Development of two-phase interleaved synchronous rectification DC-DC for commercial vehicle engine ECU

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Abstract. The commercial vehicle diesel engine ECU and the electronically controlled common rail system power supply developed in this paper adopt the two-phase BUCK converter as the main loop. Considering the problems of large current fluctuation, high continuum diode loss and possible non-uniform current in parallel connection of traditional BUCK converter, a control strategy of two-phase staggered parallel synchronous rectifier BUCK converter is proposed. The relationship between current fluctuation and inductance, switching frequency and duty cycle of different operating modes is theoretically analyzed, and the current fluctuation of traditional BUCK converter is compared. The prototype test results show that the converter structure and control strategy effectively reduce the output current fluctuation and improve the system power density.

1. Introduction

New light truck engines using 12 V, 24 V onboard power supply system needs to be converted to a 12 V power supply system to provide power to the commercial diesel engine ECU and an electronic control common rail system. The traditional commercial vehicle DC converter mentioned in reference [1, 2] adopts push-pull full bridge structure or non-isolated DC converter mode. The circuit has the advantages of simple structure and low cost, but it has the disadvantage of large fluctuation of output current.

The simulation of a two-phase staggered parallel synchronous BUCK converter is presented in reference [3], which proves the feasibility of the principle. In [4], the method of improving the efficiency of the two-phase staggered Boost DC-DC converter by integrating the design of the inductive component is proposed. And the experimental results verify the effectiveness of the proposed method. In [5], a 400 V/12 V DC conversion structure based on LLC half-bridge inverter, high-frequency boost and synchronous rectification technology is proposed. The simulation results show that the circuit topology is feasible and efficient. The literature [6] power topology and control method is similar to the literature [5], but the feasibility of the scheme is verified by a physical experiment model in this paper. In [7,8], the efficiency, control characteristics and dynamic response characteristics of the synchronous rectification technology of the interleaved Buck converter are studied. In the multi-phase technology, synchronous rectification technology and BUCK parallel current sharing technology of the converter A phase-based automatic adjustment control strategy is proposed. By analyzing the relationship between two-phase interleaved parallel BUCK converter and current ripple of traditional BUCK, a new topology of two-phase interleaved parallel non-isolated BUCK converter and synchronous rectification technology is proposed, and the power quality is
greatly improved when the duty cycle satisfies the constraints. The experimental results of the prototype show that the method can greatly reduce the current fluctuation and electromagnetic interference of the power supply for the engine electronic control system.

2. System main circuit
The main circuit of the system realizes that the 24 V DC power is converted into 12 V DC according to the control requirements to supply the electromagnetic coil of the engine injector solenoid valve. Its main circuit structure is shown in figure 1.

![Figure 1. The main loop of DC-DC.](image)

2.1. Technical requirements
According to the load characteristics, the output voltage of the power supply is greater than 11 V and lasts longer than 3 S when the output current reaches 120 A. The parameters of the power supply are shown in table 1. It has the protection functions of input overvoltage/undervoltage protection, output overvoltage/undervoltage protection, open circuit protection, battery reverse connection protection, short circuit protection and overheat protection.

| Parameters                  | Value       |
|----------------------------|-------------|
| Input Voltage [V]          | 16 -32      |
| Output Voltage [V]         | 12          |
| Rated Power [KW]           | 0.9         |
| Peak Power [KW]            | 1.44        |
| Output Voltage Ripple [V]  | 0.3         |
| Starting inrush current [A]| <125        |

2.2. Principle of main circuit
The main circuit is a non-isolated BUCK converter, in which $T_1$ and auxiliary capacitors $C_1$ and $C_2$ form input EMI filters; $Q_1$, $Q_2$, $D_1$ and $L_4$ form one synchronous rectifier BUCK converter circuit, $Q_3$, $Q_4$, $D_2$ and $L_2$ form another One-phase synchronous rectification BUCK conversion circuit, the phase difference of the control pulse timing of the two-phase synchronous rectification BUCK conversion circuit is $180^\circ$. $C_4$ is the output filter capacitor. In the actual system, six 1000μF capacitors are connected in parallel, and $T_2$ and auxiliary capacitors $C_5$ and $C_6$ are combined to form an output. EMI filter, resistor $R_1$ is a dummy load, the system operating frequency is 48 KHz.

3. Two-phase interleaved parallel synchronous rectification DC-DC circuit working principle
The two-phase interleaved parallel synchronous rectification BUCK converter is connected in parallel by two single-phase BUCK converters. The synchronous rectification technology replaces the freewheeling diode with MISEFT, which reduces the loss of the diode and improves the efficiency of the converter. The rising edges of the MOSFET $Q_1$ and $C_3$ drive pulse signals are 180 degrees apart,
so that the peaks and valleys of the currents of the inductors $L_1$, $L_2$ are staggered, and the current in the load is the algebraic sum of the currents of the inductors $L_1$, $L_2$, which greatly reduces the load current ripple and improves power quality, the equivalent main circuit is shown in figure 2.

**Figure 2.** Two-phase interleaved parallel synchronous rectification DC-DC circuit.

Definition: State 1 — increased inductor current in the BUCK transform; State 2 — the inductor current is reduced in the BUCK transform.

In the case of continuous inductor current:
- When the duty cycle is 50%, there are only two modes of operation, $A_1B_1$ and $A_1B_2$.
- When the duty ratio is less than 50%, there are four working modes, namely $A_2B_1$, $A_2B_2$, $A_1B_2$ and $A_2B_2$, of which two states are repeated, and there are only three working modes.
- When the duty ratio is greater than 50%, there are four working modes, namely $A_1B_1$, $A_1B_1$, $A_1B_1$ and $A_1B_1$, of which two states are repeated, and there are only three working modes.

The analysis method is the same as the case where the duty ratio is less than 50% and the duty ratio is greater than 50%. Here, the analysis is performed with the duty ratio greater than 50%. The equivalent circuit of the three working modes is as shown in the following figure 3:

**Figure 3.** Mode 1 $A_1B_1$ equivalent Circuit.
In mode 1: In the BUCK converter, the A-phase MOSFET $Q_1$ is turned on, the DC voltage is charged to the storage capacitor $C_4$ through the $Q_1$ and the storage inductor $L_1$, and the load is supplied with energy. The B-phase MOSFET $Q_3$ in the BUCK converter is turned on, and the DC voltage is passed through the $Q_3$. The inductor $L_2$ charges the storage capacitor $C_4$ while providing energy to the load.

In mode 2: In the BUCK converter, the A-phase MOSFET $Q_1$ is turned off, and the energy stored in the storage inductor $L_1$ charges the storage capacitor $C_4$ through the $Q_2$ freewheeling, and simultaneously supplies energy to the load. The B-phase MOSFET $Q_3$ in the BUCK converter is
turned on, and the DC voltage is passed. $Q_3$. The energy storage inductor $L_2$ charges the storage capacitor $C_4$ while providing energy to the load.

In mode 3: In the BUCK converter, the A-phase MOSFET $Q_1$ is turned on, the DC voltage is charged to the storage capacitor $C_4$ through $Q_1$, the storage inductor $L_4$, and the load is supplied with energy. The B-phase MOSFET $Q_3$ in the BUCK converter is turned off, and the storage inductor $L_2$ is stored. The energy is charged to the storage capacitor $C_4$ through the $Q_4$ freewheeling while providing energy to the load.

4. Theoretical analysis of two-phase interleaved parallel synchronous rectification DC-DC circuit

The above equivalent circuit satisfies the following assumptions: (1) The power switch tube is in an ideal working state, that is, the switch tube is turned on without a conduction voltage drop, the turn-off has no leakage current, and the switch does not require time; (2) the inductor and capacitor There are no parasitic parameters, the circuit is in linear operation; (3) phase A and phase B inductance values $L_1 = L_2 = L$.

![Figure 7. Flow current waveform in the inductor.](image)

Definition: $U_{IN}$ - input DC voltage $U_d$; $U_{OUT}$ - input DC voltage $U_0$; $D$ - phase A and phase B duty cycle; $f$ - Phase A and Phase B control pulse frequency.

Let: $t_1 = t_2 - t_1$, $t_2 = t_1 + \Delta t_1 = t_1$, $t_3 = t_2$, $t_4 = t_3 - t_1$, $t_5 = t_4 - t_1$.

Available from figure 7: $\Delta t_2 \equiv \Delta t_1 = \frac{1-D}{f}$, $\Delta t_3 \equiv \Delta t_1 = \frac{D-0.5}{f}$.

4.1. Theoretical analysis of $A_B$ mode

The A-phase MOSFET $Q_1$ is turned on, the B-phase MOSFET $Q_3$ is turned on, and the equivalent circuit is shown in figure 3. The power supply supplies power to the load through the inductors $L_1$, $L_2$, and $C$, and stores energy to the inductors $L_1$ and $L_2$, according to formula (1). Voltage and current relationship.

\[
\begin{align*}
\frac{dt_1}{dt} &= \frac{U_{IN} - U_{OUT}}{L_1} = \frac{U_{IN}(1-D)}{L} \\
\frac{dt_2}{dt} &= \frac{U_{IN} - U_{OUT}}{L_2} = \frac{U_{IN}(1-D)}{L}
\end{align*}
\]

Therefore, the corresponding current change amount of the current flowing through the inductors $L_1$ and $L_2$ is
$$\Delta i_1 = \Delta i_2 = \frac{U_{in} (1-D)}{L} t_i$$

The average value of the total current change in this mode is:

$$\Delta i = \Delta i_1 + \Delta i_2 = \frac{U_{in} (1-D)}{L} t_i \times 2 = \frac{U_{in} (1-D)}{L} (2D-1)$$

4.2. Theoretical analysis of \( A_2B_1 \) mode

The A-phase MOSFET \( Q_2 \) is turned on, and the B-phase MOSFET \( Q_3 \) is turned on. At this time, the equivalent circuit is as shown in figure 4. The power supply supplies power to the load through the inductor \( L_2 \) and the capacitor \( C \), and simultaneously stores energy to the inductor \( L_2 \), and the inductor \( L_1 \) carries out the load through the freewheeling diode. Voltage and current relations such as formula (4)

$$\begin{cases}
\frac{d i_{1,1}}{dt} = -\frac{U_{out}}{L_1} = -\frac{U_{in} D}{L} \\
\frac{d i_{1,2}}{dt} = \frac{U_{in} - U_{out}}{L_2} = \frac{U_{in} (1-D)}{L}
\end{cases}$$

Therefore, the corresponding current change amount of the current flowing through the inductors \( L_1 \) and \( L_2 \) is

$$\Delta i_1 = -\frac{U_{in}}{L} D t_i, \quad \Delta i_2 = \frac{U_{in} (1-D)}{L} t_i$$

The average value of the total current change in this mode is:

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

4.3. Theoretical analysis of \( A_1B_2 \) mode

The A-phase MOSFET \( Q_1 \) is turned on, and the B-phase MOSFET \( Q_4 \) is turned on. The equivalent circuit is shown in figure 5. The power supply supplies power to the load through the inductor \( L_1 \) and the capacitor \( C \). At the same time, the inductor \( L_1 \) is stored, and the inductor \( L_2 \) supplies power to the load via the freewheeling diode. According to formula (7), the voltage and current relationship can be obtained.

$$\begin{cases}
\frac{d i_{2,1}}{dt} = \frac{U_{in} - U_{out}}{L_1} = \frac{U_{in} (1-D)}{L} \\
\frac{d i_{2,2}}{dt} = -\frac{U_{out}}{L_2} = -\frac{U_{in} D}{L}
\end{cases}$$

The amount of current flowing through the inductors \( L_1, L_2 \) is:

$$\Delta i_1 = \frac{U_{in} (1-D)}{L} t_i, \quad \Delta i_2 = -\frac{U_{in} D}{L} t_i$$

From this, the total fluctuation of the current in the mode is:
\[ \Delta i = \Delta i_1 + \Delta i_2 = \frac{U_{in}}{L_f} (1-2D)(1-D) \]  

(9)

4.4. Theoretical analysis of single-phase BUCK converter

Taking the A phase as an example, the equivalent circuit is shown in figure 6. The A-phase MOSFET \( Q_1 \) is turned on. The power supply supplies power to the load through the inductor \( L_1 \) and the capacitor C. At the same time, the inductor \( L_1 \) is stored, the A-phase MOSFET \( Q_2 \) is turned on, and the inductor \( L_2 \) is turned through \( Q_2 \). The freewheeling supplies power to the load, and the voltage-current relationship is obtained according to (10).

\[ \frac{dL}{dt} = \frac{U_{in} - U_{out}}{L_1} = \frac{U_{in}(1-D)}{L} \]  

(10)

The amount of current flowing through inductor \( L_1 \) is:

\[ \Delta i_1 = \frac{U_{in}}{L_f} (1-D) \]  

(11)

4.5. Comparison of current changes

From the analysis of 4.1, 4.2, and 4.3, when the duty ratio is greater than 50%, the absolute value of the current change in two-phase interleaved synchronous rectification in different modes:

\[ \Delta i_1 = \frac{U_{in}(1-D)}{L_f} (2D-1) \]  

(12)

The current variation of the single-phase BUCK converter is as shown in equation (11).

Let: \( f(D) = |i_1 - i_i| = \frac{U_{in}(1-D)}{L_f} (2D-1) - \frac{U_{in}}{L_f} (1-D)D = \frac{U_{in}}{L_f} (1-D)(D-1) \)

Obtain:

\[ f(D) = -\frac{U_{in}}{L_f} (1-D)^2 \]  

(13)

And: \( 0 \leq D < 1, \ f(D) < 0, \) so:

\[ |i_1| < |i_i| \]  

(14)

The above results show that the current variation of the two-phase interleaved synchronous rectification converter is smaller than the current variation of the single-phase BUCK converter.

5. BUCK converter interleaved synchronous rectifier control strategy

According to the analysis of 4.1, 4.2, 4.3 and 4.4, the duty cycle of interleaved parallel BUCK converter is more than 50%, and the output voltage ripple decreases with the increase of duty cycle. The control block diagram is shown in figure 8. The principle is to optimize the current loop control on the basis of traditional voltage-current double closed-loop control. When the absolute value of feedback current difference is greater than the given value, the duty cycle PI regulator enters. The output of duty cycle PI regulator adds an upper limit link, so that the duty cycle can only be changed within a certain range. When the output DC current is less than a certain set value, only phase A DC conversion is started. Converter, when the output current is greater than a certain set value, the A-phase and B-phase converters are started at the same time. The DC converter works in two-phase staggered parallel mode. Its control principle and structure block diagram are shown in figure 8.
6. Experimental results and analysis

6.1. Experimental steps and experimental conditions
Experimental power supply 1: DC: 0-50 V adjustable, 50 A current limit; Experimental power supply 2: 180 AH, 24 V lead-acid battery.

Using the experimental platform shown in figure 9, an oscilloscope was used to test the waveform of $U_{GET}$ in the following cases as shown in table 2.

| status | $K_1$ | $K_2$ | $K_3$     | $K_4$       |
|--------|-------|-------|-----------|-------------|
| 1      | closed| break | break     | break       |
| 2      | closed| closed| closed    | break       |
| 3      | closed| closed| closed    | closed      |
| 4      | closed| break | break     | closure instant |
| 5      | closed| closure instant| break | closure instant |
| 6      | closed| closure instant| closure instant| closure instant |
| 7      | closed| break instant after closure| break instant after closure| break instant |
| 8      | closed| break | break instant after closure| break instant after closure |

In the above case, the voltage real-time data is recorded according to the oscilloscope display value, and the real-time voltage waveform is saved.
6.2. Experimental waveform
On the experimental platform of figure 9, the output voltage waveforms under three conditions of starting time, before and after optimization of control parameters, K2, K3 and K4 suddenly disconnected, and output voltage ripple are tested by oscilloscope, as shown in figure 10 (a), (b) and figure 11(a), (b).

6.3. Result analysis
According to experimental test data:
- As shown in figure 10(a), DC-DC has soft start function. The time required for output voltage from 0 to 13.7 V is about 520 mS.
- As shown in figure 10(b), the peak value of DC-DC output voltage ripple is about 160 mV, which meets the requirements of the project (less than 300 mV).
- As shown in figure 11(a), DC-DC can output peak current of 120 A. The output voltage of 120 A decreases instantaneously when the load is disconnected before optimization, and returns to stable state after 2 mS.
- As shown in figure 11(b), the output voltage of 120 A load is basically stable when it is disconnected by adjusting the control speed of the hardware PI of the voltage loop, and there is no transient drop.

![Figure 10. Output Voltage Change Waveform. (a) Voltage variation waveform at start (b) Output voltage ripple.](image)

![Figure 11. Output voltage waveform when state changes. (a) Waveform when K2, K3 and K4 suddenly disconnect before optimization and (b) Waveform when K2, K3 and K4 suddenly disconnect after optimization.](image)

7. Conclusion
The main circuit of DC-DC converter used in engine and fuel injection system of commercial vehicle developed in this paper adopts double non-isolated BUCK converter. Aiming at the problem of large fluctuation of output current of DC converter and large loss of continuous current diode, this paper presents a control strategy of two-phase staggered parallel synchronous rectification, which restrains...
the fluctuation of output current. The theoretical and experimental results prove the control strategy. The effectiveness of the system strategy. The DC-DC converter with this scheme has simple structure, low cost and single power up to 1.8 KW. It can adopt triple or quadruple transformation structure according to the requirement of the application object and the idea of modularization, which has strong theoretical and practical value.

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