Power factor corrector with PID loop fit by genetic algorithm

Corrector de factor de potencia con lazo PID sintonizado por algoritmos genéticos

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Palabras clave: algoritmos genéticos, control PID, convertidor *boost*, factor de potencia.

ABSTRACT

The boost converter is widely used in voltage regulation applications and active power factor correction (PFC), its proper operation and performance are directly related to final design of its control loop. The design of this control is somewhat complex due to the nonlinearity of its behavior; the commutation of a switch (power transistor) makes the equivalent circuit change continually over time (two alternating circuits in time). In this work, it is defined the poles of the transfer function in closed loop for the average model (linear model approximate) of the boost converter using evolutionary principles of genetic algorithms, with the idea of improving the dynamic response of voltage regulator. The design outline is successfully verified by simulation and on a laboratory prototype, and improvements were found in the dynamic (voltage overshoot and response time) compared to classical schemes.

RESUMEN

El convertidor *boost* es ampliamente utilizado en aplicaciones de regulación de voltaje y corrección activa del factor de potencia (PFC), su adecuada operación y desempeño están directamente relacionados al diseño final de su lazo de control. El diseño de éste control es bastante complejo debido a la no linealidad de su comportamiento; la conmutación de un interruptor (transistor de potencia) hace que el circuito equivalente cambie continuamente a lo largo del tiempo (dos circuitos alternados en el tiempo). En éste trabajo, se definen los polos de la function de transferencia en lazo cerrado para el modelo promedio (modelo lineal aproximado) del convertidor boost utilizando los principios evolutivos de los algoritmos genéticos, con la idea de mejorar la respuesta dinámica del regulador de voltaje. El principio de diseño es verificado exitosamente por simulación y sobre un prototipo de laboratorio, sobre los cuales se encontró mejoras en la respuesta dinámica (sobrepaso de voltaje y tiempo de respuesta) frente a esquemas clásicos.

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INTRODUCTION

The boost converter (step-up converter), is a topology of power to regulate voltage DC/DC that can be implemented like intermediate component of a more complex system, and that is widely used for the active correction of power factor (PFC) (Martínez, 2004). The input to this converter is often an unregulated rectifier line voltage, which will fluctuate due to changes of the line voltage magnitude. The main objective of control of this circuit is to convert the unregulated DC input voltage into a controlled DC output voltage in front of changes in the load. Additionally, in many applications it is desired to maintain a sinusoidal input current (PFC). The problem of regulating the output voltage of these converters has been a subject of great interest for many years, due to the switching property included in their structure, DC/DC converters have a non-linear behavior and consequently their controlling design is accompanied with complexities. In addition, due to the nonminimum phase nature of the boost converter, much effort has been directed at the control of this configuration.

Mathematical modelling of power DC/DC converters is a historical problem accompanying with the development of the DC/DC conversion technology since 1940's (Lin and Ye, 2004). The preliminary work on the mathematical modeling for DC/DC converters followed the traditional calculation manner using impedance analysis to obtain transfer function in the s-domain (Laplace transform) (Chan, 2007).

In this article, a PID current mode control fit by genetic algorithms (GA) is proposed and its characteristics and application to the regulation of the power converters and PFC are investigated. The advantage of the proposed hybrid control is that not only it retains the advantages of the existing current mode control, but it also affords an additional tuning parameter which can be used to modify the output response. Finally, it is presented some experimental results to illustrate the features of the proposed control.

BOOST CONVERTER

Consider the DC/DC boost converter circuit shown in figure 1. During the interval when switch Q is off, diode D conducts the current i_L of inductor L towards the capacitor C_0 and the load R. During the interval when switch Q is on, diode D is open and the capacitor C_0 discharges through the load R. The converter transfers the energy between input and output using the inductor. The continuous commutation of these two circuits gives to the converter its nonlinear characteristic.

The small signal model of boost converter is shown in equation (1) (Severns and Bloom, 1985) (Martínez, 2011), it is obtained using standard state-space averaging techniques (Chan, 2007).

$$\begin{bmatrix} \dot{\overline{i_L(t)}} \\ \dot{\overline{v_0(t)}} \end{bmatrix} = \begin{bmatrix} \frac{R_C R(d-1) - R_L(R+R_C)}{L(R+R_C)} & \frac{R(d-1)}{L(R+R_C)} \\ \frac{R(1-d)}{C_0(R+R_C)} & \frac{-1}{C_0(R+R_C)} \end{bmatrix} \begin{bmatrix} \overline{i_L(t)} \\ \overline{v_0(t)} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{in}$$

$$Y(t) = \begin{bmatrix} 1 & 1 \end{bmatrix} \begin{bmatrix} \overline{i_L(t)} \\ \overline{v_0(t)} \end{bmatrix} \quad (1)$$

Where:

- $\overline{i_L(t)}$ = average input current in the inductor L [A]
- $\overline{v_0(t)}$ = average output voltage [V]
- d = duty cycle
- V_{in} = input voltage [V]
- L = boost inductor [H]
- C_0 = output capacitor [F]
- R = boost load [Ω]
- R_C = parasitic resistance of C_0 [Ω]
- R_L = parasitic resistance of L [Ω]

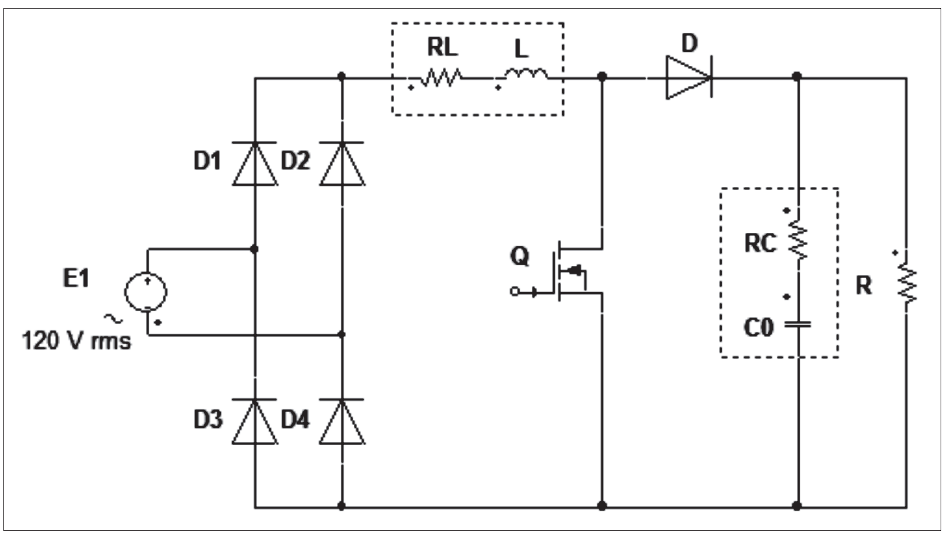

Figure 1. The DC/DC boost converter. This switching-mode converter contain two semiconductor switches (Q and D) and one energy storage element (L). The output capacitor (Co) works as filter.

Source: Own source.

The transfer function is a second order, low-pass filter with two zeros. The low-pass filter's cut off frequency is calculated through of the equation (2).

$$\omega_C = \frac{V_{in}}{v_0\sqrt{LC_0}} \quad (2)$$

The ideal voltage in the output is V_{ref}. The zero in the left half plane is determined by the equation (3).

$$\omega_{ZL} = -\frac{1+\frac{R_C}{R}}{R_C C_0} \quad (3)$$

And the zero in the right half plane is determined by the equation (4).

$$\omega_{ZR} = \frac{V_{in}^2 R}{v_0^2 L} \quad (4)$$

The cut off frequency and the zero in the right half plane depend on the output and input voltages, reason for which the transfer function in closed loop must change continuously. As the operation point varies, it is difficult for the linear PID controller to respond well (designed for one operating point).

For the experimental boost converter utilized in this work, the input voltage is the alternate of 120 V AC to 60 Hz rectified with a diode full bridge, the output voltage is 400 V DC, C_0 is 330 μF, L is 2 mH, and R is 800 Ω. The parasitic elements, R_C and R_L, are measured in laboratory with values of 0,5 Ω and 1,5 Ω respectively.

The step response (constant duty cycle of 0,61) in open loop are plotted in figure 2.

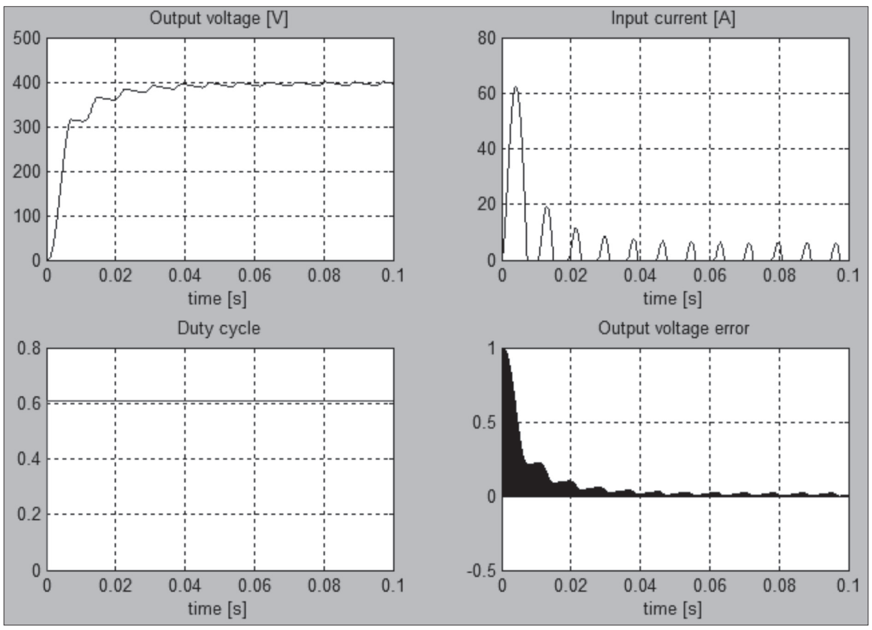

Figure 2. Step response of boost converter (simulation open loop). Starting current greater to 60 A.

Source: Own source.

CONTROL OF THE BOOST CONVERTER

The primary objective of converter is the regulation of output voltage, reason for which is necessary to eliminate the stationary error of the same. Of the classic theory of control, it's knows that is possible adding a PID network of compensation. The proportional and the integral component allow reducing the rise time and stationary state error, whereas the part differential allows controlling the overshoot.

Figure 3 shows the scheme of proposed control. In this, two feedback loops, structure very common in the active correctors of power factor, one of current and one of voltage can be appreciated. In (Sira-Ramirez, 1987) appears a study of the surface of control for constant current in the inductor, demonstrating that the equilibrium point is stable. In agreement with this, the block PID constructs a current of reference starting the error of output voltage. This current of reference is compared with the current in the inductor to determine the current error, which is given to the PWM to obtain the present value of the duty cycle.

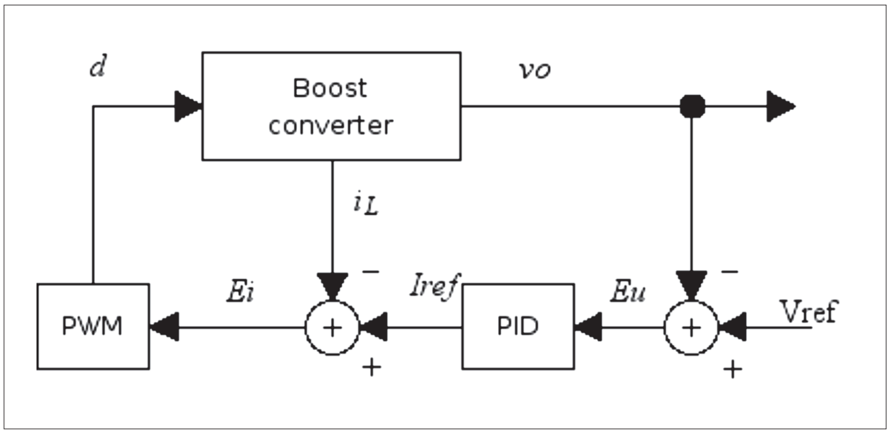

Figure 3. Control system configuration of research target. Two loops control, one in voltage mode and another in current mode are used.

Source: Own source.

The advantage of this scheme is not only its stability. In addition, when owning a reference current, is possible to modify this signal to respond to additional criteria of high speed, as it is the reconstruction of the waveform of input current. The voltage loop (of smaller speed), is in charge essentially of the regulation of the output voltage.

The integral part of the PID helps to eliminate the error and improves the speed of the answer, nevertheless, the presence of this also entails to the appearance of problems during the starting transitory, since this will prevent the change of sign in the control surface. In addition, the selection of the parameters the feedback loop becomes difficult, since if it looks for a robust system, will also be finished with one slow one in the answer in variations in the load. It is here where the design supports in the GA (Meng and Song, 2007).

A lot of methods about PID controller parameter tuning have been proposed, and most of them are based on:

- Empirical methods, such as Ziegler-Nichols methods.
- Analytical methods, for instance, the root locus based techniques.
- Methods based on optimization, such as Ciancone or López methods.

Nevertheless, the parameters tuning of PID controller is the combination and optimization of muti-variables; simple genetic algorithm could solve the shortcoming of current methods of parameters tuning (Yao and Sethaves, 1994), which can only satisfy single requirement of system.

GENETIC ALGORITHM OPERATION

Artificial intelligence techniques have come to be the most widely used tool for solving many optimization problems. GA is a relatively new approach of optimun searching (Mitchell, 1999), becoming increasingly popular in science and engineering disciplines.

GA inherits its ideas from evolution of the nature. Even a simple GA algorithm appears to be robust, and the complexity of algorithm and result of GA is irrelevant to the length of genetic string and the original state of population. GA is so simple that it only involves some selection, crossover and mutation operations, but it is so efficient that it can find a nearly optimum solution even for a large scale problem (Mitchell, 1999).

In this case, a random population of 20 real numbers double precision chromosomes is created, representing the solution space for the PID controller (K_P, K_I and K_D codified like the genes of the chromosomes, in the range 0 to 1). Each member of this random population represents a different possible solution for de GA.

The GA proceeds to find the optimal solution through several generations, the reproduction use crossover fraction of 0,6 with 2 elite count, the mutation function is adaptive feasible, and the crossover function is scattered. The objective function to minimize equation (5) was constructed using parameters of the response to step of the system, considering the magnitudes of the variables.

$$f\left(Tr, Ess, Ts, Mpu, I_{\max}\right) = 100\times Tr + Ess + 100\times Ts + Mpu + I_{\max} \quad (5)$$

Where:

- Tr = Rise time [s].
- Ess = Steady-state error [V].
- Ts = Settling Time [s].
- Mpu = Overshoot [V].
- I_{max} = Current maximum in the inductor [A].

DESIGN AND SIMULATION

For the design of the control, we development in MatLab the function to optimize (equation 5) by the GA, being calculated each 40 us the corresponding values of Tr, Ess, Ts, Mpu and I_{max}. For this, average model of the converter in equation (1) was used, calculating the values of the current in the inductor and the output voltage whenever the value of the duty cycle is updated. With the output voltage the error of voltage is calculates in each interval as equation (6).

$$E_U = \frac{V_{ref} - v_0}{V_{ref}} \quad (6)$$

This voltage error is injected to PID block to determine the value of the reference current, which is compared with the current calculated in the inductor to determine the new value of the duty cycle. The initial values equal takings to zero. This calculation is realized for all the individuals of the population of GA algorithm. Figure 4 shows the convergence of GA algorithm.

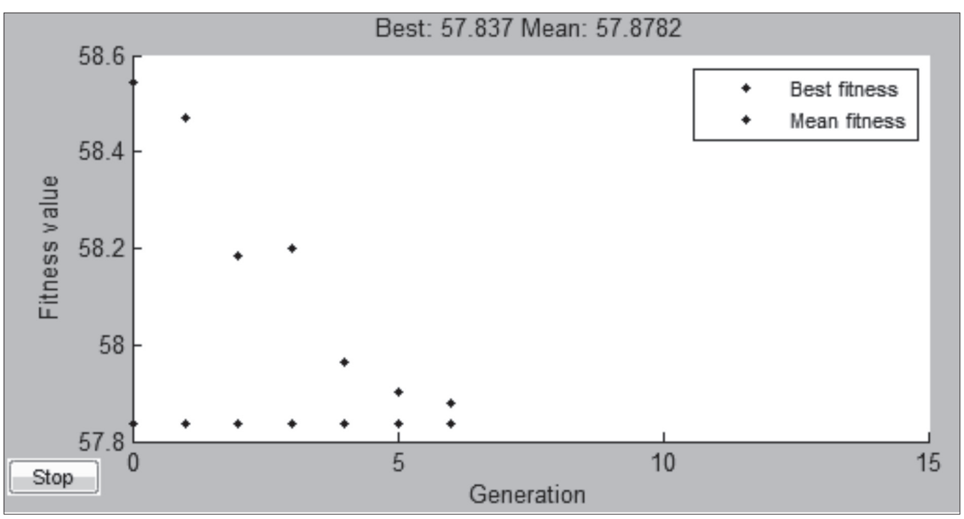

Figure 4. Convergence of the GA algorithm (one hour and 55 minutes of simulation in a AMD Athlon 64 3200+).

Source: Own source.

The values determined by GA algorithm were: K_P = 0.98, K_I = 0,51 and K_D = 0. With these values, a simulation of the transitory answer was realized in closed loop using the average model of the boost converter, the results are in figure 5.

In the simulation, it is possible to be observed as the starting current is limited to less than 25 A, and that the control places to the system in its equilibrium point in 100 ms.

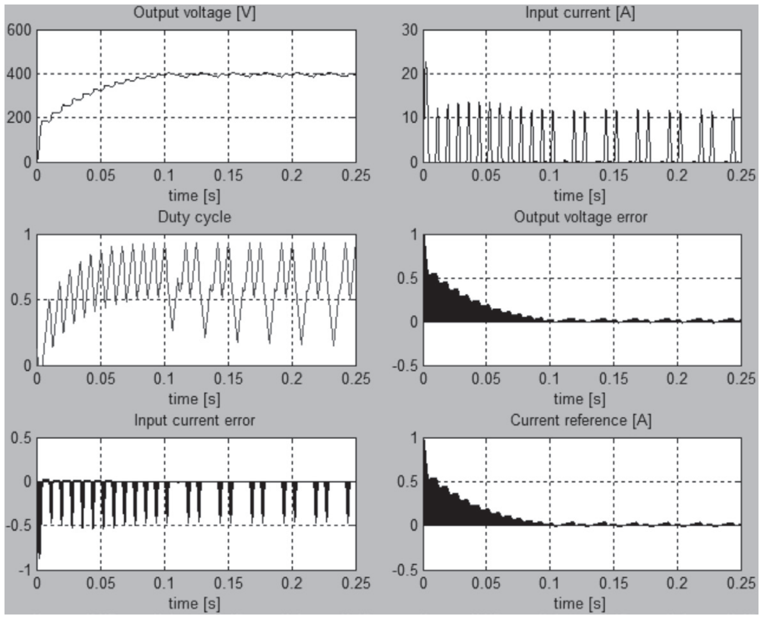

Figure 5. Step response of boost converter (simulation closed loop). Starting current smaller to 25 A.

Source: Own source.

Nevertheless, in the scheme not yet it is had including the PFC action for the input current. In order to reconstruct the waveform sine, the current of reference by the waveform of the rectified input voltage is due to multiply, of such form that the value average of the new current of reference stays, but its instantaneous value changes to behave like the rectified input voltage.

Therefore, the scheme of proposed control requires taking samples from three signals of the converter: current in the inductor (i_L), output voltage (v_0) and rectified input voltage. That is to say, the two state variables and the sine reference input.

EXPERIMENTAL RESULTS

The control scheme was evaluated in laboratory on a prototype of 200 W, 400 V. The control sequence was programmed on a microcontroller PSoC CY8C29566 of Cypress.

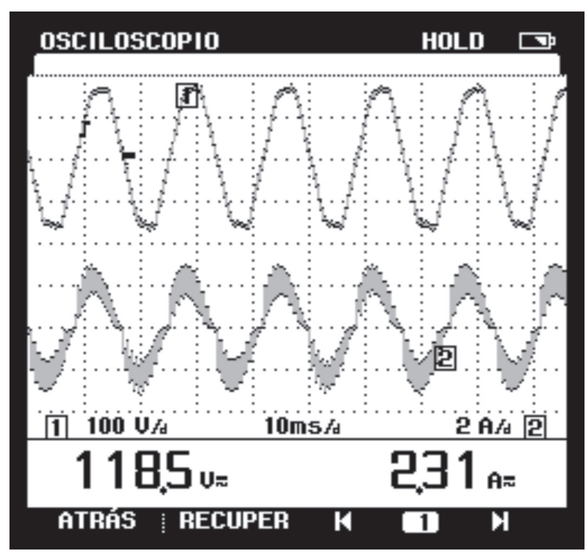

Figure 6. Input voltage and current in prototype with scheme of control in closed loop (THD = 18,32%).

Source: Own source.

The system demonstrated an excellent regulation of voltage (within the 1.4% of the nominal value) without overshoot as it was expected of the design. In relation to the PFC, for an effective input current of 2,31 A, a real THD of 18,32% was obtained (figure 6), improving schemes of direct fuzzy control on the same converter (THD = 21,1%) [10]. The maximum value of the input current was limited to 25,5 A, and was observed a approximate settling time of 90 ms.

CONCLUSION

In this paper we proposed a new hybrid algorithm for the regulation of voltage of the boost converter, and the active correction of the power factor. The algorithm integrates the main features of the current mode control (dynamic response, stability and PFC), and the reliability and design of PID controls.

As alternative of optimal adjustment of the parameters of loop PID, considering the problem of combination and optimization of muti-variables, intends to use a genetic algorithm whose objective function is evaluated on the parameters of the answer of the model calculated from the average model of the boost converter.

The scheme of control proposed was evaluated successful by simulation and on a laboratory prototype of 200 W, having demonstrated its viability and high performance in terms of output voltage regulation and PFC.

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