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A current balance strategy for multi channel interleaved power converters

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Abstract: The multi-channel scheme is a more and more popular solution in high power electronic system, due to the current limitation of an inductor, the power switch in every channel, and the reduction of output voltage or current ripple. However, the current unbalance is an issue for the multiphase scheme, because the current control is independent in high number channel scheme. To solve this issue, a novel current balance control method is introduced in this paper. Compared with the traditional method which needs a current sensor in each cannel, the bill of material cost in the proposed method is much lower, because there are only three sensors in the structure: one is used to sense the total current to control the totally current, and the other two sensors are built in the first phase and the last phase for the current balance. The simulation results will be illustrated in this paper to prove this method is workable.

Keywords: multi-channel scheme, current balance, sequential trigger

1 INTRODUCTION

In high power system, the multi-phase scheme is more and more popular. This scheme could be used to solve the limitation of the components issue, and reduce the output voltage and current ripple. But, based on this multi-channel scheme, the current unbalance will be the problem. There are several papers[1] to [6] discussed how to solve the unbalance. [1] introduced a multiphase voltage-mode hysteretic controlled point-of-load (POL) dc–dc converter. This paper used a current sharing technique to implement the voltage-mode hysteretic-controlled without current reference, current compensation and loop compensation. [2] introduced a buck converter in the multiphase scheme. It is based on the mismatch-error shaping technology to implement it. And, the proposed technology is used the concept of 1-bit Delta-Sigma DAC to implement it. [3] discussed an Automatic multi-phase digital pulse width modulator Automatic multi-phase digital pulse width modulator, it implemented in the Field- Programmable Gate Arrays (FPGA). And, it used a duty cycle distribution algorithm to divide the duty cycle in each phase, and it based on this algorithm to perform the current balance. [4] discussed an active multiphase converter with mixed-signal current programmed mode controller. This research used a capacitor charge balance algorithm to implement the current balance. [5] introduced a multiphase buck converter with single controller. This circuit only used one controller with the output voltage to be the feedback. To sense the current of each phase with a current sensor, and based on it to change the ramp of carrier to modify the duty cycle of PWM. [6] introduced a multiphase DC-DC converter, it used a average current method to balance the current in each phase. And, it used the PWM of build-in peripheral in digital control processor to control each phase.

In this paper, a current balance method is presented by different beginning time and two current sensors. The sequential triggers performed the different phase delay. By the trigger sequence, the first and last phase which build the current sensor could be assigned. Next, based on that information from the first and last phase, the current balance method can be performed. The simulation results will be discussed in the section 4 and demonstrate the efficiency of the proposed method.

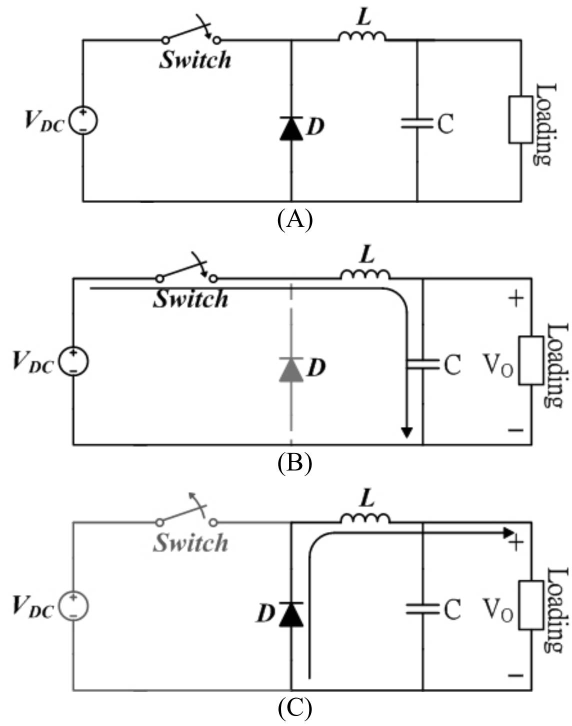

Figure 1. Buck Circuit

2 THE BASIC CONCEPT OF BUCK CIRCUIT AND MULTIPHASE SCHEME

2.1 Buck Scheme

The single phase buck circuit will be discussed in this subsection, then the operating concept of the multiphase scheme will be more clear. The buck circuit is illustrated in Fig. 1, (A). Depending on the switch state, this circuit could be divided into two modes, and shown in Fig. 1 (B), and Fig. 1, (C). And, the charged and discharged inductor current in these two modes could be described as (1) and (2). The inductor current, inductance, output voltage, and input voltage, duty and time are i_L, L, V_O, V_{DC}, D, and T, respectively. The (3) and (4) could be obtain from the (1) and (2). The (3) is a charged equation, in which, the relationship between the inductor current and charged time could be clearly identified. And, the (4) is obviously describing the discharged state for the inductor current.

$$\frac{di_L}{dt}=\frac{\Delta i_L}{\Delta t}=\frac{\Delta i_L}{Dt}=\frac{V_{DC}-V_O}{L} \tag{1}$$

$$\frac{\Delta i_L}{\Delta t}=\frac{\Delta i_L}{(1-D)T}=-\frac{V_O}{L} \tag{2}$$

$$\Delta i_{L(on)}=\left(\frac{V_{DC}-V_O}{L}\right)DT \tag{3}$$

$$\Delta i_{L(off)}=-\left(\frac{V_O}{L}\right)(1-D)T \tag{4}$$

Based on the (1) to (4), the operating concept of inductor current of buck circuit can be understood.

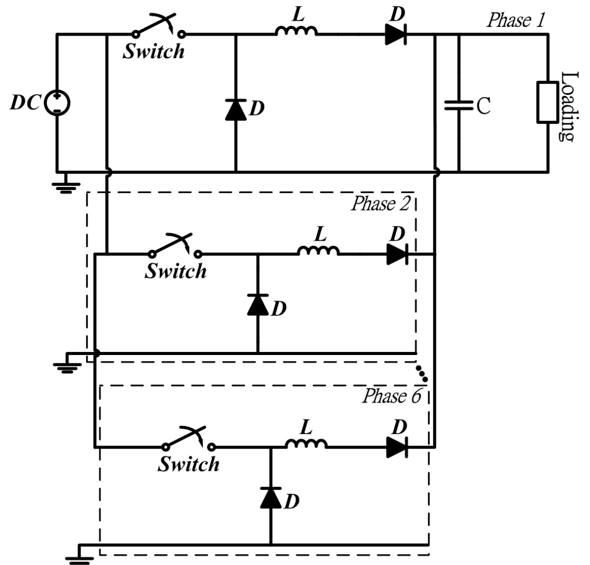

Figure 2. Multiphase Buck Converter

2.2 Multiphase Scheme of Buck circuit

The multiphase scheme is shown in fig. 2. This scheme is a parallel structure consists with more than two buck circuits. However, the output capacitor useds the same component, and input power is the same source. The Fig. 2 shows a 6 phases parallel scheme. The control method of this multi-channel scheme is called an interleave technique, which is used to turned on power switch of each phase in the same duty, but the turn-on timing of each switch are different. To perform the operation of the interleave structure above, a single controller is to used to handle all phase circuit.

Based on this structure, there are some obviously questions should be considered, like the current balance issue. The traditional method would sense each phase inductor current. For example, if this is a 6 phases scheme, it will need 6 current sensors. For approaching the current balance and reducing the cost, a low cost current balance strategy which is proposed to overcome the balance problem is proposed in this paper.

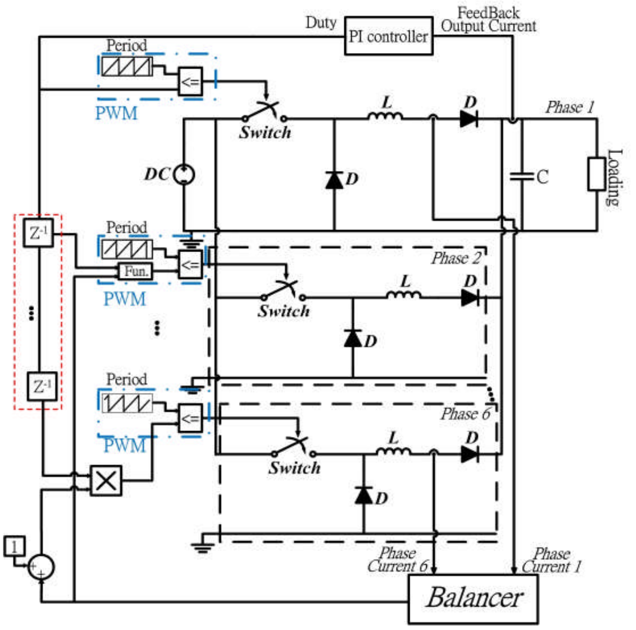

Figure 3. Diagram of System Block

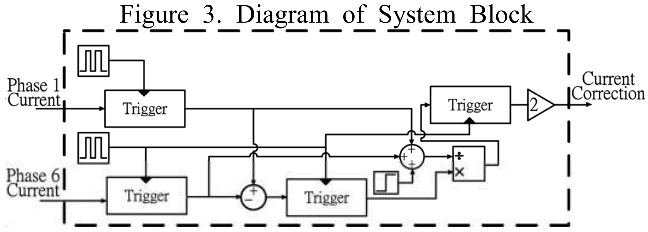

Figure 4. The block diagram of Balancer

3 CURRENT BALANCE METHOD FOR LOW COST SOLUTION

3.1 Current Balance Method

The proposed method for the current balance is a low cost strategy. Compared with traditional method, this current balance method only costs three sensors for sensing inductor current. This current balance method could be divided into two parts: sequential trigger technique and a balancer.

The Sequential trigger technique. The purpose of sequential trigger is used to perform the sequentially start timing of current phases. And, this technique is used to avoid the forward trigger issue of last phases. When the beginning of the system, the duty cycle obtains from the PI controller will be very large even close to 80% or much more. Because, the feedback signal of inductor current is very small. This situation could cause the conduction of first and last phases in the high number phase system. This forward trigger problem will cause unexpected situation of phase current which situation will be shown in sec. 4. The sequential trigger is performed by adding phase delay to the duty cycle. The phase delay time is depended on the number of the phase.

The balancer. Due to the start timing of conduction of every phase is different. The current is also non-uniform when steady state. The inductor current of every phase is should be the arithmetic progression, and the balancer uses the average of the first and last phase to calculate the adjusted proportions of the duty cycle for every phase. Then, the duty cycle is multiplied by the adjusted proportion to get a compensational duty cycle for every phase. The balance of phase current will be approached.

3.2 Simulation structure

The simulation scheme is illustrated in Fig. 3. This schematic consists of main circuit, proportional integration (PI) controller, PWM, balancer block and the function block that is used to generate adjusted duty cycle of PWM. The main circuit is a multiphase buck converter that has already discussed in section II. There is only single controller to regulate each phase circuit in this study, and the feedback signal is the total current. The PWM modulation which duty cycle is from the PI controller is used to perform the conduction time of the switches. However, the duty cycle in each phase will be delivered at different timing with the sequential trigger. And, the sequential trigger is implemented by delay block Z^{-1}, as shown in the box of dash line in the Fig. 3. Next, the balancer block is the most important part in this research. This block is used to generate the duty compensation by the first and last phase current. The balancer block diagram is shown in the Fig, 4. This block produces a total compensation ratio which will be used to adjust the duty of every phase in function block. Last, the function block is used to generate the adjusted duty cycle of PWM is shown in the dot-dash line box of the second PWM in the Fig. 3. And, this function block could be described as (5). The D_{PI} is the duty cycle from the PI controller. The $R_{compensation}$ is the total compensation ratio from the balancer. The $D_{NewDuty}$ is a calculation result that is used to be a new adjusted duty cycle of PWM. The P_i is a proportion that is depends on the ordinal number of phase circuit.

$$D_{NewDuty}=D_{PI}*(R_{compensation}*P_i+1) \qquad (5)$$

4 SIMULATION RESULTS

Simulation results are discussed in this section. The environment of the simulation is Matlab/Simulink. The specification of the system is described as below:

Input voltage = 48V
Output voltage = 15V
Output current = 60A.

This simulation could clearly illustrate the circuit function, as shown in the Fig. 5 to 10. The Fig. 5 and Fig. 6 show the inductor current of the multi-channel scheme without the sequential trigger technique, as discussed in the section 3.1. The Fig. 7 to Fig. 10 are the inductor current of each channel with the proposed current balanced method, the two enlarge figures and the balanced result, respectively. To compare with the Fig. 5 to Fig. 8, the proposed method could be demonstrated the correction impression is very well. And, the inductor current of each phase can be asthmatic progress by the sequential trigger technique. The effect of the current balanced method is very good, and it only cost 0.8ms for balanced current. The balanced processing and result are shown in the Fig. 9 and Fig. 10.

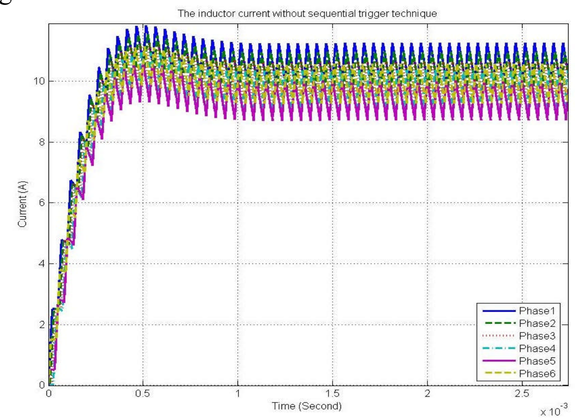

Figure 5. The inductor current of each phase without the sequential trigger

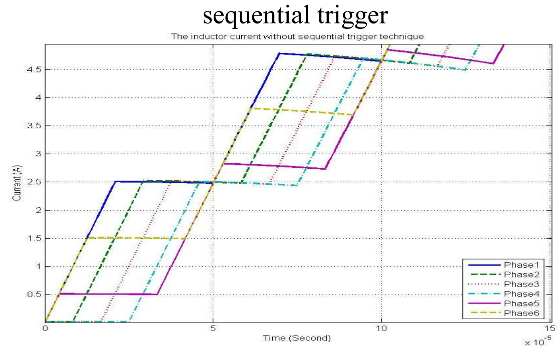

Figure 6. The enlarge figure of inductor current without the sequential trigger

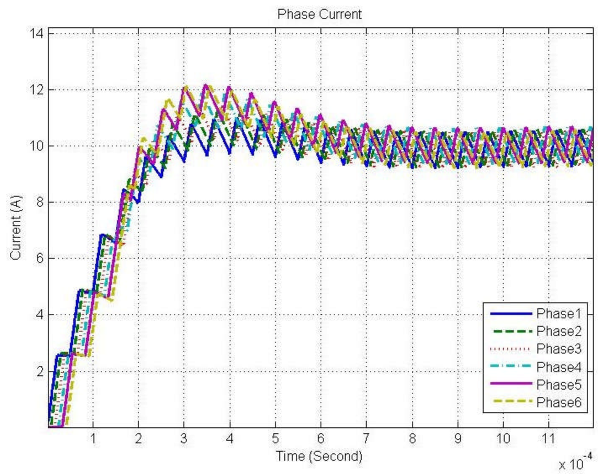

Figure 7. Phase current of each phase by the proposed current method

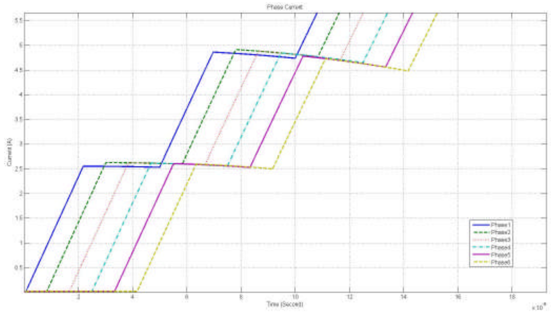

Figure 8. Enlarge figure of the beginning timing of the inductor current.

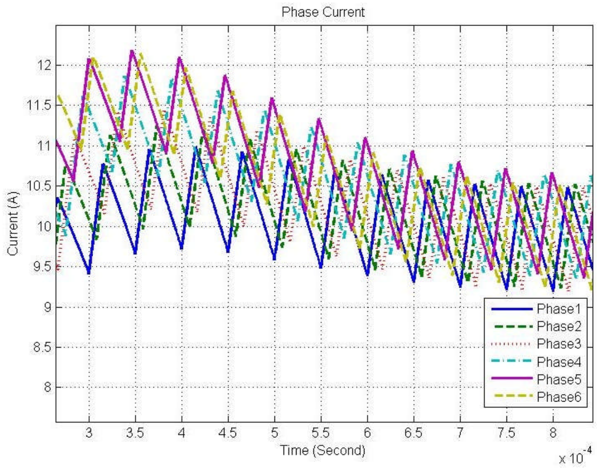

Figure 9. Enlarge figure of current balanced processing.

According to these simulation results, this multiphase buck converter with the current balance method is proved workable, and these methods are also demonstrated that could be implemented in physical circuit and the performance is well.

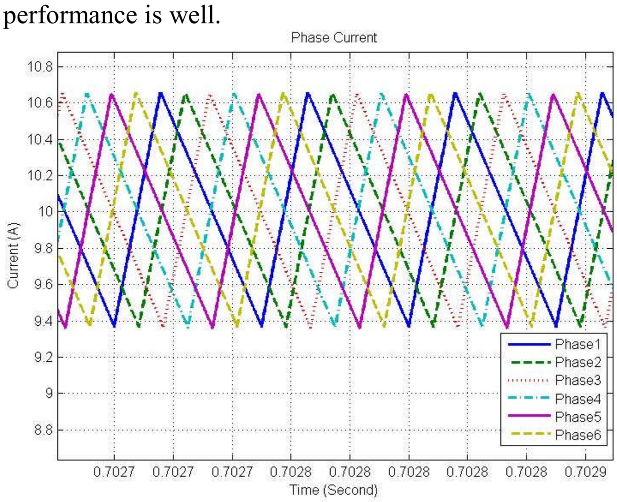

Figure 10. The result of the balanced current

5 CONCLUSION

A current balance method is proposed in this paper for the multiphase buck converter. This proposed balance method is consisting with a sequential trigger technique and a balancer. The sequential trigger technique successfully avoids the forward trigger issue of last phases and reduces the unexpected situation of the multiphase scheme. The balancer accomplishes the current balance goal by the average of the first and last phase. And, this current balance method also effectively reduces the current sensor numbers. It only costs three current sensors for implementing the current balanced. One is utilized to be the current feedback sensor for sensing the total current. And, the other two sensors are placed for sampling the first and the last phase circuit for performing the current balance. Next, the simulation results can show and demonstrate the current balance method and this simulation scheme is workable.

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