Research on Interleaved Parallel Boost-PFC Based on Average Current Control

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Abstract

The dynamic response performance of single-phase Boost power factor correction (PFC) converter is poor, which is easy to cause large input current ripple. This paper proposes the working principle of bidirectional interleaved boost-PFC in current continuous mode (CCM). And the characteristics of the system analysis, the average current control circuit is optimized, through Matlab simulation analysis, the circuit has a faster dynamic response speed, can reduce the average current stress of the switching device, while achieving higher output power; Finally, a 3.2kW staggered parallel Boost-PFC experimental sample machine was built. The experimental results show that the interleaved parallel PFC circuit has higher power factor and better current ripple suppression effect.

Keywords

Interleaved; power factor correction (PFC); Matlab; average current control; current ripple.

1. Introduction

In recent years, power electronics technology has developed rapidly, and various kinds of electrical equipment have sprung up around our lives. For example, AC/DC converters are widely used in power supplies for electrical equipment, which are used to convert alternating current into direct current and then connect. Supplying the isolated DC output voltage required on the main power supply of the electronic device, but this also causes certain harmonic pollution to the power grid, so that the generation of harmonic current seriously affects the power quality, resulting in a low input power factor; At this stage, the power factor correction (PFC) technology is usually introduced into the electrical equipment to effectively control the harmonic current, so that the entire electrical equipment can operate with a linear load and a high power factor, while the input current of the electrical equipment is sinusoidal. And can achieve the same phase effect as the grid current [1-2], which can effectively reduce the ripple of the input current, its output voltage range from 12Vdc to 400Vdc; In practice, many control methods for PFC boost converters have been proposed, such as operation for a single boost converter with discontinuous input current, for a single boost converter to operate with continuous input current, bidirectional operation The boost converter operates with an interleaved input current. In this paper, the working state and related circuit characteristics of the faulty parallel Boost-PFC in the continuous mode of inductor current are analyzed. The average current control strategy is proposed. The double closed-loop control method based on load current feed forward is used. The working principle is detailed. After analysis, the Matlab simulation software is used to build the staggered parallel Boost-PFC simulation circuit. Finally, a 3.2kW interleaved Boost-PFC experimental prototype is developed and verified by experiments.

2. Circuit Analysis and Dynamic Modeling

In the single-phase Boost-PFC circuit, the current stress of the switch tube and diode needs to be affected, which is easy to cause the conversion efficiency of the system is not high; the bidirectional interleaved Boost-PFC converter can effectively reduce the input and output currents in the PFC circuit. Ripple can reduce electromagnetic interference at the same time, simplifying the design on the EMI filter as much as possible. At the same time, the circuit works in the interleaved parallel state, which largely solves the problem of excessive stress of the switching device, and is applied in high power applications. The system stability can be ensured, the voltage and current ripple in the power system can be optimized, and the transient response of the system can be improved.

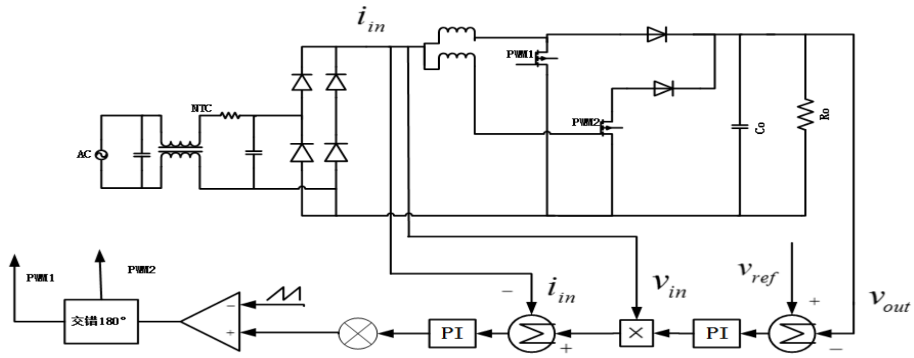

Fig 1. Interleaved parallel Boost-PFC circuit topology and working principle

The bidirectional interleaved Boost-PFC circuit topology shown in Fig 1 above is composed of two structurally symmetric single-phase Boost converters, each of which operates in a similar manner to a single-phase Boost-PFC converter, but In the working state, there will be a -180° phase shift between the two phases, and the input ripple current will be reduced by half. At the same time, for the inductor design in the interleaved parallel circuit, the inductance value is halved from the original, the circuit The allowable ripple current is also doubled; this reduces the input current ripple caused by the boost inductor[3] . Therefore, we design two-cell boost converters to be interleaved in parallel in the circuit, which can effectively reduce the capacity requirements of the input EMI filter and output filter capacitor, so that a smaller capacity capacitor can be used instead, which can save the cost of the capacitor. And can make the system's dynamic response performance better.

In order to solve the operating conditions of the boost converter and the uncertainty of the system components, a nonlinear control system for the energy function of the boost PFC converter is established, which can be retained in relation to the nonlinear term in the dynamic model of the boost converter. Key system information, with inherent immunity to changes in system parameters and disturbances, caused by an integral state representing the error integral, the actual state variable and its reference value, tending to zero, and having a faster transient response; Through the analysis of the literature [4] and [5], the steady-state analysis of the boost-interleaved AC/DC converter shown in Figure 1 above is carried out, and the equation of the interleaved boost converter is:

$$\frac{di_{L_1}}{dt}=\frac{1}{L}\cdot v_{in}-\frac{R}{L}\cdot i_{L_1}-\frac{1}{L}\cdot\left(1-d\right)\cdot v_{out} \tag{1}$$

$$\frac{di_{L2}}{dt}=\frac{1}{L}\cdot v_{in}-\frac{R}{L}\cdot i_{L2}-\frac{1}{L}\cdot\left(1-d\right)\cdot v_{out} \tag{2}$$

$$\frac{dv_{out}}{dt}=\frac{1}{C_o}\cdot\left(1-d\right)\cdot\left(i_{L1}+i_{L2}\right)-\frac{1}{C_o\cdot R_o}\cdot v_{out} \tag{3}$$

In the above formula, L1 and L2 are each boost inductor in the interleaved parallel circuit and its inductance is equal, R is the equivalent series resistance of the boost inductor, and Ro is the resistor seeing the load at the output of the boost-PFC converter. Resistance, Co is the output capacitance of the converter. The above formula establishes a matrix relationship equation,

$$\begin{bmatrix} \frac{di_{L1}}{dt} \\ \frac{di_{L2}}{dt} \\ \frac{dv_{out}}{dt} \end{bmatrix} = \begin{pmatrix} -\frac{R}{L} & -\frac{1}{L} & 0 \\ -\frac{R}{L} & 0 & -\frac{1}{L} \\ \frac{1}{C_o} & -\frac{1}{C_o R_o} & 0 \end{pmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_{out} \end{bmatrix} + \begin{pmatrix} 0 & \frac{R}{L} & 0 \\ 0 & 0 & \frac{R}{L} \\ -\frac{1}{C_o} & 0 & 0 \end{pmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_{out} \end{bmatrix} d + \begin{bmatrix} \frac{1}{L} \\ \frac{1}{L} \\ 0 \end{bmatrix} v_{in} \tag{4}$$

Can be drawn

$$\frac{dx}{dt} = Ax + Bxn + Fv_{in} \tag{5}$$

The energy error function represented by equation (5) in the above process can synthesize the optimal duty cycle under all operating conditions, and can achieve very fast response load variation even under severe conditions, due to the proposed mechanism of the tracking mechanism. The system's state variables follow their minimum error to achieve a fast transient response voltage control of the PFC and DC bus voltages, thereby reducing the circuit frequency ripple at the output of the PFC converter in order to achieve high power operation of the system.

3. Average Current Control Strategy

In the average current control circuit, the voltage and current double loop control mode is adopted, and the feedback voltage loop does not affect the stability of the current loop operation under reasonable design conditions[6-7]. In the system, the voltage outer loop acts as a stable output voltage, which can achieve a good transient response, while the current inner loop can ensure the input current is sinusoidal and can be in phase with the input voltage; it is set higher in the current loop. The gain current integrator ensures that the average value of the inductor current accurately tracks the set value, thereby achieving current sharing and improving control accuracy. Fig 2 shows the control block diagram of the average current type boost-PFC, which optimizes the compensation network and transfer function of the voltage and current loops.

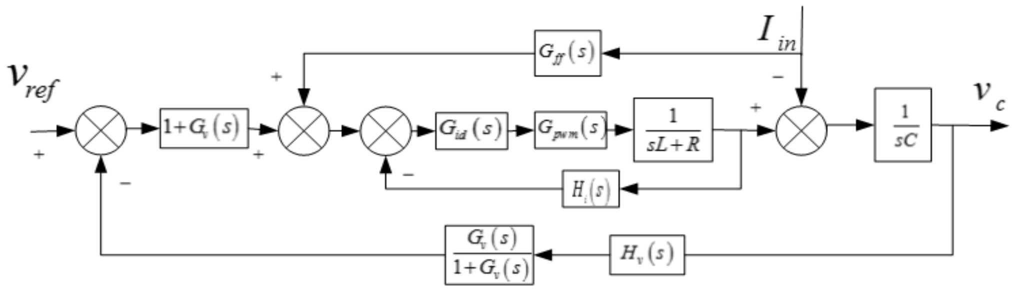

Fig 2. Average current control block diagram

In the average current control loop, $G_V(s)$ is the transfer function of the voltage loop regulator, and Gid(s) is the transfer function of the current loop regulator. They all use the PI control parameter adjustment, $H_V(s)$ is The voltage sampling coefficient of the voltage loop; Hi(s) is the inductor current sampling coefficient in the current loop, and R is the equivalent series resistance of the inductor;

Gpwm(s) is the gain of the pulse width modulation (PWM) modulator. Usually the value is $1/V_m$[8]. As can be seen from Fig 2 above, the load current feed forward can effectively improve the dynamic performance of the Boost-PFC converter under load conditions. Considering the influence on the output voltage, the load current feed forward control branch is introduced, and the branch is The transfer function is:

$$G_{ff}(s)=\frac{sL+R+G_{id}(s)G_{pwm}(s)H_i(s)}{G_{id}(s)G_{pwm}(s)} \tag{7}$$

In the average current control system, the transfer function of the current loop is:

$$A(s)=\frac{G_{id}(s)G_{pwm}(s)}{sL+R+G_{id}(s)G_{pwm}(s)H_i(s)} \tag{8}$$

The transfer function of the equivalent voltage outer loop control is:

$$G(s)=\frac{\left[1+G_v(s)\right]A(s)}{\left[sCG_{ff}(s)+G_v(s)H_v(s)\right]G_{id}(s)G_{pwm}(s)+1} \tag{9}$$

In the average current control system, adding a load current feedforward control, we can see that the reference value of the current loop is controlled by the input current and the error voltage signal. After the load current feedforward control is added to the entire control system, It can effectively improve the dynamic performance of the converter and make the system operate at high power factor.

4. Simulation and Experiment

4.1. Simulation

The Matlab simulation circuit model of staggered parallel Boost PFC based on average current control is built. The simulation parameters in the circuit are as follows: AC input voltage is 50Hz/220V, output voltage is 400V; switching frequency is 50kHz; boost inductor value is 200μH; output capacitance is 1830μF; load is 50Ω. In the simulation circuit, the step size is 1e-6s, the relative precision is 1e-3, the algorithm is ode23tb for circuit model simulation, and Figure 4 shows the input voltage, current waveform and output boost simulation waveform. The output voltage is above 400V. Fluctuation, single inductor and composite input current simulation waveforms are shown in Figure 5. From the simulation results, the circuit has a higher power factor and better ripple current suppression.

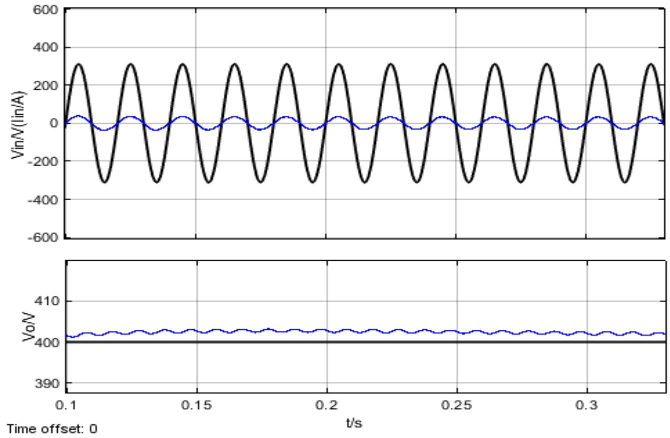

Fig 4. Input voltage and current waveforms and output voltage waveforms

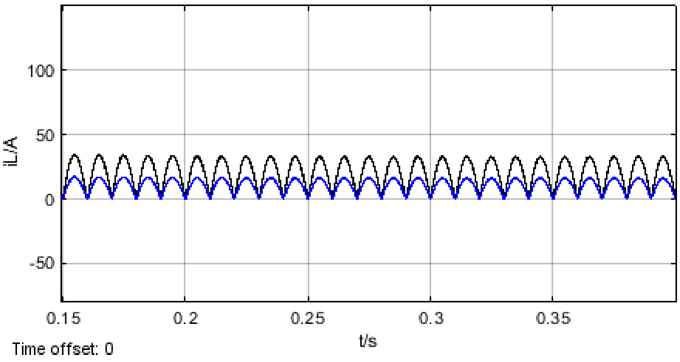

Fig 5. Single Inductor and Synthetic Current Waveforms

4.2. Experiment

Through the above simulation analysis of Matlab, a 3.2kW experimental prototype was built for verification, using TI's control chip: UCC28070, input AC voltage 220V (25% voltage error range), input frequency is 50Hz, load status The output DC voltage is 400V, the switching frequency is 50kHz, the boost inductor uses 200uH ferrosilicon aluminum inductor; the output filter capacitor uses three 680μF/450V capacitors in parallel; the selected MOSFET model is FDH44N50: 450V/44A; diode The selected SiC model is CSD20060: 600V/20A; in the load state, the input voltage, current waveform and boost waveform are shown in Fig 6. The actual output voltage is around 400V, and the input current waveform quality is improved. Single inductor current waveform are shown in Fig 7.The converter can be Operates at high power factor.

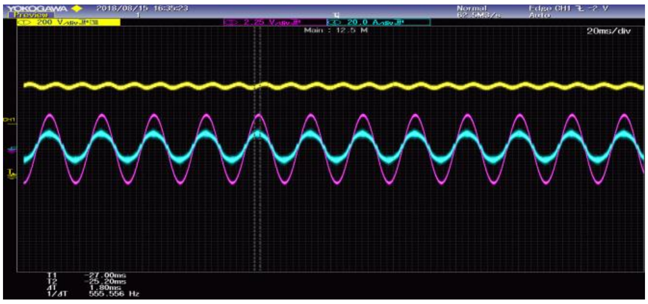

Fig 6. Input voltage and current experimental waveform and boosted waveform

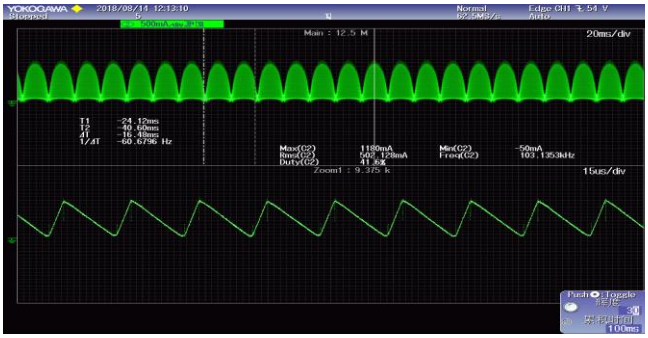

Fig 7.Single inductor current waveform

Acknowledgements

In this paper, the working state and related circuit characteristics of the faulty parallel Boost-PFC in continuous mode of inductor current are analyzed. The voltage and current double closed loop control method of average current control is adopted. Then, the interleaved parallel Boost-PFC is built by using Matlab simulation software. Simulation circuit, finally using UCC28070 to develop an experimental prototype of staggered parallel Boost-PFC. The experimental results verify the correctness of the correlation analysis of the interleaved Boost-PFC and the effectiveness of the average current control strategy. At the same time, the design requirements of the circuit, the boost

inductor can be halved, and the output power can be greatly improved. In the circuit, the capacity requirements of the input EMI filter and the output filter capacitor can be effectively reduced, so that a smaller capacity can be used. Capacitor replacement not only saves the cost of the capacitor, but also makes the system's dynamic response better. Therefore, the interleaved parallel technology can be highly practical in high-power AC/DC converters.

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