Proposal of A Timer Controller with Constant Switching Frequency and Power Factor Correction

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Abstract— **The proposal of this paper is to introduce a new control technique for power factor correction in ac-dc converters. It combines the advantages of conventional hysteresis control strategy and the prominent characteristics of constant switching frequency. The fundamental idea consists in determining the ideal time period that exists between the moment when the input current crosses with the reference current and the converter commutation. Thus the input current can oscillate around the reference current with constant frequency of operation. The operating principles, theoretical analysis and results on a single-phase Boost converter are presented to validate the proposal.**

Keywords ***—constant switching frequency, low harmonic distortion, power factor correction.***

I. INTRODUCTION

Nowadays, the growing number of nonlinear loads such as diode or thyristor rectifiers, switch-mode power supplies and adjustable speed drives, generate harmonic currents causing various problems to other equipment connected to the point of common coupling. Typical problems are overheated machines, transformers and power cables, current flow in the neutral conductor, flicker effects, and malfunctioning of sensitive devices. The reduction of the harmonic content and also high power factor are desirable aspects in ac-dc converters, because they are potential harmonic sources and may affect power quality [1].

For such aspects, several standards have been proposed to normalize and limit harmonic pollution, such as IEEE Std 519 and IEC 61000-3-2. Throughout the years, switching techniques have been introduced to static converters in order to minimize such disturbances, as two strategies became popular i.e. PWM and hysteresis modulation. The hysteresis control introduces a minor error in the average input current and provides better dynamic response than the PWM control, but an inherent drawback is the variable switching frequency. Therefore the control circuit has to be designed for a large band, otherwise it will cause low frequency harmonics [2].

In front of this limitation, this paper introduces a novel control technique that allows ac-dc converters to operate at constant switching frequency with the advantages of usual hysteresis control strategy.

II. TIME CONTROLLER WITH POWER FACTOR CORRECTION

The basic idea of the proposed technique is to determine the ideal time interval between the switch commutation and the moment when the input current crosses the reference current. With these intervals, it is possible to implement a timer circuit to control the commutation of switches with constant frequency. Fig. 1 shows the behavior of the input current along an incremental time interval, where the reference current is practically constant, what is possible since the switching frequency is much greater than the line frequency.

This strategy can be applied to most single-phase ac-dc converters, without any essential change in the original topology [3]-[7]. For this study, a conventional hard-switched Boost converter operating in continuos conduction mode is chosen due to simplicity, because it has only two operating stages.

III. MATHEMATICAL ANALYSIS

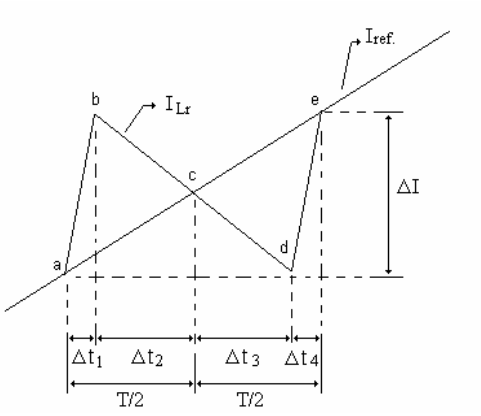


Fig. 1. Current profile along a switching period.

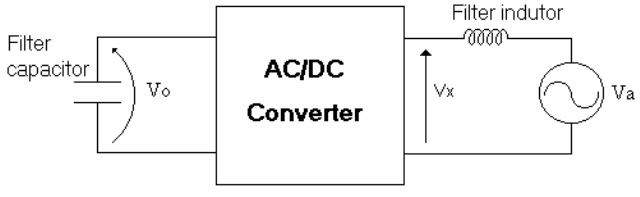


Fig. 2. Generic power converter with two operating stages.

In order to analyze the proposed control strategy, the circuit shown in Fig. 2 must be considered, where it can be seen that the generic converter operation can be defined in two distinct stages. Voltage V_x in the first and second stages is defined as V_{x1} and V_{x2}, respectively. Such values depend on the type of the converter in question. For instance, if the converter is a full-bridge topology, voltages V_{x1} and V_{x2} will be respectively V_o and $-V_o$. For a boost converter, voltages V_{x1} and V_{x2} will be V_o and null, respectively. However, independently of the topology, voltage V_{x1} will always be greater than the input voltage, and voltage V_{x2} is less than the input voltage or null. Additionally, if the switching frequency is considered much greater than the line frequency, the behavior of the inductor current can be described according to Fig. 1, which corresponds to an ideal situation i.e. triangles ABC and CDE have the same area. To obtain this, it is necessary to determine time intervals Δt_1 and Δt_3, which correspond to the exact moments when the switch is commutated. Intervals Δt_1 and Δt_3 are determined as function of the circuit parameters, in order to maintain constant switching frequency.

Expressions (1) and (2) represent the increasing and decreasing rates of the input current, respectively.

$$I_{Lb} = \frac{\int (-V_{x2} + V_a)dt}{L_b} \tag{1}$$

$$I_{Lb} = \frac{\int (-V_{x1} + V_a)dt}{L_b} \tag{2}$$

Within these aspects, the output voltage is constant and the reference current variation is considered linear. In addition to this, the increasing and decreasing rates of the inductor current can be considered constant. Therefore triangles ABC and CDE have the same area and the following expressions are valid:

$$\Delta t_2 \cong \Delta t_3 \tag{3}$$

$$\Delta t_1 \cong \Delta t_4 \tag{4}$$

Δt_1 – time period in which the current derivative is positive, from the crossing point with the reference current to the instant of commutation;

Δt_2 – time period in which the current derivative is negative the instant of commutation to the crossing point with the reference current;

Δt_3 – time period in which the current derivative is negative from the crossing point with the reference current to the instant of commutation;

Δt_4 –time period in which the current derivative is positive the instant of commutation to the crossing point with the reference current.

Time interval Δt_1 can be calculated from (5) and (6).

$$\Delta t_1 + \Delta t_2 = T_s/2 \tag{5}$$

$$\int_{t}^{t+\Delta t_1} \frac{(-V_{x2} + V_a)\,dt}{L} + \int_{t+\Delta t_1}^{t+T/2} \frac{(-V_{x1} + V_a)\,dt}{L} = \frac{\Delta I_{ref}}{2} \tag{6}$$

where ΔI_{ref} is the reference current variation, and T_s is the switching period. Assuming that current I_{ref} is linear along the switching period, ΔI_{ref} can be given as:

$$\Delta I_{ref} = T\frac{dI_{ref}}{dt} \tag{7}$$

Finally, from the previous expressions, interval Δt_1 is given as:

$$\Delta t_1 = \frac{T}{2(V_{x1} - V_{x2})}\left(V_{x1} - \frac{2}{T}\int_{t}^{t+T/2} V_a dt + \frac{L\Delta I_{ref}}{T}\right) \tag{8}$$

The same procedure can be used to calculate Δt_3. Equation (8) can be simplified as follows:

$$\Delta t_1 = \frac{T}{4V_0}\left(V_0 - V_a + L\frac{dI}{dt}\right) \tag{9}$$

Analogously, Δt_3 can be obtained from (10).

$$\Delta t_3 = \frac{T}{4V_0}\left(V_0 + V_a - L\frac{dI}{dt}\right) \tag{10}$$

From time intervals Δt_1 and Δt_3, it is possible to develop a circuit that allows one switch to be controlled (or more switches, in some topologies) with constant frequency, emulating hysteresis band. Therefore the behavior of the input current is represented in Fig. 3, Δt_1 and Δt_3 maintain the input current inside an envelope. Analogously to the hysteresis control, both reference currents can be calculated from (11) and (12), respectively.

$$I_{ref\,(\mathrm{up})} = \frac{1}{L}\int_{0}^{\Delta t_1}\left(V_0 + V_a - L\frac{dI_{ref}}{dt}\right)dt + I_{ref} \tag{11}$$

$$I_{ref\,(low)} = \frac{1}{L}\int_{0}^{\Delta t_3}\left(-V_0 + V_a - L\frac{dI_{ref}}{dt}\right)dt + I_{ref} \tag{12}$$

Since the reference current is the same parameter in (11) and (12), they can be simplified and adequately represented as (13) and (14), respectively.

$$I_{ref\,(\mathrm{up})} = \frac{1}{L}\left(V_0 + V_a - L\frac{dI_{ref}}{dt}\right)\Delta t_1 + I_{ref} \tag{13}$$

$$I_{ref\,(\mathrm{low})} = \frac{1}{L}\left(-V_0 + V_a - L\frac{dI_{ref}}{dt}\right)\Delta t_3 + I_{ref} \tag{14}$$

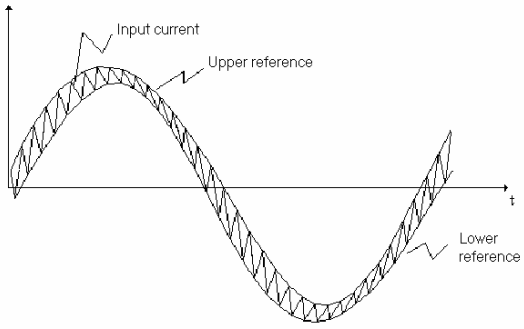


Fig.3. Input current behavior.

IV. BOOST CONVERTER

The single-phase boost converter shown in Fig. 4 has just two operating stages. When S_1 switch is off, the voltage across the filter inductor is (V_a-V_o), otherwise it is V_a.

For this converter, the expressions corresponding to time intervals Δt_1 and Δt_2 i.e. (9) and (10) can be written as:

$$\Delta t_1 = \frac{T}{2V_0}\left(V_0 - \frac{2}{T}\int_t^{t+T/2}|V_a|\,dt + \frac{LdI_{ref}}{T}\right) \quad (15)$$

$$\Delta t_2 = \frac{T}{2V_0}\left(\frac{2}{T}\int_t^{t+T/2}|V_a|\,dt - \frac{LdI_{ref}}{T}\right) \quad (16)$$

Both equations can be approximated to expressions (17) and (18), respectively:

$$\Delta t_1 = \frac{T}{2V_0}\left(V_0 - |V_a|\,dt + \frac{LdI_{ref}}{T}\right) \quad (17)$$

$$\Delta t_2 = \frac{T}{2V_0}\left(|V_a|\,dt - \frac{LdI_{ref}}{T}\right) \quad (18)$$

Time intervals Δt_3 and Δt_4 can be calculated analogously, but they are not necessary in the control development, because they are not directly involved in the process itself.

Fig. 4 shows the main control block. The operation of this circuit is quite simple. When the filter inductor current crosses with the reference current in ascendant direction, switch S_1 is turned off, and the output comparator turns on the OR logic device output, as the ramp generator creates a voltage ramp with inclination ($2V_o/T$), until this voltage reaches $V_{\Delta t1}$, consequently setting the JK flip flop output to low and turning off switch S_1.

When S_1 is off, the filter inductor current decreases until it crosses with the reference current. At this moment, the comparator drives its output to low, setting the OR logic device output to high, and the ramp generator starts a new ramp until it reaches $V_{\Delta t3}$. When this happens, the JK flip flop output is low, turning on switch S_1, and the filter inductor current starts increasing, as a new cycle begins.

Fig. 5 shows the simplified control circuit used in a Boost converter. Reference signals are generated by sum and multiplier blocks. Parameter K_2 is proportional to inductor L_f and constant K_1, and it must be defined in order to keep voltages $V_{\Delta t1}$ and $V_{\Delta t2}$ within the voltage band used for the circuit control. Therefore parameter K_1 can be defined as:

$$K_1 \approx \frac{T}{2V_o L} \quad (19)$$

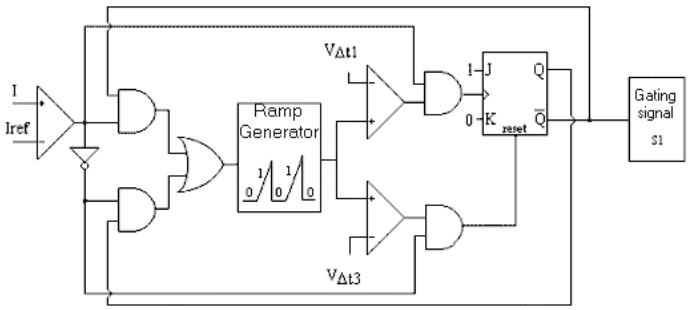


Fig 4. Block diagram of the main control circuit.

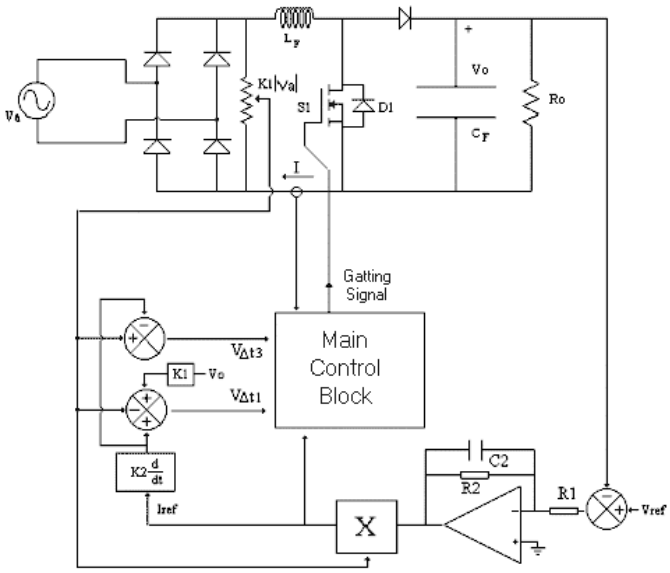


Fig. 5. Simplified block diagram using timer control applied to a Boost converter.

V. SIMULATION RESULTS

Simulation tests were performed on a Boost converter to demonstrate the control strategy. Conventional hysteresis control was also implemented to establish an eventual comparison between both techniques. One must mention that in both cases the average switching frequency is basically the same. The parameters employed in the tests are specified in Table I.

Fig. 6 shows the inductor current waveform. Fig. 7 (a) and (b) compares the switching frequency oscillation in a Boost converter operating with the proposed technique and the conventional hysteresis strategy, respectively.

TABLE I
PARAMETERS SET USED IN THE TESTS

Parameter	Value
Input voltage	V_i=220Vrms
Output voltage	V_0=400Vdc
Filter inductor	L_f=1.73mH
Filter capacitor	C_f=1000μF
Load current	I_o=5.5A
Switching frequency	f_s=20kHz
Switch S_1	IRFP460
Diodes	MUR1560

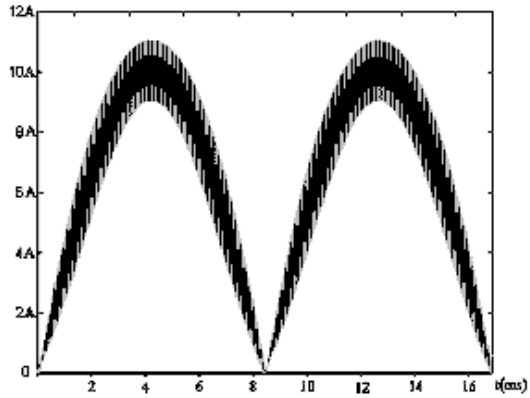
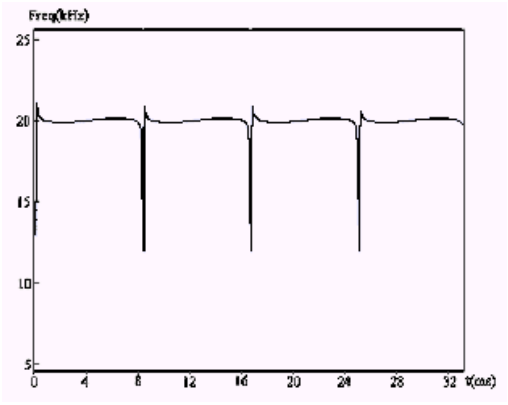
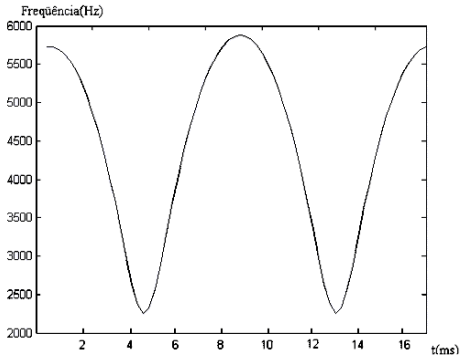


Fig 6. Inductor current waveform.



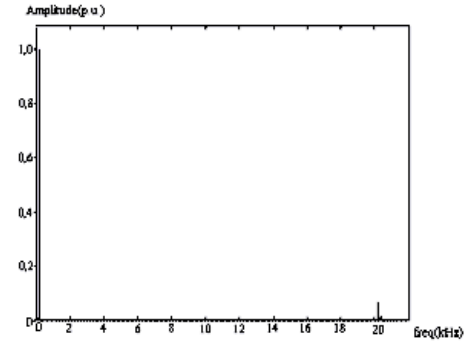
(a) Proposed hysteresis technique



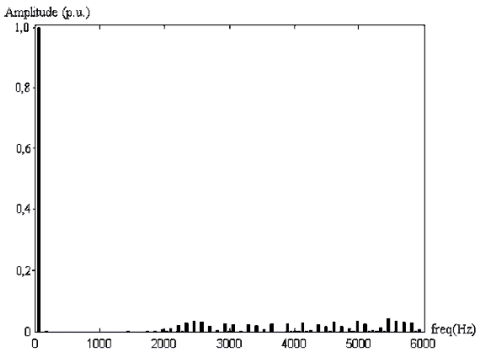
(b) Conventional hysteresis technique

Fig 7. Switching frequency oscillation.

Fig. 8 (a) and (b) compares the harmonics amplitudes in the frequency domain with both control techniques.



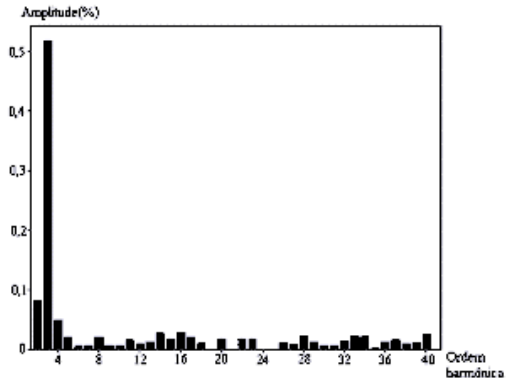
(a) Proposed hysteresis technique



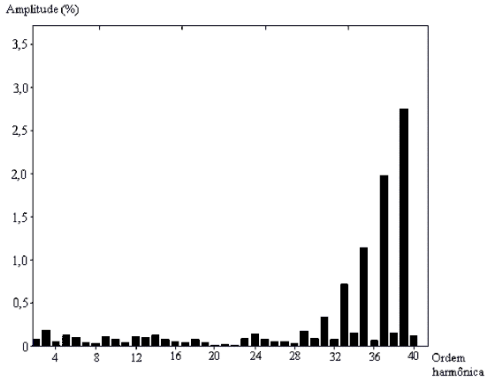
(b) Conventional hysteresis technique

Fig. 8. Harmonic amplitudes in the frequency domain.

Fig. 9 (a) and (b) compares the harmonic content as a function of the harmonic order.



(a) Proposed hysteresis technique



(b) Conventional hysteresis technique

Fig. 9. Harmonic amplitude as a function of the harmonic order .

VI. EXPERIMENTAL RESULTS

A Boost converter was experimentally developed and evaluated. The parameters employed in the tests are specified in Table I.

Fig. 10 evidences power factor correction. Figs. 11 and 12 show the harmonic contents of the input voltage and input current, where voltage *THD* is 3.4% and current *THD* is 1.9%. Figs. 13 and 14 show details of output voltage and ramp voltage, and filter inductor current and ramp voltage, respectively.

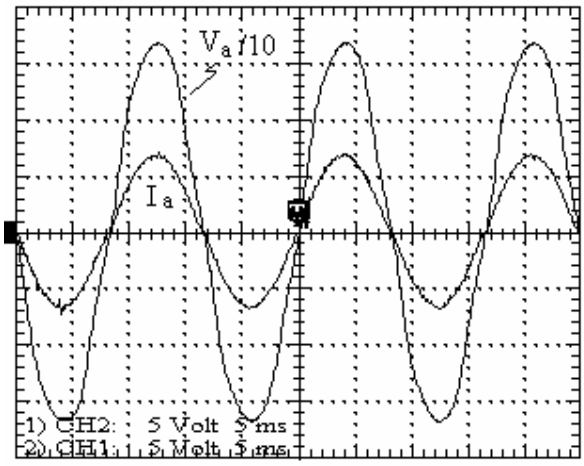


Fig 10. Input voltage and input current waveforms.

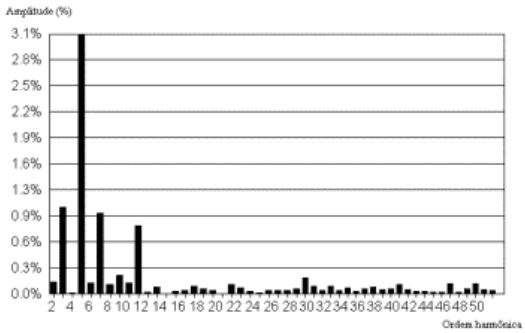


Fig 11. Harmonic content of the input voltage.

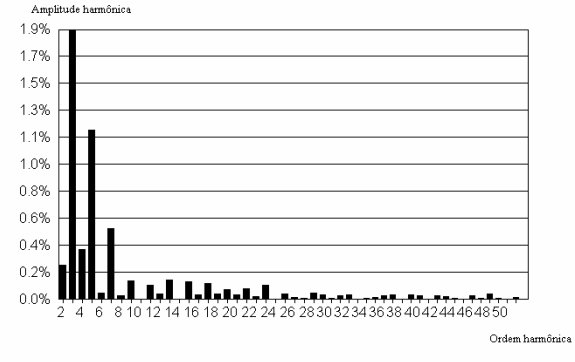


Fig 12. Harmonic content of the input current.

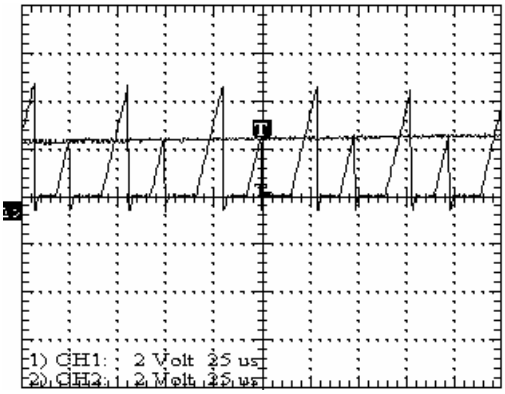


Fig 13. Output voltage and ramp voltage.

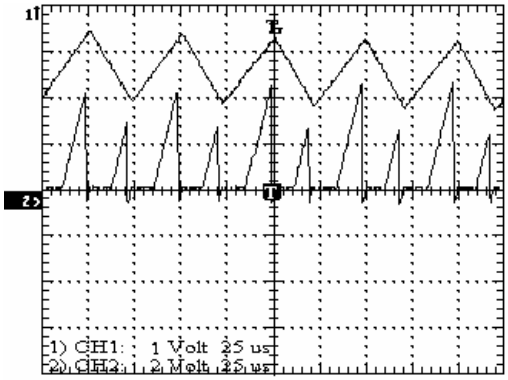


Fig 14. Filter inductor current and ramp voltage.

VII. CONCLUSION

This paper has presented a novel control technique that has the advantages of conventional hysteresis control and also constant switching frequency. The proposal control consists in a combination of the hysteresis control and PWM control, where constant switching frequency is obtained when a timer circuit is employed.

As it can be seen in the tests, the switching frequency variation is small as expected according to the mathematical study. It is also possible to say that the frequency variation relative error decreases with the switching frequency increasing, as it may become negligible.

ACKNOWLEDGMENT

The authors gratefully acknowledge CAPES, CNPq and FAPEMIG for the financial support to this work, and also Texas Instruments and ON Semiconductor for sending samples.

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