Three-Phase Rectifier with Near-Sinusoidal Input Currents and Capacitors Parallel Connected with the Upper Diodes

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Abstract- **In order to improve the distorted current of the conventional uncontrolled rectifier connected with the capacitance load, former researchers used to propose a new rectifier where inductors are series connect with the ac side and capacitors are parallel connected with the upper diodes. Although improved input current is achieved, the rectifier uses LC filter in the dc side, resulting in large size of the equipment. Moreover, no valid design method is proposed, limiting the application of the rectifier. This paper proposes a novel three-phase rectifier with near-sinusoidal input currents, which is composed of ac-side inductors, three-phase uncontrolled rectifier, commutation capacitor parallel connected with the upper diode and the dc-side filter capacitor. The operation principle of this novel rectifier is analyzed, and the differences of the characteristics between two rectifiers are compared. Additionally, practical parameter optimal design methods of the two rectifiers are proposed. Experimental results show that good harmonic rejection is obtained by using the two rectifiers. Compared with the rectifier with dc-side LC filter, the novel rectifier with dc-side C filter has better comprehensive performance.**

I. Introduction

Due to the rapid development of the power electronic technology, a number of power electronic equipments have been utilized. The conventional uncontrolled three-phase rectifiers with dc-side C filter are widely used as interface circuits between the utility grid and the power electronic equipments for their simplicity and reliability.

A large amount of harmonic components of current drawn from ac mains by the nonlinear load bring serious problems [1]. Active power filter (APF) technology has attracted more and more attention for its excellent harmonic filtering performance. However, the active filters are slightly inferior in cost and efficiency to the passive filters [2].

The passive power factor correction (PPFC) technology is more widely used for its low cost, high reliability and simple fabrication. Traditional method to improve three-phase power factor is using passive LC filters, which can be placed in ac side or dc side of the rectifiers. However, ac-side LC filter bring about dc voltage varying in a wide range and dc-side LC filter hardly obtain satisfactory performance [3], [4]. At present, some other PPFC technologies have been proposed and utilized. Multiple pulse rectifiers eliminate low-order harmonics through autotransformer, making the input current near-sinusoidal [5]-[7]. Rectifiers applying current injection contribute to the reduction of other harmonics present in input current, where the frequency of the injecting current is equal to the triple of the line frequency [8], [9]. Novel topology rectifiers, such as three-phase rectifiers with near sinusoidal input currents [10] and three -phase diode rectifiers with LC resonance in commercial frequency [11]-[14] have caught increasing attention in recent years.

Three-phase rectifier with sinusoidal input currents and capacitors parallel connected with the upper diode was proposed by K. Ohtsuka in [11] in 2001. Compared with the various active power correction circuits, this rectifier can achieve power factor correction without using switching device. So switching losses and switching noise such as EMI, are not generated. The system cost is reduced because a control circuit for the switching device is also unnecessary. But following faults limit the application of this rectifier.

--First, no practical optimal parameter design method is proposed;

--Second, LC filter is used on the dc side, resulting big size and heavy weight of the rectifier.

In order to solve the demerits, a novel three-phase rectifier with near sinusoidal currents and dc side C filter is proposed in this paper where the operation principle of the novel rectifier is analyzed. From the differences of the characteristics of the two rectifiers, we could draw the conclusion that the novel rectifier with dc-side C filter has better comprehensive performance. Additionally, optimal parameter design methods both for the two rectifiers are given. Experimental results verify the validity of the analysis and the feasibility of the method.

II. Operation Principle

To analyze the operation principle, the following assumptions are made:

- ideal diodes and passive components
- stead state already

The phase voltages and input currents are supposed as follows:

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$$
\begin{aligned}
e_u &= U_m \sin \omega t & i_u &= I_m \sin \omega t \\
e_v &= U_m \sin(\omega t - \frac{2}{3}\pi) & i_v &= I_m \sin(\omega t - \frac{2}{3}\pi) \\
e_w &= U_m \sin(\omega t + \frac{2}{3}\pi) & i_w &= I_m \sin(\omega t + \frac{2}{3}\pi)
\end{aligned}
\tag{1}
$$

Where U_m is the amplitude of phase voltage, I_m is the amplitude of input current.

A. Three-phase rectifer with dc-side LC filter

Fig.1 shows the configuration of three-phase rectifier with sinusoidal input currents and capacitors parallel connected with the upper diode. Detail analysis of this converter which has been studied by K. Ohtsuka could be found in [11].

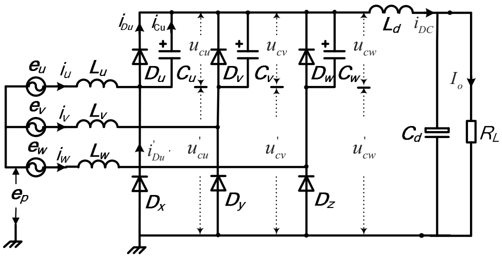


Fig.1. Topology of three-phase rectifier with dc-side LC filter

As Fig.2 illustrates, four operation stages exist in one period of the rectifier. LC resonance happens in all operation stages except stage III, so the input current is improved and the power factor is increase as well.

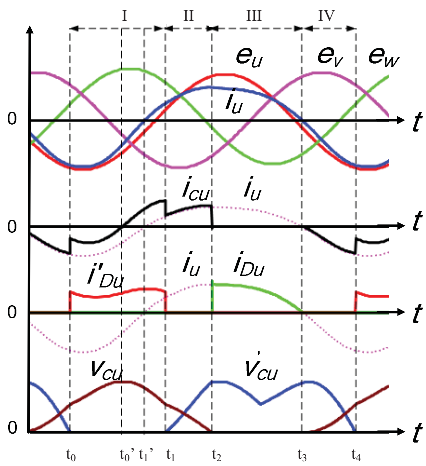


Fig.2. Key waveforms of the three-phase rectifier with dc-side LC filter

The rectifier has following properties: a nearly constant current characteristic due to the LC resonance; only one operation mode exists in the rectifier, meanwhile the conduction intervals of diodes keep constant.

B. Proposed three-phase rectifer with dc-side C filter

A novel three-phase rectifier with near sinusoidal currents and dc side C filter is proposed in this paper. Fig.3 shows the configuration of the rectifier, which is composed of three series inductors L_u, L_v, L_w of equal inductance values L and three commutation capacitors C_1-C_3 of equal capacitance values C, where C_d is the output filter capacitor.

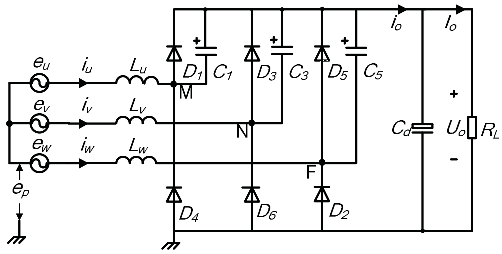
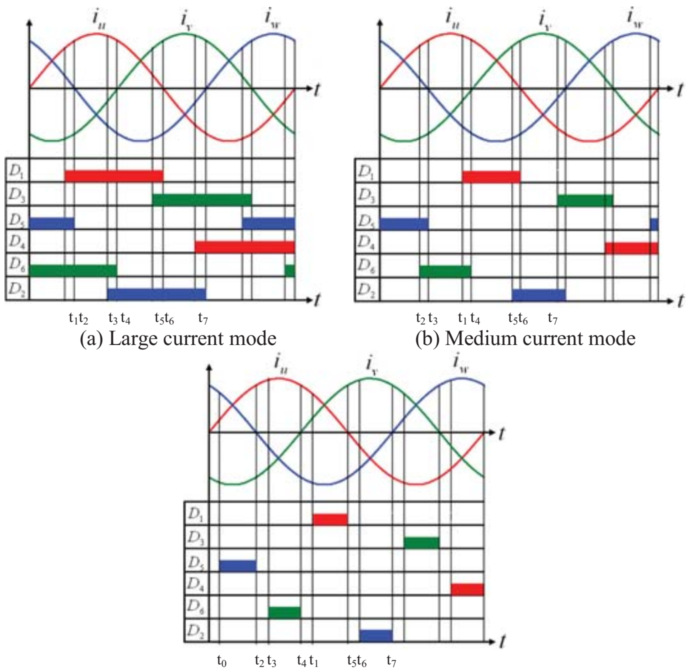


Fig.3. Topology of the novel three-phase rectifier with dc-side C filter

Different durations of the current charging the commutation capacitor, which vary with the load, determine the distinct operation modes of the rectifier: large current mode, medium current mode and small current mode.

The duration of the current charging or discharging the capacitors is defined as t_1. Because capacitors begin to charge or discharge when the input currents cross zero, the conduction intervals of each diodes equal to $\pi/\omega - t_1$ due to the parallel connection of the capacitors and diodes.



(a) Large current mode

(b) Medium current mode

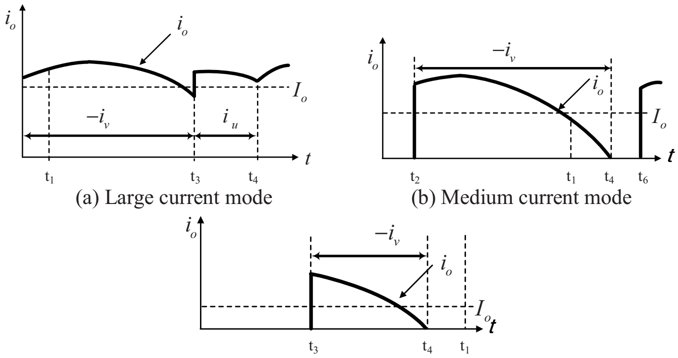
(c) Small current mode

Fig. 4. Key waveforms of the novel rectifier working in different modes

In small current mode ($2\pi/3 < \omega t_1 < \pi$), none or one diode is conducting at any time. The conduction intervals of diode increase when the load current increases, as well as t_1 decreases. Rectifier changes into the medium current mode ($\pi/3 < \omega t_1 < 2\pi/3$), in which one or two diodes are conducting. With the load current increasing continuously, rectifier changes into the large current mode ($0 < \omega t_1 < \pi/3$), in which two or three diodes are conducting. The waveforms of the phase currents and conduction intervals of the diodes are shown in Fig.

4, from which differences among the three modes can be deduced.

When the rectifier is working in the large current mode, the dc-side current i_o become a 12-pulse waveform with different width (as shown in Fig. 5(a)). When the rectifier is working in the medium current mode and small current mode, the dc-side current i_o is discontinuous (as shown in Fig. 5(b) and (c)). The input currents flow through the passive components during the discontinuous intervals, transferring no power to load from the mains.



(a) Large current mode (b) Medium current mode

(c) Small current mode

Fig. 5. Dc-side current waveforms of the proposed rectifier working in different modes

From Fig.5, the output current I_o, namely the mean value of i_o, could be derived. The output current I_o, the mean value of i_o, in three operation modes could be expressed respectively:

In large current mode,

$$I_o = \frac{3}{2\pi}\left[\int_0^{\omega t_1+\frac{1}{3}\pi} -I_m \sin(\omega t - \frac{2}{3}\pi)\, d\omega t + \int_{\omega t_1+\frac{1}{3}\pi}^{\frac{2\pi}{3}} I_m \sin\omega t\, d\omega t\right] \tag{2}$$

In medium current mode,

$$I_o = \frac{3}{2\pi}\int_{\omega t_1-\frac{1}{3}\pi}^{\frac{2\pi}{3}} I_m \sin\omega t\, d\omega t \tag{3}$$

In small current mode,

$$I_o = \frac{3}{2\pi}\int_{\omega t_1-\frac{1}{3}\pi}^{\frac{2\pi}{3}} I_m \sin\omega t\, d\omega t \tag{4}$$

By simplifying (2), (3), (4), we could find that I_o in three modes has the same expression as follow:

$$I_o = \frac{3\sqrt{3}}{2\pi} I_m (1+\cos(\omega t_1 + \frac{\pi}{6})) \tag{5}$$

The rectifier has following properties: performing as voltage-source type of harmonic source ("harmonic voltage source"); three operation modes exist in the novel rectifier, conduction intervals of diodes are different in every modes; the dc-side current i_o is discontinuous in the medium and small current modes.

III. Parameter Design

A. Three-phase rectifer with dc-side LC filter

As shown in Fig.2, during the interval [t_0, t_1],

$$i_{cu} = i_u + i_{DC} \tag{6}$$

So

$$\sin\omega t_0' = -\frac{I_o}{I_m} \tag{7}$$

Where t_0' is the time point when the current i_{cu} crosses zero.

While,

$$e_p + e_a = L\frac{di_a}{dt} + u_{ca}' \tag{8}$$

Where $a=u, v, w$

During the interval [t_0, t_1], following expressions are satisfied,

$$u_{cu}' = 0 \tag{9}$$

$$u_{cv}' = U_o \tag{10}$$

Substituting (9) for u_{cu}', (10) for u_{cv}', and (1) for u_u, u_w, i_u, i_w into (8) gives:

$$L\int_{\omega t_0}^{\omega t_0'} (\frac{di_w}{dt} + 2\frac{di_u}{dt})\, d\omega t = \int_{\omega t_0}^{\omega t_0'} (U_o + e_w + 2e_u)\, d\omega t \tag{11}$$

Substituting (7) for $\omega t_0'$ into (11) gives,

$$L = \int_{\omega t_0}^{\omega t_0'} (U_m \sin(\omega t + \frac{2\pi}{3}) + 2U_m \sin\omega t)\, d\omega t + (\omega t_0' - \omega t_0)U_o / \\ (-\omega I_m \sin(\omega t + \frac{2\pi}{3} + \omega(t_0' - t_0)) + \omega I_m \sin(\omega t + \frac{2\pi}{3}) \\ + 2\omega I_m (\sin\omega t_0' - \sin\omega t_0)) \tag{12}$$

The mains frequency is selected to be the resonance frequency.

$$f_r = 1/(2\pi\sqrt{LC}) = 50 \tag{13}$$

So the optimal capacitance is given as follow:

$$C = \frac{1}{4\times\pi^2\times f_r^2\times L} \tag{14}$$

B. Proposed three-phase rectifer with dc-side C filter

The key factor of designing the novel rectifier is to determine the value of inductors and capacitors, achieving high power factor under given load. Kelly *et al.* [3] gives the recommendable value of the output filter capacitor C_d equal to $1000\mu F$. Because the operation principle and equivalent circuit varies in different modes, the optimal value of L and C should be determined separately, according to the given mode.

Because of the symmetry of three-phase circuit, only 1/6 period should be considered. From above analysis, it can be seen that any 1/6 period includes two intervals in which the numbers of conducting diodes are different. So the rectifier could be designed as follow:

--First, determine the operation mode of the rectifier according to the value of ωt_1 which can be derived from (5);

--Second, deduce the expressions of the passive components in two different intervals, respectively;

--Third, obtain the conclusive optimal value by time averaging the two values derived from above in the 1/6 period.

Following the above approach, optimal value of the inductors in medium current mode will be derived as follows:

$$L=\frac{L_1(\omega t_1-\frac{\pi}{3})+(\frac{2\pi}{3}\text{-}\omega t_1)L_2}{\frac{\pi}{3}} \qquad (15)$$

Where

$$L_1=\int_{\frac{\pi}{3}}^{\omega t_1}\frac{e_S-e_R}{3(1-\cos\omega t)}(\cos\omega t+\cos(\omega t+\frac{2\pi}{3}))+\frac{U_o}{3}+e_S d\omega t$$
$$/\ \ I_m\omega[\int_{\frac{\pi}{3}}^{\omega t_1}\frac{\cos\omega t+\cos(\omega t+\frac{2\pi}{3})}{3(1-\cos\omega t)}\cos(\omega t-\frac{2\pi}{3})d\omega t+ \qquad (16)$$
$$\sin(\omega t_1-\frac{2\pi}{3})-\int_{\frac{\pi}{3}}^{\omega t_1}\frac{\cos\omega t+\cos(\omega t+\frac{2\pi}{3})}{3(1-\cos\omega t)}\cos\omega t d\omega t]$$

$$L_2=\frac{\int_{\omega t_1}^{\frac{2\pi}{3}}(\ e_S-e_R-U_o)\ d\omega t}{\int_{\omega t_1}^{\frac{2\pi}{3}}I_m\omega(\ \cos\omega t-\cos(\omega t+\frac{2\pi}{3}))\ d\omega t} \qquad (17)$$

Optimal value of the capacitors in medium current mode is given as follow:

$$C=\frac{C_1(\omega t_1-\frac{\pi}{3})+(\frac{2\pi}{3}\text{-}\omega t_1)C_2}{\frac{\pi}{3}} \qquad (18)$$

Where

$$C_1=\frac{\int_{\frac{\pi}{3}}^{\omega t_1}I_m(1-\cos\omega t)d\omega t}{\omega[\int_{\frac{\pi}{3}}^{\omega t_1}e_R-e_S+I_mL_1\omega(\cos(\omega t-\frac{2\pi}{3})-\cos\omega t)d\omega t]} \qquad (19)$$

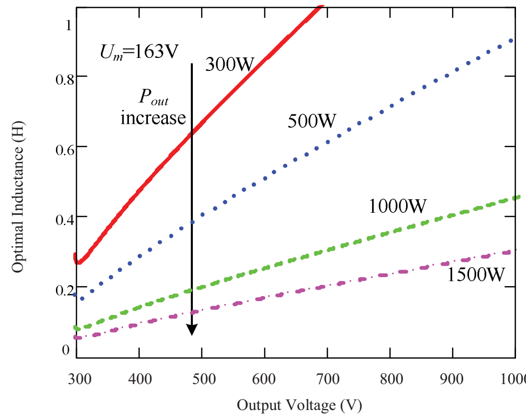
$$C_2=\frac{\int_{\frac{\pi}{3}}^{\omega t_1}I_m(1+\cos(\omega t+\frac{2\pi}{3}))d\omega t}{3\omega[\int_{\frac{\pi}{3}}^{\omega t_1}(\frac{2U_o}{3}+e_S)d\omega t++I_mL_1\omega\sin(\omega t_1-\frac{2\pi}{3})]} \qquad (20)$$

Detail deduction of the optimal value of the passive components of the proposed rectifier in each operation modes could use the same method proposed in [15].

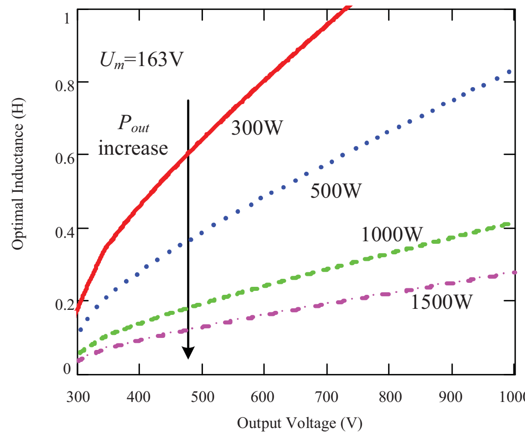
IV. CHARACTERISTIC COMPARASON

From the analysis and expression of optimal inductance L and capacitance C, we can plot some curves describing the characteristics of these two rectifiers.

Fig.6 presents the variation of the optimal inductance L as a function of the output voltage U_o and the output power P_{out} when U_m is set to be 163 V. For the output power P_{out}, we have adopted the value of 300 W, 500 W, 1000 W, 1500 W. As the figures show, the optimal inductance of these two rectifiers has similar trends. As the output voltage U_o increases, the optimal inductance is increased, as the output power increases, the optimal inductance is decreased, which is an interesting phenomenon.



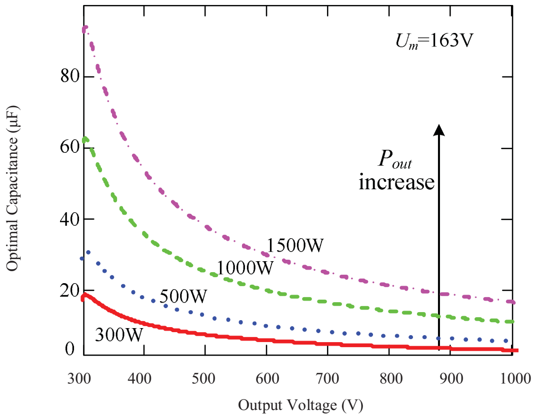
(a) Three-phase rectifier with dc-side LC rectifier



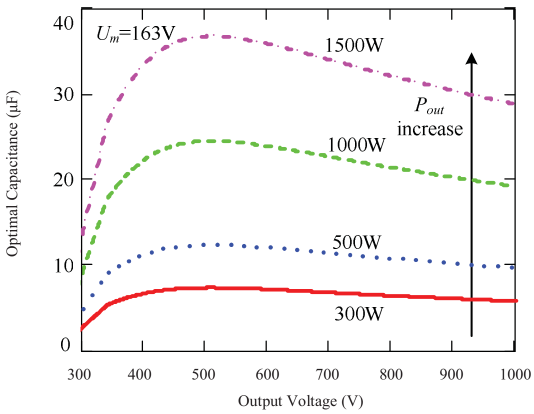
(b) Proposed three-phase rectifier with dc-side C rectifier

Fig. 6. Variations of optimal inductance L as a function of the output voltage U_o and the output power P_{out} in the two rectifiers

Fig.7 presents the variation of the optimal inductance C as a function of the output voltage U_o and the output power P_{out} when U_m is set to be 163 V. For the output power P_{out}, we have adopted the value of 300 W, 500 W, 1000 W, 1500 W. As the figures show, the optimal inductance of these two rectifiers has distinct trends. To the three-phase rectifier with dc-side LC filter, As P_{out} increases, the optimal capacitance is increased, under a given P_{out}, as U_o increases, the optimal inductance is decreased. To the novel three-phase rectifier with dc-side C filter, As P_{out} increases, the optimal capacitance is increased, under a given P_{out}, as U_o increases, the optimal inductance is increased when U_o is small and is decreased subsequently.



(a) Three-phase rectifier with dc-side LC rectifier



(b) Proposed three-phase rectifier with dc-side C rectifier

Fig. 7. Variations of optimal capacitance C as a function of the output voltage U_o and the output power P_{out} in the two rectifiers

Using these diagrams, we can draw the following conclusions:

● Optimal value of the inductors in the two rectifiers are very close, having the similar trends. The proposed three-phase rectifier with dc-side C filter is more attractive for the filter inductor is taken off, making the rectifier more practical in the large power application.

● Optimal value of the capacitors in the two rectifiers have different trends. When the output voltage is not very high, value of the capacitors in the proposed rectifier is smaller than those in the rectifier with dc-side LC filter. When a much higher output voltage is demanded, the proposed rectifier with dc-side C filter may be less competitive for its more bulky capacitors to ensure sinusoidal input current.

V. Experimental Result

In order to verify the feasibility of the analysis and the proposed design method, four prototype systems consisted of rectifier with dc-side LC filters and rectifiers with dc-side C filter working in distinct operation modes were built with the following specification:

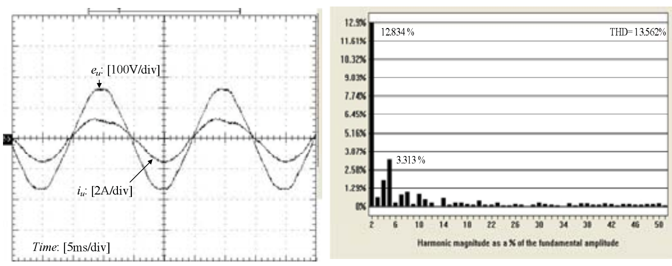
TABLE I
Specification of Four Prototype Systems

Prototype	U_m /V	U_o / V	P_{out} /W	L/mH	C/μF
1	163	500	355	554	9.2
2	250	500	359	554	2.24
3	150	500	328	554	9.45
4	55	500	125	554	15.8

Prototype 1 is the three–phase rectifier with dc-side LC filter. Prototype 2-4 are the proposed rectifier with dc-side C filter, the durations of current charging or discharging the capacitor of the three prototypes were derived as ① $\omega t_1 = 0.904 < \pi/3$; ② $\pi/3 < \omega t_1 = 1.166 < 2\pi/3$; ③ $2\pi/3 < \omega t_1 = 2.16 < \pi$. It means that they will work in the following modes: large current mode, medium current mode and small current mode.

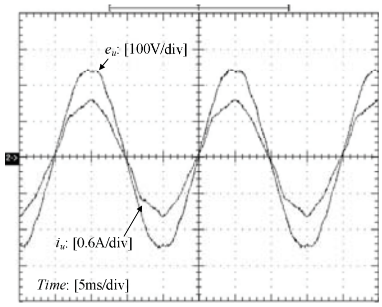
From Tab.1, we could find that value of the capacitors of prototype 1 and 3 which work in the similar condition (similar input voltage, output voltage and output power) is near close. So the proposed rectifier with dc-side C filter is more competitive for a bulky filter inductor is removed, making the rectifier more compact.

Fig. 8 shows the phase voltage, the input current and the spectrum of the current of prototype 1. We find that the input current is near sinusoidal and the displacement factor is near unity. Figs. 9(a), (b), (c) show the experimental waveforms of the phase voltage and input current of the prototypes 2, 3, 4, respectively. It can be seen that the input currents are nearly sinusoidal and the displacement factors are nearly unity. Figs. 9(d), (e), (f) show the spectrums of the input currents of the three prototypes. It is measured that the THDs are all below 10% and power factors are all above 0.995.

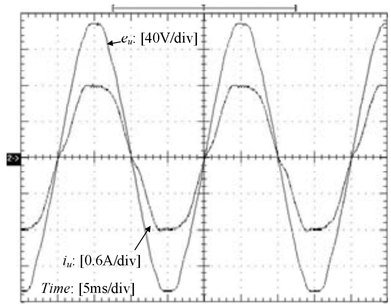


(a) Phase voltage $e_u(t)$ and current $i_u(t)$ (b) Normalized line current harmonics

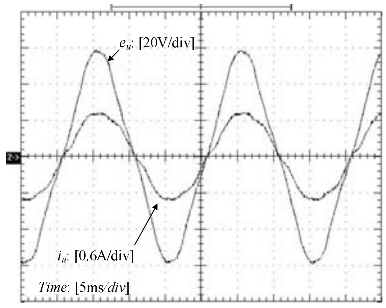
Fig. 8. Experimental waveforms of prototype 1



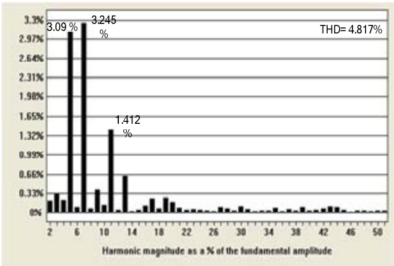
(a) Phase voltage $e_u(t)$ and current $i_u(t)$ of prototype 2



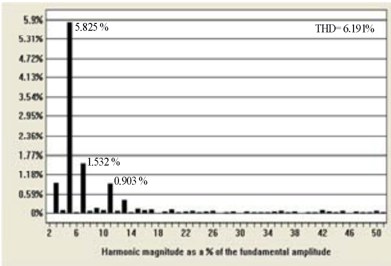
(b) Phase voltage $e_u(t)$ and current $i_u(t)$ of prototype 3



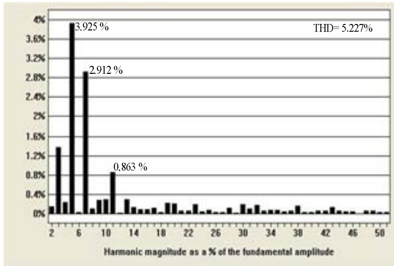
(c) Phase voltage $e_u(t)$ and current $i_u(t)$ of prototype 4



(d) Normalized line current harmonics of prototype 2



(e) Normalized line current harmonics of prototype 3



(d) Normalized line current harmonics of prototype 4

Fig. 9. Experimental waveforms of proposed rectifiers

VI. CONCLUSION

Three-phase rectifier with sinusoidal input currents and capacitors connected with the upper diode has the advantage of high reliability, simple fabrication and low harmonic input currents. Two distinct topologies exist in the rectifier, according to the different dc-side filter types, LC filter and C filter.

Compared with three-phase rectifier with dc-side LC filter, the proposed rectifier with dc-side C filter is more competitive for its eliminated filter inductor and smaller capacitors in the most common application.

High power factor is only derived at the rated condition. So the rectifier suit to work in the application with strict input current limit, high power factor demand and small load change range.

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