A New Digital Controller for Boost PFC Converter with the Reduced Harmonic Distortion at the DCM Mode

Zhihao Wang[1], Jun Yan[1], Yu Yao[2] and Daying Sun[2a)]
[1]*College of Telecommunications& Information Engineering, Nanjing University of Posts and Telecommunication, 66 mofan road, Nanjing, China*
[2] *School of Electronic and Optical Engineering, Nanjing University of Science and Technology, 200 Xiaoling Wei, Nanjing, China*
[a)] *hasdysun@126.com*

Keywords: Power factor correction, discontinuous conduction mode, digital controller, reduced harmonic distortion.

Abstract: In this paper, motivated by improving the characters of the power factor correction (PFC) converter at the discontinuous-conduction mode (DCM), a new digital controller for the digital PFC converter is proposed. The digital controller mainly consists of the modulation control loop and the self-adjusting voltage control loop. The simulation results demonstrate that the converter with the proposed digital controller can aim high output stability and reduced harmonic distortion.

1 INTRODUCTION

With the development of electronic technology, the power factor correction（PFC）converters have been widely used to reduce the input current harmonic distortion and satisfy the required harmonic standards, so as to improve energy utilization efficiency and system stability of the electric power system (K. Billings., 1999; R.W.Erickson, 2004). The voltage control loop and the current control loop are often used to regulate the output voltage and the input current, respectively. The output voltage is preferred to be stable near the reference voltage and the input current is preferred to follow the input voltage perfectly.

Meanwhile, due to the advantage such as the improved flexibility and increased functionality, the digital controller has been widely used in the PFC converter system (Angel de Castro, 2003). However, owing to the two digital control loops, the performance improvement of the digital PFC converter is inevitably limited by the relatively complex digital calculation. So when the practical application under the low power level, the signal digital control loop for the digital PFC converter is often preferred, and the digital PFC converters often work at the discontinuous conduction mode (DCM). When the digital PFC converter operating at the DCM mode, many control methods have been proposed to improve the final power factor and reduce the distorted input current, while the total control circuit complexity and the calculation burden are increased (Barry A. Mather, 2011; Jong-Won Shin, 2012; S.F.Lim, 2011).

A new digital controller is proposed in our paper to improve the characters of the digital PFC converter operating at the discontinuous conduction mode. The whole digital PFC converter structure with the proposed digital controller is illustrated in section 2, the detailed control method of the digital controller is described in section 3, and the simulation results and the conclusion are presented in section 4 and section 5, respectively.

2 THE WHOLE BOOST CONVERTER STRUCTURE WITH THE PROPOSED DIGITAL CONTROLLE

The whole boost PFC converter structure with the proposed digital controller is shown in Figure. 1. The input and output voltages of the digital PFC converter are sampled by the analog-to-digital converter (ADC), respectively. The proposed digital

Wang, Z., Yan, J., Yao, Y. and Sun, D.
A New Digital Controller for Boost PFC Converter with the Reduced Harmonic Distortion at the DCM Mode.
In *3rd International Conference on Electromechanical Control Technology and Transportation (ICECTT 2018)*, pages 518-521
ISBN: 978-989-758-312-4

controller mainly consists of the modulation control loop and the self-adjusting voltage control loop. The final duty cycle signal for the switching tube is converted via the digital pulse width modulator (DPWM).

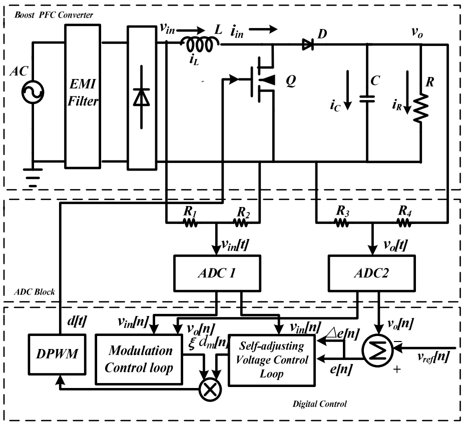


Figure 1: The whole boost PFC converter structure with the proposed digital controller

3 THE DESIGN OF THE DIGITAL CONTROLLER

3.1 The modulation control loop

When the digital PFC converter working at the DCM mode, the typical inductor current of the boost PFC converter during each switching cycle can be shown in Figure. 2

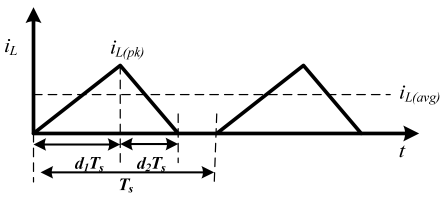


Figure 2: The typical inductor current during each switching cycle at DCM

From the above figure, the peak inductor current of the PFC converter $i_{L(pk)}$ can be calculated as

$$i_{L(pk)} = \frac{v_{in}}{L}T_{on} = \frac{v_m\left|\sin(\omega t)\right|}{L}T_{on} = \frac{v_m\left|\sin(\omega t)\right|}{L}d_1T_s \tag{1}$$

Where v_{in} is the input voltage value of the PFC converter, v_m is the magnitude value of the input voltage, L is the inductance of the boost inductor, T_{on} is the on-time during each switching cycle, ω is the line frequency, d_1 is the duty cycle value and T_s is the switching period.

According to the volt-second balance principle of inductor current, the average inductor current $i_{L(av)}$ of the PFC converter during each switching cycle can be derived as

$$i_{L(av)} = \frac{1}{2}i_{L(pk)}(d_1+d_2) = \frac{1}{2}i_{L(pk)}(1+{v_{in}}/{v_o - v_{in}})d_m \tag{2}$$

Where d_2 is the falling time ratio of inductor current and v_o is the output voltage value of the PFC converter. Based on the formula (1) and (2), the input current i_{in} can be rewritten as

$$i_{in} = i_{L(av)} = \frac{{d_m}^2T_s}{2L}\left(\frac{v_o v_m\left|\sin\omega t\right|}{v_o - v_m\left|\sin\omega t\right|}\right) \tag{3}$$

When the digital PFC converter is regulated to the steady mode, the output of the voltage control loop d_m can be defined as a constant under the constant switching frequency. Based on the formula (3), the actual input current i_{in} of the PFC converter is not sinusoidal, so the input current cannot follow the input voltage perfectly, which resulting in the improved harmonic distortion and the low power factor.

To reduce the harmonic distortion and improve the power factor, the modulation control loop in the digital controller is adopted to regulate the final duty cycle value, and the output of the modulation control loop ξ is concluded as

$$\xi = \sqrt{1-{v_{in}}/{v_o}} \tag{4}$$

Based on the formula (3) and (4), the actual input current i_{in} of the digital PFC converter can be regulated, and can be concluded as

$$i_{in} = \frac{(d_m\,\xi)^2T_s}{2L}\left(\frac{v_o v_m\left|\sin\omega t\right|}{v_o - v_m\left|\sin\omega t\right|}\right) = \frac{{d_m}^2T_s}{2L}v_{in} \tag{5}$$

According to the formula (5), the input current of the digital PFC converter is sinusoidal, and the input current can follow the input voltage perfectly, the harmonic distortion can be reduced and the final power factor can be improved effectively under the DCM mode.

3.2 The self-adjusting voltage control loop

Meanwhile, the digital controller of the PFC converter is preferred to regulate the output voltage v_o to the reference voltage v_{ref}, which is aimed by the self-adjusting voltage control loop in Figure 1. In the conventional control loop, the PI compensator is often used, which can be typically expressed as

$$G_v(s) = K_p + \frac{K_i}{s} \tag{6}$$

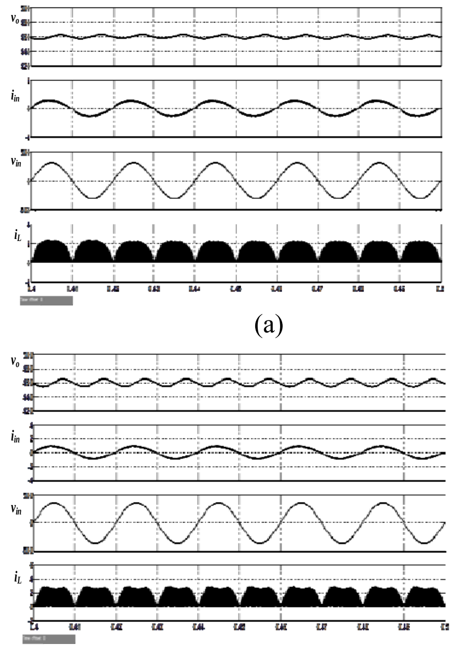
Furthermore, based on the above control principle, the digital compensator for the digital controller of the PFC converter should be redesigned by the pole-zero mapping technique and the discrete time control law of the digital compensator can be redesigned as

$$d_m[k] = d_m[k-1] + K_p e_v[k] + K_i e_v[k-1] \tag{7}$$

Where $e_v[k]$ and $e_v[k\text{-}1]$ are the errors between the output voltage and the reference voltage, and $d_m[k]$ and $d_m[k\text{-}1]$ are the output values of the self-adjusting voltage control loop during the k_{th} and $(k\text{-}1)_{th}$ switching cycle, respectively. Bases on the formula (7), the digital control characteristic of the self-adjusting voltage control loop can be effectively adjusted by changing the gain and the parameters, which determine the frequency of the compensator zero. If the amplitude of the voltage error signal is smaller than the threshold value, the digital voltage loop enters into the low-bandwidth mode, which can eliminate the second harmonic pollution and reduce the harmonic distortion. If the amplitude of the voltage error signal is higher than the threshold value, the digital PFC converter is preferred to regulate the output voltage to the reference voltage quickly, and the digital controller is preferred to regulate into the middle-bandwidth mode or high-bandwidth mode. The change of control loop mode is implemented via the change of the compensator coefficient value K_p and K_i, and the change principle of the coefficient are based on the low-frequency model of the digital PFC converter, which is obtained by the averaging value over half line cycle.

4 SIMULATION RESULTS

The digital boost PFC converter at the DCM mode with the proposed digital controller has been simulated via the Matlab/Simulink environment. The converter parameters are as follows: input voltage v_{in}=90-264V, output voltage v_o=460V, output power P_o=120W, line frequency f_{line}=50Hz, the switching frequency f_s=100kHz. Furthermore the power device components of the prototype are as follows: boost inductor L=200uH, output filter capacitor C=200uF.



(a) (b)

Figure 3: The waveforms of the output voltage, input current, input voltage and the inductor current of the digital PFC converter

The output voltage, input current, input voltage and the inductor current waveforms of the digital PFC converter under the input voltage 220VAC with 20% load and the input voltage 264VAC with 100% load are shown in Figure 3, respectively. From the figure, it can be observed that the input current of the digital PFC converter can follow the input voltage perfectly whenever at the high or low input voltage, or under the light or heavy load. The digital PFC converter based on the proposed digital controller can aim high system stability and low harmonic distortion.

5 CONCLUSIONS

This paper proposes a new digital controller for the digital boost PFC converter at the DCM mode. The digital controller mainly consists of the modulation control loop and the self-adjusting voltage control loop. Finally the simulation results confirm the satisfactory performance in harmonic distortion for the digital boost PFC converter.

ACKNOWLEDGEMENTS

The authors should like to thank the National Nature Science Foundation of China (61604075 and 61504065), and the Fundamental Research Funds for the Central Universities (30917012202).

REFERENCES

K. Billings. Switch-mode Power Supply Hand-book [M]. Second Edition. New York: McGraw-Hill, 1999.

R.W.Erickson, D.Maksirnovic. Fundamentals of power electronics[M].Second Edition. New York: Kluwer Academic Publishers, 2004.

Angel de Castro, Pablo Zumel, Oscar García, Teresa Riesgo, Javier Uceda. Concurrent and Simple Digital Controller of an AC/DC Converter With Power Factor Correction Based on an FPGA [J]. IEEE Transactions on Power Electronics, 2003, 18(1): 334 – 343.

Barry A. Mather, Dragan Maksimovic. A Simple Digital Power-Factor Correction Rectifier Controller[J] IEEE Trans. Power Electron., 2011,26(1): 9-19.

Jong-Won Shin, Bo-Hyung Cho. Digitally Average Implemented Current Mode Control in Discontinuous Conduction Mode PFC Rectifier [J]. IEEE Trans. Power Electron., 2012, 27(7): 3363-3373.

S.F.Lim, A. M. Khambadkone. A simple digital DCM control scheme for boost PFC operating in both CCM and DCM[J]. IEEE Trans. Ind. Appl., 2011, 47(4): 1802–1812.