Simulation research on phase selection control algorithm of a four-phase interleaved parallel Boost converter

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Abstract. In order to increase the rated power of the DC/DC converter, the interleaved parallel connection is widely used. Although the interleaved and parallel Boost converters can increase the operating power of the system, at the same time, it has the advantages of smaller system output current ripple and can reduce the stress of switching devices, but when the system is running in low power mode, due to the use of multi-phase Boost, the increase in loss makes the conversion efficiency of the system lower. A phase selection control algorithm is proposed in this paper, by which the conversion efficiency of multi-phase interleaved parallel Boost converters can be effectively improved. Finally, the feasibility of the phase selection control algorithm designed is verified through simulation in this paper.

1. Introduction

Since the non-isolated Boost converter does not require electrical isolation, the number of components required by the relatively isolated DC/DC converter is small, and the magnetic components are smaller. The inductance of the interleaved parallel Boost converter is small, the switch tube current stress is low, and because it has a lower inductor current peak value, and can reduce the input current ripple and output voltage ripple, it has been widely studied [1-5]. The performance of the Boost converter can be greatly improved by appropriate control algorithms [6-8], however, the staggered and parallel Boost also faces unstable conversion efficiency [9-10], when the interleaved parallel Boost runs at low power, the conversion efficiency will also become lower.

Therefore, the four-phase interleaved and parallel Boost converter is taken as the research object in this paper, and the phase selection control algorithm is used to keep the conversion efficiency of Boost converter as high as possible under different powers, and the feasibility of the program is verified by the simulation research.

2. Topological structure and principle analysis

The topology of the four-phase interleaved parallel Boost converter is shown in Figure 1. K1-K4 are switching switches that control the number of phases of the Boost converter.

As shown in Figure 1, the switching devices of the four-phase interleaved parallel Boost converter are turned on interleaved, and the phases of each phase are sequentially different by T/4, that is, lead or lag 90°.
When the four-phase interleaved and parallel Boost converter works in CCM mode, the power loss during its operation is mainly divided into three categories [11].

1. The loss of the power switch tube mainly includes switching loss and conduction loss; the switching loss is greatly affected by the operating frequency of the system, the turn-on and turn-off time, and the pulsating waveform of the voltage and current flowing through the power tube; the conduction loss and the input inductor current, duty cycle such as circuit factors and the on-resistance of the switch tube itself;

2. Inductance resistance consumption;

3. The loss of the diode is the loss caused by the tube voltage drop when the switch tube is turned off.

Taking into account the interleaved parallel system, the consistency of the parasitic parameters of each phase device. Therefore, by accumulating the single-phase Boost loss formula, when the Boost converter works when k-phase is interleaved in parallel, the loss equation formula of the device is as follows.

\[
P_{\text{loss}(k)} = k \left( a \left( \frac{I_{\text{in}}}{k} \right)^2 + b \left( \frac{I_{\text{in}}}{k} \right) + c \right)
\]

Where \( I_{\text{in}} \) is the input current of the Boost converter and \( k \) is the number of modules.

From the loss equation of the device, the efficiency equation for \( k \)-phase staggered parallel operation can be obtained as follows.

\[
\eta(I_{\text{in}})_k = \frac{V_{\text{in}}I_{\text{in}} - P_{\text{loss}(k)}}{V_{\text{in}}I_{\text{in}}} = -\frac{a}{V_{\text{in}} \left( I_{\text{in}} / k \right)} - \frac{c}{V_{\text{in}} \left( I_{\text{in}} / k \right)} + \left( 1 - \frac{b}{V_{\text{in}}} \right)
\]

Where the coefficient \( a \) represents conduction losses such as switching tubes and inductor copper losses; \( b \) is the primary coefficient of system power loss the coefficient; \( c \) represents AC losses such as switching losses, ripple current losses, and core losses.

Obviously, the four-phase interleaved parallel system works under light load, where a small change in the total input current leads to a huge change in efficiency. Therefore, full-phase operation under partial load is unreasonable.

Based on the above analysis, the phase selection control algorithm is used to determine the number of working phases of the Boost converter to improve the conversion efficiency of the Boost converter in this paper.

3. Phase selection control algorithms
For this reason, the steps of the Boost converter phase selection control algorithm can be obtained as follows.

Step 1: Determine the number of operating phases of the Boost converter in the main circuit according to the output power requirements of the load;
Step 2: Real-time control Each working Boost converter is controlled in real time; Step 3: Overall regulation, so that the output of the Boost converter meets the demand.

In order to achieve the above control steps, the research scheme of the Boost converter phase selection control algorithm is obtained as follows.

In the Boost converter, the rated power of the Boost converter (denoted as $P_0$) and the required rated power of the load are called the target power (denoted as $P_1$), and the ratio between $P_1$ and $P_0$ is called the switching coefficient. Its value can be obtained as follows.

$$k = \frac{P_1}{P_0}$$

According to the value of the switching coefficient $k$, and set three thresholds $F_1, F_2, F_3$, the Boost converter is switched. The specific method is as follows:

1. When $k \geq F_1$, all 4-phase Boost converters are put into operation, and the target power is evenly distributed to the 4-phase Boost converters.
2. When $F_2 \leq k < F_1$, all 3-phase Boost converters are put into operation, and the target power is evenly distributed to the 3-phase Boost converters.
3. When $F_3 \leq k < F_2$, the 2-phase Boost converter is put into use, and the target power is distributed evenly to the 2-phase Boost converter; when the on-time of the 2-phase Boost converter is longer than $T_1$, $T_1$ is the two-phase switching time, the already-connected Boost converter is disconnected and the other 2 phases. Boost converter is put into use.
4. When $k < F_3$, only one Boost converter is put into use; when the on-time of the Boost converter is longer than $T_2$, $T_2$ is the single-phase switching time, the current Boost converter module is disconnected, and the Boost converter that has not been connected for the longest time is switched on.

4. Simulation analysis
Matlab simulation tool is used to build a simulation model of the Boost converter to verify the simulation performance of the designed algorithm in this paper. The simulation time is set to 0.012s, the rated power required by the load is 5kW, the input voltage is 48V, and the given voltage value is 200V. Four-phase, three-phase, two-phase interleaved parallel and single-phase Boost converters were put into operation respectively. The conversion efficiency of the system can be observed when the Boost converter with different phase numbers is put into operation through the change of the input current of the system. The simulation structure diagram of a two-phase interleaved parallel Boost converter is shown in Figure 2.

![Two-phase interleaved parallel Boost simulation structure diagram.](image)

Figure 3 is the waveform of the system output voltage $V_o$, which can be seen from Figure 3, the system output voltage is stable at 200V, and the output voltage ripple is less than 1%.
The system input current waveforms of single-phase, two-phase interleaved parallel, three-phase interleaved parallel, and four-phase interleaved parallel can be shown Figure 4 - Figure 7 in respectively. As shown in the figure, the system input currents for single-phase, two-phase interleaved parallel, three-phase interleaved parallel, and four-phase interleaved parallel are 108.4A, 109.4A, 110.8A, and 111.5A, respectively.

**Figure 3.** System output voltage $V_o$ waveform.

**Figure 4.** Single-phase Boost input current waveform.

**Figure 5.** Two-phase interleaved parallel Boost input current waveform.
Because the input voltage of the system is constant, the input power of the single-phase Boost converter is 5203.2W, the input power of the two-phase interleaved parallel Boost converter is 5251.2W, the input power of the three-phase interleaved parallel Boost converter is 5318.4W, and the four-phase interleaved parallel Boost converter is 5318.4W. The input power of the converter is 5352W. The relationship between the number of working phases of the Boost converter and the conversion efficiency is shown in Figure 8.
Since the load power is constant in the simulation experiment, the input power varies with the number of phases of the Boost converter, and the loss of the device is also different, resulting in a change in the input power. The simulation experiment verifies that the phase selection control algorithm can improve the conversion efficiency of the Boost converter when the system power is constant.

5. Conclusions
While the multi-phase interleaved and parallel Boost converter has good performance, there is a problem of low conversion efficiency in the low-power operation mode. In order to solve this problem, four-phase interleaved parallel Boost is taken as an example, a phase selection control algorithm is adopted to reduce system loss and improve the conversion efficiency of Boost converter, in this paper, and the feasibility of the scheme is verified through simulation.

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