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Dual-phase/Multi-Phase Soft-Switching Converter with Current Balance

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Dual-phase/Multi-Phase Soft-Switching Converter with Current Balance

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Declaration

I hereby declare that this submission is my 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 acknowledgment has been made in the text.

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Abstract

This thesis deals with the output current imbalance in resonant converters for electronic equipment. Simultaneously, a circuit design that can automatically balance the output current is proposed, which can be applied to multi-phase full-wave and half-wave voltage resonant converters.

For the resonant converter, its operating frequency is unstable due to the influence of power supply voltage, load, and ambient temperature. Therefore, its multi-phase structure is very complicated. We have adopted a saw-tooth wave peak voltage holding technique and developed dual-phase and four-phase resonant converters. On the other hand, the current balance is very important to reduce the output voltage ripple. However, due to the variations of the components in the resonant circuit, the output current is easily to be imbalanced. Therefore, we have developed an automatic current balance technique applied to full-wave and half-wave resonant converters, which can also be applied to dual-phase and four-phase converters.

Content

1. Introduction

In recent years, information and communication equipment has been widely used in personal computers [1]. The operating frequency and current capacity of switching converters, for personal computers, are becoming higher and higher, especially in server CPU [2]. Nowadays, multi-phase buck converters are often used in these CPUs, and the number of multi-phases is increasing, such as four-phase or six-phase. Multi-phase technology is considered to be necessary for the high-frequency operation, in order to reduce the ripple current [3] and ripple voltage in the output capacitor, because the output ripple is distributed to each phase, so the total ripple is reduced. The buck converter is easy to realize a multi-phase converter configuration because this type of converter uses a fixed frequency clock pulse. To achieve fast response and high efficiency, it is the best to use a multi-phase converter with ripple control or soft switching with resonance. However, in the absence of a clock power supply, the switching frequency often fluctuates, so people think that it is difficult to control the switching power supply in two phases [4]. Simultaneously, to make the dual-phase or four-phase DC-DC converter have good performance, the output current balance is the most important.

Generally, in an ideal dual-phase converter, the average current of the two phases is equal to half of the total current I_o, and in an ideal four-phase converter, the output current of each phase is one-fourth of the total current, thus achieving a good current balance. However, once the current of any phase shifts from the balance value, the current offset $\Delta I_L(IL=I_{L1\ or\ L2}- I_o/2)$ is an important indicator to evaluate the current balance performance, so its ratio σ $(\sigma=2\Delta I_{L1\ or\ L2})\ /\ I_o)$. In the case of a large load current, the total current is evenly distributed to each phase, thereby reducing the load on the main phase. The equipment at each stage is also designed based on distributed current loads. Once the current balance changes, the efficiency of the imbalanced phase is not ideal, and the output ripple voltage is also unsatisfactory. The balance of the output current is very important for some delicate instruments. Once a large imbalanced output is produced, it causes damage to electronic equipment.

In this thesis, a dual-phase DC-DC converter is realized by two PWM signals with a phase difference of 180 degrees. By detecting the phase when the saw-tooth signal reaches half of the peak hold voltage, a phase shift of 180 degrees is formed and used to make another saw-tooth signal with a phase shift of 180 degrees. In this way, a hysteresis PWM signal is generated accordingly. In the same way, we also realize a four-phase DC-DC converter through four PWM signals with a phase difference of 90 degrees. From the simulation results, it can be confirmed that the output ripple voltage of the dual-phase/four-phase converter is better than that of the conventional converter, and good dynamic performance is achieved in the transient response of large load current.

1.1 Research Background

DC-DC converters can be divided into three types: low dropout linear regulator (LDO), capacitive regulator, and inductive regulator (switching power supply). Among them, LDO is the earliest DC-DC converter. It has the following advantages and disadvantages: simple circuit structure, no need for the external inductor, low output noise, low conversion efficiency, buck only, single application, etc.

Capacitive regulators can be realized by only switching and power supply, relying on the charging and discharging of capacitors to achieve buck-boost conversion. It has the following characteristics: no inductance, simple circuit, buck-boost, the output voltage being a multiplier of input voltage, high power consumption, and high noise [5].

Switching power supplies use inductors as energy storage components and rely on inductors and capacitors for energy transfer. Switching power supplies have the following characteristics: they can achieve buck-boost, high efficiency, low cost, and wide application range. There are three main types of switching power supplies: Buck, Boost, and Buck-Boost.

Switching power supply mainly consists of the following development directions:

1. More efficient

The loss inside the switching power supply can be roughly divided into four aspects: switching loss, conduction loss, additional loss, and resistance loss. These losses usually occur simultaneously in lossy components, which will be discussed separately below.

In recent years, the switching power supply has been developed towards high frequency, which means that the switching loss generated during the transient response of fast turn-on and off affects the efficiency of the switching power supply.

Input and output filter capacitors are not the main loss source of switching power supplies, although they have a great impact on the working life of the power supply. If the input capacitor is not selected correctly, it makes the power supply not reach its actual high efficiency when it works.

Each capacitor has small resistance and inductance in series with the capacitor. Equivalent series resistance (ESR) and equivalent series inductance (ESL) are parasitic elements caused by the structure of the capacitor, and they both prevent external signals from being added to the internal capacitance. Therefore, the performance of the capacitor is the best in DC operation, but the performance is much worse at the switching frequency of the power supply.

The input and output capacitors are the only sources (or storages) of the high-frequency current generated by the power switch or output rectifier, so by observing these current waveforms, the current flowing through the ESR of these capacitors can be reasonably determined. This current inevitably generates heat in the capacitor.

The power loss caused by the ESR of the capacitor can be described as follows:

$$P_{D(eas)} \approx I_{SW}^2 \times R_{ESR} \tag{1.3}$$

or

$$P_{D(eas)} \approx I_D^2 \times R_{ESR} \tag{1.4}$$

2. Higher response speed

The response speed is an important performance of the power system, and many electronic products have higher requirements for response speed.

With the continuous increase of the load current variation range, the chip is required to have a high load current tolerance and high transient response speed. The purpose of increasing the operating speed is to improve the output ripple and transient response (output voltage ripple during transient response/overshoot). To increase the speed, it is important to reduce the loop delay, and it is also important to reduce the delay of switching, switching drive circuit, arithmetic capacitor, comparator, etc.

3. Low EMI

The DC-DC converter generates very high current and voltage pulses during the switching process, which cause serious electromagnetic interference (EMI), and it affects the normal operation of the DC-DC converter itself and the surrounding electronic equipment. Therefore, the switching frequency of the DC-DC converter is the main cause of EMI. The higher the switching frequency, the more serious the EMI noise. Reducing $\Delta v/\Delta t$ and $\Delta i/\Delta t$ can effectively suppress the EMI effect of the DC-DC converter. Soft switching technology can be used to reduce $\Delta v/\Delta t$ and $\Delta i/\Delta t$.

Research shows that the EMI effect of DC-DC converters is the most obvious at the switching frequency and its integer multiples. Therefore, we can expand the EMI spectrum to spread the EMI effect, thereby reducing the EMI effect, switching frequency modulation, chaotic modulation technology. After applying this method, the EMI effect of DC-DC converters can be reduced substantially.

1.2 Hysteresis Control Switching Converter

In the field of switching power supply, there are generally two methods to control the DC-DC converter; they are linear control and nonlinear control. Among them, the linear control, such as the voltage mode control and the current mode control, stabilizes the output voltage by using fixed frequency PWM (pulse width modulation) signal to adjust the on and off time of switching elements. The signal is used in a wide range of fields from portable electronic equipment to industrial electronic equipment. In other words, it can be applied from low power output to high power output. The converter with the voltage control mode has the advantages of a relatively simple circuit structure, strong anti-interference ability, and low output impedance ratio. However, its disadvantage is that the response speed to sudden load change is relatively slow; its reason is the delay caused by the frequency characteristic of the error amplifier in the feedback loop. The nonlinear control mode such as lag control has the advantage of high response speed to sudden load change and can be realized by simple circuit configuration.

Hysteresis control can meet the requirements for quick load transient response. This method is also called the ripple control method because it is controlled by detecting the ripple in the output. This method can monitor the output voltage directly through the hysteresis comparator without using the error amplifier. When the output voltage is detected to be above or below the set threshold, the comparator directly turns on / off the switch. Figure 1.1 shows the diagram and figure 1.2 shows the operation waveforms of the hysteresis control buck converter.

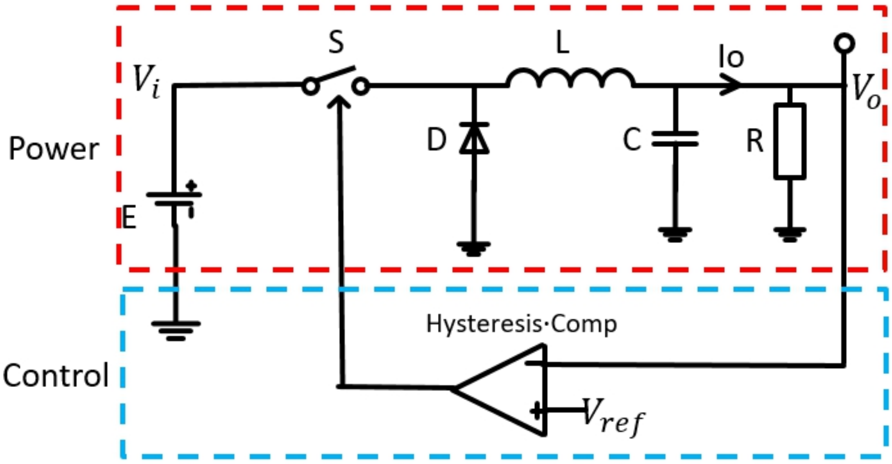


Figure 1.1 Diagram of the hysteresis control buck converter.

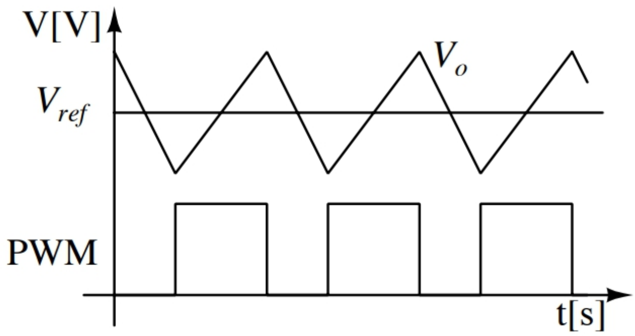


Figure 1.2 Operation waveforms of the hysteresis control buck converter.

The basic operation of the hysteresis control method is explained as the following:

1. When the switching turns off, the output voltage V_o decreases.

2. When the output voltage V_o falls below the reference power supply voltage V_{ref} of the non-inverting terminal, the PWM signal output from hysteresis·comp becomes high with a slight delay and controls the switching turns ON. Then, V_o increases.

3. Repeating the above operation, V_o matches a constant voltage V_{ref}.

2. DC-DC Buck Converter with PWM Control

DC-DC switching converters can be classified by function and operation method, as shown in Figure 2.1. Figure 2.2 shows the basic configuration of the DC-DC switching converter. The DC-DC switching converter can both reduce the input voltage and increase the input voltage, and can also meet the needs of buck/boost.

The operation modes for controlling the output voltage can be divided into Pulse Width Modulation (PWM) and Pulse Frequency Modulation (PFM). PWM provides regulation by adjusting the on/off time ratio with a constant switching period (frequency), while PFM uses a fixed on/off time ratio and variable frequency. Compared with PWM, the output current of PFM is small, but because the DC/DC converter controlled by PFM stops operating when the voltage exceeds the set voltage, the current consumption becomes small. Therefore, the reduction in current consumption can improve efficiency at low load. Although PWM is inferior efficiency at low load, its ripple voltage is small and the switching frequency is fixed, so it is easier to design the noise filter and eliminate noise. Similarly, current mode, voltage mode, and hysteresis (or ripple or comparator) control modes are feedback control methods that can be used to adjust the output.

The switching converter is configured by a combination of these elements. The best combination must be selected based on the expected application, input/output conditions, design specifications and performance goals, cost, size, and other constraints to be met. Designers need to understand the characteristics, advantages, and disadvantages of each element. We hope to combine various factors to design a switching converter with low noise, high efficiency, low cost, compactness, small ripple, low power consumption, and fast response speed.

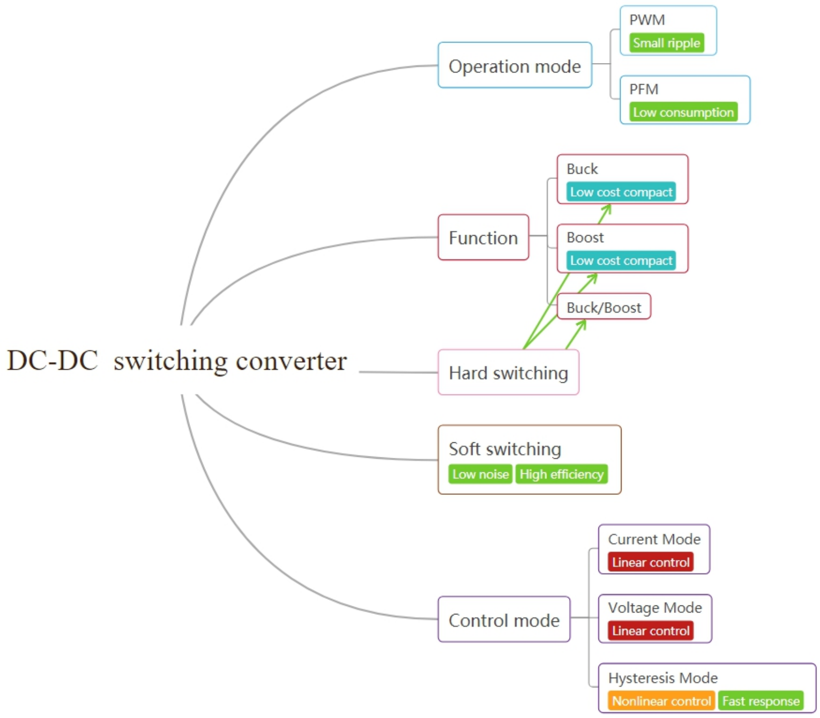


Figure 2.1 Performance of DC-DC switching converter.

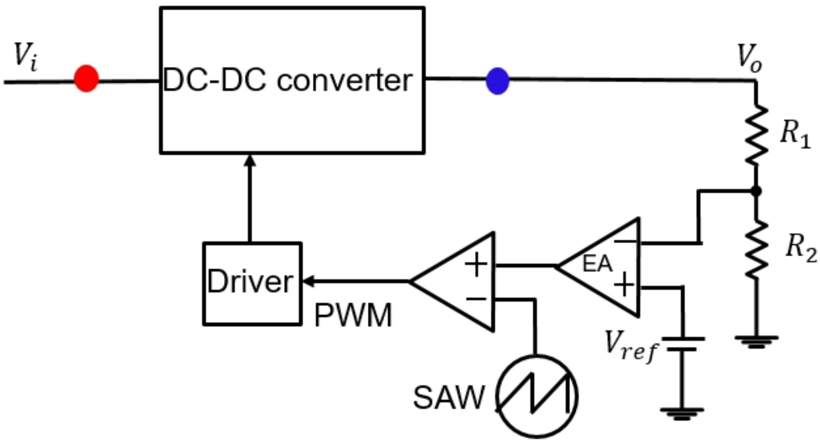


Figure 2.2 Basic configuration of the DC-DC switching converter.

2.1 Operation of DC-DC Buck Converter

This section discusses the operation of the basic DC-DC Buck converter. Figure 2.3 shows the schematic diagram of the buck converter. When the PWM signal controls the CMOS Q to turn on, the diode D is disconnected and the capacitor C is charged. Figure 2.4 shows the buck converter in switching on. At this time, V_{Lon} could be described as following:

$$V_{Lon} = V_{in} - V_o = L \times (\Delta I_{L+} / \Delta T_{on}) \tag{2.1}$$

When Q is turned off, the diode D is conducting and the capacitor C is discharged. Figure 2.5 shows the buck converter in switching off. At this time, V_{Loff} could be described as following:

$$V_{Loff} = -V_o = L \times (\Delta I_{L-} / \Delta T_{off}) \tag{2.2}$$

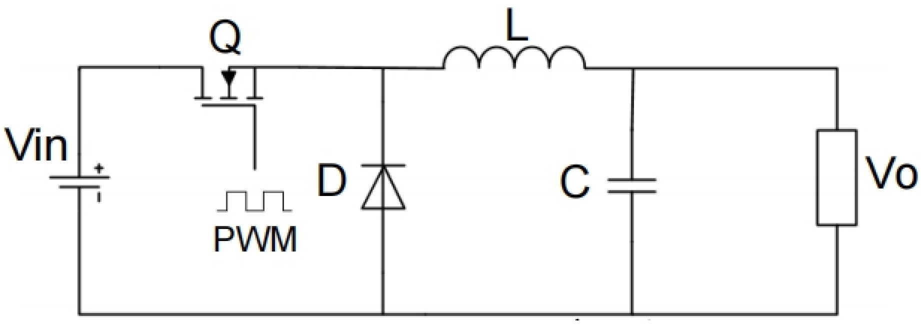


Figure 2.3 Circuit of buck converter.

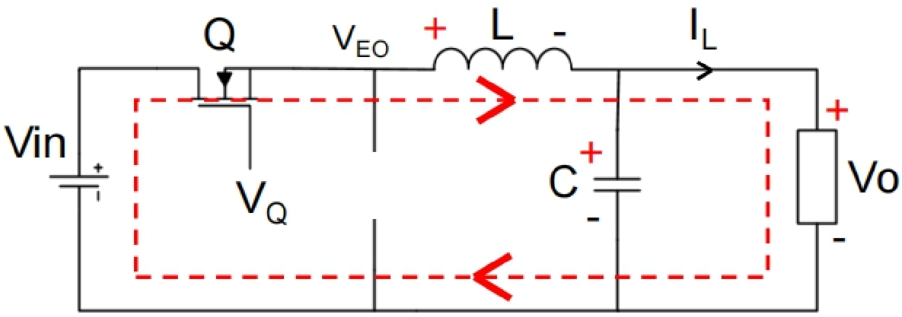


Figure 2.4 Switching on.

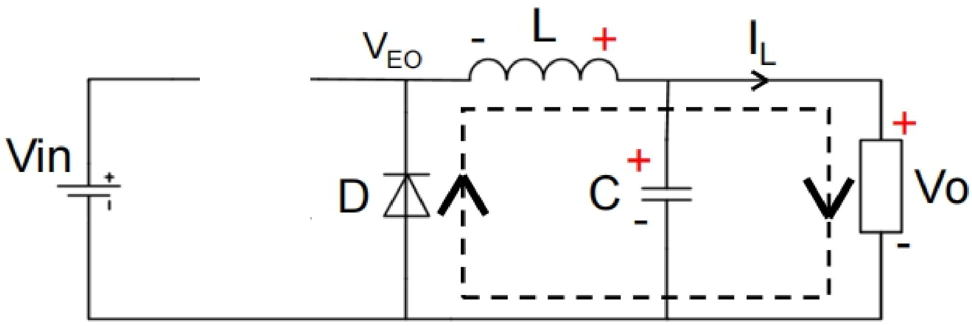


Figure 2.5 Switching off.

Figure 2.6 shows the main waveforms of the DC-DC buck converter. The switch is controlled by a PWM signal, which is composed of the operational amplifier, comparator, and reference voltage source. When the PWM signal is in a high-level state, the switch is on, the inductance current I_L flows into C_o and R_L, and the output voltage V_o increases. When PWM is in the low-level state, the switch is closed and the inductance current I_L flows through D_i. Simultaneously, its current value decreases, and the output voltage V_o decreases. The output voltage V_o is compared with the reference voltage V_r and amplified to obtain the amplified error voltage ΔV. The PWM is generated by comparing the error voltage ΔV with the saw.

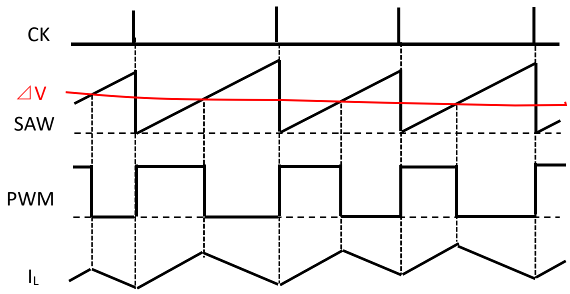


Figure 2.6 Waveform of DC-DC buck converter.

2.2 Features of DC-DC Buck Converter

Figure 2.7 shows the simulation waveforms of DC-DC buck converter, Figure 2.8 shows the simulated spectrum of PWM in DC-DC buck converter, and Figure 2.9 shows the output ripple during the transient response of the output voltage V_o when the output current I_o increases from 0.25A to 0.5A which is about 30mV. However, the output voltage ripple ΔV_o is not affected by the increase in output current I_o which is stable at 5.4mV. Table 2.1 shows the main component parameters of the simulation circuit.

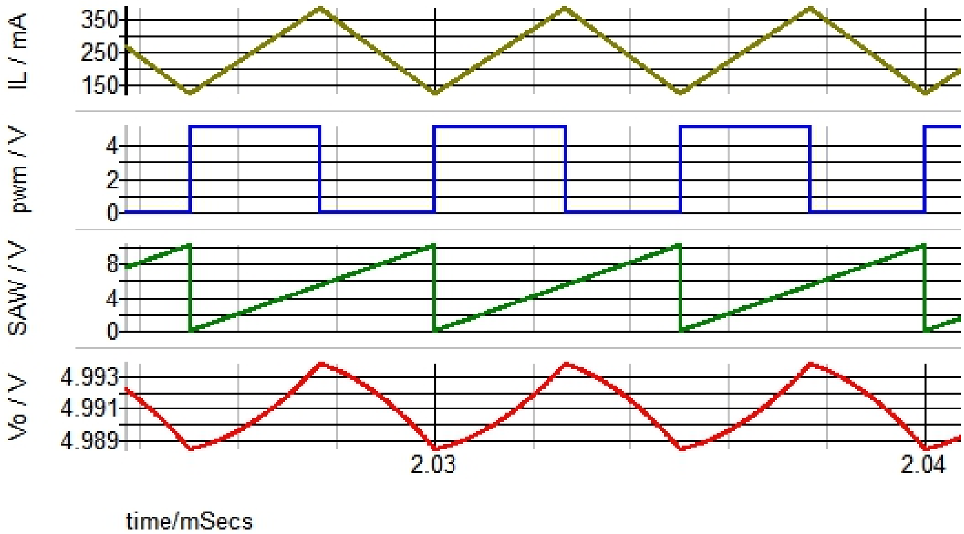


Figure 2.7 Simulation waveforms of DC-DC buck converter.

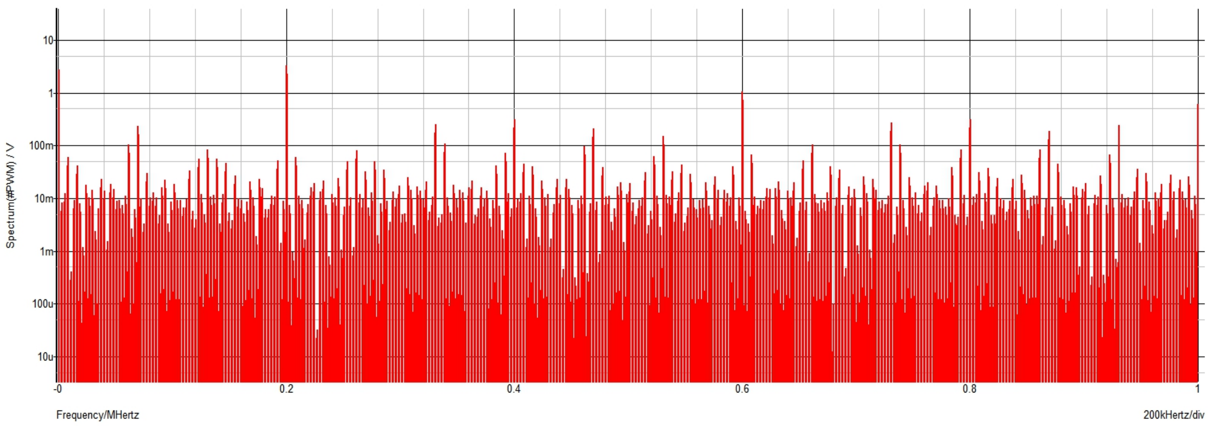


Figure 2.8 Simulated spectrum of PWM in DC-DC buck converter.

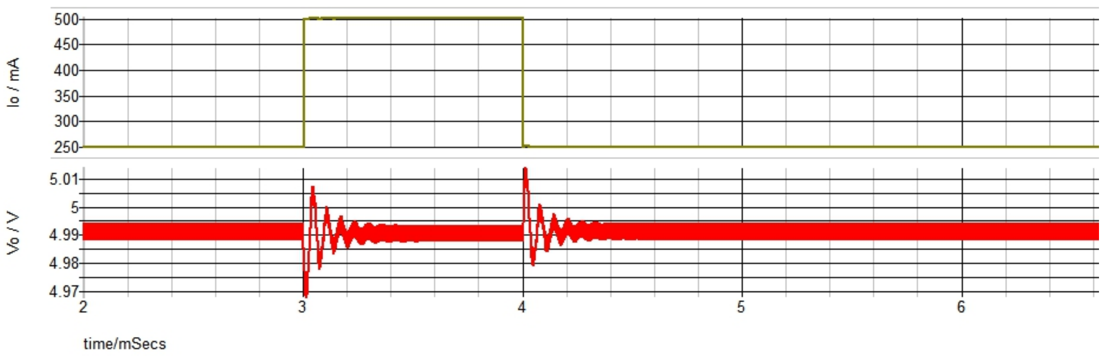


Figure 2.9 Output ripple during transient response of the output voltage.

Table 2.1 Parameter values of the simulation circuit

V_i	V_o	I_o
10V	5V	0.25A
L	C	T_{ck}
50μH	100μF	5.0μs

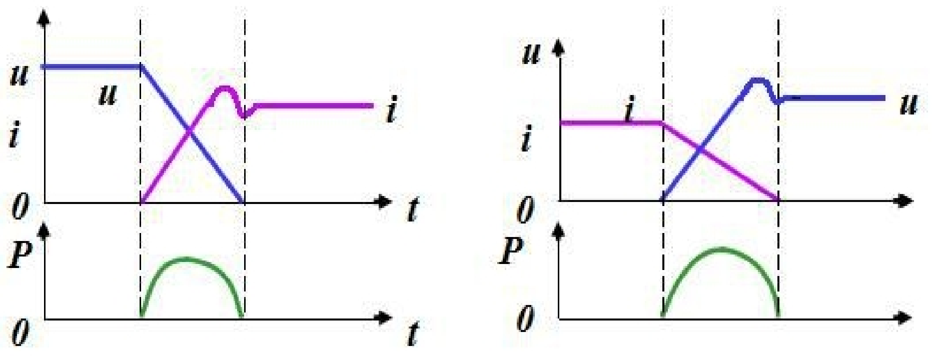
3. Soft-Switching DC-DC Converter

3.1 Soft Switching and Hard Switching

The development of modern electronic equipment tends to be miniaturized and lighter, simultaneously there are also higher requirements for efficiency and electromagnetic compatibility. On the other hand, the high frequency of electronic equipment has led to an increase in switching loss and electromagnetic interference. Therefore, we have adopted soft switching technology to reduce the loss and noise of the switch, while further increasing the switching frequency.

3.1.1 Hard switching

The voltage and current of the hard switching are not zero in the actual switching process, and there is overlap. Simultaneously, because the voltage-current changes too fast, the waveform appears obvious overshooting phenomenon, which leads to the generation of the switching noise. Figure 3.1.6 shows the waveform diagram of the hard switch during opening and closing.

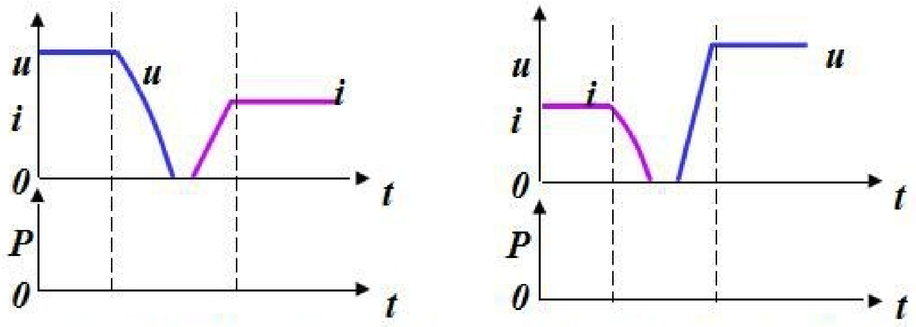


A) Opening of hard switching   B) Closing of hard switching

Figure 3.1 Waveforms of hard switching.

3.1.2 Soft switching

Unlike hard switching, soft switching adds inductance, capacitance, and other resonant elements to the original circuit, and resonance is introduced before and after the switching process to eliminate the overlap of voltage and current, thus reducing switching loss and switching noise. Figure 3.2 shows the waveform diagram of the soft switch during opening and closing.



A) Opening of soft switching   B) Closing of soft switching

Figure 3.2 Waveforms of the soft switching

3.1.3 Zero voltage switch and zero current switch

1． Zero voltage opening

Before the switch is turned on, its voltage is zero, no loss, and noise will be generated when it is turned on.

2．Zero current closing

Before the switch is closed, its current is zero, and no loss and noise will be generated when it is closed.

3．Zero voltage closing

The capacitor connected in parallel with the switch can delay the voltage rise rate after the switch is turned off, thereby reducing the loss of turn-off

4．Zero current opening

The inductance connected in series with the switch can delay the current rise rate after the switch is turned on, and reduce the turn-on loss

The above is achieved through resonance in the circuit.

3.2 Operation of Full-Wave Soft-Switching DC-DC Converter

To regulate the output of a switching converter, negative feedback control is generally used. Figure 3.3 shows the full-wave resonant converter in the voltage mode presented in this thesis. The power-stage consists of the main switch SW (usually MOSFET) with the body diode D_b, the free-wheel diode D_o, the main inductance L_o, the main capacitance C_o and the resonant elements which are denoted as L_r, C_r, and D_r, respectively. The output voltage V_o is compared with the reference voltage V_{ref} and the voltage error is amplified to be compared with the saw-tooth signal SAW. This SAW signal is generated by the trigger, which is provided by comparator 2 as the comparison result between the resonant voltage V_r and the free-wheel diode voltage V_d. Therefore, when V_r goes across V_d, the SAW signal starts to rise.

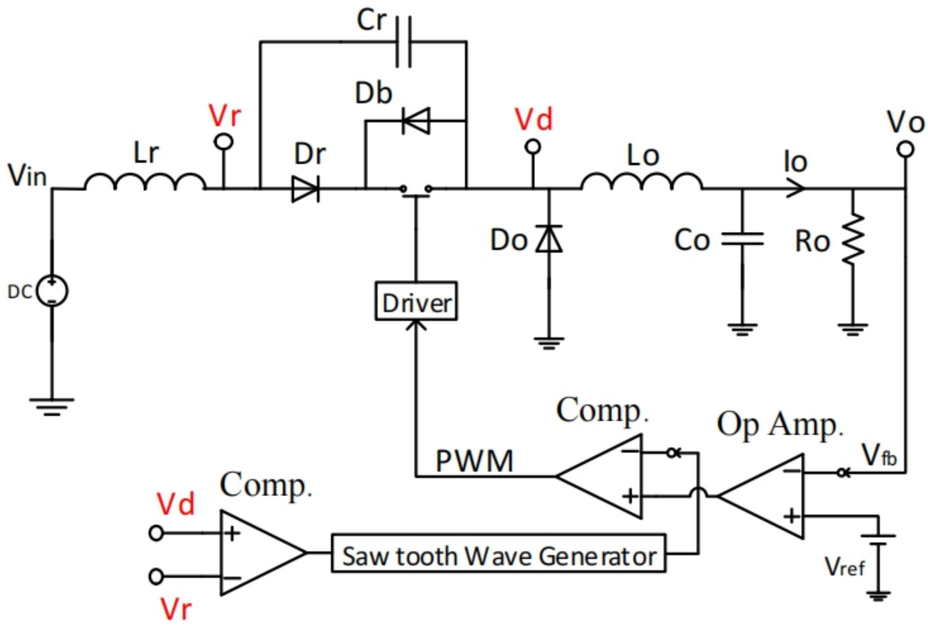


Figure 3.3 Resonant converter with full-wave.

Figure 3.3 shows a resonant converter configuration and its operation is as follows:

(1) When SW turns OFF, V_d goes to 0.0 V from V_i, and C_r is charged.

(2) Then L_r, C_r goes resonant and V_r rises up and down.

(3) After V_r goes down under V_d which is about 0.0 V, SW turns ON, but D_r blocks the forward current through SW.

(4) Therefore, V_r goes the negative voltage and returns to higher than V_d.

(5) Then SW flows the current through D_r.

(6) V_d rises and D_o turns OFF.

Figure 3.4 shows the ideal waveforms of full-wave resonant and Figure 3.5 shows the simulation waveforms of the resonant converter with full-wave. In Figure 3.3, we see that the SW turns off before C_r rises. When C_r becomes minus, SW turns on when both sides of it are equipotential. Table 3.1 shows the operating parameters of the resonant converter with full-wave.

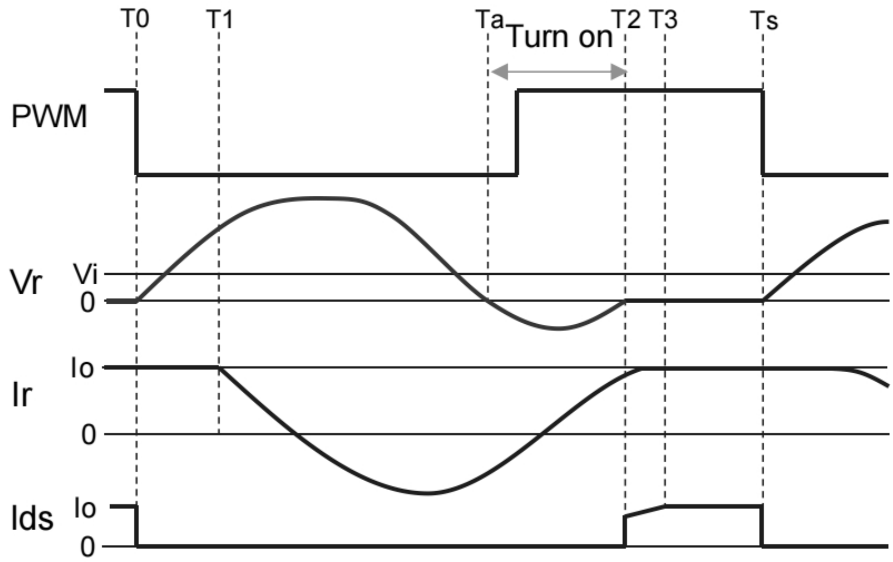


Figure 3.4 Waveforms of the resonant converter with full-wave.

Table 3.1 Operating parameters of the resonant converter with full-wave

V_i	V_o	I_o
10V	5V	0.25A
L_r	C_r	F_{op}
50μH	500pF	471kHz
L_o	C_o	R_o
50μH	470μF	20Ω

The operating frequency of the soft-switching power supply has a great relationship with the frequency of the resonance circuit. The frequency of the resonance circuit F_{res} can be described as the following:

$$F_{res} = \frac{1}{2\pi\sqrt{LC}} \tag{3.1}$$

F_{op} can be described as the following:

$$F_{op} = F_{res} \times (1 - D_{PFM}) \tag{3.2}$$

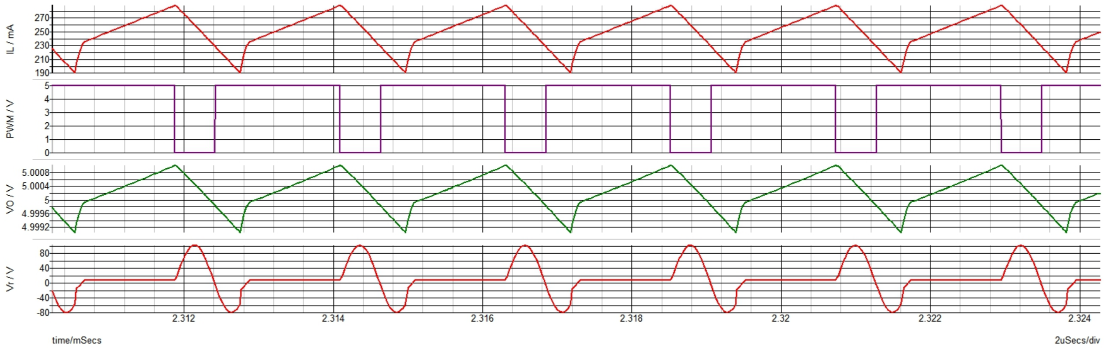


Figure 3.5 Simulation waveforms of the resonant converter with full-wave

3.3 Operation of Half-Wave Soft-Switching DC-DC Converter

The difference between the half-wave resonant converter and the full-wave resonant converter in the circuit is that the diode D_r is removed. Figure 3.6 shows the circuit structure of the half-wave resonant converter and Figure 3.7 shows the simulation waveforms of the half-wave resonant. Table 3.2 shows the operating parameters of the resonant converter with half-wave

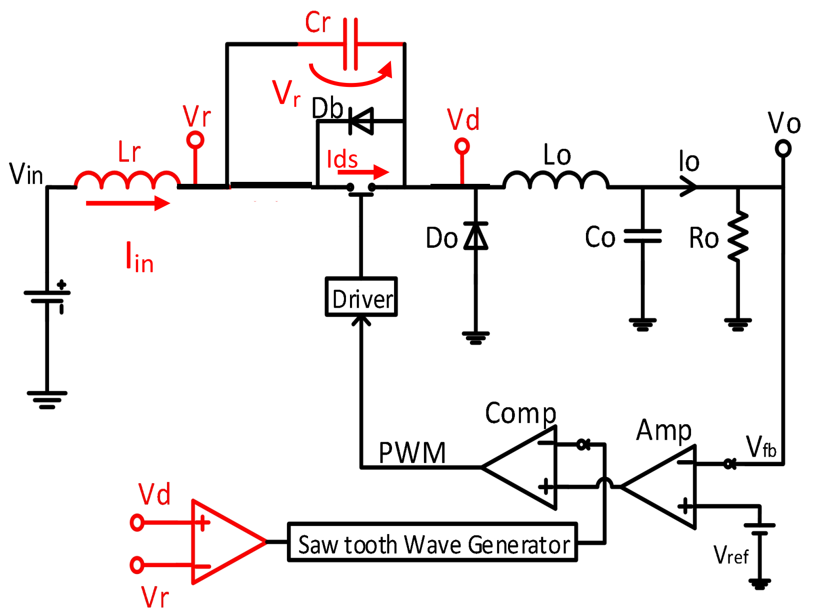


Figure 3.6 Resonant converter with half-wave.

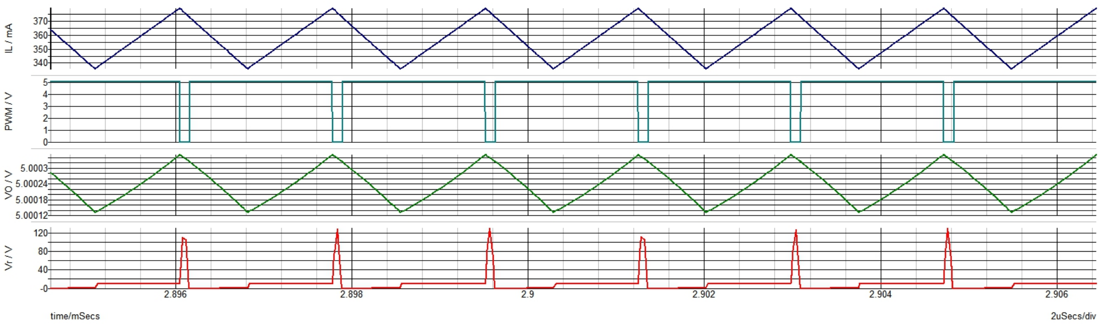


Figure 3.7 Simulation waveforms of the half-wave resonant

Table 3.2 Operating parameters of the resonant converter with half-wave

V_i	V_o	I_o
10V	5V	0.35A
L_r	C_r	F_{op}
10μH	100pF	576kHz
L_o	C_o	R_o
100μH	470μF	14Ω

The resonance and the major signals are explained as follows:

(1) When SW turns on, the resonance voltage V_r increases and goes down through the peak voltage. When V_r decreases, the input current I_{in} flows reversely.

(2) When V_r equals to V_{Do}, The body diode D_b turns on and the resonance stops. Simultaneously, the reverse current I_{in} is provided by D_o. On the other hand, the comparator detects V_r equals to V_D and triggers the SAW generator. SW opens to implement zero voltage switching (ZVS) operation.

(3) The current I_{in} turns to flow forward direction, D_o turns off, and the current I_L flows. Then V_o is increased, and finally, the PWM pulse is turned off.

3.4 Features of Half/Full-Wave DC-DC Converter

Figure 3.8 shows the main output waveforms of the full-wave DC-DC converter when the output current I_o gradually increases from 0.25A to 1.5A (the increased value ΔIo is 0.25A). Figure 3.9 and Figure 3.10 shows the ripple of output voltage V_o with different I_o. We can see that in the full-wave converter, the current increase of I_o does not affect the peak value and the frequency of the saw-tooth signal which is 451kHz when I_o is 0.25A, when I_o becomes 1.5A, the frequency of the saw-tooth signal is 397kHz, nor does it affect the ripple of the output current which has been stable at about 2mV. The maximum output ripple during transient response is 9mV, and the value of the resonance voltage V_r is proportional to the output current I_o, showing a high-voltage form, and its value is between 100V and 500V.

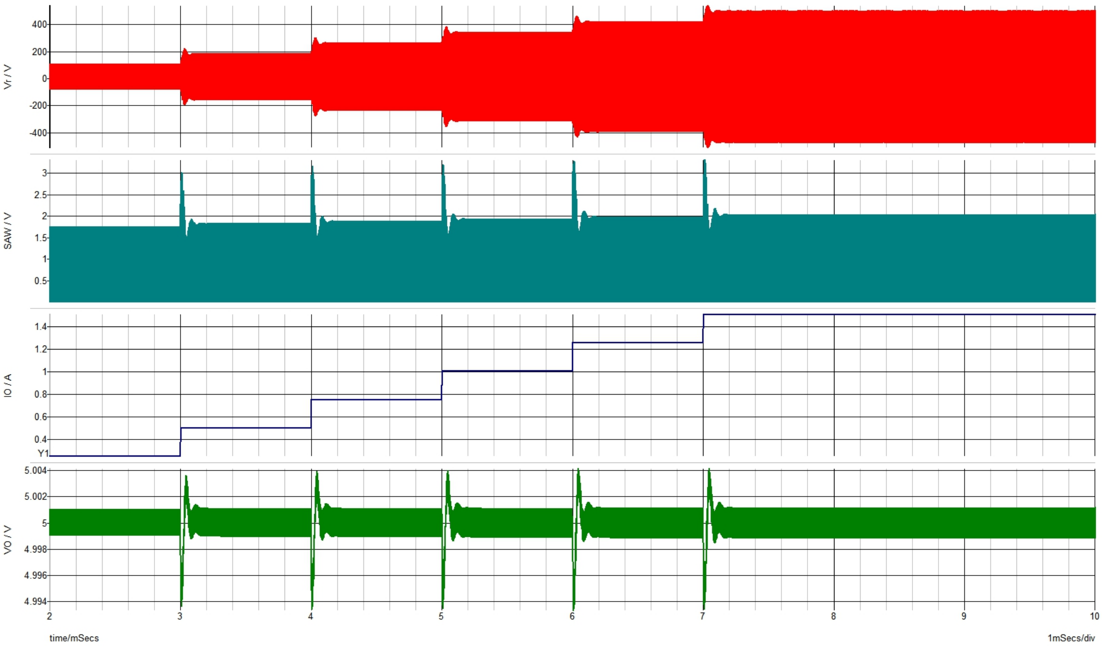


Figure 3.8 Simulation waveforms of the full-wave resonant with increased I_o.

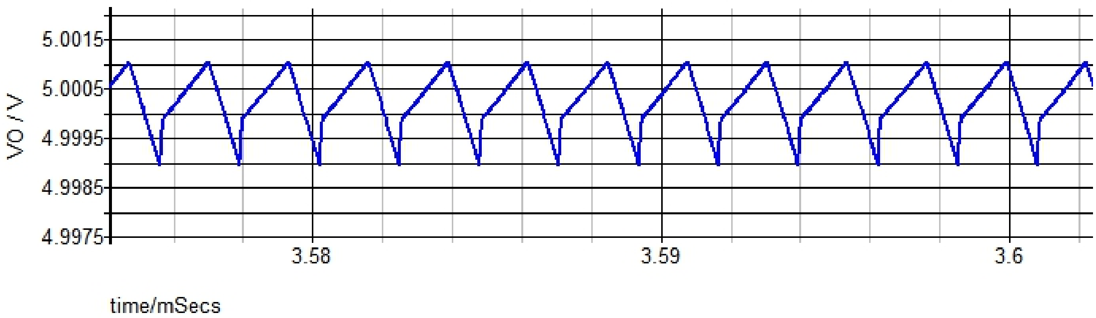


Figure 3.9 Ripple of the output voltage V_o(I_o=0.25A) in full-wave resonant.

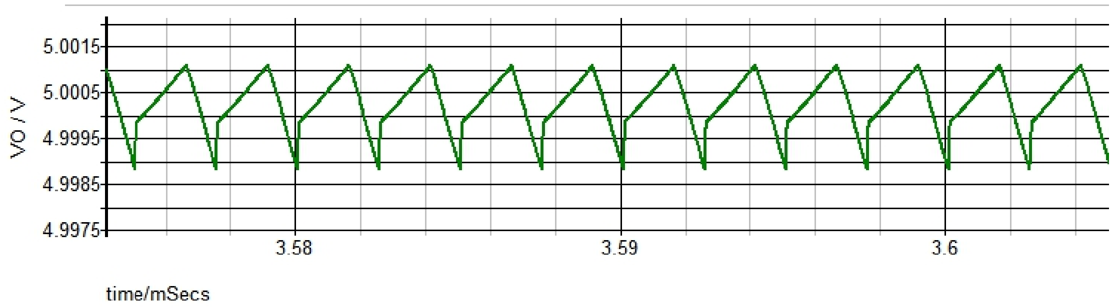


Figure 3.10 Ripple of the output voltage $V_o(I_o=1.5A)$ in full-wave resonant.

Figure 3.11 shows the main output waveforms of the half-wave DC-DC converter when the output current I_o gradually increases from 0.35A to 1.6A (the increased value ΔIo is 0.25A). We can see that in the half-wave converter, the current increase of I_o does not only affect the peak value and frequency of the saw-tooth signal which has been decreased from 576kHz (when I_o is 0.35A) to 141kHz(when I_o is 1.6A), but also the ripple of the output voltage, which expands from 0.21mV(when I_o is 0.35A) to 0.85mV(when I_o is 1.6A). The maximum output ripple during transient response has also increased from 5mV to 11mV. The value of the resonance voltage V_r is proportional to the output current I_o, presenting a high-voltage form, and its value is between 100V and 550V.

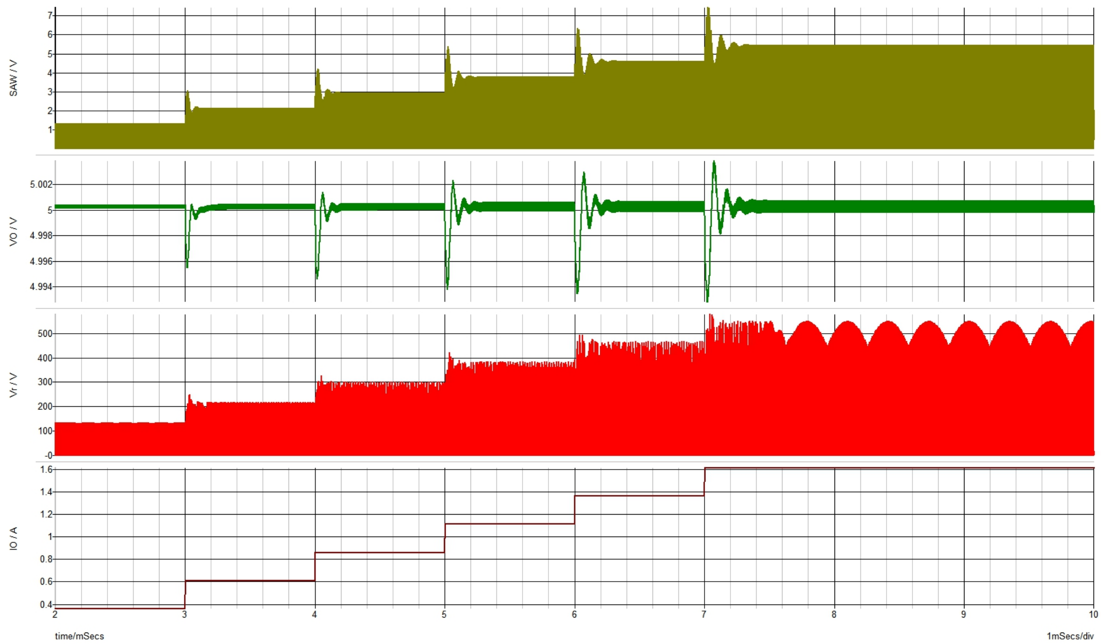


Figure 3.11 Simulation waveforms of the half-wave resonant with increased I_o.

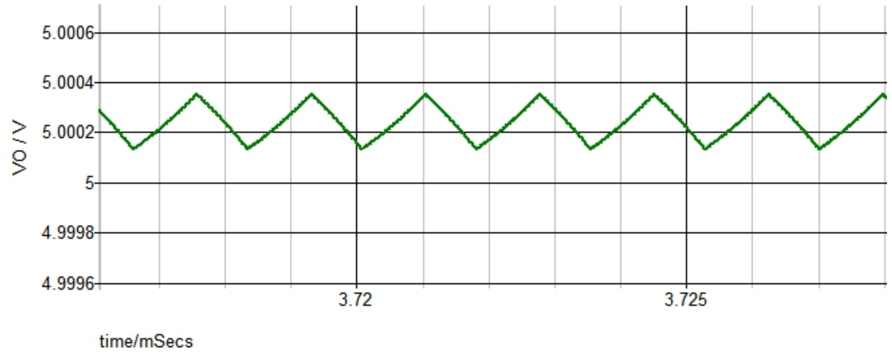


Figure 3.12 Ripple of the output voltage $V_o(I_o=0.35A)$ in half-wave resonant.

Figure 3.13 Ripple of the output voltage $V_o(I_o=1.6A)$ in half-wave resonant.

4. Multi-Phase Full-Wave Soft-Switching DC-DC Converter

4.1 Dual-Phase Soft-Switching DC-DC Converter

Figures 4.1 and 4.2 shows the circuit configuration of our proposed self-excited two-phase converter with voltage resonant switch control and the simulated waveforms of the dual-phase soft-switching DC-DC converter. Since the two-phase converter is always realized by moving the phase of the fixed frequency clock, another PWM signal with phase lag can be easily generated. However, the self-excitation converter does not have a fixed clock. The signal pwm1 is the result of the comparison between the resonant voltage V_r and the freewheeling diode voltage V_d. Then, half of the peak holding voltage is detected and compared with SAW1 to generate a 180° shifted SAW2, thus generating PWM2, thus realizing two-phase control of the self-excited converter. Figures 4.3 and 4.4 show the output voltage ripple in single-phase and dual-phase converters, respectively. In a single-phase converter, when the output voltage is 3V, the generated ripple is 0.26mV and the frequency is 567KHz; in a dual-phase converter, under the same output voltage, the generated ripple is 0.10mV and the frequency is 1.98MHz, reducing by 61.5%.

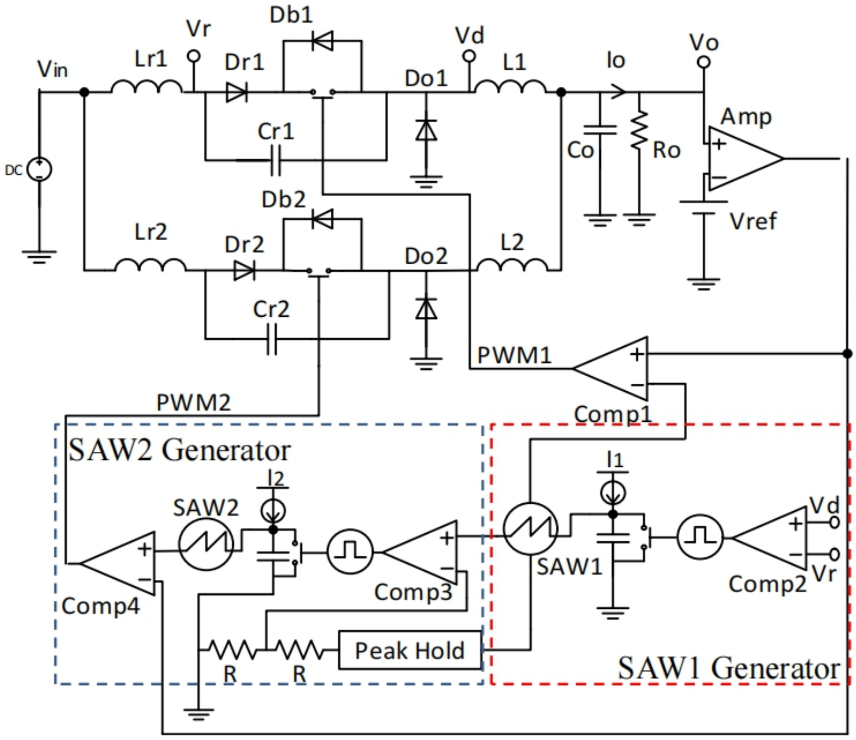


Figure 4.1 Proposed two-phase circuit configuration.

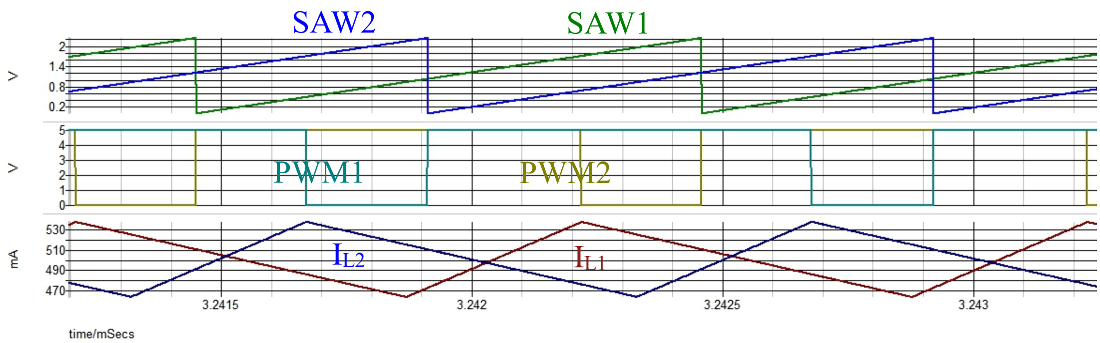


Figure 4.2 Simulated waveforms of the dual-phase soft-switching DC-DC converter.

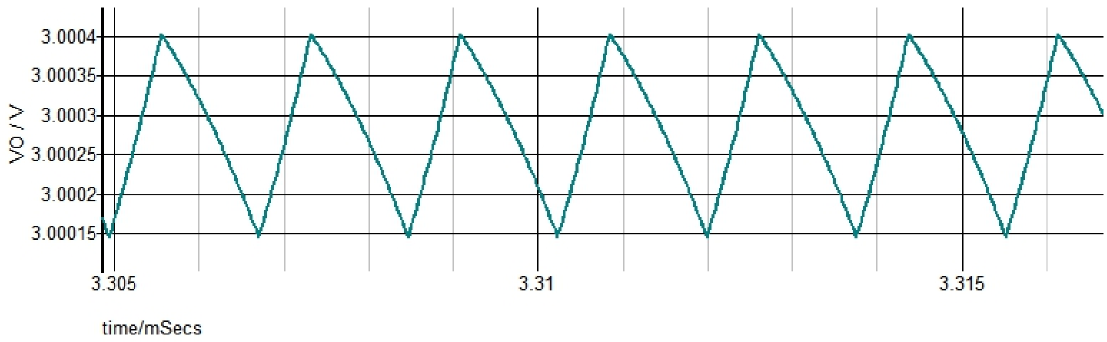


Figure 4.3 Ripple of output voltage in the single-phase converter.

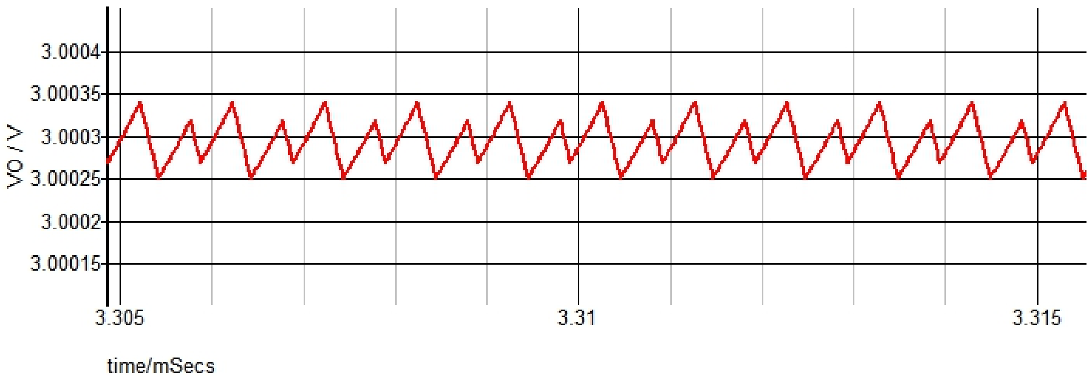


Figure 4.4 Ripple of output voltage in the dual-phase converter.

4.2 Features of Dual-Phase Soft-Switching DC-DC Converter

Figures 4.5 and 4.6 show the excessive response waveforms produced by the output voltage V_o of the single-phase and dual-phase converters when the output current I_o increases from 1A to 2A($\Delta I_O = 0.5A$). Among them, in the single-phase converter, the maximum output ripple during transient response is 5.5mV; in the two-phase converter, the maximum output ripple during transient response is 2.4mV. When the output current reaches 2A, the output voltage ripple has no change; however, the output voltage ripple in the single-phase converter is increased from 0.26mV to 0.47mV.

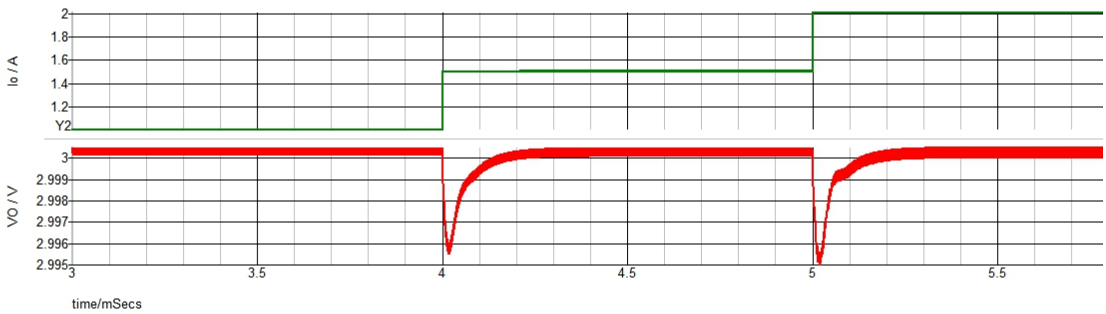


Figure 4.5 Waveforms of single-phase converter (I_O=1.0A~2.0A).

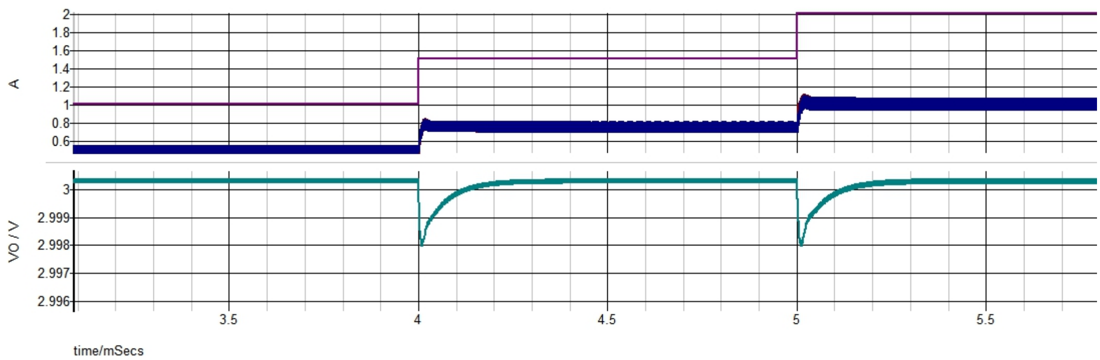


Figure 4.6 Waveforms of the dual-phase converter (I_O=1.0A~2.0A).

4.3 Four-Phase Soft-Switching DC-DC Converter

Figure 4.7 shows the main structure of the four-phase converter. Among them, the three sub-converters have the same structure as the main converter, and the PWM signal generation principle of the four-phase converter is roughly the same as that of the dual-phase converter. The difference is that the four-phase converter divides V_p into four parts. As shown in Figure 4.8, the input comparator generates four SAW signals with a 90° delay. The final PWM signal is used to control each switch of the sub-converter.

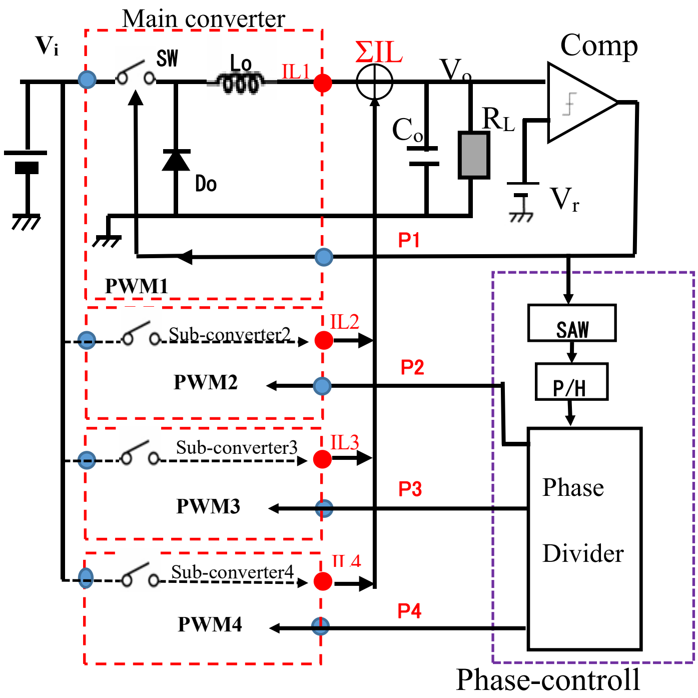


Figure 4.7 Four-phase converter.

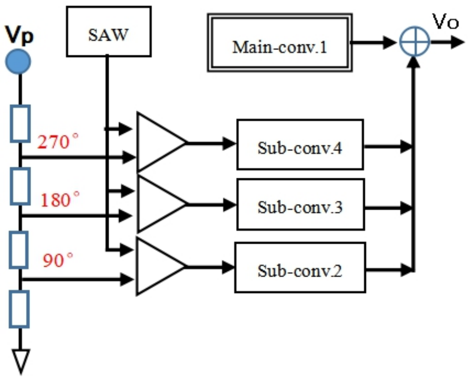


Figure 4.8 Voltage divider and comparison circuit.

Figures 4.9 shows the simulated waveforms of the four-phase converter. It can be seen that the output currents have a good balance (ΣI_L=1A). Figure 4.11 shows the ripple of the output voltage, which is about 0.25mV.

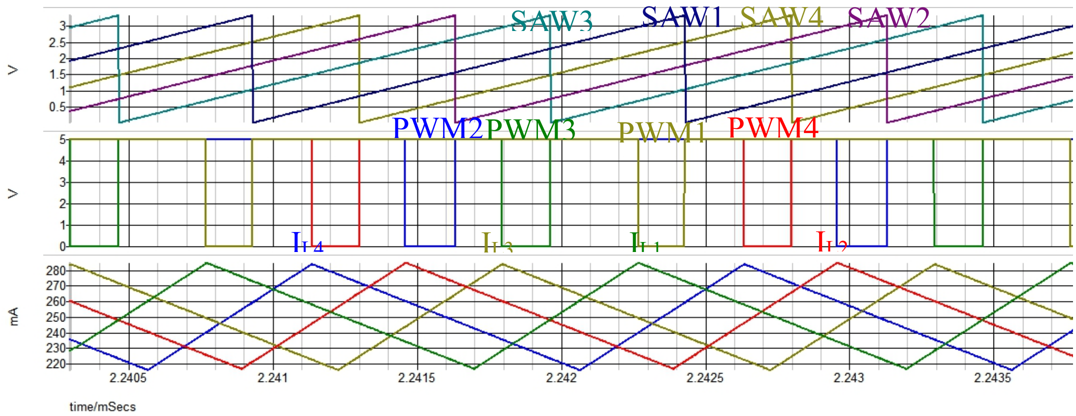


Figure 4.9 Simulated waveforms of the four-phase soft-switching DC-DC converter

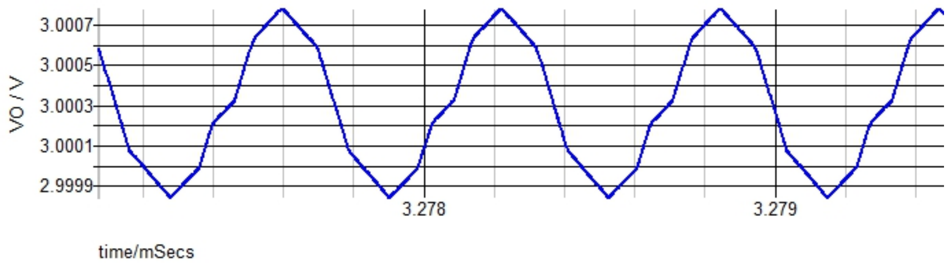


Figure 4.10 Ripple of output voltage in the four-phase converter

4.4 Features of Four-Phase Soft-Switching DC-DC Converter

The following mainly discusses the excessive response of the four-phase converter. Figure 4.11 shows the corresponding output voltage waveform and the current waveform between phases when the current ΣI_L gradually increases from 1A to 3A ($\Delta I = 0.5A$). It can be seen that the ripple of the output voltage has increased from 0.25mV to 3mV, and the output ripple during transient response has also increased from 5mV to 13mV. Compared with the dual-phase converter, under the similar operating frequency ($F_{OP} = 373KHz$) and output voltage ($V_O = 3V$), the four-phase converter still has a better balance when the current I_L reaches 2A to 2.5A, and the excessive response is not obvious. When the current reaches more than 3A, the current between the phases appears imbalanced, and the output ripple during transient response also reaches a higher than 13mV, and as shown in Figure 4.12 the ripple of the output voltage reaches 3mV.

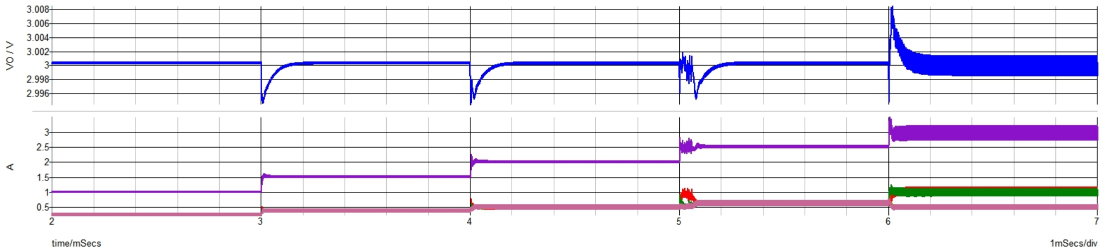


Figure 4.11 Waveforms of the four-phase converter (I_O=1.0A~3.0A).

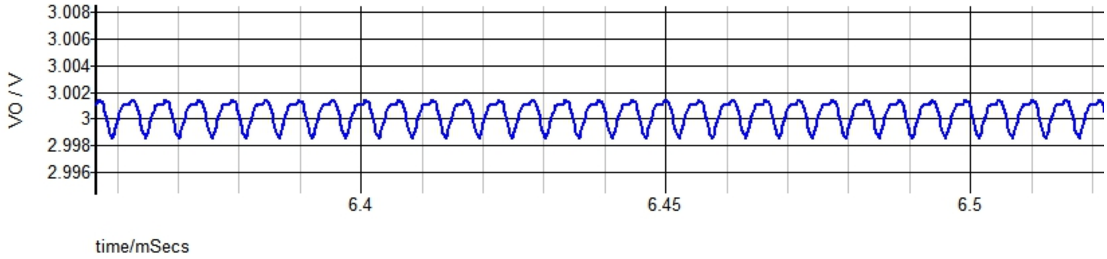


Figure 4.12 Ripple of the output voltage in the four-phase converter(I_O=3.0A)

5. Automatic Current Balance

In precision circuits, due to temperature changes or EMI, the property values of some electronic components, such as capacitors, inductors, and other components, may change. Once the attribute value of the component is changed, the inductor current is likely imbalanced. The factor that causes the inductor current I_L to vary is the manufacturing variation of L_r and C_r for resonance. To balance this current, L_r and C_r are usually selected and manufactured. The imbalance of the current output causes heating or even damage of semiconductor switches or energy storage components, which greatly affects the stability of the circuit. Because of this, we have developed an automatic current balance circuit, which can automatically correct when the switching power supply circuit produces imbalanced output, to ensure the current output balance, thereby achieving the goal of stabilizing the circuit.

5.1 Automatic Balance of Multi-Phase Inductor Current

Figure 5.1 shows the circuit of the automatic current balance, which consists of the operational amplifier and the current correction part. The difference between two inductor currents, I_{L1} and I_{L2}, is amplified and its output controls the bias voltage of the voltage divider circuit which sets the 180-degree for the sub-converter.

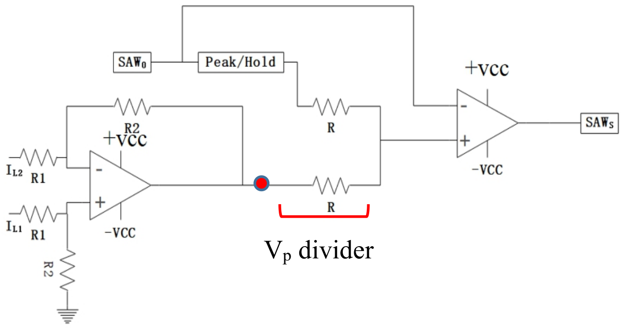


Figure 5.1 Circuit of automatic current balance for dual-phase converter.

Figure 5.2 shows the simulation result of the dual-phase converter with the element variation of L_{r1} which equals to +10% when the element variation of C_{r1} is zero. The current balance is not good and the imbalance ratio of the current variation of I_{L1} becomes +27.3% when the output current I_o is 5A. Of course, when the elements of the inductor/capacitor of the sub-converter are variant, the current balance is in reverse relation. Once the current of the output inductor current is imbalanced, it is usually necessary to select the corresponding inductor, which causes the volume of the inductor to become larger, and the manufacturing cost increases, and the efficiency of the circuit becomes also low.

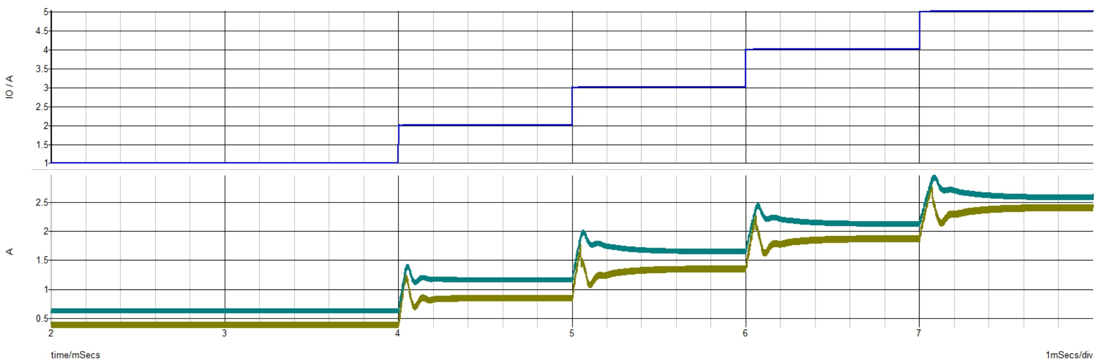


Figure 5.2 Imbalance of output current in the dual-phase converter.

Figure 5.3 shows the simulation result with the automatic current balance circuit for the characteristics of Figure 5.2. The current balance is wonderful and the current imbalance ⊿I is 1.2mA and the ratio is 0.4% when I_o is 5A.

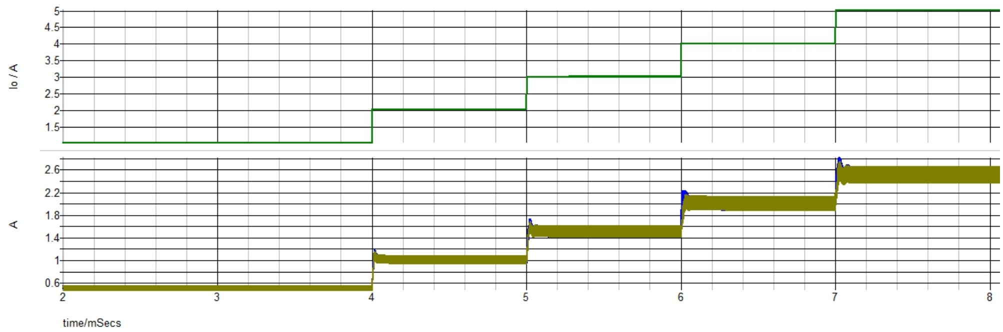


Figure 5.3 Balance of the output current dual-phase converter.

Figure 5.4 shows the automatic current balance circuit for the four-phase converter, which consists of the current detectors of I_{L1} and ΣI_{L2}~I_{L4} and the amplifier. The output of the amplifier controls the bottom level of the V_p divider and modifies the phases of the sub-converters.

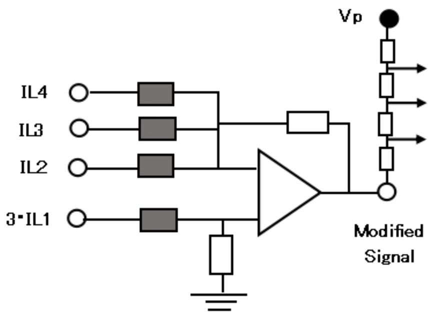


Figure 5.4 Circuit of the automatic current balance for four-phase converter.

Figure 5.5 shows the current imbalance result of the four-phase resonant converter with the 10% variation of L_{r1}. The average current of four-phase converter I_L should be 1.5A. According to Figure 5.5, I_{L1} is 2.85A, which means the imbalance ratio of the current variation of I_{L1} becomes +90% when the output current I_o is 6A.

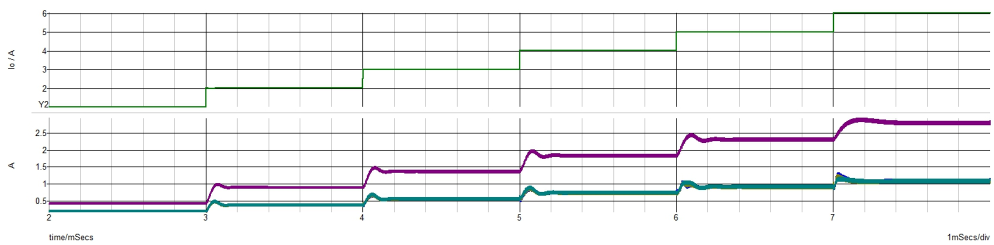


Figure 5.5 Imbalance of the output current four-phase converter.

Figure 5.6 shows the simulation result of the four-phase converter with the automatic current balance circuit. The current imbalance is less than ±0.01A (0.06%) when the output current I_o is 6A.

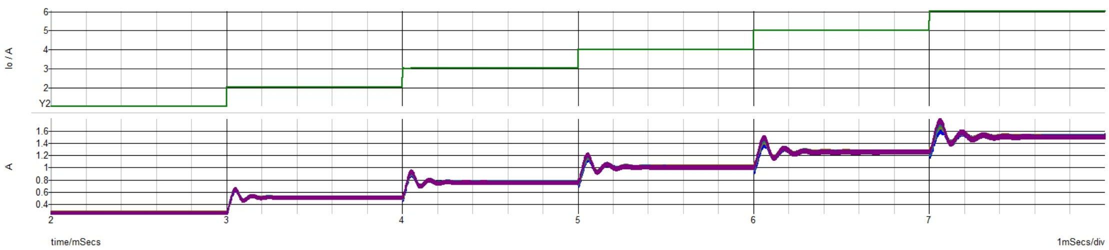


Figure 5.6 Balance of the output current four-phase converter.

6. Conclusion

6.1 Conclusion

This thesis introduces dual-phase/multi-phase DC-DC buck converters based on soft-switching technology and discusses the operation principles of full-wave and half-wave buck converters. Simultaneously, an automatic current balance technology is proposed, which can automatically correct the output current imbalance caused by the output inductance and capacitance changes.

In Chapter 1, we introduced the research background of DC-DC buck converters. Based on this background, we have noticed the research direction of DC-DC buck converters. We proposed that the objectives of this research are the multi-phase processing of switching power supplies based on soft switching and proposed automatic current balancing technology to control the balance of output current.

In Chapter 2, we reviewed the functions and operations of basic DC-DC switching converters and sorted out the characteristics of various switching power supplies based on previous studies. Among them, the advantages of buck, boost, and buck-boost converters are high efficiency, low cost, and compact structure. Besides, we mainly discussed the buck converter based on the PWM signal and simulated it. In the simulation results, we can see that when the output current changes, the output voltage has a transient response. On the other hand, we give the specific parameters of the circuit and show the spectral characteristics.

In Chapter 3, we first discussed the advantages and disadvantages of soft switching and hard switching. Among them, soft switching can effectively reduce switching loss and noise compared to hard switching. Secondly, we proposed full-wave and half-wave DC-DC buck converters based on soft switching, discussed their basic operation principles, and simulated them. In a full-wave DC-DC converter, as the output current increases, the transient response of the output voltage also increases, but it does not affect the ripple of the output voltage and the frequency and the peak value of the SAW signal. Simultaneously, the voltage of V_r is high. On the other hand, in the half-wave DC-DC converter, the frequency of the SAW signal decreases with the increase of the output current, meanwhile, the ripple and transient response of the output voltage also increases to a certain extent. Consistent with the full-wave converter, V_r also has a large voltage value.

In Chapter 4, we proposed a multi-phase DC-DC converter structure based on full-wave soft switching. Among them, in the dual-phase structure, we use the peak hold circuit to generate a SAW2 signal with a delay of 180° and use this to drive the second-stage converter to produce a dual-phase output. In the simulation results, the output ripple of the dual-phase DC-DC converter is reduced by 61.5% compared to the single-phase. Simultaneously, when the output current changes, the corresponding transient response of the dual-phase converter is reduced by 56.3% compared with the single-phase, there is better stability. In the four-phase structure, we also generate three SAW signals through the peak hold circuit, each of which has a 90° delay between them, and controls the three sub-converters respectively. Through simulation, the output voltage ripple of the four-phase structure is reduced by 60.5% compared with the single-phase structure. At the same time, when the output current gradually increases, the corresponding transient response is also significantly improved.

In Chapter 5, we consider that in the multi-phase structure, the influence of the manufacturing process and the operating environment of the circuit may cause the inductance and capacitance in the circuit to be changed. This change results in an imbalanced output current, which means an imbalanced current between phases. Therefore, we propose an automatic current balance circuit, which is a negative feedback regulation structure. In the dual-phase structure, we input the dual-phase current I_{L1} and I_{L2} into the comparator, and then compare it with the SAW1 signal processed by the voltage divider circuit and the peak hold circuit to generate a modified SAW2 signal to correct phase current. In the simulation results, when the input inductance changes by 10% and the output current reach 5A, the imbalance rate of the phase-to-phase current reaches 27.3%. Through the correction of the current balance circuit, the error of the phase-to-phase current is reduced to 0.4%. Different from the dual-phase structure, in the four-phase structure, we compare the three-phase currents with three times the I_{L1} and output them through the voltage divider circuit to correct the respective SAW signals. In the simulation results, when the input inductance changes by 10% and the output current reach 6A, the imbalance rate of the phase-to-phase current reaches a larger 86%. Through the automatic current balance circuit, we control the phase-to-phase current error to 0.06%, showing good stability.

6.2 Items for Future Study

In the full-wave and half-wave soft-switching converters proposed in Chapter 3, we also need to consider a problem, that is, when the output current is large, such as 30A, according to the simulation, the V_r in the input structure will reach thousands of volts, which is unrealistic in the actual application environment. Because of this problem, we can improve it through methods such as active clamping, which requires future discussion.

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List of Published Papers

[1] Chen-Hao Zhang, Yi-Fei Sun, Tran Minh Tri, Yasunori Kobori, Anna Kuwana, Haruo Kobayashi, "Current Balancing Circuit for Multiphase Half/Full Wave Resonant Converter", 5th Taiwan and Japan Conference on Circuits and Systems, Nikko, Japan (Aug. 2019).

[2] Chen-Hao Zhang, Yi-Fei Sun, Tran Minh Tri, Yasunori Kobori, Anna Kuwana, Haruo Kobayashi,"Multi-Phase Full/Half Wave Type Resonant Converters with Automatic Current Balance against Element Variation", 13th IEEE International Conference on ASIC, Chongqing, China (Nov. 2019).