A Robust and Embedded Efficient PFC Controller Based on Storable Reference Current Rebuilt Strategy

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***Abstract*— This paper describes a digital controller used as power factor correction rectifiers (PFC) which can be implemented by universal chips to achieve the unity power factor instead of application specific integrated circuit (ASIC). The main novelty of this method is that discrete data of sinusoidal wave can be stored in the controller, using this data the system can be simplified by cutting down the number of sampling circuits, and the discrete data provides sinusoidal reference current and sinusoidal input current even if the input voltage is distorted. Discussion of the hardware implementation is given, followed by the analysis of robustness and efficiency in this method. The performance of this PFC controller is demonstrated on a 100 KHz, 500W BOOST-bases PFC experimental prototype.**

***Keywords*— Power Factor Correction, Robustness, Embedded Universal Chip, Reference Current Rebuilding**

I. INTRODUCTION

To meet the Electro Magnetic Compatibility (EMC) requirement, power factor corrector (PFC) has been a hot research in recent years. Analog and digital control methods have been exploited to achieved unity power factor and reduce the total harmonics distortion (THD) [1], [2]. The advantages of digital controllers over analog ones are programming and flexibility for requirement changes [3], for this reason, the digital ones are much more popular. On the other hand, the previous implementations of the digital controlled PFC have some restrictions. The main one is that the sampling, calculation and processing time are limited to the switching frequency in [4]–[8]. In order to save time and reduce the size of the system, some measurement in PFC is avoided in some previous paper [9]–[11]. For instance, in [9], the current sensor is avoided. Instead, the input current is digitally rebuilt, using the estimated input current in the current loop. The problem of the methods mentioned is that when the input voltage is distorted, the current will follow the distortion and spread it to the whole gird.

This work, for cleaner grid, which attempts to find a simplified system solution, presents a controller which is valid for robust and efficient power factor correction in power driver and based on universal chip. The reference input current i_{ref} can be rebuilt by the data stored in the controller, and the controller controls the input current i_{in} to the shape and phase of the input voltage u_{in} by providing a switching sequence for the controllable switch that forces the inductor current toward i_{ref}. After this work, the power factor can achieve unity power factor.

The rest of this paper is organized as follows. In Section II, the simplification of the circuit is given. Robustness and efficiency of the PFC controller are presented in Section III. Experiment results are shown and discussion in Section IV. Section V concludes the work and shows the outlook.

II. SIMPLIFICATION OF THE CIRCUIT

The method introduced can be applied in many prototypes of DC/DC converters, such as BUCK, CUCK and BOOST. In this paper, this method is introduced through the PFC controller mainly by taking research on the BOOST DC/DC converter. This type of converter is widely used in PFC applications because of its characteristic to achieve high power factor with simple control methods [12]-[15]. Usually, three sensing points are used for the BOOST: rectified input voltage U_g, inductor current I_L and output voltage U_o. As shown in the Fig.1, only tow sensing points are needed in this method, which are input incurrent and output voltage. The reference current i_{ref} is rebuilt based on I_L and U_o.

50Hz AC mains input sinusoidal full-wave is rectified after the bridge, and then goes through the BOOST DC/DC converter, which is controlled by the PFC controller. The controller controls the input current i_{in} to the shape and phase of the input voltage u_{in} by providing a switching sequence for the controllable switch that forces the inductor current toward the reference current i_{ref} ,so that the unity power factor can be achieved. In many papers, the algorithms about how to get the duty cycle of switching sequence are exploited [16]-[18]. The problem needed to be solved in this paper is how this system performs well without the rectified input voltage sensor. The demonstration is below.

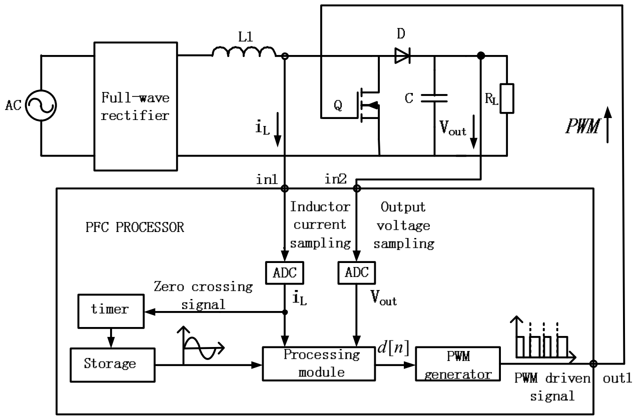

Figure 1. PFC controller in BOOST DC/DC converter

It is known to all that sine wave is symmetry, taking advantage of this feature and the storage capacity of the PFC controller, a complete waveform of sine can be kept as discrete data. Due to the symmetrical characteristic of sine wave that 1/4 (the phase is from 0 to π/2) of a sine wave is enough to rebuild a complete sine wave. In the end of every control period T_s, a discrete data is extracted and stored one by one. Assuming that the control frequency f_s is 100 KHz and the mains input frequency f_{line} is 50Hz, the number of the discrete data needed to be stored in the storage module can calculated by the formula below:

$$N = f_s / 4 f_{line} = 100000 / 4 \times 50 = 500 \tag{1}$$

Due to the values of the discrete data in the controller, which is noted as I_N (N=0, 1, 2, … , 499) the complex procedure of recreate the i_{ref} is omitted. But these data can not be used as i_{ref} directly before they have been multiplied by a proportionality factor K. K depends on the value of the output voltage U_o, and then the reference current can be expressed as:

$$i_{ref} = K_1 \times I_n \tag{2}$$

With the i_{ref} implemented by the proportionality factor K and the discrete data of the sinewave, the number of the sampling circuits can be cut down and the total cost will reduce. So the problem proposed above is solved.

III. ROBUSTNESS OF THE PFC CONTROLLER

As discussed above, reference current i_{ref} is obtained based on the rectified input voltage U_g in most of the PFC module, so if the distortion of input voltage occurs, it will make serious consequences to the whole electric system. While the method proposed in this paper is totally different. The PFC controller can perform very well when the fluctuations of electric supply occur as well as under the normal circumstances. The analysis of the robustness is below.

A. Waveform Distortion

When the waveform distortions of electric supply occur, output voltage U_o receives little compact. Because the change of output voltage is much slower than input voltage. So the proportionality factor of output voltage K keeps unchanged. The i_{ref} is implemented by the proportionality factor K and the discrete data of the sinewave. Since K and I_N keep unchanged, the reference current can still keep correct shape of sinusoidal. Using the correct reference current, the computing part can offer the precise duty cycles to the PWM generator, and the PWM signals to control the switch state of the transistor to achieve the unity power factor.

B. Frequency Fluctuations

In China, the national standard mains voltage frequency is 50Hz, under normal circumstances fluctuations shall not exceed ±0.2Hz, at special circumstances can be relaxed to ±0.5Hz, but can not exceed the maximum limit of ±1Hz. In this paper, the research is based on the maximum limit of the frequency, which is ±1Hz.

The reference current i_{ref} should follow the shape and phase of the input rectified voltage. Let f_{line} be the line frequency, when f_{line} is not 50Hz, the timer still offers the precise time intervals according to the standard line frequency. The trigger of the timer is the zero-crossing signal detected from the inductor current sampling circuit, which also reflects the zero-crossing signal of the rectified voltage. Let T_g be the period of the rectified voltage, and at the every beginning of T_g, the phase of the reference current keeps synchronous with the phase of the rectified voltage. At the end the period of T_g, the phase difference between the reference current and rectified voltage can be expressed as below:

$$\theta = \left| \left(\int_0^{\frac{1}{2 \times f_{line}}} 2 \times 50 \pi \, dt \right) - \pi \right| \tag{3}$$

θ does not be accumulated, because the zero-crossing signal clean it at every beginning of T_g. It is can be seen from the Fig.2 that the reference current ends before the rectified voltage when the f_{line} is 49Hz, and reference current ends after the rectified voltage when the f_{line} is 51Hz.

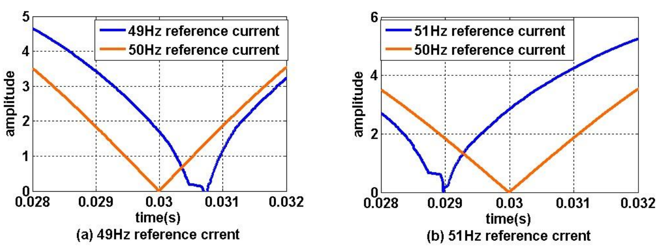

Figure 2. reference current under frequency fluctuations: (a) 49*Hz* reference current compare to 50*Hz*; (b) 51*Hz* reference current compare to 50*Hz*

At the middle of the rectified voltage period comes the peak, which is the moment that the power is at its maximum, the phase difference only achieve θ/2. Let cos(α) be the displacement factor, and α is the phase difference of the input current i_{in} and input voltage u_{in}. Under the conditions described in this article, the α of the displacement factor is approximately equal to the θ/2. At the peak of the rectified voltage, the displacement factor can be expressed as cos (θ/2).

The PF can be obtained from the equation below:

$$PF = \frac{1}{\sqrt{1+THD^2}} \cos\alpha \quad (4)$$

The θ/2 is small, and cos(α) is close to 1, so the displacement factor cos(α) makes little difference to PF.

Assuming the f_{line} is 51Hz, it is derived from (3) the θ_1 is 0.0196π, and the $\theta_1/2$ is 0.0098π, so the cos (α_{51}) is 0.9953. In the case of the 49Hz, the θ_2 is 0.0204π, and the $\theta_2/2$ is 0.0102π, so the cos(α_{49}) is 0.9949. As be seen from these data that the cos(α_{51}) and cos(α_{49}) are both very close to 1, which means the frequency fluctuations have little impact on the displacement factor and power factor in further level.

IV. EXPERIMENTS AND DISCUSSION

Simulations have been carried out in the MATLAB/simulink environment to verify the excellent performance of the proposed method. The following circuit parameters are used in the simulation of a BOOST DC/DC converter: L1=3mH, C1=470μF, switching frequency f_s is 100 KHz, the output voltage U_o is 500V, the output power P_o is 500W.

A. Normal circumstance

The steady-state waveforms of the scaled input voltage and output voltage are shown in the Fig.3(a) The power factor is 0.9940, and the DC output voltage is stabilized at the desired value of 500V with a 1.7% ripple at 50Hz. The FFT of input current in Fig.3(b) shows that the over 90% of the energy of input current concentrated in the 50Hz. It is clear that the PFC controller performs well under the normal circumstance.

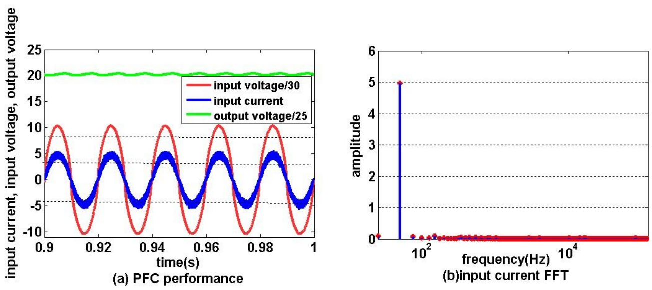

Figure 3. controller performance under the normal circumstance: (a) includes input current I_{in}, input voltage U_{in}, output voltage U_o; (b) input current FFT

B. Waveform Distortion

Fig.4 (a) shows the distortion of the input voltage u_o. In this experiment, a frequency component of 150Hz are added to u_o, and the input voltage is not a sinusoidal wave, so the FFT of u_o gives a rise at the frequency of 150Hz, which can be seen in Fig4.(b). Because of the reference current are not rebuilt based on the input voltage, the reference current i_{ref} and the input current i_{in} gets little impact. The FFT of i_{in} in Fig.4 (d) shows no rise at the other frequency, basically remains flat at the frequency of 150Hz. This verifies that when the u_o dose not keep sinusoidal wave, the i_{in} in Fig.4(c) still shows the correct shape, and reflects the great robustness of the controller function.

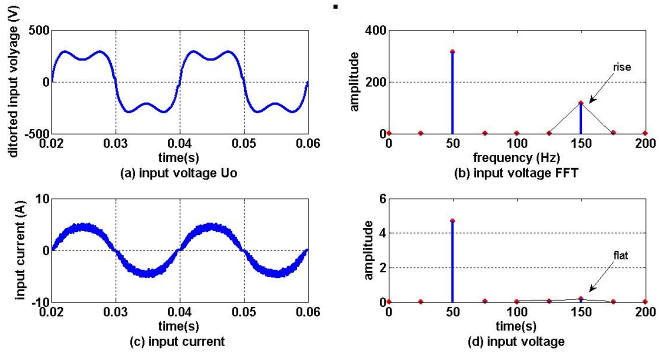

Figure 4. distortion of waveform : (a) the distorted input voltage u_{in}; (b) the FFT of u_{in} (c) input current i_{in} under the distortion of u_{in}; (d) the FFT of the i_{in}

C. Frequency fluctuation

Fig.5 demonstrates that when the frequency of input voltage changes, the input current i_{in49} and i_{in51} can keep energy concentrated in the 49Hz and 51Hz respectively. Even there is some tiny phase difference between the reference current and input voltage, the input current can follow the input voltage.

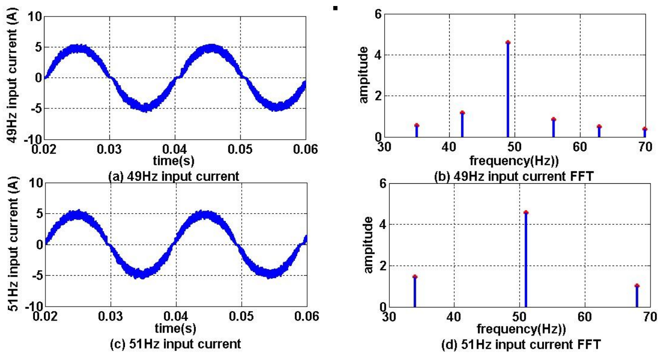

Figure 5. frequency distortion: (a) input current i_{in49} when the line frequency is 49Hz; (b) the FFT of i_{in49}; (c) input current i_{in51} when the f_{line} is 51Hz; (d) the FFT of i_{in51}

D. Discussion

From the experimental results, it's not hard to find that with the discrete data to rebuild reference current, the controller can perform very well. Even when the electric supply changes, the input current still can keep energy concentrated in the line frequency and keep sinusoidal wave. It should be noted that all the data is obtained under the ideal simulation condition, and if the transistor pipe pressure drop and power consumption of other components are taken into account, the results will be different, but the experimental data fully demonstrated the feasibility of the method.

V. CONCLUSION AND OUTLOOK

The proposed digital PFC controller in power driver has several advantages. First of all, this method can be implemented by universal chips instead of ASIC to make the input current follow the input voltage to achieve unity power factor. Secondly, the method can improve the robustness under the fluctuations of the electric supply. Thirdly, using the storage of the controller can simplify the system and reduce the total cost and system size. The experimental results are presented verify the advantages.

With the decreasing cost of controllers and increasing functionality, the method proposed in this paper can perform better for cleaner grid. The future work will focus on two aspects. The first one is taking advantage of function expanding, and making the PFC controller multifunctional in power driver to meet the need of other applied requirement. Another one is the soft switching technique. Because of the programmable ports of the controller, it is not impossible to implemented soft switching at the start time of the devices. In that way can reduce the electromagnetic interference caused by the shock wave.

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