APPLICATION OF TECHNIQUES TO IMPROVE THE EFFICIENCY OF A 600W PWM PFC BOOST CONVERTER

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Abstract – The aim of this paper is to apply techniques to improve the efficiency of a PWM PFC Boost converter. A profile of the losses distribution is determined, considering that the converter operates in continuous conduction mode and average-current-control scheme. The simulation results for a converter with 600W, 100kHz and universal input voltage line is presented and discussed.

KEYWORDS:

Telecomunications, high efficiency, boost PFC, optimization, TDH.

I. INTRODUCTION:

Power supplies are well known harmonics sources that introduce distorted currents in the utility power system. Harmonics cause several undesirable problems such as voltage distortion, heating, noise and reduce power transference capability of the system. This fact and the existence of the standards or recommendations have lead to the use of power factor correction circuits in power supplies.

Unity power factor and tight output voltage regulation are achieved with the very well known two-stage approach, shown in fig.1. Since the power stage is composed by two converters, size, cost and efficiency are penalized, mainly in low power applications. However, this is probably the best option for AC/DC converters due to the followings reasons:

- Sinusoidal line current guarantees the compliance of any regulation;
- It is proper to operate with universal line voltage;
- It offers many possibilities to implement isolation between line and load and hold-up time;
- The penalty on the efficiency due to the double energy processing is partially compensated by the fact that the voltage on the storage capacitor is controlled and it allows a good design of the second stage.

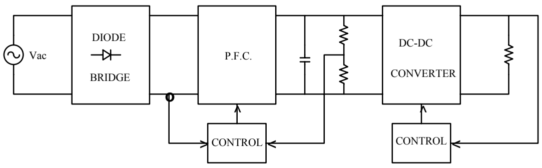


Fig.1: Two-stage AC/DC PFC converter.

Although unity power factor is the ideal objective, it is not necessary to meet the regulations. For example, both IEEE 519 and IEC 61000-3-2, even being very different in nature, allow the presence of harmonics in the line current [17-18]. This fact has lead to the publication of a great number of papers in the last years, with solutions that obtain some advantages over the two-stage approach. Some of the proposed circuits are practical but many others are too complex and difficult to implement.

This works presents techniques to improve the efficiency of a pre-regulator PWM boost converter of 600W. Considering restrictions and particular aspects of this application the boost topology has chosen due to its step-up voltage conversion ratio, continuous input current, simple topology and efficiency. From the profile of the losses distribution, strategies that offer an improvement in the overall performance of the converter is discussed and then compared.

II. APPLICATION OF THE METHODOLOGY FOR OPTIMIZATION TO POWER FACTOR PRE-REGULATOR CIRCUITS:

The methodology for optimization presented in [1] will be applied to the power factor pre-regulator circuit, which must attend the following specifications:

Design Specifications:	
Input voltage (V_{in}):	89 to 264V_{rms}
AC source frequency (f_r):	60Hz
Input current ripple (ΔI_{in}):	10%
Output power (P_o):	600W
Output voltage ripple (ΔV_o):	2%
Switching frequency (f):	100kHz
Output voltage (V_o):	400V_{dc}

The second stage will employ a ZVS-PWM-PS Full Bridge DC-DC converter.

Selection of topology and control strategy:

Some DC-DC converters are suitable to work as a power factor pre-regulator (PFP) or resistor emulator in AC/DC applications. These require two control loops (input current and output voltage) to achieve this purpose (see fig. 1).

When the input current is sinusoidal, the input power is pulsating and, since the power demanded by the load is constant, it is necessary to include an element to store the energy.

This element usually is a capacitor, but it should be dimensioned for twice the line frequency (100 or 120Hz) and therefore it is a large component. Finally, a second DC-DC converter is required to regulate the voltage at the output.

Therefore, the price that is paid for the highest quality waveform (sinusoidal) and tight output voltage regulation is the following:

- Two control loops in the pre-regulator;
- A big storage capacitor;
- An additional DC-DC converter with its own control.

The boost converter operating in continuous conduction mode has been the most popular topology employed in the industry, as PFP due to the structural advantages, especially the reduced ripple in the input current and the possibility of operation over a wide range of the input voltage. Besides, the components are subjected to lower current stresses. However, it requires the output voltage feedback, which is the variable to be controlled, and also the instantaneous sample of the input voltage so that the current draw by the power system can be adequately controlled. Once that it is desirable to control the output voltage and the current, by imposing a sinusoidal shaping to it, the control strategy to be employed is the instantaneous average value scheme.

It can be performed via UC3854 IC, which generates a reference current that follows the input voltage waveform [11]. Multiplying a synchronism signal that defines its form and the frequency of the reference current, by a feedback signal of the output signal that determines the reference current amplitude, creates this reference.

The input current is measured, and it is regulated according to the reference. A signal that defines the pulse width to be used in order to impose the desired current wave shape is then generated. Fig.2 shows the diagram concerning both power and control circuits.

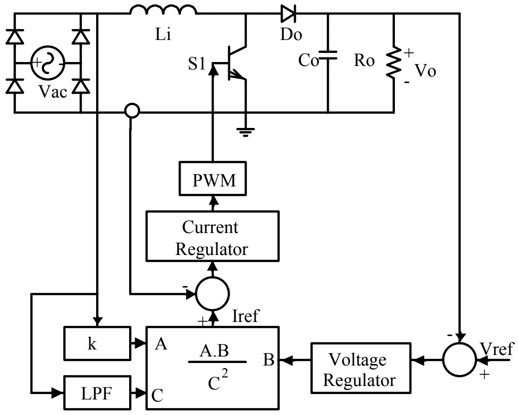


Fig.2: Block diagram of the boost converter using the average current control technique.

Profile of the losses distribution and efficiency:

The losses in the converter components and auxiliary circuits have been calculated by using the expressions shown in table 1.

Table 1: Expressions losses to PFC components and auxiliary circuits:	
Input diode bridge (P_{rt}):	$P_{rt} = 4 \cdot \left[V_f \cdot I_{dav} + R_s \cdot I_{drms}^2\right]$
Boost diode conduction (P_{cdd}):	$P_{cdd} = V_f \cdot I_{av} + R_s \cdot I_{rms}^2$
Boost diode commutation (P_{cmd}):	$P_{cmd} = \frac{Vin_{pknom}}{12} \cdot I_{rm} \cdot t_{rr} \cdot f_s$
Switch conduction (P_{cdm}):	$P_{cdm} = R_{DSon(Tj)} \cdot I_{rmsmx}^2$ (MOSFET) $P_{cdm} = V_{ce(sat)} \cdot I_{av}$ (IGBT)
Switch turn-on (P_{on}):	$P_{on} = \left(\frac{V_o}{\pi} - \frac{Vin_{pknom}}{4}\right) \cdot Iin_{pknom} \cdot (t_{ri} + t_{fv}) \cdot f_s$
Switch turn-off (P_{off}):	$P_{off} = \left(\frac{V_o}{\pi} - \frac{Vin_{pknom}}{4}\right) \cdot Iin_{pknom} \cdot (t_{fi} + t_{rv}) \cdot f_s$
Boost diode reverse recovery (P_{rr}):	$P_{rr} = \left(\frac{V_o}{\pi} - \frac{Vin_{pknom}}{4}\right) \cdot I_{rm} \cdot t_{rr} \cdot f_s$

Switch intrinsic capacitor (P_{Coss}):	$P_{Coss} = \frac{2 \cdot V_{dsoff}^2 \cdot C_{oss}}{3} \cdot f$
Boost inductor core (P_{nu}):	$P_{nu} = V_e \cdot C_m \cdot f_s^{\,x} \cdot \Delta B_{mx}^{\,y}$, toroid geometry and kool-Mμ material x=1.5, y=2 and C_m=1.
Boost inductor copper (P_{cb}):	$P_{cb} = R_{eq} \cdot I_{rmsmx}^{\,2}$, Neglecting skin and proximity effects and considering R_{eq}=R_{cc} for operating temperature of 80°C.
Filtering Capacitor (P_{Co}):	$P_{Co} = R_{se} \cdot I_{rms}^2$
Shunt resistor (P_{rsh}):	$P_{rsh} = R_{sh} \cdot I_{inrms}^2$
Auxiliary source (P_{aux}):	$P_{aux} = V_{aux} \cdot I_{aux}$

Once the topology and the respective control strategy are defined, the power components can be design and the losses are estimated from the design specifications and relevant equations, in an interval equal to half of the input voltage period.

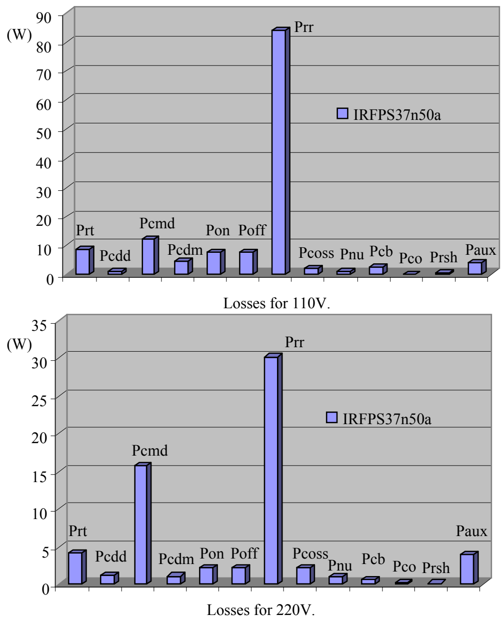


Fig.3: Profile of the power losses under 110V_{rms} and 220V_{rms}.

The graphs shown in fig.3 demonstrate clearly that the reverse recovery losses (P_{rr}) in diodes are predominant, which is inherent to topologies with high output voltages such as the boost converter.

Once that the loss in the auxiliary source that supplies the drive and control circuits is 4.0W, the theoretical efficiency can be obtained with the following expressions:

$$\eta_{110} = \frac{P_o}{P_o + \sum \text{Losses}}, \qquad \eta \approx 81{,}49\%$$

$$\eta_{220} = \frac{P_o}{P_o + \sum \text{Losses}}, \qquad \eta \approx 90{,}25\%$$

The results were obtained by using MOSFET type IRFPS37n50a where the gate resistance is 6.8Ω.

Standard TELEBRAS 240-510-273 predicts a minimum efficiency equal to 85% for operation under input voltages equal to 110V_{rms} and 220V_{rms} and nominal loads, as the use of strategies to minimize the converter performance are necessary.

III. APPLICATION OF STRATEGIES TO IMPROVE EFFICIENCY:

Within the available strategies that can improve the converter efficiency, one must mention:
- use of technologically improved switches;
- use of auxiliary commutation circuits;
- association of components and circuits;

The analysis of the technical and economical viability consists in an example of application of the proposed methodology. Besides, it will even establish new statements for other types of design.

1.Technology of semiconductors:

1.1. Diodes:

The reverse recovery current is responsible for the major part of the commutation losses not only in the boost diode but also in the main switch. The use of soft-recovery diodes, with reduced recovery time, aids the minimization of losses. The cost of such devices is higher than that of conventional diodes, although it does not consist in a limitation for this specific application.

1.2. Active switches:

The technological development concerning the manufacturing of switches has caused their performance to improve. A comparison between plastic (TO220) and metallic (TO262) encapsulement types shows that the first one presents higher resistances (R_{dson}), where the conduction losses also increase.

On the other hand, components with reduced transition periods between conduction and blocking tend to present lower commutation losses. However, the reverse recovery process of the diode must be controlled. Reduced commutation periods imply increased current rates, contributing to reverse recovery effect and commutation losses in the switches.

The graphs shown in fig.4 demonstrate clearly the predominance of reverse recovery losses in the boost diode, which are increased when switches with reduced commutation periods are used, just as IRFPS37n50a [19].

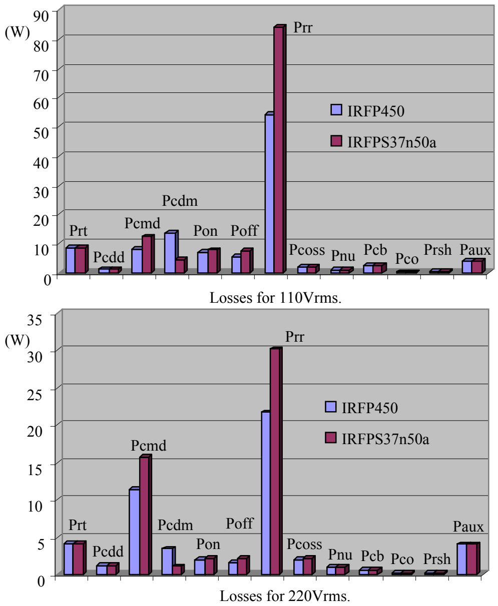


Fig.4: Profile of the power losses as the switch is changed.

1.3. Exchanging MOSFETs for IGBTs:

The technology involving the manufacturing of IGBTs has increased significantly. Nowadays there are components that can operate at high frequencies from 80kHz to 150kHz. Such components have not been intensively tested yet, and reliability at frequencies higher than 60kHz are questionable. On the other hand, IGBTs operating in an optimum way between 8kHz and 40kHz, although they can operate even at 60kHz [9].

As the application of pre-regulators demands high power density, the exchange of MOSFETs for IGBTs causes increasing of magnetic size and worse the dynamic response of controllers, which are designed to operate at lower cut frequency. As advantages reduce the temperature of magnetic component for a given flux density and current, the commutation losses in the switches, and the volume of heat sinks also. It can be demonstrated that the efficiency increases about 8.78%, if compared to the original design under $110V_{rms}$, and 4.76% under $220V_{rms}$.

Table 2 shows a comparison among some parameters involved in design when MOSFETs and IGBTs are used operating at 40kHz.

Table 2: Comparison among design parameters for MOSFET e IGBT:

	MOSFET:	IGBT:
Switching frequency:	40kHz	40kHz
Inductor volume:	$10{,}5cm^3$	$15{,}93cm^3$
Sinker thermal resistance (R_{th}):	$0{,}13^oC/W$	$0{,}23^oC/W$
Efficiency ($110V_{ac}$):	81,49%	90,27%
Efficiency ($220V_{ac}$):	90,25%	94,92%

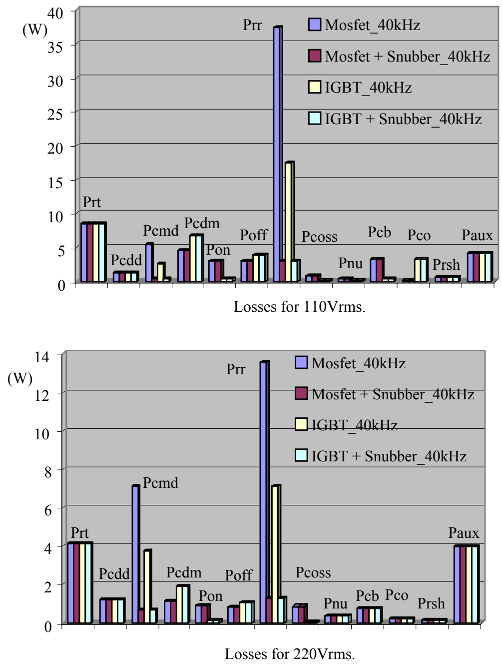


Fig.6: MOSFET versus IGBT at 40kHz under $110V_{rms}$ and $220V_{rms}$.

2. Auxiliary commutation circuits:

2.1. Non-dissipative snubbers:

Snubbers that do not present resistive elements are classified as non-dissipative. In this type of circuit, the energy that should be lost during commutation is transferred to the power supply or to the load via snubber. Therefore there is a considerable increase in the converter efficiency. A prominent advantage generally lies in the use of components with reduced size, which are easily specified than the remaining elements of the converter. Additionally it does not employ driven switches.

The analyses of the non-dissipative snubbers, when the conduction starts, is presented in [21], and the study of the non-dissipative snubber, when the conduction and blocking occur, is presented in [22]. For simplicity, and since most of the energy wasted in commutation comes from the beginning of the switch conduction, an snubber that limits the positive current rate during the beginning of conduction has been chosen, as presented in [21].

The converter topology using the non-dissipative snubber is presented in fig.7. Diodes Dsb1 and Dsb2, capacitor Csb and inductor Lsb compose the snubber.

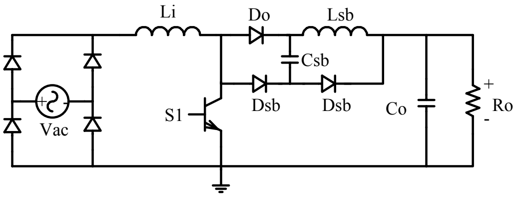
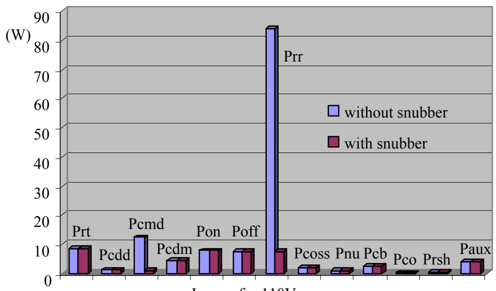


Fig.7: Boost converter topology associated to non-dissipative snubber.

The snubber must be employed when the reverse recovery in the main diode is high. It must be designed so that the operation is optimum under critical conditions.



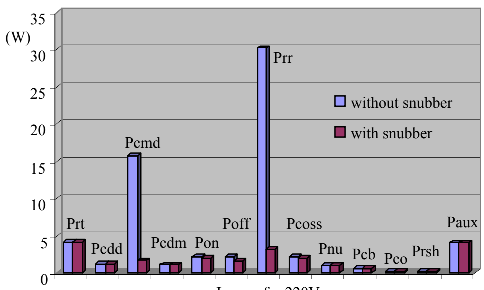


Fig.7: Profile of losses distribution with non-dissipative snubber.

The snubber has shown it satisfactorily, as the reverse recovery of the diode is controlled and the efficiency increases about 11.01%, when the input voltage is $110V_{rms}$ and $220V_{rms}$.

It must be mentioned that the use of four additional components, therefore increasing cost and volume, the efficiency increases too, what justifies its application.

3. Association of components and circuits:

The boost converter presents high output voltage, allowing the use of techniques that consist in associating switches or even converters in series as the voltage stresses are shared. Thus, the creation of new technologies becomes possible, commonly known in literature as multilevel-voltage converters. Such topologies overcome the limitation of semiconductors in supporting voltage stress. This strategy is also widely employed with inverters.

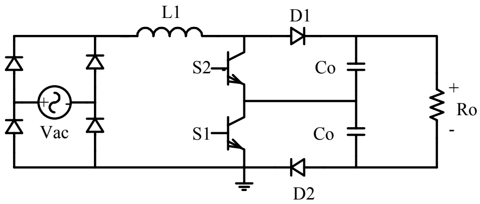


Fig.8: Boost converters associated in series.

The analysis involving two series connected switches applied to the classical topology has been performed. The voltage stresses are shared between the switches, causing the reverse recovery losses to be reduced. If this technique is employed alone, the efficiency increases 7.31% for $110V_{rms}$ and 3.08% for $220V_{rms}$. If the technique is employed simultaneously with the non-dissipative snubber, the obtained results are 9.82% and 5.18%, respectively.

The cost of additional components is returned when lower nominal voltage switches are employed, which are less expansive and present lower R_{dson}, what favours the reduction of conduction losses. Such arrangement presents some disadvantages, i.e., the drive circuit complexity and the increased volume of heat sinks.

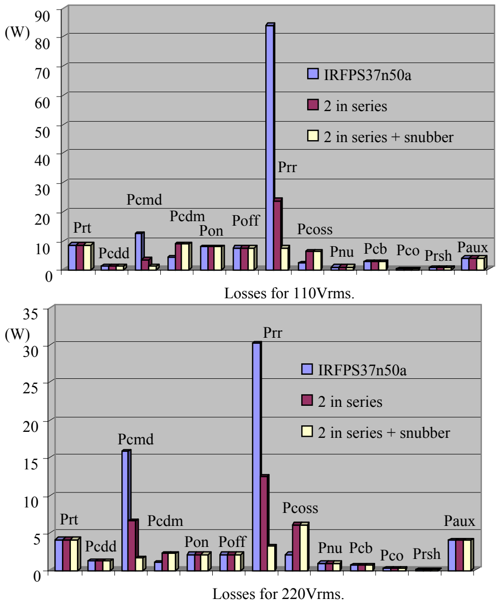


Fig.9: Profile of losses regarding series-connected components.

In order to reduce conduction losses, parallel connection techniques are employed, originating multilevel-current converters. The results obtained with the association of two IRFPS37n50a MOSFETs are shown in fig.10.

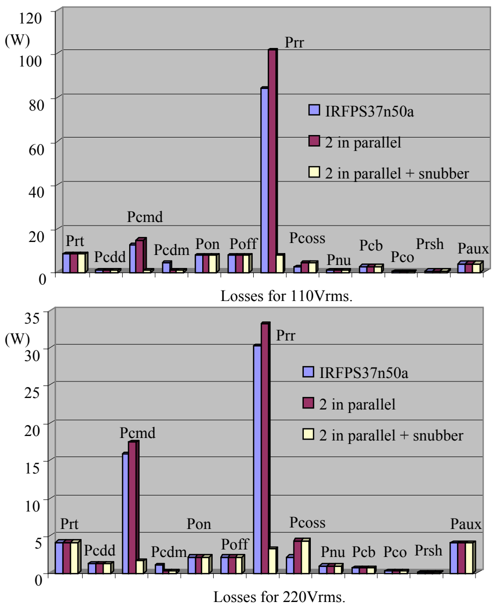


Fig.10: Profile of losses regarding parallel-connected components.

This technique must be employed with non-dissipative snubber, as the efficiency increases 11.17% for $110V_{rms}$ and 5.75% for $220V_{rms}$. The main disadvantages to be considered are the current sharing equalization to each component and the drive circuit complexity.

The most conventional topology available in literature, widely employed in power factor correction, is the interleaved boost converter, show in fig.11. The converters operate at the same frequency but they are half cycle phase-shifted. The rms current in the switches and the output voltage ripple are both reduced.

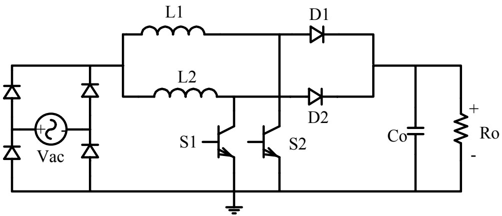


Fig.11: Parallelism of boost converters.

IV. CONCLUSIONS:

From the profile of losses distribution in a boost converter used as power factor pre-regulator (PFP), some strategies aiming to improve the efficiency without affecting overall performance are described. Within the proposed techniques one must mention the exchanging of the type of the switch, the association of components or circuits and the use of snubber circuit.

The reverse recovery of the boost diode is the major source of losses in the classical topology. If it is limited by the use of a non-dissipative snubber just as the one shown in fig.7, efficiency increases 11.01% when the input voltage is $110V_{rms}$ and 6.12% for $220V_{rms}$.

The voltage stress sharing by the use of series-connected switches has also propitiated the reverse recovery losses to decrease. If this technique is used simultaneously with snubbers, the efficiency may increase up to 9.82%. This type of association favours the use of switches with maximum voltages and lower conduction resistances, contributing to the reduction of conduction losses.

Although the parallelism of components associated to a snubber, increase the efficiency to 11.07% for $110V_{rms}$, the current sharing problem in the switches and the increasing complexity of the control circuit, limit the application of this technique.

The choice of a toroid core Kool-Mμ 196Z-77083-A7 [23] for the boost inductor, calculated as [25], is very interesting because this type of core presents excellent characteristics of shielding and heat transfer. The use of another core geometry represents the increasing volume core. For this type of application the use of toroid core with Kool-Mμ material becomes important once that it reduces EMI levels significantly. However, the increased cost recommends it to applications where operating frequencies are higher than 100kHz.

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