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On the enhancement of DC-DC converters nonlinear behaviors

***Abstract**. Power electronics circuits are rich in nonlinear dynamics. They are characterized by cyclic switching between a finite number of the circuit topologies, which gives rise to a variety of nonlinear behaviors. This paper gives an overview on some chaotic dynamics and bifurcation scenarios that complicate and even make impossible the analysis and the control of such processes. Then a solution, based on optimized PI, is proposed to suppress the occurring nonlinear phenomena in a DC-DC converter.*

***Streszczenie.** W artykule zaprezentowano różne scenariusze zakłóceń dynamicznych przekształtników DC-DC. Przedstawiono metody korekcji tych nieliniowych zjawisk dynamicznych. (**Poprawa właściwości dynamicznych przekształtników DC-DC**)*

Keywords: Power converters, PI controller, PSO Method, Bifurcation-Chaos.
Słowa kluczowe: przekształtniki DC-DC, nieliniowe właściwości dynamiczne

Introduction

The DC-DC converters are electronic systems that allow the electric energy conversion by the commutation between the circuit configurations. They are characterized by a continuous dynamics in each configuration with a mechanism for jumping from configuration to another.

To ensure the desired performance, the DC-DC converters can be voltage or current controlled and there is two conduction modes to take into consideration, the discontinuous conduction mode (DCM) and the continuous conduction one (CCM). The DCM is preferred for use in power factor correction (PFC) schemes to obtain a maximum of energy conversion ratio and CCM is used, generally, in regulation schemes. Indeed, in CCM the system analysis is easier and some features appear only in this conduction mode [1, 2].

Controllers, based on linear systems theory, can be used to achieve some results in low frequency scale and offer advantages like the easy and low cost implementation. Nevertheless, the linear controllers can't deal with the exhibited nonlinear phenomena by the converter in high scale frequencies and can't guarantee any more the system stability in this scale. To solve this problem, many solutions are proposed in the literature [3, 4, 5, 6]. The most part of these approaches stabilize the system only in restrict neighborhood of the considered operating. Hence, the control performances are ensured only in this small neighborhood. Indeed, perturbations can drive the system away from the operating point and thus affect the whole system performances and even destroy the system stability. Furthermore, the main objective of these approaches is the system orbit stabilization and they ignore the other performances.

To alleviate these drawbacks, solutions are proposed in [7, 8, 9, 10,11], among which we can mention the use of fuzzy logic and LMI method [7] to stabilize the system and to ensure the desired performances. In [12] a fuzzy PID is proposed with parameters determined by identification with of a well tuned classical PID.

However, the use of fuzzy logic with or without LMI complicates the control scheme and needs an important calculation time and large memory space.

In this context and to deal with the aforementioned problems, we propose in this paper, a new and enhanced version of the PI compensation technique. This last is optimized using the Particle Swarm Optimization (PSO) method, to enhance the DC-DC converters behavior and to eliminate the undesired nonlinear phenomena that complicate the converter behavior and makes its forecasting difficult and even impossible. A boost converter is considered as example, in this study, and its model is given. The PSO method is described; then simulation results are presented, to validate the proposed approach and to show its performances in term of current regulation, desired period-one region widening and nonlinear phenomena suppressing in the cases of varying reference current, input voltage and load.

Converter model

We use the boost converter, given in figure 1, as example and we choose the CCM as functioning mode. The current mode of control is considered to explore the most part of nonlinear phenomena exhibited by this converter [1].

The system parameters are r_L, r_{SW}, r_{VD} and r_C which denote respectively the resistors of inductor L, switch sw, diode VD and capacitor C. R is the load, V_g the supply voltage, u_o the output voltage and i_L the input current.

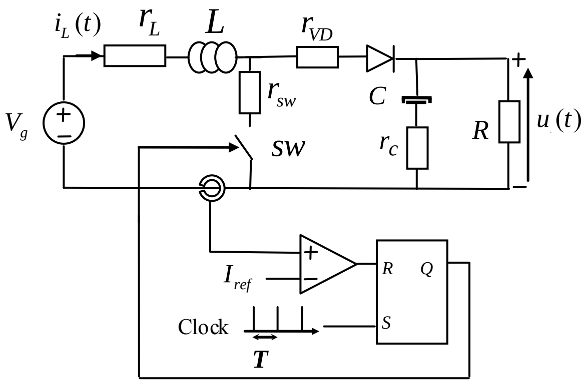


Fig.1. Boost converter under current mode (simplified version)

The Boost converter is operating in continues conduction mode when the inductor current never drops to zero ($i_L(t) > 0$), in this case we have two configurations related to the switch sw position (Fig. 2). In each configuration, the system is given by a set of continuous differential equations. The switching from the first configuration to the second is related to the reference reaching. Then a clock pulse returns back the converter to its first configuration.

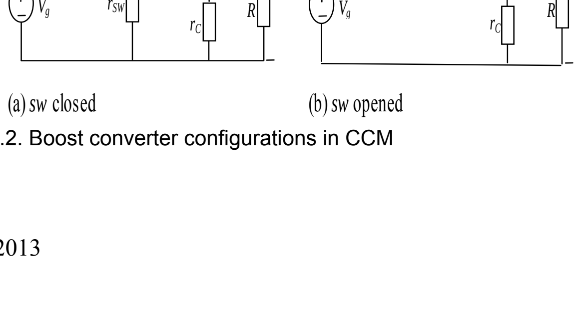


Fig.2. Boost converter configurations in CCM

The switch sw is closed initially in each switching period (Fig. 2a.) which allows the increase of current i_L until reaching the reference I_{ref}. Then the comparator and the RS latch open the switch sw (Fig. 2b.), enabling the inductor discharging and the capacitor charging until the next external clock pulse.

If we denote by T the clock cycle, the system dwells in its first configuration $t_1 = dT$ seconds and $t_2 = d'T = (1-d)T$ seconds in the second configuration. Hence, the duty cycle $d = t_1/T$ is :

(1) $$d(n) = \frac{L}{T(r_L + r_{sw})} \ln\left(\frac{V_{in} - (r_L + r_{sw}) - i_L(n)}{V_{in} - (r_L + r_{sw}) I_{ref}} \right)$$

The system state is presented by:

(2) $$\dot{x}_i = A_i x_i + B_i U$$

Where A_i are the state matrices in each configuration with

$$A_1 = \begin{bmatrix} -\frac{1}{C(R+rc)} & 0 \\ 0 & -\frac{r_L + r_{SW}}{L} \end{bmatrix}, \quad A_2 = \begin{bmatrix} -\frac{1}{C(R+r_C)} & \frac{R}{C(R+r_C)} \\ -\frac{R}{L(R+r_C)} & -\frac{r_L + r_{VD} + \frac{Rr_C}{R+r_C}}{L} \end{bmatrix},$$

(3) $$B_{1,2} = \begin{bmatrix} 0 & \frac{1}{L} \end{bmatrix}^t$$

The state is $x = [v_c i_L]^t$ (v_c voltage across capacitor, i_L inductor current)

The solution of (2) can be expressed by:

(4) $$X_i(t) = e^{A_i(t-t_0)} (X_i(t_0) + A_i^{-1} B_i V_g) - A_i^{-1} B_i V_g$$

The system model is obtained using (4) to describe the converter behavior in each configuration and using the state final value, in actual configuration, as the state initial value for the next configuration and so on until obtaining the system response during the whole time rang.

PSO Method

Particle swarm optimization algorithm was proposed firstly by Dr. Kennedy and Dr. Eberhart in 1995 [13, 14] to simulate the migration and the aggregation of bird flock when they seek for food. Particle swarm optimization (PSO) is a heuristic method and stochastic population-based search approach to find the best particle who gives the optimal solution of the problem [15].

In nowadays, the PSO algorithm gains more and more interest and becomes a main issue in many fields like functions optimization, combination optimization, neural network training, robot path programming, pattern recognition and fuzzy control [17].

In PSO, the position x_i of the i^{th} particle is given by:

(5) $$x_i(j+1) = x_i(j) + v_i(j+1)$$

where v_i represents the particle speed expressed by:

(6) $$v_i(j+1) = wv_i(j) + c_1 rand\{Pbest_i - x_i(t)\} + c_2 rand\{Gbest - x_i(t)\}$$

with w the inertia weight, c_1 and c_2 the acceleration coefficients, $Pbest_i$ the personal best position i and $Gbest$ the best position of the particles in the entire population. Figure 3 shows the typical movement of particles in the optimization process [16].

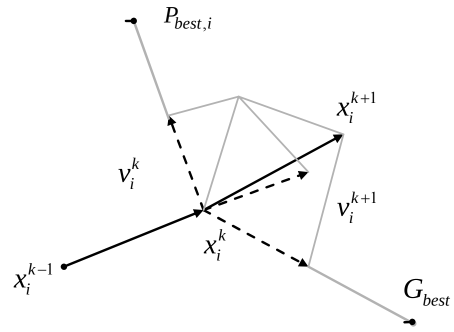


Fig.3. Movement of particles

Application of PSO

In our study we use the PSO method to find optimal values for the PI regulator parameters. The word "optimal" means in our case, obtaining the values of PI parameters that guarantee the minimum error between the reference current and the measured one. For this purpose, let us define the following objective function:

(7) $$f_{obj} = \int_0^{t_f} \left(i_L - I_{ref} \right)^2 dt$$

The scheme of the closed loop system with the PSO method is given by figure 4.

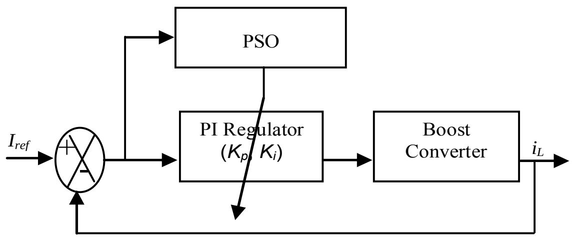


Fig.4. Proposed control scheme

The parameters of the PSO in our algorithm are given in this table:

Table 1. PSO parameters

Number of particles	w	c_1	c_2
100	0.5	2	2

The expression of the optimized PI regulator is given by:

(8) $$d(n) = K_p e(n) + K_i \sum_{i=0}^{n-1} e(i)$$

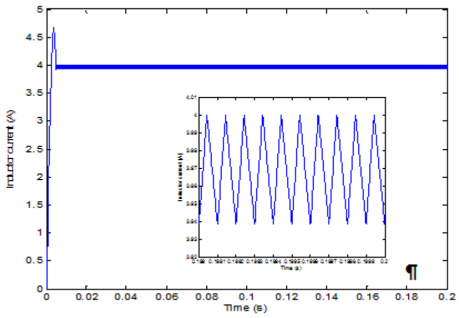
where $e(n) = I_{ref} - i_L(n)$ is the error between the reference current and the measured one , K_p and K_i are respectively the proportional and integral coefficients obtained by the PSO.

In the next section we present the obtained results by the optimized regulator and we compare them with other results from the literature.

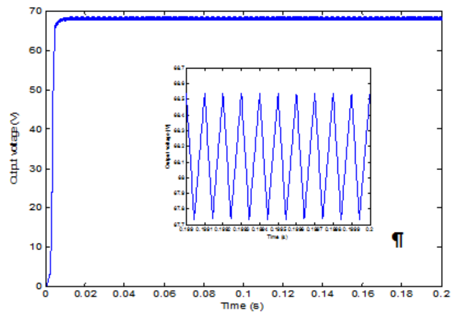
Simulation Results

To illustrate the improvement of the system behavior using the optimized PI regulator and to prove the efficient of our proposition we compare the obtained results with those given in [7]. The parameters of the used Boost converter are: $I_{ref} = 4A$, $V_g = 45\ V$, $L = 27\ mH$, $R = 30\ \Omega$, $C = 120\ \mu F$, $r_l = 1.2\ \Omega$, $r_c = 0.2\ \Omega$, $r_{sw} = 0.3\ \Omega$, $r_{vd} = 0{,}24\ \Omega$ and the switching frequency $f_{sw} = 1/T = 10\ kHz$.. The converter elements values are chosen to satisfy the condition of functioning in CCM: 2L/RT>4/27..

Using the detailed model, the normal (desired) behavior of the boost converter under classical feedback (Fig .1.) is presented in figure 5 for a reference current $I_{ref} = 4A$.

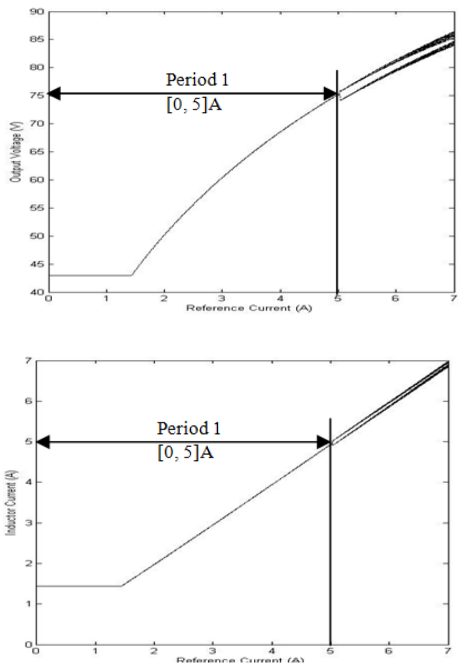


(a) Inductor current

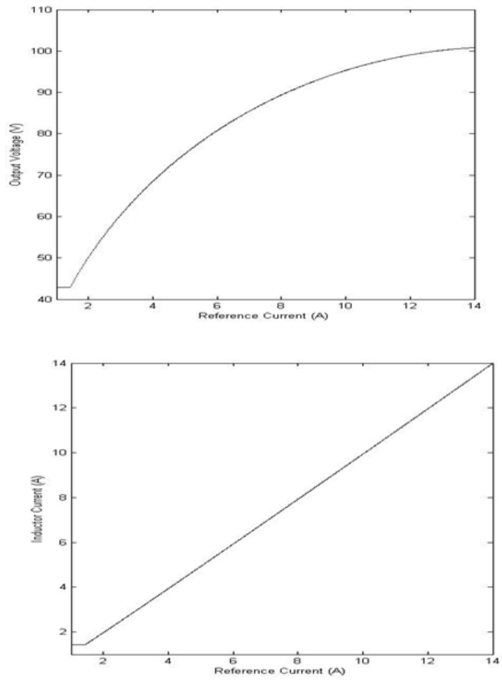


(b) capacitor voltage
Fig.5. Boost converter normal behavior (Period 1)

To obtain a whole overview on the converter behavior, figure 6 represents the bifurcation diagrams (output voltage/inductor current) for different values of the reference current. We remark from figure 6a that the converter exhibits period 1 behavior (desired behavior) in the domain $I_{ref} \in [0,5]\ A$, followed by period 2 and chaos for I_{ref} upper than 5A. Using the optimized regulator, figure 6b shows the total elimination of undesirable phenomena and the period one region widening to $I_{ref} \in [0,14]\ A$.

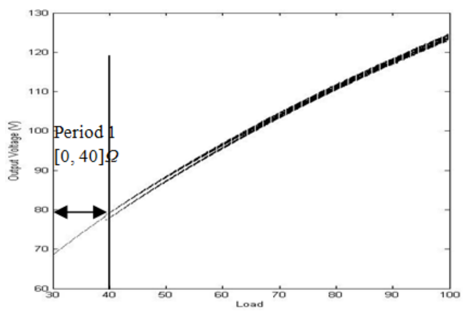


(a) Original behavior

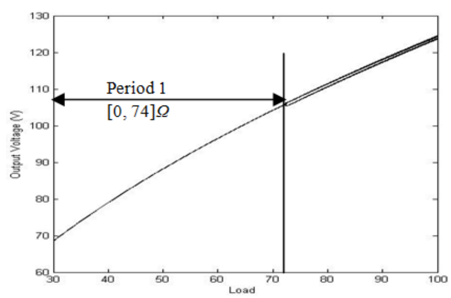


(b) Optimized behavior
Fig.6. Bifurcation diagrams (varying reference current)

Figure 7 shows the bifurcation diagrams according to the load variation. The converter exhibits period 1, in his original behavior, for $R \in [30,40]\ \Omega$, followed by period doubling and chaos phenomena for load values upper than $40\ \Omega$ (Fig .7a). In figure 7b we remark the enhancement introduced by the proposed regulator; indeed we have the desired behavior in a wide domain from $R = 30\ \Omega$ to $R = 74\ \Omega$ with total suppress of up-normal phenomena.

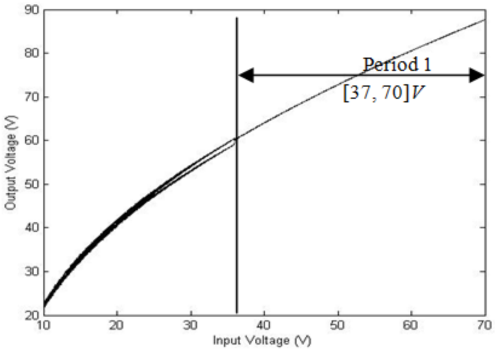


(a) Original behavior

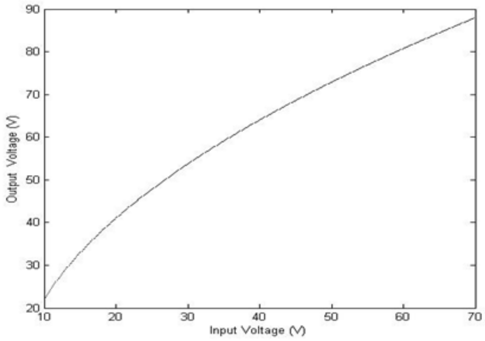


(b) Optimized behavior
Fig.7. Bifurcation diagram (varying load)

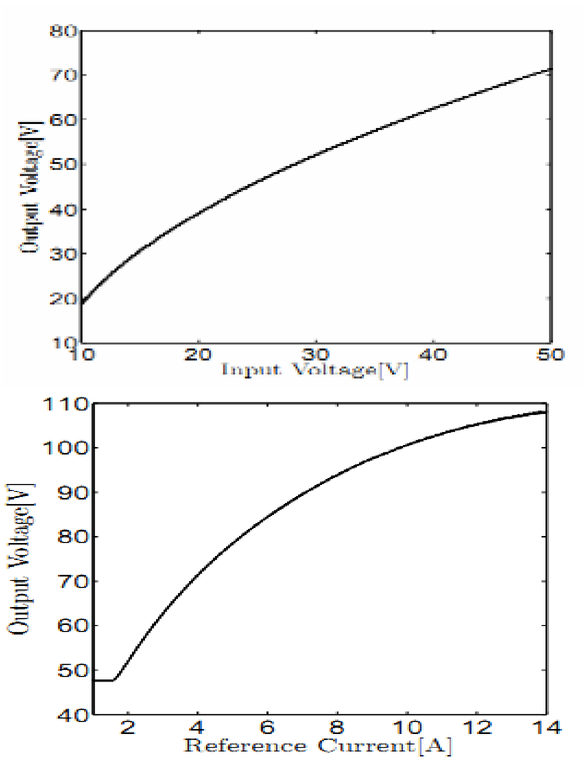
Figure 8 represents the original bifurcation diagrams in the case of supply voltage variation. In figure 8a the converter exhibits a period 2 and chaos behaviors for input voltage in the range [10,37] V , flowed by a period 1 for supply voltage higher than 37V. However, the use of the optimized regulator (Fig. 8b) allows the suppress of the undesirable phenomena and we obtain the period 1 behavior in wider range of operation [10,70] V.



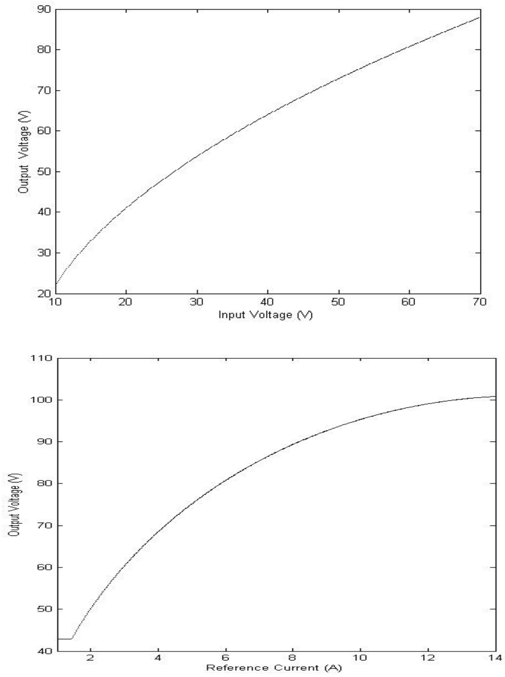
(a) Original behavior



(b) Optimized behavior
Fig.8. Bifurcation diagram (varying supply voltage)



a) Figures captured from [7]



(b) Results with the optimized regulator
Fig.9. Optimized regulator performance evaluation

In order to evaluate the performances of the optimized regulator, we captured some results obtained in [7] by fuzzy logic and LMI (Fig. 9a) and we have our results given in figure 9b. We remark that the proposed approach ensures a better performances and a wider range for period one behavior (when varying the input voltage). In the worst case (when varying the reference current) the proposed regulator ensures the same results than the approach proposed in [7] at the difference that our approach is cheaper, simpler and less consuming in terms of computing time and memory space allocated for data processing and storage.

Conclusion

In this paper, an optimized PI regulator is proposed for a boost converter. We showed that the optimized PI regulator could efficiently achieve the nonlinear phenomena shifting or suppressing from the converter behavior. A comparison between the behavior under the optimized regulator and the original behavior and with the results obtained in a recent work, based on fuzzy logic and LMI, shows the efficiency of our approach to suppress the undesirable nonlinear phenomena and to ensure a wide range of desired behavior. We observed that the proposed regulator ensures, at least, the same performance as fuzzy-LMI controller with less complexity and implementation cost.

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