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Design of Three-phase Interleaved Parallel Bidirectional DC-DC Converter based on Current Sharing Control

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Abstract

In recent years, with the development of power electronics related technology and the continuous derivation of circuit topology, Bidirectional DC-DC converter topology has been produced. It can realize the two-way flow of energy. It has the advantages of small volume, low cost, high efficiency and good dynamic performance. It has a very wide range of application scenarios in the fields of electric vehicles and photovoltaic power generation systems. However, due to the difference of parasitic parameters between phases, the current of each phase is unbalanced. Therefore, starting from the actual demand, a three-phase staggered parallel Bidirectional DC-DC converter is designed, and its current sharing causes and suppression methods are deeply studied to solve the problems existing in the traditional converter.

Keywords

Power Electronics; Bidirectional DC-DC Converter; Current of Each Phase; Out-off-balance; Current Sharing.

1. Introduction

With the rapid development of power electronics related technology, switching power supply with DC-DC converter as the core has been widely used. The early DC-DC converters worked in one direction, the flow direction of energy was fixed and did not have reversibility. For the occasion requiring two-way energy flow, the structure of reverse parallel connection of two unidirectional DC-DC converters is generally adopted. According to the actual situation, it is necessary to control the two converters to realize the two-way flow of energy. Although this method is easy to control, the system is in a semi working state, which virtually causes a waste of resources. Moreover, this structure is equivalent to two converters.[1] There are many system components, and the volume and weight will be large, which is not in line with the development trend of modularization and miniaturization of converters. In order to solve the above problems and realize energy bidirectional transmission, "Bidirectional DC-DC converter" came into being.[2].

Compared with the traditional dual unidirectional DC-DC converter, the Bidirectional DC-DC converter has incomparable advantages in realizing the bidirectional flow of energy, which is mainly reflected in:

(1) A converter is needed to realize the two-way flow of energy, which greatly reduces the volume and weight of the system;

(2) It can quickly realize the switching of energy flow direction and fast dynamic response. It is a typical "one machine dual-purpose" equipment;

From the above analysis, it can be seen that Bidirectional DC-DC converter has the advantages of high circuit conversion efficiency, low cost and small volume and weight, so it has important practical significance.

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2. Working Principle of Three-phase Interleaved Bidirectional DC-DC Converter

2.1 Converter Topology and Structure

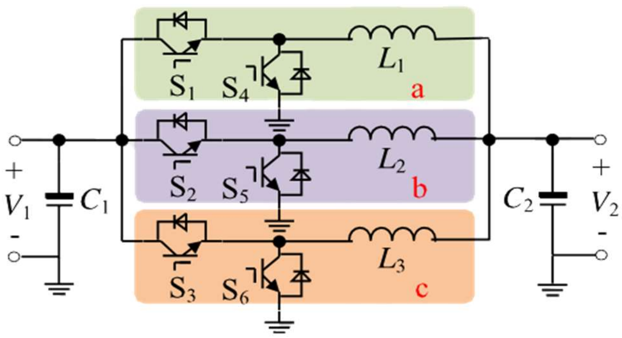

Figure 1. topology of converter

The topology of the converter is designed, as shown in Figure 2. The characteristics of three-phase interleaved Bidirectional DC-DC converter are analyzed from the perspective of mathematical theory. The topology of three-phase interleaved parallel Bidirectional DC-DC is shown in Figure 1. S1 ~ S6 are the six power switches of the converter. The driving signal with a phase difference of 120 ° is used to realize the energy conversion of the three-phase staggered parallel Bidirectional DC-DC converter, which corresponds to the reverse parallel freewheeling diode. L1, L2 and L3 are the three-phase energy storage inductors, and C1 and C2 are the filter capacitors on the low voltage side and high voltage side respectively. The circuit is composed of three identical Bidirectional DC-DC converters in parallel. When the circuit is in boost working state, the switches S1, S2 and S3 work, and the energy flows from V1 end to V2 end; When the circuit is in the buck state, the switch tubes S4, S5 and S6 work, and the energy flows from the V2 end to the V1 end.

2.2 Converter Boost Mode

The circuit topology of three-phase interleaved parallel Bidirectional DC-DC converter working in boost mode is shown in Figure 2. Among them, L1, L2 and L3 are the energy storage inductors of phase a, B and C of the converter respectively, C1 and C2 are the filter capacitors on the low-voltage and high-voltage sides respectively, and the energy flows from V1 to v2. The driving signals of any two-phase switching tubes of the converter differ by 120 °, so that the power switching tubes S1, S3 and S5 are staggered, and the diodes D2, D4 and D6 work to play the role of freewheeling.[3].

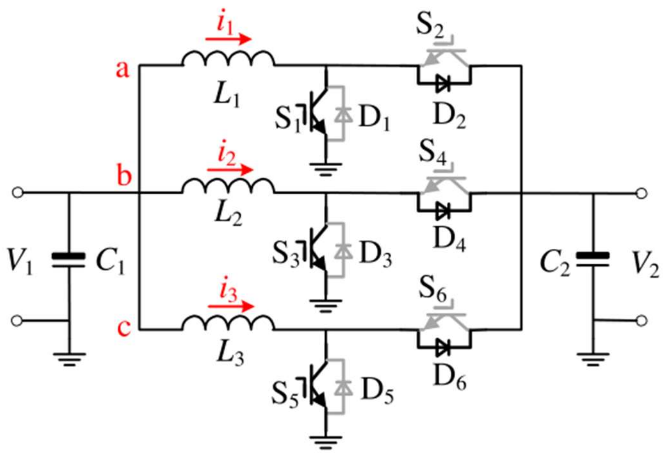

Figure 2. boost mode topology of three-phase interleaved Bidirectional DC-DC converter

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2.3 Buck Mode of Converter

The circuit topology of three-phase interleaved parallel Bidirectional DC-DC converter working in step-down mode is shown in Figure 3. The energy flows from V2 to V1, and the driving signals of any two-phase switching tubes of phase a, B and C of the converter differ by 120 °, so that the power switching tubes S2, S4 and S6 are staggered, and the diodes D1, D3 and D5 work to play the role of freewheeling.

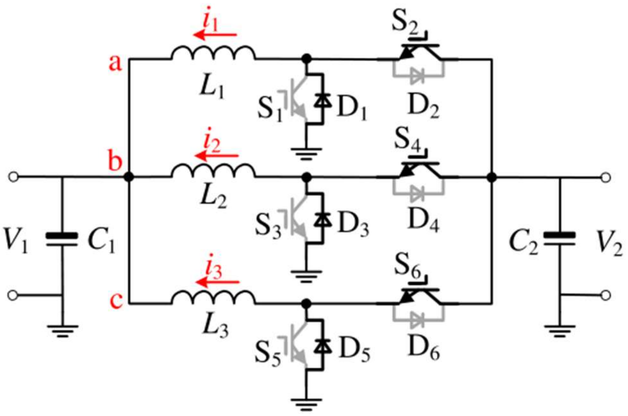

Figure 3. buck mode topology of three-phase interleaved Bidirectional DC-DC converter

3. Design of Current Sharing

According to the basic principle of current sharing, a current sharing control strategy with single current sensor is proposed. Using the state space average method and the equivalent circuit method, the single-phase inductance current expressions of the converter under different working modes are obtained. On this basis, the duty cycle components of each corresponding compensation are derived respectively.

The current at the output side of the converter is sampled, and the compensation component is calculated according to the sampling value, so as to realize current sharing. Firstly, the mathematical expressions of phase-to-phase current, device parasitic parameters and steady-state duty cycle are derived by using state space average method and equivalent circuit method.[4] It is clear that the main reason for phase-to-phase current imbalance is impedance mismatch and the difference of component parasitic parameters. In order to eliminate the current imbalance caused by it, this design will deduce the duty cycle to be compensated at the other two-phase switching nodes based on any phase, so as to improve the current sharing performance of the system.

The system control target and compensation network are designed, the boost and buck working modes of three-phase interleaved Bidirectional DC-DC converter are modeled, and the controller is designed. Based on the simulation platform of MATLAB / Simulink, the simulation model of three-phase staggered parallel Bidirectional DC-DC converter is built to evaluate the current sharing performance of single current sensor current sharing control strategy and verify the control effect. The current sharing performance of interleaved parallel converter is measured by current sharing error or current imbalance. The better the current sharing performance, the smaller the system current sharing error. According to GB / t3797-1989, when the load changes within the range of 50% ~ 100%, the current sharing error cserror% shall not exceed 5%.

The definition of current sharing error is as follows: $CS_{error}\% = \dfrac{\max[\mathrm{I_i} - \mathrm{I_j}]}{\sum_{k=1}^{n} I_k / n}$.

Where: n is the number of phases of the converter; IK is the output current of the k-th phase; Max [II ij] is the maximum difference in the output current of all phases.

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In practical work, the converter usually encounters sudden load change, short-circuit fault, input voltage change, interference and other situations. In order to keep the output voltage constant and hope that the system can make appropriate regulation stably, accurately and quickly, negative feedback control needs to be introduced and a reasonable controller needs to be designed to make the controlled object have good steady-state and dynamic performance. The two working modes of boost and step-down of three-phase interleaved Bidirectional DC-DC converter are modeled, and the controllers of different modes are designed. Finally, the simulation performance is verified based on the simulation platform of MATLAB / Simulink.

4. Converter Modeling

Based on the frequency domain analysis method of classical control theory, the converter is modeled. Firstly, the relationship between low frequency, medium frequency and high frequency of system Bode diagram and steady-state and dynamic performance indexes is analyzed. Then the small signal model of the system is established, the bipolar point double zero compensation network is designed, and the amplitude frequency and phase frequency characteristic curves of the controlled object are drawn. Finally, based on MATLAB / Simulink platform, the simulation model of three-phase interleaved parallel Bidirectional DC-DC converter is built to verify the feasibility of current sharing strategy.

5. Design of Hardware Circuit

In order to verify the correctness of the current sharing control strategy of the current sensor and the parameter design of the controller, an experimental prototype of three-phase staggered parallel Bidirectional DC-DC converter is built, and the design of hardware circuits such as sampling conditioning circuit and isolation driving circuit is given. [5]Based on the real-time code generation tool RTW, build the controller model, and finally import the code to carry out steady-state and dynamic experiments under different working modes.

The system structure and main circuit layout are shown in Figure 4. Firstly, the input, output voltage and output current signals of three-phase interleaved parallel Bidirectional DC-DC converter under different modes are sampled, filtered and amplified by the sampling conditioning circuit, injected into the DSP processor, controlled according to the selected compensation network and current sharing control strategy, and finally controlled the on and off of the power switch through the isolation drive circuit.

6. Conclusion

Compared with the single-phase converter, the three-phase interleaving can effectively reduce the current ripple and device loss, and reduce the voltage and current stress borne by the power switch. Because the current of each phase depends not only on its own parasitic resistance and duty cycle, but also on the parasitic resistance and duty cycle of other phases. In order to reduce the influence of device parameter mismatch on the current sharing performance of the converter, this study aims to design three-phase staggered parallel Bidirectional DC-DC converter, and deeply study the causes of current sharing and suppression methods.

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