A LOW COST HIGH POWER FACTOR THREE-PHASE DIODE RECTIFIER WITH CAPACITIVE LOAD

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ABSTRACT - **This paper presents a novel method to improve the power factor of three-phase diode rectifiers with capacitive load, which implementation requires three additional four-quadrant switches rated at very small power. These switches in conjunction with input filter inductors constraint the line current to start increasing every time the corresponding line voltage crosses zero. Besides, they remain at on state during small fractions of the line period and process a small amount of the total rectifier power. Because they commutate at the line frequencies and process a small fraction of the power, the additional losses are small and the overall converter efficiency is very high. It is also demonstrated that the output DC voltage can be regulated by varying the conduction time of the auxiliary switches. Principle of operation, theoretical analysis, design procedure and example and simulation results are presented. In order to verify the theoretical studies, a laboratory prototype has been built rated at 6kW and the corresponding experimental results are presented in the paper. The additional switches are rated at a power sixty times less than the total power delivered to the load.**

1. INTRODUCTION

Efforts have been made recently by engineers to improve the power factor of three-phase diode rectifiers with capacitive load without using the traditional passive filters, which are large, heavy and expensive.

A very interesting technique has been introduced in reference [1], which employs a single switch boost converter operating in discontinuous current mode. This technique has been generalized in references [2] and [3], where various circuits with low commutation losses have been proposed.

The circuits introduced in references [1], [2] and [3] have in common the fact that discontinuous current flows through the AC side inductors. These discontinuous currents are modulated in amplitude by the input voltage, so that the fundamental component of the current remains in phase with the corresponding voltage. Besides, the low harmonic currents are naturally attenuated, whereas the high frequency harmonics are eliminated by small pre-filters.

Although simple and elegant, these converters have not been tested in high power applications. It seems that their major drawback is the high conduction losses.

In reference [4] a very simple and robust method has been introduced. However, as it does not use any active switch, there is no way to regulate the output DC voltage. Furthermore, it requires line-side interphase transformers operating at the line frequency, resulting in a relatively expensive and heavy product.

In an attempt to improve the power factor for higher power applications without sacrificing the size and the cost, this paper introduces a novel method which features: auxiliary converters rated at a fraction of the nominal converter power, operation at the line frequency, high power factor, low input current harmonic content.

The converter has been successfully tested in a 6kW prototype and it is expected that it will be advantageous in comparison to the known converters for even higher power applications. It has been demonstrated in laboratory that the active switches are design to process 300W for a 6kW of power delivered to the load.

2. PRINCIPLE AND STAGES OF OPERATION

The proposed converter consists of a three-phase diode rectifier, with a series line inductance and auxiliary bi-directional switches connected across each phase, as shown in Fig. 1.

The switches are gated on at the moment the corresponding phase voltage crosses zero. Therefore, the current through the phase is composed of the switch and the rectifier currents, resulting in a line current almost in phase with the input voltage. That yields a power factor near unity and a low harmonic distortion, because of the presence of the filter inductor.

The stages of operation of the proposed converter are shown in Fig. 2 and described as follows:

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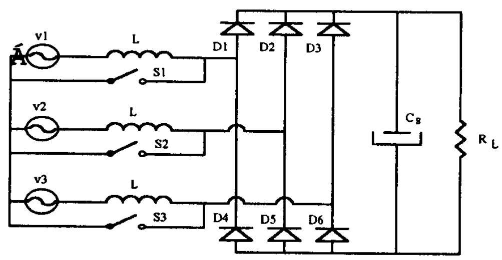

Fig. 1 - Structure of the proposed converter.

1st stage (t_0,t_1): At $t=t_0$ the voltage in phase 1 (v_1) crosses zero and switch S_1 is gated on. The current in that phase (i_1) grows up from zero, governed by expression (1). The currents in phases 2 (i_2) and 3 (i_3) are equal and have the same value of the output current (i_o) of the converter.

$$i_1 = \frac{\sqrt{2}V_1}{\omega L}(1-\cos\omega t) \tag{1}$$

$$i_2 = i_3 = i_o \tag{2}$$

2nd stage (t_1,t_2): At instant $t=t_1$ S_1 is turned off and diode D_1 assumes the current of phase 1. This stage continues until $t=t_2$, when the voltage in phase 3 crosses zero. At this moment the current in that phase is zero and diode D_3 is off. During this time interval,

$$i_1 + i_3 = i_2 = i_o \tag{3}$$

3rd stage (t_2,t_3): When the voltage in phase 3 crosses zero ($t=t_2$), S_3 is gated on. The current in this phase grows up from zero, according the expression (4).

$$i_3 = \frac{\sqrt{2}V_3}{\omega L}(1-\cos\omega t) \tag{4}$$

$$i_1 = i_2 = i_o \tag{5}$$

4th stage (t_3,t_4): At instant $t=t_3$ S_3 is turned off and diode D_6 takes on the current of phase 3. This stage goes on until the zero crossing of the voltage of phase 2, at $t=t_4$. During this time interval,

$$i_1 = i_2 + i_3 = i_o \tag{6}$$

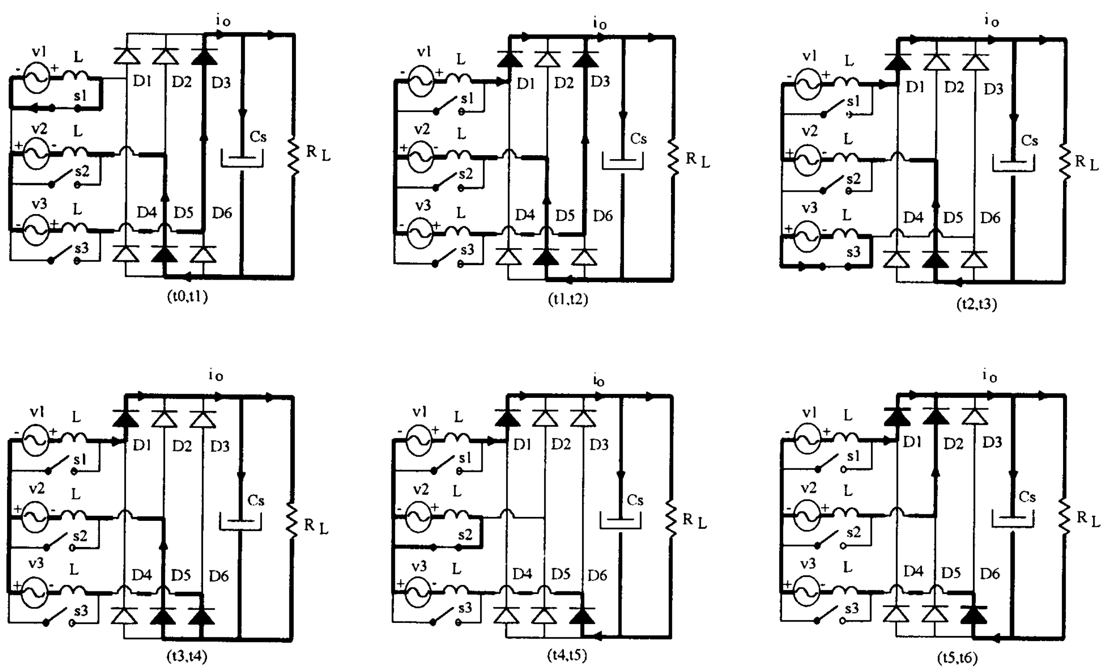

Fig.2 - Stages of operation of the converter.

5th stage (t_4,t_5): At $t=t_4$ the voltage in phase 2 crosses zero and S_2 is gated on. The current rises from zero according to expression (7). The currents in phases 1 and 3 are equal and have the same value of the output current of the converter.

$$i_2 = \frac{\sqrt{2}V_2}{\omega L}(1-\cos\omega t) \tag{7}$$

$$i_1 = i_3 = i_o \tag{8}$$

6th stage (t_5,t_6): At $t=t_5$ S_2 is turned off and diode D_2 assumes the current of phase 2. This stage continues until the moment when the voltage on phase 1 reaches zero, at $t=t_6$. During this stage we have:.

$$i_1 + i_2 = i_3 = i_o \tag{9}$$

The described stages represent a half period of the input voltage.

The waveforms of the line currents and voltages, generated by simulation, are shown in Fig. 3.

3. STEADY-STATE CHARACTERISTICS

The analysis of the proposed converter has been performed numerically. The most important characteristics, namely conversion ratio and input power factor, are shown in figures 4 and 5 respectively, against the output current. The angle α , which represents the control variable of the system, is taken as the parameter of these curves.

The variables involved in the analysis are defined as follows:

$$XL\% = \frac{2\pi f \cdot L \cdot I_o \cdot 100}{V_{in}/\sqrt{3}} \tag{10}$$

f = AC line frequency [Hz]
I_o = output current [A]
V_{in} = RMS line voltage [V]
L = filter inductance [mH]
α = duration of the switches gate signal.

The behavior of the converter is interpreted as follows. For constant values of V_{in} and α , the output voltage reduces in a linear way, as long as the output current increases. On the other hand, both the output voltage and the input power factor depend on the value of α. These difficulty is easily overcame when the output voltage is controlled in a close loop way. The value of α changes to compensate for the input inductor voltage drop and simultaneously the input power factor is maximized.

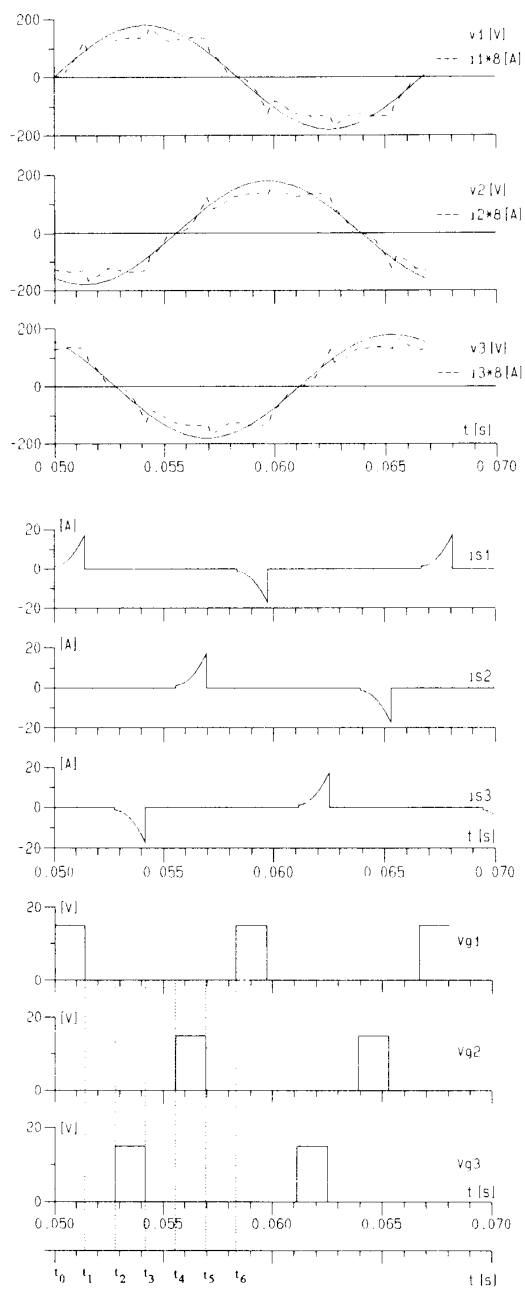

Fig. 3 - Line current, line voltage, current in auxiliary switches and gate signals in each phase.

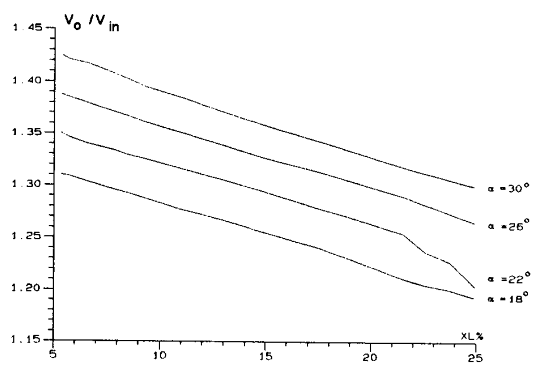

Fig 4 - Output characteristic of the converter.

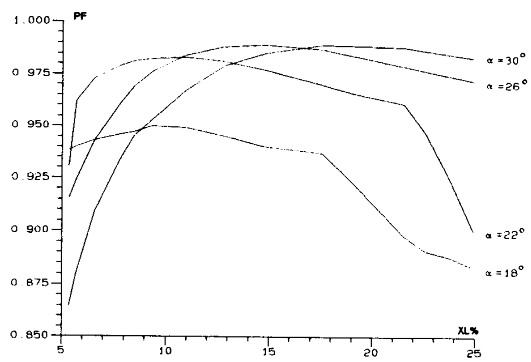

Fig 5 - Power factor (PF) presented by the converter.

4. DESIGN AND EXPERIMENTATION

In order to demonstrate the principle of operation and to point out the performance of the proposed technique for power factor correction, a prototype was designed and built, with the following specifications:

- AC input voltage: V_{in} = 220/127V
- output power: P_o = 6 kW
- power factor: PF = 0.98

The parameter $\overline{X}L\%$ is obtained from Fig. 5 to the required power factor (PF) and is equal to 25%, for α=30°. From Fig. 4 it is possible to obtain the relationship between the output voltage (V_o) and the rms line voltage (V_{in}):

$$\frac{V_o}{V_{in}} = 1.30 \quad \Rightarrow \quad V_o = 1.3 \bullet 220 = 286V$$

And, from the stipulated output power:

$$I_o = \frac{P_o}{V_o} = \frac{6000}{286} \quad \therefore \quad I_o = 21A$$

From expression (1):

$$L = \frac{\overline{X}L\% \bullet V_{in}/\sqrt{3}}{I_o \bullet 100 \bullet 2\pi f} \quad \therefore \quad L = 4mH$$

The power stage of the implemented converter is shown in Fig. 6. The list of the components is presented below:

- Cs = 660μF (output capacitor);
- R_L = 13.6Ω (load resistance);
- D1-6 = rectifier diodes (SKN 12/12-Semikron);
- L = 4.0mH (input filter inductor);
- M = IRF740-Motorola (auxiliary switch);
- da1-a4 = 1N5404-Motorola (auxiliary diodes);
- rs = 500Ω/50W (snubber resistor);
- ds = 1N5404-Motorola (snubber diode);
- Csb = 4.4μF (snubber capacitor).

The experimentally obtained line current and voltage waveforms, for α=30°, are shown in Fig. 7. The measured values are:

V_o = 286V (output voltage)
PF = 0.98 (power factor)
φ_1=8.8° (displacement angle of the input current)
THD = 12% (total harmonic distortion)

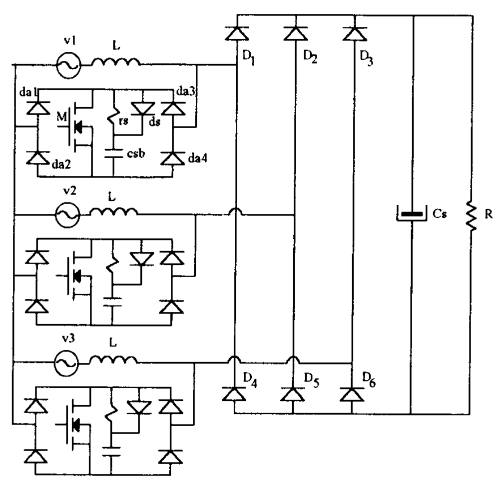

Fig. 6 - Power stage diagram of the implemented converter.

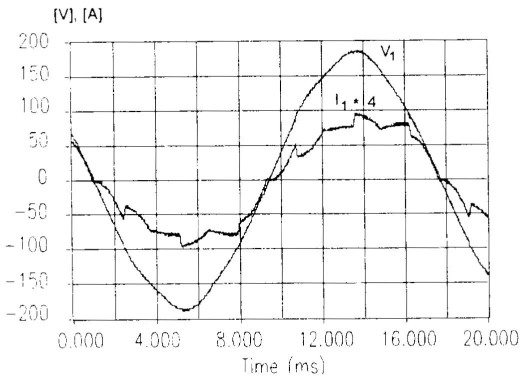

Fig. 7 - Waveforms of line voltage and current.

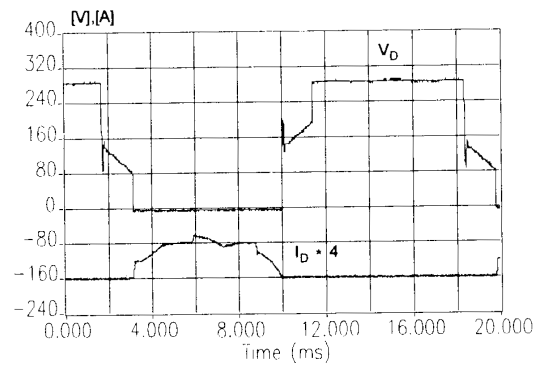

Fig. 9 - Voltage and current across a bridge rectifier diode.

Fig. 8 shows the voltage and current over an auxiliary switch, pointing out the low current required by the device.

The voltage and current across a bridge rectifier diode is shown in Fig. 9.

Fig. 10 presents the output voltage and current of the converter.

A comparison of three different possibilities of the three-phase diode rectifier can be made considering figures 7 and 11 to 15.

In Fig. 11 a classical structure is considered, without input filter inductor neither auxiliary switches. The correspondent spectral analysis of the current is presented in Fig. 12.

Fig. 13 corresponds to a structure with an input filter inductor, without auxiliary switches. The spectral analysis of the current is shown in Fig. 14.

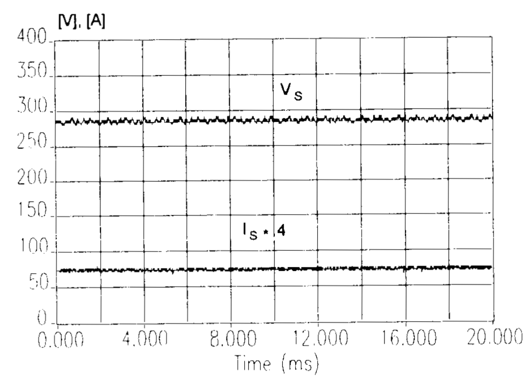

Fig. 10 - Output voltage and current.

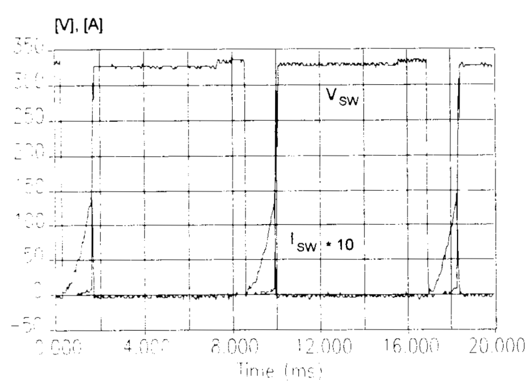

Fig. 8 - Voltage and current across an auxiliary switch.

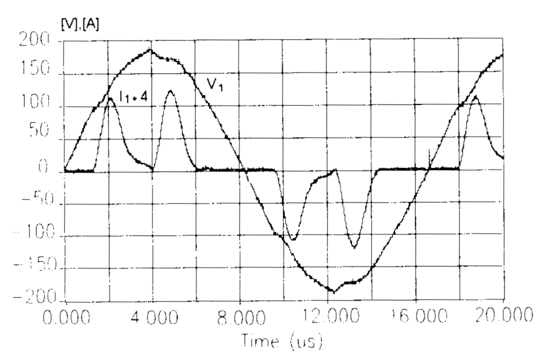

Fig. 11 - Waveforms of line voltage and current for the classical three-phase diode rectifier.

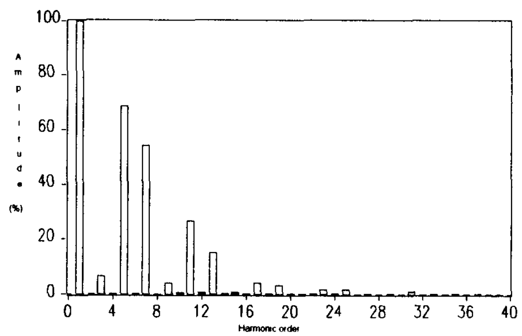

Fig 12 - Harmonic contents for the classical three-phase diode rectifier.

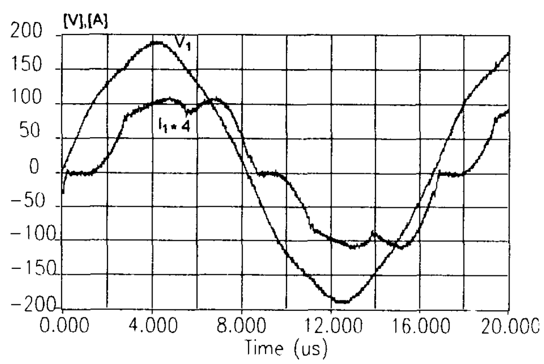

Fig. 13 - Waveforms of line voltage and current for the three-phase diode rectifier with filter inductor.

Fig. 15 shows the spectral analysis of the line current of the proposed converter.

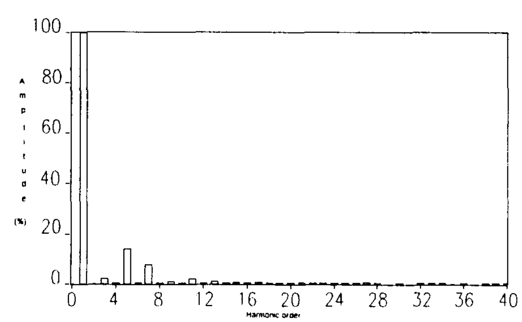

Fig. 14 - Harmonic contents for the three-phase diode rectifier with filter inductor.

One can notice from the figures presented that the harmonic content of the current of the proposed converter is lower than the other two converters, that means a higher power factor. Moreover, it is evident from figures 7 and 13 that the power factor presented by the proposed converter is considerably increased.

At the instants t_1, t_3 and t_6, when the active switches are gated off, the sum of the currents through the input inductors is not zero. Therefore, to prevent an overvoltage across the switches, clamping circuits should be used. In Fig. 6 each switch is connected in parallel with a clamping circuit, formed by r_s, C_{sb} and d_s. During a short period of time the current of the corresponding input inductor is deviated to the capacitor C_{sb}. This energy is dissipated in the resistor r_s.

Another point of concern is the circulation of current through the neutral wire, which is shown in Fig. 16, for the converter designed in this paper. To avoid this current from circulating in the AC mains a solution may be encountered.

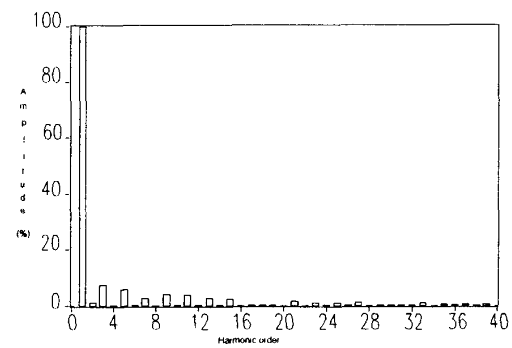

Fig. 15 - Harmonic contents for the proposed converter.

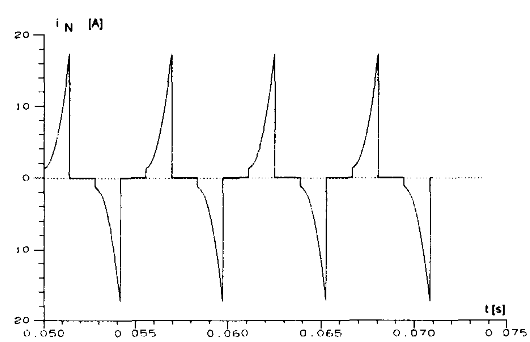

Fig. 16 - Neutral current for the proposed converter.

5. CONCLUSIONS

A novel version of a three-phase full-wave rectifier with active power factor correction was presented. The principal characteristics of such structure are: high power factor, robustness, and simplicity.

The paper has presented a design methodology for the proposed converter based on the use of simulation results and graphs, which are very simple to use and give good results.

A prototype was designed and tested, showing the efficiency of the proposed technique and the validity of the theoretical results.

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