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Implementation of a High-Power-Factor Hybrid Three-Phase Unidirectional Rectifier

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***Abstract*: -- This paper describes the conception and analysis of a unidirectional hybrid three-phase rectifier suitable for medium-and high-power applications. The rectifier is composed of a single-switch diode bridge boost-type rectifier in parallel with a pulse width modulation (PWM) three-phase unidirectional boost rectifier. The objective is to obtain a structure capable of providing sinusoidal input currents with low harmonic distortion and dc output voltage regulation. The diode rectifier operates at low frequency and has a higher output power rating. Therefore, the PWM unidirectional rectifier is designed to operate with a small power rating and at a high switching frequency. The total harmonics distortion of the proposed structure varies between 0% and 32%, depending only on the amount of power processed by the PWM three-phase unidirectional rectifier. The rectifier topology conception, principle of operation, control scheme, and simulation and experimental results of a 20-kW laboratory prototype are also presented in this paper.**

***Index Terms* — High-power application, hybrid rectifier, power factor improvement, pulse width modulation (PWM) unidirectional rectifier.**

I. INTRODUCTION

TRADITIONALLY, three-phase ac-to-dc high power con-version is performed by diode or phase-controlled rectifiers. Due to the commutation of these structures at the zero crossing of the current, they are also called “line-commutated” rectifiers. These rectifiers are robust and present low cost, but draw non sinusoidal currents or reactive power from the source, which deteriorate the power quality. To compensate for the harmonic distortion generated by the standard diode rectifiers, passive linear filters or power factor correction structures can be employed [1]–[3]. The multi pulse three-phase rectifiers achieve harmonic cancelation by introducing phase shift by means of special three-phase transformers [4], [5]. Moreover, the simplicity and reliability ability of the diode rectifiers are preserved. However, they are heavy, bulky, and expensive. Three-phase pulse width modulation (PWM) rectifiers are widely employed in low- and medium-power drive applications where the requirements established by international standards should be satisfied [6]–[8]. These structures are the most promising rectifiers from a power quality viewpoint [1] since they can present low harmonic distortion and unity power factor. Recent trends in high-power rectifiers have introduced a new class of three-phase rectifiers, the hybrid rectifiers [2], [13]–[15]. The term “hybrid rectifier” denotes the series and/or parallel connection of a line-commutated rectifier and a self-commutated converter [2]. The line-commutated rectifier operates at low frequency and has a higher output power rating. The active rectifier is designed to operate with a small power rating and at a high switching frequency.

The number of publications in the literature shows that rectifiers research is concentrating on self-commutated and hybrid rectifiers. The great challenge is to obtain a rectifier that is as robust, light in weight, simple, and cheap as the passive rectifiers and presents the efficient reduction of input current harmonic content of PWM rectifiers. This research field has great potential for future applications.

II. PROPOSED HYBRID RECTIFIER

The parallel connection of a three-phase diode bridge rectifier and a unidirectional three-phase PWM rectifier is the basis for the proposed hybrid converter, which is depicted in the diagram of Fig. 1 The total output power of the hybrid converter is processed largely by the uncontrolled rectifier operating at low frequency while the PWM controlled rectifier, operating at high frequency, only processes about 45% of the power. By doing so, the overall efficiency of the system will increase.

A. Single-Switch Three-Phase Boost Rectifier

The single-switch three-phase boost rectifier, presented in Fig. 2, is the basis for the proposed hybrid converter. It presents a relatively high power factor and is characterized, in general, by a very high utilization of the power components [2], [10]–[13]. However, despite its simplicity and robustness, the current waveforms of this topology do not comply with the IEEE 519 and IEC61000-3-4 standards. The single-switch boost rectifier imposes a rectangular shape to the input current wave-forms. The current control loop can only control the amplitude

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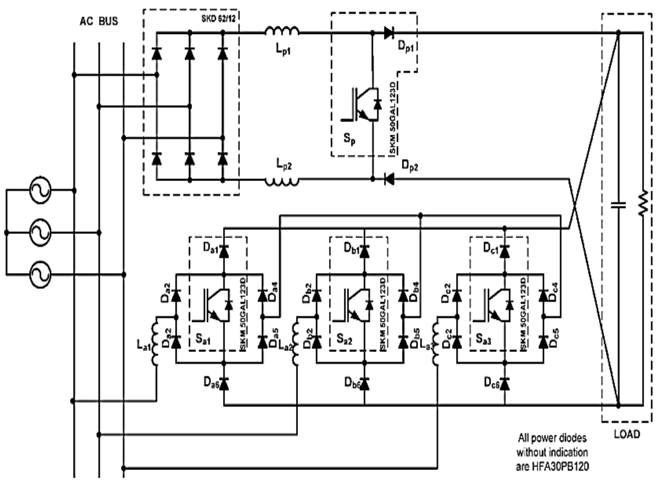

Fig. 1. Hybrid three-phase high -power-factor rectifier. The traditional single-switch three-phase boost rectifier and the three-phase boost unidirectional rectifier connected in parallel.

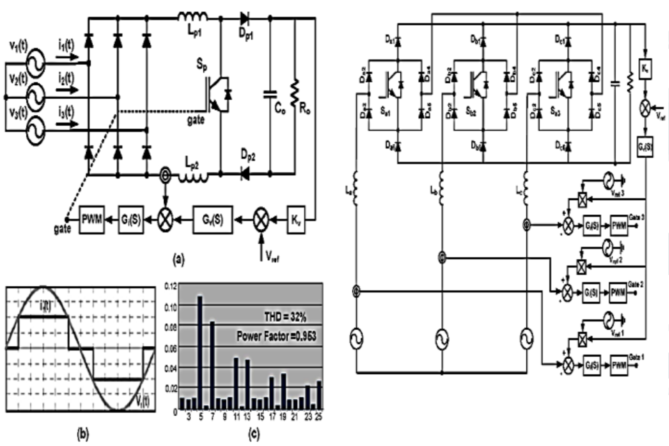

Fig. 2. (a) Single-switch three-phase boost rectifier power stage. (b) Waveform of the input voltage and current. (c) Harmonic content of the input current.

TABLE I
SPECIFICATIONS USED IN SIMULATION

Variable*	Description	Value
V_p	Line Voltage (peak)	311V
V_{in}	RMS input voltage	220V
V_o	Output Voltage	700V
P_o	Output Power	20kW
f_s	Unidirectional PWM Switching Frequency	10kHz
L_{p1}, L_{p2}	Single switch three-phase boost inductor	2.0mH
L_{a1}, L_{a2}, L_{a3}	Active rectifier input inductors	2.5mH
C_o	Output Capacitor	4500µF

*The variables are referred to Fig. 3.

The preestablished load sharing of (9) is guaranteed by gains k1 and k2 , which must be chosen to satisfy the following

$$0 \le a \le 0.552, \quad \text{where} \quad a = \frac{k_2}{k_1}. \qquad (11)$$

To obtain perfect sinusoidal currents, it is important that the gains ratio of (11) be adjusted as close to 0.552 as possible, but never greater than this value. If the ratio is greater than 0.552, the imposed line currents will be distorted. The power processed by the PWM rectifier increases as the value of α decreases. At the limit α = 0, the PWM rectifier processes the total load power.

The proposed control scheme can be implemented by com-mercial analog integrated circuits, such as the UC3854, or by digital signal processors. The presented results are obtained by using classical con-trol methods, and the prototype was implemented employ-ing four commercial UC3854B integrated circuits. The control loops were designed in accordance with the datasheet design procedures.

V. SIMULATION RESULTS

The specifications used in the simulation are presented in Table I. At first, the operation mode selected was α = 0.55 and sinusoidal input currents are obtained. In a second simulation, α was chosen to be 0.68 to exemplify an operation mode where the condition established by expression (11) is not satisfied. The line voltages and the line currents for α = 0.55 are pre-sented in Fig. 8. Power factor correction is achieved since the line currents are sinusoidal with low total harmonic distortion (THD) and do not present a displacement factor. The mains current and the input currents of phase 1 of the passive and active rectifiers are depicted in Fig. 9. The mains current presents a sinusoidal shape, as expected. Note that the power processed by the passive and active rectifiers (propor-tional to the amplitudes of the passive rectifier's and the active rectifier's input currents) is 55% and 45% of the total output power, respectively.

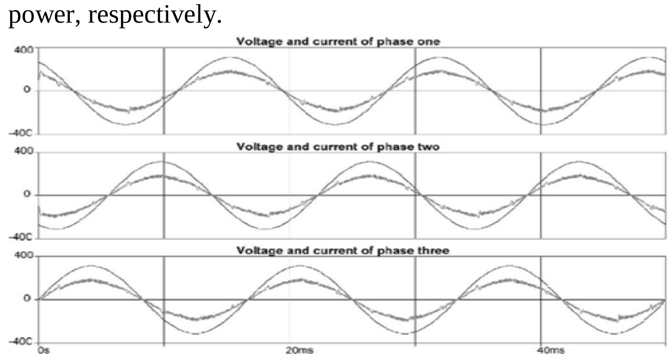

Fig. 8. Input voltages and input currents (scaled up 4×) of the simulation

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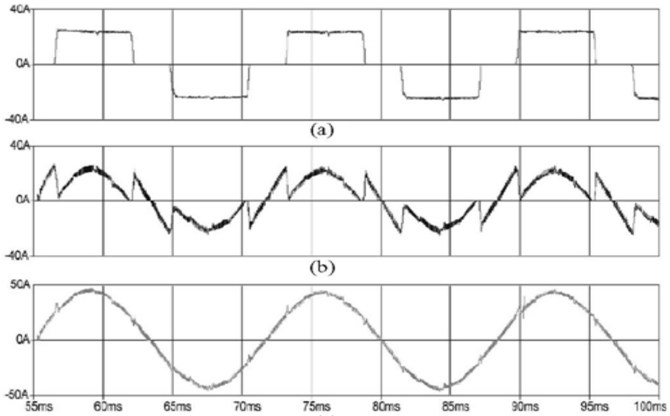

Fig. 9. Simulation results. (a) Current at the input of the passive rectifier. (b) Current at the input of the active rectifier. (c) Total current drawn from the source

The THD of the input currents is approximately 3.22%. To verify the dynamic response of the system, a load variation was performed and the results are presented in Fig. 10. Between 0 and 50 ms, the converter operates at half of the rated power. After this interval, the converter operates at full-load for 50 ms. At 100 ms, the converter operates at low load again. The output voltage transient observed in the simulation is presented in Fig. 11. As previously demonstrated, values of α greater than 0.55 cause distortion in the input current. In Fig. 12, the distortion in the line current of phase 1, which occurs when α = 0.68, can be observed. For the case presented in Fig. 12, the passive rectifier pro-cesses about 75% of the rated power while the active rectifier processes the remaining 25% of the output power (α was chosen to be 0.68). The line currents do not meet the harmonic content limit defined by standard IEC 61000-3-4**.**

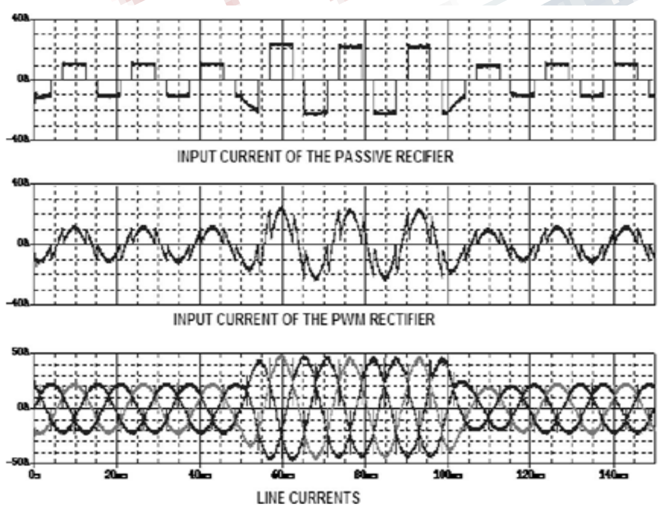

Fig. 10. Load step response generated by simulation.

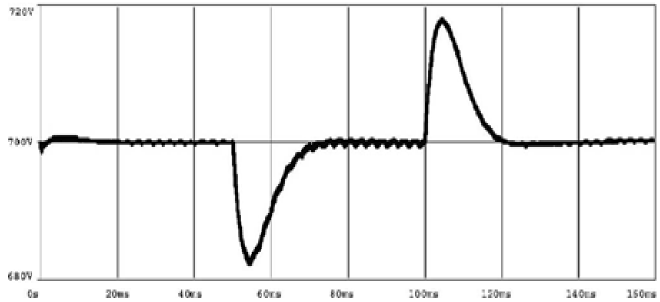

Fig. 11. Output voltage transient response to a load change

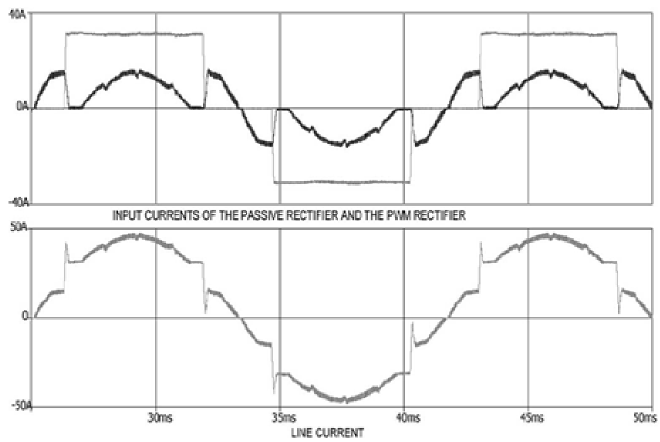

Fig. 12. Simulation results for the ratio of k1 and k2 equal to 0.68.

VI. EXPERIMENTAL RESULTS

A 20-kW laboratory prototype of the proposed structure, pre-sented in Fig. 13, was built using the components presented in Table II**.**

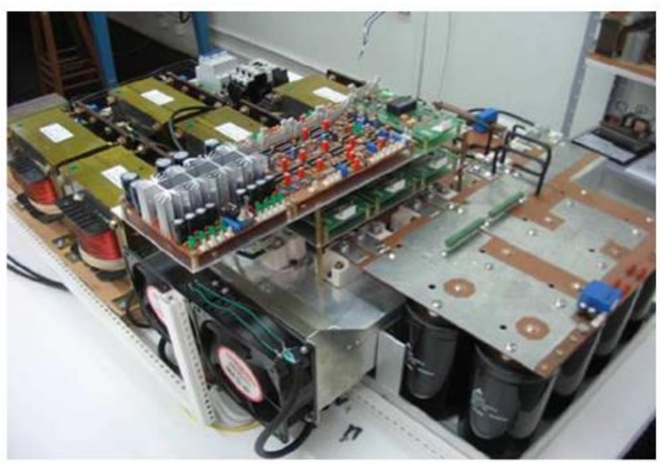

Fig. 13. Picture of the prototype.

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TABLE II
SPECIFICATIONS OF THE LABORATORY PROTOTYPE

Variable	Description	Value
D_n	Power Diodes	HFA30PB120
S_{a1}, S_{a2}, S_{a3}, S_b	Power IGBTs	SKM50GAL123D
f_s	Switching Frequency	10kHz
L_{p1}, L_{p2}	Single switch three-phase inductor	2.0mH/50A
L_{a1}, L_{a2}, L_{a3}	Active rectifier input inductors	2.5mH/15A
C_o	Output Capacitor	4400µF

The control circuit board was implemented using four com-mercial analog integrated circuits, the UC3584B, that were con-ceived for power factor correction applications. The experimental results for the current generated by the single-switch boost rectifier (Ch4), the current generated by the PWM unidirectional rectifier (Ch3), and the line current (Ch2) are presented in Fig. 14. These results was obtained for α = 0.55. As expected, the mains currents present a sinusoidal shape. The transient response of the system can be observed in Figs. 15 and 16, where the current waveforms and the output voltage waveform are depicted, respectively. The power quality analysis is presented in Table III. The power factor is 0.989 at 20.7 kW and the THDi is 7.9%. The harmonic analysis depicted in Fig. 17 compares the in-dividual amplitudes of the current harmonics with standard IEC 61 000. Note that the 17th and 23rd harmonic components of the current do not meet the standard. This can be attributed to the fact that the line voltages are used as references for the current control loop. The distortion present in the line voltages generates an equivalent distortion in the currents. This prob-lem can be solved by using external sinusoidal references with

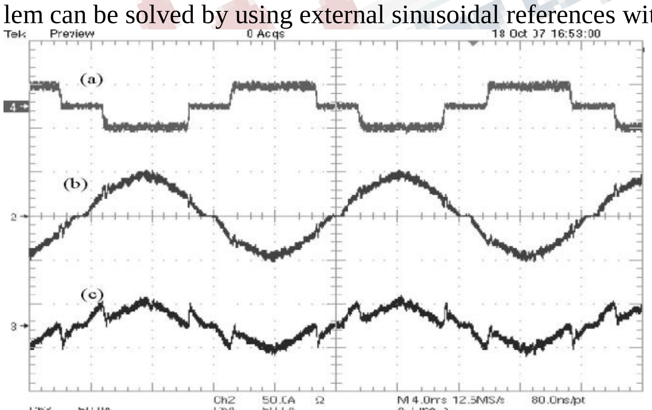

Fig. 14. Experimental waveforms. (a) Single-switch boost rectifier current. (b) Line current. (c) PWM unidirectional rectifier current

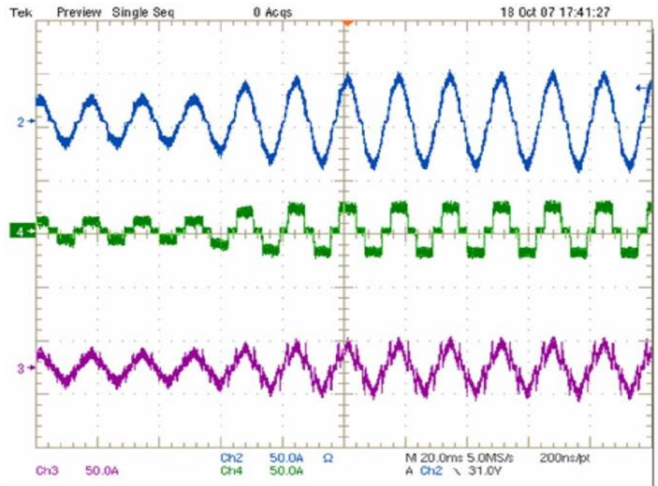

Fig. 15. Experimental waveforms to a load step. (a) Line current. (b) Single-switch boost rectifier current. (c) PWM unidirectional rectifier current.

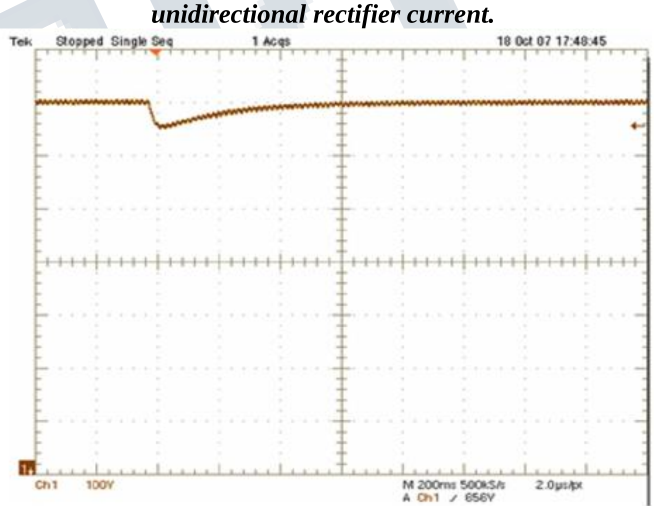

Fig. 16. Experimental waveform to output voltage transient response.

TABLE III POWER QUALITY ANALYSIS

Description	Value
True Power	20.76kW
Apparent Power	20.99kVA
Power Factor	0.9889
V – THD	5.7%
I – THD	7.9%
Line frequency	60.02Hz

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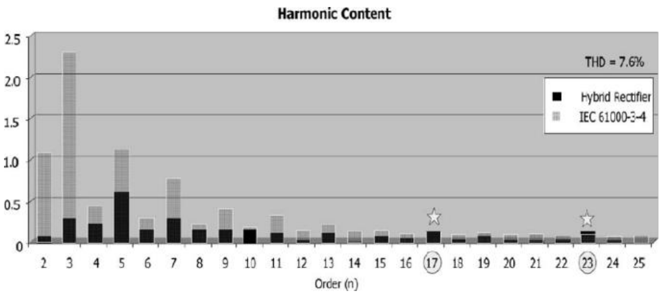

Fig. 17. Harmonic analysis.

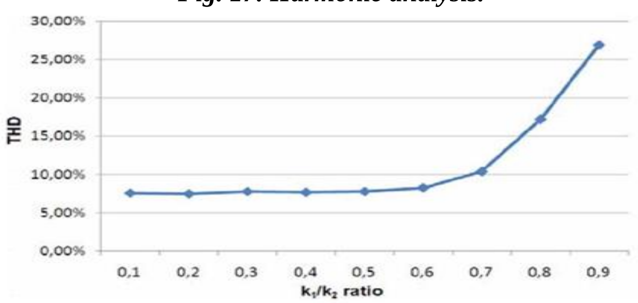

Fig. 18. THD versus ratio of k1 and k2 .

some gain adjustments in control loops. These modifications are suggestions to future works. The THDs obtained for deferment values for the ratio of k1 and k2 are presented in Fig. 18. As previously mentioned, if the ratio is greater than 0.552, the THD will increase. On the other hand, the power processed by the PWM rectifier increases as the value of α decreases. To investigate the semiconductor stress reduction, a 20-kW three-phase unidirectional rectifier and a 20-kW hybrid recti-fier with the same design parameters were implemented. Th current stress of each power semiconductor was measured an compared to that of the hybrid rectifier in Table IV.

TABLE IV CURRENT STRESS ANALYSIS

Component	Unidirectional		Hybrid		% reduction	
	Average	RMS	Average	RMS	Average	RMS
Switch S_{a1}	9.63A	14.63A	5.9A	9.5A	38.73	35.06
Diode D_{a1}	9.68A	16.59A	5.43A	9.84A	43.90	40.69
Diode D_{a2}	14.43A	22.7A	7.6A	12.02A	47.33	47.05
Diode D_{a3}	5.30A	10.51A	2.57A	6.29A	51.51	40.15
Diode D_{a4}	14.43A	22.7A	7.6A	12.02A	47.33	47.05
Diode D_{a5}	5.30A	10.51A	2.57A	6.29A	51.51	40.15
Diode D_{a5}	9.61A	19.89A	5.43A	9.84A	43.50	50.53

Component	Boost		Hybrid		% reduction	
	Average	RMS	Average	RMS	Average	RMS
Switch S_b	13,43A	23,14	6,31A	12,1A	53,02	47,71
Diode D_{b1}	28,6A	33,85A	17,3A	20,39A	39,51	39,76
Diode D_{b2}	28,6A	33,85A	17,3A	20,39A	39,51	39,76

The disadvantage of the system appears in the control scheme, since an extra current sensor and an additional current control loop in the single-switch boost rectifier are required. Some simulation results show that the hybrid rectifier can also operate with a two-phase power system; however, the power factor is decreased. New researches are in development focusing on other con-trol and modulation strategies, e.g., modulation of the output current of the single-switch rectifier with six times the mains frequency [16], aiming to improve the power distribution be-tween the single-switch rectifier and the unidirectional PWM rectifier. As can be observed, the increased component count of the proposed hybrid rectifier does not greatly affect the volume, since each semiconductor handles approximately 50% less cur-rent. Therefore, semiconductors with better characteristics, e.g., diodes with minimum recovery time or insulated gate bipolar transistors (IGBTs) with small storage time, can be used, which will result in reduced losses and heatsink volume.

VII. CONCLUSION

A novel three-phase hybrid rectifier for high-power applica-tions was proposed in this paper. The structure is composed of a passive rectifier in parallel with an active rectifier. The fact that each rectifier is responsible for processing approximately 50% of the output power improves the robustness of the power converter and guarantees a high efficiency. The adopted control strategy regulates the output voltage and controls the input currents to achieve high power fac-tor. The increase in the component count due to the use of two rectifier topologies does not greatly affect the volume, since the components are designed for the half of the output power. Experimental results obtained from 20 kW prototypes show that the hybrid rectifier presents high power factor and dc volt-age regulation. Moreover, the hybrid rectifier presents 50% less current stress than the traditional three-phase rectifier operating at the same power rating. The advantage of this hybrid system is its capability of pro-cessing high power levels due to the parallel connection of the rectifiers. The increase in the efficiency is another expected advantage.

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