A THREE-PHASE THREE-SWITCH TWO-LEVEL PWM RECTIFIER

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***Abstract* – This paper presents a new topology for a high power factor three-phase PWM rectifier system, without a neutral wire, with output voltage control and high efficiency. The control is simple and was implemented using commercial single phase modulators with independent current loops and a voltage loop. The power circuit is also very simple, permitting the use of low cost power devices. A mathematical analysis for the converter will be presented, including the determination of all the power devices, the current and voltage transfer functions and a project procedure. Finally, results obtained through digital simulations and the experimental results obtained from a 6kW prototype will be presented.**

I. INTRODUCTION

Three-phase AC-DC converters without neutral wires are used in many applications, such as telecommunications power supplies, UPS's and electric drives. Conventional circuits, using thyristors and diodes with passive filters, despite their simplicity and reliability, do not comply with international current harmonic standards.

Therefore, efforts have been made by engineers to develop the so-called PWM rectifiers, capable of drawing practically sinusoidal current from the mains. Many different PWM three-phase topologies featuring low input current THD, most of them belonging to the family of three-level converters, have recently been proposed in the literature. These converters require a complex strategy to balance the voltage across the output filter capacitors.

The circuit introduced in this paper does not need a output capacitor mid-point connection to work properly. Therefore, it is much simpler to design and control than its three-level counterpart. However, all the remaining desirable features are preserved, presenting unity power factor with low THD and output voltage control.

II. STRUCTURE AND CHARACTERISTICS

The proposed circuit for the high power factor PWM three-phase rectifier is presented as a natural evolution of the most widely used topology to control the input current of single-phase rectifiers, the boost converter in continuous conduction mode (CCM), presented in the top left-hand corner of Fig.2. The development of the three-phase PWM rectifier's basic structure is presented in Fig.2.

Fig.2 presents three independent single-phase rectifiers with output capacitors large enough to maintain the output voltage practically constant. However, the presence of a neutral point is undesirable. The neutral wire can be removed and the converter will still work properly, even though the topological stages are different.

The proposed circuit for the three-phase PWM rectifier is presented in Fig.1:

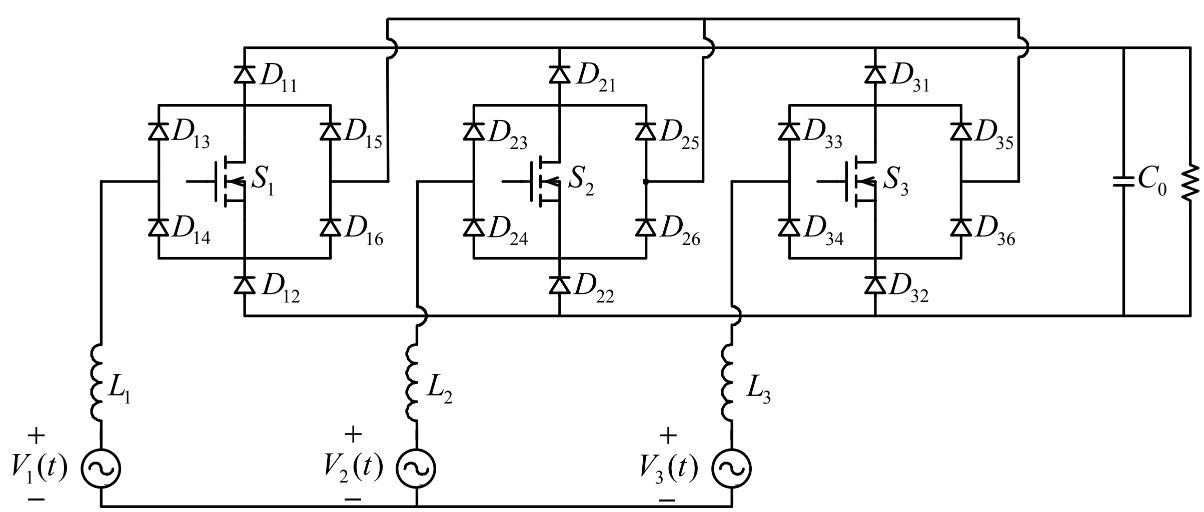

Fig.1: Proposed circuit for the three-phase PWM rectifier.

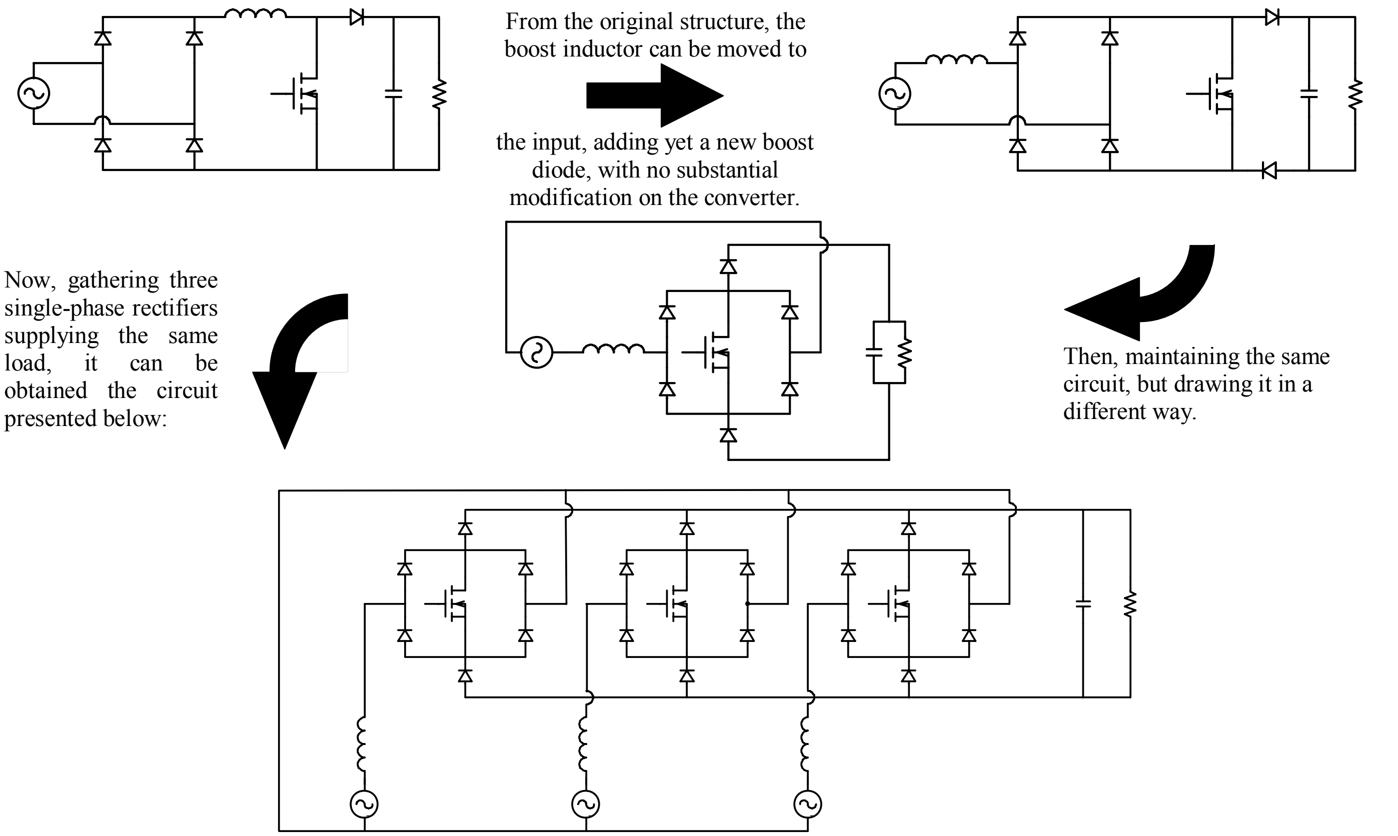

Fig. 2: Three single-phase rectifiers supplying the same load.

It can be noted that the three-phase converter presents an interesting symmetry. The input current period can be divided into 6 sectors, and in each sector the converter works symmetrically. So, the analysis can be performed for a chosen sector and be then easily extended to the others. Each sector is defined by the line that presents the highest absolute value of the input current, defined by the sum of the absolute values of the other two input currents.

Therefore, the topological stages and all the theoretical analysis for the converter will be presented for one sector. So, initially, the input voltages are given by:

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

Considering that the input currents are images of the input voltages, thus the sector defined by: $60° < wt < 120°$, where $V_1(t)>0$, $V_2(t)<0$ and $V_3(t)<0$, so $I_1(t)>0$, $I_2(t)<0$ and $I_3(t)<0$, was randomly chosen. The converter presents three active switches, each one with two possible logical states, On or Off, so eight (2^3) possible combinations can be obtained.

III MODULATION STRATEGY

Fig.3 shows that there are only four distinct topological states, despite the eight possible combinations for the switches. States 5, 6, 7 and 8 are redundant. This redundancy occurs when the switch connected to the phase that presents the largest absolute current is Off (phase 1, for this sector).

In this manner, the suggested modulation strategy maintains the switch connected to the phase that presents the highest absolute current “On”, activating the other two switches and directly controlling their respective currents. So if these two currents follow the format of the input voltages, obviously the current related to the switch that is maintained “On” will also follow its respective input voltage.

Using the proposed strategy, the converter presented in Fig.2 can be represented, for the given sector, without loss off generality, by the circuit shown in Fig.4.

Due to the observed symmetry, the mathematical analysis can be developed for a sub-stage of 60º, and can then be extended to the complete 360º period. The developed mathematical analysis will not be shown due to its complexity and extensiveness. Only the obtained results, in the form of graphs, are presented.

This was expected, because the absence of a neutral wire generates a restriction, defined by: $I_1(t) + I_2(t) + I_3(t) = 0$, so only two currents can be controlled at a time, the third current being given by this restriction. This fact reduces the control degree from three to two, so the converter presents only 4 (2^2) independent topological stages and the others are redundant.

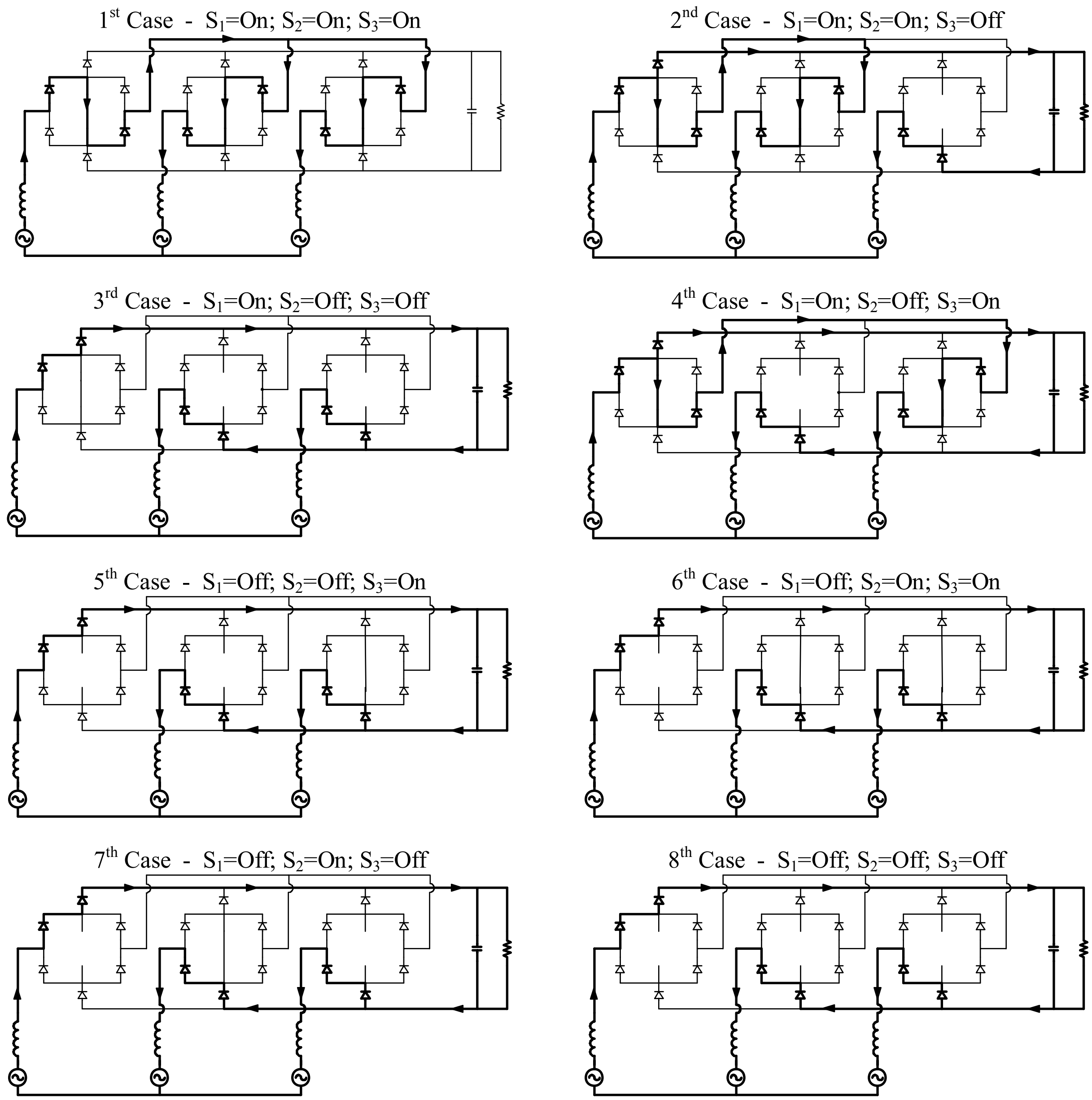

Fig. 3: State of switches and current flow for the analyzed sector.

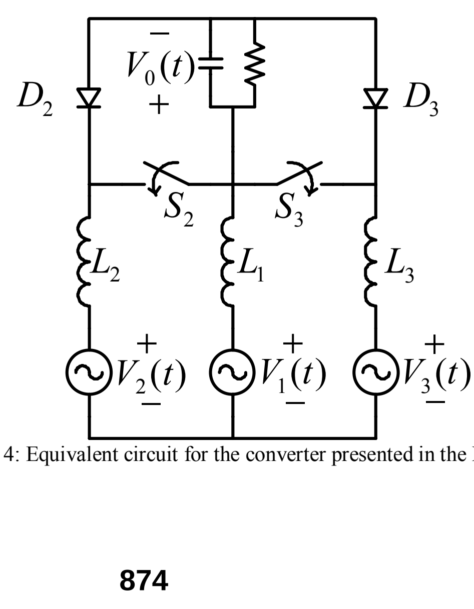

Fig. 4: Equivalent circuit for the converter presented in the Fig.1.

IV MATHEMATICAL ANALYSIS RESULTS

Only the results of the mathematical analysis of the converter are presented because the whole of the analysis is too extensive to be presented here. It should be said that the mathematical analysis was developed based on the equivalent circuit presented in Fig.4.

Dynamic Transfer Functions:

$$\frac{I(s)}{D(s)} = \frac{V_0}{s \cdot L} \tag{2}$$

$$\frac{V_o(s)}{I_P(s)} = \frac{3 \cdot V_P \cdot V_o}{2 \cdot P_o} \cdot \frac{s \cdot [R_{SE} \cdot C_o] + 1}{s \cdot \left[\frac{C_o \cdot V_o^2}{P_o} \cdot \left(1 + \frac{R_{SE} \cdot P_o}{V_o^2} \right) \right] + 1} \tag{3}$$

Input Inductors:

$$L_{IN} \geq \frac{3 \cdot V_P{}^2 \cdot [2 \cdot V_0 - 3 \cdot V_P]}{fs \cdot \Delta I_L \% \cdot 4 \cdot P_0 \cdot V_0} \tag{4}$$

$$I_{L\_rms} = \frac{\sqrt{2} \cdot P_0}{3 \cdot V_P \cdot \eta} \tag{5}$$

Output Capacitor:

$$C_0 \geq \frac{P_0 \cdot (2 \cdot V_0 - 3 \cdot \eta \cdot V_P)}{2 \cdot \eta \cdot V_0^2 \cdot fs \cdot \Delta V_0} \tag{6}$$

$$I_{Co\_rms} = \frac{P_0}{V_0} \cdot \sqrt{\frac{0,613 \cdot V_0 - V_P}{V_P}} \tag{7}$$

Observation: In reality, the output capacitor is determined by its RMS current.

Switches:

$$I_{S\_rms} = \frac{P_0}{\eta \cdot V_P} \cdot \sqrt{\frac{V_0 - 1,63 \cdot V_P}{5,7 \cdot V_0}} \tag{8}$$

$$I_{S\_av} = \frac{P_0}{\eta \cdot V_P} \cdot \left(\frac{V_0 - 1,57 \cdot V_P}{2,356 \cdot V_0} \right) \tag{9}$$

$D_{i\text{-}1/2}$ Diodes (see Fig.2):

$$I_{Di\_1-2\_rms} = \frac{P_0}{\eta \cdot V_P} \cdot \sqrt{\frac{V_0 + 6,1 \cdot V_P}{43 \cdot V_0}} \tag{10}$$

$$I_{Di\_1-2\_av} = \frac{P_0}{\eta \cdot 3 \cdot V_0} \tag{11}$$

$D_{i\text{-}3/4}$ Diodes (see Fig.2):

$$I_{Di\_3-4\_rms} = \frac{P_0}{\eta \cdot 3 \cdot V_P} \tag{12}$$

$$I_{Di\_3-4\_av} = \frac{2 \cdot P_0}{\eta \cdot 3 \cdot \pi \cdot V_P} \tag{13}$$

$D_{i\text{-}5/6}$ Diodes (see Fig.2):

$$I_{Di\_5-6\_rms} = \frac{P_0}{\eta \cdot V_P} \cdot \sqrt{\frac{V_0 - 1,63 \cdot V_P}{11,5 \cdot V_0}} \tag{14}$$

$$I_{Di\_5-6\_av} = \frac{P_0}{\eta \cdot V_P} \cdot \left(\frac{V_0 - 1,57 \cdot V_P}{4,7 \cdot V_0} \right) \tag{15}$$

V DESIGN EXAMPLE

Based on the mathematical analysis, an AC-DC converter was designed for an output power of 6kW, using the IC UC3854B in the current control loop (for each phase) and only one voltage loop (feedback and feedforward). In this manner, classical control theory was used to project the PID controllers for the current loops and a PI controller for the voltage loop. The project of these controllers is classical, so it will not be presented here.

The snubbers and other auxiliaries circuits will not be presented, either. The project input parameters are:

- *Output power → P_0=6kW;*
- *Performance → η=90%;*
- *Peak voltage of the mains → V_P=180V*
- *Output voltage → V_0=450V;*
- *Input current ripple → ΔI_{IN}=10%;*
- *Output voltage ripple → ΔV_0=5%;*
- *Switching frequency → fs=50KHz.*

Thus, the obtained parameters are: L_{IN} = 650uH and C_0 = 8,2uF. However, the output capacitor will be defined by its RMS current, so an equivalent capacitance of 3mF was used. Using the mathematical analysis, the obtained results are presented in Table I.

Table I
Devices definition:

	Switches (3)	$D_{i\_1\text{-}2}$ (6)	$D_{i\_3\text{-}4}$ (6)	D_{i_56} (6)	L_{IN} (3)	C_0 (1)
I_{med}	12,5A	5A	11,5A	6,5A	0A	0A
I_{ef}	16,5A	13,5A	17,5A	11,5	22,5A	14,5A
I_P	32A	32A	32A	32A	32A	------
V_P	475V	475V	475V	475V	------	475V
Devices	IXFK44 N60	HFA15 PB60	HFA25 TB60	HFA25 TB60	400uH	3mF

VI SIMULATION AND EXPERIMENTAL RESULTS

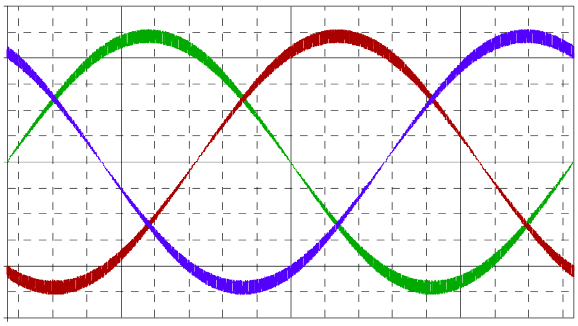

Fig.1: Input currents obtained through simulation, using the software Pspice.

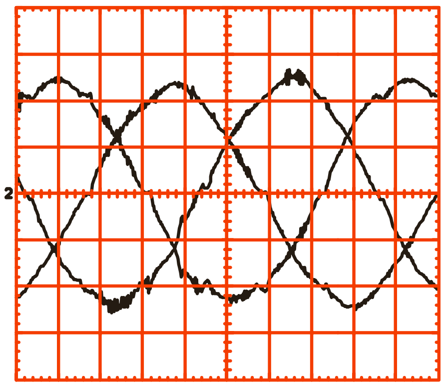

Fig.2: Input currents of the prototype.

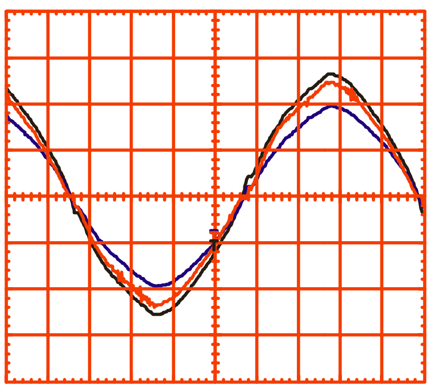

Fig. 3: Input voltage, current reference and input current, of phase 1 of the prototype.

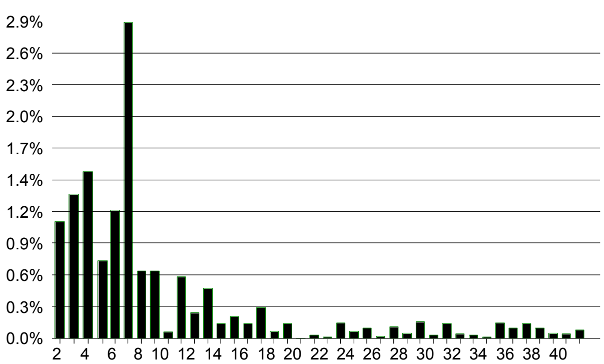

Fig. 4: Harmonic magnitude as a % of the fundamental amplitude of the current.

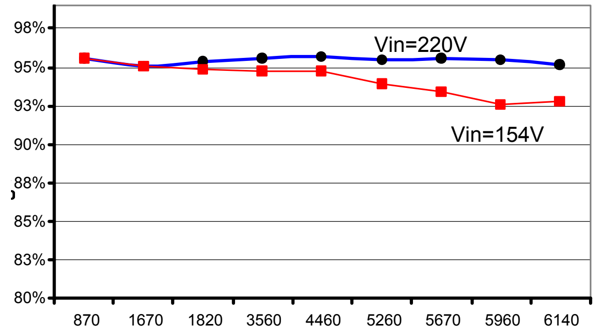

Fig. 5: Efficiency curve obtained from the prototype (efficiency X output power).

A THD of 3% was obtained with a power factor of 0.999. The input currents' THD was not lower due to the current reference THD, caused by distorted input currents.

In spite of this fact, the THD and the power factor comply with the telecommunications standards. The output voltage was not presented, because it was regulated at 450V, satisfying the ripple limits. An efficiency of 96% was measured at rated conditions.

VII CONCLUSION

Based on the single-phase AC-DC boost rectifier with unity power factor, this paper presented a topology for a three-phase PWM rectifier. A project example, simulations and experimental results were also presented.

In this manner, the following characteristics were observed in the proposed converter:

- Very simple power circuit, using only three switches;
- Simple control system, using conventional devices normally employed in single-phase AC-DC PWM boost rectifiers;
- High power factor and low input current THD;
- High efficiency, with low weight, volume and cost.

VIII REFERENCES

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