Design of a discrete-time active disturbance rejection control strategy applied to the current loop of a Bridgeless AC/DC Boost converter

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Abstract. This document describes the analysis of a control technique based on active disturbance rejection (ADRC). This technique uses a generalized proportional integral (GPI) observer in discrete time that estimates the disturbances inherent in the system for their subsequent elimination. The efficiency of the controller is verified by simulations of a Boost bridgeless single phase power converter. The analysis was performed in the context of the reduction of the percentage RMS error between the reference signal and the input current signal of the converter which results in the correction of the power factor (PF) and the reduction of the total harmonic distortion (THD). The performance of the proposed control strategy was demonstrated since the tracking error was reduced even in the presence of disturbances.

1. Introduction

Power converters, also known as AC/DC converters, are used in power electronics applications, such as inverters, power supplies and others [1],[2]. Most of these applications have a power factor correction (PFC) system to improve efficiency and meet power quality standards [3].

Among the AC/DC converters for PFC applications, it is worth mentioning the Boost bridgeless topology (Figure 1), which consists of two Boost converters that work alternately [4].

The Boost Bridgeless topology is presented as a resource to minimize conduction losses by reducing the number of semiconductor devices. However, the control of harmonics is still a research topic due to problems related to the presence of harmonics in the electrical network caused by switching effects.

This document proposes a control strategy based on active disturbance rejection for the current loop of the bridgeless Boost converter. This technique uses a robust linear GPI controller for non-linear disturbance systems [5],[6]. This strategy estimates disturbances through a discrete observer called a generalized proportional integral observer (GPI observer). Disturbances (harmonic components of the fundamental frequency of the 60Hz network) and uncertainty

Are modelled as additive components, either external or plant-specific, and are estimated by the GPI observer, in a unified way [7], [8]. The aim is to reduce the percentage of total harmonic distortion (THD) and bring the power factor (PF) into the unit by tracking a sinusoidal reference signal [9].
The document is organized as follows: section 2 presents the model of the Boost Bridgeless AC/DC converter. Section 3 presents the design of the GPI observer-based control in discrete time. Section 4 shows the Matlab simulation of the discrete-time GPI observer-based control for the simplified averaged model of the AC/DC converter. Section five shows the results of the simulations of the proposed array, and section six presents some conclusions.

2. Another section of your paper Circuit operation and analysis

The control strategy that was designed was implemented in a bridgeless AC/DC Boost converter whose schematic diagram is shown in Figure 1. This converter is composed of a pair of inductors (L1 and L2) of 707μH each with their respective parasitic resistances (RL1 and RL2) of 0.5Ω; two power diodes in the upper part (D1 and D2) and two Mosfets in the lower part (Q1 and Q2). The DC bus consists of the 660μF capacitor (C), and a 32Ω charge resistor (R). The converter is powered by AC voltage, which enters to the power factor correction stage. In this stage, there are two Boost converters that operate alternately in each half cycle of the line voltage [10].

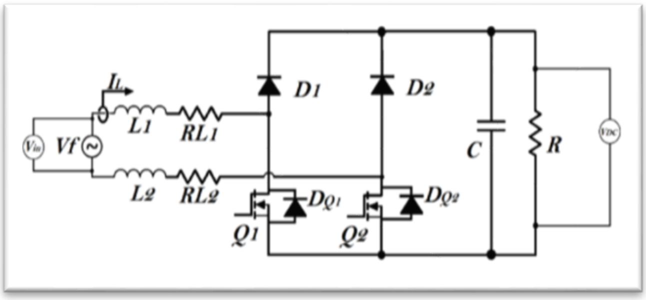

Figure 1. Schematic diagram of the Bridgeless PFC Boost.

Taking into account the current path, the analysis of the circuit is made using Kirchhoff's voltage law.

$$v_f = L\frac{di_L}{dt} + R_L i_L + v_{ab} \qquad (1)$$

where v_f is the mains voltage $\left(v_f = V_f\sqrt{2}\,sin(\omega_n t)\right)$, i_L is the current that passes through the coil, L is the equivalent inductance of the circuit, R_L is the equivalent circuit resistance equal to R_{L1}+R_{L2}, and v_{ab} is the voltage from the nodes of the resistors R_{L1} and R_{L2} of the circuit [11].
When $v_{f(t)}$ is positive, the average voltage v_{ab} is:
When $v_{f(t)}$ is negative, the average voltage v_{ab} is:

$$\overline{\mathrm{v_{ab}}} = -(1-\mathrm{D})(\mathrm{v_c}+\mathrm{v_{D2}}) - \mathrm{v_{Q2}}\mathrm{D} - \mathrm{v_{DQ1}} \qquad (2)$$

where v_{D1} is the voltage of diode D1, v_c is the DC voltage of the output capacitor, v_{DQ2} is the voltage of the internal diode of the Mosfet Q2, v_{DQ1} is the voltage of the internal diode of the Mosfet Q1, v_{Q1} is the drain-to-source voltage of Mosfet Q1, v_{Q2} is the drain-to-source voltage of Mosfet Q2 [11].

In Equations (2) and (3), D corresponds to the duty cycle of the PWM signal which takes values in a closed interval of [0,1]. By adding Equations (2) and (3), it is possible to say that the averaged-simplified model of the plant is:

$$\frac{di_L}{dt} = -\frac{R_L}{L} i_L + \frac{v_f}{L} + \frac{\alpha}{L} \qquad (3)$$

Where α is:

$$\alpha = \begin{cases} (1-D)v_c;\ semi-positive\ cycle \\ -(1-D)v_c\ ;semi-negative\ cycle \end{cases} \qquad (4)$$

By applying the Laplace transform to Equation (4), and taking v_f as a disturbance, Equation (5) is obtained.

$$sI_L = -\frac{R_L}{L} I_L + \frac{\alpha}{L} \qquad (5)$$

By clearing I_L/α from equation (6), the averaged-simplified model is obtained:

$$\frac{I_L}{\alpha} = \frac{1}{(Ls+R_L)} \qquad (6)$$

3. GPI OBSERVER-BASED CONTROLLER

The proposed control strategy uses the simplified model of the system which is based on the ADRC method. As mentioned in section 1, the objective of the controller is to ensure that:

$$i_L^* = i_d \sin(\omega_n t) \qquad (7)$$

Where the current i_d is constant in a steady state. Based on Equation (4), it can be said that:

$$\frac{di_L}{dt} = \mathbf{K}\alpha + \xi \qquad (8)$$

Where $\boldsymbol{K}$ is $\frac{1}{L}$ and

$$\xi_1 = \frac{v_f}{L} - \frac{R_L}{L} i_L \qquad (9)$$

Using Euler's method for derivative approximation, the following is obtained:

$$\frac{di_L}{dt} \approx \frac{i_L(k+1)}{Ts} \qquad (10)$$

The discrete representation of the system is given by:

$$\frac{i_L(k+1) - i_L(k)}{Ts} = Ku(k) + \xi_2(k) \qquad (11)$$

with

$$\xi_2(k) = \xi_1(k) - \left[\frac{i_L(t)}{dt}\bigg|_{t=kTs} - \frac{i_L(k+1) - i_L(k)}{Ts}\right] \quad (12)$$

It is worth noting that $\xi_2(k)$ takes into account the discretization error of Euler's method. Equation 11 is rewritten in terms of the tracking error $e_y(k) = i_L(k) - i_L^*(k)$:

$$\frac{e_y(k+1) - e_y(k)}{Ts} = Ku(k) + \xi(k) \quad (13)$$

With,

$$\xi(k) = \xi_2(k) - \frac{i_L^*(k+1) - i_L^*(k)}{Ts} \quad (14)$$

$\xi(k)$ can be taken as the additive disturbance function without considering any particular internal structure.What is sought is that, given a smooth reference path i_L^*, the tracking error e_y is brought to a proximity close to zero, regardless of the unknown but uniformly constrained nature of the disturbance function $\xi(k)$. The disturbance function $\xi(k)$ groups internal and external disturbances that affect system dynamics.

For the system shown in equation 11, the following assumptions are made.

- The disturbance function $\xi(k)$ is unknown, while the control input gain, K, is fully known.
- The sampling period Ts is small enough to achieve accurate results when using, as a discretization method, the Euler's method.
- Be m a given integer. The successive differences of $\xi(k)$ are uniformly bounded in absolute values. In other words, there are constants k_j such that:

$$\sup_k \left| \left(\frac{q-1}{Ts}\right)^j \xi(k) \right| \leq k_j, \text{con } j = 0, 1, \dots, m \qquad (15)$$

Where q is the forward operator; the first assumption is made to ensure independence of $\xi(k)$ from $u(k)$. The third assumption is used to establish the existence of a solution of the difference equation (12). With respect to the simplified system (11), in order to propose a discrete GPI observer for a state-space representation and an estimate of the disturbance function, the approach uses the fact that the disturbance input, x (k), can be modeled approximately by

$$\left(\frac{q-1}{Ts}\right)^m \xi(k) \approx 0 \qquad (16)$$

Where m is a large enough integer. The operator applied to the estimated disturbance input corresponds to a composite difference of order m

Equation 11 can be expressed in discrete time as:

$$\left(\frac{q-1}{Ts}\right) i_L = Ku(k) + \xi(k) \qquad (17)$$

From equation 11, the following is obtained:

$$i_L(k+1) = i_L(k) + TsKu(k) + Ts\xi(k) \qquad (18)$$

It is stated that the m-th derivative of the disturbance is zero, for m=2 we have:

$$\left(\frac{q-1}{Ts}\right)^2 \xi(k) = 0 \qquad (20)$$

It is then possible to carry out a state variable implementation of the system described in Equation 19, so that one of the states corresponds to the estimate of $\xi(k)$.

Upon completion of this process, the system is represented as shown in Equation 21. In this last representation, it can be seen that the state variable $x_1(k) = i_L(k)$ corresponds to the output of the plant, $x_2(k) = \xi(k)$ corresponds to the plant disturbance, and $x_3(k) = \left(\frac{q-1}{Ts}\right)\xi(k)$ corresponds to the first derivative of the plant disturbance.

$$\begin{aligned} x_1(k) &= i_L(k) \\ x_2(k) &= \xi(k) \\ x_3(k) &= x_2(k+1) - x_2(k) \qquad (21) \\ \left(\frac{q-1}{Ts}\right) x_3(k) &= 0 \end{aligned}$$

Now, the extended system as a function of the state variables is:

$$\begin{aligned} x_1(k+1) &= x_1(k) + Ts\, x_2(k) + Ts\, Ku(k) \\ x_2(k+1) &= 0 + x_2(k) + 0 + x_3(k)Ts \\ x_3(k+1) &= x_3(k) \end{aligned} \qquad (22)$$

Resulting in the following system

$$x(k+1) = Ax(k) + Bu(k) \qquad (23)$$
$$y(k) = Cx(k) \qquad (24)$$

where:

$$A = \begin{bmatrix} 1 & Ts & 0 \\ 0 & 1 & Ts \\ 0 & 0 & 1 \end{bmatrix} \in \mathbb{R}^{(1+m)\times(1+m)}$$
$$B = \begin{bmatrix} Ts\, K \\ 0 \\ 0 \end{bmatrix} \in \mathbb{R}^{(1+m)\times 1}$$
$$C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \in \mathbb{R}^{1\times(1+m)}$$

The observer proposed is given by:

$$\hat{x}(k+1) = A\hat{x}(k) + Bu(k) + L\big(y(k) - \hat{y}(k)\big) \qquad (25)$$
$$\hat{y}(k) = C\hat{x}(k) \qquad (26)$$

Where the difference of equation (23) minus equation (25) results in the estimation error e_x, whose dynamics is given by:

$$e_x(k+1) = Ae_x(k) + LCe_x(k) \qquad (27)$$

With

$$e_x(k+1) = [A - LC]e_x \qquad (28)$$

4. Gpi observer-based controller simulation

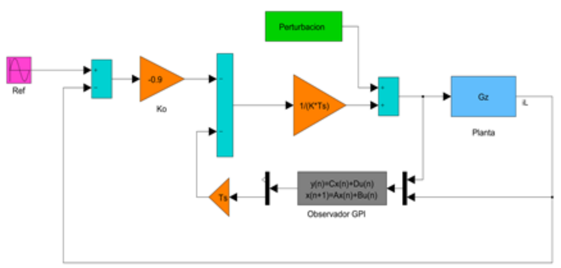

Figure 2. Matlab simulink diagram of the system with the addition of disturbance

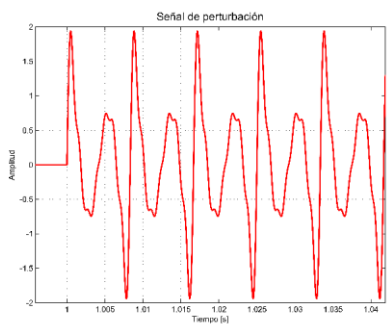

Figure 3. Disturbance signal

This section describes the simulations performed to evaluate the performance of the proposed discrete-time GPI observer-based control applied to a Bridgeless Boost converter. Two different operation cases are presented and analyzed. Firstly, the tracking of the reference signal, a sinusoidal signal with a nominal frequency of 60 Hz, is analyzed. Secondly, the disturbance rejection, for which a signal is added that simulates the harmonic currents generated by the system in Figures 2 and 3.

5. RESULTS

This section describes the results obtained when evaluating the performance of the proposed discrete-time GPI observer-based control applied to a Bridgeless Boost converter. Observer poles were selected on the left side of the complex plane for system stability, as shown in table 1. This shows the decrease in the tracking error of the system, even in the presence of disturbances.

Table 1. Performance evaluation

#	Observer poles			% Mean square error (Tracking without disturbance)	% Mean Square Error (Reference Tracking with Disturbance)
1	**-0,015**	**-0,018**	**-0,020**	31.86 %	33.20 %
2	**-0,030**	**-0,035**	**-0,040**	14.24 %	17.02 %
3	**-0,060**	**-0,070**	**-0,080**	3.98 %	9.71 %
4	**-0,120**	**-0,140**	**-0,160**	2.08 %	7.66 %
5	**-0,24**	**-0,28**	**-0,32**	1.90 %	5.05 %
6	**-0,48**	**-0,56**	**-0,64**	1,8873 %	2.83 %
7	**-0,96**	**-1,12**	**-1,28**	1,8854 %	2.08 %
8	**-1,5**	**-1,75**	**-2**	1,8851 %	1.97 %

Figures 4 and 5 show how the system output is added to the reference when the poles are moved away from zero.

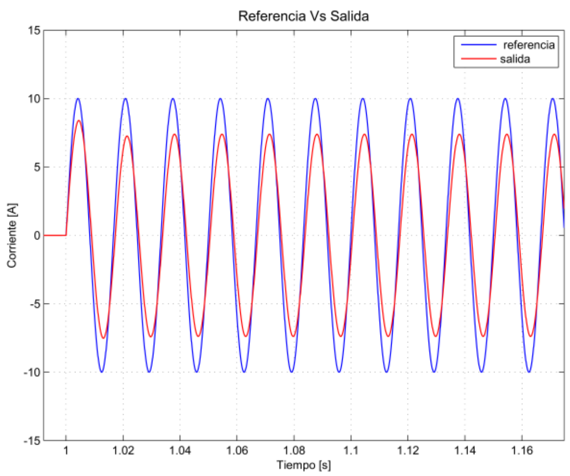

Figure 4. Reference tracking with poles [-0,015 -0,018 -0,02].

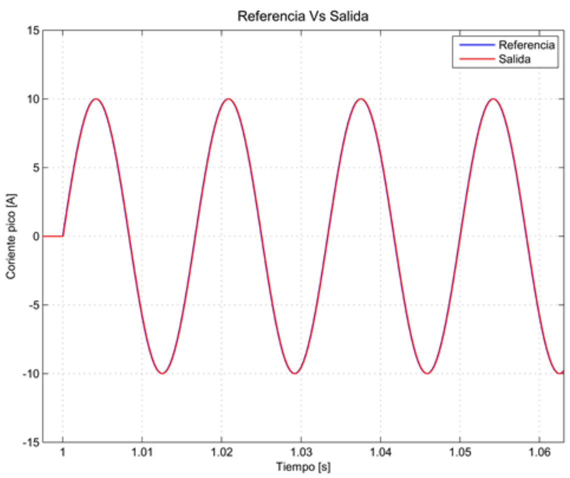

Figure 5. Reference tracking with poles [-1,5 -1,75 -2].

6.CONCLUSIONS

This paper presents a discrete control by a disturbance observer as a possible solution to Bridgeless Boost AC/DC converter control. The proposed control objective was to reduce the tracking error of the reference signal even in the presence of disturbances. In a possible real implementation, this would reduce the percentage of total harmonic distortion (THD) and power factor correction (PF).

The estimate of the disturbance depends on the sampling frequency. As the sampling frequency increases, the degree of the polynomial approximation decreases. For the proposed case, the approximation was of degree 2, and a good performance was obtained.

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