Tao MENG, Yingying SUN, Hongqi BEN, Guo WEI

School of Electrical Engineering and Automation, Harbin Institute of Technology

Analysis and Harmonics Suppression of Input Current in a Three-Phase Single-Stage Full-Bridge PFC Converter

Abstract. *In this paper, the quality of input current waveforms was investigated for a three-phase single-stage full-bridge power factor correction (PFC) converter, which operates in DCM mode. The three-phase input current expression of the PFC converter was derived, and the parameter which can determine the input harmonics current was analyzed in details. Based on them, the method of sixth order harmonics injection was adopted in the control circuit to suppress its input harmonics current. Finally, computer simulation and experimental results prove the validity of the analysis in this paper.*

Streszczenie. *Zbadano jakość kształtu prądu wejściowego trójfazowego pełnomostkowgo układu korekcji współczynnika mocy PFC pracującego w trybie DCM. Analizowano parametry wpływające na zawartość harmonicznych tego prądu. Zaproponowano układ wstrzykiwania harmonicznych w celu poprawy jakości prądu. (**Analiza i tłumienie harmonicznych prądu wejściowego trójfazowego pełnomostkowego przekształtnika PFC**)*

Keywords: harmonics analysis, harmonics injection, power factor correction (PFC), three-phase single-stage.
Słowa kluczowe: tłumienie harmonicznych, przekształtnik, współczynnik mocy

Introduction

To comply with the international standards, such as IEC 555-2, high power quality achievement with low harmonic current and high power factor is increasing required in the power supply systems. Power factor correction (PFC) technique is a most effective method to reduce harmonic current and increase power factor [1-5]. There are two kinds of PFC due to the different circuit structures: two-stage and single-stage approaches. Compared with two-stage PFC, single-stage PFC has the advantages such as high efficiency, simplicity and low cost. At present, single-stage PFC is an important researching orientation of PFC techniques [6-8].

The isolated full-bridge boost topology is attractive in applications such as isolated DC/DC converter, single-phase and three-phase single-stage PFC, because: (1) it can realize electrical isolation between input and output sides and output voltage regulation, (2) achieve soft-switching for all switches, and (3) avoid short-through problem of the bridge legs switches [9, 10]. While the main drawbacks of the topology are: (1) due to the existing of the transformer leakage inductance, there is a voltage spike across each bridge leg switch, (2) an additional starting-up circuit is required to establish an initial output voltage [11, 12]. To solve these drawbacks, a number of techniques have been proposed. In an effort to suppress the voltage spike across the bridge leg switches, a method based on active clamp technique is introduced in [13-16], a passive clamping technique is proposed in [17], and two passive snubber method are proposed in [18, 19] respectively. For the starting problem, a flyback winding is coupled with boost inductor to realize starting-up of the DC/DC converter in [12, 20, 21], and two starting method based on flyback mode are presented for three-phase PFC in [22, 23] respectively.

In this paper, aiming at a three-phase single-stage PFC converter based on isolated full-bridge boost topology and active clamping technique, the problems of input current analysis and harmonics suppression are investigated, and the validity of the analysis is proved by computer simulation and experimental results.

PFC converter and its basic principle

The PFC converter with active clamping circuit is shown in Fig.1, where the active clamping circuit that made up of S_C and C_C is to suppress the voltage spike. The driving signal of each switch is shown in Fig.2, where duty cycle of switches S_1-S_4 is fixed at 50%, the switching state of S_1, S_2 is contrary to that of S_3, S_4 respectively, and the switching phase between S_1 or S_3 and S_2 or S_4 can be controlled. The switch S_C opens when the bridge diagonal leg switches (S_1, S_4 or S_2, S_3) are turning on, and the dead time t_{d1}, t_{d2} are used to avoid that S_C opens when the bridge leg switches are shorted (S_1, S_2 or S_3, S_4 are turning on).

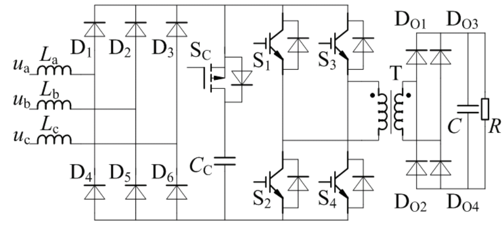

Fig.1 The PFC converter with active clamping circuit

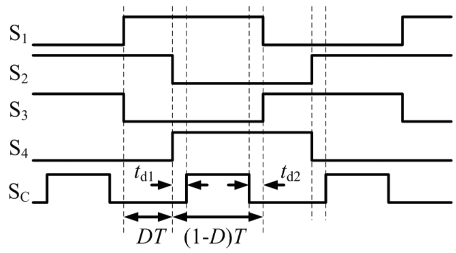

Fig.2 Driving signal of each switch

The converter operates in discontinuous current mode (DCM). When the bridge leg switches are shorted, the boost inductors L_a, L_b, L_c are charged by three-phase input source, and their current i_{La}, i_{Lb}, i_{Lc} increases from zero almost linearly. When the bridge diagonal leg switches turn on, the output current is provided by both three-phase input source and boost inductors, and i_{La}, i_{Lb}, i_{Lc} decreases. It can be seen that the process above is repeated periodically, the discontinuous current i_{La}, i_{Lb}, i_{Lc} follow envelopes which is proportional to the respective phase voltage, so PFC and AC/DC conversion can be achieved.

Analysis of input current

To simplify the analysis, the following calculation is during the time $0 \le \omega t \le \pi/6$, where $u_{bn} \le 0 \le u_{an} \le u_{cn}$ (u_{an}, u_{bn}, u_{cn} are the phase voltage of three-phase input source). The converter operates in DCM, so there are four stages in each charging period T of the boost inductors L_a, L_b, L_c. The waveforms of i_{La}, i_{Lb}, i_{Lc} during one charging period are shown in Fig.3.

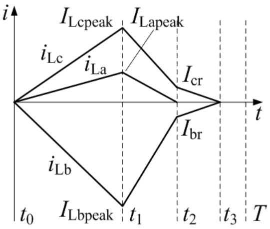

Fig.3 Waveforms of i_{La}, i_{Lb}, i_{Lc} during one charging period

Stage 1 (t_0~t_1): The bridge leg switches are shorted, i_{La}, i_{Lb}, i_{Lc} increases from zero and the output current is provided by the capacitor C alone. In this stage, the following relationship can be obtained:

$$(1)\quad \begin{cases} u_{an} - L\dfrac{di_{La}}{dt} + L\dfrac{di_{Lb}}{dt} = u_{bn} \\ u_{cn} - L\dfrac{di_{Lc}}{dt} + L\dfrac{di_{Lb}}{dt} = u_{bn} \\ u_{an} + u_{bn} + u_{cn} = 0 \\ i_{La} + i_{Lb} + i_{Lc} = 0 \end{cases} \Rightarrow \begin{cases} i_{La}(t) = \dfrac{u_{an}}{L}(t - t_0) \\ i_{Lb}(t) = \dfrac{u_{bn}}{L}(t - t_0) \\ i_{Lc}(t) = \dfrac{u_{cn}}{L}(t - t_0) \end{cases}$$

where, L_a=L_b=L_c=L.

Stage 2 (t_1~t_2): The bridge diagonal leg switches are turning on, i_{La}, i_{Lb}, i_{Lc} begin to decrease and the output current is provided by both the three-phase input source and the boost inductors L_a, L_b, L_c. In this stage, the following relationship can be obtained:

$$(2)\quad \begin{cases} u_{an} - L\dfrac{di_{La}}{dt} - nU_o + L\dfrac{di_{Lb}}{dt} = u_{bn} \\ u_{cn} - L\dfrac{di_{Lc}}{dt} - nU_o + L\dfrac{di_{Lb}}{dt} = u_{bn} \\ u_{an} + u_{bn} + u_{cn} = 0 \\ i_{La} + i_{Lb} + i_{Lc} = 0 \end{cases} \Rightarrow$$

$$\begin{cases} i_{La}(t) = \dfrac{u_{an}}{L}(t_1 - t_0) - \dfrac{nU_o - 3u_{an}}{3L}(t - t_1) \\ i_{Lb}(t) = \dfrac{u_{bn}}{L}(t_1 - t_0) + \dfrac{2nU_o + 3u_{bn}}{3L}(t - t_1) \\ i_{Lc}(t) = \dfrac{u_{cn}}{L}(t_1 - t_0) - \dfrac{nU_o - 3u_{cn}}{3L}(t - t_1) \end{cases}$$

Where U_o is the output voltage of the PFC converter and n is the voltage ratio of the transformer T.

Stage 3 (t_2~t_3): The switching mode is the same as that of stage 2. In this stage, the current of the phase which is minimum among three-phase reduces to zero, in other words i_{La}=0. So the following relationship can be obtained in this stage:

$$(3)\quad \begin{cases} u_{cn} - L\dfrac{di_{Lc}}{dt} - nU_o + L\dfrac{di_{Lb}}{dt} = u_{bn} \\ i_{Lb} + i_{Lc} = 0 \end{cases} \Rightarrow$$

$$\begin{cases} i_{La}(t) = 0 \\ i_{Lb}(t) = -i_{Lc} = \dfrac{u_{bn} + nU_o - u_{cn}}{2L}(t - t_2) + I_{br} \end{cases}$$

where I_{br}=$i_{Lb}(t_2)$.

Stage 4 (t_3~T): In this stage, i_{La}, i_{Lb}, i_{Lc} reduces to zero and the output current is provided by the capacitor C alone.

Here we define: t_{on}=t_1-t_0 is the time that the bridge leg switches are shorted and the boost inductors are charged, t_{off1}=t_2-t_1, t_{off2}=t_3-t_2 are the time that the bridge diagonal leg switches are turning on and the boost inductors are discharged. So the duty cycle of this PFC converter can be defined:

$$(4)\quad D = \frac{t_{on}}{T}$$

From (2), t_{off1}, I_{br}, I_{cr} can be calculated:

$$(5)\quad t_{off1} = \frac{3u_{an}}{nU_o - 3u_{an}} DT$$

$$(6)\quad I_{br} = -I_{cr} = \frac{u_{bn}}{L} DT + \frac{t_{off1}}{3L}(2nU_o + 3u_{bn})$$

Where I_{cr}=$i_{Lc}(t_2)$.

From (3) and (6), t_{off1} can be calculated:

$$(7)\quad t_{off2} = \frac{-2LI_{br}}{u_{bn} + nU_o - u_{cn}}$$

From Fig.3, the relationships of i_{La}, i_{Lb}, i_{Lc} can be obtained:

$$(8)\quad \int_0^T i_{La}dt = \frac{I_{Lapeak}}{2}(t_{on} + t_{off1})$$

$$(9)\quad \int_0^T i_{Lb}dt = \frac{I_{Lbpeak}}{2}t_{on} + \frac{I_{Lbpeak} + I_{br}}{2}t_{off1} + \frac{I_{br}}{2}t_{off2}$$

$$(10)\quad \int_0^T i_{Lc}dt = \frac{I_{Lcpeak}}{2}t_{on} + \frac{I_{Lcpeak} + I_{cr}}{2}t_{off1} + \frac{I_{cr}}{2}t_{off2}$$

where I_{Lapeak}, I_{Lbpeak}, I_{Lcpeak} are the peak value of i_{La}, i_{Lb}, i_{Lc} during one charing period of the boost inductors, which can be calculated as:

$$(11)\quad \begin{cases} I_{Lapeak} = \dfrac{t_{on}}{L}u_{an} \\ I_{Lbpeak} = \dfrac{t_{on}}{L}u_{bn} \\ I_{Lcpeak} = \dfrac{t_{on}}{L}u_{cn} \end{cases}$$

So from (8), the mean value of i_{La} during one charging period of the boost inductors can be calculated:

$$(12)\quad I_{Laavg} = \frac{D^2TnU_o}{2L}\frac{\sin\omega t}{\sqrt{3}M - 3\sin\omega t}$$

In (12), M is the voltage ratio of the converter, which is defined as:

$$(13)\quad M = nU_o / \sqrt{3}U$$

where U is the maximum value of u_{an}, u_{bn}, u_{cn}.

The charging frequency of of the boost inductors L_a, L_b, L_c is much higher than the frequency of the three-phase input source, so we can use the mean value of i_{La} during one charging period as shown in (12) as the instantaneous value of i_{La} during the time $0 \le \omega t \le \pi/6$. Analogously, the instantaneous value of i_{La} during the time $\pi/6 \le \omega t \le \pi/3$ and $\pi/3 \le \omega t \le \pi/2$ can be calculated from (9) and (10). So the instantaneous value of i_{La} during the time $0 \le \omega t \le \pi/2$ can be calculated.

(14)

$$\begin{cases} i_{\mathrm{La}[0,\frac{\pi}{6}]}(t)=\dfrac{D^2TnU_{\mathrm{o}}}{2L}\dfrac{\sin\omega t}{\sqrt{3}M-3\sin\omega t} \\ i_{\mathrm{La}[\frac{\pi}{6},\frac{\pi}{3}]}(t)=\dfrac{D^2TnU_{\mathrm{o}}}{4L}\dfrac{2M\sin\omega t+\sin(2\omega t-\frac{2\pi}{3})}{[\sqrt{3}M-3\sin(\omega t+\frac{2\pi}{3})][M-\sin(\omega t+\frac{\pi}{6})]} \\ i_{\mathrm{La}[\frac{\pi}{3},\frac{\pi}{2}]}(t)=\dfrac{D^2TnU_{\mathrm{o}}}{2L}\dfrac{M\sin\omega t+\sin(2\omega t-\frac{\pi}{3})}{[\sqrt{3}M+3\sin(\omega t+\frac{2\pi}{3})][M-\sin(\omega t+\frac{\pi}{6})]} \end{cases}$$

While, in the time other than 0≤*ωt*≤*π*/2, the exppression of i_{La} are similar to that in 0≤*ωt*≤*π*/2, so we ignore them here. From (14), we can see that as the voltage ratio *M* increases, the quality of the input current will be increase. As shown in (15), when *M* became infinity, the input current will be normal sinusoidal.

(15) $$\lim_{M\to\infty} i_{\mathrm{La}[0,\frac{\pi}{2}]}(t)=\frac{D^2T}{2L}U\sin\omega t$$

Harmonics suppression of input current

The PFC converter in Fig.1 is with three-phase three-wire input, so the order of its input current harmonics is 6k±1 (k is natural number), namely, the main orders of harmonics are: 5, 7, 11, 13, 17, 19. From (15), we can see that the power factor (PF) will increase and the total harmonic distortion (THD) will decrease as the voltage ratio *M* increases. However, the voltage stress of each switch will be increasing when *M* increases, so this method can not be adopted. The method of sixth order harmonics injection has been studied in the three-phase single-switch PFC converter [24-26], and it is also suitable for the PFC converter in Fig.1. So it can be adopted and analyzed.

Expression of the duty cycle after a sixth order harmonic being injected in the control circuit is:

(16) $$D(t)=D\left[1+m\sin(6\omega t+\frac{3\pi}{2})\right]$$

where *m* is the modulation ratio, and 0<*m*<1.

Generally, the content of 5th order harmonic is larger than others, so the three-phase input current can be approximated as:

(17) $$\begin{cases} i_{\mathrm{La}}=I_1\sin\omega t+I_5\sin(5\omega t+\pi) \\ i_{\mathrm{Lb}}=I_1\sin(\omega t-\frac{2\pi}{3})+I_5\sin(5\omega t-\frac{\pi}{3}) \\ i_{\mathrm{Lc}}=I_1\sin(\omega t-\frac{4\pi}{3})+I_5\sin(5\omega t+\frac{\pi}{3}) \end{cases}$$

where I_1 is the fundamental current and I_5 is the 5th harmonic current.

From (14) and (16), after fourier analysis, we can get approximately:

(18)

$$\begin{cases} i_{\mathrm{La}}=I_1\sin\omega t+(I_5-mI_1)\sin(5\omega t+\pi)-mI_1\sin 7\omega t \\ i_{\mathrm{Lb}}=I_1\sin(\omega t-\frac{2\pi}{3})+(I_5-mI_1)\sin(5\omega t-\frac{\pi}{3})-mI_1\sin(7\omega t-\frac{2\pi}{3}) \\ i_{\mathrm{Lc}}=I_1\sin(\omega t-\frac{4\pi}{3})+(I_5-mI_1)\sin(5\omega t+\frac{\pi}{3})-mI_1\sin(7\omega t-\frac{4\pi}{3}) \end{cases}$$

From (18), we can see that: after a sixth order harmonic being injected in the control circuit, the content of 5th order harmonic decreases and the content of 7th order harmonic increases. The THD is calculated from (17) and (18) respectively, and we can see that: after a sixth order harmonic being injected in the control circuit, the THD of the PFC converter is decreasing obviously, as shown in (19).

(19) $$\mathrm{THD}=\sqrt{\frac{(I_5-mI_1)^2+(mI_1)^2}{I_1^2}}<\frac{I_5}{I_1}$$

Fig.4 is the typical circuit of sixth order harmonics injection, and Fig.5 shows the waveforms of U_{d} and U_{inj}. The harmonics injection signal U_{inj} is injected into the PWM controller of the PFC converter, and the duty cycle can be regulated to suppress the 5th harmonic current. In fact, the variable of duty cycle *d*(t) is proportional to U_{inj}, so during one line cycle, the duty cycle can be expressed as:

(20) $$D(t)=D\left[1+d(t)\right]$$

After fourier analysis, the periodic function *d*(t) can be expressed as:

(21) $$d(t)=\sum_{\mathrm{k}=1}^{+\infty}m_{\mathrm{k}}\cos(6\mathrm{k}\omega \mathrm{t})$$

Where m_{k} is the modulation ratio of 6kth harmonic current.

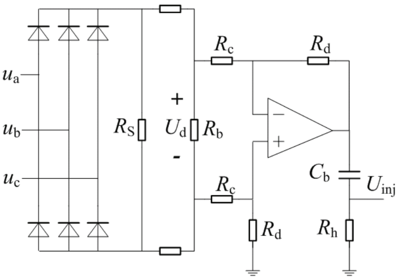

Fig.4 Typical circuit of sixth order harmonics injection

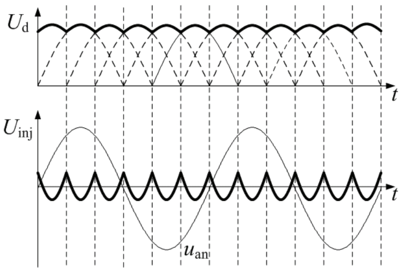

Fig.5 Waveforms of U_{d} and U_{inj}

From (21), we can see that the injection signal contains the 6kth harmonics components. From the analysis above, it can be seen that the content of 6k±1th harmonics current can be improved with the 6kth harmonics signal injection.

Simulation and Experiment

Computer simulation and prototype experiment are carried out to verify the analysis in this paper, where $L_{\mathrm{a}}=L_{\mathrm{b}}=L_{\mathrm{c}}$=76μH, C_{C}=4μF, *C*=1000μF, *n*=2, the switching frequency of S_1-S_4 is 20kHz. Fig.6-Fig.9 show the simulation results and Fig.10-Fig.12 show the experimental results.

Fig.6 shows three-phase input current waveforms, we can see that the PFC converter operates in DCM, and the peak of its input current is sinusoidal.

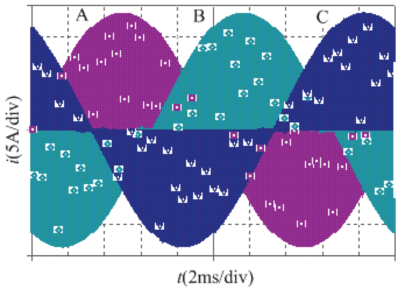

Fig. 6 Simulation results of three-phase input current

Fig.7 shows the harmonics analysis of input current, and it shows that the main order of harmonics is: 5, 7, 11, 13, 17, 19. Fig.8 and Fig.9 show that the power factor (PF) of the PFC converter will increase and its total harmonics distortion (THD) will decrease as the voltage ratio *M* increase, which verifies the analysis above.

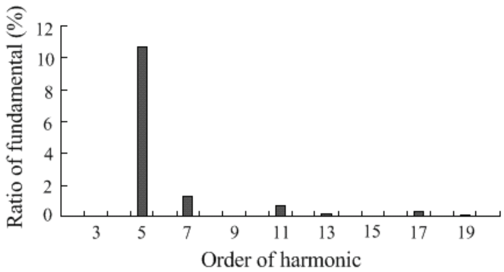

Fig.7 Harmonics analysis of input current

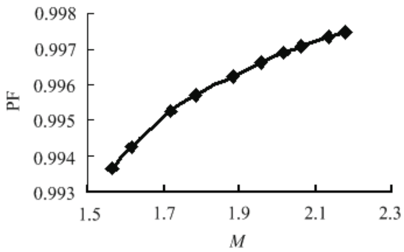

Fig.8 Relationship between power factor (PF) and voltage ratio (*M*)

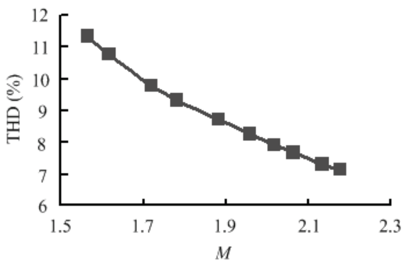

Fig.9 Relationship between total harmonics distortion (THD) and voltge ratio (*M*)

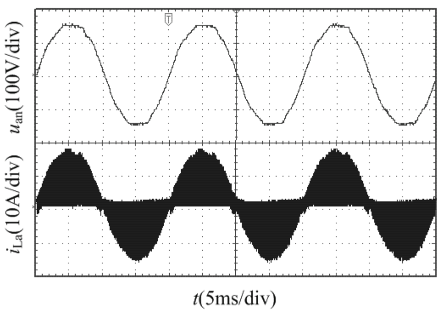

Fig.10 Waveforms of Input voltage and current of phase A

Fig.10 shows the input voltage and current waveforms of phase A. We can see that the discontinuous input current follow envelopes which is proportional to the respective voltage.

Fig.11 is the waveform of U_{inj}, which is the injection signal. Fig.12 gives the experimental results of the 5th and 7th harmonics current content in the input current. We can see that: after the method of sixth order harmonics injection is adopted, the content of 5th harmonic in input current is suppressed obviously and the total harmonics distortion (THD) also decreases, which verifies the analysis above. From the simulation results, we can see that compared to the content of 5th and 7th harmonics, the content of other orders harmonics is very small, so their influence on the THD of the input side can be neglected.

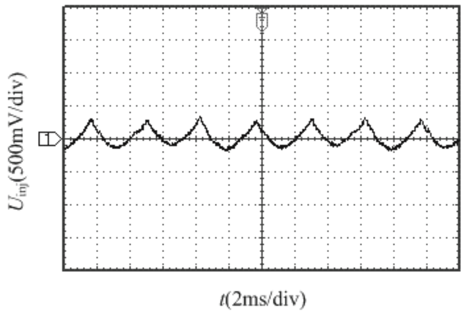

Fig.11 Waveform of harmonic injected signal U_{inj}

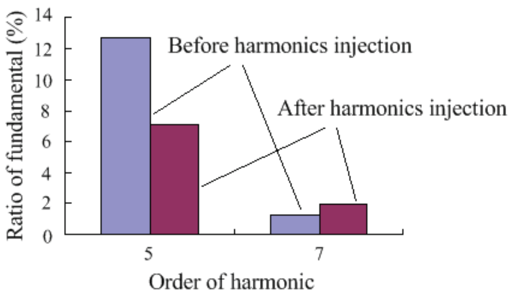

Fig.12 Comparation of input current harmonics before and after harmonics injection

Conclusions

Analysis and harmonics suppression of input current in a three-phase single-stage PFC converter is investigated in this paper. The three-phase input current expression of the PFC converter is derived in details, through which it concludes that the voltage ratio *M* can determine the quality of the input current waveforms. After harmonics analysis of the input current, the method of sixth order harmonics injection is adopted to suppress the input harmonics current of the PFC converter. Through 6kth harmonics signal being injected into the duty cycle of the PFC converter, the content of 6k±1th harmonics current can be improved efficiently. Finally, simulation and experiment results verify the analysis of this paper.

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***Authors**: dr. Tao Meng, 426#, School of Electrical Engineering and Automation, Harbin Institute of Technology, Harbin, 150001, China, E-mail: mengtao@hit.edu.cn, mengtaohit@163.com; Yingying Sun, master student, School of Electrical Engineering and Automation, Harbin Institute of Technology, Harbin, 150001, China; prof. Hongqi Ben and prof. Guo Wei, School of Electrical Engineering and Automation, Harbin Institute of Technology, Harbin, 150001, China.*