Analysis and Design of Three-Phase Rectifier with Near-Sinusoidal Input Currents

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***Abstract*-A three-phase rectifier with near-sinusoidal input currents is studied in this paper. Based on the analysis of the operation principle of this rectifier which can work in three modes: small current mode, medium current mode and large current mode, a practical design method used for the rectifier is proposed to obtain the optimum value of the passive components. Additionally, the characteristic of the rectifier is presented and discussed in detail. To verify the analytically derived results, three prototypes with different specifications are built and tested in the laboratory. Experimental results are shown to confirm the validity of the analysis and the feasibility of the proposed design method.**

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 diode rectifiers with LC resonance in commercial frequency [10], three-phase rectifiers with near sinusoidal input currents (RNSIC) [11]-[14] and other novel rectifier [15] have caught increasing attention in recent years.

RNSIC was proposed by D. Alexa in [13] in 2004. Compared with the conventional three-phase full-bridge rectifier with passive filter, the RNSIC has following attractive characteristics: sinusoidal input current for large variations of the load, lower size volume and cost of the passive components. But the operation of RNSIC is not analyzed in detail when the dc-side current is small. Meanwhile, the design of RNSIC is unprecise theoretically, e.g., the reason why the values of inductors *L* and capacitors *C* fulfill the relation $0.05 \le LC\omega^2 \le 0.1$ is not explained in [13]. Moreover, the demerit that the displacement factor varies with different loads, according to the experimental results in [14], limits the application of RNSIC.

This paper analyzes the operation principle of RNSIC in detail. Based on the analysis, a method valid for the parameter design of the rectifier is proposed, achieving near sinusoidal input currents and near unity displacement factor. According to the proposed method, the optimal value of the passive components will be obtained, which makes RNSIC more practical. Experimental results obtained from three prototypes working in different operation modes verify the validity of the analysis and the feasibility of the method.

II. OPERATION PRINCIPLE

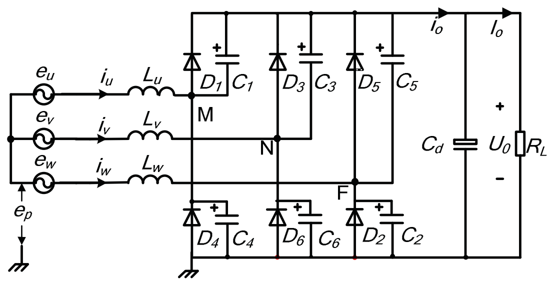


Fig.1. Topology of three-phase rectifier with near sinusoidal input currents

Fig.1 shows the configuration of RNSIC, which is composed of three series inductors L_u, L_v, L_w of equal inductance values *L* and six commutation capacitors C_1-C_6 of equal capacitance values *C*, where C_d is the output filter capacitor.

The phase voltages and input currents are supposed as follows:

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

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

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

- ideal diodes and passive components
- stead state already

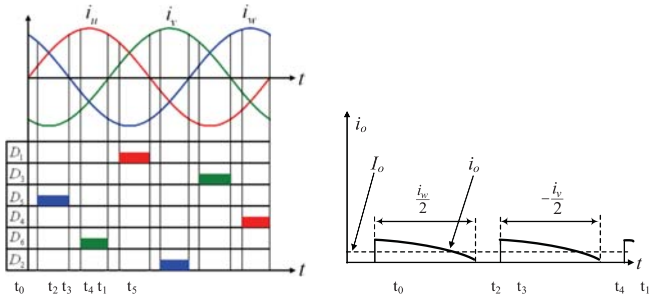
Different durations of the current charging the commutation capacitor, which vary with the load, determine the distinct operation modes of the rectifier: large current mode, medium current mode and small current mode.

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.

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. 2(a), 3(a) and 4(a), from which differences among the three modes can be deduced.

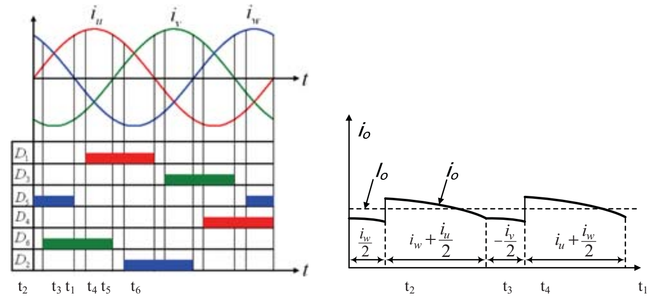
Fig. 2(b), 3(b) and 4(b) illustrate the dc-side current i_o of the rectifiers working in different modes. Current i_o is discontinuous when the rectifier is working in the small current mode, whereas i_o become a 12-pulse waveform when the rectifier is working in the medium current mode and large current mode.

In what follows we describe the operation principle of RNSIC which works in the small current mode in detail.



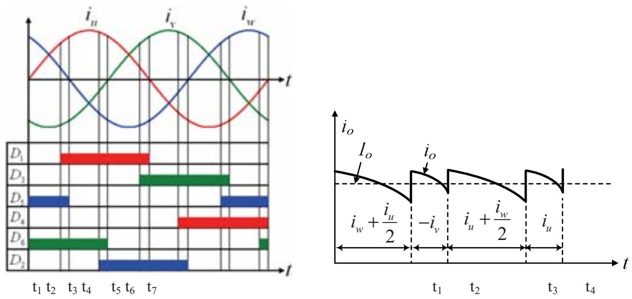
(a) Input current (b) Dc side current

Fig. 2. Key waveforms of RNSIC working in small current mode



(a) Input current (b) Dc side current

Fig. 3. Key waveforms of RNSIC working in medium current mode



(a) Input current (b) Dc side current

Fig. 4. Key waveforms of RNSIC working in large current mode

Fig. 2(b), 3(b) and 4(b) illustrate the dc-side current i_o of the rectifiers working in different modes. Current i_o is discontinuous when the rectifier is working in the small current mode, whereas i_o become a 12-pulse waveform when the rectifier is working in the medium current mode and large current mode.

In what follows we describe the operation principle of RNSIC which works in the small current mode in detail.

A. Small Current Mode

As Fig. 5 shows, four different stages exist in small current mode.

Stage 1 [0, t_0]: Prior to 0, D_4 conducts, $u_{c4}=0$, $u_{c1}=U_o$. The input current i_w, which is positive, charges the capacitor C_2 and discharges the capacitor C_5, simultaneously. The input current i_v which is negative, charges the capacitor C_3 and discharges the capacitor C_6.

In the stage, the input current i_u which becomes positive charges the capacitor C_4 and discharges the capacitor C_1, as shown in Fig.5 (a). No diode conducts until t_0 when the voltage across C_2 reaches U_o. In this stage, the dc side current of the rectifier i_o is given by

$$i_o = 0 \tag{2}$$

Input currents charge one capacitor and discharge the other one of the same leg, simultaneously. So the current flowing through capacitor C_4 is given by

$$i_{c_4} = \frac{1}{2} i_u = \frac{1}{2} I_m \sin \omega t \tag{3}$$

So that the midpoint voltage of leg u (u_M) is

$$u_M = \frac{1}{C}\int_0^{\omega t}\frac{1}{2}I_m \sin \omega t dt \tag{4}$$

The equation simplifies to

$$u_M = \frac{I_m}{2\omega C}(1-\cos\omega t) \tag{5}$$

Similarly, the voltages u_N, u_F can be derived as

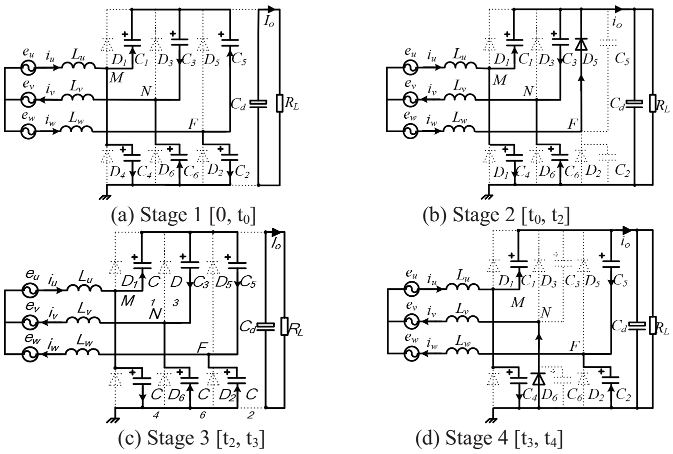
$$u_N = U_o - \frac{I_m}{2\omega C}(\cos(\omega t - \frac{2\pi}{3})+1) \tag{6}$$

$$u_F = \frac{I_m}{2\omega C}(-\cos(\omega t + \frac{2\pi}{3})+1) \tag{7}$$

Stage 2 [t_0, t_2]: At t_0 when the voltage across C_5 reaches zero, diode D_5 starts conducting. In the stage, the input current i_u which is positive keeps charging the capacitor C_4 and discharging the capacitor C_1, simultaneously. The input current i_v which is negative keeps charging the capacitor C_3 and discharging the capacitor C_6, as shown in Fig. 5(b). In this stage, the dc side current i_o, is given by

$$i_o = -\frac{1}{2}i_v - \frac{1}{2}i_u = \frac{1}{2}i_w = \frac{1}{2}I_m \sin(\omega t + \frac{2\pi}{3}) \tag{8}$$

Diode D_5 gets blocked at t_2 (equal to $\pi/3\omega$), when current i_w crosses zero, indicating the end of stage 2.



(a) Stage 1 [0, t_0] (b) Stage 2 [t_0, t_2] (c) Stage 3 [t_2, t_3] (d) Stage 4 [t_3, t_4]

Fig. 5. Equivalent circuits of working stages in small current mode

Stage 3 [t_2, t_3]: At t_2, the input current i_w whose direction is changed into negative, begin to charge the capacitor C_5 and discharges the capacitor C_2, simultaneously. In the stage, the input current i_u which is positive keeps charging the capacitor C_4 and discharging the capacitor C_1. The input current i_v which is still negative keeps charging the capacitor C_3 and discharging the capacitor C_6, as shown in Fig. 5(c). Just like stage 1, no diode conducts and i_o keep zero until t_3, when the voltage across C_3 reaches U_o.

Stage 4 [t_3, t_4]: At t_3 when the voltage across C_6 reaches zero, diode D_6 starts conducting. In the stage, the input current i_w which is negative keeps charging the capacitor C_5 and discharging the capacitor C_2, simultaneously. The input current i_u which is negative keeps charging the capacitor C_4 and discharging the capacitor C_1, as shown in Fig. 5(d). In this stage, the dc side current i_o, is given by

$$i_o = \frac{1}{2}i_u + \frac{1}{2}i_w = -\frac{1}{2}i_v = -\frac{1}{2}I_m \sin(\omega t - \frac{2}{3}\pi) \tag{9}$$

Diode D_6 gets blocked at t_4 (equal to $2\pi/3\omega$), when current i_v crosses zero, indicating the end of the stage.

The dc side current i_o discontinues in the small current mode, as shown in Fig. 2(b). The output current I_o, namely the mean value of i_o, could be expressed as follow:

$$I_o = \frac{3}{2\pi}[\int_{\omega t_1 - \frac{2}{3}\pi}^{\frac{\pi}{3}} \frac{1}{2}I_{\mathrm{m}} \sin(\omega t + \frac{2}{3}\pi)d\omega t + \int_{\omega t_1 - \frac{\pi}{3}}^{\frac{2\pi}{3}} -\frac{1}{2}I_{\mathrm{m}} \sin(\omega t - \frac{2}{3}\pi)d\omega t] \tag{10}$$

The equation simplifies to

$$I_o = \frac{3}{2\pi}[I_{\mathrm{m}}(1+\cos\omega t_1)] \tag{11}$$

B. *Medium Current and Large Current Mode*

As Fig. 3 and 4 depict, one or two diodes are conducting in medium current mode and two or three diodes are conducting in large current mode. Operation principle of the rectifier in medium current mode and large current mode could be derived by using the same analysis. The output current I_o in the two modes has the same expression as (11).

III. Parameter Design

The key factor of designing this 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 (11);

--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 values of the passive components in different modes will be derived.

A. Small Current Mode

As Fig.1 shows, following equations are obtained:

$$e_p = \frac{u_M + u_N + u_F}{3} \tag{12}$$

$$e_p + e_a = L\frac{di_a}{dt} + u_A \tag{13}$$

Where $a=u, v, w$, $A=M, N, F$

In stage4 [t_3, t_4], the two capacitors connected with phase u and the two capacitors connected with phase w are charging or discharging. The voltages u_M, u_N, u_F are:

$$u_M = \frac{1}{2C}\int_0^{\omega t} I_m \sin \omega t dt \tag{14}$$

$$u_N = 0 \tag{15}$$

$$u_F = \frac{1}{2C}\int_{\frac{\pi}{3}}^{\omega t} I_m \sin(\omega t + \frac{2\pi}{3}) dt + U_o \tag{16}$$

Substituting (14) for u_M, (15) for u_N and (16) for u_F into (12) gives:

$$e_p = [(\frac{I_m}{2\omega C}(-\cos \omega t - \cos(\omega t + \frac{2}{3}\pi)) + U_o]/3 \tag{17}$$

Substituting (17), (15) into (13) gives:

$$L = [\int_{\omega t_1 - \frac{\pi}{3}}^{\frac{2\pi}{3}} (\frac{e_v - e_u}{3(1-\cos \omega t)}(\cos \omega t + \cos(\omega t + \frac{2}{3}\pi) + \frac{U_o}{3} + e_v) d\omega t]/[\omega I_m \sin \omega t_1 + I_m \omega \int_{\omega t_1 - \frac{\pi}{3}}^{\frac{2\pi}{3}} (\cos \omega t + \cos(\omega t + \frac{2}{3}\pi)\frac{\cos(\omega t + \frac{2}{3}\pi) - \cos \omega t}{3(1-\cos \omega t)}) d\omega t] \tag{18}$$

Substituting (18), (17), (15) into (13) gives:

$$C_1 = [\int_{\omega t_1 - \frac{\pi}{3}}^{\frac{2}{3}\pi} I_m (1 - \cos \omega t) d\omega t]/[2\omega \int_{\omega t_1 - \frac{\pi}{3}}^{\frac{2}{3}\pi} (e_u - e_v + I_m L\omega \cos(\omega t - \frac{2}{3}\pi) - \cos \omega t) d\omega t] \tag{19}$$

In stage3 [t_2, t_3], for no diode is conducting, the equivalent single phase circuit could be simplified, as shown in Fig. 6.

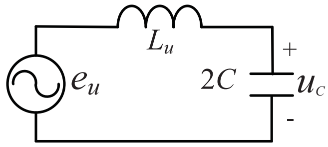


Fig. 6. Simplified circuit of phase u in stage 3 [t_2, t_3]

Considering the near unity displacement factor, as well as the acceptable voltage across the capacitors v_C, the appropriate resonant frequency f_r could be determined around grid frequency (50 Hz). Optimal value of the capacitor during the interval [$\pi/3$, $\omega t_1 - \pi/3$] C_2 will be derived as follow:

$$C_2 = \frac{1}{2(2\pi \cdot f_r)^2 L} \tag{20}$$

Then, conclusive optimal value of the capacitors C is the mean value of C_1 and C_2 in the 1/6 period [t_2, t_4]:

$$C = \frac{C_1(\pi - \omega t_1) + (\omega t_1 - \frac{2\pi}{3})C_2}{\frac{\pi}{3}} \tag{21}$$

B. Medium Current and Large Current Mode

Using the same method, the optimal value of the passive component of the rectifier working in medium current mode and large current mode will be derived as well.

IV. Discussion

From the analysis and expression of optimal inductance L and capacitance C derived above, we can plot some curves describing the characteristic of RNSIC.

Fig.7 presents the variation of the angle ωt_1 as a function of the input voltage U_m and the output voltage U_o. For the output voltage U_o, we have adopted the value of 300 V, 400V, 500 V, 600 V. Which operation mode the rectifier works in is determined by the input voltage U_m and output voltage U_o (actually the ratio U_o/U_m) in a given power. Rectifiers with the high input voltage and the low output voltage suit to work in the large current mode, while those with low input voltage and high output voltage should be designed to work in the small current mode.

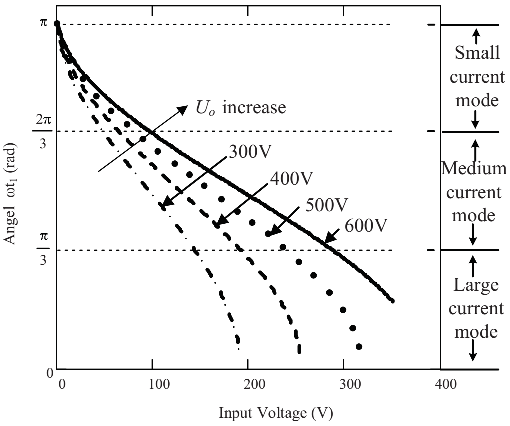


Fig. 7. Variations of angle ωt_1 as a function of the input voltage U_m and the output voltage U_o

Fig.8 presents the variation of the optimal inductance L as a function of the input voltage U_m and the output power P_{out}. For the output power P_{out}, we have adopted the value of 100W, 150 W, 200 W, 250 W, 300 W. As the output power is increased, the optimal inductance is decreasing, which is an interesting phenomenon. As the input voltage on the horizontal axis is increased from lower value to high one, the optimal inductance increases to its maximum and then decreases to zero.

But if the input voltage is increased without limit, the optimal inductance gets negative (the shadowed area). It means that the stage with three conducting diodes dominate the large current mode as the input voltage increase. This invalidates the assumption that the displacement factor is near unity.

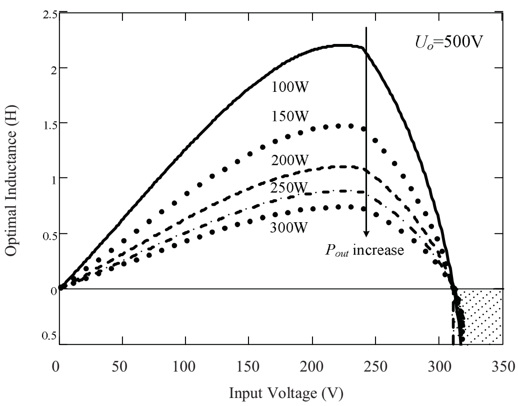


Fig. 8. Variations of optimal inductance L as a function of the input voltage U_m and the output power P_{out}

Fig.9 presents the variation of the optimal inductance C as a function of the input voltage U_m and the output power P_{out}. For the output power P_{out}, we have adopted the value of 100W, 150 W, 200 W, 250 W, 300 W. As the input voltage on the horizontal axis is increased from lower value to high one, the optimal capacitance is decreasing. As the output power is increased, the optimal capacitance is increasing.

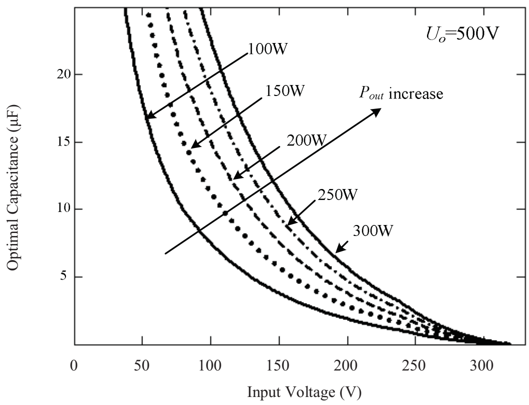


Fig. 9. Variations of optimal capacitance C as a function of the input voltage U_m and the output power P_{out}

Using these diagrams, one can draw the following conclusions:

- Large current mode is most attractive for the biggest flexibility in choosing value of the inductance and lowest capacitance, compared with other two modes.
- When the rectifier is working in large current mode, the maximum input voltage should be limited to make the inductance be designed in the appropriate value.
- Small current mode is attractive for the application with low input voltage and high output voltage.

V. Experimental Result

In order to verify the feasibility of the analysis and the proposed design method, three prototype systems working in different modes were built with the following specification:

Here, we would like to explain that the inductance of the three prototypes is fixed to be 554mH for the consideration of cost reduction and experiment convenience. This means that high power factor will be achieved by changing the capacitor connected with the diode bridge, without changing the inductor according to the various input voltages and load resistors.

TABLE I
Specification of Three Prototype Systems

Prototype	U_m /V	U_o / V	P_{out} /W	L/mH	C/μF
1	280	500	234	554	1.125
2	150	500	335	554	5.04
3	55	500	125	554	7.902

The durations of current charging or discharging the capacitor of the three prototypes were derived as ① $\omega t_1 = 0.963 < \pi/3$; ② $\pi/3 < \omega t_1 = 1.446 < 2\pi/3$; ③ $2\pi/3 < \omega t_1 = 2.284 < \pi$. It means that they will work in given modes: large current mode, medium current mode and small current mode.

Figs. 10, 12 and 14 show the experimental waveforms of the phase voltage and input current of the prototypes working in the large current mode, medium current mode and small current mode, respectively. It can be seen that the input currents are practically sinusoidal and the displacement factor is near unity. Figs. 11, 13 and 15 show the spectrum of the input current of the three prototypes, where the THDs are 5.018%, 5.842%, 5.606%, respectively.

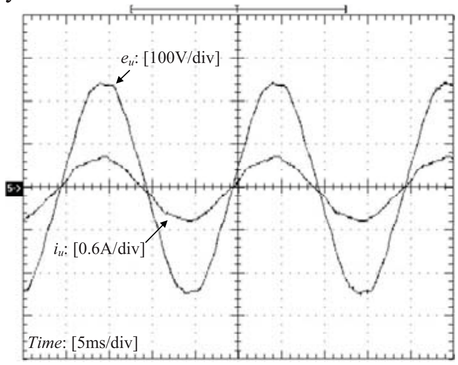


Fig. 10. Phase voltage $e_u(t)$ and current $i_u(t)$ in large current mode

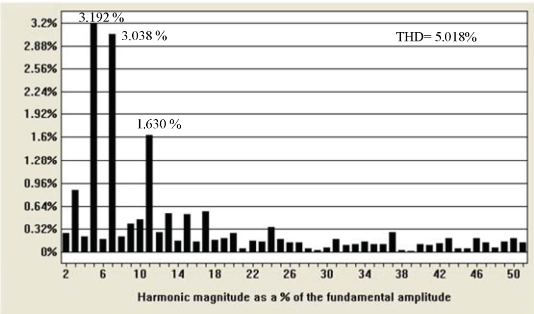


Fig. 11. Normalized line current harmonics in large current mode

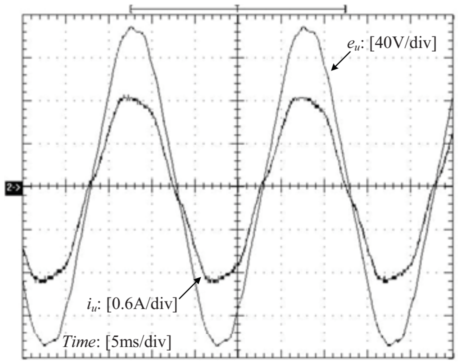


Fig. 12. Phase voltage $e_u(t)$ and current $i_u(t)$ in medium current mode

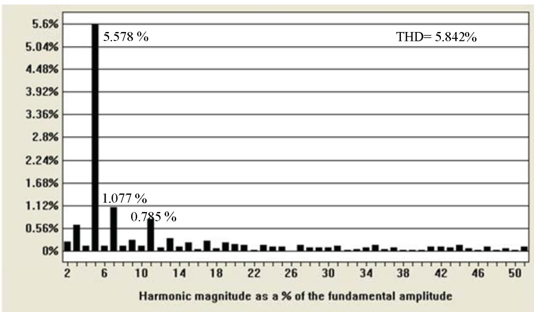


Fig. 13. Normalized line current harmonics in large current mode

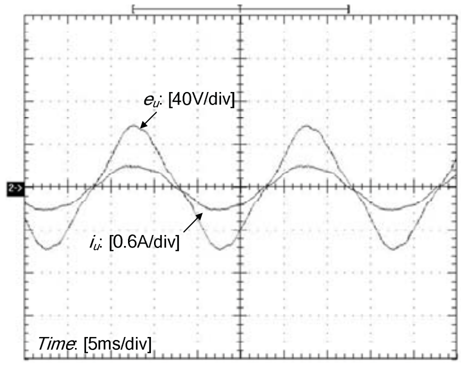


Fig. 14. Phase voltage $e_u(t)$ and current $i_u(t)$ in small current mode

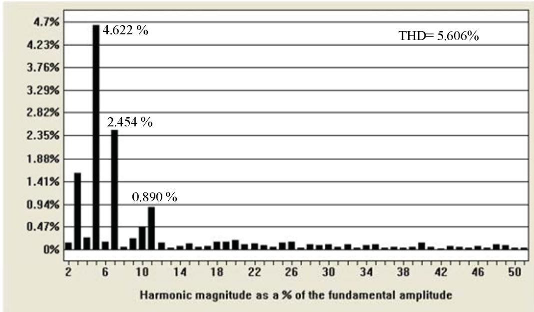


Fig. 15. Normalized line current harmonics in small current mode

A disappointing phenomenon that the output voltage drops slightly compared with the designed value appears, especially in the small current mode. This is mainly caused by the ESR (Equivalent Series Resistance) of the inductors.

When the rectifier is working in the small current mode, the voltage conversion ratio is very large which means that high output voltage will be derived with low input voltage. But we should mention that the small current mode is not propositional for its high sensitivity with components, large value of the capacitor, and high loss caused by the high input current.

Relatively, when the rectifier is designed to work in the medium mode, the highest stability the rectifier will achieve. But the small flexibility in choosing the inductance will hinder its application in the field requiring compact volume and size, especially for the small power application.

Large current mode is most attractive, for the biggest flexibility in choosing value of the inductance, lowest capacitance and the highest efficiency.

VI. CONCLUSION

The RNSIC converter catches increasing attention for its simple configuration, high reliability, as well as the reduced cost. This paper has proposed a practical design method of RNSIC on the basis of analysis of the rectifier's operation principle. Experimental results that the THD lower than 10% and power factor higher than 0.99, which are obtained from three prototypes working in different modes have verified both the validity of theoretical analysis and the feasibility of the design method.

Moreover, based on the discussion about the characteristic of

RNSIC and the experimental results, the most suitable applications for various operation modes have been given.

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