Improvement of Input Power Factor for a 1-Φ Rectifier based on Two Quadrant SAF

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Abstract – This paper presents a new technique to improve the input power factor of a single-phase rectifier followed by an inductive filter and also consists of the employment of a two-quadrant active power filter, based on a conventional bidirectional DC-DC converter, connected to the output side of the diode bridge. This technique allows the extension of this rectifier range operation in the continuous conduction mode. Circuit description, operation principle, modeling, design and simulation results are presented in this paper. By the experimental results obtained, the system presented a unity power factor[16].

Key words — Active Power Filter, Power Factor Correction, Single-Phase Inductive Filter Rectifier, and Two-Quadrant.

I. INTRODUCTION

The increasing of the electronic devices in industry and residences has created a major concern on the electric power quality issue, due to the fact that these equipments draw a current with high harmonic content from the grid. The devices which present this characteristic are known as nonlinear Loads. Harmonic mitigation methods have been exhaustively discussed in the literature [1]-[14], and the active power filters have been considered a dynamic and adjustable solution to the power quality issue, [6]- [14]. Shunt active power filters (APF) consist of a power electronic converter which injects a Compensating current to the grid, with the harmonic contents equal to the nonlinear load, but with opposite phase, result in a sinusoidal grid current, in phase with the voltage, achieving an unity input power factor. The single-phase diode rectifier is a usual nonlinear load, which is widely used in industry for providing DC loads or DC-DC converters and inverters. The conventional single phase rectifier topology consists of a full-bridge diode rectifier followed by a capacitive filter, presents an input current with impulsive characteristic, resulting in a high total harmonic distortion (THD) and a poor input power factor. Many passive [3]-[5] and active [11]- [14] methods for the input current harmonic distortion reduction applied to this rectifier topology have been already presented in literature. Another example of usual nonlinear load is the single-phase rectifier with output inductor, which is commonly used in industry applications where high output current is demanded. The addition of an inductor on the diode bridge output allows the rectifier input current peak reduction and, therefore, its total distortion harmonic reduction and the input power factor improvement. Thus, the reactive power flow from this rectifier is smaller than the conventional one. However, two drawbacks of this rectifier topology must be emphasized: the inductor large size and the possible resonance between the output Capacitor and inductor. For the inductive filter rectifier, a passive method for input current harmonic mitigation was proposed in [1]. The input power factor of this topology was improved. Nevertheless, the rectifier operation was in the discontinuous conduction mode (DCM), not allowing the output voltage regulation. In [2], an active power filter was used for input current harmonic reduction applied to this rectifier topology operating as the nonlinear load. However, as the APF was connected to the alternating current (AC) side of the rectifier, for a load value in which the original rectifier operated in the DCM, the APF insertion to the system was not capable of changing the rectifier operation mode, resulting in no output voltage regulation. The application of a shunt active power filter, for current harmonics reduction, applied to an inductive filter rectifier will process a smaller amount of reactive power than in the case of a conventional rectifier, if the same active power flow is taken into account. Then, the APF converter may be designed for smaller power operation and control effort. In this paper, a new technique to improve the input power factor of a single-phase rectifier with output inductor, based on a two-quadrant shunt active power filter, is proposed [14]. Still, the application of the proposed APF to this rectifier topology enabled the extension of the rectifier operation range in the continuous conduction mode (CCM), in other words, with regulated output voltage.

II. PROPOSED SINGLE-PHASE SHUNT ACTIVE POWER FILTER

The proposed active power filter (APF) topology consists in a bidirectional DC-DC converter with capacitive energy storage. This converter presents the same operation stages of a VSI converter used on conventional single-phase APF application for the positive half-cycle of input voltage. The proposed APF converter is connected on the DC side of a rectifier followed by an inductive filter. The active filter operation results in input side power factor correction and input current harmonic contents reduction. In Addition, the extension of the operating range on continuous conduction mode for this rectifier is another motivation for this proposed APF application.

A. Load Characteristics – Single-Phase Rectifier with Inductive Filter

The non-unit power factor load employed in this work is composed by a single-phase rectifier followed by an inductive filter. It is commonly used on applications that demand high output current. Also, this rectifier presents a higher input side
power factor than the rectifier followed by a capacitive filter, since the last one presents an input current with impulsive characteristic, resulting in a high total harmonic distortion (THD). Even though, the load introduced contains some disadvantages, as the inductor volume and the load inductor-capacitor resonance issue. This rectifier can operate in the continuous conduction mode (CCM), when the load inductor current never reaches zero and, consequently, the diode bridge is always conducting. When operating in this mode, the load output voltage, \( V_o \), depends only on the effective input voltage, as shown in expression (1).

\[
V_o (\text{CCM}) = 0.9V_{i\text{(ref)}}
\]  

On the other hand, the operation in the discontinuous conduction mode (DCM) occurs when the load inductor current goes to zero for a period of time, resulting on the diodes conduction block. When operating in the DCM, this rectifier presents a varying load output voltage characteristic which depends on two parameters: the effective input voltage and the load current value. The DCM rectifier operation analysis is detailed on the Appendix section. For very low current load values, the output voltage can achieve the input voltage peak. The main theoretical waveforms for the inductive filter rectifier on both operation modes are shown in Fig.1. However, in order to obtain a constant output load voltage for several load current values, the operation in the CCM is desired.

### III. SYSTEM MODELING AND CONTROL STRATEGY

There are two main control strategies used in single-phase active power filter control: the active power filter current control and input current control. Both strategies require voltage and current control. The APF DC-link voltage \( V_{dc} \) control is responsible for the system active power flow control, since the APF active power flow must be zero, besides the components losses. The current control is responsible for the input current shape control, which must be a sine waveform in phase with the input voltage.

#### A. control strategy

The control strategy applied here is based on the average current mode control, using the rectified input current as the control variable, which is similar to the input current control strategy. This strategy is effective and simple, because it uses only one current sensor, and load current harmonic contents calculation is not necessary. A few changes on this strategy were needed due to the inductor-capacitor load resonance issue. For solving this problem, a band-stop filter, \( F_N(s) \), with the rejection center frequency tuned in the load resonance frequency, was used in the APF DC-link voltage monitoring. Therefore, the signal applied on voltage loop control presented its resonance frequency oscillations attenuated, not interfering on the system control. The voltage controller also had to be configured with a low cutoff frequency, resulting in an active power flow control strongly slow. By that, the transient voltage and current oscillations were increased, exceeding design limits and compromising the system operation. For solving the dynamic active power flow control problem, a feed-forward control of the load output current was necessary. Due to the low components losses in the APF converter, it is considered that the load average active power is the same as the input one. Then, using expression, the average load output current is related to the input current peak. From this expression, it is seen that the system active power flow can be controlled through the load output current value. Expression (11) shows the constant gain used in the feed-forward output current loop for the system active power flow control. In addition, the APF DC-link voltage control is used for APF losses compensation.

\[
P_i = P_{in}
\]

### Fig 2: Block Diagram of the Implemented Control Strategy
After established the system control strategy, current and voltage transfer functions models must be defined. As the current loop control must be fast, since it is responsible for the input current waveform control, the obtained rectified input current model is high frequency defined, being based on small-signal average current modeling, for switching periods. The APF converter equivalent circuit, in which the variables are the average values in one switching period in which the average voltage \( V_a(\theta) \). From this equivalent circuit, the rectified input current transfer function model is obtained.

\[
V_a(\theta) = (1 - d(\theta)) \cdot V_{clf}
\]  
(7)

**B. Current Transfer Function Modeling**

**C. Voltage transfer function modeling**

On the other hand, the APF DC-link voltage control must be slow, even slower than the input source frequency. Its transfer function model is obtained by the average values of The APF variables accounted in one input source half-period presents the equivalent circuit for voltage transfer function modeling, in which each variable is defined for its average value in one input source half-period.[16].

\[
\frac{\Delta I_s(s)}{\Delta d(s)} = \frac{V_{clf}}{sL_f}
\]  
(8)

**IV. EXPERIMENTAL RESULTS**

The implemented system was tested for different load values. Fig. 5 shows the input voltage and current waveforms and, also, the load output voltage for the inductive filter rectifier operation without and with the proposed APF – Fig. 5(a) and Fig. 5(b) respectively – in nominal load value. For this load value, the original rectifier operates in CCM; therefore the load output voltage remains the same in both cases. However, with the APF operation, the input power factor correction is achieved – from 0.88 to 1 – and the input current harmonic contents are reduced – from 43% to 4% – as expected.

**V. CONCLUSION**

This paper presented modeling and simulation results of a new technique to improve the input power factor of a single-phase rectifier followed by an inductive filter. It consists in the employment of a two-quadrant active power filter, based on a conventional bidirectional DC-DC converter, connected to the output side of the diode bridge. This technique allows the extension of this rectifier range operation in the continuous conduction mode.

**REFERENCES**

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