UNIDIRECTIONAL THREE PHASE HIGH POWER FACTOR HYBRID RECTIFIER

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***Abstract* – Power factor corrected rectifiers are new tendency in development of power supplies. This paper presents a brief review of some high power rectifiers structures and provides an assessment of each analyzed technology. As contribution, a novel hybrid high power rectifier topology is proposed and analyzed. An active unidirectional three phase rectifier is associated in parallel with a three-phase 6-pulse diode bridge. The main objective is to achieve a unity power factor high power converter, so that 50% of the total power are processed by the diode bridge and the other ones 50% for the active rectifier. The mathematical analysis and simulation results for a 26kW converter are presented.**

***Keywords* – Hybrid Rectifier, High power Factor, Load Sharing.**

I. INTRODUCTION

The industrial rectifiers have its origin in the USA. In the late 1890s Peter Cooper-Hewitt, an American electrical engineer, invented an arc lamp working with mercury vapor and observed the unidirectional behavior of current flow through this device. In 1902 Hewitt designed a reasonable working mercury arc rectifier and received as well a German patent. Before this, the use of rectifiers in industrial applications was made with the electromechanical contact converters (an AC motor coupled with a DC generator).

The mercury converter technology remained until the late 1950s, when, in 1948, the diode and the bipolar transistor were developed by the Bell Telephone Labs. In 1960, the first diode rectifier above 100kA was placed to the market, and, ten years later, the first thyristor plant of this rating was operational.

Rectifier units of more than 150kA and industrial plants with process currents above 350kA are often today. The future in the aluminum industry goes toward 500kA [1].

The use of a semiconductor element mainly depends on its capability to dissipate the semiconductor losses. This way, to medium and high power converters forced-cooled heat sinks is frequently used.

However, to obtain low THD in high power converters can be quite a complex job. Some technological limitations restrict the use of certain topologies in pre-established power levels. The latest advances in high-power semiconductor devices have introduced newer solutions for high power conversion systems, however, the degree of acceptance of each technology vary in according with various industry and applications.

A. Diode Rectifiers

Diode rectifiers are the simplest of all rectifier topologies. Robustness and low cost are main attractive characteristics that allow these structures to be applied in high power applications. In the other hand, the low power factor and high harmonic distortion of the input currents are the factors that make the rectifier to be seldom applied in industrial applications. A power factor improvement can be achieved by inserting a high value of inductance to filter the output current, as showed in Fig. 1. The maximum theoretical power factor obtained is 0,95 and a 31% of total harmonic distortion of input currents. However, the standards requirements can not be contemplated with this structure.

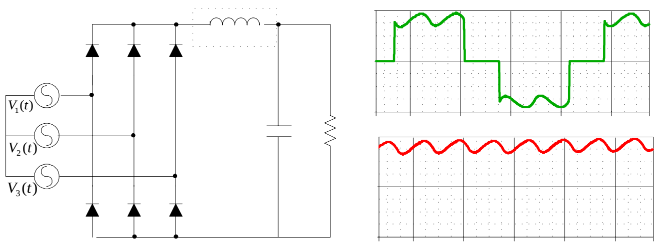


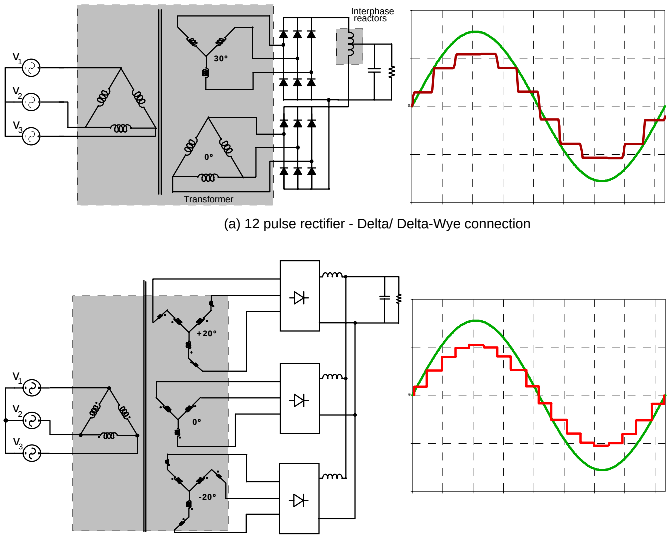
Fig. 1. Six pulse diode bridge rectifier

The concerns regarding restrictions in the harmonic content generated by the power converters, above all the framing in the standards IEEE 519 and IEC 61000 3-4, it has been objective of many recently studies. To compensate the harmonic distortion generated by the standards diode rectifiers, passive linear filters or power factor correction structures can be employed. In multipulse rectifiers special winding connections are used in transformers and, for this reason, they become, as the linear filters, heavy and bulky, however are extremely robust.

In Fig. 2 a 12 and 18 pulse high power rectifiers are depicted. For the twelve pulse rectifier, the total harmonic distortion is approximately 14%, while for the eighteen pulse structure, the obtained THD is of approximately 9% [1, 10].

A significant reduction in the final weight and volume can be achieved replacing the transformers by autotransformers with delta-differential connections, however, for the 12 pulse structure 6 secondary windings and 4 interphase reactors are necessary. For the 18 pulse, 12 secondary and 6 interphase reactors. The disadvantage is that the insulation will be lost, but, in the other hand, the power processed by the autotransformer is only 20% of the rated power [2,10].

Other interesting ideas to obtain the reduction of these structures can be obtained in [3] and [4].



(a) 12 pulse rectifier - Delta/ Delta-Wye connection

(b) 18 pulse rectifier - Delta/ Zigzag-Wye-Zigzag connection

Fig. 2. 12 pulse (a) and18 pulse (b) high power rectifiers.

B. Thyristor Rectifiers

The thyristor rectifiers present the same robustness of the diode rectifiers. The complexity and the costs are a little increased due to gate drive circuit. The harmonic distortion of input currents is worst if compared with diode rectifiers but the output voltage regulation is possible with this structures. Due to the simplicity, reliability and efficiency, the thyristor rectifier has been, until today, the most commonly used rectifier configuration for high power applications [1].

C. Active Rectifiers

Active rectification techniques are the most promising rectifier technology from a power quality viewpoint. A unity power factor and a very low harmonic distortion can be achieved. The topology illustrated in Fig. 3 is an example of an active high power factor rectifier. The most important characteristics of this structure are the unidirectional power flow and a low number of active switches.

The commonly high power factor PWM rectifier topologies are Boost type. The Buck is little spread topologies because they present low frequency input inductors and need bulky input filters.

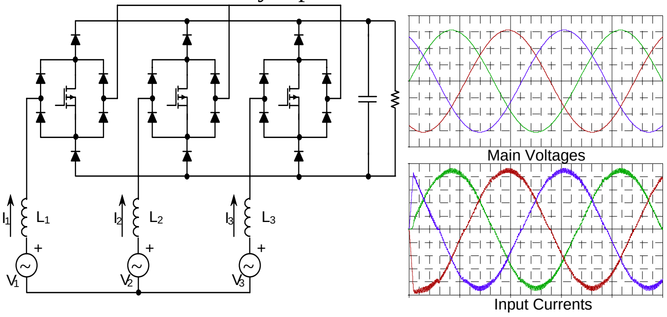


Fig. 3. Unidirectional Three Phase High Power Rectifier.

The use of active rectifier is standard in low and medium power drive applications. However, these topologies are current not available for high power rectifier applications, partly due to unavailable of suitable cost-effective power electronic devices. In applications where the weigh and volume are decisive factors, active power factor correction structures are employed, but, the complexity and the cost obtained are significantly increased.

This way, to obtain a rectifier capable to gather the robustness, lightness, simplicity and the low cost of passive rectifiers with the efficient reduction of the harmonic content obtained with the PWM rectifiers becomes a quite interesting challenge and with great possibility of practical application.

A new hybrid rectifier, based on the connection of two converters in parallel operation, composed by the association of the previously presented rectifiers with the capacity to assemble the characteristics before mentioned is the aim of this paper.

II. THE PROPOSED HYBRID RECTIFIER

Hybrid rectifier denotes the series and/or parallel connection of a line-commuted (in this case, the six pulse diode bridge) and a self-commuted converter (PWM rectifier) [5], [6]. It can not be classified as an active filter due to the fact that the active rectifier, in this case, process active power while the active filters have the characteristic of process only reactive power and compensate the harmonic content.

The proposed hybrid rectifier is presented in Fig. 4.

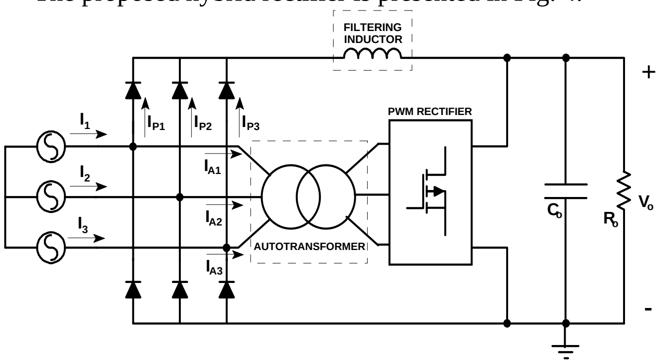


Fig. 4. Proposed Hybrid Rectifier.

To perform the mathematical analysis the input voltages are supposed perfectly sinusoidal and expressed by (1):

$$\begin{cases} V_1(t) = V_p \cdot \sin(\omega \cdot t) \\ V_2(t) = V_p \cdot \sin(\omega \cdot t - 120^\circ) \\ V_3(t) = V_p \cdot \sin(\omega \cdot t + 120^\circ) \end{cases} \tag{1}$$

It is known that the diode bridge output voltage is dependent of the input voltages rms value [7] according to the expression (2). This way, the output voltage of the Hybrid rectifier is also dependent of the mains voltage.

$$\overline{V_o} = \frac{3 \cdot \sqrt{3}}{\pi} \cdot V_p \tag{2}$$

In normal operation, the output voltage of the boost type PFC structures must be higher than to the line peak voltage to achieve high power factor. But, if the voltage produced by the rectifier PWM goes larger than the limit imposed by the expression (2), the diode bridge blocks and the whole power begin to be supplied by the active structure. To solve this incompatibility an autotransformer can used to reduce the PWM rectifier input voltages, as can be observed in Fig. 4. The autotransformer leakage inductances are added to the input inductors of the PWM rectifier. This way, the input inductors are reduced or can be suppressed, just depending of the autotransformer leakage inductances.

To achieve unity power factor, the mains currents must be sinusoidal. However they are composed by two parts; the first one originated by the active rectifier and the other by the passive structure. This statement allows establishing the expression (3):

$$\begin{cases} i_1(t) = i_{1a}(t) + i_{1p}(t) = I_p \cdot \sin(\omega \cdot t) \\ i_2(t) = i_{2a}(t) + i_{2p}(t) = I_p \cdot \sin(\omega \cdot t - 120^\circ) \\ i_3(t) = i_{3a}(t) + i_{3p}(t) = I_p \cdot \sin(\omega \cdot t + 120^\circ) \end{cases} \tag{3}$$

Where:

$i_1(t)$, $i_2(t)$, $i_3(t)$	- Line input currents.
$i_{1a}(t)$, $i_{2a}(t)$, $i_{3a}(t)$	- Active rectifier input currents.
$i_{1p}(t)$, $i_{2p}(t)$, $i_{3p}(t)$	- Passive rectifier input currents.
I_p	- Peak value of line input currents

Considering the input currents perfectly sinusoidal:

$$I_p = \frac{2 \cdot V_o \cdot I_o}{3 \cdot V_p} = \frac{2 \cdot P_o}{3 \cdot V_p} \tag{4}$$

In normal operation the diode bridge currents can not be controlled [7]. Their amplitudes are imposed by the load. However, the PWM rectifier allows that the currents to follow a predetermined reference signal [8]. So, substituting (4) in (3):

$$\begin{cases} i_{1a}(t) = \frac{2}{3} \cdot \frac{P_o}{V_p} \cdot \sin(\omega t) - i_{1p}(\omega t) \\ i_{2a}(t) = \frac{2}{3} \cdot \frac{P_o}{V_p} \cdot \sin(\omega t - 120^\circ) - i_{2p}(\omega t) \\ i_{3a}(t) = \frac{2}{3} \cdot \frac{P_o}{V_p} \cdot \sin(\omega t + 120^\circ) - i_{3p}(\omega t) \end{cases} \tag{5}$$

To simplify the analysis, the filter inductor used in six pulse diode bridge is considered sufficiently large that the output current can be considered constant as can be observed in Fig. 5.

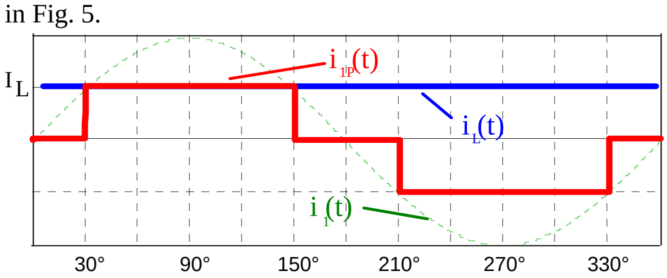


Fig. 5. Six pulse diode bride relevant wave forms.

So, the filter inductor current ($i_L(t)$) can be expressed in function of passive rectifier output power (P_{op}) and the input voltage:

$$i_L(t) = I_L = \frac{P_{op}}{V_p} \cdot \frac{\pi}{3 \cdot \sqrt{3}} \tag{6}$$

Substituting (6) in (5) and analyzing the waveform of Fig. 5:

$$i_{1a}(t) = \begin{cases} \frac{2}{3} \cdot \frac{P_o}{V_p} \cdot \sin(\omega t) - \frac{P_{op}}{V_p} \cdot \frac{\pi}{3 \cdot \sqrt{3}} & \text{if } 30^\circ \le \omega t \le 150^\circ \\ \frac{2}{3} \cdot \frac{P_o}{V_p} \cdot \sin(\omega t) & \text{if } \begin{cases} 0^\circ \le \omega t \quad \text{or} \\ 150^\circ \le \omega t \le 180^\circ \end{cases} \end{cases} \tag{7}$$

Due to unidirectional characteristic of the PWM rectifier, the instantaneous power only can assume positive or zero values. Analyzing (7), the solution that satisfies this condition is presented in (8):

$$P_{op} \le \frac{\sqrt{3}}{\pi} \cdot P_o \approx 0.552 \cdot P_o \tag{8}$$

So, the active power rectifier operation limit is:

$$P_{oa} \le (1 - 0,552) \cdot P_o \approx 0.448 \cdot P_o \tag{9}$$

The expression (8) is very important to define the load sharing between the two converters. If this relation is not satisfied, the input currents will be distorted as depicted in Fig. 6. The shaded areas denote the intervals were the relation is not satisfied.

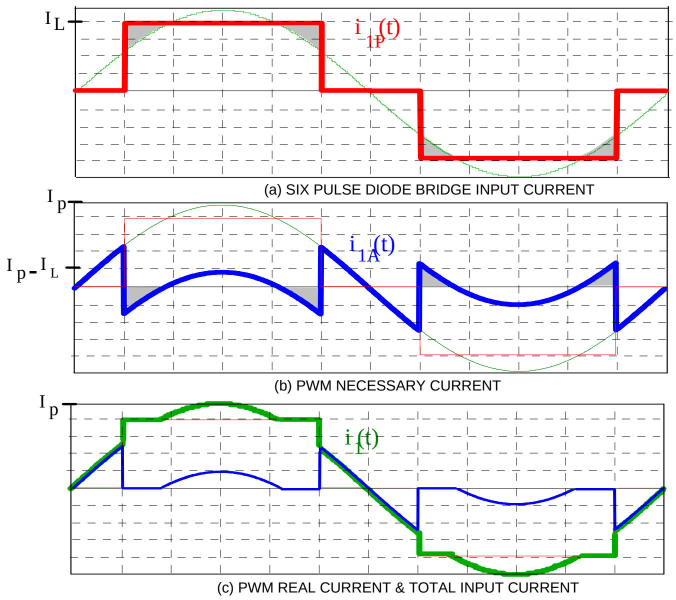


Fig. 6 – Currents on phase 1.

III. CONTROL STRATEGY

The control loop scheme is presented in Fig. 7. The currents on the mains must be sensored and compared with their respective sinusoidal references. These references signals should be synchronized with the mains voltages. A good practical way to obtain these signals is through synchronization transformers. The error signals produced by these comparisons are applied in respective compensators and the PWM modulators generate the gate signals.

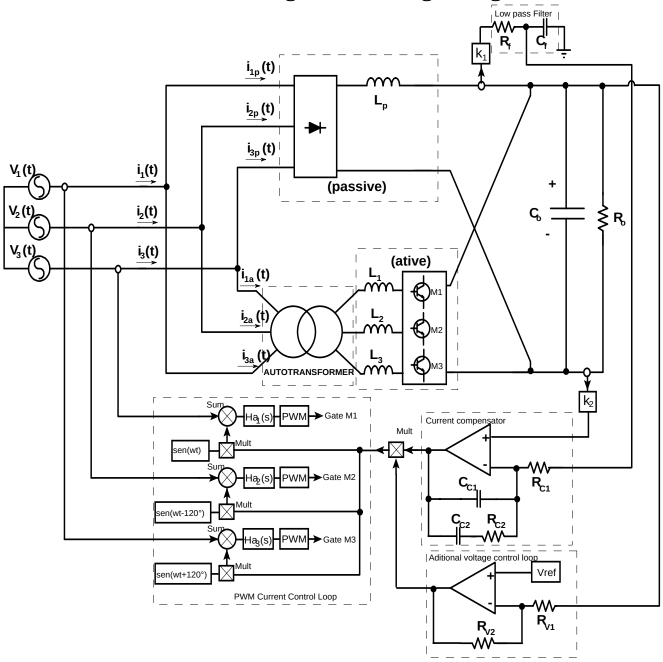


Fig. 7. Control loop.

The load sharing pre-established by (8) is guaranteed by the current control loop. The passive current is sensored and used as reference signal to be compared with the load current. A low pass filter should be used to eliminate the low frequency component present in sampled passive rectifier current.

The gains k_1 e k_2 must be settled to satisfy the expression (10).

$$0 \le \frac{k_1}{k_2} \le 0.552 \tag{10}$$

It is extremely important that the gains are adjusted for the ratio established by (10) to be quite close to 0.552, but never greater than this. If this occurs, the imposed line currents will provoke an elevation of the output voltage and, this way, the passive rectifier currents decreases causing instability to the system. Values far from 0.552 will result in input current distortion.

An additional control loop can be used to improve reliability and a fast dynamic response to the system. When a negative load step occurs, the energy stored in the passive filter inductor produces an output voltage elevation. Depending of the relation between the passive inductor filter and the output capacitor values some oscillations may occur due to slow response of the low pass filter used in current control loop. The proposed additional control scheme consists in output voltage comparison with a constant reference that should be multiplied by the current compensator output signal. The important considerations to design the voltage control loop is that the compensator must be a proportional type and the gain should be smaller than 1.

IV. SIMULATION RESULTS

The specifications used in simulation are presented in Table I

TABLE I
Specification used in simulation

Variables	Description	Value
V_p	Peak of line voltage	311V
V_{in}	Input voltage rms value	220V
V_o	Output voltage	514V
P_o	Rectifier rated load power	26kW
n_t	Autotransformer turns ratio	1.5:1
L_p	Passive rectifier filter Inductor	5mH
L_1, L_2, L_3	active rectifier Input Inductors	350μH
C_o	Output Capacitor	1500μF
f_s	Switching frequency	30kHz

A. Operation with k_1, k_2 ratio = 0.55

In Fig. 8 the mains currents and the input current on phase 1 of passive and active rectifiers are depicted. As expected, the mains currents present a sinusoidal shape. It must be observed that the power processed by passive and active rectifiers (proportional to the amplitudes of the passive and the active currents) correspond to about 50% of the total input power.

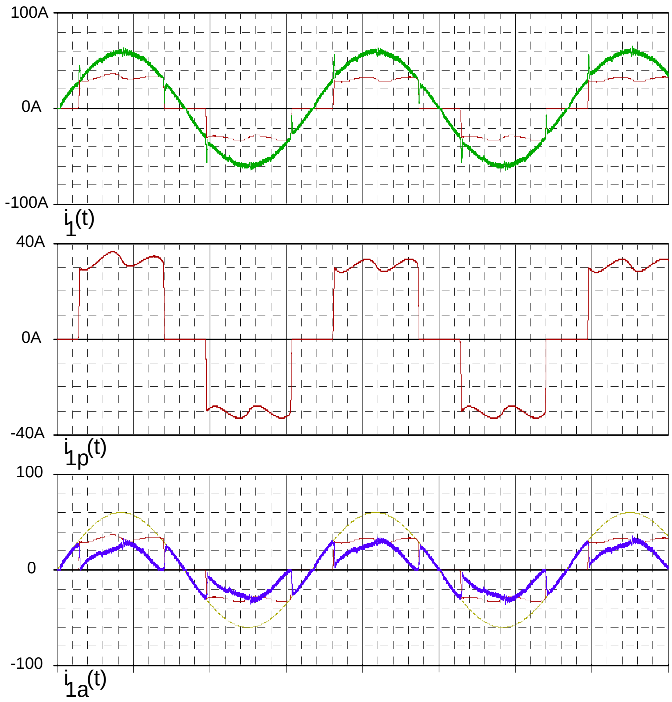


Fig. 8. Currents on phase 1.

Some peaks can be observed in line current presented in Fig. 8.This is due to the impossibility of to impose a high current derivate on active rectifier. If the line impedances were contemplated in simulation, the passive rectifier input currents would present slow derivates and, consequently, the peaks would be minimized.

The total harmonic distortion observed in input currents is about 3.18%. In Fig. 9 the harmonic amplitudes and the limits imposed by the IEEE 6100-3-4 are depicted. As can be observed, the harmonics 7, 11, 13, 17 and 19 are not in according with IEEE 61000-3-4, however, a better result can be achieved if the line impedances are contemplated in simulation.

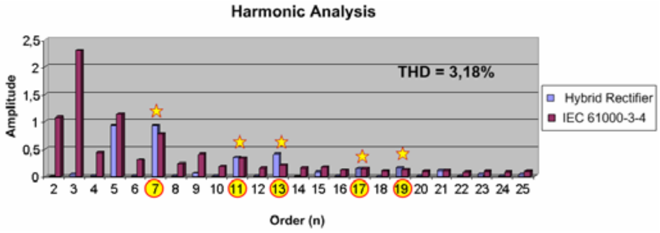


Fig. 9. Harmonic amplitudes

To verify the dynamic response of the system, a load variation was performed and presented in Fig. 10. Between 0 and 20ms the converter operates with 50% of the rated power. After this interval the converter operates with the rated power until 50ms, when the load current is 50% again. In 80ms the converter operates with full load again.

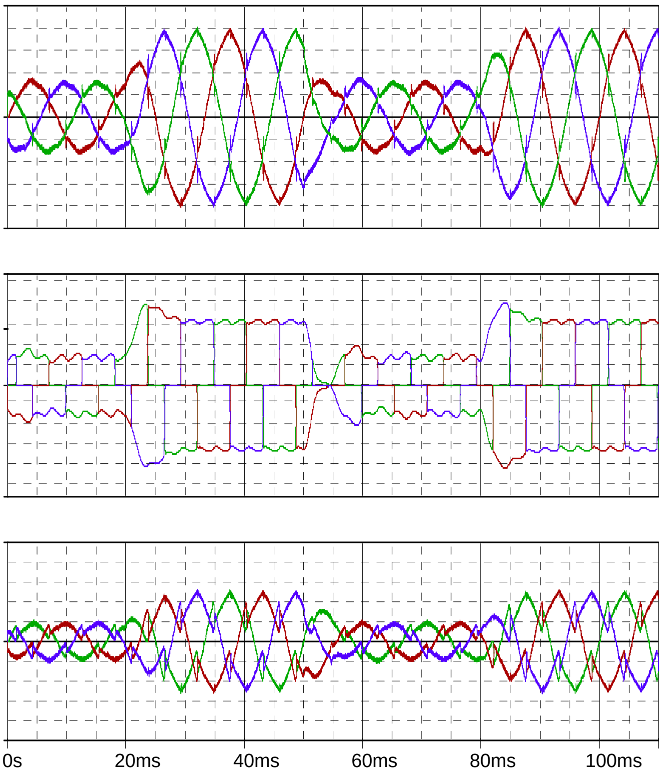


Fig. 10. Load step response.

The output voltage transient is similar to the 6 pulse rectifier with a large filter inductor, as can be observed in Fig. 11.

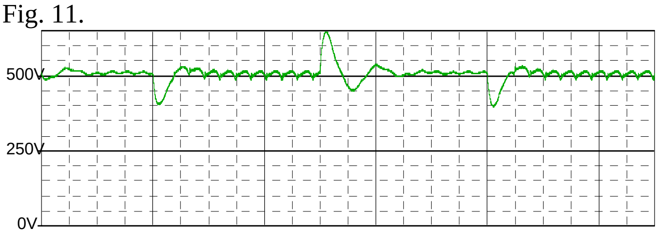


Fig. 11. Output voltage transient response

The current compensator output, the sinusoidal references and the control signals, can be observed in Fig. 12

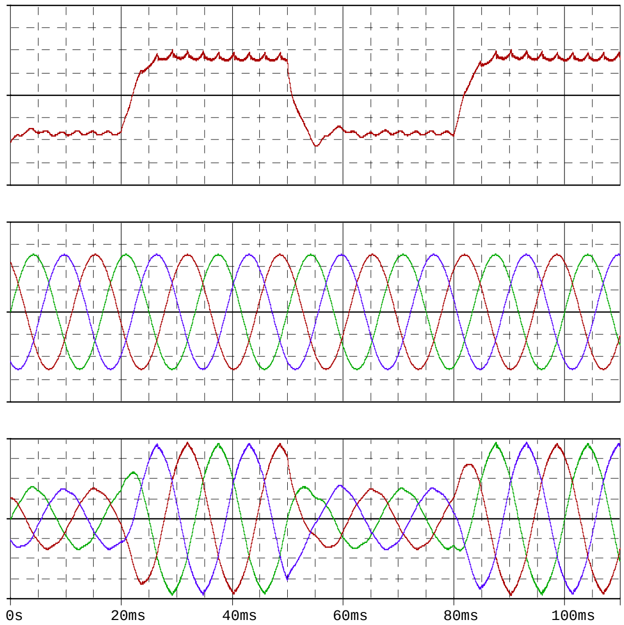


Fig. 12. Control signals

B. Operation with k_1, k_2 ratio = 0.45

As previously mentioned, values far from 0.552 for the ratio established by k_1 and k_2 will result in input current distortion.

In Fig. 13 the distortion generated by a 0.45 ratio can be observed.

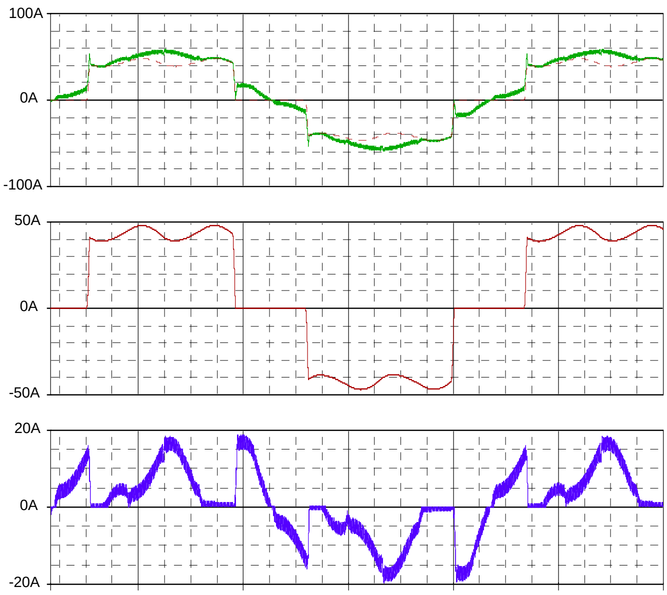


Fig. 13 – Simulation results to k_1, k_2 ratio = 0.45.

The power stage and the control circuit used in simulation are presented in Fig. 14 and Fig. 15. It should be observed that only the phase 1 control circuit is presented. However, the phase 2 and 3 uses the same circuit, just the references should be changed.

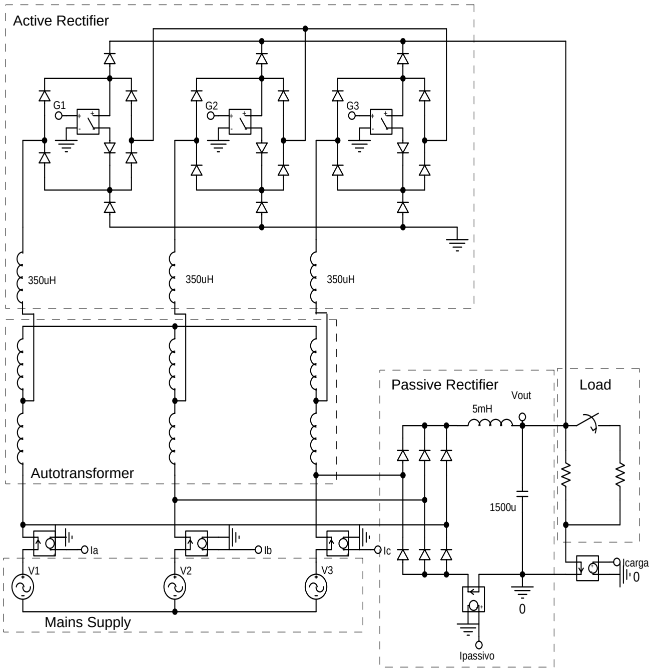


Fig. 14. Power stage circuit used in simulation.

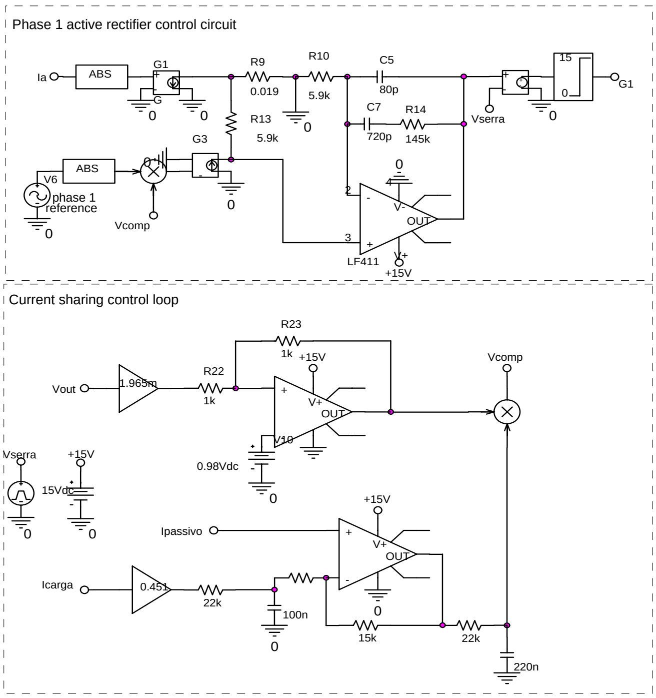


Fig. 15. Control circuit used in simulation.

V. EXPERIMENTAL RESULTS

A 20kVA hybrid rectifier is currently under development. Experimental results and practical implementation details will be available during the conference presentation.

VI. CONCLUSION

A novel three phase hybrid rectifier to high power applications has been proposed. The structure is composed by the parallel association of a passive and an active rectifier. The fact that the passive rectifier is responsible to about 50% of the output power allows using the active structure and improves the robustness, reliability, costs and providing a high efficiency to the power converter.

An autotransformer is required; however, the input inductors of the active rectifier are reduced or can be suppressed, just depending of the autotransformer leakage inductances.

The simulation results show that the approach can compensate up to 3.2% making this structure interesting and with great possibility of practical application in high power AC to DC conversion.

REFERENCES

[1] Siebert, A.; Troedson, A.; Ebner, S. “AC to DC Power Conversion Now and in the Future”, *IEEE Transactions on Industry Applications*, vol. 38, no. 4, pp. 934-940, July/August 2002.

[2] Choi, S. et al. “Poliphase Transformer Arrangements with Reduced Kva Capacities for Harmonic Current Reduction Type Utility Interface”, *in Power Electronics Specialists Conference, IEEE - PESC’95. Proceedings*, pp. 353-359, 1995.

[3] Choi, S. et al. “A New Active Interphase Reactor for 12 Pulse Rectifiers Provides Clean Power Utility Interface” *IEEE Transactions on Industry Applications*, vol. 32, no. 6, pp. 1304-1311, November/December 1996.

[4] Choi, S., Lee, B. Eneti, P. N. “New 24-Pulse Diode Rectifier Systems for Utility Interface of High-Power AC Motor Drives.” *IEEE Transactions on Industry Applications*, vol. 33, no. 2, pp. 531-541, March 1997.

[5] Kolar, J. W., Ertl, H. “Status of the techniques of three-Phase Rectifier Systems with Low Effects to the mains.” *Proceedings of the 21st International Telecommunications Energy Conference – INTELEC, Copenhagen, Denmark*, June 6-9, pp 14-1. (1999)

[6] de Freitas, L.C.G, Simões, M.G, Canesin, C.A, de Freitas, L.C. “A Novel Programmable PFC based Hybrid Rectifier for Ultra Clean Power Application” *in Power Electronics Specialists Conference, IEEE - PESC’04* vol. 3, pp. 2172-2177, June 2004.

[7] Rice, D.E “A detailed analysis of six-pulse converter harmonic currents” *IEEE Transactions on Industry Applications*, vol. 30, no. 2, pp. 294-304, March-April 1994.

[8] G. Spiazzi, and F. C. Lee, “Implementation of single-phase boost power factor correction circuits in three-phase applications”, *Switching Rectifiers for Power Factor Correction*, Volume V, VPEC Publication Series

[9] Hengchun Mao; Lee, C.Y. Boroyevich, D.; Hiti S *“Review of high-performance three-phase power-factor correction circuits”; IEEE Transactions on Industrial Electronics*, vol. 44, no. 4, pp. 437-446, Aug 1997.

[10] Seixas , F. J M and Barbi, I. “A robust 12kW three phase Rectifier using a 18-pulse Autotransformer and Isolated DC-DC Converters” *in COBEP’01 proceedings* - vol. 2, pp. 686-691, November 2001.