# DISCRETE-TIME CURRENT CONTROL TECHNIQUES APPLIED IN PFC BOOST CONVERTER AT INSTANTANEOUS POWER INTERRUPTION

Tiago Kommers Jappe, Samir Ahmad Mussa
Federal University of Santa Catarina UFSC
Electrical Engineering Department / Power Electronics Institute – INEP
P.O: Box 5119 - 88040-970 - Florianópolis-SC, BRAZIL
Phone: +55(48)3721-9204 / Fax: +55(48)3234-5422
(tiagokj), (samir)@inep.ufsc.br

*Abstract* - **Recently, power quality disturbances such as voltage sags and instantaneous power interruptions are, probably, the most frequent and damaging phenomenon in industrial environments. Thus, to improve the sustainability of electrical equipment, the power supplies should tolerate these disturbances. The PFC boost converter operating in CCM is exhaustively used as a first-stage in power supplies. The average current mode control is the most popular technique and is usually implemented by IC UC3854. However, at instantaneous power interruption, the inner controllers go to saturation mode. Consequently, the switching device (MOSFET) of the converter might be permanently damage when the power returna after voltage interruption. Another current control technique is self-control. In this case, the dynamics controllers are different. Therefore, this paper investigates the operation of the converter at instantaneous power interruption. The average current mode control and self-control are analyzed. Protection strategy is implemented, by FPGA, in a single-phase CCM PFC boost converter. Simulation and experimental results confirm and validate the analysis.**

***Keywords*** **– Anti wind-up PI, FPGA, PFC boost, power interruption, Self-control, Voltage sags.**

## I. INTRODUCTION

The most common power quality disturbances are the voltage sags and instantaneous power interruption, lasting only a few cycles and happening randomly [1–4]. Assuming that the fault time is less than the hold-up time in switched mode power supplies (SMPS), hence the SMPS must to support the load without turn-off under instantaneous power disturbances. Nevertheless, the PFC pre-regulator often breaks under these disturbances, even when nominal voltage returns in just a few cycles.

The single-phase PFC boost converter is, generally used as a first-stage in switched mode power supply, with average current mode control [5], as shown in Figure 1. At instantaneous power interruption the controllers go to saturation, because of the dynamics of each controller in the three control loops. After the power returns, the transitory AC current is higher than the steady state current and can damage the switching power device (MOSFET or IGBT) [6].

There are some devices which can mitigate power quality disturbance, such as uninterruptible power supply, voltage regulator, and dynamic sag restorers. These devices are effective but expensive. Therefore, to improve sustainability of electrical equipment, the PFC boost converter should tolerate common power disturbances. It makes more economic sense to implement the protection strategy in first stage of power supply, to reject power disturbances more often, without additional support.

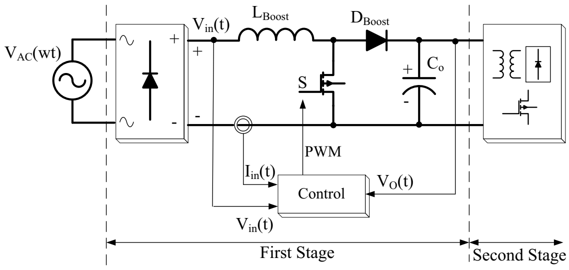


Fig. 1. Single-Phase PFC boost converter as first stage in SMPS.

This paper analyzes the dynamics of controllers under instantaneous power interruption, in average current mode control and current self-control. The protection strategy is implemented, in first stage of power supply, to limit the transitory AC current after power returns. The protection method will be implemented with discrete time controllers by FPGA.

## II. AVERAGE CURRENT MODE CONTROL AT INSTANTANEOUS POWER INTERRUPTION

The configuration to control the PFC boost converter, with average current mode control, is shown in Figure 2. There are three control loops: the inner current loop, the line voltage feedforward loop (signal C(t)), and the outer DC voltage loop (signal B(t)).

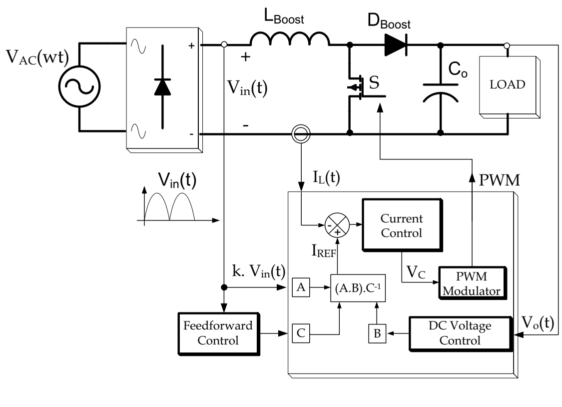


Fig. 2. Average current mode control technique applied in PFC boost converter.

978-1-4244-3370-4/09/$25.00 © 2009 IEEE 

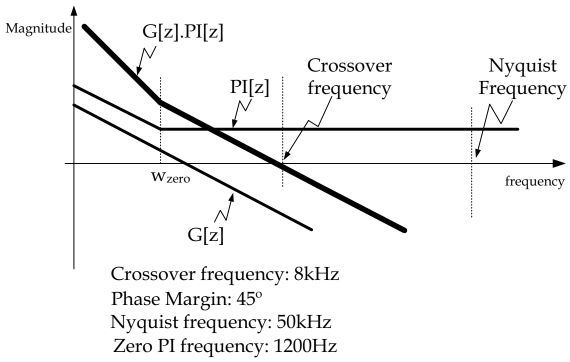


Fig. 3. Asymptotic waveforms of inductor current loop.

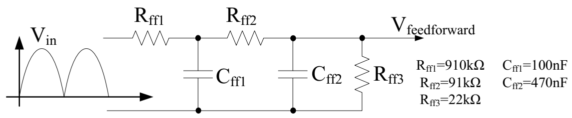


Fig. 4. Feedforward controller.

The inner current loop is the fastest loop and acts to ensure that the input current will follow the sinusoidal waveform. In this case, a reference is required for the current shape and generally the absolute value of the AC input voltage is used (signal A(t)). The discrete-time transfer function is shown in (1). In inner loop, a Proportional-Integral (PI) controller (2) is generally used and designed as per Figure 3.

$$G[z] = \frac{i_L[k]}{D[k]} = \frac{V_o}{L_b}.\frac{T_A}{2}.\frac{z+1}{z-1} \quad (1)$$

$$PI[z] = K_p.\frac{z - e^{-2\pi.f_{zero}.T_A}}{z-1} \quad (2)$$

where:

$i_L$ - Inductor current.
$D$ - Duty cycle.
$V_o$ - Output voltage.
$L_b$ - Inductor of Boost Converter.
$T_A$ - Sampling period.
$K_p$ - Proportional gain of PI.
$f_{zero}$ - Zero frequency of PI.

The voltage feedforward loop is applied to compensate the line voltage variations and is the slowest loop. In this case, a second-order low pass filter is used as the controller, as in Figure 4, thus, the signal C(t) is proportional to the RMS value of the AC input voltage.

The outer DC voltage loop regulates the output voltage for the given reference. The PI controller is also used in this loop, to reject load disturbance. The dynamics of this loop should be slowest than that of the current control loop, to avoid AC current distortion. The discrete-time transfer function to control DC voltage output is shown in (3). The PI controller for the DC voltage loop is designed as per Figure 5 .

$$\frac{V_O[k]}{I_L[k]} = \frac{R_O.T_A(z+1)(1-D)}{2.R_O.C_O(z-1)+T_A(z+1)} \quad (3)$$

Where:

$R_O$ - Resistive Load.
$C_O$ - Output Capacitance.

Both signals, B(t) and C(t), determine the inductor current magnitude reference (signal $I_{REF}$), as per (4) while A(t) shapes the sinusoidal waveform.

$$i_{REF}[k] = \frac{A[k].B[k]}{C[k]} \quad (4)$$

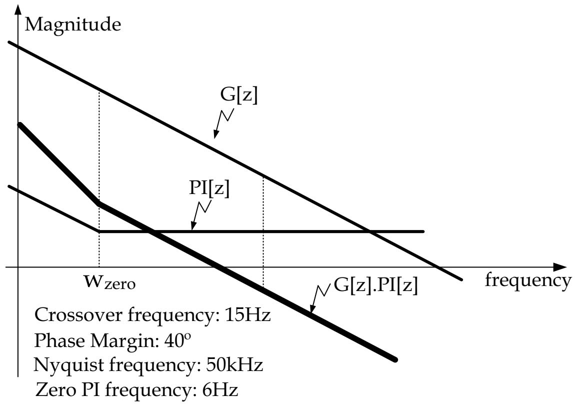


Fig. 5. Asymptotic waveforms of DC output loop

Figure 6 shows the theoretical waveforms of the PFC boost converter under instantaneous power interruption. Considering $t < t_o$, the converter works in the steady state mode.

1.$t_0 \leq t < t_1$ At $t = t_0$ the power interrupt occurs, then the rectified input voltage $V_{in}$, (signal A), becomes 0V. The feedforward voltage, (signal C), and the output DC voltage

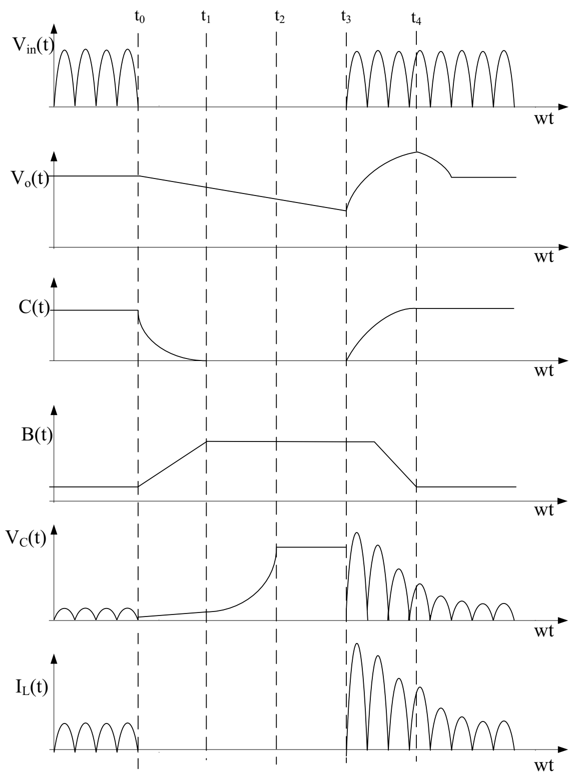


Fig. 6. Theoretical waveforms of PFC converter at instantaneous power interruption

$V_o(t)$ decrease slowly. The signal of the DC voltage feedback controller (B(t)) increases because the DC voltage decreases.

2. $t_1 \le t < t_2$: The output DC voltage controller reaches the maximum value and the feedforward signal becomes zero Volts. Therefore, the division of a higher value by a smaller signal value occurs, thus, the current controller will be saturated.

3. $t_2 \le t < t_3$: The PWM signal reaches to the maximum value because the signal B is in saturation while the signal C is null.

4. $t_3 \le t < t_4$: When the power returns ($t = t_3$), the switch is in short circuit because of control action and then the amplitude of AC input current takes above magnitude. This transitory current is higher than the steady state current and generally the switching device (MOSFET or IGBT) of the PFC boost converter permanently is damaged.

Hence, to improve sustainability of the PFC boost converter a protection strategy is required when the converter operates with average current mode control at instantaneous power interruption. Therefore, the next section will investigate the self-control current technique at instantaneous voltage interruption.

## III. SELF-CONTROL CURRENT TECHNIQUE AT INSTANTANEOUS POWER INTERRUPTION

The self-control current technique also called resistive input, needs only a proportional controller to shape the AC current, such as AC voltage, employing leading-edge modulation (DOFF) [7, 8]. In this technique is not required a reference for the current shape, because the current will follow the AC voltage as in a resistive load. Figure 7 shows how the PFC converter can act as a fictitious impedance.

The discrete-time transfer function to control the AC current is (5):

$$G_{SELF}[k] = \frac{I_L[k]}{V_{in}[k]} = \frac{1}{R_E} \cdot \frac{1}{1 + \frac{2}{T_A} \cdot \frac{L_b}{R_E} \cdot \frac{z-1}{z+1}} \tag{5}$$

where:

$I_L$ - Inductor current.
$V_{in}$ - Input Voltage.
$R_E$ - Fictitious impedance.

The fictitious impedance is:

$$R_E = \frac{V_{AC}}{I_{AC}} \tag{6}$$

where:

$I_{AC}$ - RMS AC input current.
$V_{AC}$ - RMS AC input voltage.

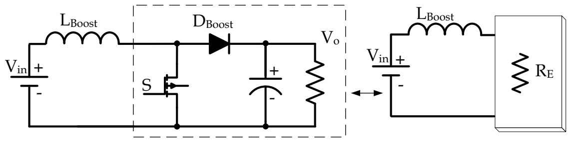


Fig. 7. PFC converter act as a fictitious impedance $R_E$.

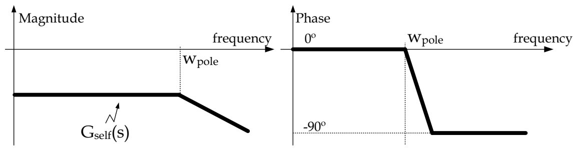


Fig. 8. Asymptotic waveforms of self-control current loop.

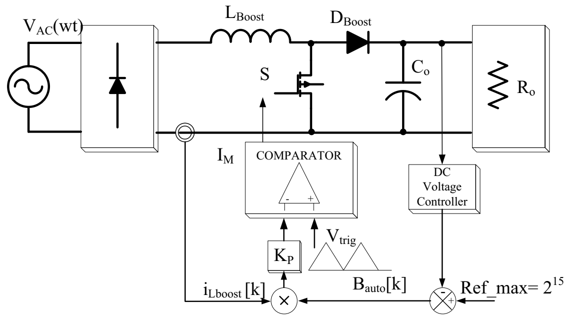


Fig. 9. PFC converter controlled by self-control technique.

And the pole is of this control technique is:

$$f_{pole} = \frac{R_E}{2\pi L_b} \tag{7}$$

Figure 8 shows the asymptotic waveforms of the self-control current loop and explain how the gain is constant until the pole frequency. Thus, using only a proportional controller to improve the gain, the converter can operate as a resistive load to the power system.

The non-linear relation between DC voltage control and current control, because of the leading-edge modulation ($D_{OFF}$) is explained in [7]. Nevertheless, in this paper the outer DC voltage loop is designed in the same ay as the average current mode, so a PI controller is used, as per Figure 9.

Figure 10 shows the self-control technique controlling the PFC boost converter at instantaneous power interruption. The Proportional controller dynamics is unlike that of the PI compensator thus, the PFC boost converter operates differently in each control technique. Therefore, because of the current controller, the self-control technique is naturally protected, when the PFC converter operates at instantaneous voltage interruption.

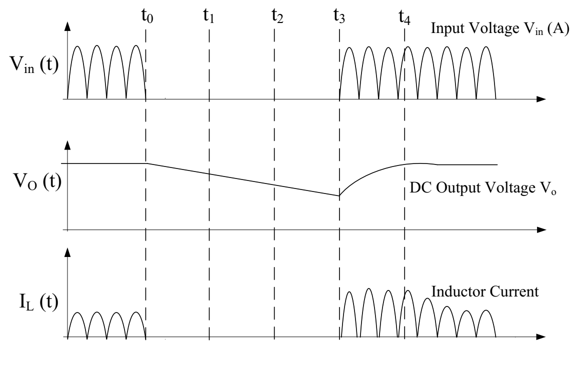


Fig. 10. Theoretical waveforms of PFC converter at instantaneous power interruption, with self-control technique.

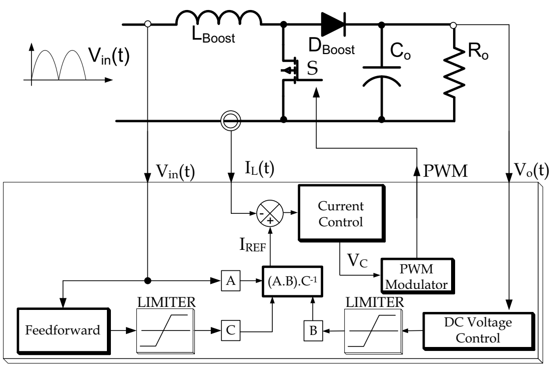


Fig. 11. Average current mode control technique with protection strategy proposed.

## IV. PROTECTION STRATEGY

Section II describes the PFC converter controlled by average current mode control, at instantaneous power interruption. The signals C(t) and B(t) are responsible to control the magnitude of signal $I_{REF}$(t) and at power interruption these signals to cause $V_C$(t) saturation. Thus, controlling the magnitude of signals C(t) and B(t) is possible to limit the transitory inductor current, when instantaneous power interruption occurs.

Figure 11 shows the protection strategy implemented in average current model control. Signals B(t) and C(t) are limited to a predetermined value. The DC voltage output signal is saturated at a maximum predetermined value. The signal C(t) is saturated at a minimum value when the power interruption occurs. Hence, when the power returns, the magnitude of signal $V_C$(t) will limit the AC current.

Independently of whether analog or digital controllers are used, the protection strategy can be implemented in the normal way without drastic alteration. The main idea is to limit the AC current magnitude after power interruption.

Figure 12 presents the theoretical waveforms of PFC converter at instantaneous power interruption with protection strategy. The signals C(t) and B(t) are limited to predetermined values, controlling the magnitude of signal $V_C$(t) after the power returns, independently of the fault time.

The DC output voltage controller is a PI compensator, implemented by digital control. At power interruption the DC voltage feedback controller goes into saturate mode. The integral action tracks null steady state error, but it never occurs at power interruption. Thus, the wind-up phenomenon occurs and it is caused only by excessive integral calculation of integral element of PI controller [9]. Therefore by limiting inner PI operations, the wind-up phenomenon is avoided. The difference equation (6) for a conventional discrete PI controller (2) is given in Figure 13, while Figure 14 shows the PI controller with anti wind-up protection.

$$u[k] = u[k-1] + A.error[k] - B.error[k-1] \quad (8)$$

where:

$$\begin{aligned} A &= K_p \\ B &= K_p.e^{-2\pi.f_{ZERO}.T_A} \end{aligned} \quad (9)$$

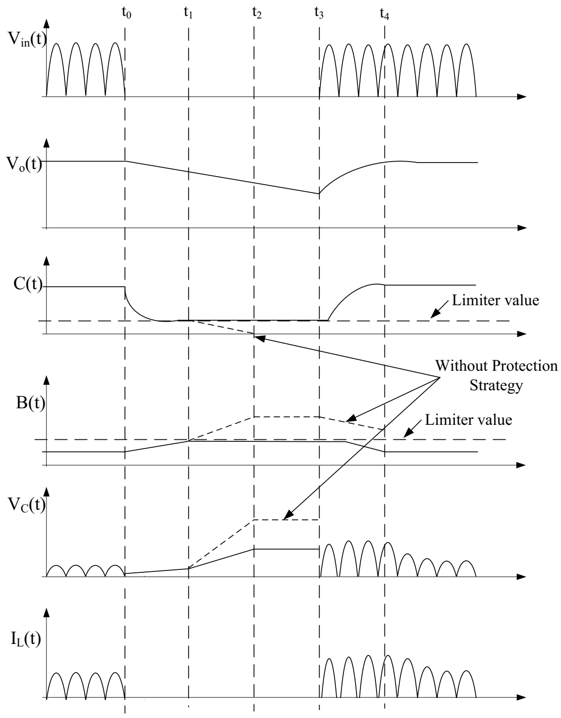


Fig. 12. Theoretical waveforms of PFC converter at instantaneous power interruption with protection strategy.

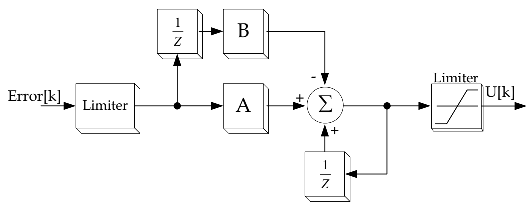


Fig. 13. Blocks diagram of discrete PI controller.

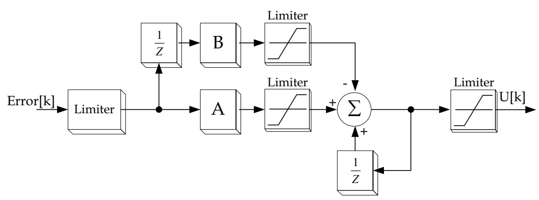


Fig. 14. Blocks diagram of discrete PI controller with anti wind-up protection.

## V. SIMULATION RESULTS

Simulation results were development in PSIM software. Figure 15 presents the transitory AC input current after power interruption without protection strategy, while Figure 16 shows the AC input current when anti wind-up PI controller is implemented in DC output voltage compensator.

In this case, the AC voltage interruption was only 16.66 ms and without protection the transitory peak current takes more than 24 A. Thus, without protection the amplitude of input current was five times higher than the steady state value. Nevertheless, using the protection strategy, the current is limited after the power returns.

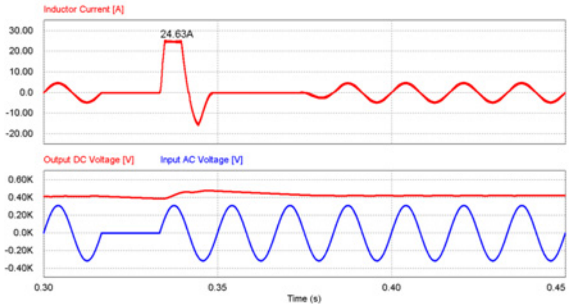


Fig. 15. Transitory input current, AC voltage and DC voltage without protection strategy.

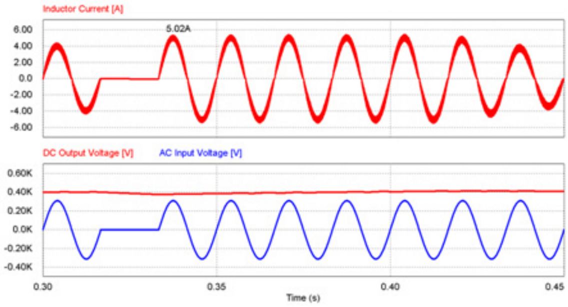


Fig. 16. Transitory input current, AC voltage and DC voltage with protection strategy.

## VI. EXPERIMENTAL RESULTS

The experimental investigation was performed based on a single-phase PFC boost converter (Figure 1) with the specifications listed in Table I.

The discrete-time controllers were implemented in FPGA by ALTERA DE2 development and education board. This kit has an EP2C35F672C6 FPGA and some peripherals (crystal oscillators, SRAM and SDRAM memory etc). The development environment used is the Quartus II Web Edition to synthesize by block diagram the control strategy.

In this control strategy three variables are necessary to control the PFC converter (input and output voltage and input current). Thus, in this project, were used three ADC channels (Analog to Digital) of IC AD 7367 (Analog Device) operating in parallel independently.

To generate instantaneous power interruption was employing a controlled voltage source of *Agilent Technologies* model 6813B AC Power Source/Analyzer.

Figure 17 shows input AC current, AC voltage and DC voltage without protection strategy. In just 16.66 ms of fault time, the transitory peak current takes more than 25 A after power returns, in other words, the transitory input current was five times higher than the steady state value.

**TABLE I**
**Single-Phase PFC Boost Specifications**

| | |
|---|---|
| Power | 600 W |
| Switching Frequency | 50 kHz |
| RMS AC Input Voltage | 220 V |
| Output DC Voltage | 400 V |
| Sampling Frequency | 100 kHz |

Figure 18 shows input AC current, AC voltage and DC voltage when is used the protection strategy. These results validate the previous study, as well the protection strategy design.

Figure 19 depicts experimental results of self-control technique, applied in PFC boost converter under instantaneous power interruption.

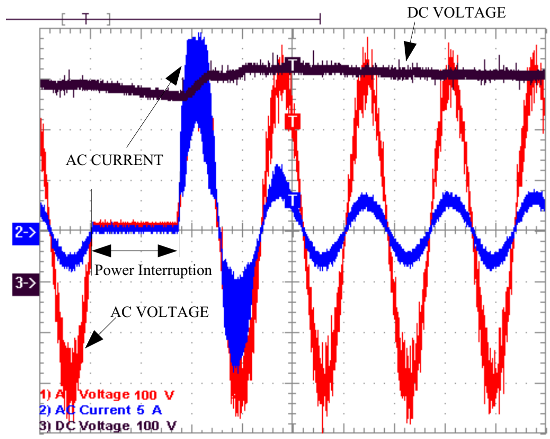


Fig. 17. AC Voltage [100 V/DIV], input current [5 A/DIV] and DC voltage [100 V/DIV] without protection strategy.

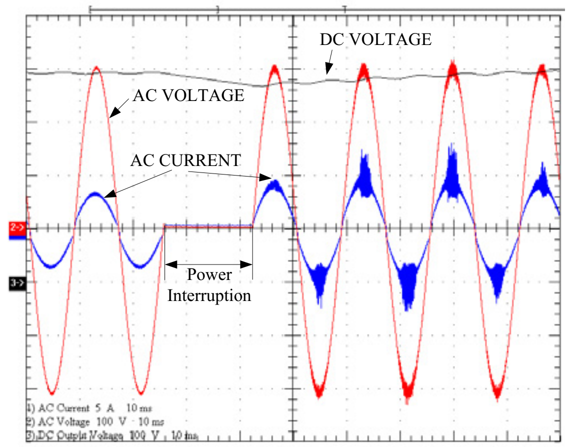


Fig. 18. AC Voltage [100 V/DIV], input current [5 A/DIV] and DC voltage [100 V/DIV] with protection strategy.

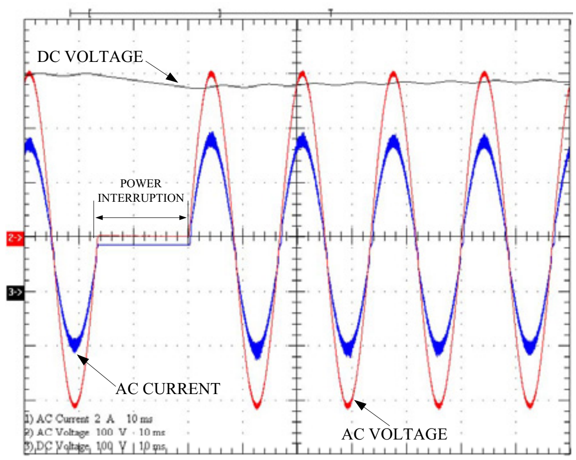


Fig. 19. AC Voltage [100 V/DIV], input current [2 A/DIV] and DC voltage [100 V/DIV] with current self-control technique.

## VII. CONCLUSION

This paper presents a study on the operation of a single-phase PFC boost converter at instantaneous power interruption. The average current model control and current self-control technique were investigated. When average current mode is used, at AC voltage interruption, the controllers go into the saturation state and, thus, at power returns, the transitory input AC current is higher. This transitory current may damage the switching device permanently. Therefore, a simple protection strategy is proposed to improve the sustainability of the PFC pre-regulator boost under instantaneous power interruption.

When current self-control technique is used, a protection strategy is not required, because this control technique is naturally protects against of instantaneous power interruption.

Simulation and experimental results validate the protection strategy. The anti wind-up PI controller is implemented in FPGA to control the DC voltage output and limits the magnitude of the AC current after power interruption. Experimental results also demonstrated that the self-control technique is, as expected protected against instantaneous power interruption.

## ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support provided by CAPES, UFSC and INEP.

## REFERENCES

[1] M. H. Bollen, *Understanding power quality problems: voltage sags and interruptions*. IEEE Press, New York, N.Y.: USA, 2000.

[2] R. Dugan, M. McGranaghan, and H. Beaty, *Electrical Power Systems Quality*. McGraw-Hill, New York, N.Y.: USA, 1996.

[3] C. M. C. Brito, R. P. S. Leao, and F. L. M. Antunes, "Avaliação da proteção do acionamento de um motor de indução e de métodos para melhoria de sua suportabilidade sob afundamentos de tensão," *Revista Brasileira de Eletrônica de Potência (SOBRAEP)*, vol. v.10,n.2,p.9-16, 2005.

[4] IEEE, *Std. 1159-1995 - IEEE Recommended Practice for Monitoring Electric Power Quality*. IEEE Press, New York, N.Y.: , 1995.

[5] C. Todd, *UC3854 Controlled Power Factor Correction Circuit Design*. UNITRODE Application Note U-134,Merrimack, N.H.,EUA: , 1996.

[6] H. Lee and G. Choe, "A study on the operation characteristics of pfc at instantaneous power interrupt," in *Proc. of IECON*, November 2004.

[7] D. Borgonovo, J. Remor, I. Barbi, and A. Perin, "A self-controlled power factor correction single-phase boost pre-regulator," in *Proc. of PESC*, pp. 2351–2357, June 2005.

[8] S. Ben-Yaakov and I. Zeltser, "The dynamics of a pwm boost converter with resistive input," *IEEE Transactions on Industrial Electronics*, vol. v.46,n.3,p.613-619, June 1999.

[9] K. J. Aström and B. Wittenmark, *Computer-controlled systems: theory and design*. $2^{nd}$ Edition,Prentice-Hall, Inc.: Upper Saddle River, NJ, USA, 1990.

[10] D. Borgonovo, S. Mussa, and A. Perin, "A self-controlled single-phase voltage-doubler boost using fpga," in *Proc. of COBEP*, pp. 849–853, October 2007.

[11] W. Zhang, Y.-F. Liu, and B. Wu, "A new duty cycle control strategy for power factor correction and fpga implementation," *IEEE Transactions on Power Electronics*, vol. v.21,n.6,p.1745-1753, November 2006.

[12] S. Mussa, H. Mohr, J. Neto, and R. Silva, "Control strategy based on dft for pfc converter," in *Proc. of COBEP*, October 2005.

[13] S. Mussa and H. Mohr, "Voltage-doubler rectifier with pfc, regulation and balancing of the output voltages using dsp," in *Proc. of COBEP*, pp. 241–246, October 2001.