Improvement of Input Current Zero Crossing Distortion of Boost-PFC Converter with Average Current Control

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Abstract

There is a common phenomenon of input current zero crossing distortion in Boost-PFC converter, which will affect the performance of the converter. Therefore, a current zero crossing distortion suppression is proposed. The duty ratio feedforward control method can reduce the lead angle and lag angle of the input current, correct the current phase, suppress the current zero crossing distortion, and make the input current ideally track the input voltage. The simulation results show that the duty ratio feedforward control can effectively suppress the current zero crossing distortion and improve the performance of Boost-PFC converter.

Keywords

Boost-PFC, Current distortion, Current phase correction, Average current control, Duty ratio feedforward control.

1. Introduction

With the ever widening application of switching power supply and various types of power electronics equipment in industry and life, switching power supply is non-linear devices, when connecting to the grid, it will cause a certain degree of distortion to happen in the input current, form harmonic current, and harmonic pollution brings a series of harm to the system itself and other surrounding equipment [1] [2] [3]. There are simple circuit structure, low cost, high operating efficiency, and relatively small current harmonics in Boost-PFC converter, therefore, Boost-PFC converter has been widely used [4] [5] [6] [7]. There is a common problem of current zero crossing distortion in active power factor correction converter, the current zero crossing distortion increases high-order harmonics, causes the phase deviation of the current waveform, and affects the performance of the converter. Especially when the input frequency is high, the distortion is more serious [8], but the impact of the current zero crossing point distortion is not trivial when the input frequency is the power frequency. Literatures [9] [10] [11] [12] came up with double-side modulation methods, adding switched capacitors on the input side, three-level converter, and phase compensation methods, respectively, all of which have a relatively good suppression effect on current distortion, improve power factor, and all are realized based on analog control method. Literature [13] [14] came up with digital-controlled interleaved parallel technology and digital phase lead filter, respectively, both of which adopt digital control algorithm to achieve power factor correction and improve current distortion.

After the above control methods were analyzed, the duty ratio feedforward control method was proposed and implemented in a simulation environment. The simulation model was built in Matlab/Simulink. The simulation waveform proves that the duty ratio feedforward control can reduce the lead angle and lag angle of the input current, which effectively suppress the input current zero crossing distortion.

2. Working Principle of Boost-PFC Converter

The main circuit of Boost-PFC is shown in Fig.1.

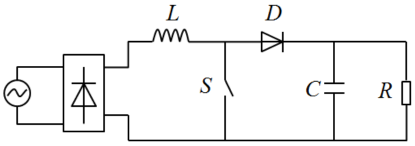


Fig. 1 Main circuit diagram of Boost-PFC

The following assumptions are needed first before analyzing the working mode of the main circuit of Boost-PFC: 1) the components in the circuit are ideal components, and the turn-on and turn-off delays of the switch tube are negligible; 2) the output voltage is constant; 3) the switching frequency of the switching tube is far greater than the frequency of the input voltage, the input voltage can be regarded as unchanged in a single PWM cycle. Furthermore, supposing that the output voltage of the rectifier bridge is: $v_{in} = |V_{in} \sin(\omega t)|$, among which Vin is the input peak voltage.

The working modes of the main circuit of Boost-PFC under CCM mode can be divided into two: the working mode 1 is the charging process of the inductance L, as shown in Fig.2(a); the working mode 2 is the discharging process of the inductance L, as shown in Fig.2(b).

The working mode 1: when the switching tube S is turned on, the current passes through the rectifier diode, the inductance L, and the switch tube S to form a loop. At this time, the inductance L is charged, the voltage rises, the current increases, and the capacitor C discharges to the load. Such as "equation (1)":

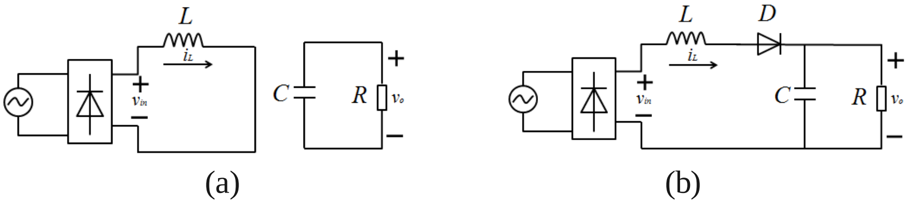
$$L\frac{di_L}{dt} = v_{in} \quad 0 \le t \le T_{on} \tag{1}$$

L is the inductance value; i_L is the inductance current; v_{in} is the output voltage of the rectifier bridge; T_{on} is the turn-on time of the switching tube.

The working mode 2: when the switching tube is turned off, the current passes through the rectifier diode, the inductance L, the diode D, and the load resistance R to form a loop. At this time, v_{in} and the inductance L discharge the load together, the voltage of the inductance L decreases, the current decreases, and charge the capacitor C at the same time. Such as "equation (2)":

$$L\frac{di_L}{dt} = v_{in} - v_o \quad 0 \le t \le T_{off} \tag{2}$$

v_o is the output voltage; T_{off} is the turn-off time of switching tube.



(a) (b)

Fig. 2 Diagram of working mode of Boost-PFC: (a) Mode 1; (b) Mode 2

The volt second product balance principle is applied in one switching cycle, the duty ratio of CCM mode can be gotten as "equation (3)":

$$D = 1 - \frac{V_{in}}{V_o} \tag{3}$$

V_{in} is the input peak voltage; V_o is the output voltage.

It can be seen from equation (3) that the duty ratio of the switching tube changes with the input voltage based on the sine law. In half a power frequency cycle, the duty ratio decreases when the input voltage increases, the duty ratio increases when the input voltage decreases, this is the basis for power factor correction. On this basis, the average current control is introduced to achieve power factor correction.

3. Control of Average Current

The diagram of control of average current mode is shown in Fig.3.

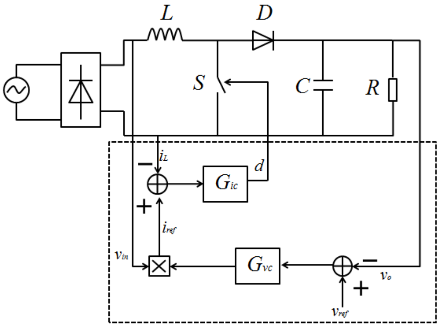


Fig. 3 Diagram of control of average current mode

The circuit is divided into 2 parts: main circuit of Boost-PFC and control circuit. The main circuit of Boost-PFC is the power stage, and the control circuit provides the control algorithm of average current mode. The average current mode is divided into the current inner loop and the voltage outer loop, the current inner loop is used to control the input current and track the input voltage, and the voltage outer loop is used to keep the output voltage stable.

The control algorithm of average current mode is: separately collect the output voltage v_o, input voltage v_{in}, inductance current i_L; compare the output voltage v_o with the reference voltage v_{ref}, after the comparison, the voltage loop compensator G_{vc} is used as one input of the multiplier, and the input voltage v_{in} is used as the other input of the multiplier, the reference current i_{ref} of the current loop is gotten after multiplication; the reference current i_{ref} is compared with the inductance current i_L, PWM duty ratio signal is gotten through the current loop compensator G_{ic} after comparison, and PWM duty ratio signal is used to control the turn-on and turn-off of the switching tube.

4. Links of Duty Ratio Feedforward Control

The small signal model of Boost-PFC circuit [15] is "equation (4)":

$$L\frac{d\acute{i}_L}{dt} = \acute{v}_{in} - (1-D)\acute{v}_o + V_o\acute{d} \tag{4}$$

Laplace transform is made for equation (4) to get "equation (5)":

$$sL\acute{i}_L(s) = \acute{v}_{in}(s) - (1-D)\,\acute{v}_o(s) + V_o\acute{d}(s) \tag{5}$$

The duty cycle feedforward control link is set to be: $\Delta d = \frac{V_o-V_{in}}{V_o}$, and make small signal transformation on it to get "equation (6)":

$$\Delta\acute{d} = \frac{V_{in}}{V_o^2}\acute{v}_o - \frac{\acute{v}_{in}}{V_o} \tag{6}$$

After simultaneous equations (3) and (6), Laplace transform is made for them to get "equation (7)":

$$\Delta\acute{d}(s) = \frac{(1-D)\acute{v}_o(s) - \acute{v}_{in}(s)}{V_o} \tag{7}$$

Putting equation (7) into equation (5), the small signal model of the Boost-PFC circuit after adding the duty ratio feedforward control can be gotten as "equation (8)":

$$sL\acute{i}_L(s) = \acute{v}_{in}(s) - (1-D)\acute{v}_o(s) + V_o(\acute{d}(s) + \Delta\acute{d}(s)) \tag{8}$$

The equation (8) is expanded and simplified to get "equation (9)":

$$sL\acute{i}_L(s) = V_o\acute{d}(s) \tag{9}$$

Equation (9) shows that after the duty ratio feedforward control is compensated, the influence of the input voltage and output voltage changes on the duty ratio is offset, since the inductance L and the output voltage V_o are unchanged, the inductance current is only influenced by the duty ratio.

Volume 7 Issue 11, 2021
DOI: 10.6919/ICJE.202111_7(11).0007

After obtaining the links of the duty ratio feedforward control, the duty ratio feedforward control simulation model is built in Matlab/Simulink for verification, the simulation parameters are shown in appendix table 1. The duty ratio simulation waveform is shown in Fig.4. The simulation waveform of PWM duty ratio is shown in Fig.5.

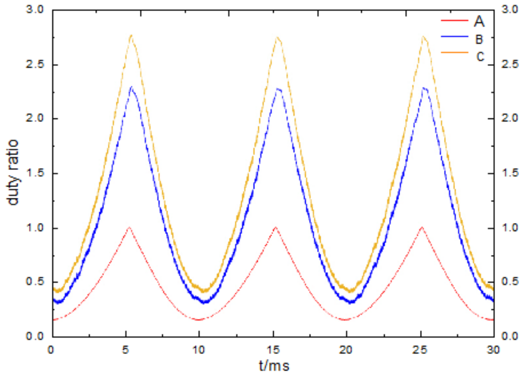
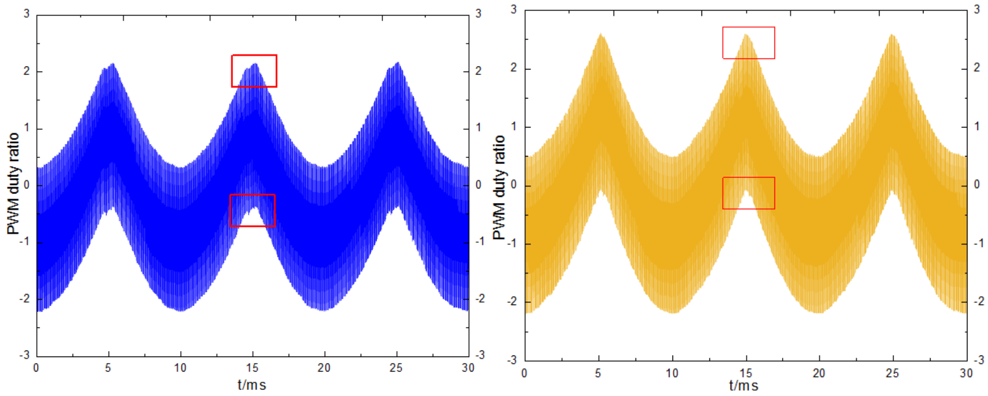


Fig. 4 Simulation waveform of duty ratio

In Fig.4, A represents the output waveform of the duty ratio feedforward control link, when the input voltage V_{in} is the zero crossing point, the duty ratio reaches the maximum value 1; when the input voltage reaches the peak value, the duty ratio is the smallest. The basic idea of the duty ratio feedforward control is to calculate the duty ratio in advance to relieve the task of the current loop compensator. The current loop compensator will change the duty ratio around this calculated duty ratio mode. B represents the output duty ratio waveform of the current loop compensator, which conforms to the statement of equation (3). C represents the duty ratio waveform after compensated by the duty ratio feedforward control link, it can be seen that the rise and decline speed of the ratio cycle have been significantly improved, especially at the zero crossing point. By combining equation (9), it shows that since the inductance current was only related to the duty ratio, for the transients of the input voltage and output voltage, the response speed of the inductance current was accelerated and the current distortion was reduced.



(a) (b)

Fig. 5 Simulation waveform of PWM duty ratio: (a) Before duty ratio feedforward control; (b) After duty ratio feedforward control

As can be seen from the simulation waveform of PWM duty ratio in Fig.5, after the duty ratio feedforward control is added, PWM duty cycle is increased near the zero crossing point, as shown in the red box, and the waveform is more stable. Because the impedance of the boost inductance is very low at the line frequency, a small change in the duty ratio will produce enough voltage in the whole inductance to produce the sine current waveform required. As a result, the lead and lag angles of the input current are suppressed near the zero crossing point, and the current dead zone is reduced.

After calculating the duty cycle Δd, it is added to the output side of the current loop compensator, and the final duty ratio can be used to generate the PWM signal which controls the PFC. The diagram of control of average current mode after adding duty ratio feedforward control is shown in Fig.6.

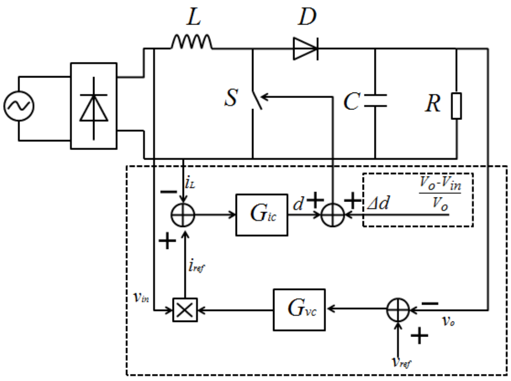


Fig. 6 Diagram of control of average current mode after adding duty ratio feedforward control

5. Simulation and Data Analysis

The simulation circuit model of Boost-PFC is shown in Fig.7.

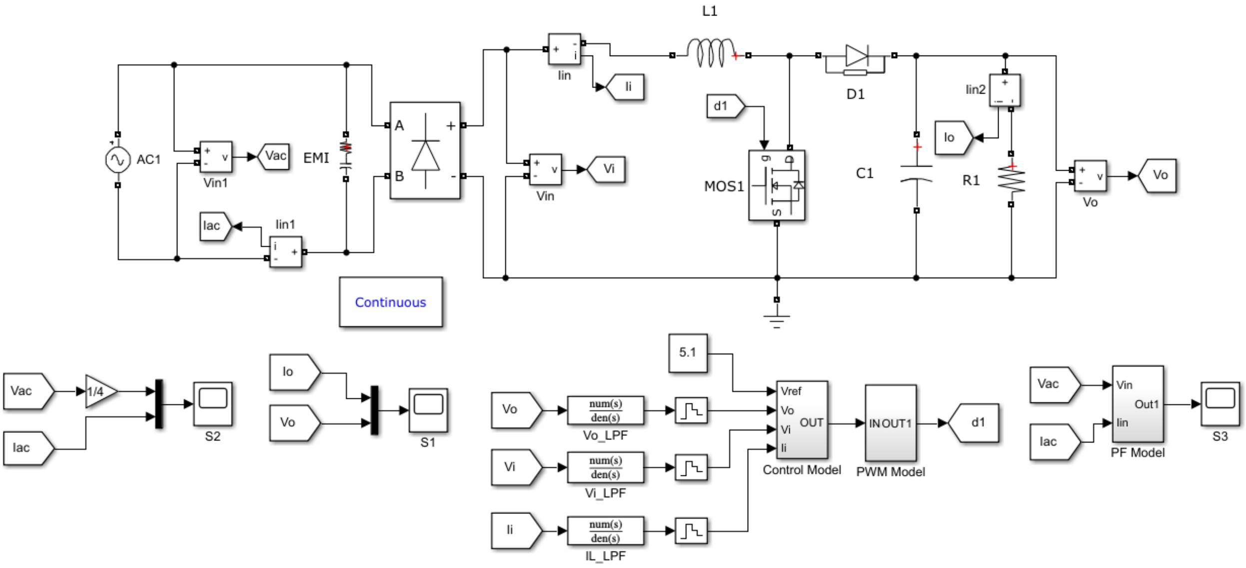


Fig. 7 Simulation circuit model of Boost-PFC

The average current control mode without duty ratio feedforward control is shown in Fig.8.

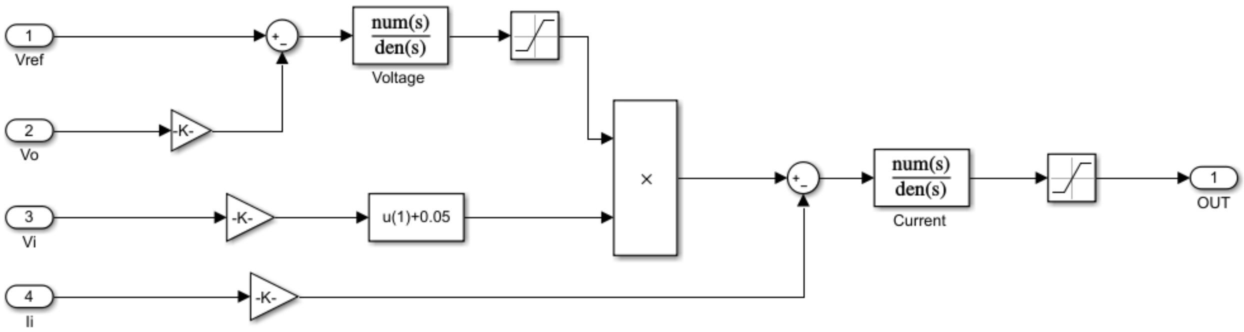


Fig. 8 Average current control mode without duty ratio feedforward control

The average current control mode with duty ratio feedforward control is shown in Fig. 9.

Fig.10 and Fig.11 are the input voltage and current simulation waveforms without and with duty ratio feedforward control, respectively. When the duty ratio feedforward control is not added, the phase of the current waveform leads voltage phase to the left side of the zero crossing point, and lags the voltage phase on the right side of the zero crossing point, and it shows that the current reaches the zero point in advance at the zero crossing point. However, since the rectifier bridge is the uncontrolled rectifier, there is a dead zone when the current maintains a zero value near the zero crossing point, and the current waveform is distorted. After adding the duty ratio feedforward control, the dead zone of the current near the zero crossing point is eliminated, the current phase is corrected, and the sine degree is better. It shows that the duty ratio feedforward control accelerates the response speed of the current near the zero crossing point, the current lead angle and lag angle are effectively suppressed, and the current zero crossing distortion is reduced.

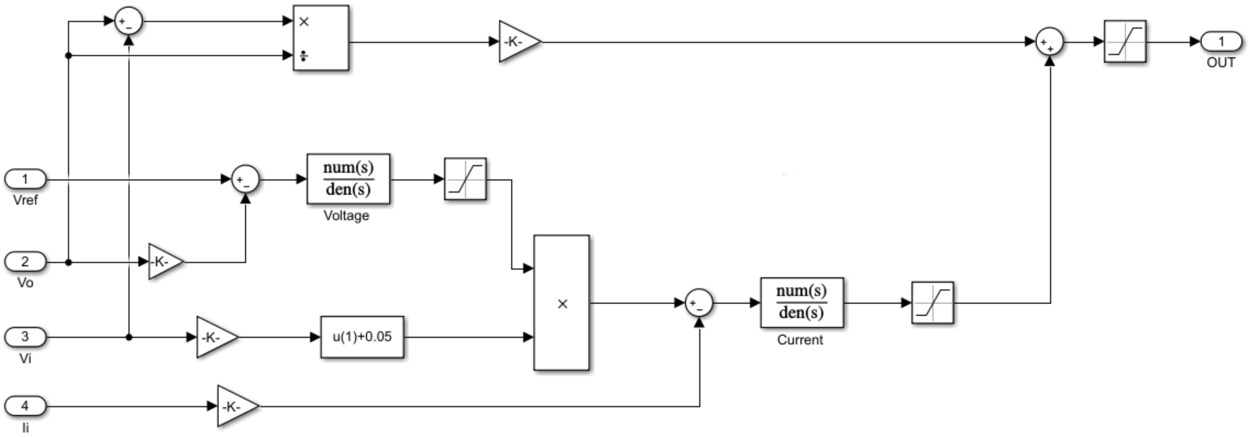


Fig. 9 Average current control mode with duty ratio feedforward control

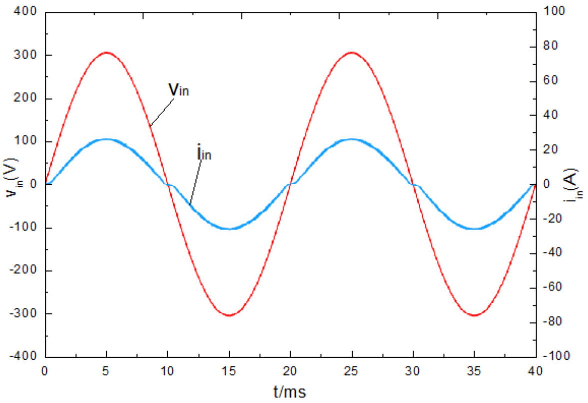


Fig. 10 Input voltage and current simulation waveforms without duty ratio feedforward control

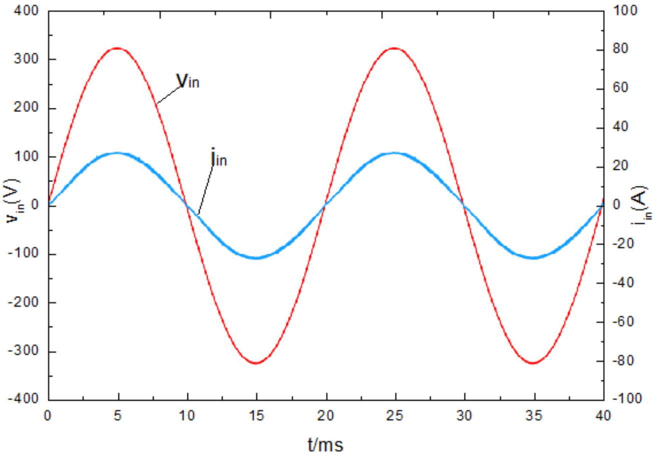


Fig. 11 Input voltage and current simulation waveforms with duty ratio feedforward control

Fig.12 is the input current harmonic analysis before and after the duty ratio feedforward control. In order to be easy for observation, the harmonic amplitude is reduced by 10 times, A is after control, and B is before control. It can be seen that the odd harmonic of the current without the duty ratio feedforward control is very large, and the total harmonic distortion rate reaches 6.65%; after the duty ratio feedforward control is added, the harmonic amplitude is greatly reduced. The reduction of subharmonics is particularly obvious, the total distortion rate of the harmonic is reduced to 2.96%, and the total distortion rate the harmonic is reduced by more than 55%.

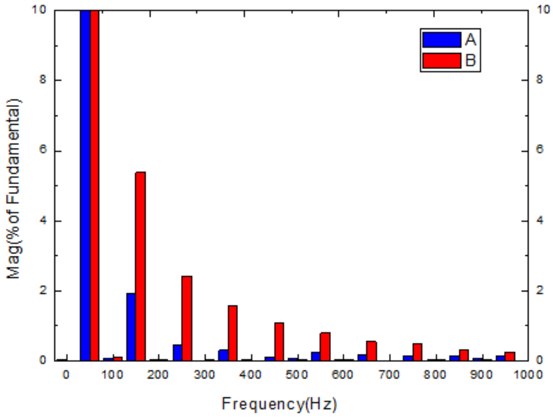


Fig. 12 Analysis of input current harmonic before and after duty ratio feedforward control

Fig.13 is the input power factor analysis before and after the duty ratio feedforward control. A is after duty ratio feedforward control, and B is before duty ratio feedforward control. It can be seen that the power factor fluctuation with the duty cycle feedforward control is smaller, the response speed is faster, and the waveform is more stable after stabilization, it is closer to 1, which improves the power factor.

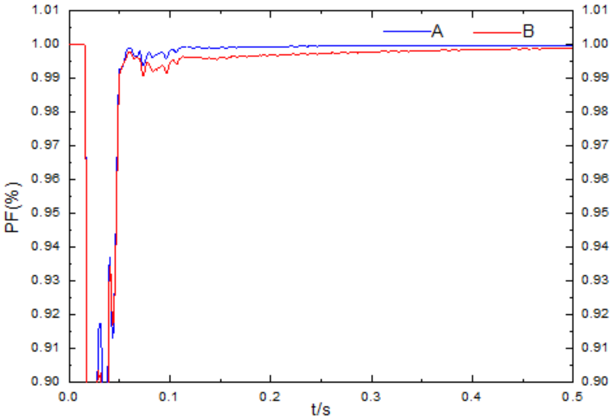


Fig. 13 Analysis of input power factor before and after duty ratio feedforward control

Table 1. Table of simulation parameters

parameter	value
input voltage peak(AC)	310V
input voltage frequency	50Hz
switching tube frequency	20KHz
output voltage	400V
reference voltage	5.1V
boost inductance	3mH
output capacitor	1mF
load resistance	40Ω
simulation time	0.5s
transfer function of simulation current loop	$G_I(s)=\frac{10s+27}{s}$
transfer function of simulation voltage loop	$G_U(s)=\frac{20}{0.06s+1}$

6. Conclusion

This paper studied the zero crossing distortion problem of the input current of Boost-PFC converter, came up with a control method for duty ratio feedforward control, and gave theoretical derivations and specific implementation methods. The modeling and simulation research was carried out in Matlab/Simulink, the simulation results showed that the duty ratio feedforward control can reduce the lead angle and lag angle of the input current, correct the current phase, and effectively suppress the input current zero crossing distortion; after adding the duty ratio feedforward control, the distortion rate of total harmonic of the system input current is lower, the power factor is more stable, and the performance of the PFC system has been optimized.

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