A NEW BIDIRECTIONAL HYBRID THREE-PHASE RECTIFIER

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Abstract – **This paper presents a new bidirectional hybrid three-phase rectifier suitable for high power applications. The rectifier employs a three-phase diode bridge rectifier and a Boost-type three-phase PWM rectifier. The proposed rectifier is capable of providing sinusoidal input currents with low harmonic distortion and DC output voltage regulation. The rectifier topology generation, the principle of operation, control scheme and simulation results are described in the paper.**

Keywords – **High power application, High power factor, Hybrid rectifier, Output voltage regulation, Three-phase electronic power conversion.**

I. INTRODUCTION

Nowadays, governments and international organizations have introduced the IEEE 519 and IEC 61000-3-2/61000-3-4 standards for limit the harmonic content of the currents drown from the AC power line.

To address the problem a great number of new single-phase and three-phase rectifier topologies have been developed. In high power applications, where three-phase systems are required to avoid the system load unbalance, the search for three-phase rectifier topologies with high efficiency, high reliability, simple control scheme and high quality input currents were increased in the last decade.

Three-phase diode bridge rectifiers are commonly used as front-end converters due their simplicity, reliability and low cost. However, they do not meet the harmonic content imposed by the IEEE 519 and IEC 61000-3-2/61000-3-4 international standards.

The use of multi-pulse three-phase rectifiers achieve lower harmonic content of the input current by cancellation the harmonic components generated by each group of six-pulse diode bridge rectifier. Moreover, they keep the simplicity and reliability features. However, they are heavy, bulky and expensive [1, 7].

Three-phase PWM rectifiers, particularly the one's based on Boost topology, meet the international standards for harmonic current limit, providing sinusoidal input currents with low harmonic distortion. PWM rectifiers are more expensive and less reliable than diode bridge rectifiers.

In the last years, the search for rectifiers that comprise the better features of diode bridge rectifiers and the better features of PWM rectifiers introduces a new class of three-phase rectifiers with low effect on the mains, the Hybrid Rectifiers [2, 4, 6].

The basic idea of the Hybrid Rectifiers is that they are generated by the connection of a passive rectifier with an active rectifier. Moreover, the passive rectifier operates with low frequency and it handles the higher output power rating. Therefore, the active rectifier is designed to operate with small power ratings and with high switching frequency.

This conception proposes that the semiconductors will commutate with high power rating/low switching frequency and low power rating/high switching frequency. It suggests that the efficiency will increase, the reliability will increase and the EMI generation will decrease.

This paper proposes a new bidirectional hybrid three-phase rectifier with high power factor and DC output voltage regulation. The rectifier employs a three-phase diode bridge rectifier and a Boost-type three-phase PWM rectifier.

First of all, the rectifier topology generation is presented in Section II. Section III of this paper presents the principle of operation and the modes of operation. The analysis of the hybrid rectifier is described in Section IV. Section V shows the control scheme and finally, simulation results are described in Section VI.

II. THE PROPOSED RECTIFIER

The origin of the proposed rectifier can be explained from the three-phase diode bridge rectifier. The traditional diode bridge rectifier is presented in Fig. 1 a). The LC filter in the DC-side of the rectifier decreases the total harmonic distortion of the input currents. A large value of inductance can achieve about 30% of total harmonic distortion in the input currents.

To achieve DC output voltage regulation, a Boost converter is connected after the diode bridge, as showed in Fig. 1 b). The Boost converter operating in Continuous Conduction Mode does not affect the input currents shape, excepted by the high frequency current ripple.

Sinusoidal input currents can be obtained employing a three-phase active filter at the AC power line. Figure 1 c) shows the circuit connection. In that case, the active filter processes just the reactive power necessary to achieve high power factor.

The proposed bidirectional hybrid three-phase rectifier is presented in Fig. 1 d). It was generated connecting the three-phase active filter from Fig. 1 c) at the DC output voltage rail. Split Boost inductors and split Boost diodes are necessary to avoid inappropriate current paths in the rectifier [8].

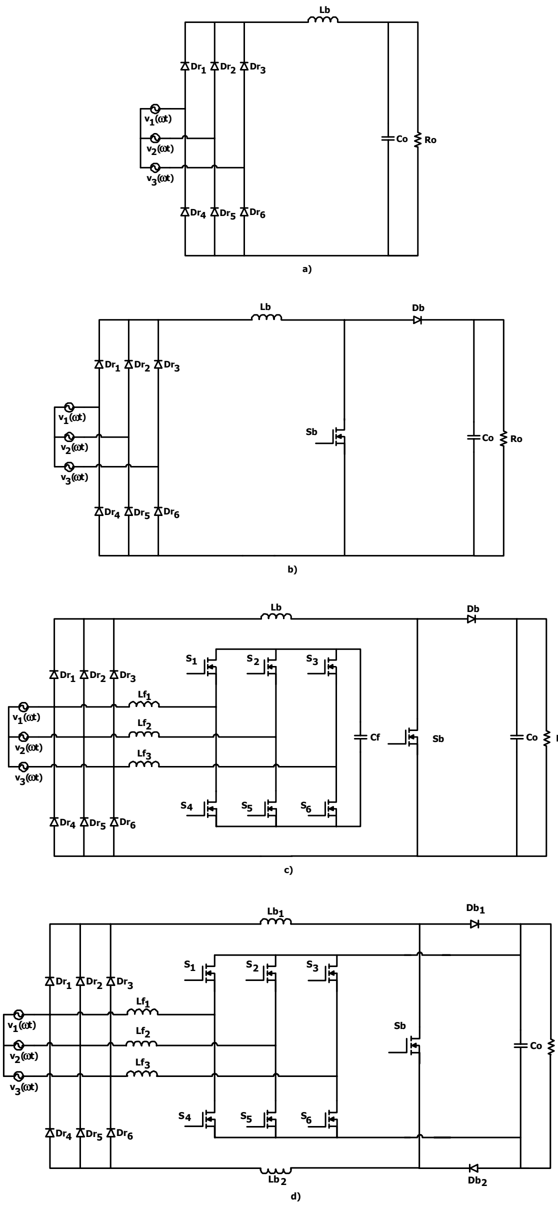

Fig. 1. Circuit generation of the proposed rectifier.

The connection of the active filter to the output configures a new active power path to supply the load. In fact, this connection configures a bidirectional Boost-type three-phase PWM rectifier from the AC mains to the load.

Since the Boost converter operates in Continuous Conduction Mode, the three-phase diode bridge keeps his features of low frequency commutation.

III. PRINCIPLE OF OPERATION

The proposed bidirectional hybrid three-phase rectifier is showed in Fig. 2. The line currents $i_{1,2,3}$ are obtained by the sum of currents $i_{1a,2a,3a}$ and currents $i_{1b,2b,3b}$. Similarly, in the output, the load current i_o is the sum of currents i_{oa} and i_{ob}.

To achieve high power factor, the line currents $i_{1,2,3}$ must be sinusoidal, with low harmonic distortion and without displacement factor. This way, the currents $i_{1a,2a,3a}$ and currents $i_{1b,2b,3b}$ will be controlled to provide the line currents with a sinusoidal shape.

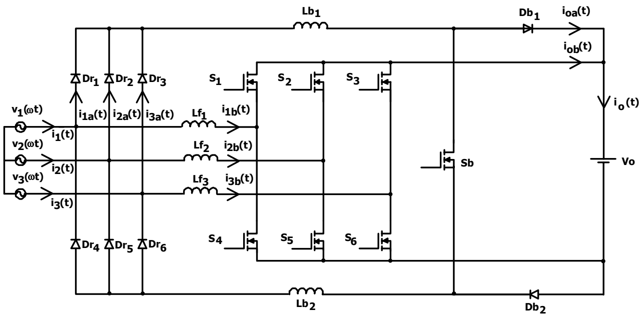

Fig. 2. Proposed bidirectional hybrid three-phase rectifier.

The shape of the currents $i_{1a,2a,3a}$ are imposed by the diode bridge and, by the control of the Boost inductor current, the peak current of these currents can be controlled.

The currents $i_{1b,2b,3b}$ are controlled to follow a desired reference, so that the sum of these currents with the currents $i_{1a,2a,3a}$ results in sinusoidal input currents.

The power level processed by each rectifier will be controlled by the peak currents. Theoretically, any combination of power can be performed by each rectifier. Therefore, it is interesting that the diode bridge rectifier processes the greatest part of the output power, according to the conception of the Hybrid Rectifiers.

Each combination between the powers processed for each rectifier represents a specific mode of operation. Figure 3 shows two different modes of operation. The first operation mode, called operation mode 1, is related with the situation where the diode bridge and the Boost converter supply the output rated power. Thus, the PWM rectifier processes just the energy necessary to achieve high power factor in the input. For this situation, the current waveforms are presented in Fig. 3 a), Fig. 3 b) and Fig. 3 c).

The second operation mode, called operation mode 2, is related with the situation where each rectifier supplies a half of the output power. In this case, the current waveforms are presented in Fig. 3 d), Fig. 3 e) and Fig. 3 f).

IV. ANALYSIS OF THE HYBRID RECTIFIER

As mentioned early, the rated power processed by each rectifier will be controlled by the peak current of currents i_1, i_{1a} and i_{1b}, for phase 1 for instance.

The goal of the analysis presented here is to quantify the relationship between the power processed by each rectifier and the peak current of i_1, i_{1a} and i_{1b}.

The hybrid rectifier must be operating with high power factor. Therefore, the line currents will present sinusoidal shape and without displacement factor.

Assuming that AC mains are balanced and without harmonic distortion, the input voltage and the input current are given by (1) and (2), respectively.

$$v_1(t) = V_p.\sin(\omega.t) \tag{1}$$

$$i_1(t) = I_p.\sin(\omega.t) \tag{2}$$

Where:

V_p – peak value of input voltage;

I_p – peak value of input current.

The instantaneous power in phase 1 is presented in (3).

$$p_1(t) = v_1(t).i_1(t) \tag{3}$$

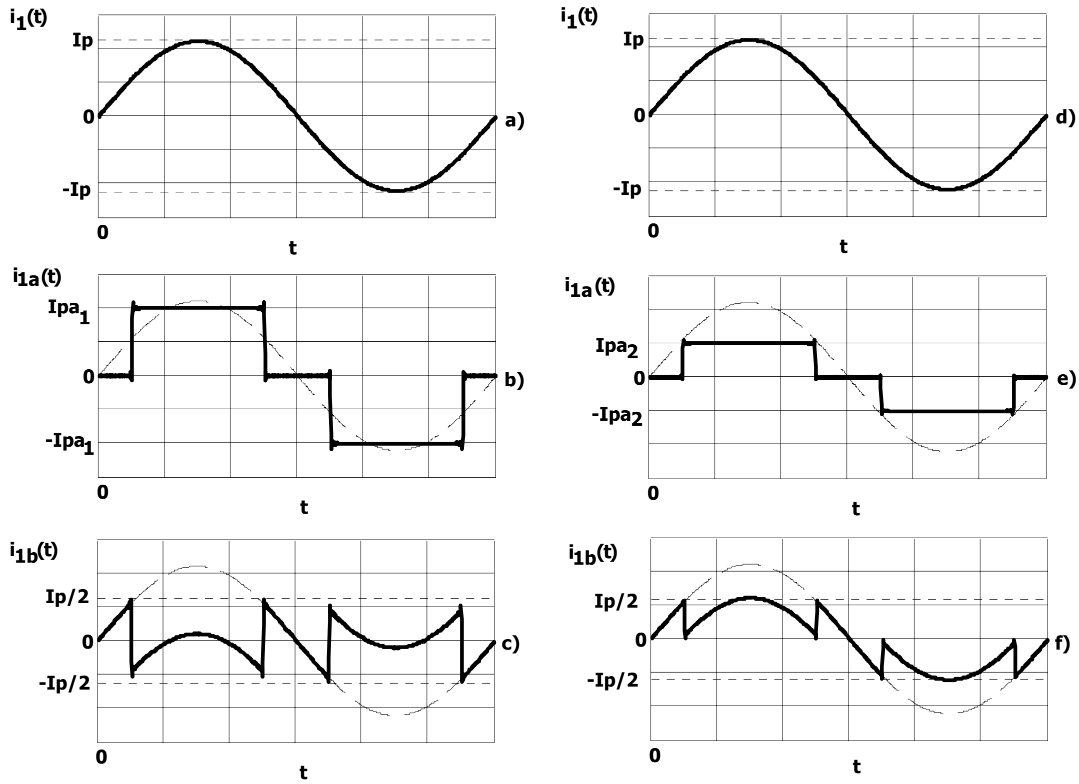

Fig. 3. The ideal currents waveforms for different modes of operation: a) line current i_1, b) current i_{1a} and c) current i_{1b} for operation mode 1; d) line current i_1, e) current i_{1a} and f) current i_{1b} for operation mode 2.

The line current i_l is the sum of currents i_{1a} and i_{1b}. It yields to:

$$i_l(t) = i_{1a}(t) + i_{1b}(t) \tag{4}$$

Substituting (4) in (3) leads to (5).

$$p_l(t) = v_l(t).\left[i_{1a}(t) + i_{1b}(t)\right] \tag{5}$$

Defining p_{1a} as the instantaneous power processed by the passive rectifier and p_{1b} as the instantaneous power processed by the active rectifier, it leads to:

$$p_l(t) = p_{1a}(t) + p_{1b}(t) \tag{6}$$

Where:

$$p_{1a}(t) = v_l(t).i_{1a}(t) \tag{7}$$

$$p_{1b}(t) = v_l(t).i_{1b}(t) \tag{8}$$

The current i_{1a} has the shape according to the waveforms of Fig. 3 b) and Fig. 3 e). The Fourier representation of this current is showed in (9).

$$i_{1a}(t) = \sum_k b_k.\sin(k.\omega.t) \tag{9}$$

Where the Fourier term b_k is presented in (10). The constant value I_{pa} is the peak current.

$$b_k = \frac{1}{\pi}.\left(\int_{\frac{\pi}{6}}^{\frac{5.\pi}{6}} I_{pa}.\sin(k.\omega.t).d(\omega.t) - \int_{\frac{7.\pi}{6}}^{\frac{11.\pi}{6}} I_{pa}.\sin(k.\omega.t).d(\omega.t)\right) \tag{10}$$

The current i_{1b} is obtained by (2), (4) and (9).

$$i_{1b}(t) = I_p.\sin(\omega.t) - \sum_k b_k.\sin(k.\omega.t) \tag{11}$$

The active power P_1 is the average value of instantaneous power p_1. It is given by (12).

$$P_l = \frac{1}{T}\int_0^T p_l(t) = \frac{V_p.I_p}{2} \tag{12}$$

Therefore, the active power processed by the passive rectifier and the active power processed by the active rectifier are presented in (13) and (14), respectively.

$$P_{1a} = \frac{1}{T}\int_0^T p_{1a}(t) = \frac{\sqrt{3}.V_p.I_{pa}}{\pi} \tag{13}$$

$$P_{1b} = \frac{1}{T}\int_0^T p_{1b}(t) = \frac{V_p}{2.\pi}.\left(\pi.I_p - 2.\sqrt{3}.I_{pa}\right) \tag{14}$$

The relationships between the active power processed by each rectifier and the input active power are obtained from (12), (13) and (14). They are presented in (15) and (16).

$$\frac{P_{1a}}{P_l} = \frac{2.\sqrt{3}}{\pi}.\frac{I_{pa}}{I_p} \tag{15}$$

$$\frac{P_{1b}}{P_l} = \frac{\left(\pi.I_p - 2.\sqrt{3}.I_{pa}\right)}{\pi.I_p} \tag{16}$$

The dependency of the power processed by each rectifier in terms of the line peak current and peak current in the input of three-phase diode bridge is demonstrated in (15) and (16).

The magnitude of the input apparent power of each rectifier can be related with the peak currents in a similar manner. The input apparent power of the rectifier is given by (17), where, ideally, it is the same value of the active power, featuring high power factor in the input.

$$S_1 = V_{ef}.I_{ef} = \frac{V_p.I_p}{2} \quad (17)$$

Where:
V_{ef} – RMS value of input voltage;
I_{ef} – RMS value of input current.

The RMS values of currents i_{1a} and i_{1b} are presented in (18) and (19), respectively.

$$I_{efa} = \sqrt{\frac{1}{T}\int_0^T i_{1a}^2(t)} = \sqrt{\frac{2}{3}}.I_{pa} \quad (18)$$

$$I_{efb} = \sqrt{\frac{1}{T}\int_0^T i_{1b}^2(t)} = \sqrt{\frac{I_p^2}{2} - \frac{2.\sqrt{3}.I_p.I_{pa}}{\pi} + \frac{2.I_{pa}^2}{3}} \quad (19)$$

Therefore, the magnitudes of apparent powers in the inputs of each rectifier are present in (20) and (21).

$$S_{1a} = V_{ef}.I_{efa} = \frac{\sqrt{3}.V_p.I_{pa}}{3} \quad (20)$$

$$S_{1b} = V_{ef}.I_{efb} = V_p.\sqrt{\frac{I_p^2}{4} - \frac{\sqrt{3}.I_p.I_{pa}}{\pi} + \frac{I_{pa}^2}{3}} \quad (21)$$

The relationships between the magnitudes of apparent power processed by each rectifier and the input apparent power are obtained from (17), (20) and (21). They are presented in (22) and (23).

$$\frac{S_{1a}}{S_1} = \frac{2}{\sqrt{3}}.\frac{I_{pa}}{I_p} \quad (22)$$

$$\frac{S_1}{S_{1b}} = \frac{\frac{I_p}{2}}{\sqrt{\frac{I_p^2}{4} - \frac{\sqrt{3}.I_p.I_{pa}}{\pi} + \frac{I_{pa}^2}{3}}} \quad (23)$$

For the operation mode 1, where the diode bridge and the Boost converter supply the output rated power, the relations for the active powers are:

$$\begin{cases} P_{1a} = P_1 \\ P_{1b} = 0 \end{cases} \quad (24)$$

Therefore, the value of relation between the peak currents can be obtained by (15) or (16). With this value, (22) and (23) solve the values of the magnitudes of apparent power. Table I summarizes these correspondent values.

In the operation mode 2, each rectifier processes a half of the output power, thus the relations for the active powers are:

$$\begin{cases} P_{1a} = \frac{P_1}{2} \\ P_{1b} = \frac{P_1}{2} \end{cases} \quad (25)$$

Table I also presents the values of relation between the peak currents and the magnitudes of apparent power for the operation mode 2.

The curves presented in Fig. 4 show the behavior of the active power processed for each rectifier for different operation modes. The parameter α represents the variation of peak current I_{pa} in (15) and (16), for the same value of input peak current I_p. Notice that the curves are parameterized by the input active power P_1.

TABLE I
The values of relations between the peak currents and the magnitudes of apparent power

	Operation Mode	
	1	2
I_{pa}/I_p	0.91	0.45
S_{1a}/S_1	1.05	0.52
S_{1b}/S_1	0.31	0.52

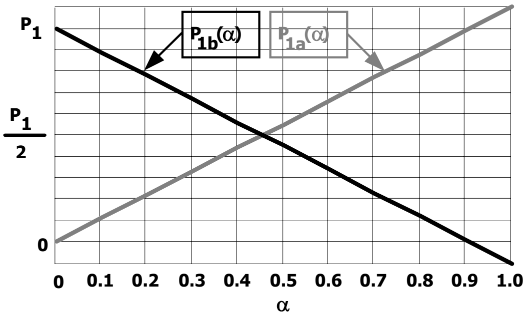

Fig. 4. Curves for the active power processed by each rectifier.

It is interesting observe that, in the operation mode where $I_{pa} = I_p$, the PWM rectifier acts as a load for the passive rectifier. In fact, in this case the active power P_{1b} is negative and the relation obtained is $P_{1b} = -0.103P_1$. This situation does not have any experimental interesting and it must be avoided.

The results presented in Table I for operation modes 1 and 2 can also be verified in Fig. 4.

In a similar manner, the magnitudes of apparent power processed by each rectifier, presented in (22) and (23), can be plotted for every operation mode. Notice that the curves are parameterized by the magnitude of input apparent power S_1.

Figure 5 shows the curves for the magnitudes of apparent power processed by each rectifier. The region of operation where $\alpha \geq 0.75$ is interesting for the PWM rectifier operation, because his apparent power processed is minimized.

The curves presented in Fig. 4 and Fig. 5 shows a region of operation with improved performance. The region among the interval $0.75 \leq \alpha \leq 0.91$ minimizes the active power and the apparent power processed by PWM rectifier and maximizes the active power processed by diode bridge rectifier.

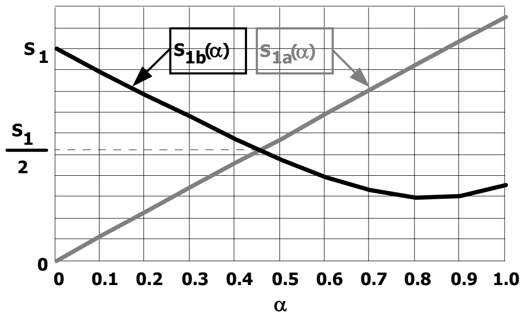

Fig. 5. Curves for the magnitudes of apparent power processed by each rectifier.

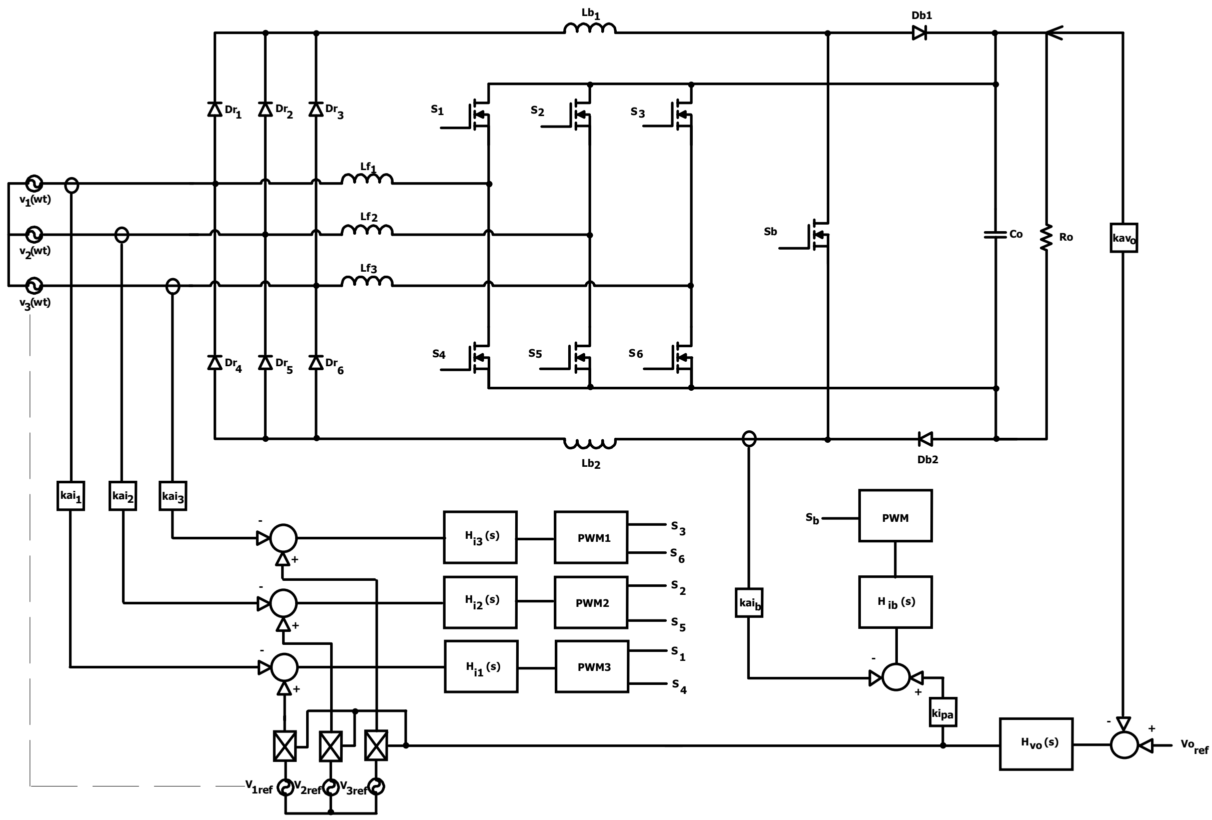

Fig. 6. The control scheme.

V. CONTROL SCHEME

The control scheme of the hybrid rectifier is showed in Fig. 6. It is composed by four current control loops and a voltage control loop.

The voltage control loop provides DC output voltage regulation and the references for the current control loops.

The Boost converter current control loop provides the peak current regulation for input currents $i_{1a,2a,3a}$. Thus, the active power processed by the three-phase diode bridge and the Boost converter is set up.

The currents $i_{1b,2b,3b}$ are controlled indirectly by the sensing and control of input currents. In this case, it is an interesting approach because it is easier provides sinusoidal references than the references with the shape of currents $i_{1b,2b,3b}$.

The control can be implemented by analog commercial integrated circuits for power factor correction or by a digital signal processor [3].

VI. SIMULATION RESULTS

A closed-loop numerical simulation was realized according to simulation parameters from Table II. The operation mode 1 is selected to present the simulation results.

The input currents $i_{1,2,3}$ are showed in Fig. 7. Figure 8 shows the input voltage and the input current in phase 1, where the input current is multiplied by a factor 2. The power factor correction is achieved.

Figure 9 shows the input current i_1, the current i_{1a} and the current i_{1b}.

TABLE II
Simulation parameters

RMS Phase Input Voltage	220V
Line Frequency	60Hz
Output Voltage	700V
Output Power	20kW
Switching Frequency	10kHz

The output voltage is presented in Fig. 10.

VII. CONCLUSIONS

This paper presents a new bidirectional hybrid three-phase rectifier suitable for high power application. The rectifier employs a three-phase diode bridge rectifier and a Boost-type three-phase PWM rectifier.

The analysis presented show the region of operation which improves the operation of the rectifier by the active power processed for each rectifier. The region among the interval $0.75 \le \alpha \le 0.91$ minimizes the active power and the apparent power processed by PWM rectifier and maximizes the active power processed by diode bridge rectifier.

The advantages and the expected advantages of the rectifier are the increase of efficiency, increase of the reliability, all passive components are designed in high frequency and decrease of EMI generation.

The increase of component count does not affect strongly the volume of the converter because the components are designed for lower currents rates.

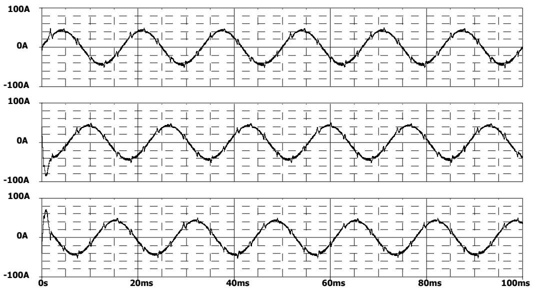

Fig. 7. The input currents $i_{1,2,3}$.

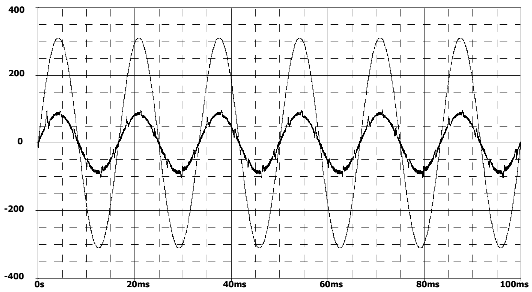

Fig. 8. Input voltage and input current in phase 1.

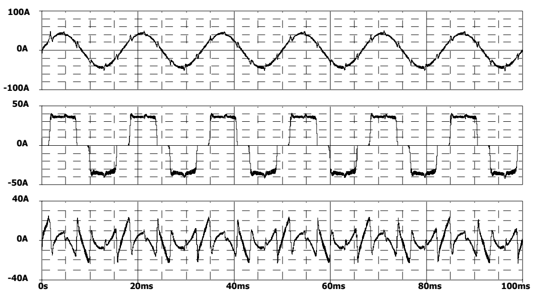

Fig. 9. Input current i_1, current i_{1a} and current i_{1b}.

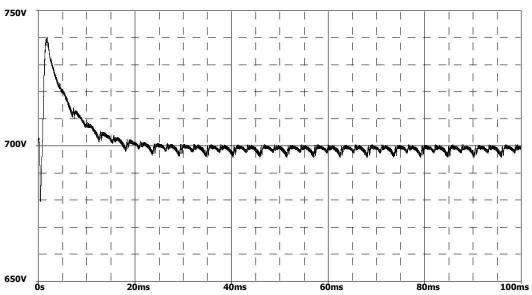

Fig. 10. Output voltage.

The disadvantage of the system appears in the control scheme, by the use of an extra current sensor and an additional current control loop.

As may be seen from the simulation results, the hybrid rectifier presents high power factor and DC voltage regulation.

Future works are the assembling of the prototype and the experimental results of this conception.

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