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

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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](image)

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...
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.

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).

\[
\begin{aligned}
\frac{dL_1}{dt} &= \frac{U_{in} - U_{out}}{L_1} \\
\frac{dL_2}{dt} &= \frac{-U_{out}}{L_2} \\
\frac{dC}{dt} &= \frac{i_{1} + i_{2}}{C} - \frac{U_{out}}{(R_0 + R)C}
\end{aligned}
\]

Where \( U_{in}, U_{out} \) 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:

\[
\Delta i_1 = \frac{U_{in}}{L_1} (1 - D) \theta \\
\Delta i_2 = \frac{-U_{out}}{L_2} \theta^2
\]

Where the \( \theta \) is the switching frequency.

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

\[
\Delta i = \Delta i_1 + \Delta i_2 = \frac{U_{in}}{L_1} (1 - 2D) \theta
\]

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).

\[
\begin{aligned}
\frac{dL_1}{dt} &= \frac{-U_{in}}{L} \\
\frac{dL_2}{dt} &= \frac{i_{1} + i_{2}}{C} - \frac{U_{out}}{(R_0 + R)C}
\end{aligned}
\]

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

\[
\Delta i_1 = \Delta i_2 = \frac{-U_{in} \theta}{L_1} \left( \frac{1}{2} - \theta \right)
\]

Thus the total current fluctuation in mode two is:

\[
\Delta i = \Delta i_1 + \Delta i_2 = \frac{-U_{in}}{L_1} (1 - 2\theta) \theta
\]

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).
\[
\begin{align*}
\frac{d i_{2}}{dt} &= \frac{U_{in} - U_{out}}{L} = \frac{U_{in}(1-D)}{L} \\
\frac{d i_{1}}{dt} &= \frac{-U_{out}}{L} = -\frac{U_{in}D}{L} \\
\frac{d L}{dt} &= \frac{i_{1} + i_{2}}{c} - \frac{U_{out}}{cR_{S} + c} \\
\end{align*}
\]

The corresponding current ripple flowing through the inductor \(L_1\), \(L_2\) is:
\[
\Delta i_{2} = \frac{U_{in}}{L} (1-D) D, \quad \Delta i_{1} = -\frac{U_{in}}{L} D^2
\]

From this, the total current fluctuation in mode three is:
\[
\Delta i = \Delta i_{1} + \Delta i_{2} = \frac{U_{in}}{L} (1 - 2D) D
\]

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).
\[
\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out} + P_{1}}{P_{out} + P_{0}}
\]

Where \(\eta\) represents efficiency, \(P_{out}\) represents output power, \(P_{in}\) is input power, \(P_{1}\) 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 \(f_{S}\) 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:
\[
P_{out} = \left(\frac{U_{in} + 0.7}{4}I_{max1}\right)f_{s}t_{con} + \left(\frac{U_{in} + 0.7}{4}I_{max2}\right)f_{s}t_{coff}
\]

\[
= \left(\frac{U_{in} + 0.7}{2}\right)f_{s}(t_{con} + t_{coff}) + \left(\frac{U_{in} + 0.7}{4L}\right)(U_{in} - U_{out} - R_{Q}I_{S})(t_{coff} - t_{con})D
\]

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, \(f_{s}\) 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:
\[
P_{10} = \left(\frac{U_{in} + 0.7}{4L}\right)I_{con}f_{s}(t_{on} + t_{off}) + \left(\frac{U_{in} + 0.7}{4L}\right)(U_{in} - U_{out} - 2R_{Q}I_{L})(t_{off} - t_{on})D_{1}
\]

Two-phase interleaved BUCK switching loss is:
\[
P_{20} = \left(\frac{U_{in} + 0.7}{2L}\right)I_{con}f_{s}(t_{on} + t_{off}) + \left(\frac{U_{in} + 0.7}{4L}\right)(U_{in} - U_{out} - R_{Q}I_{L})(t_{off} - t_{on})D_{2}
\]

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:
\[
\begin{align*}
\begin{cases}
R_Q = R_{Q1} D + R_{Q2} (1 - D) = R_{Q1} = R_{Q2} \\
P_{21} = I_{L1}^2 R_{Q1} + I_{L2}^2 R_{Q2} = 0.5I_L^2 R_Q
\end{cases}
\end{align*}
\] (14)

Among them, \(I_{L1}\) and \(I_{L2}\) 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:

\[
P_{\text{conduction}} = I_L^2 R_Q
\] (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:

\[
\Delta P = P_{10} + P_{11} - P_{20} - P_{21} = I_L R_Q \left[ 0.5I_L - \frac{(0.5\text{in} + 0.2)}{4L} (t_{\text{off}} - t_{\text{on}}) \right] D_1
\] (16)

\(\Delta P\) 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 difference 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.

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.

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