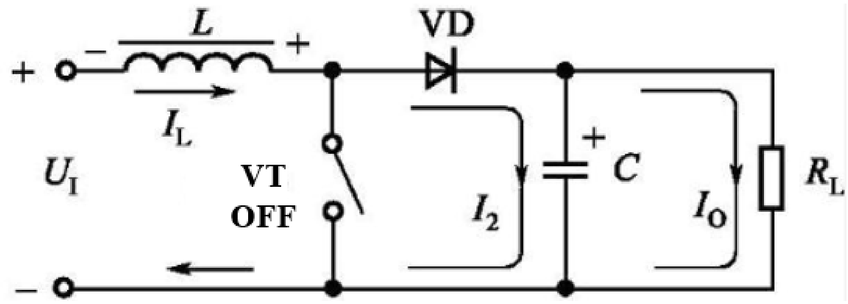


Fig. 1.8 Current path when VT is off

1.4.3 Operation waveform of DC-DC boost converter

The operation waveform of DC-DC boost converter is shown in the Fig.1.9. Since the duty ratio D is more than 1, this kind of converter is called a boost converter.

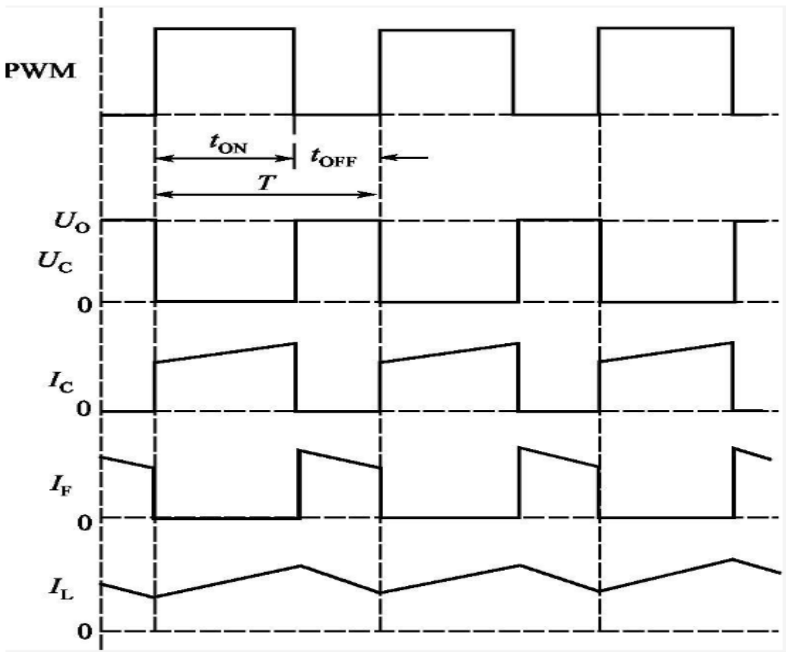


Fig. 1.9 Operation waveform of buck converter

1.5 BASIC OF DC-DC BUCK-BOOS CONVERTER

1.5.1 Topological structure of DC-DC buck-boost converter

The topological structure of the DC-DC buck-boost converter is shown in Fig.1.10.

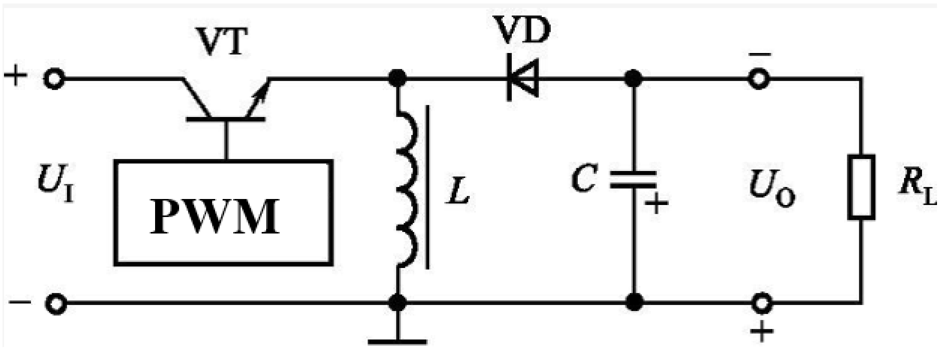


Fig. 1.10 Topological structure of buck-boost converter

1.5.2 Operation of DC-DC buck-boost converter

When VT is turned on, the input voltage UI is applied to the inductor L.

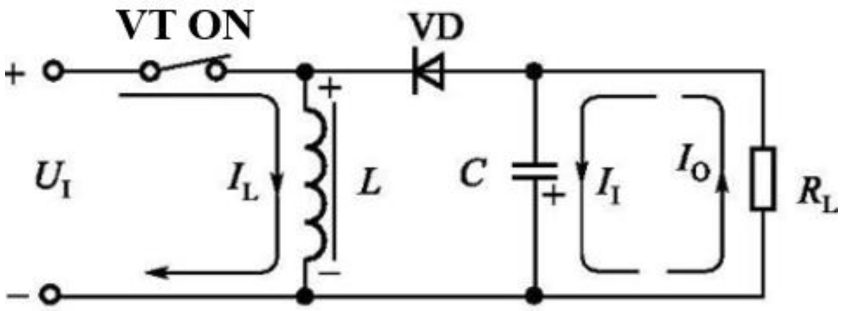


Fig. 1.11 Current path when VT is on

When the switch is off, the diode turns on because the inductor current is continuous. The output voltage Vo is applied to the inductor L in the reverse direction to the on state, and the inductor magnetic flux is reset.

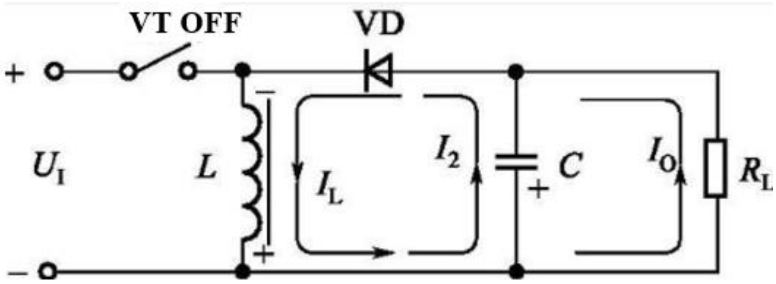


Fig. 1.12 Current path when VT is off

1.5.3 Operation waveform of DC-DC buck-boost converter

The operation waveform of DC-DC buck-boost converter is shown in the Fig.1.13. The output voltage Uo of this kind of converter can be larger than U_I and can be smaller than U_I, so it is called buck-boost converter.

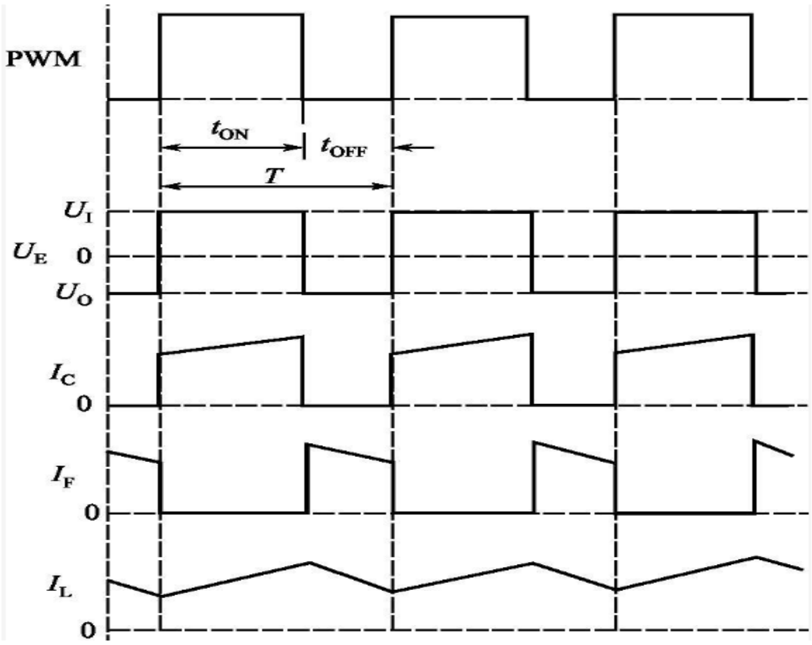


Fig. 1.13 Operation waveform of buck-boost converter

1.6 BASIC RIPPLE CONTROL CONVERTER

The topological structure of the ripple control converter is shown in Fig.1.3. Ripple control converter does not use an operational amplifier. The comparator compares the output voltage with the reference voltage to control the on / off of the switching element.

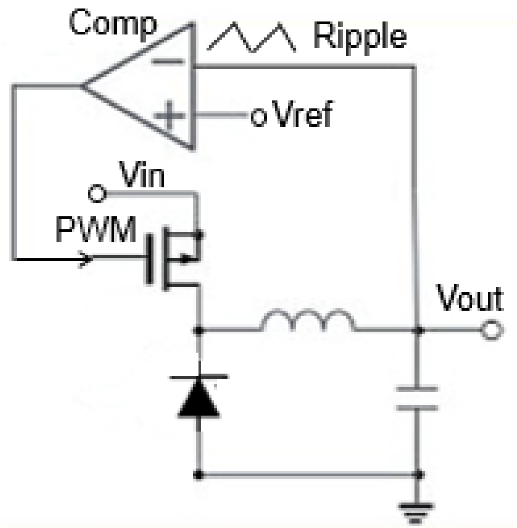


Fig. 1.3 Topological of basic ripple control converter

Fig.1.4 shows the waveforms of Fig. 1.3. In the ripple control method, when the output voltage ripple reaches the minus reference voltage, the switch turns on, when the ripple goes up to the plus reference voltage, the switch turns off. The switching frequency usually swings by the change of load current.

The ripple control scheme does not use an operational amplifier. Therefore, no delay due to the frequency characteristic of the operational amplifier or a dead time delay for one cycle of switching operation occurs. The response speed is determined by the LC filter at the output. Therefore, there is an advantage that a very high response speed can be obtained.

However, there is no fixed frequency clock in the ripple control converter. So, it's operation frequency is changed by the load current, and the noise of the circuit is large.

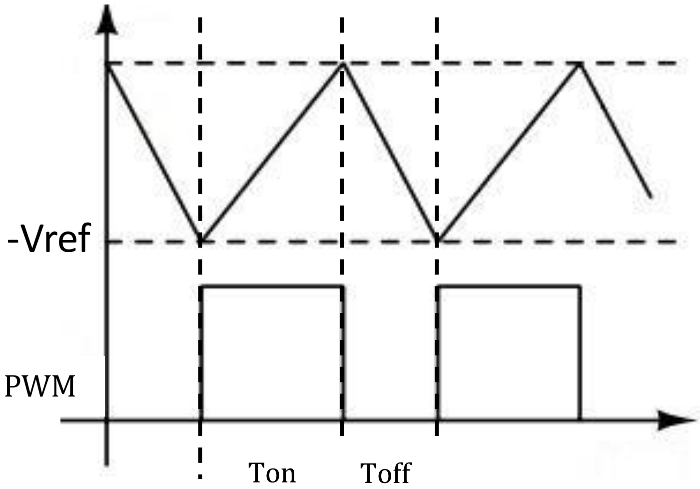


Fig. 1.4 Operational signal diagram of basic ripple control converter

1.7 CONSTANT ON-TIME CONTROL

The topological structure of the ripple control converter is shown in Fig.1.5. Unlike traditional voltage- or current-mode control, constant on-time (COT) control provides a way to eliminate the compensation loop.

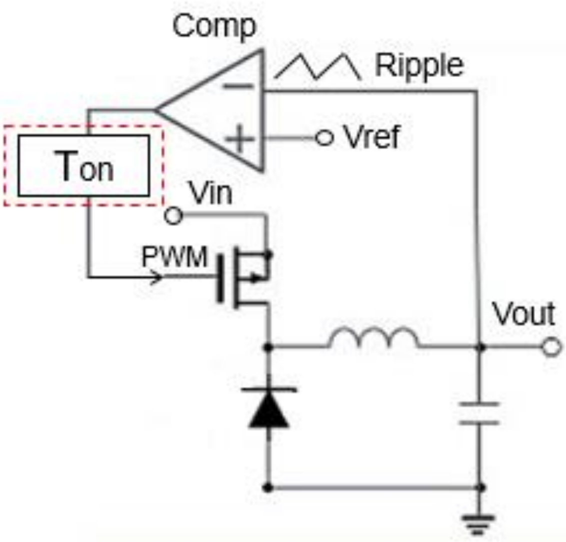


Fig. 1.5 Topological of basic ripple control converter

Fig.1.6 shows the waveforms of Fig. 1.5. The constant on-time control can make the on time constant by a timer circuit inside the feedback loop, so that the frequency will keep stable according to the equation below.

$$V_o = V_i\, T_{on} / T_s \quad (1.4)$$

$$f_s = 1/T_s \quad (1.5)$$

Here, fs is the operational frequency.

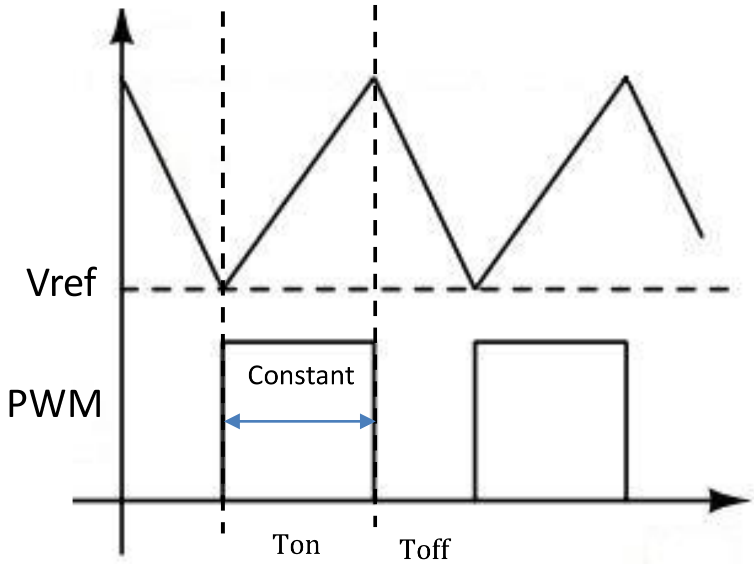


Fig. 1.6 Operational signal diagram of COT control converter

1.8 CONTROL OF CONSTANT ON-TIME RIPPLE CONTROLLED CONVERTER

1.8.1 Circuit configuration of COT ripple controlled converter

The configuration of the buck converter with the constant on-time control is shown in Fig.1.7. 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.

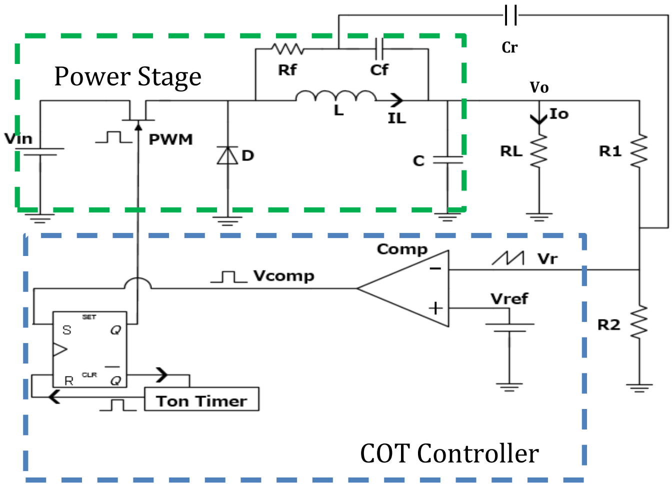


Fig. 1.7 Buck converter with COT ripple controlled converter

1.8.2 Waveform of single-phase COT ripple controlled converter

Fig. 1.8 shows the operation principle waveforms of the single-phase COT ripple controlled converter. From t0 to t1, the ripple voltage Vr reaches to the Vref, the comparator outputs a pulse Vcomp, and the SR flip-flop is started, then the output of Q port will be HIGH, resulting to the turning on of switch SW. The on-time of SW is set up constantly by the Ton timer. When the timing is over at t1, the Ton timer outputs a pulse to the R port to reset the SR flip-flop and Q becomes low level thereby, resulting to the turning off of the switch SW. Then Vr starts to decrease from peak, so does the inductor current IL. From t1 to t2, the SW keeps turning off, during which Vr and IL keeps decreasing. When it comes to t2, Vr becomes lower than Vref again, the pulse Vcomp will be output again. Then the SW turns on again in the next cycle.

In this case, all the output current will flow only through inductor L, so that L must be large in size. The output voltage ripple is also high.

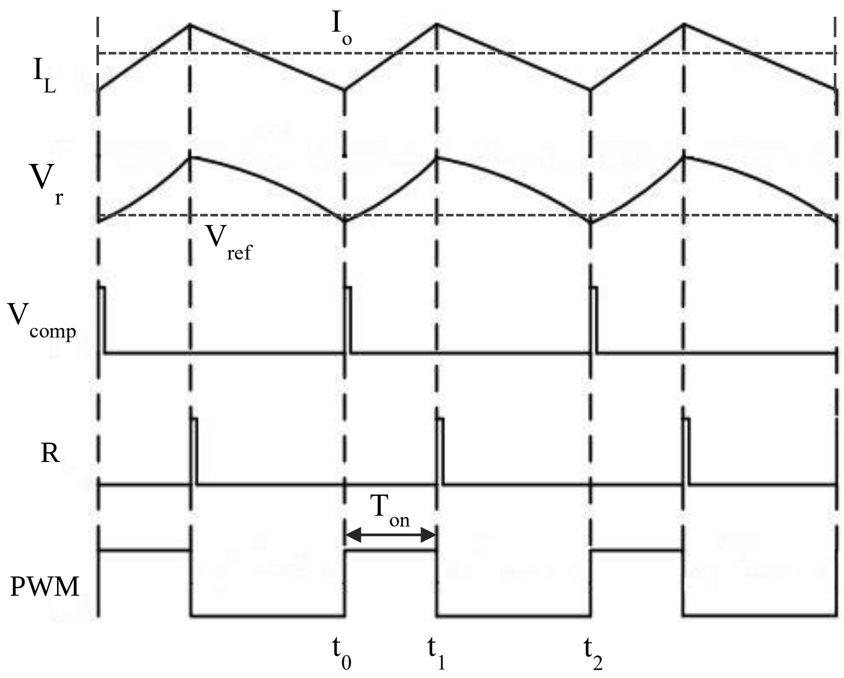


Fig. 1.8 Waveforms of the single-phase converter

CHAPTER II

MULTI-PHASE RIPPLE CONTROLLED CONVERTER

This chapter describes a dual-phase switching converter using a ripple control without a stable clock pulse. By dividing the peak hold voltage by two which is supplied from the saw-tooth signal of the main converter, two phase clocks are generated. In our converter, the output voltage ripple is reduced by 10% and the settling time is decreased to one-half. transfer function. Finally, the control system design is introduced.

2.1 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 [6]. The ripple-controlled multi-phase converter can achieve high-speed response. The conventional multi-phase method in switching power supply uses an external clock, and the multi-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 multi-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 other 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 [7]. In this method, the multi-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.

2.2 MULTI-PHASE CONVERTER WITH RIPPLE CONTROL

2.2.1 Dual-phase system

Fig.2.1 shows the configuration of the dual-phase converter with COT control. Besides the main converter, there is a sub-converter below.

Sub-converter receives the same input voltage Vin and includes the same components as the main converter, but it is controlled by different PWM signal whose phase positions differ by 180° from each other.

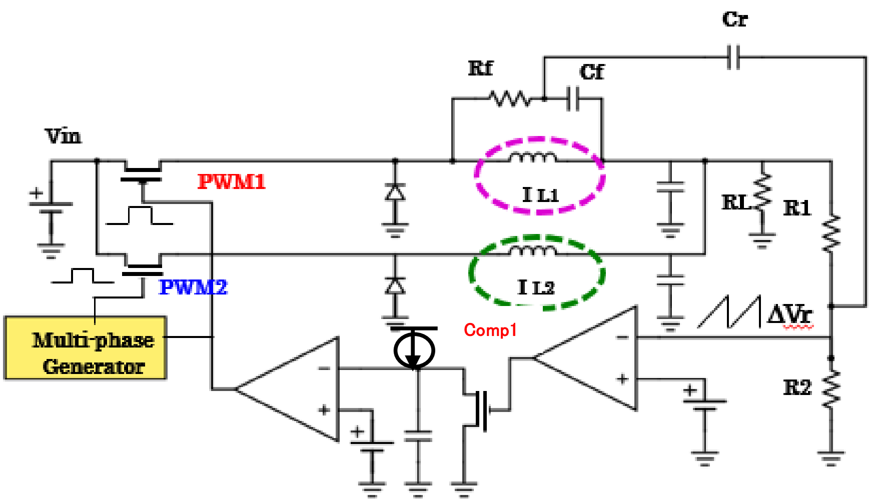


Fig. 2.1 Dual-phase buck converter with ripple controlled converter

2.2.2 Generation method of dual-phase PWM

In Fig. 2.2, as for the dual-phase generator, a saw-tooth signal tracking with PWM1 is generated by SAW generator.

The peak-hold circuit is also shown in the Fig. 2.2. The Vcomp is picked up to generate a sampling pulse and a delayed reset pulse. 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 the saw-tooth 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 immediately.

Once the sampling pulse is over, the switch turns off. The saw tooth generator will be reset, and the voltage on the capacitor C stays at the peak value.

Then we used a voltage divider to divide the peak voltage of the saw-tooth into one half parts, and by comparing each divided voltage to the saw-tooth wave, the other pulse is generated. the generated PWM is following the main PWM, keeping the phase difference regularly

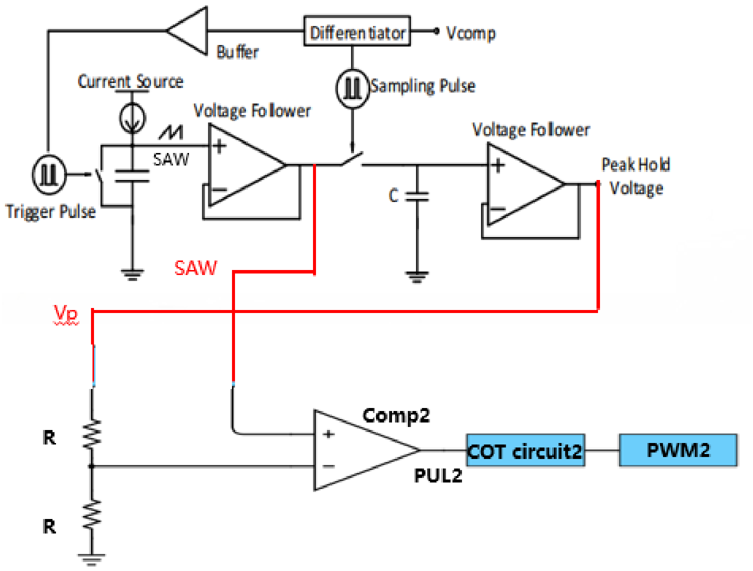


Fig. 2.2 Operation process of dual-phase PWM generator

2.2.3 Waveform of dual-phase COT ripple controlled converter

The operation principle waveforms of the dual-phase COT ripple controlled converter is shown in Fig. 2.4. In the case of dual-phase converter, two power stages are set and inductor L_1 and L_2 will go shares with the output current, so that the size of each inductor will be small in size.

Besides, the two power stages are driven by a set of PWM signals, the phase difference between themselves is 180 degrees, so do the inductor current. The total output current is the sum of each phase. By this operation, the frequency can be simulative multiplication, and by the effect of shifted wave peak of each phase, the output voltage ripple also reduces a lot.

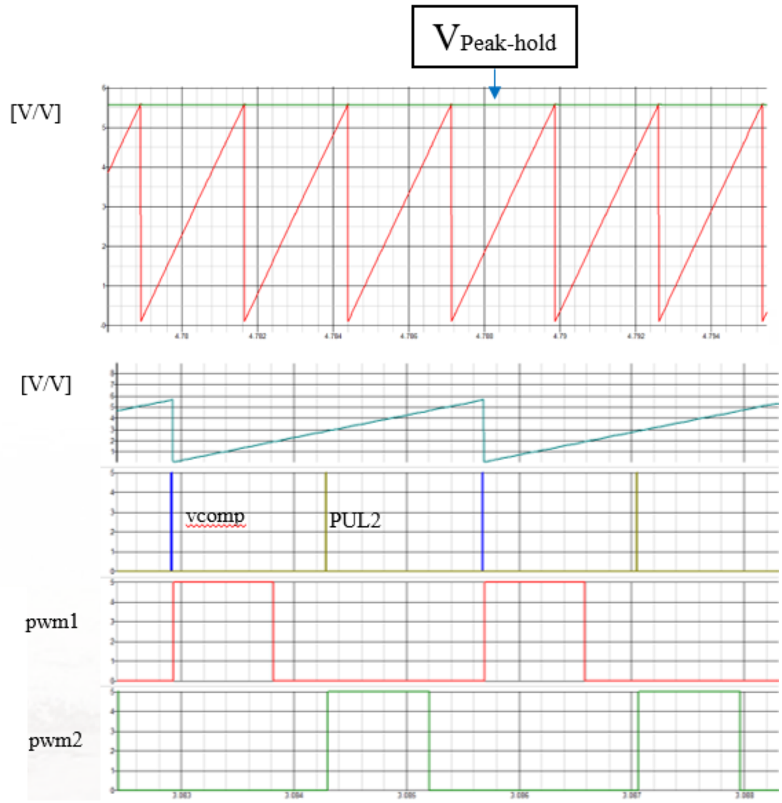


Fig. 2.3 Waveforms of the dual-phase converter.

2.2.4 Multi-phase current balance

Fig.2.4 is the simulation result of the current balance of dual-phase converter. When without element variations, the inductor current in each phase shows good current balance.

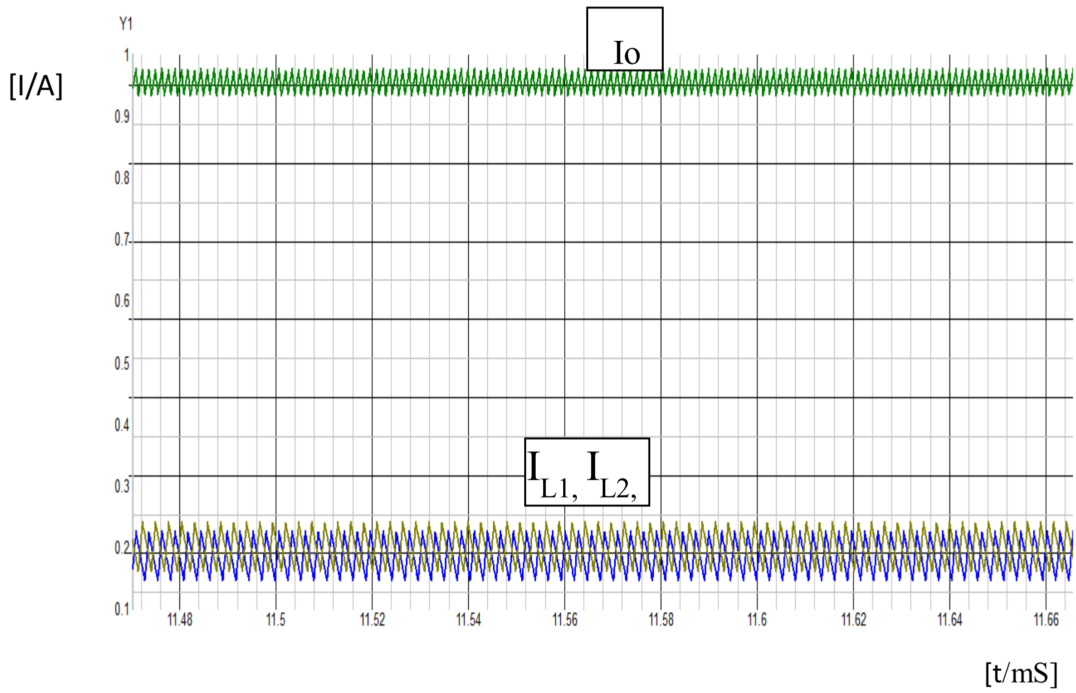


Fig. 2.4 Simulated waveforms of dual-phase converter.

2.2.5 Static and dynamic characteristics

Ripple is an unwanted component in DC output. Smaller value of ripple factor is desirable. As Fig. 2.5 and Fig. 2.6 show, the output voltage ripple of the four-phase converter decreases by 44% (from 0.09mV to 0.05 mV) compared to that of the single-phase converter at Io=0.5 A. When the load current is changed from 5A to 10A and returned to 5A. We can see that the voltage fluctuation decreases a lot in both the load fluctuation and light load fluctuation, so do the recovery time.

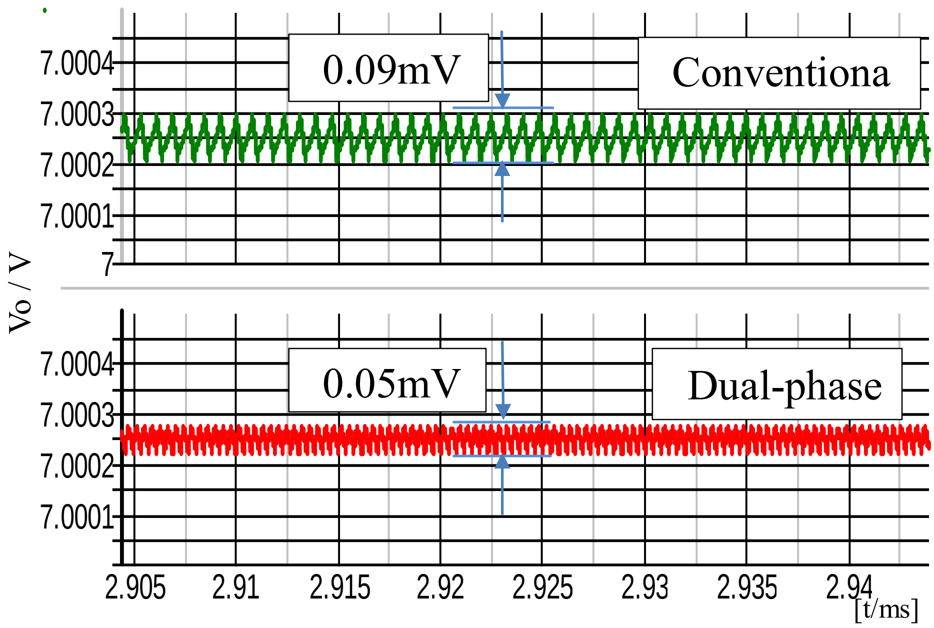


Fig. 2.5 Comparison of the output voltage ripples.

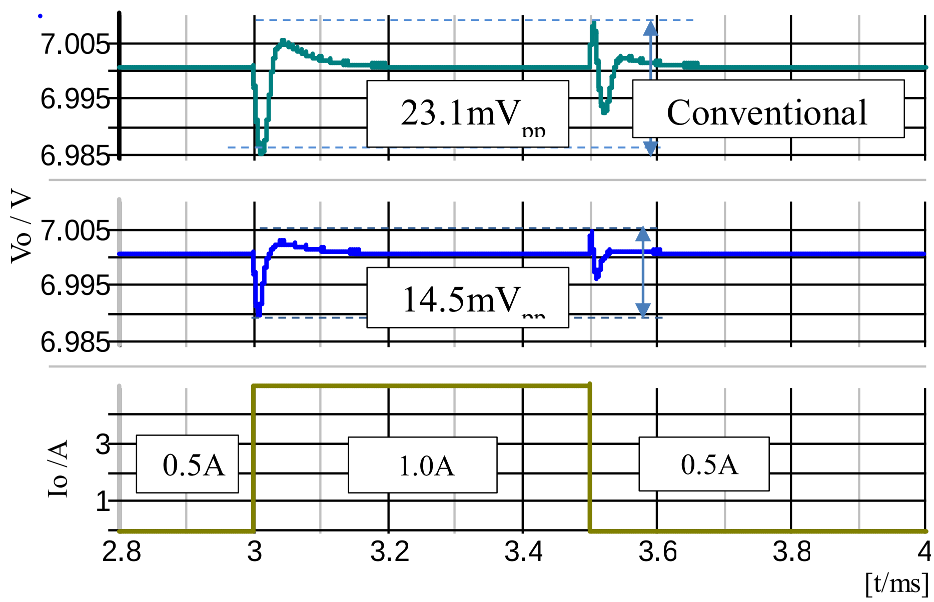


Fig. 2.6 Comparison of the load fluctuations.

CHAPTER Ⅲ

AUTOMATIC CORRECTION OF CURRENT IMBALANCE

In the two-phase power supply according to the system witch mentioned in the previous chapter, a method of detecting a phase of 180 degrees by detecting a peak voltage of a SAW signal has been reported to generate an inverted clock [8]. In this method, the variation in each phase power supply becomes large at the time of large current due to the error of detection of 180 degrees and the variation of inductance and capacitance elements, that is, "current imbalance" becomes a problem.

Therefore, a method capable of automatically correcting this current variation is considered. In this chapter, we focus on steady-state current balance correction and current imbalance correction methods due to element variations, employing a new multi- phase of “ripple control power supply” as a clockless power supply.

3.1 CONTROL OF AUTOMATIC CORRECTION CURRENT IMBALANCE CONVERTER

3.1.1 Circuit configuration and operation principle

Fig.3.1 shows the configuration of the COT ripple control switching power supply. This circuit has a configuration in which a fixed time with the pulse generation circuit is provided at the control pulse output stage of a normal ripple control power supply. In the power stage, a step-down power supply is generally used, and it comprises a power switch, an inductor, a free-wheeling diode and an output capacitor. Vr and the reference voltage Vref are directly compared by the comparator, and then it achieves the constant on- time.

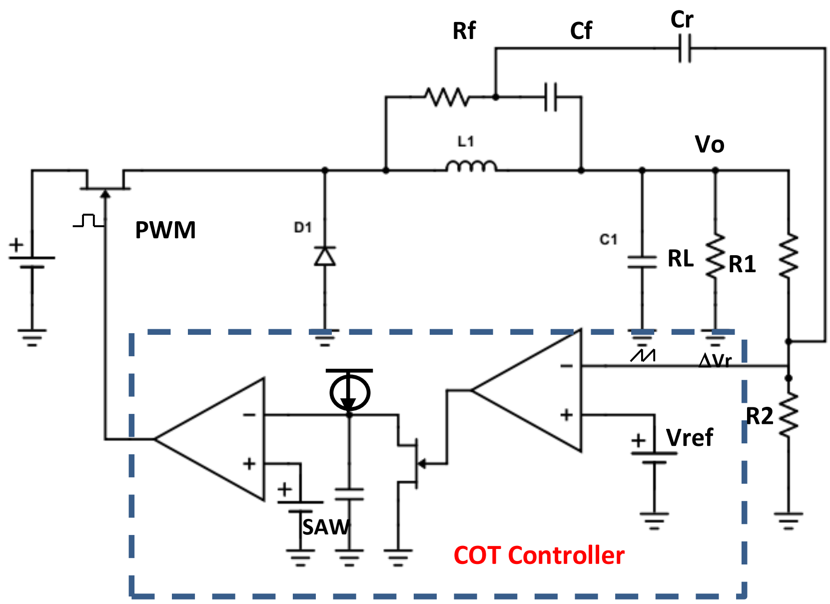


Fig. 3.1 Ripple converter with COT control.

3.1.2 Simulation waveform

Fig.3.2 shows the operating waveforms as a result of simulation using the parameters in Table 3.1 according to the circuit in Fig. 3.1. The input voltage Vin = 10 V, the output voltage Vo = 3V, the output current Io = 5.0 A, and the COT pulse width TCOT = 0.817 μs.

Table 3.1 Parameters in COT control circuit

V_{in}	10[V]
V_o	3.0[V]
L	10[μH]
C	200[μF]
R_f	10[kΩ]
C_f	1.0[nF]
C_r	1.0[mF]
R_1	3.9[kΩ]
R_2	470[kΩ]

In Fig.3.2, the inductor current IL is increased or decreased according to the PWM pulse, and the output voltage ripple waveform also has a similar waveform. At the same time as Vo decreases and Vo = Vref, the PWM pulse turns to H.

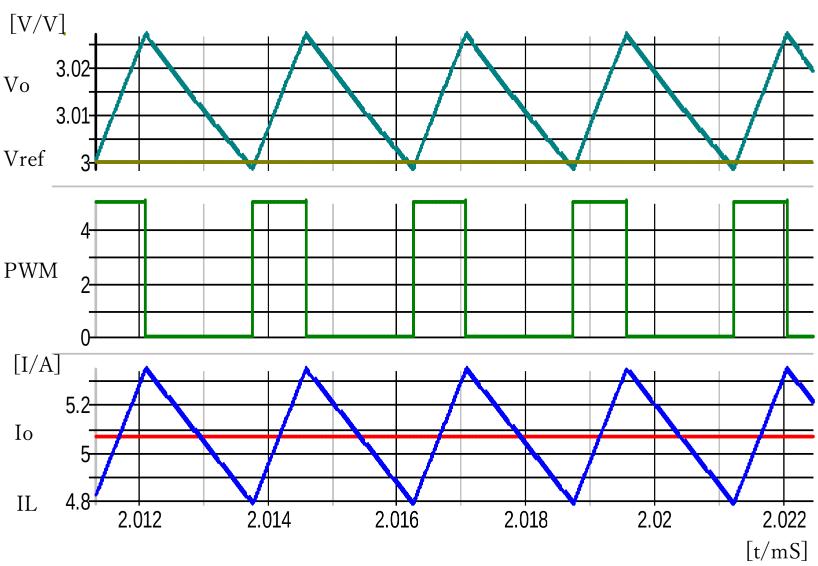


Fig. 3.2 Simulation of COT circuit.

3.2 AUTOMATIC CORRECTION TECHNOLOGY FOR BALANCE OF ELEMENT VARIATION

3.2.1 Dual-phase imbalance current

Fig.3.3 shows the simulation result of current of the conventional two-phase converter. When the value of the inductor in the main power supply changes from 10μH to 11μH, that is, when it increases by 10%. Due to the dispersion of inductance element, the current dispersion of each phase power supply becomes large at the time of large current, and then current imbalance becomes a problem. In the case of Io =8.58 A, the means of inductor currents in each phase will be 4.29 A, but I_{L1} varies to 5.43 A and I_{L2} varies to 3.15 A, obtaining offset by 27% which shows deteriorated current balance in this two-phase converter.

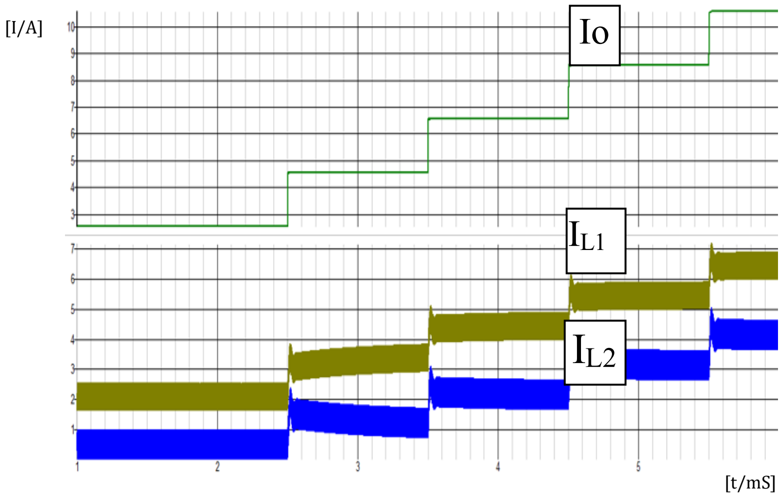


Fig. 3.3 Imbalance result for dual-phase current.

3.2.2 Configuration of the automatic correction current imbalance convert

The proposed pulse phase modulation circuit is shown as Fig. 3.4 which generates the COT pulse for the sub-converter. The width of the COT pulse T_{COT} is generated by the comparator which compares the SAW signal generator with the control voltage Vcont.

As for pulse phase modulation the phase of rising edge of a pulse is modulated while the pulse period and width are kept constant. This is realized by inserting a modulation circuit for phase-modulating the pulse in front of the COT circuit. A saw-tooth wave whose frequency is synchronous with Vcomp is generated. By comparing the triangular wave signal to the saw-tooth wave voltage, phase modulated pulse is obtained, and the phase modulated PWM is generated thereby. And we can infer the modulation ratio by the equation below.

$$TCOT = k \cdot V — = k \cdot (VCOT + Vamp) = TCOT + \Delta TCOT \quad (3.1)$$

$$\text{Modulation Ratio: } \alpha = \Delta TCOT / TCOT = Vamp / VCOT \quad (3.2)$$

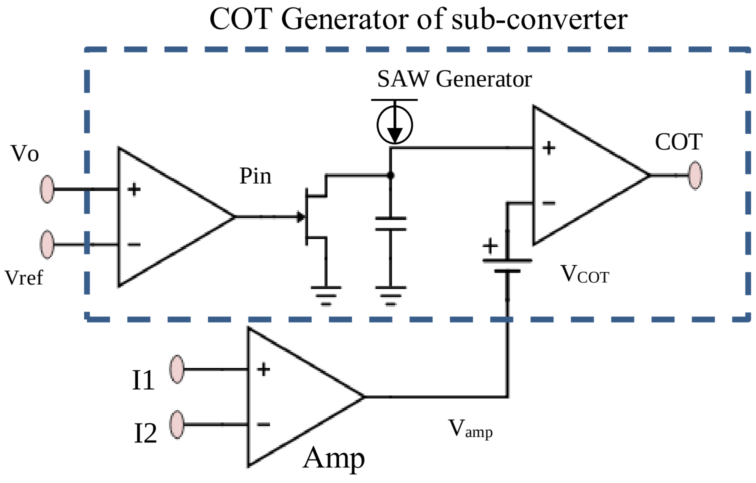


Fig. 3.4 Proposed COT phase modulation circuit.

3.2.3 Operation of Proposed COT Generator

The input pulse Pin is supplied from the comparator, whose positive edge resets and restarts the SAW generator. The gradient is decided with the current Io and the capacitance C_{COT} in the COT pulse generator. The COT pulse is generated by comparing between this SAW signal and the Vcont. When the Vcont increases, the width of the TCOT increases and the current of the sub-converter increases. The Vcont is controlled as below.

$$\text{Vcont} = V_{COT} + \text{Vamp} \tag{3.3}$$

Here, the Vamp is the output of the amplifier.

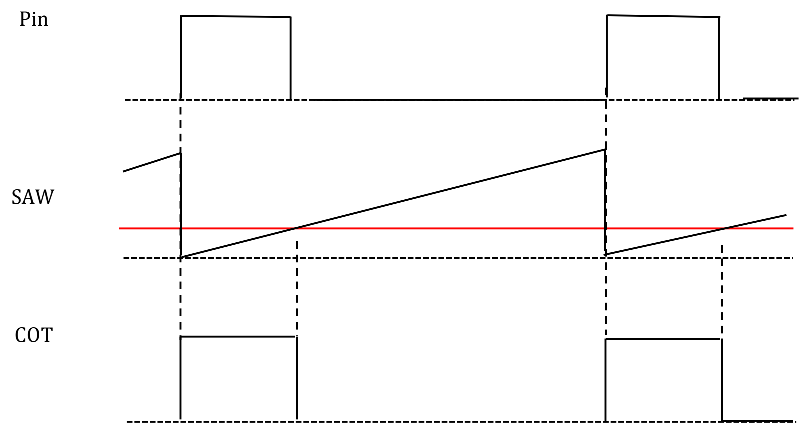


Fig. 3.5 Waveforms of the COT generator

3.2.4 Dual-phase balance current.

As shown in Fig.3.6, when the inductance in the main power supply increases by 10% in the case of Io =6.81 A, the inductor current in each phase are almost the same as 3.40 A, which shows good current balance in automatic correction current imbalance converter.

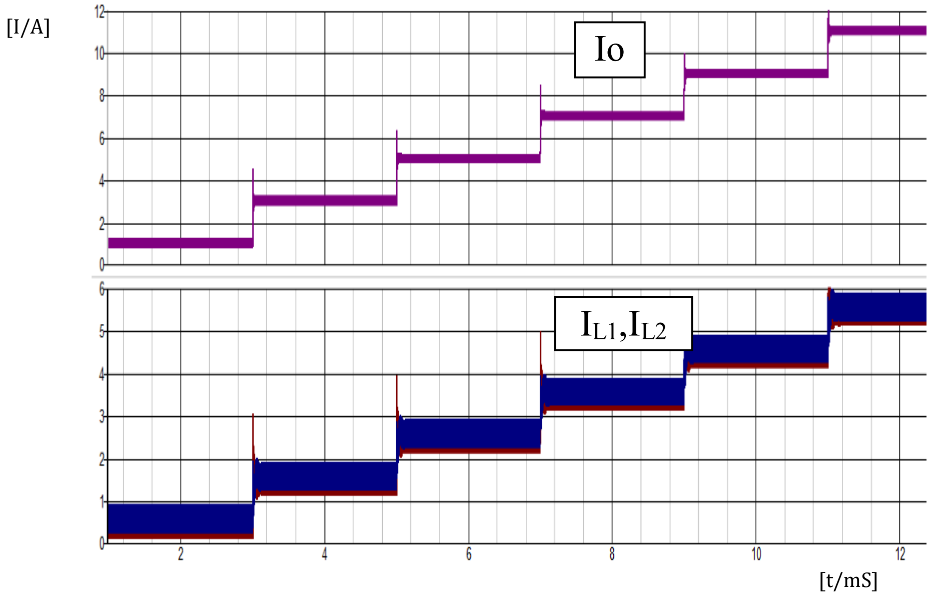


Fig. 3.6 Balance result for dual-phase current.

3.2.5 Four-phase imbalance current

Fig.3.7 shows the simulation result of current of the conventional four-phase converter. When the value of the COT capacitor in the main power supply changes from 500pF to 495pF. When the capacitance decreases by 1%, in the case of Io =8.52 A, the means of inductor currents in each phase will be 2.13 A, but I_{L1} varies to 3.88A, obtaining offset by 82% which shows substantial current imbalance in this four-phase converter.

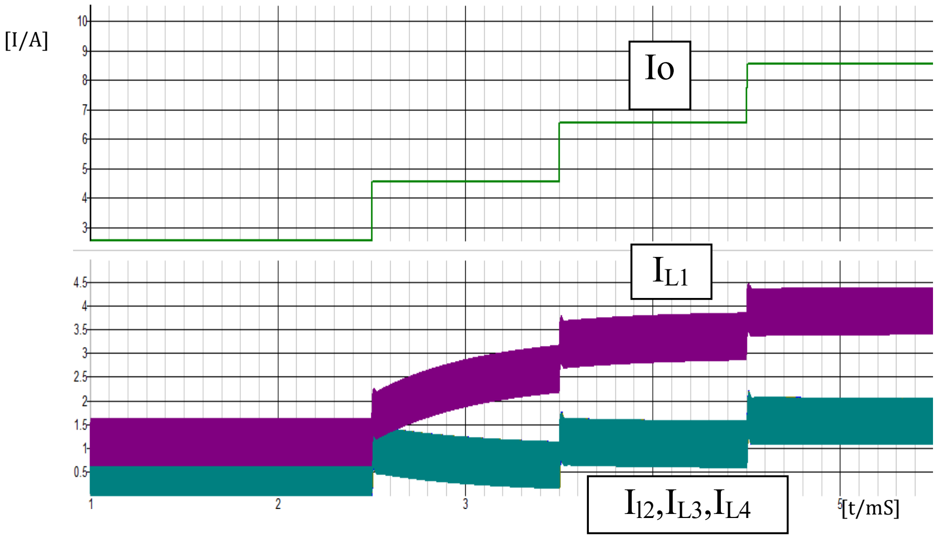


Fig. 3.7 Balance result for four-phase current.

3.2.6 Four-phase balance current

When the COT capacitance of the main power supply fluctuates in the four-phase power supply, as shown in Fig. 3.7, only the current of the main power supply is largely imbalanced. As the improvement method, the current balance can be corrected as shown in Fig. 3.8, by correcting the COT pulse width of the main power supply.

By comparing the currents between three times of I_{L1} and $\Sigma(I_{L2} \sim I_{L4})$ using the circuit shown in Fig 3.4, the inductor current of the main converter is decreased.

As a result, in the case of Io =7.41 A, the inductor current in each phase are almost the same as 1.85 A, which also shows better current balance. The response characteristic to the change of load current is a little worse, but it can be improved if the characteristic is reviewed.

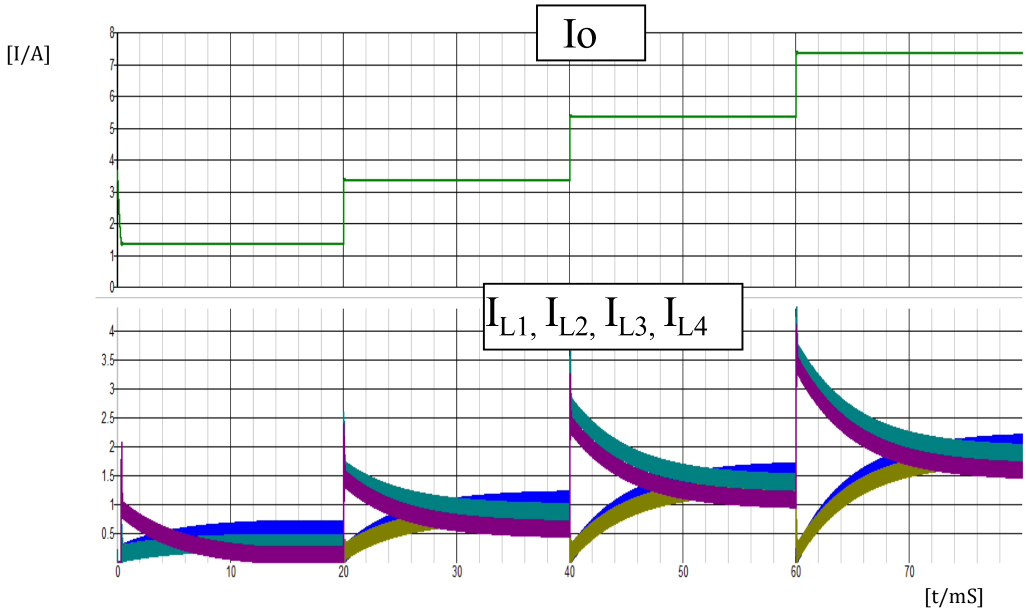


Fig. 3.8 Balance result for four-phase current.

CHAPTER IV

EMI NOISE REDUCTION IN MULTI-PHASE CONVERTER

Electro Magnetic Interference (EMI) is a disturbance that affects an electrical circuit. EMI is caused by induction or outside radiation. It can temporary and permanently disrupt circuit components, so it is a big design issue for new products [9].

In multiphase power supplies, there is a concern about the influence of 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.

Therefore, in this chapter, we propose a scheme of the EMI noise reduction.

4.1 EMI NOISE REDUCTION FOR MULTI-PHASE CONVERTER

The proposed pulse phase modulation circuit is shown as Fig. 4.1. The phase is randomly changed while maintaining the on time fixed for each clock. As shown in Fig. 4.1, 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.

Here, Vm is the modulation signal amplitude. Ccot is equal to Vb plus Vm.

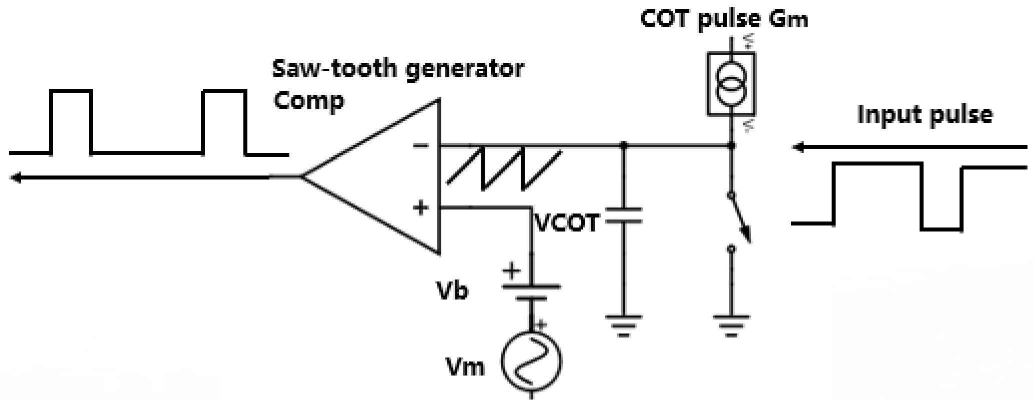
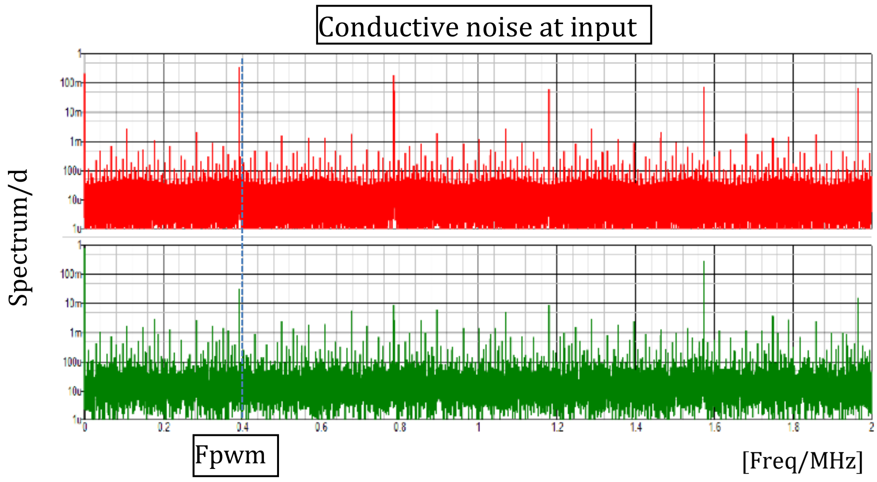


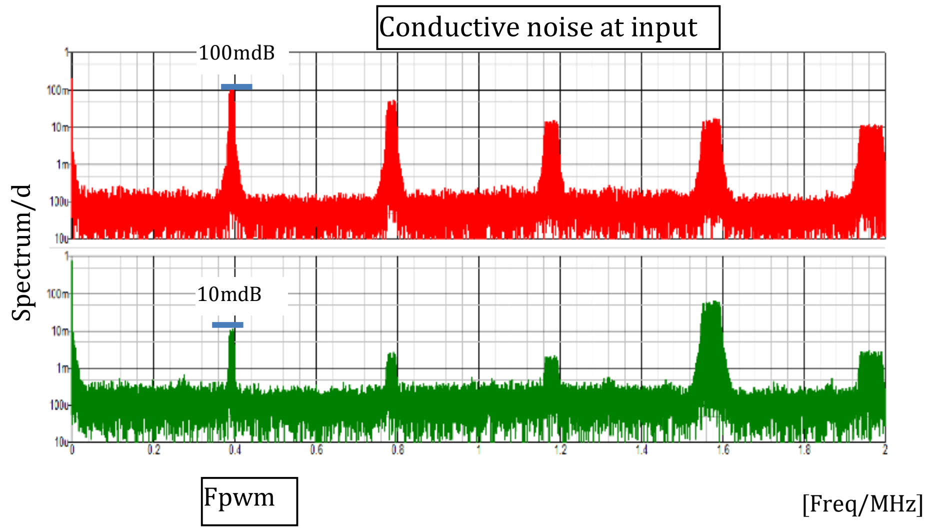
Fig. 4.1 Proposed COT phase modulation circuit.

Fig. 4.2 shows the spectrum of the conductive noise (input current) without the EMI reduction and Fig. 4.3 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.



Top: Single phase, Bottom: Four-phase

Fig. 4.2 Spectrum without EMI reduction.



Top: Single phase, Bottom: Four-phase

Fig. 4.3 Spectrum with EMI reduction.

4.2 RELATIONSHIP BETWEEN CONDUCTIVE NOISE AND REFERENCE VOLTAGE

Fig. 4.3 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.4.2, the minimum level of the conductive noise is -30 dB, theoretically this level will be less level at Vref=0.9848 V.

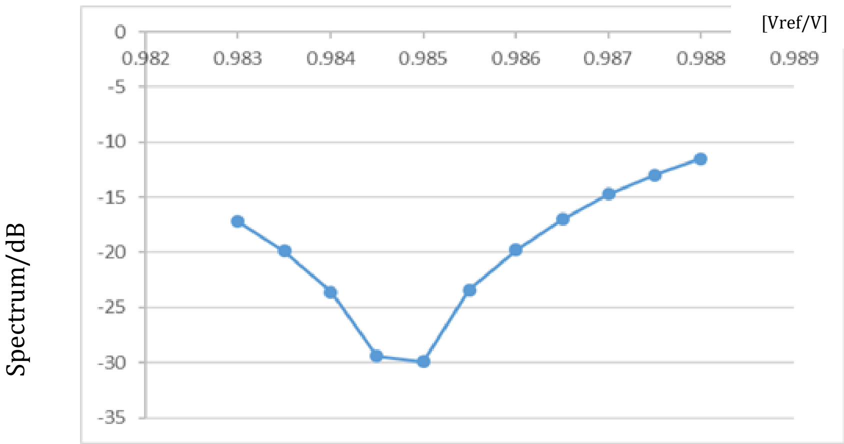


Fig. 4.3 Relationship between Vref of COT pulse and converter output spectrum level of conductive noise at Fpwm.

CHAPTER V

CONCLUSION

5.1 CONCLUSION

In daily life, the power supplies are demanded everywhere to convert the power from grid or battery to provide appropriate voltage for electronic devices. In electronic devices, some different DC supply voltages are required for different function modules. Power supply circuits demand both low-ripple-voltage in the steady state (stability) and fast response for large load changes. However, since in general stability and fast response are trade-off in control systems, it is difficult to satisfy both simultaneously with conventional approaches [10].

In order to meet this demand, a multi-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, as for the dual-phase converter, the output voltage ripple is decreased by 44% and the voltage fluctuation decreases a lot in both the load fluctuation and light load fluctuation, so do the recovery time.

In order to avoid the hazard due to current imbalance, I also proposed a technique of automatic correction of current imbalance due to element variations in multi-phase ripple controlled converter. The current imbalance due to inductance and capacitor variations is well improved.

5.2 FUTURE WORK

In this research, I only do the simulation by SIMetrix. The future work is to realize the mounting of the simulation circuit on the electronic board, then compare the theory with the experimental results.

REFERENCES

[1] Middlebrook, R. D. "Power electronics: an emerging discipline." IEEE International Symposium on Circuits and Systems. 1981.

[2] Middlebrook, R. D. "Power electronics: topologies, modeling, and measurement." Proc. IEEE Int. Symp. Circuits Syst. 1981.

[3] Cuk, Slobodan. "Basics of switched-mode power conversion: topologies, magnetics, and control." Power Conversion International 7.9 (1981): 22-27.

[4] Mohan, Ned. "Power electronic circuits: An overview." Proceedings. 14 Annual Conference of Industrial Electronics Society. Vol. 3. IEEE, 1988.

[5] Bose, Bimal K. "Power electronics-a technology review." Proceedings of the IEEE 80.8 (1992): 1303-1334.

[6] Kobayashi, Haruo, and Takashi Nabeshima. Handbook of Power Management Circuits. Pan Stanford, 2016.

[7] Asaishi, K., et al. "Hysteresis Control Power Supply with Switching Frequency Insensitive to Input/Output Voltage Ratio." IEEE 13th International Conference on Solid-State and Integrated Circuit Technology. 2016.

[8] Xiong, Yi, et al. "Two-phase soft-switching DC-DC converter with voltage-mode resonant switch." 2017 International Symposium on Intelligent Signal Processing and Communication Systems (ISPACS). IEEE, 2017.

[9] Born, Max, and Emil Wolf. Principles of optics: electromagnetic theory of propagation, interference and diffraction of light. Elsevier, 2013.

[10] Kono, Masashi, et al. "Low-Ripple-Voltage and High-Speed Control System for Load Regulation of DC-DC Converter.".

PUBLICATIONS

International Conference Papers

[1] **Jing Li**, Yi Xiong, Yifei Sun, Tran Minh Tri ,Yasunori Kobori and Haruo Kobayashi, "Four-phase Ripple Controlled Switching Converter with EMI Noise Reduction Circuit," ICMEMI 2018: International Conference on Mechanical, Electrical and Medical Intelligent System, Kiryu, Japan (Nov 4-5, 2018).

[2] Shogo Katayama, **Jing Li**, Yasunori Kobori and Haruo Kobayashi, "A Simple Feed-Forward Controller Design for DC-DC Buck Converter," 9th International Conference on Advanced Micro-Device Engineering (AMDE2013)Kiryu, Japan (Dec. 6, 2018)

[3] Noriyuki Oiwa, Shotaro Sakurai, Yifei Sun, Minh Tri Tran, **Jing Li,** Yasunori Kobori, Haruo Kobayashi, "EMI Noise Reduction for PFC Converter with Improved Efficiency and High Frequency Clock", IEEE 14th International Conference on Solid-State and Integrated Circuit Technology, Qingdao, China (Nov. 2018).

[4] **Jing Li**, Yifei Sun, Yasunori Kobori, Anna Kuwana, Haruo Kobayashi, " Automatic Adjustment of Current Imbalance due to Component Variations in Multi-Phase Ripple Controlled DC-DC Converter"TJCAS 2019: Conference on Circuits and Systems Tochigi, Japan, (Aug.2019)

Domestic Papers

[1] **Jing Li,** Yifei Sun, Yasunori Kobori, Anna Kuwana, Haruo Kobayashi, "Automatic Correction of Current Imbalance due to Element Variations in Multi-Phase Ripple Controlled Converter," 電子情報通信学会 電子通信エネルギー技術研究会 東京（2019 年 5 月）

HONOR AND AWARD

Best Student Presentation Award, ICMEMIS2018, Nov. 6