Three-Phase Rectifier With Near Sinusoidal Input Currents and Capacitors Connected on the AC Side

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***Abstract*—An analysis of a three-phase low-harmonic diode rectifier equipped with inductors, capacitors connected on the ac side, and diodes is presented. Inductors and capacitors are used in conjunction with the three-phase diode bridge rectifier 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. 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, three-phase rectifiers with near sinusoidal input currents and capacitors connected on the dc side, and three-phase low-harmonic rectifiers applying the third harmonic current injection) are also presented. Several possible applications of the two variants of the three-phase rectifiers with near sinusoidal input currents (with capacitors connected on the dc side or on the ac side) are mentioned. Analytically derived 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 input power supply is in the form of a 50- or 60-Hz sine-wave ac voltage provided by the electric utility, which is eventually converted to a dc voltage.

As power electronic systems proliferate, ac-to-dc rectifiers are playing an increasingly important role. A large majority of the power electronics applications 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, where two variants are possible.

The first variant, i.e., a three-phase rectifier with constant dc current, has the ac side inductances L_s practically zero. A filter L_f, C_f, is connected on the dc side of the rectifier. The average value of the output dc voltage, denoted by V_{d0}, is $1.35\mathrm{V_{LL}}$, where $\mathrm{V_{LL}}$ is the rms value of the line voltage [1]. Of course, if the load resistor R is constant, the capacitor C_f can miss. The waveform of the i_R current is depicted in 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 $I_{(n)} = I_{(1)}/n$, where n represents the harmonic order $n = 5, 7, 11, 13, \ldots$. The presence of the constant current I'_d has the advantage of increased lifetime of the capacitors used in the dc link [3].

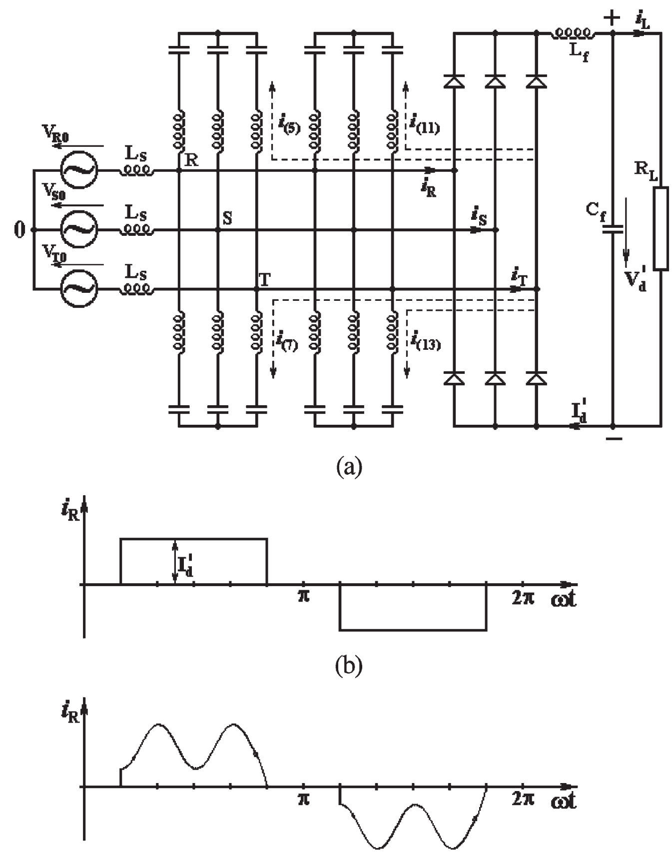

Fig. 1. Three-phase six-pulse full-bridge diode rectifier with passive filters. (a) Classical configuration. (b) Current waveform i_R with additional inductance L_f in dc link and $L_s = 0$. (c) Current waveform i_R without any dc link inductance L_f and with ac inductances L_s.

The second variant, i.e., a three-phase rectifier with additional ac side inductances L_s and without any dc link inductance, has the waveform of the i_R current depicted in Fig. 1(c). The total harmonic line current distortion (THD) factor of this current is greater than the corresponding one in the first variant, and this is the reason why the second variant is used for lower powers. This rectifier can be considered as having a practically constant dc voltage if the capacitor C_f has an adequate capacitance. This voltage depends on the ratio between the average load current I_d and the short-circuit current I_{sc} at the input of the bridge. For usual values of this ratio I_d/I_{sc}, belonging to

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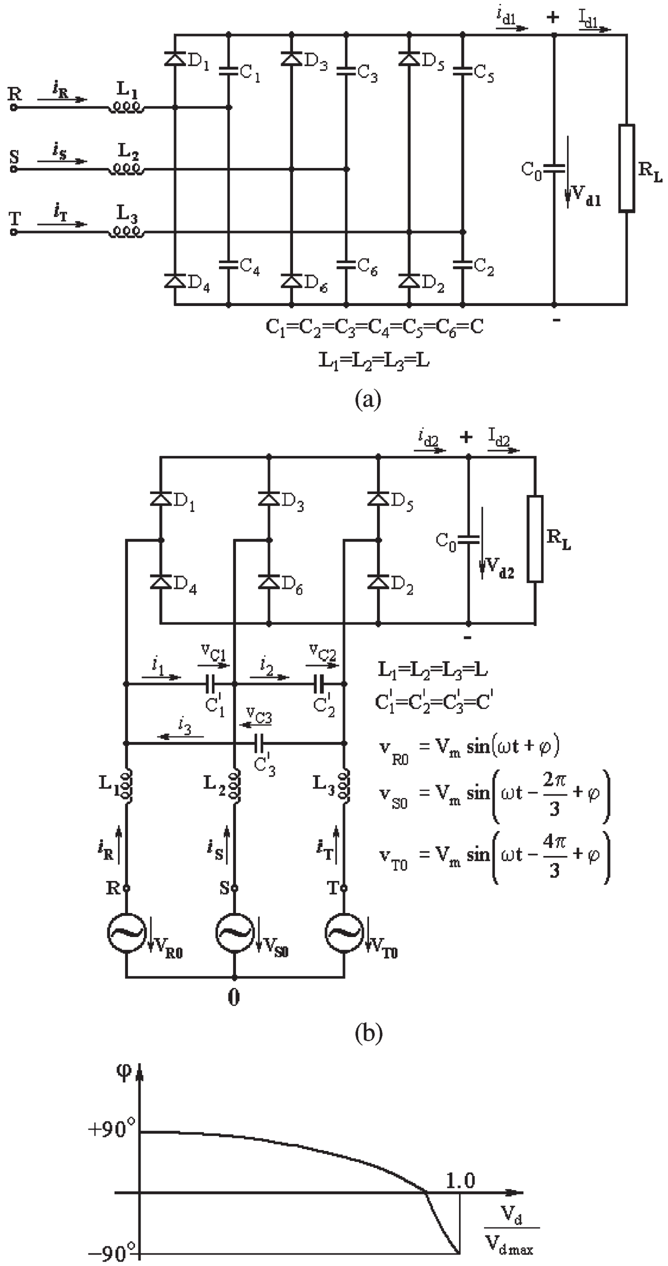

Fig. 2. Constructive variants for RNSIC converter (a) with six dc capacitors on dc side named RNSIC-1 and (b) with three ac capacitors on ac side named RNSIC-2. (c) Variation of angle φ as function of ratio $V_d/V_{d\max}$ for both variants.

the interval 0.01 and 0.05, the dc voltage varies between 1.003 and 0.98 V_{d0} [1].

To draw a conclusion, typical ac currents are far from a sinusoid. The power factor is also very poor because of the harmonic contents in the line current. Moreover, these harmonics cause additional harmonic losses in the utility grid and may excite electrical resonance, leading to large overvoltages [2].

Therefore, governments and international organizations have introduced new standards (in the United States, IEEE 519, and in Europe, IEC 61000-3) that limit the harmonic content of the current drawn from the power line by rectifiers [3].

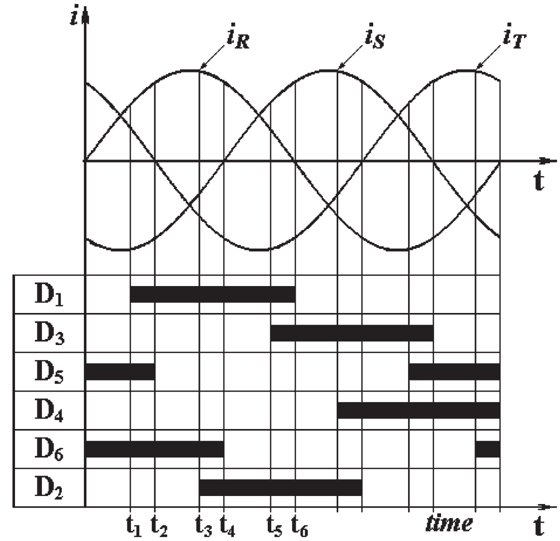

Fig. 3. AC current waveforms for large values of I_d current for both RNSIC-1 and RNSIC-2 ($0 \leq \omega t_1 \leq \pi/3$).

The first alternative to reduce current harmonics is the use of classical passive filters (CPFs) made of LC series circuits. However, passive filters have the following disadvantages [1]–[7].

1) Filtering characteristics are strongly affected by the source impedance.
2) 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.
3) Excessive harmonic currents flow into the passive filter due to the voltage distortion caused by the possible series resonance with the source.

One way to overcome the drawbacks of the passive filter is to use an active power filter (APF) consisting of voltage- or current-source pulsewidth-modulated (PWM) inverters [3]–[5]. 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:

1) difficulty to construct large rated current source with a fast current response;
2) high initial and running costs.

Obviously, the reduction of higher order current harmonics generated by a three-phase ac–dc converter can be obtained using a PWM rectifier as well [3], [8], [9]. The PWM rectifier, although having near sinusoidal input currents, has the following important limitations as compared with the three-phase diode rectifier: larger commutation losses, higher costs, EMI-related problems, and less reliability.

Recently [10]–[12], a rectifier with near sinusoidal input currents, which generates reduced higher-order current harmonics in the mains, named in what follows for short RNSIC-1, was proposed. As presented in Fig. 2(a), this converter is composed of three inductors L_1, L_2, and L_3 of equal inductance values L and six dc capacitors C_1-C_6 of equal capacitance values C. It was shown that for large variations of the load resistor R_L,

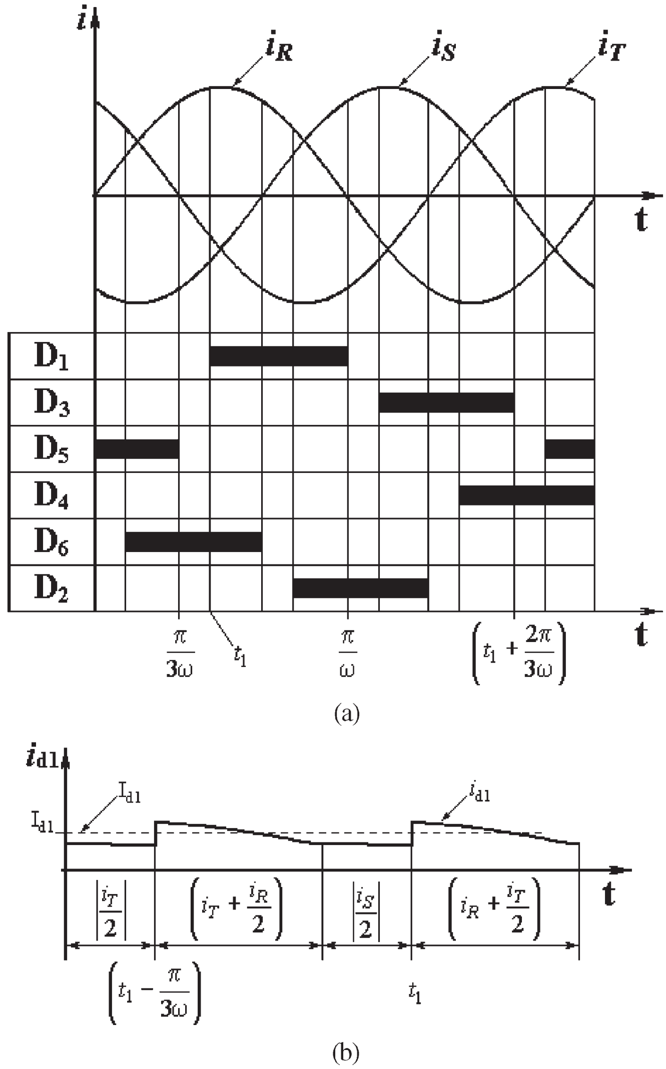

Fig. 4. Waveforms for small values of I_{d1} current for RNSIC-1 ($\pi/3 \leq \omega t_1 \leq \pi$). (a) AC current waveforms. (b) DC current i_{d1}.

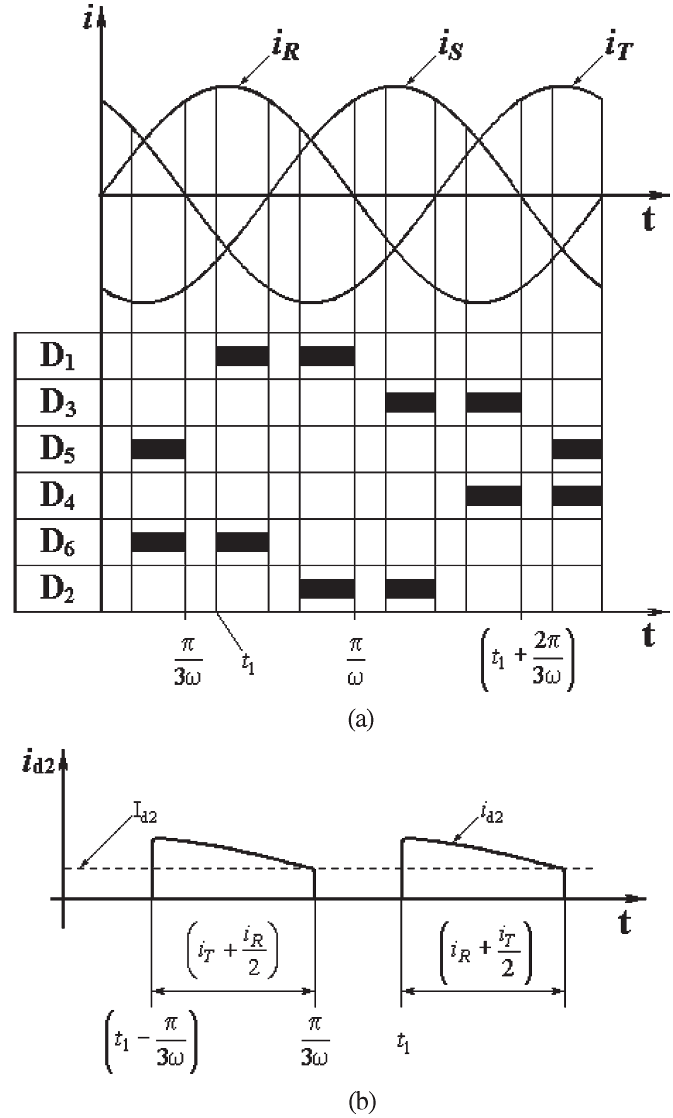

Fig. 5. Waveforms for small values of I_{d2} current for RNSIC-2 ($\pi/3 \leq \omega t_1 \leq 2\pi/3$). (a) AC current waveforms. (b) DC current i_{d2}.

the THD factor can be maintained under 5% if one fulfils the condition

$$0.05 \leq LC\omega^2 \leq 0.10. \tag{1}$$

In what follows, we propose a new converter configuration named RNSIC-2, as presented in Fig. 2(b). This circuit is characterized by the fact that it has the capacitors C_1', C_2', and C_3' connected on the ac side in order to reduce the higher-order harmonics generated in the ac mains. We will compare the two constructive variants and propose different applications for these converters.

II. New Converter Configuration

A very important property of the RNSIC-2 converter is that the voltages applied across the capacitors C_1', C_2', and C_3' are limited to $\pm V_{d2}$.

In Fig. 3, we present the waveforms of the phase currents i_R, i_S, and i_T for both constructive variants in the case of large values of the mean rectified current I_{d1} and I_{d2}. In this situation, the angle φ is close to zero for the rated operation, and two or three of the diodes D_1–D_6 are conducting ($0 \leq \omega t_1 \leq \pi/3$). Of course, for the particular case when $R_L = 0$, the angle φ is $+90^\circ$ inductive, the angle ωt_1 is zero, and the voltage V_{d2} is also zero [according to Fig. 2(c)].

The difference between the working principles of the two variants can be deduced from Figs. 4 and 5, which present the waveforms of the phase currents and the conduction intervals of the diodes for small values of the I_d current. In the case of the RNSIC-1 converter, two, one, or no diode can conduct, and the angle ωt_1 can vary between $\pi/3$ and π. In the other case, for the RNSIC-2 converter, two or no diode can conduct, and the angle ωt_1 can vary between $\pi/3$ and $2\pi/3$. For this last converter, the discontinuous current mode appears [according to Fig. 5(b)]. This situation cannot be considered as a drawback since the value of I_{d2} is small and the capacitor C_0 is dimensioned in the rated operation for large values of I_{d2}.

In what follows, we describe two stages of operation for the RNSIC-2 converter for a time interval of $\pi/(3\omega)$ (where ω denotes the mains angular frequency).

Stage 1: The diodes D_1-D_6 are off, and the current i_d is zero [according to Fig. 5(a)]. The voltage across the capacitor C_2' varies from $V_{C2}^{(1)}(0)$ at $t=0$ to $-V_{d2}$ at $t=t_1-(\pi/3\omega)$. So, the duration of this stage is $(t_1-(\pi/3\omega))$, and its equations are [according to Fig. 2(b)]

$$v_{R0}-L\frac{di_R^{(1)}}{dt}-V_{C1}^{(1)}(0)-\frac{1}{C'}\int_0^t i_1^{(1)}dt=v_{S0}-L\frac{di_S^{(1)}}{dt} \quad (2)$$

$$v_{S0}-L\frac{di_S^{(1)}}{dt}-V_{C2}^{(1)}(0)-\frac{1}{C'}\int_0^t i_2^{(1)}dt=v_{T0}-L\frac{di_T^{(1)}}{dt} \quad (3)$$

having the solutions

$$\begin{aligned} i_R^{(1)} &= \frac{3V_mC'\omega}{(1-3LC'\omega^2)} \\ &\quad\times\left[\frac{\sin\left(\omega_0 t-\frac{\pi\omega_0}{3\omega}\right)}{\sin\left(\frac{\pi\omega_0}{3\omega}\right)}\cos\varphi+\cos(\omega t+\varphi)\right] \end{aligned} \quad (4)$$

$$\begin{aligned} i_S^{(1)} &= -I_{(h)}\frac{\sin\left(\omega_0 t-\frac{\pi\omega_0}{3\omega}\right)}{\sin\left(\frac{\pi\omega_0}{3\omega}\right)} \\ &\quad+\frac{3V_mC'\omega}{(1-3LC'\omega^2)}\sin\left(\omega t-\frac{\pi}{6}+\varphi\right). \end{aligned} \quad (5)$$

By $I_{(h)}$, we denote an equivalent harmonic current that appears in the phase current as

$$\begin{aligned} I_{(h)} =& \frac{\sin\left(\frac{\pi\omega_0}{3\omega}\right)}{\sin\left(\frac{\pi\omega_0}{3\omega}\right)+2\sin\left(\omega_0t_1-\frac{2\pi\omega_0}{3\omega}\right)} \\ &\times\left\{\frac{3V_mC'\omega\sin\left(\omega_0t_1-\frac{2\pi\omega_0}{3\omega}\right)}{(1-3LC'\omega^2)\sin\left(\frac{\pi\omega_0}{3\omega}\right)}\cos\varphi-\frac{V_{d2}}{L}\left(t_1-\frac{2\pi}{3\omega}\right)\right. \\ &\quad-\frac{\sqrt{3}V_m}{2L\omega(1-3LC'\omega^2)}\left[\sin\varphi+3(1-4LC'\omega^2)\cos\varphi\right] \\ &\quad\left.+\frac{\sqrt{3}V_m}{L\omega(1-3LC'\omega^2)}\sin\left(\omega t_1-\frac{\pi}{3}+\varphi\right)\right\} \end{aligned} \quad (6)$$

where the angular frequency ω_0 fulfils the condition $3LC'\omega_0^2=1$.

Stage 2: The diodes D_5 and D_6 are conducting. The current $i_2^{(2)}=0$, and the voltage $V_{C2}^{(2)}=-V_{d2}$ until $t=\pi/3\omega$. The equations describing this stage are [according to Fig. 2(b)]

$$\begin{aligned} v_{T0}-L\frac{di_t^{(2)}}{dt}-V_{d2} \\ =v_{S0}-L\frac{di_S^{(2)}}{dt} \end{aligned} \quad (7)$$

$$\begin{aligned} v_{T0}-L\frac{di_t^{(2)}}{dt}-V_{C3}^{(2)}\left(t_1-\frac{\pi}{3\omega}\right)-\frac{1}{C'}\int_{\left(t_1-\frac{\pi}{3\omega}\right)}^{t} i_3^{(2)}dt \\ =v_{R0}-L\frac{di_R^{(2)}}{dt} \end{aligned} \quad (8)$$

having the solutions

$$i_R^{(2)}=i_R^{(1)}+I_{(h)}\frac{\sin\left[\omega_0(t-t_1)+\frac{\pi\omega_0}{3\omega}\right]}{\sin\left(\omega_0t_1-\frac{2\pi\omega_0}{3\omega}\right)} \quad (9)$$

$$\begin{aligned} i_S^{(2)} =& -\frac{i_R^{(2)}}{2}-\frac{\sqrt{3}V_m}{2L\omega}\sin(\omega t+\varphi)+\frac{V_{d2}}{2L}\left(t-\frac{\pi}{3\omega}\right) \\ &+\frac{I_{(h)}}{2}+\frac{\sqrt{3}V_m}{4L\omega(1-3LC'\omega^2)} \\ &\times\left[\sin\varphi+3(1-4LC'\omega^2)\cdot\cos\varphi\right]. \end{aligned} \quad (10)$$

As the RNSIC-2 converter has at its input a three-phase symmetric system [according to Fig. 2(b)], further on, the waveforms of the input currents i_R, i_S, and i_T can be deduced based on the above-described working principle for Fig. 5.

One can observe from (4), (5), (9), and (10) that, if the load resistor R_L is infinite, the current i_{d2} becomes null, the diodes D_1-D_6 are off, the angle ωt_1 becomes $2\pi/3$, and the angle $\varphi=-90°$. The equivalent current $I_{(h)}$ also becomes zero. In this case, the RNSIC-2 converter has a capacitive behavior, and the input currents become purely sinusoidal, having minimum values

$$\begin{aligned} i_{R\min 2} &= I_{\min 2}\sin\omega t \\ &= \frac{3V_mC'\omega}{1-3LC'\omega^2}\sin\omega t \end{aligned} \quad (11)$$

$$\begin{aligned} i_{S\min 2} &= I_{\min 2}\sin\left(\omega t-\frac{2\pi}{3}\right) \\ &= \frac{3V_mC'\omega}{1-3LC'\omega^2}\sin\left(\omega t-\frac{2\pi}{3}\right) \end{aligned} \quad (12)$$

where $I_{\min 2}$ denotes the holding current.

For comparison, we present the expressions of the minimum input currents for the RNSIC-1 as [10]–[12]

$$\begin{aligned} i_{R\min 1} &= I_{\min 1}\sin\omega t \\ &= \frac{2V_mC\omega}{1-2LC\omega^2}\sin\omega t \end{aligned} \quad (13)$$

$$\begin{aligned} i_{S\min 1} &= I_{\min 1}\sin\left(\omega t-\frac{2\pi}{3}\right) \\ &= \frac{2V_mC\omega}{1-2LC\omega^2}\sin\left(\omega t-\frac{2\pi}{3}\right). \end{aligned} \quad (14)$$

In what concerns the maximum amplitude of the input current, it has the same value for both converters and is obtained when the voltage $V_d=0$ (that is, $R_L=0$), i.e.,

$$I_{\max}=\frac{V_m}{L\omega}. \quad (15)$$

It is to be mentioned that, even for the rectifier in Fig. 1(a), having passive filters at the input, tuned for the harmonics of order fifth, seventh, 11th, and 13th, there exist purely capacitive

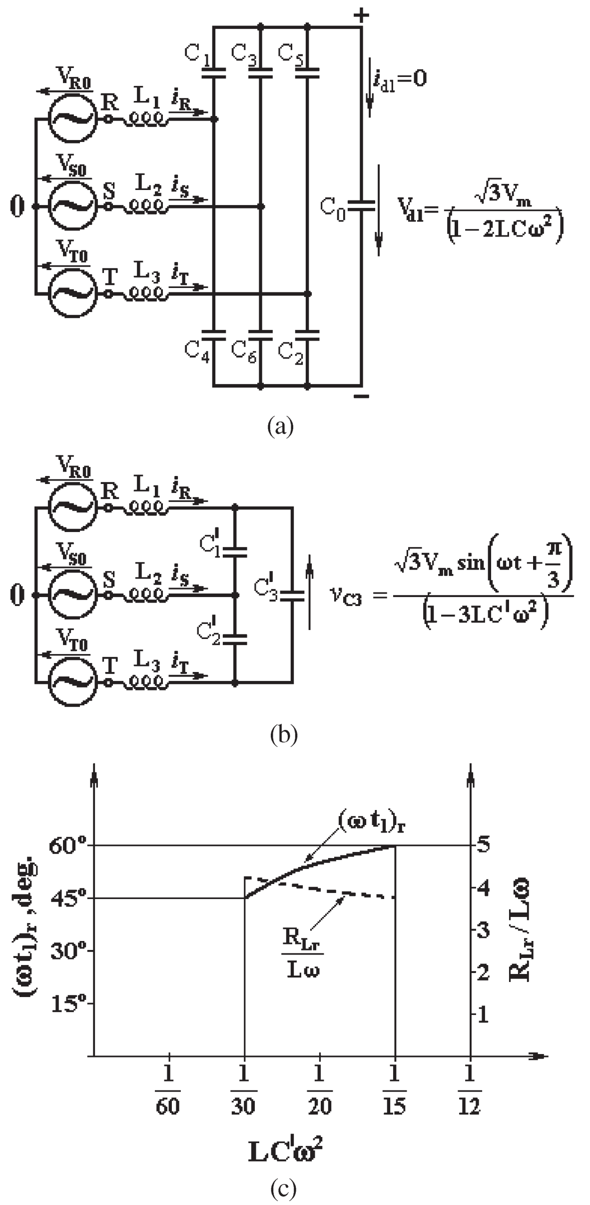

Fig. 6. Equivalent circuits for RNSIC converters for case $R_L = \infty$. (a) RNSIC-1 converter. (b) RNSIC-2 converter. (c) Variations of rated angle $(\omega t_1)_r$ and of ratio $R_L/L\omega$ as functions of $LC'\omega^2$ for RNSIC-2 converter.

input currents of fundamental frequency if the load resistor R_L is infinite, and so, the diodes are off.

III. RNSIC-2 Converter Design

In order to choose the values of the passive components L and C', one has to proceed as follows. For the beginning, to establish the relationships between the values of the capacitors C and C', we have to consider the equivalent schemes of the two RNSIC variants in the case when the load resistor R_L has infinite value (that is, the currents i_{d1} and i_{d2} are zero). For both variants, the phase currents i_R, i_S, and i_T are perfect sinusoidal, and the angle φ is $-90°$. For RNSIC-1 [shown in Fig. 6(a)], with the currents i_R and i_S given by (13) and (14), the voltages across the capacitors C_1–C_6 vary sinusoidally between zero and V_{d1} (that is, one can use dc capacitors). For the case of the RNSIC-2 variant, shown in Fig. 6(b), with the currents i_R and i_S given by (11) and (12), one must choose three ac capacitors C_1', C_2', and C_3' having the capacitance C'.

For ac–dc conversions of equal powers, equal V_m voltages (that is, equal phase currents i_R, i_S, and i_T), and equal inductors L_1, L_2, and L_3, the relation between C and C' is given by

$$C' = \frac{2}{3}C. \tag{16}$$

In order to obtain good performances (reduced higher order harmonics content and acceptable costs), for the case of the RNSIC-2 converter, the following condition has to be satisfied for the rated operation:

$$0.033 \leq LC'\omega^2 \leq 0.067. \tag{17}$$

Imposing the condition that, for the rated load resistor R_{Lr} (that is, $\varphi = 0°$), the voltages across the ac capacitors should vary from 0 to $\pm V_{d2}$ within a rated angle $(\omega t_1)_r$ of optimum value belonging to the interval (45°, 60°), one gets the characteristics given in Fig. 6(c) for the RNSIC-2 converter. For this optimum value of $(\omega t_1)_r$, it results in the voltage drop $\Delta V = L\omega I_{(1)}$ across the inductors L_1, L_2, and L_3 being between 0.45 V_m and 0.75 V_m. Although one could consider the value of ΔV quite large, it is compensated by the presence of the capacitors C_1'–C_3', so that the load voltage V_{d2} exceeds, with 15%–25% the value $V_{d0} = 1.35\mathrm{V_{LL}}$ obtained at the output of the classical three-phase rectifier in Fig. 1(a), for both variants.

Of course, the presence of the inductors L_1, L_2, and L_3 at the input of RNSIC-1 and RNSIC-2 converters could be considered as a drawback. Nevertheless, these inductors replace the passive filter inductors and the L_f inductor on the dc side for the first variant or the L_s inductors on the ac side for the second variant, which exist in the classical three-phase rectifier, those latter being bulkier and more expensive.

To conclude, one can specify that the value of the inductance L is inversely proportional to the rated load current and that the value of the capacitance C' is directly proportional to this current.

From the description of the working principle of the RNSIC-2 converter, one can easily deduce that its efficiency is greater than that of the ac–dc converter presented in Fig. 1(a) and in [13] or that of the PWM rectifiers.

IV. RNSIC-2 Converter With Small Holding Current

For the design of RNSIC-2 converters with small holding current, one can use several capacitive sections as functions of the load current I_{d2}. For example, in Fig. 7(a), a converter with two capacitive sections is presented. For larger load currents I_{d2}, capacitors C_1''–C_3'' are connected in parallel with C_1'–C_3' by means of switches S_1–S_3. In this case, the amplitude of the fundamental harmonic current $I_{(1)}$ is increased, the ratio $I_{\mathrm{sc}}/I_{(1)}$ can be reduced (for example, less than 20), and so the THD of the phase currents has to be less than 5%, according to

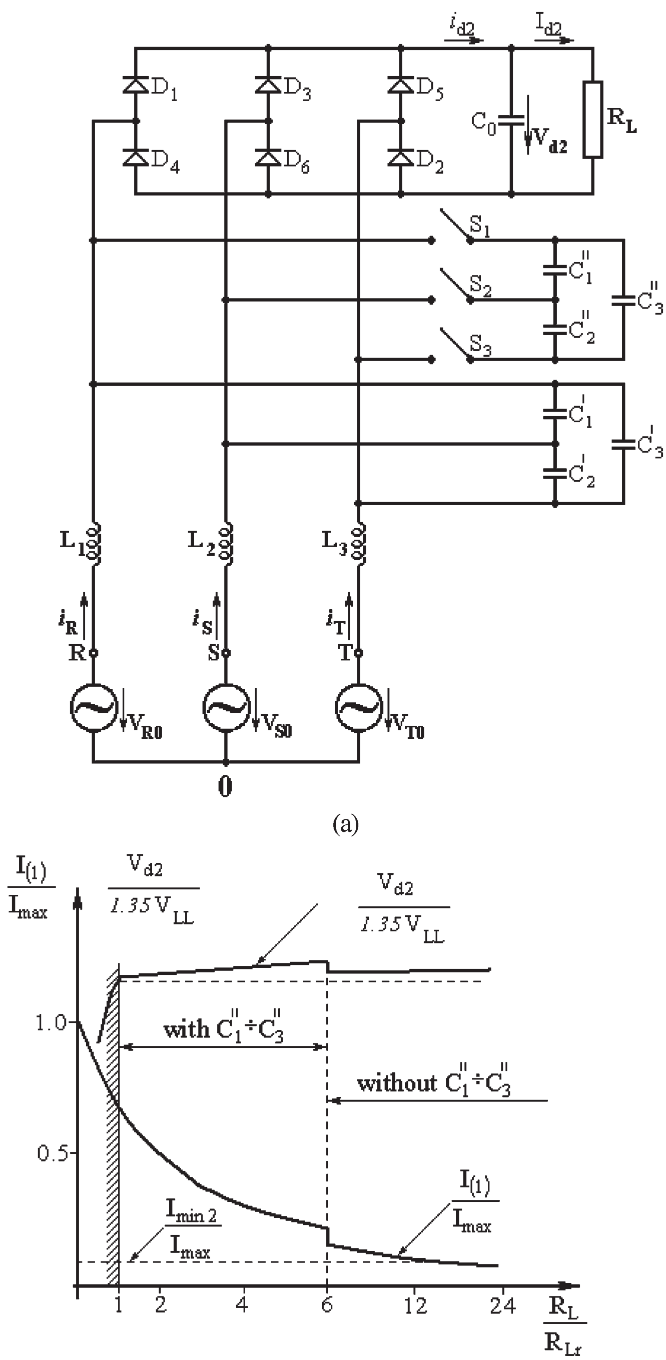

Fig. 7. RNSIC-2 converter with small holding current. (a) Basic configuration. (b) Variations of ratios $V_{d2}/1.35\mathrm{V}_{\mathrm{LL}}$ and $I_{(1)}/I_{\max}$ as function of R_L/R_{Lr}.

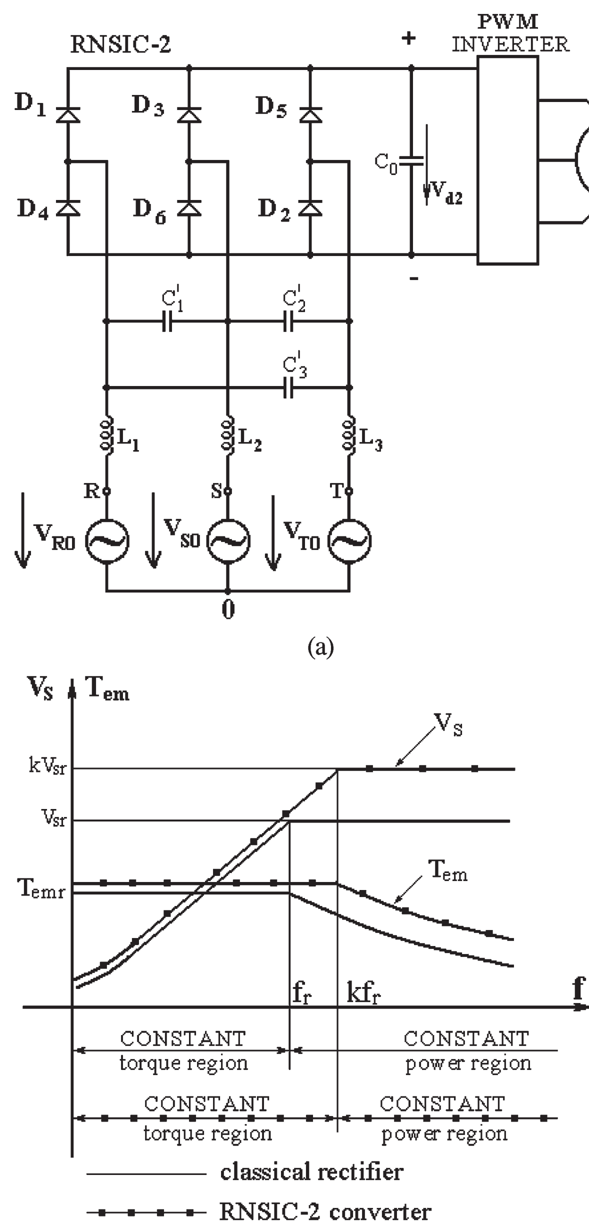

Fig. 8. Frequency converter with RNSIC-2. (a) Basic configuration. (b) Induction machine characteristics and capabilities.

the IEEE standard 519/1992 (I_{sc} denotes the amplitude of the short-circuit currents at the R, S, and T terminals).

For small load currents I_{d2}, capacitors C_1''–C_3'' are decoupled from the converter. In this case, the amplitude of the fundamental harmonic current $I_{(1)}$ is reduced, the ratio $I_{\mathrm{sc}}/I_{(1)}$ can be between 50 and 100, and so the THDs of the phase currents have to be less than 12%. Using this method, as suggested in Fig. 7, the holding current $I_{\min 2}$ can be reduced approximately by the ratio $C_1'/(C_1' + C_1'')$. The optimum ratio of the capacitors in the two sections C_1'/C_1'' is unity.

In Fig. 7(b), we present the characteristics of the RNSIC-2 converter as a function of the ratio between the load resistor R_L and the rated resistor R_{Lr}.

V. Possible Applications of RNSIC-2 Converter

Possible applications of the RNSIC-2 converters are their usage in static frequency converters with dc voltage link, designed for supplying the three-phase induction motor drive with variable voltage and frequency, as in Fig. 8(a).

Because the output of an RNSIC-2 converter has the V_{d2} voltage 15%–25% larger than the voltage V_{d0} 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 on overmodulation technique (as, for example, methods of PWM pattern generation with third harmonic injection or with partially constant modulating waves) [14], [15].

The rectifier rated voltage $V_{\mathrm{dr}} = 1.35\mathrm{V}_{\mathrm{LL}}/(1 - 3LC'\omega^2)$ exceeds the value $1.35\mathrm{V}_{\mathrm{LL}}$ ($V_{\mathrm{dr}} = k1.35\mathrm{V}_{\mathrm{LL}}$, where $k = 1/(1 - 3LC'\omega^2)$ is an overvoltage coefficient varying between 1.15 and 1.25). This is the reason for which one can get stator phase voltages V_S applied to the induction machine, surpassing practically with the same coefficient k the rated voltage V_{Sr} [according to Fig. 8(b)]. From this figure, it results that the motor supplied from a frequency converter with RNSIC-2 connected at its input is used more efficiently even at frequencies larger than the rated one, i.e., f_r. In this case, the region of functioning at a rated nominal torque T_{emr} is larger, and the power obtained from the motor at frequencies larger than f_r is larger.

Other interesting applications of the RNSIC-2 converter are enumerated as follows.

1) Charging of battery banks [11].
2) Supplying dc voltages to isolated consumers situated at relatively large distances from the utility grid. RNSIC-2 converters act as voltage boosters even at unity power factor, and so, one can compensate for the voltage drops on the power lines.
3) Variable speed wind generation systems and small hydro generators with induction machines. The energy provided by the induction generator is transmitted to the utility grid by means of a frequency converter. This converter is made up of an RNSIC-2 converter, a capacitor C_0, and a PWM inverter. For this generator, the RNSIC-2 converter represents a resistive–capacitive load that ensures the necessary magnetizing current for the induction generator. For the capacitive part of the RNSIC-2 converter, more than two sections can be adopted for the case of large variations of stator angular frequency.

VI. Experimental and Simulation Results

Laboratory experiments and simulation results have proved the effectiveness of the proposed three-phase low-harmonic rectifier. According to Fig. 7(a), the laboratory prototype consists of a three-phase voltage source (with $V_m = 311$ V and $f = 50$ Hz) and an RNSIC-2 converter. This converter is composed of six diodes, three inductors, and six ac capacitors $C_1'{-}C_3'$ and $C_1''{-}C_3''$ with capacitance of 22 μF. The filtering capacitor C_0 is 1000 μF, and the load resistor R_L can be varied between 20 and 1000 Ω. For the inductors L_R, L_S, and L_T, we have adopted the value of 18 mH.

In Tables I and II, we present the values of V_{d2}, $I_{(1)}$, THD, $I_{(5)}$, and I_{Crms} as functions of R_L for two distinct cases, namely: 1) switches $S_1{-}S_3$ are on and 2) switches $S_1{-}S_3$ are off, where I_{Crms} is the rms value of the currents through capacitors $C_1'{-}C_3'$. Using these tables, one draw the following conclusions.

1) Once the value of $LC'\omega^2$ is increased, the value of the output voltage V_{d2} increases too.
2) The input currents i_R, i_S, and i_T are practically sinusoidal for large variations of the load resistor R_L.

TABLE I
Switches $S_1{-}S_3$ Are on, $L(C_1' + C_1'')\omega^2 = 0.0782$

R_L [Ω]	V_{d2} [V]	$I_{(1)}$ [A]	φ [°]	THD [%]	$I_{(5)}/I_{(1)}$ [%]	I_{Crms} [A]
20	611	40.7	+10.2	3.92	3.7	8.17
40	661	27.2	-30.4	3.92	3.8	7.6
60	671	22.9	-45.3	3.91	3.7	7.5
80	675	21.2	-54.8	3.68	3.57	7.42
100	676	20.2	-61.0	3.72	3.6	7.37
150	677	19.0	-69.9	3.39	3.26	7.26
200	678	18.4	-74.4	3.01	2.86	7.18

TABLE II
Switches $S_1{-}S_3$ Are off, $LC_1'\omega^2 = 0.0391$

R_L [Ω]	V_{d2} [V]	$I_{(1)}$ [A]	φ [°]	THD [%]	$I_{(5)}/I_{(1)}$ [%]	I_{Crms} [A]
100	580	10.7	-47.4	8.67	8.3	3.33
150	580	9.2	-58.6	8.48	8.25	3.23
200	581	8.7	-65.3	8.24	8.03	3.19
400	582	7.9	-76.7	7.01	6.78	3.11
600	585	7.7	-80.8	5.76	5.24	3.06
800	588	7.6	-83.0	4.94	4.69	3.04
1000	590	7.5	-84.3	4.23	3.97	3.03

3) Increasing the value of R_L from 20 to 200 Ω for $C_1' + C_1'' = 44$ μF, the output voltage V_{d2} increases with approximately 11%. For the classical three-phase rectifier, in accordance with Fig. 1(a), the increase is of about 4.7% from V_{d0} to $\sqrt{3}V_m$. Obviously, in the real case, for the circuit in Fig. 1(a), there are inductors L_{sc} in the mains, and the previous percentage increases.
4) The current I_{Crms} is almost two times less than the sum of the rms currents that flow through the fifth-, seventh-, 11th-, and 13th-order filter capacitors on each phase [according to Fig. 1(a)]. As the elements $C_1'{-}C_3'$ of the RNSIC-2 are chosen for voltages that are two to three times smaller than those corresponding to filter capacitors, it implies that the costs and dimensions of the ac capacitors of the proposed converters are smaller.

In Fig. 9, we present the waveform of the line current together with its spectrum. It is to be observed that the fifth current harmonic is about 4.3% of the fundamental, while the simulation results indicated 3.7% (this can be further adjusted by increasing the product LC').

In Fig. 10, the waveforms of the voltage across the filter capacitors and the current thorough the capacitors are shown,

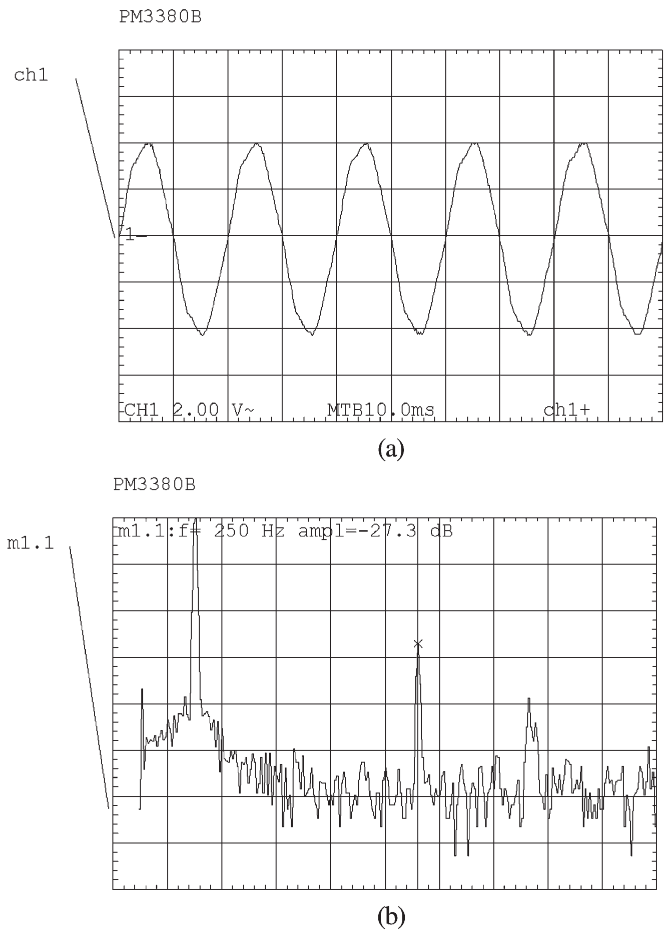

Fig. 9. Line current for RNSIC-2 converter ($L = 18$ mH, $C' = 44$ μF). (a) Waveform (probe 1:10). (b) Spectrum.

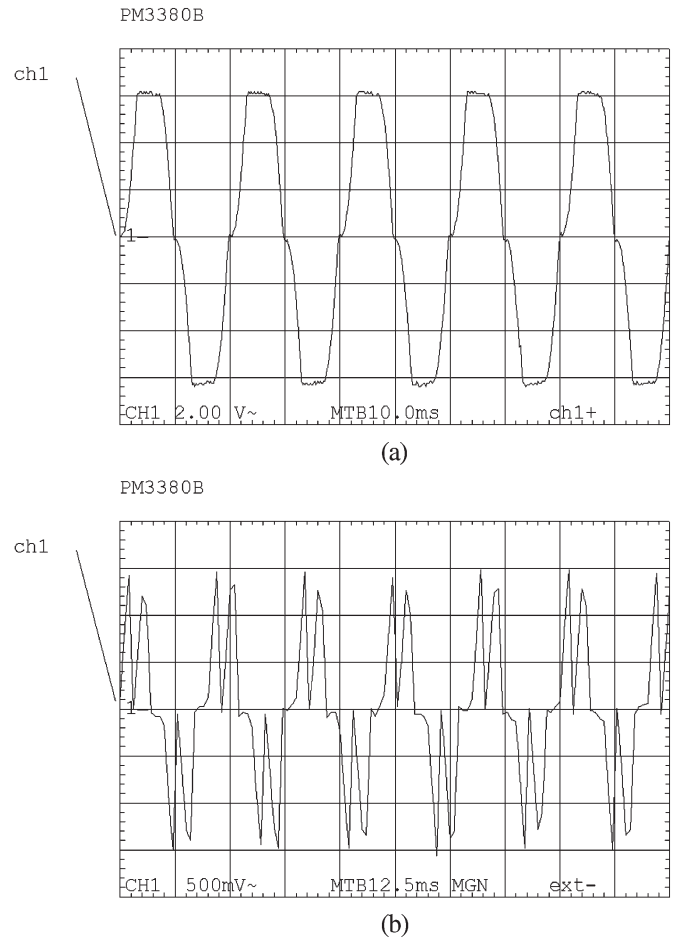

Fig. 10. Waveforms for RNSIC-2 converter ($L = 18$ mH, $C' = 44$ μF). (a) Voltage across the capacitor (probe 1:10). (b) Current through capacitor (probe 1:10).

validating the property that the voltages applied across the capacitors C_1', C_2', and C_3' are limited to $\pm V_{d2}$.

The presence of the fifth-order voltage harmonic in the mains, which is less than 4% of the fundamental voltage, has practically no influence over the functioning of the RNSIC-2 converter. Another advantage of the RNSIC-2 converter results: its operation is not influenced by the presence of higher current harmonics in the mains.

It is also important to notice that the capacitor C_0 strongly damps the resonant processes that could appear between the power supply and the inductors and ac capacitors of the RNSIC-2 converter.

From Tables I and II, one concludes that the angle φ varies within relatively large limits from 0° to $-90°$ when the load current I_{d2} varies from the rated value to zero. For the case $\varphi = -90°$, the current $I_{(1)}$ reaches the minimum value $I_{\min 2}$, and RNSIC-2 behaves like a purely capacitive load. The reactive power $Q = 3V_m I_{\min 2}/(\sqrt{2})^2$ sent to the utility grid does not exceed 15%–20% of the rated power of the rectifier $P_r = (V_{\rm dr})^2/R_{\rm Lr}$. The same variation of the angle φ is produced still at the classical three-phase rectifier in Fig. 1(a) for both variants, where the power Q can exceed even 25% of P_r because the passive filters must be overdimensioned to cope with overloads. These overloads can be due to the presence of other close harmonic generator consumers or by the occurrence of serial or parallel resonance (these types of phenomena cannot appear at RNSIC-1 or RNSIC-2 converters).

Comparing converters RNSIC-1 and RNSIC-2, which were dimensioned for the same output power, having identical L_1, L_2, and L_3 inductors along with dc and ac capacitors fulfilling (16), one can draw the following conclusions.

1) As the ac capacitors are characterized by a dielectric dissipation factor $\tan \delta_0$ of about 20–30 times less than dc capacitors, it results in the RNSIC-2 efficiency being larger.
2) For high power and large values of the V_m voltage, the RNSIC-2 variant is more appropriate as ac capacitors are available for larger rated voltages V_R and currents I_R.
3) For the rated load ($\varphi = 0°$) and with no load ($\varphi = -90°$), the THD current factor has the same values for both variants. When the load resistance varies between $R_{\rm Lr}$ and infinity, the THD current factor is larger for the RNSIC-2 converter.

Following conclusion 3), it implies that one can get an RNSIC-1 converter with a larger ratio $I_{\max}/I_{\min}$ (for example, between 7 and 9), having the parameter $LC\omega^2 = 0.055$ without the necessity of several sections of capacitors.

VII. Conclusion

A new converter configuration with the property of reducing the higher order harmonics generated in the ac mains was proposed.

The simulation and experimental results proved that the fifth current harmonic is the most significant one generated in the ac mains, and that its value is within the limits imposed by the IEEE Standard 519/1992.

Another important property of the new converter is that it provides a rectified voltage that is 15%–25% larger than the dc voltage obtained from a three-phase classical diode rectifier, a fact that makes it attractive for various applications.

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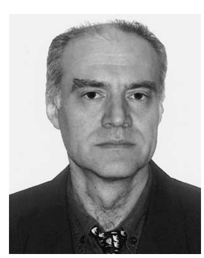

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