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Input Current Parameters Analysis for PFC based on Quasi-Resonant and Conventional Boost Converters

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***Abstract*—This article presents a comparative analysis of the input current parameters for active power factor corrector (PFC) based on conventional boost converter (BC) and zero-current-switching quasi-resonant boost converter (ZCS-QRBC). The comparison was performed taking into account the spectral composition of the input current (individual harmonic levels, total harmonic distortion) and power factor. It has been shown that both converters rated for 1 kW output power are compliant with the requirements of international standard IEC61000-3-2.**

***Keywords*—active power factor correction; conventional boost converter; quasi-resonant boost converter; zero-current-switching; total harmonic distortion**

I. INTRODUCTION

Nowadays modern domestic and industrial electronic devices, rated for small and medium power, as usual contain pulse converters with transformerless input. The presence of such converters leads to distortion of the input current, i.e. lower power factor, which entails increasing the overall power consumption and harmonics emission to the supply network. The presence of harmonics in the mains leads to increased power consumption of the adjacent loads and emergency operation. In many countries there are special standards normalizing the emission of harmonics in the supply network [1]. To improve the power factor and hence decrease the overall power consumption and reduce the emission of harmonics is possible using active and passive power factor correctors (PFC). Some features and drawbacks of which are described in [2], [3], [4].

Active PFCs based on boost converters avoid most shortcomings of passive PFCs [4]. The active PFCs in which power switches are synchronized to supply voltage are known (so-called low-frequency active PFCs). Their operation frequency is equal to the line frequency (50 Hz) or its lower harmonics [2]. To provide better correction of the input current the active PFCs, in which operation frequency lies beyond the audible range, are commonly used. In this paper two high-frequency active PFCs containing bridge rectifier are considered. The first one is based on conventional boost converter (BC) while the second one is based on zero-current-switching quasi-resonant boost converter (ZCS-QRBC).

Desirable energy efficiency (close to unity power factor and high efficiency) in steady-state mode of the PFC converter is achieved by selecting the switching frequency of the power switch and appropriate control method. However, the switching frequency affects on the aforementioned energy parameters oppositely. The higher switching frequency as usual leads to increasing the switch power losses, but reducing the amplitudes of the input current harmonics. This contradiction can be resolved using PFC comprising ZCS-QRBC [5]. Such solutions allow increase the switching frequency up to 1 MHz and higher with minimal switch power losses [6]. Dimensions and weight of such PFC are reduced simultaneously.

Input current distortion comparative analysis of the conventional BC and ZCS-QRBC is important for appropriate selection the necessary pulse converter type in PFC. Some of these issues are discussed in [7]. A dynamic model that allows investigating the input current distortion of the PFCs based on conventional BC and ZCS-QRBC was proposed in [8].

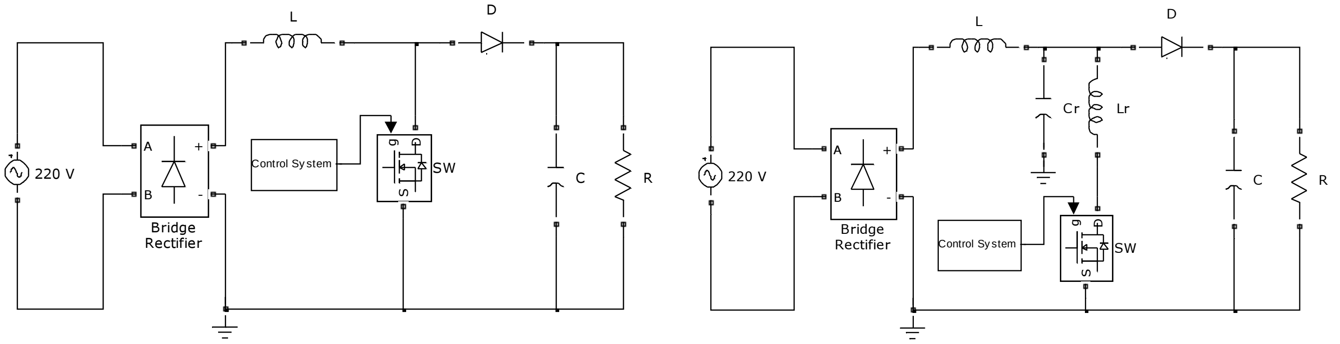
The aim of this article is a comparative analysis of the input current quality and power factor for PFC based on conventional BC and ZCS-QRBC under different control methods. The input current quality assumes individual harmonic levels and total harmonic distortion (THD). The assessment made based on modeling in MATLAB Simulink.

Two methods were used to control the conventional BC rated for the same parameters of passive elements. The first method is based on pulse width modulation (PWM) with constant frequency 100 kHz and variable duty cycle. The second method is based on frequency pulse width modulation (FPWM) with variable frequency and variable duty cycle. For ZCS-QRBC control system two control methods were used as well. They are based on frequency modulation (FM) for rated resonant frequency 100 kHz and the same parameters of passive elements as they were in BC.

The operation of each converter was explored under the same resistive load. The supply network is considered ideal. The presented investigation omits efficiency assessment and output voltage regulation issues. These problems represent the subject of the further research.

II. POWER STAGE DESCRIPTION AND CALCULATION

Fig. 1a represents the active PFC circuit based on conventional boost converter, while Fig. 1b illustrates active PFC circuit based on zero-current-switching quasi-resonant boost converter.



(a) (b)

Fig. 1. Active PFC circuits based on conventional boost converter (a) and zero-current-switching quasi-resonant boost converter (b)

The input of the circuit is connected to supply network, where AC voltage $u_{IN}(t) = U_m \sin \omega t$, $U_m = \sqrt{2} \cdot 220 \approx 311 V$. The output DC voltage average value $U_{OUT} = 360\,V$. The load resistance is $R = 120\,\Omega$. Thus, the output power of the converter is $P_{OUT} = 1080\,W$. Putting efficiency $\eta \approx 0{,}9$, we obtain the input active power $P_{IN} = 1200\,W$.

Consider the features of the passive elements selection. The output capacitance in conventional BC according to [9]

$$C = \frac{\gamma U_{OUT}}{\Delta U R f_S}, \tag{1}$$

where $\gamma = \frac{\tau}{T_S}$ – duty cycle of the control signal, τ – pulse width of the control signal, T_S – period of the control signal, U_{OUT} – output voltage average value, ΔU – specified output voltage ripple level, R – load resistance, $f_S = \frac{1}{T_S}$ – switching frequency.

In conventional BC supply voltage is smoothed enough as usual, while the input voltage of active PFC comprising conventional BC varies from 0 to U_m at 100 Hz frequency. Obviously, (1) does not imply the specified feature. According to [10], the value of output capacitance of the PFC should be

$$C = \frac{P_{IN}}{2\omega K U_{OUT}^2}, \tag{2}$$

where $K = \frac{U_{OUT(2)m}}{U_{OUT}}$ – ripple factor, $U_{OUT(2)m}$ – pulsation amplitude of the output voltage harmonic at frequency 100 Hz. Equation (2) is valid for both constant and variable switching frequency of the power switch. Putting ripple factor is equal 5% and based on (2) the output capacitance $C = 300\,\mu F$.

The storage inductance of conventional BC according to [9]

$$L = \frac{(1-\gamma)^2 \gamma R}{2 f_S}. \tag{3}$$

Equation (3) implies that inductor operates at the border between continuous conduction mode (CCM) and discontinuous conduction mode (DCM), i.e. it works in boundary conduction mode (BCM). In such case the inductor current ripple will have a maximum value. For a more accurate calculation an acceptable coefficient for current ripple must be taken into account. According to [11]

$$L = \frac{U_{IN}(U_{OUT} - U_{IN})}{\Delta I_L \cdot f_S \cdot U_{OUT}}, \tag{4}$$

where U_{IN} – average value of the input voltage. In our case the input voltage of BC is the rectified supply network voltage, whose average value

$$U_{IN} = \frac{1}{T/2} \int_0^{T/2} U_m \sin \omega t \, dt = \frac{2U_m}{\pi} \approx 198\,V, \tag{5}$$

where T – period of the supply network voltage. Inductor current ripple amplitude

$$\Delta I_L = (0{,}2...0{,}4) \cdot I_{OUTm} \cdot \frac{U_{OUT}}{U_{IN}}, \tag{6}$$

where I_{OUTm} – maximum output current. Based on the requirements to ensure minimum specified inductor current ripple at maximum operating frequency 100 kHz and using (4)-(6) we obtain the storage inductance $L = 820\,\mu H$.

Active PFC circuit based on ZCS-QRBC (Fig. 1b) differs from active PFC based on conventional BC (Fig. 1a) in the presence of the parallel resonant circuit $C_r L_r$. It provides zero current switching of the power switch SW and thus significantly reduces the switching losses and improves efficiency [12]. Its operation discussed in more details in [13].

The period of oscillations in the resonant circuit

$$T_0 = 2\pi\sqrt{L_r C_r}\ , \tag{7}$$

where L_r – value of the resonant inductance, C_r – value of the resonant capacitance. Since in the ZCS-QRBC frequency modulation is used, the duty cycle of the control signal must satisfy the condition of the switching at zero current. The corresponding parameters of the resonant circuit for this condition to be satisfied L_r = 6.1 mH, C_r = 220 nF. The values of the storage inductance and output capacitance were calculated using (2) and (4) and they are the same as they were for conventional BC.

III. CONTROL SYSTEM DESCRIPTION

Two control methods were used for a conventional BC. A simplified control scheme for the first method is shown in Fig. 2a. The PWM is used to generate control signals for power switch. The adder summarizes three signals. The reference signal $|U_m \sin \omega t|$, which represents the rectified voltage and sets the necessary input current shape. The factor K_1 defines the DC component of the output voltage. The feedback signal is an instantaneous value of the storage inductor current $I_L(t)$. The factor K_2 is a negative value, which performs scaling of the feedback signal. Values of the factors K_1 and K_2 are adjusted on the basis of a predetermined DC output voltage and taking into account their mutual compensation. The comparator C compares the output signal of the adder and the reference triangular signal with an amplitude U_m and frequency 100 kHz. The resulting rectangular pulses with variable duty cycle come to the gate of the power switch.

Fig. 2b shows a control scheme for the second method. This is hysteresis control method with variable frequency and variable duty cycle (frequency pulse width modulation). The instantaneous current in the storage inductor is monitored and compared with two envelopes. The shape of the envelope represents the reference signal $|U_m \sin \omega t|$, which is scaled by the factor K_4. The levels of the top and bottom envelopes are adjusted by factors K_3 and K_5 respectively. When current $I_L(t)$ reaches the upper envelope it activates the high comparator C_H. When $I_L(t)$ reaches the bottom envelope it activates the low comparator C_L. The output signal of the lower comparator goes on trigger T which clocked by the signal fronts from each comparator. The output signal of trigger T forms the control signal for power switch.

Fig. 2c shows the first control scheme for ZCS-QRBC using frequency modulation (FM1). The adder summarizes three signals which are formed similarly as it was in Fig. 2a. The feature of this method lies in the shaping of the control signal. The reference voltage is generated using totalizer Counter, which is clocked by the generator of rectangular pulses at frequency 35 MHz. When the reference signal is equal to the output signal of adder, the comparator C activates the monostable multivibrator. It generates a control signal with a duration $t_1 = 5$ µs, that is about half of the oscillation period of the resonant circuit. This signal is supplied to the power switch and the Counter is reset to zero.

Fig. 2d shows the second control scheme for ZCS-QRBC using frequency modulation (FM2). The reference signal $|U_m \sin \omega t|$ is scaled by K_8 and thus defines the desired lower limit of the input current. This value is supplied to comparator C_L, where it is compared with the measured instantaneous value of $I_L(t)$, which is scaled by K_9. Comparator output signal is input to D-trigger, which is clocked by the generator of rectangular pulses. The output signal Q launches monostable multivibrator that generates a control signal for power switch.

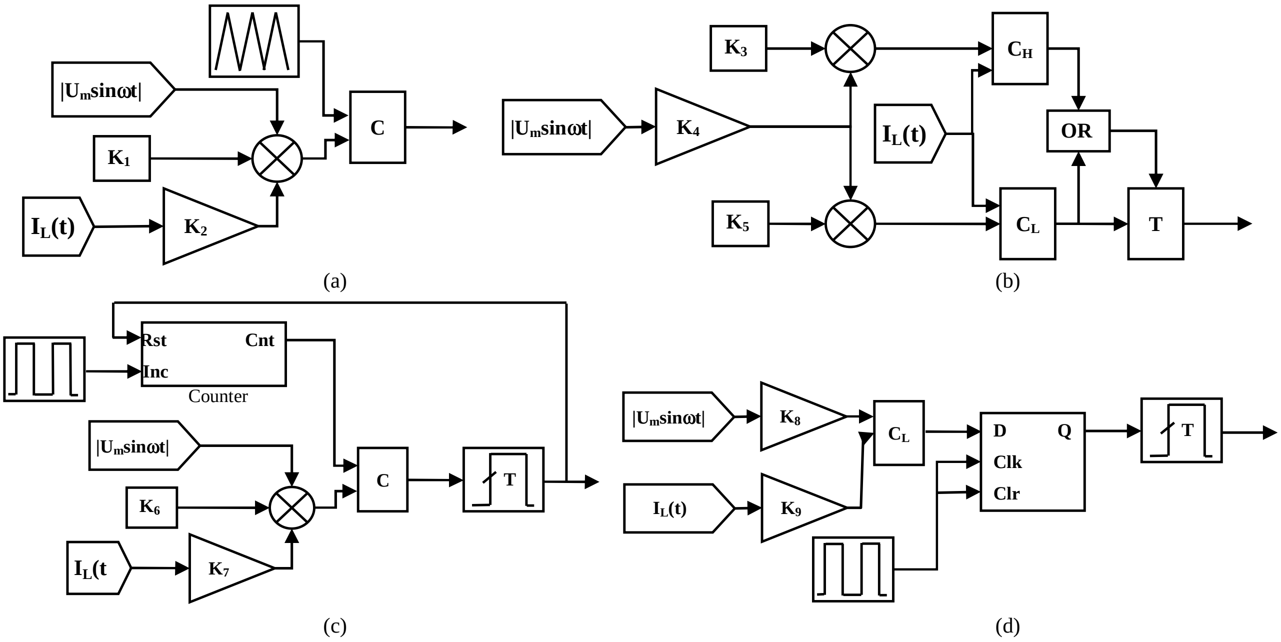


Fig. 2. Control schemes for PFC based on conventional BC using PWM (a) and FPWM (b), for PFC based on ZCS-QRBC using FM1 (c) and FM2 (d)

IV. SIMULATION RESULTS AND DISCUSSION

The simulation results for PFC based on conventional BC and ZCS-QRBC are shown in Fig. 3. In steady-state the output DC voltage is 360 V with ripple up to 5%.

The input current THD for PFC based on conventional BC using PWM is 10.34% (Fig. 4a). The input current amplitude at the fundamental frequency is 7.36 A. The power factor in this case is 0.9947. The input current THD for the same converter using FPWM is only 3.12% (Fig. 4b). The input current amplitude at the fundamental frequency is 7.271 A. The power factor in this case is 0.9995.

The input current THD for PFC based on ZCS-QRBC using FM1 is 8.85% (Fig. 4c). The input current amplitude at the fundamental frequency is 7.156 A. The power factor in this case is 0.9961. The input current THD for this converter using FM2 is 8.01% (Fig. 4d). The input current amplitude at the fundamental frequency is 7.951 A. The power factor in this case is 0.9968.

Fig. 5a and Fig. 5b show compliance of the input current harmonic levels with IEC 61000-3-2 for both converters. The limiting envelope was built in accordance with the requirements of IEC 61000-3-2 for class A equipment. As it shown, both converters with different control methods are capable of providing high-quality correction of the input current, i.e. power factor above 0.99 and spectrum of the input current that with a margin meets the requirements of the international standard [1].

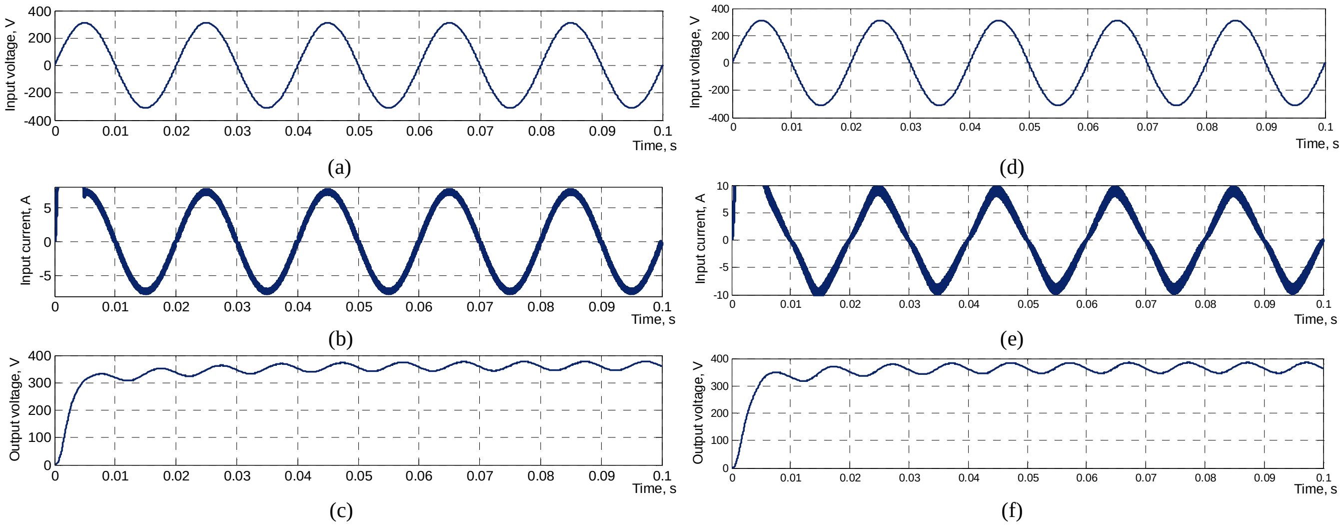


Fig. 3. Operation of PFC based on conventional BC using FPWM: input voltage (a), input current (b), output voltage (c) and operation of PFC based on ZCS-QRBC using FM1: input voltage (d), input current (e), output voltage (f)

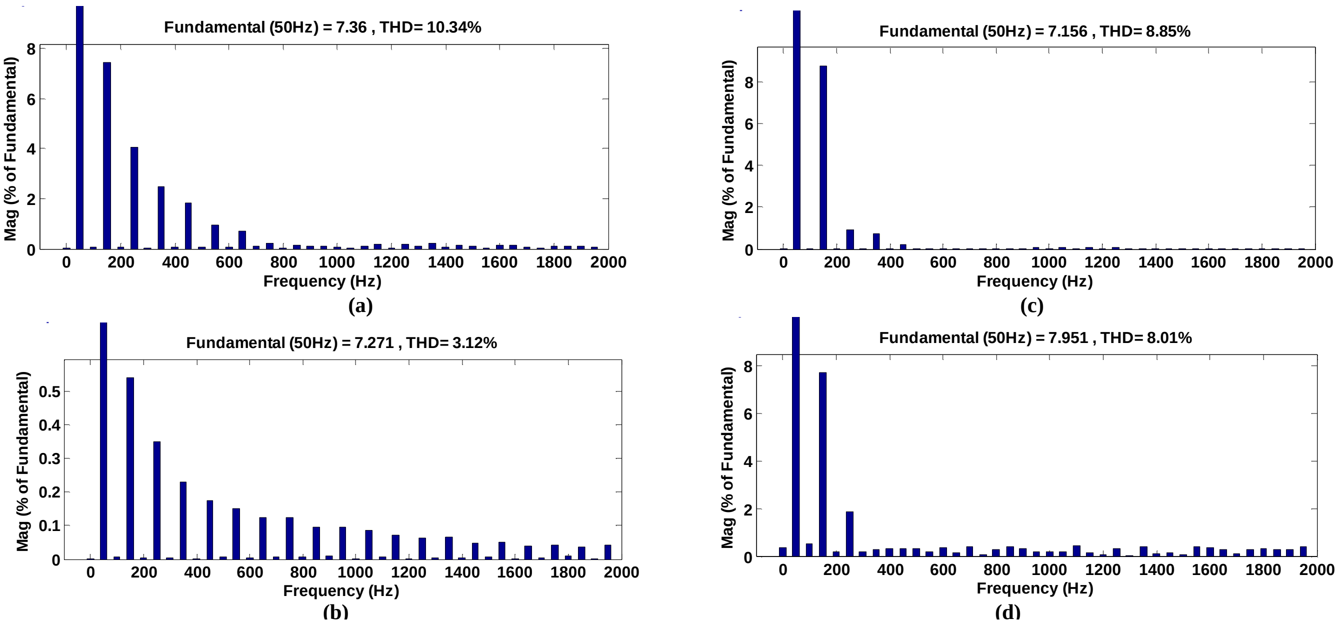
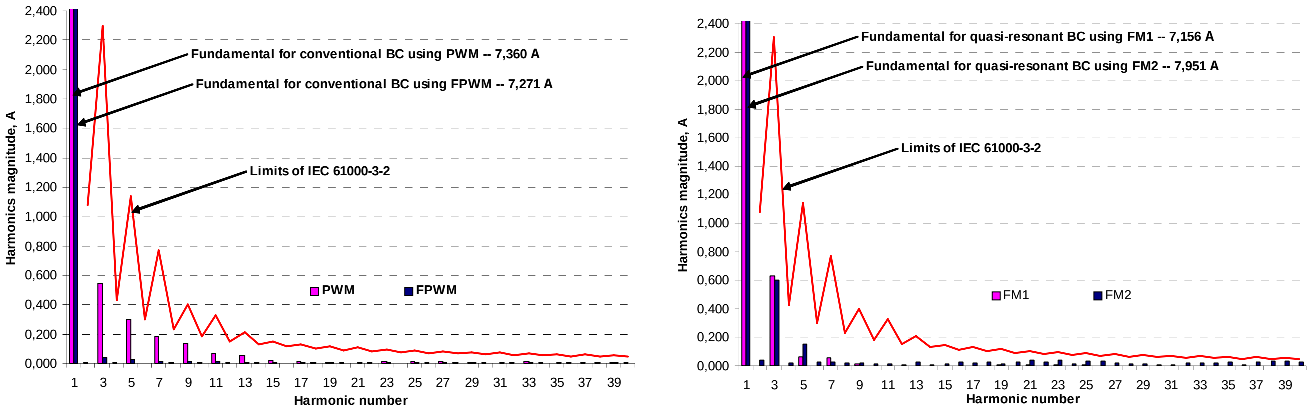


Fig. 4. Input current spectra for PFC based on conventional BC using PWM (a), using FPWM (b) and based on ZCS-QRBC using FM1 (c), using FM2 (d)



(a) (b)

Fig. 5. The input current spectra compliance with IEC 61000-3-2 limits for PFC based on conventional BC (a) and PFC based on ZCS-QRBC (b)

V. CONCLUSIONS

The results of the input current parameters analysis of the PFC based on conventional boost converter and zero-current-switching quasi-resonant boost converter have been presented. The investigations were made for different control methods in each converter. It was shown, that for the same parameters of the power stage PFCs based on conventional BC using PWM and based on ZCS-QRBC using FM have similar THD rates about 8-10%. The best quality of the input current is provided by PFC based on conventional BC using FPWM in which THD = 3%. It is achieved due to hysteresis control which is implemented in simulation with a sufficiently small width of the hysteresis. However, such quality of the input current will be difficult to obtain in practical implementation.

An achieved margin in the absolute values of the input current harmonics compared with the limits of IEC 61000-3-2 (Fig. 5a, Fig. 5b) for each method is caused not only by the quality of compensation, but also due to the low input power (1.2 kW). It is likely that higher power at the same conditions can increase significantly the input current harmonic rates. In such case the advantage of using hysteresis control is obvious.

Nevertheless, for more objective comparison of energy efficiency of PFCs based on conventional BC and ZCS-QRBC under different control methods, the power losses must also be taken into account, which in this study was not considered. The influence of the storage inductor value on the energy losses, that is quite interesting problem in switched-mode converters [14], could be investigated for PFCs based on conventional BC and ZCS-QRBC.

It should be noted that investigations were performed for the rated switching frequencies about 100 kHz. This frequency range is common used for conventional boost converter based on MOSFET. At the same time such operation frequency does not allow to fully realize the benefits of ZCS-QRBC in terms of energy efficiency. For higher operation frequencies the efficiency of conventional BC will drop considerably, while the efficiency of ZCS-QRBC will be high due to minimizing losses in the power switch. Besides that, at high frequencies the requirements for reference current accuracy and high speed of the control loops in PFC increases significantly.

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