IOP Conf. Series: Materials Science and Engineering **439** (2018) 052032 doi:10.1088/1757-899X/439/5/052032

Mechanism Analysis and Closed Loop Simulation of Two-phase Interleaved BUCK Converter

Luo Tao[1, a], Zhao-zhao Wang[2, b], Jian-wei Mei[3, c]

([1,2,3]College of Electrical and Information Engineering, Hubei University of Automotive Technology, Shiyan 442002, China)

[a]ltmail1@qq.com, [b]wang1024936755@qq.com, [c]10740163@qq.com

Abstract. Interleaved Buck converters can increase power level and improve converter efficiency under the same stress conditions. Based on the two-phase interleaved buck converter model, several working conditions are analyzed in detail. The current ripple is deduced by the current-voltage relationship. Then the loss model is established to calculate and compared the efficiency of the the single phase and two intersecting converter. Finally, the closed-loop simulation analysis is carried out by MATLAB. The experimental results show that the converter combined with the double closed loop algorithm reduces the ripple current and improves the robustness of the system.

1. Introduction

Buck converter is the simplest topological structure in switching power supply. The demand of integrated circuit for DC-DC converter is often low voltage and high current. If the traditional single-phase DC-DC is applied to the micro-processing system, the volume of the circuit will be increased, the volume also cannot meet the microprocessor's efficiency and power density requirements at the same time. The two-phase interleaving BUCK converter with 180-degree control has the advantages of output ripple cancellation and phase-to-phase shunt. Combined with closed-loop control, the converter's anti-jamming ability can be improved and the robustness of the system can be enhanced.

2. Two-phase interleaved parallel buck converter operating principle

The two phase staggered parallel BUCK converter adds a MOSFET tube, a diode and an inductor on the basis of a single-phase BUCK converter, which is equivalent to parallel two single-phase BUCK converters. On the pulse drive signal, the control mode with a difference of 180 degrees drives two tubes, which makes the ripple of the output current greatly reduced, thus improving the efficiency of the converter, and the corresponding main circuit is shown in Figure 1.

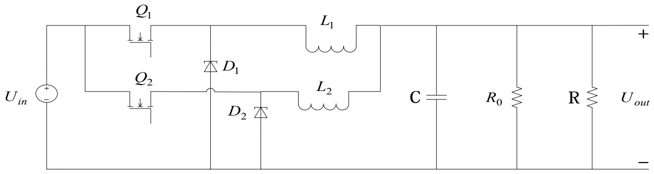

Figure 1. Main circuit topology

In the actual circuit, if the dead zone effect is considered and the duty cycle is less than 50%, there will be only three modes of working, and the specific mode equivalent circuit is shown in figure

IOP Conf. Series: Materials Science and Engineering **439** (2018) 052032 doi:10.1088/1757-899X/439/5/052032

2-Figure 4. In theoretical analysis, the device is assumed to be an ideal device, and the parallel MOSFET tube and the freewheeling diode are of the same type.

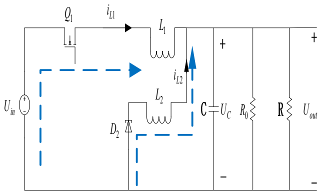
Figure 2. Mode one

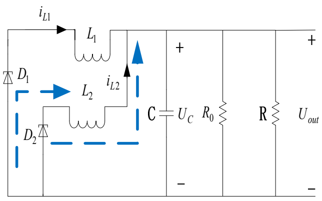
Figure 3. Mode two

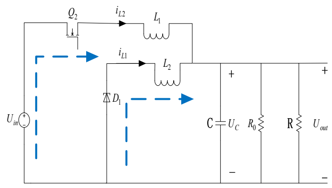
Figure 4. Mode three

2.1. Mode one

The switch tube Q_1 is closed and D_1 is turned on. The equivalent circuit is shown in Figure 2. At this time, the inductor L_1 and capacitor C are charged to store energy. The inductor L_2 and freewheeling diode form a discharge loop. At this time, the voltage and current relationship can be used to derive equation (1).

$$\begin{cases} \frac{di_{L1}}{dt} = \frac{U_{in}-U_{out}}{L_1} = \frac{U_{in}(1-D)}{L} \\ \frac{di_{L2}}{dt} = \frac{-U_{out}}{L_2} = \frac{-U_{in}D}{L} \\ \frac{dU_C}{dt} = \frac{i_{L1}+i_{L2}}{C} - \frac{U_{out}}{(R_0+R)C} \end{cases} \quad (1)$$

Where Uin, Uout are input, output voltage, inductance value $L_1 = L_2 = L$, D is duty cycle.

The corresponding current ripple flowing through inductor L_1 ,L_2 is:

$$\Delta i_1 = \frac{U_{in}}{Lf_1}(1-D)D \quad , \quad \Delta i_2 = \frac{-U_{in}}{Lf_1}D^2 \quad (2)$$

Where the f_1 is the switching frequency

From this we can get the total fluctuation of the current in the mode one:

$$\Delta i = \Delta i_1 + \Delta i_2 = \frac{U_{in}}{Lf_1}(1-2D)D \quad (3)$$

2.2. Mode two

Diode D_1 and D_2 conduction, Q_1 and Q_2 turn off, the equivalent circuit at this time is shown in Figure 3. In this mode, the inductor L_1 , L_2 and capacitor C are discharged, according to the corresponding voltage and current relationship can be used to derive equation (4).

$$\begin{cases} \frac{di_{L1}}{dt} = \frac{di_{L2}}{dt} = \frac{-U_{out}}{L} = \frac{-U_{in}D}{L} \\ \frac{dU_C}{dt} = \frac{i_{L1}+i_{L2}}{C} - \frac{U_{out}}{(R_0+R)\ C} \end{cases} \quad (4)$$

The corresponding current ripple flowing through the inductor L_1 , L_2 is:

$$\Delta i_1 = \Delta i_2 = \frac{-U_{in}D}{Lf_1}\left(\frac{1}{2} - D\right) \quad (5)$$

Thus the total current fluctuation in mode two is:

$$\Delta i = \Delta i_1 + \Delta i_2 = \frac{-U_{in}}{Lf_1}(1-2D)D \quad (6)$$

2.3. Mode three

The diode D_1 is turned on and the Q_2 is turned on. At this time, the equivalent circuit is shown in Figure 4. The inductor L_1 and the capacitor C form a charging loop, and the inductor is freewheeling diode discharge. According to the corresponding voltage and current relationship can be used to derive equation (7).

$$\begin{cases} \frac{di_{L2}}{dt} = \frac{U_{in}-U_{out}}{L} = \frac{U_{in}(1-D)}{L} \\ \frac{di_{L1}}{dt} = \frac{-U_{out}}{L} = \frac{-U_{in}D}{L} \\ \frac{dU_C}{dt} = \frac{i_{L1}+i_{L2}}{C} - \frac{U_{out}}{(R_0+R)\,C} \end{cases} \tag{7}$$

The corresponding current ripple flowing through the inductor L_1 , L_2 is:

$$\Delta i_2 = \frac{U_{in}}{Lf_1}(1-D)D \quad , \quad \Delta i_1 = \frac{-U_{in}}{Lf_1} D^2 \tag{8}$$

From this, the total current fluctuation in mode three is:

$$\Delta i = \Delta i_1 + \Delta i_2 = \frac{U_{in}}{Lf_1}(1-2D)D \tag{9}$$

3. Efficiency model

The power loss determines the level of work efficiency. For the two-phase interleaved parallel BUCK circuit, this article mainly discusses the conduction loss and switching loss of the MOS tube. It starts with the loss and establishes a corresponding mathematical model to analyze the efficiency of the BUCK converter. The working efficiency of the converter can be described with equation (10).

$$\begin{cases} \eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out}+P_l} \\ P_l = P_0 + P_1 \end{cases} \tag{10}$$

Where η represents efficiency, P_{out} represents output power, P_{in} is input power, P_l is loss, P_0 represents switching loss, and P_1 represents conduction loss.

3.1. Switching loss

The switching loss is mainly caused by the parasitic capacitance and the parasitic diode of the MOS tube. Correspondingly, the loss increases as the switching frequency f_1 increases. Since there is a capacitor between the gate and source of the MOS tube, the gate and drain is same, in order to simplify the calculation, the voltage between the MOS tube is used to calculate the loss when considering the loss. Assuming that the voltage drop across the freewheeling diode is 0.7V. Thus, the switching loss can be calculated as:

$$\begin{aligned} P_0' &= \frac{(U_{in}+0.7)I_{max1}}{2} f_1 t_{Con} + \frac{(U_{in}+0.7)I_{max2}}{2} f_1 t_{Coff} \\ &= \frac{(U_{in}+0.7)I_S}{2} f_1 (t_{Con}+t_{Coff}) + \frac{(U_{in}+0.7)}{4L}\left(U_{in}-U_{out}-R_Q I_S\right)(t_{Coff}-t_{Con})D \end{aligned} \tag{11}$$

The U_{in} and U_{out} represent input and output voltage , I_{max1}、I_{max2} are the maximum currents for turning on and off the mos tube respectively, f_1 is the switching frequency, t_{Con} and t_{Coff} are turn on and turn off time, I_S is the average current of the inductor, R_Q is the MOSFET's on resistance, the D is the duty cycle.

Through the formula (11), the single-phase BUCK switch loss can be obtained as follows:

$$P_{10} = (U_{in}+0.7)I_L f_1 (t_{on}+t_{off}) + \frac{(U_{in}+0.7)}{4L}\left(U_{in}-U_{out}-2R_Q I_L\right)(t_{off}-t_{on})D_1 \tag{12}$$

Two-phase interleaved BUCK switching loss is:

$$\begin{aligned} P_{20} &= (U_{in}+0.7)I_L f_1 (t_{on}+t_{off}) + \frac{(U_{in}+0.7)}{2L}\left(U_{in}-U_{out}-R_Q I_L\right)(t_{off}-t_{on})D_2 \\ &= (U_{in}+0.7)I_L f_1 (t_{on}+t_{off}) + \frac{(U_{in}+0.7)}{4L}\left(U_{in}-U_{out}-R_Q I_L\right)(t_{off}-t_{on})D_1 \end{aligned} \tag{13}$$

3.2. Conduction loss

The conduction loss is mainly due to the existence of internal resistance of the MOS tube, resulting in loss. A specific mathematical model is established to analyze the conduction loss of single-phase BUCK converter and two phase BUCK converter. Assuming that the selected MOS tubes are the same type, that is, the conduction resistance of the MOS tube is equal, while the dead time is ignored in the calculation, the duty ratio of the two MOS tubes is complementary, and the corresponding two interleaved BUCK conduction loss:

$$\begin{cases} R_Q = R_{Q1}D + R_{Q2}(1-D) = R_{Q1} = R_{Q2} \\ P_{21} = I_{L1}^2 R_{Q1} + I_{L2}^2 R_{Q2} = 0.5 I_L^2 R_Q \end{cases} \tag{14}$$

Among them, I_{L1} and I_{L1} are currents flowing through the inductors L_1 and L_2 respectively, and I_L is the total average current.

The corresponding single-phase BUCK conduction loss is as follows:

$$P_{11} = I_L^2 R_Q \tag{15}$$

Through the above analysis, the loss of the single-phase BUCK converter is normalized with the two interphase error, and the combined (11) - type (15) can be obtained:

$$\Delta P = P_{10} + P_{11} - P_{20} - P_{21} = I_L R_Q \left[0.5 I_L - \frac{(U_{in}+0.7)}{4L}(t_{off} - t_{on}) D_1\right] \tag{16}$$

ΔP is the loss difference between single phase BUCK converter and two phase interleaved BUCK converter.

4. Simulation analysis

Using MATLAB to simulate the two-phase interleaved parallel BUCK converter, the voltage closed-loop model is constructed by taking the input voltage 100V, output voltage 50V, output current 1A, and Switching frequency 40K as an example to build a closed loop voltage model. The driving pulse waveform is shown in Figure 5, with a differ ence of 180 degrees. The voltage output waveform combined with the closed-loop algorithm is shown in Figure 6. The voltage is basically stable at about 50V, and fluctuates up and down by 0.01V, which shows good control performance. In order to intuitively reflect the magnitude of the current ripple and compare the current waveforms before and after synthesis, Figure 7 shows the current waveforms flowing through the inductors L_1 and L_2. Figure 8 shows the resultant current waveforms. From this, the current ripple cancellation can be seen. It confirms the improvement of the efficiency of the two-phase interleaved parallel BUCK converter.

Figure 5. Drive Pulse

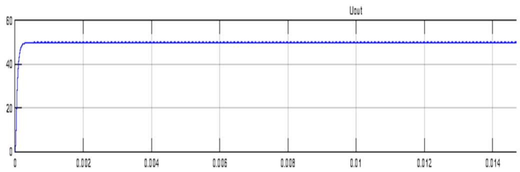

Figure 6. Output Voltage Waveform

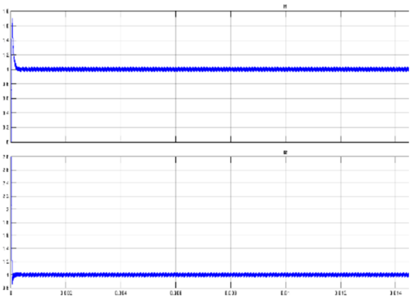

Figure 7. The Current of L_1, L_2

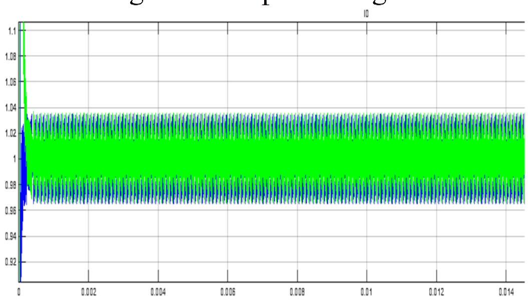

Figure 8. Output Current Waveform

5. Conclusion

Through the establishment of a corresponding model, the two phase interlaced parallel BUCK converter is analyzed and the size and efficiency of the ripple are carried out. Meanwhile the 100V-50V model is built using MATLAB, which intuitively reflects the mechanism of current ripple mutual elimination and help us to have a better understanding of the topology of multiphase interleaved parallel converters.

Acknowledgements

This work won the key discipline project in Hubei Province ---Research on Key Fundamental Problems in Parameter Identification and Decoupling Control of Brushless Doubly - Fed Machine(D20171802)funding.

IOP Conf. Series: Materials Science and Engineering **439** (2018) 052032 doi:10.1088/1757-899X/439/5/052032

References

[1]Yang Bo. Research of interlaced Synchronous BUCK Tracking source[D].Harbin Institute of Technology,2014.

[2]Zhang Feifei.Research on interleaving parallel Buck converter[D].Northeast Petroleum University,2015.

[3]Fei Yang;Xinbo Ruan;Gang Wu;Zhihong Ye.Discontinuous Current Mode Operation of Two-Phase Interleaved Boost Dc-dc Converter with Coupled-inductor[J].IEEE Transactions on Power Electronics.2017：1.

[4]Yang, Xi-Jun;Qu, Hao;Yao, Chen;Zhang, Ning-Yun;Tang, Hou-Jun;Chen, Quan;Blaabjerg, Frede.Research on two-channel interleaved two-stage paralleled Buck DC-DC Converter for plasma cutting power supply[J].Proceedings - 2014 International Power Electronics and Application Conference and Exposition, IEEE PEAC 2014.2014：914-919.

[5]Lai Lianyou.Design and simulation of two-phase interleaving synchronous Buck converter[J].Power Technology,2012,36(08):1162-1163+1212.2012

[6]Ning Haoxuan. Research on efficiency of multiphase interleaving bidirectional DC-DC Converter at light load[D].Liaoning Technical University,2013.