An Analysis of Three-Phase Rectifiers With Near-Sinusoidal Input Currents

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***Abstract*—An analysis of a three-phase low-harmonic diode rectifier equipped with inductors, capacitors, and diodes is presented. Inductors and capacitors are used in conjunction with the three-phase diode rectifier bridge to improve the waveform of the currents drawn from the utility grid. The operation of the proposed converter is analyzed and, on this basis, design considerations are commented upon. The converter characteristics are determined as a function of the load current. Comparisons between the studied converter and other rectifiers (classical rectifiers, with passive or active filters, and three-phase low-harmonic rectifiers applying the third-harmonic current injection) are also presented. Several possible applications of the three-phase rectifiers with near-sinusoidal input currents are mentioned. Analytically obtained results are experimentally verified.**

***Index Terms*—AC–DC power conversion, power converters, power quality, power system harmonics, rectifiers.**

I. Introduction

IN MOST power electronics applications, the ac input power supply, in the form of 50- or 60-Hz sine-wave ac voltage provided by the electric utility, is converted to a dc voltage. Increasingly, the trend is to use the inexpensive single-phase or three-phase rectifiers with diodes to convert the input ac into dc in an uncontrolled mode. A large majority of the power electronics applications such as switching dc power supplies, ac motor drives, static frequency converters, dc servo drives, and so on, use such uncontrolled three-phase rectifiers [1]–[3]. The three-phase six-pulse full-bridge diode rectifier, shown in Fig. 1(a), is a commonly used circuit configuration. A filter L_f, C_f, is connected at the dc side of the rectifier. In the circuit of Fig. 1(a), the ac side inductance is assumed to be zero and the dc side is replaced by a constant dc current I_d, in accordance with Fig. 1(b). The rms harmonic components $I_{(n)}$ of the phase current can be determined in terms of the fundamental frequency component $I_{(1)}$ as

$$I_{(n)} = \frac{I_{(1)}}{n} \tag{1}$$

where n represents the harmonic number, $n = 5, 7, 11, 13 \ldots$. To draw a conclusion, an important disadvantage of the scheme in Fig. 1(a) is the introduction of high-order harmonics of the input current, with values inadmissible in the power supply.

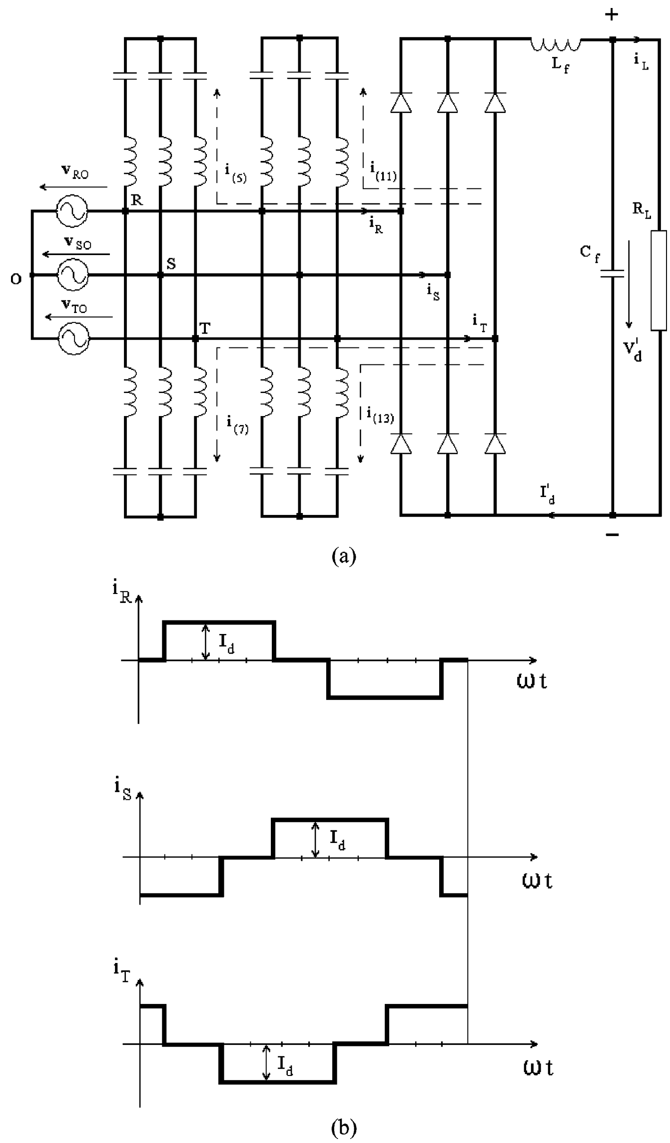

Fig. 1. Three-phase six-pulse full-bridge diode rectifier with passive filters. (a) Classical configuration. (b) Current waveforms.

A first alternative to reduce the current harmonics is the usage of classical passive filters (CPFs) made of *LC* series circuits. However, passive filters have the following drawbacks. [1]–[6]:

- Filtering characteristics are strongly affected by the source impedance. Purely passive filtering is insensitive to unbalanced conditions. Due to the resonant nature of passive filters there may be unwanted resonant interactions with

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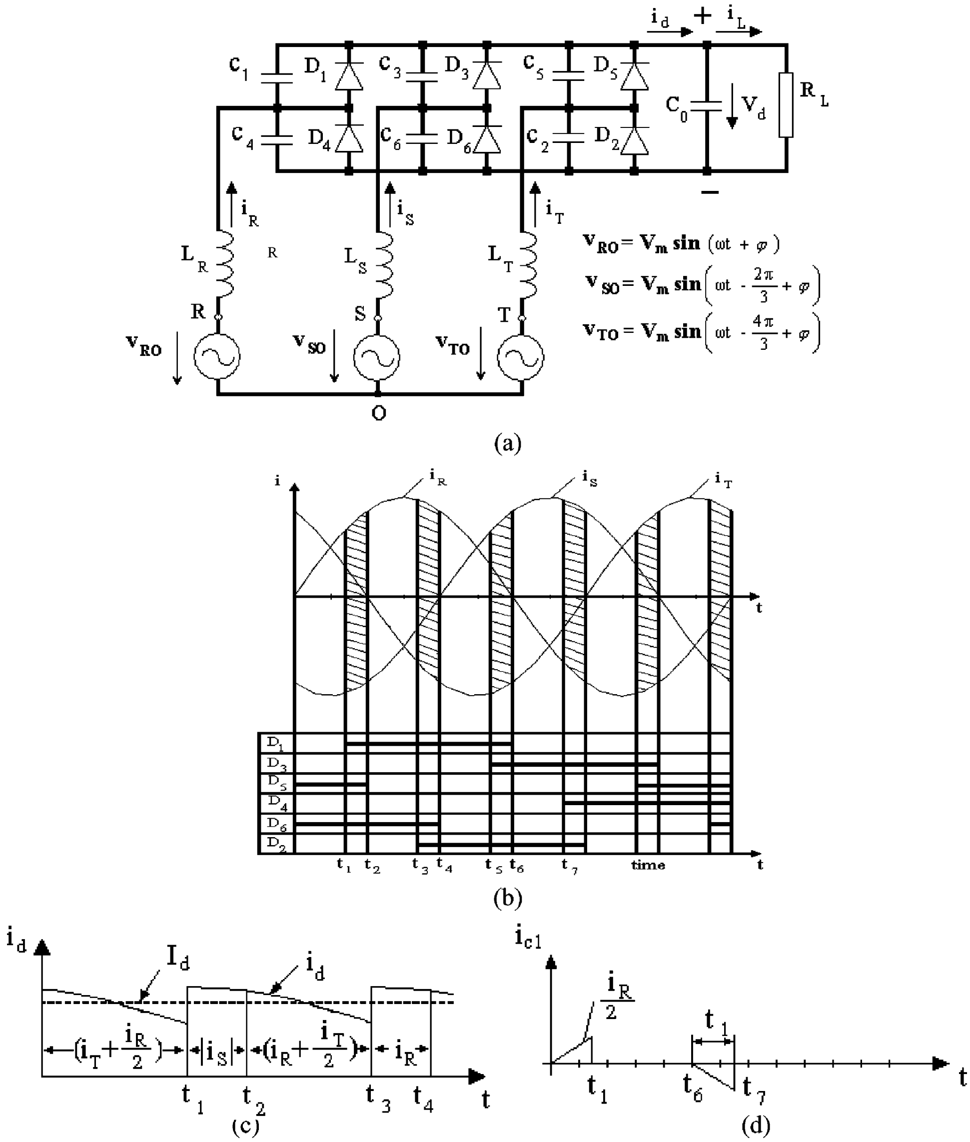


Fig. 2. Three-phase rectifier with near sinusoidal input currents (RNSIC converter). (a) New configuration. (b) AC current waveforms. (c) DC current i_d. (d) Waveform of the capacitor current i_{c1}.

the supply system. To reduce resonant interactions, the filters are often off-tuned or dumping is added which reduces their performances.

- Amplification of the currents on the source side at specific frequencies can appear due to the parallel resonance between the source and the passive filter.
- Excessive harmonic currents flow into the passive filter due to the voltage distortions caused by the possible series resonance with the source.

Active power filters (APFs) consisting of voltage or current-source pulsewidth-modulation (PWM) inverters have been studied and put into practical use because they have the ability to overcome the drawbacks inherent to passive filters [4]–[6]. The active filter eliminates the harmonics that are present in the ac lines by injecting the compensating current into the ac side. However, the active filters have the following drawbacks:

- difficulty in constructing large-rated current source with a rapid current response;
- high initial and running costs.

Obviously, the reduction of higher current harmonics generated by a three-phase ac–dc converter can be obtained as well using a PWM rectifier, [7], [8]. The first version of such a rectifier was proposed in [9].

In what follows we present a new uncontrolled three-phase rectifier, which does not inject inadmissible current harmonics in the ac mains. Such a rectifier does not require filters on the ac side.

II. New Converter Configuration

In Fig. 2(a) we present a new ac–dc converter generating reduced higher current harmonics in the mains, named, in what follows as rectifier with near-sinusoidal input current (RNSIC) [10]. The capacitors C_1–C_6 have the same value C and they are dc capacitors [11]–[13]. The inductors L_R, L_S, and L_T have the same value, denoted by L, and they are connected on the ac side. The values of L and C fulfill the relation

$$0.05 \leq LC\omega^2 \leq 0.1 \quad (2)$$

in order for the phase currents i_R, i_S, and i_T to be practically sinusoidal, according to Fig. 2(b). The working principle of this rectifier can be explained by the help of the following stages which last for one-third of the mains period $T = 2\pi/\omega$ (ω denotes the mains angular frequency).

A. Stage 1

The diodes D_5 and D_6 are conducting. The current $i_R^{(1)}$ charges the capacitor C_4 from zero to V_d and discharges the capacitor C_1 from V_d to zero. This stage has duration equal to t_1 and its equations are

$$v_{TS}^{(1)}(t) = \sqrt{3}V_m \cos(\omega t + \varphi) = L\frac{di_T^{(1)}}{dt} - L\frac{di_S^{(1)}}{dt} + V_d \quad (3)$$

$$v_{RT}^{(1)}(t) = \sqrt{3}V_m \cos\left(\omega t - \frac{2\pi}{3} + \varphi\right) = L\frac{di_R^{(1)}}{dt} - L\frac{di_T^{(1)}}{dt} - V_d + \frac{1}{2C}\int_0^t i_R^{(1)} dt \quad (4)$$

having the solutions

$$i_R^{(1)} = \frac{V_m\omega}{L(\omega_0^2 - \omega^2)}\cos(\omega t + \varphi) - \frac{V_m\omega}{L(\omega_0^2 - \omega^2)}\cos\varphi\cos\omega_0 t + K_1 \sin\omega_0 t \quad (5)$$

$$i_T^{(1)} = -\frac{1}{2}i_R^{(1)} + \frac{\sqrt{3}V_m}{2L\omega}\sin(\omega t+\varphi) - \frac{V_d}{2L}t + \frac{\pi V_d}{3L\omega} - \frac{3V_m}{2L\omega}\cos\varphi \quad (6)$$

where the angular frequency ω_0 fulfills the condition $3LC\omega_0^2 = 1$, and the constant K_1 is given by the expression

$$K_1 \sin\omega_0 t_1 = \frac{4\pi V_d}{9L\omega} - \frac{V_d}{3L}t_1 - \frac{V_m}{L\omega}\cos\varphi - \frac{V_m\omega_0^2}{L\omega(\omega_0^2 - \omega^2)}\cos(\omega t_1 + \varphi) + \frac{V_m\omega}{L(\omega_0^2 - \omega^2)}\cos\varphi\cos\omega_0 t_1. \quad (7)$$

B. Stage 2

The diodes D_1, D_5, and D_6 are conducting. The R and T phases are short circuited until $t_2 = \pi/3\omega$. The equations describing this stage are

$$v_{RS}^{(2)}(t) = L\frac{di_R^{(2)}}{dt} - L\frac{di_S^{(2)}}{dt} + V_d \quad (8)$$

$$v_{RT}^{(2)}(t) = L\frac{di_R^{(2)}}{dt} - L\frac{di_T^{(2)}}{dt} \quad (9)$$

whose solutions are

$$i_R^{(2)} = -\frac{V_m}{L\omega}\cos(\omega t+\varphi) + \frac{V_d}{3L\omega}\left(\frac{4\pi}{3} - \omega t\right) - \frac{V_m}{L\omega}\cos\varphi \quad (10)$$

$$i_T^{(2)} = \frac{V_m}{L\omega}\cos\left(\omega t - \frac{\pi}{3} + \varphi\right) + \frac{V_d}{3L\omega}\left(\frac{\pi}{3} - \omega t\right) - \frac{V_m}{L\omega}\cos\varphi. \quad (11)$$

C. Stage 3

The diodes D_1 and D_6 are conducting. This stage lasts between t_2 and $t_2 + t_1$. The current $i_T^{(3)}$ charges the capacitor C_5 from zero to V_d and discharges C_2 from V_d to zero. The solutions describing this stage are

$$i_T^{(3)} = -\frac{V_m\omega}{L(\omega_0^2 - \omega^2)}\cos\left(\omega t - \frac{\pi}{3} + \varphi\right) - K_1 \sin\omega_0(t - t_2) + \frac{V_m\omega}{L(\omega_0^2 - \omega^2)}\cos\varphi\cos\omega_0(t - t_2) \quad (12)$$

$$i_R^{(3)} = -\frac{1}{2}i_T^{(3)} + \frac{\sqrt{3}V_m}{2L\omega}\sin\left(\omega t - \frac{\pi}{3} + \varphi\right) - \frac{V_d}{2L}t + \frac{\pi V_d}{2L\omega} - \frac{3V_m}{2L\omega}\cos\varphi. \quad (13)$$

D. Stage 4

The diodes D_1, D_2, and D_6 are conducting. The S and T phases are short circuited until $t_4 = \pi/3\omega$. The solutions of the equations related to this stage are

$$i_R^{(4)} = -\frac{V_m}{L\omega}\cos(\omega t + \varphi) - \frac{2V_d}{3L}t + \frac{7\pi V_d}{9L\omega} - \frac{2V_m}{L\omega}\cos\varphi \quad (14)$$

$$i_T^{(4)} = \frac{V_m}{L\omega}\cos\left(\omega t - \frac{\pi}{3} + \varphi\right) + \frac{V_d}{3L}t - \frac{5\pi V_d}{9L\omega} + \frac{V_m}{L\omega}\cos\varphi. \quad (15)$$

The converter presented in Fig. 2(a) has at its input a symmetric three-phase system and, so, the expressions of the currents i_R, i_S, and i_T for the remaining two-thirds of the period T can be deduced using the above relations.

The ac–dc converter in Figs. 1(a) and 2(a) have a simplified equivalent circuit as in Fig. 3(a), in which Z_{in} denotes the phase input impedance of the three-phase system. Due to the presence of the passive power filters for the 5th, 7th, 11th, and 13th harmonics, Z_{in} becomes zero for these harmonics according to Fig. 3(b). In the case of the RNSIC converter, the input impedance Z_{in} grows nonlinearly as presented in Fig. 3(c). From what we have mentioned above, another advantage of the RNSIC converter results, namely, its working is not influenced by the presence of the higher current harmonics in the mains.

Another constructive alternative of the RNSIC converter can be obtained connecting three capacitors on the ac side, between the phases, instead of the six capacitors in parallel with the diodes D_1–D_6.

III. RNSIC Converter Characteristics

In order to design the RNSIC converter it is necessary to determine the duration t_1 for the charging or discharging of the capacitors $C_1 - C_6$ using the relation

$$V_d = \frac{1}{C}\int_0^t \frac{i_R^{(1)}}{2} dt. \quad (16)$$

There are two extreme cases during converter functioning. In the first case, if $R_L = 0$ (and so $V_d = 0$), the capacitors

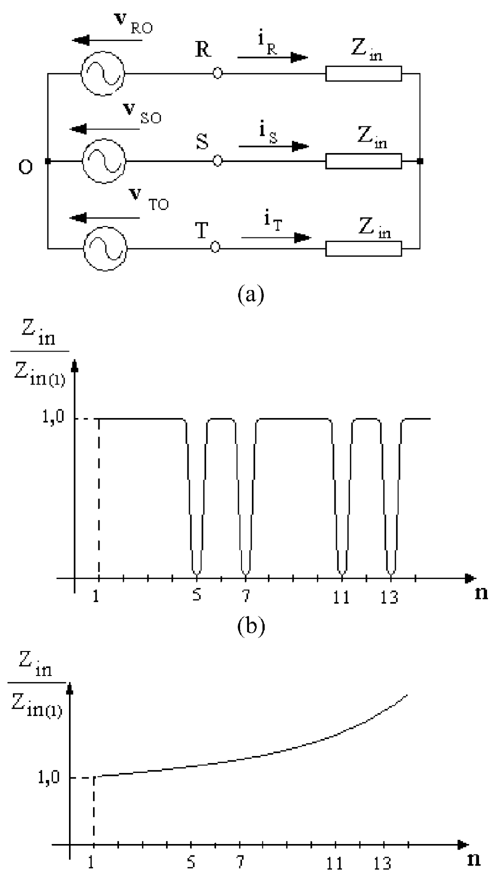


Fig. 3. Simplified equivalent circuit for ac–dc converter (a) Configuration. (b) Variation of the ratio $Z_{\rm in}/Z_{\rm in(1)}$ in the classical configuration. (c) Variation of the ratio $Z_{\rm in}/Z_{\rm in(1)}$ in the RNSIC converter.

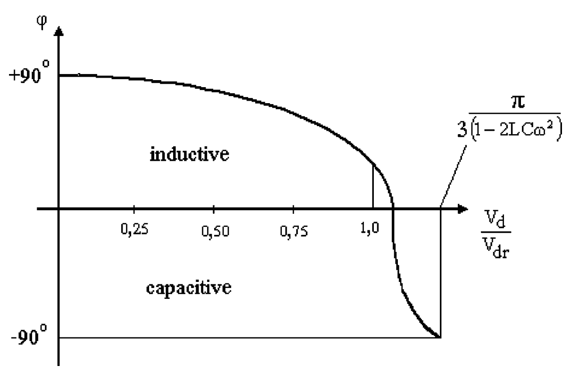


Fig. 4. Variation of the angle φ as a function of the ratio V_d/V_{dr}.

C_1–C_6 are short circuited and the angle $\varphi = 90°$ is inductive. In this case, the phase currents are sinusoidal and have maximum amplitude, equal to $I_{\max}$. In the second case, if the voltage V_d exceeds the value $\sqrt{3}V_m/(1 - 2LC\omega^2)$, the diodes D_1–D_6 do not conduct any more and the angle $\varphi = -90°$ is capacitive. For this last case, the phase currents are also sinusoidal and the amplitude has a minimum, denoted $I_{\min}$. The ratio $I_{\max}/I_{\min}$ has the value $(1 - 2LC\omega^2)/2LC\omega^2$.

Fig. 4 depicts the variation of the angle φ, the phase displacement angle between the phase voltage and the fundamental of the phase current, as a function of the mean rectified voltage V_d rated to the reference value $V_{dr} = 3\sqrt{3}V_m/\pi$ specific for the classic three-phase rectifier, as in Fig. 1(a). The voltage V_d can be established at a certain value by the load current i_L.

Another important parameter of the RNSIC converter is the mean rectified current I_d

$$I_d = \frac{1}{2\pi}\int_0^{2\pi} i_d d\omega t \tag{17}$$

which can be calculated by the help of Fig. 2(c).

In order to choose the capacitors C_1–C_6, besides the necessity to determine the maximum mean rectified voltage $\sqrt{3}V_m/(1 - 2LC\omega^2)$, one has to determine the rms current $I_{\rm CRMS}$ that flows through such a capacitor [Fig. 2(d)].

Due to the fact that the currents that flow through the capacitors $C_1 - C_6$ have small values as compared with $I_{\max}$, in order to get the necessary ωt_1 angle, it implies that one has to choose (for continuous operation) capacitors with relatively large rated capacitance C_R and rated voltage V_R. The condition is better fulfilled by the dc capacitors, [13]. At an approximately same volume, dc capacitors have a larger $C_R V_R$ as compared with ac capacitors, in exchange, they have smaller rated current I_R. For applications using RNSIC there is no need for capacitors with large I_R.

The converters in Figs. 1(a) and 2(a) can be compared from the currents flowing through their devices point of view, supposing they are dimensioned for the same load current i_L. At the rectifier in Fig. 1(a), if one has to suppress the current harmonics in the ac mains using passive filters for the orders 5, 7, 11, and 13, the overall sum of the rms currents flowing through the ac capacitors of the passive filters is several times larger than the overall sum of the rms currents flowing through the dc capacitors in the converter from Fig. 2(a). Moreover, ac capacitors have to be chosen for voltages V_R far greater than for the dc capacitors, due to the overstresses that can appear in the case of the passive filters. Another advantage of the RNSIC converter consists of the fact that its diodes D_1–D_6 are less current stressed as compared with the case of the converter in Fig. 1(a), because a part of the currents i_R, i_S, and i_T flows through the capacitors C_1–C_6.

From the above description of the working principle of the RNSIC converter one can easily deduce that its efficiency is greater than that of the ac–dc converters presented in Fig. 1(a) and in [4] or [14].

IV. Possible Applications of the RNSIC Converter

One of the possible interesting applications of the ac–dc converter in Fig. 2(a) is for battery charging.

The need of a fast charging of high-energy accumulator batteries (of tens of kilowatthours) becomes more and more obvious with the extension of electric vehicles, transport equipment, mobile telecommunication stations, robots supplied by electric batteries, uninterruptible power supplies, etc. [1]–[3]. The fast charging of a battery represents a process lasting between 15–30 min and having as a result an increase in the battery voltage from $E_{\min}$ to $E_{\max}$. In order to accomplish this, one must use, in particular, a phase-controlled rectifier with thyristors or a diode rectifier bridge cascaded with a step-down

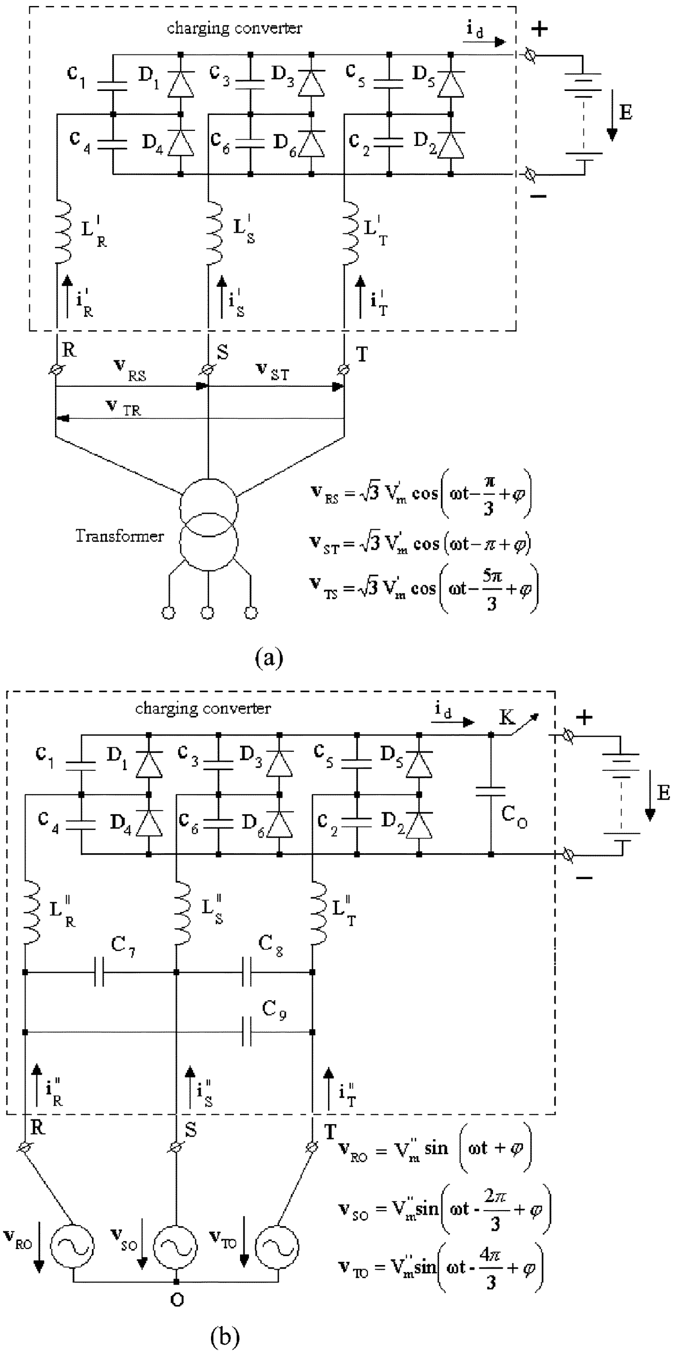


Fig. 5. Versions of battery banks charging converters. (a) With transformer. (b) With direct connection to the mains.

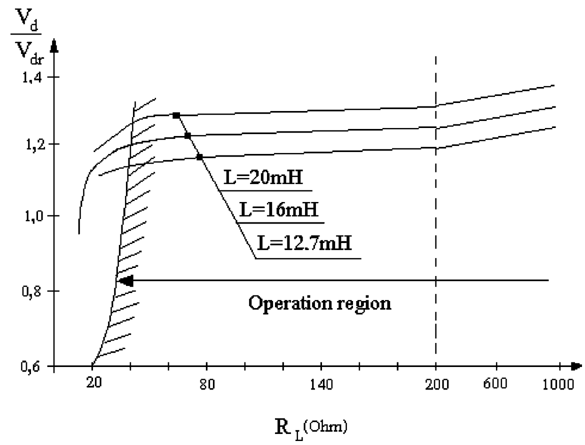


Fig. 6. Variations of the ratio V_d/V_{dr} as a function of R_L and L.

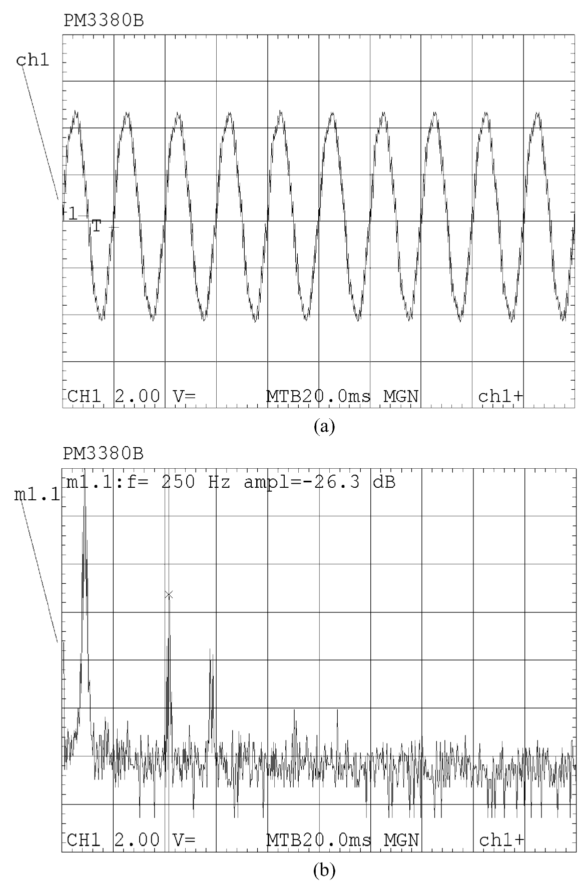


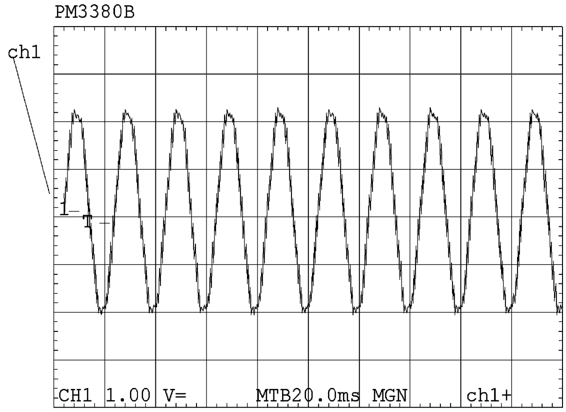
Fig. 7. Experimental results for $L = 16$ mH, $C = 40$ μF, and $R_L = 20$ Ω. (a) Waveform of the phase current. (b) Spectrum of the phase current.

(buck) dc–dc converter [1]. When an electrical isolation from the mains is required, it is possible to use a rectifier consisting of a high-frequency isolation transformer [1].

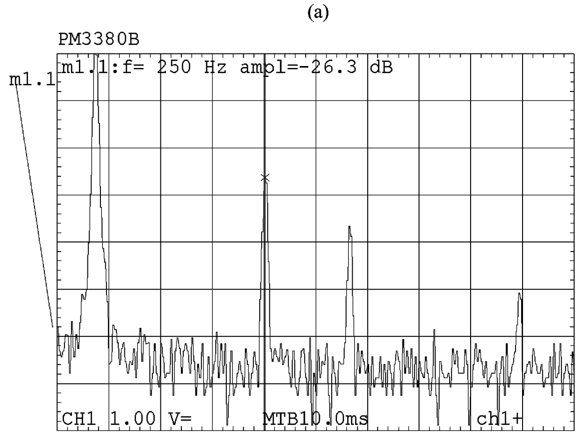
All of these above-mentioned ac–dc converters with adjustable average dc output voltage have the drawbacks that they introduce inadmissible higher current harmonics in the ac mains, are quite complex, and are of high cost.

In Fig. 5(a) and (b), two variants of RNSIC converters for the charging of identical battery banks are presented: the first, with a transformer, the second with direct connection to the three-phase mains. The capacitors C_1–C_6 from both variants are considered to have the same capacitance C and they can be dc capacitors. The inductors L'_R, L'_S, and L'_T in Fig. 5(a) have the same value L' and are connected on the ac side [10]. L' and C values fulfil relation (2) for the phase currents i'_R, i'_S, and i'_T from the electric mains to be practically sinusoidal, in accordance with Fig. 2(b) [10]. Denoting by $E_{\rm nom}$ the battery rated voltage, for the case in Fig. 5(a), the amplitude of the phase voltage V'_m at the input of the charging converter is given by the relation $E_{\rm nom} = 3\sqrt{3}V'{}_m/\pi$.

The solution in Fig. 5(b) presents the advantage that it does not require any mains transformer. The charging of the battery

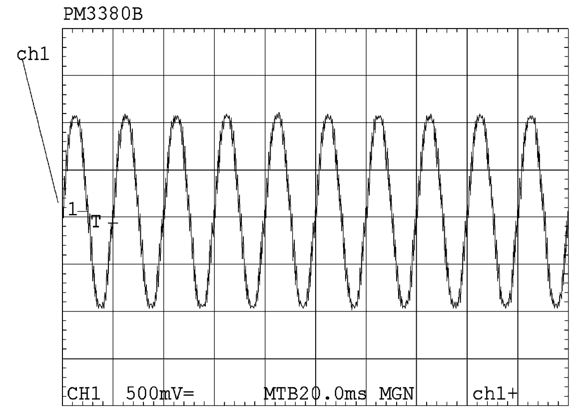


(a)

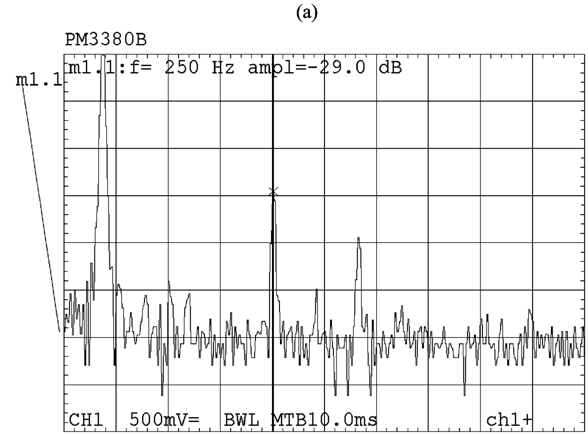


(b)

Fig. 8. Experimental results for $L = 16$ mH, $C = 40\ \mu$F, and $R_L = 60\ \Omega$. (a) Waveform of the phase current. (b) Spectrum of the phase current.



(a)



(b)

Fig. 9. Experimental results for $L = 16$ mH, $C = 40\ \mu$F, and $R_L = 1000\ \Omega$. (a) Waveform of the phase current. (b) Spectrum of the phase current.

from $E_{\max}$ to $E_{\max}$ is made at a practically constant current I_d, but when the maximum voltage $E_{\max}$ is reached, the switch K must disconnect the battery from the charging converter. Due to the presence of the inductors L''_R, L''_S, and L''_T of relatively large values, $\cos\varphi$ is small, having values between 0.2–0.4. In order to increase this factor toward unity one can use three capacitors C_7–C_9.

Another possible application of the RNSIC converters is their usage in static frequency converters with dc voltage link, designed for supplying with variable voltage and frequency the three-phase induction motor drives. In this case, the asynchronous drives are connected to the outputs of the PWM three-phase inverters. Due to the fact that the output of an RNSIC converter has the V_d voltage that is 15%-20% larger than the reference voltage V_{dr} obtained from a three-phase classical diode rectifier, it implies that at the output of the PWM inverter one can get the rated voltages for the three phases supplying the induction motor drive. In this way, there is no need to apply an overmodulation PWM technique (as, for example, methods of PWM pattern generation with third harmonic injection or with partially constant modulating waves) [15].

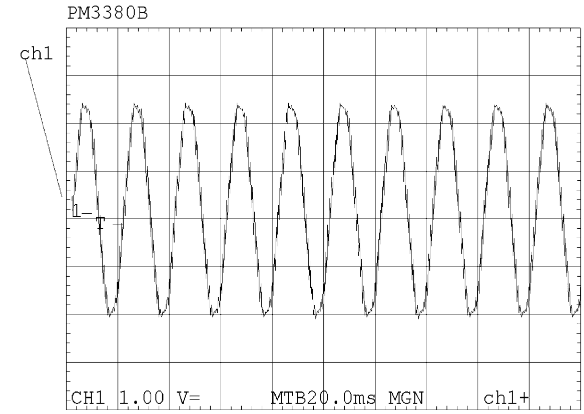
V. Experimental and Simulation Results

Laboratory experiments and simulation results have proved the effectiveness of the proposed three-phase low-harmonic rectifier. The laboratory prototype according to Fig. 2(a) consists of a three-phase voltage source (with $V_m = 100$ V and $f = 50$ Hz) and an RNSIC converter. This converter is composed of six diodes, three inductors, and six dc capacitors with capacitance 40 μF. The filtering capacitor C_0 is 1000 μF and the load resistor R_L can be varied between 5–1000 Ω.

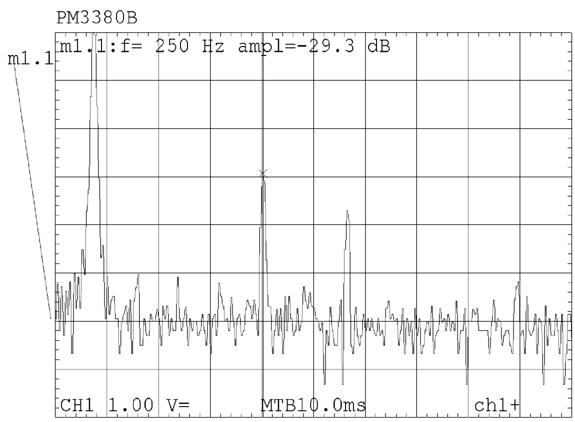
Fig. 6 presents the variation of the output voltage V_d normalized with the reference value V_{dr} as a function of R_L and L. For the inductors L_R, L_S, and L_T we have adopted successively the values 12.7, 16, and 20 mH. Using these diagrams one can draw the following conclusions.

- Once the value of L is increased, the value of the output voltage increases too.
- The input currents i_R, i_S, and i_T are practically sinusoidal for large variations of the load resistor R_L.
- Increasing the value of R_L from 20 to 1000 Ω for $L =$ 12.7 mH (that is, $LC\omega^2 = 0.05$), the output voltage V_d increases by approximately 13%. For the classical three-phase rectifier, in accordance with Fig. 1(a), this increase is about 4.7% from V_{dr} to $\sqrt{3}V_m$. Obviously, in the real case of the circuit in Fig. 1(a), there are inductors L_s in the mains and the above percentage increases.

In Figs. 7–10 we present the waveforms of the phase currents and their spectra for several values of the inductance L and different load resistors.



(a)



(b)

Fig. 10. Experimental results for $L = 20$ mH, $C = 40\ \mu$F, and $R_L = 60\ \Omega$. (a) Waveform of the phase current. (b) Spectrum of the phase current.

One can observe that for $L = 16$ mH, the 5th harmonic is approximately 4.5% for load resistor $R_L = 20$–$60\ \Omega$ becoming 3.9% for $R_L = 1000\ \Omega$. In the case when $L = 20$ mH, the 5th harmonic is approximately 3.4% for load resistor $R_L = 60\ \Omega$, while for $L = 12.7$ mH the 5th harmonic is approximately 5.6% for load resistor $R_L = 60\ \Omega$.

The simulation and experimental results also prove that the 5th current harmonic is the most significant harmonic generated in the ac mains and that its value respects the limits imposed by the IEEE Standard 519–1992 (7.0% for $20 < I_{\text{sc}}/I_{(1)} < 50$, where I_{sc} is the maximum short-circuit current and $I_{(1)}$ is the maximum fundamental-frequency load current at the point of common coupling [1]). For smaller ratios ($I_{\text{sc}}/I_{(1)} < 20$), the product $\omega^2 LC$ can be increased. The presence of a 5th-order voltage harmonic in the mains, smaller than 4% of the fundamental voltage, has practically no influence over the functioning of the RNSIC converter.

The experimental results have proved to be in good agreement with the simulation results that provided for the total harmonic distortion (THD) the values in Table I. The last column represents the THD for the case of the classical diode rectifier. The comparison between the last two columns shows the significant improvement in the THD obtained using the proposed converter.

TABLE I
TOTAL HARMONIC DISTORTION FOR THE RNSIC CONVERTER AND FOR THE CLASSICAL DIODE RECTIFIER

Inductance L	Load resistor R_L	THD (%) RNSIC	THD (%) Classical diode rectifier *
16 mH	20 Ω	4.90	22.4
16 mH	60 Ω	4.48	
20 mH	60 Ω	3.47	24.5
12.7 mH	60 Ω	5.91	
16 mH	1000 Ω	3.95	37.1

* considering inductors L_s= 2mH on the AC side and L_f = 50 mH on the DC side.

VI. Conclusion

The authors have proposed a new three-phase low-harmonic rectifier equipped with inductors, capacitors, and diodes. Inductors and capacitors are used in conjunction with the three-phase diode rectifier bridge to improve the waveform of the current drawn from the utility grid. The operation of this converter is thoroughly analyzed. The theory developed in this paper was verified by simulation and laboratory experiments.

The proposed RNSIC converter, as compared with the classical three-phase full-bridge rectifier with passive filters or active filters, presents the main advantages of being lower in size, volume, and cost.

The input currents of this converter have practically sinusoidal waveforms for large variations of the load resistor.

The output voltage is 10%–15% greater than the value obtained with the classical three-phase full-bridge rectifier. This can constitute an advantage for which the RNSIC converter is used for implementing static frequency converters with dc voltage link, having at output a PWM inverter for supplying the asynchronous drive.

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