The Journal of Engineering and Exact Sciences – jCEC, Vol. 09 N. 03 (2023)
journal homepage: https://periodicos.ufv.br/jcec
eISSN: 2527-1075
ISSN: 2446-9416

Shifting of Nonlinear Phenomenon in the Boost converter Using Aquila Optimizer

Article Info:
Article history: Received 2023-02-27 / Accepted 2023-05-16 / Available online 2023-05-16
doi: 10.18540/jcecvl9iss3pp15744-01e

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Abstract

Power electronics circuits are characterized by nonlinear dynamics, because of the cyclic switching between a finite number of topologies, which can give rise to a variety of behaviors. DC/DC converters are prone to nonlinear phenomena, such as bifurcations, quasi-periodic and chaotic responses, which can make it difficult or even impossible to analyze, predict, and control the converter's behavior. This paper offers an examination of the chaotic behavior of the DC/DC boost converter and suggests an optimized PID controller as solution to the nonlinear phenomena. Aquila optimizer AO is employed to determine the ideal parameters for the controller by computing the discrepancy between the reference current and the value of the inductor current, as well as the discrepancy between the inductor current readings during switch openings. The simulation results using MATLAB demonstrate the effectiveness of the proposed solution.

Keywords: boost converter. nonlinear phenomenon. PID controller. Aquila optimizer

1. Introduction

DC/DC converters are widely used for both residential and industrial purposes, ranging from a hundred watts to hundreds of kilowatts. These circuits are composed of several nonlinear elements, such as switches and diodes, and controlled through strategies like pulse width modulation, making them nonlinear and time-varying dynamical systems (Chan *et al.*, 1997). As the parameters of the circuit vary, the converters may cause amplified noise, EMI problems, and nonlinear oscillations - phenomena that have been explored and analyzed in detail since many years. It is amazing to note that even the simplest of systems can produce seemingly random oscillations when their parameters are changed, and even though the starting conditions are familiar, the interactions between them might not be easy to anticipate. This phenomenon is called chaos, and is a prevalent component of real-world systems (Banerjee and Chakrabarty, 1998).

In recent years, analyzing the nonlinear dynamics of power converters has been a widely studied area of research. Many solutions have been proposed to address the aforementioned issues. Authors in references (El Aroudi *et al.*, 1999; El Aroudi *et al.*, 2001; Banerjee *et al.*, 2001; Tse, 2003) delved into the non-linear modeling and intricate dynamics of switch-mode power converters. References (lu *et al.*, 2003; Ghosh, 2012; Ghosh *et al.*, 2013; Ghosh *et al.*, 2014) investigated low-frequency phenomena and fast-scale instabilities in switching converters and their various applications. The authors of (Arjun *et al.*, 2015; Zhioua *et al.*, 2016) discussed their research on modeling, dynamics, bifurcation behavior, and stability analysis of switching converters in renewable energy.

In reference (Yfoulis *et al.*, 2015), a novel approach for the design of a boost converters' feedback control for was proposed that was both stable and robust. This technique involved using bifurcation analysis to examine the bilinear averaged model and then applying constrained stabilization principles. Reference (Singha *et al.*, 2015) used discrete-time models of a boost converter to analytically solve and predict nonlinear behavior in a power converter's digital current mode controlled

Reference (Angulo-Garcia *et al.*, 2018) presented a new method for designing a controller that would guarantee global system stability, built on the principles of the switched systems’ contraction theory.

These works, which involve analytical solutions, can be difficult to implement in actual plants due to their complexity.

In recent studies, fuzzy logic controls have been applied to control chaos. Despite the complexity of the control system and the time-consuming and memory-intensive nature of the calculations, these controllers have had success in a variety of settings (Guesmi *et al.*, 2008; Guesmi *et al.*, 2008; Mehran *et al.*, 2009; Hu *et al.*, 2019; gozim *et al.*, 2018; Ayati *et al.*, 2016; Yuan *et al.*, 2015; Duranay *et al.*, 2018; Behih *et al.*, 2019).

Controllers utilizing metaheuristic algorithms are just as efficacious as fuzzy controllers, however they are less complex and cheaper to implement. (Abderrezek *et al.*, 2017; Fu *et al.*, 2018; Abdelgawed *et al.*, 2016). When using these types of controllers, the Integral Absolute Error (IAE) is often used as a coefficient of adaptation. However, this does not provide an accurate measurement of the quality of each solution during the search.

Research on the removal of nonlinear occurrences in power converters is still an open topic, yet there have been successful conclusions recorded in the literature. This article introduces a method for changing the nonlinear phenomena and increasing of the converters’ stability range, without having to use intricate analysis methods or additional circuitry.

A PID regulator was developed using MATLAB programming and the boost converter’s state-space model to guarantee global stability of the system, as well as the rejection of parameter disturbance as: reference current, load and input voltage.

This design was based on the Aquila Optimizer (AO) which was used to calculate the optimum gains of the controller with the help of the suitable adaptation coefficients (Abdualigah *et al.*, 2021; Zhao *et al.*, 2022).

2. DC-DC boost converter

Figure 1 displays the schematic of a current mode control (CMC) of boost converter. It consists of a MOSFET switch SW, an inductor L, a diode D, a capacitor C and a resistance R as a load. The output of a comparator is used to control the switching pulses of the MOSFET via a driver circuit.

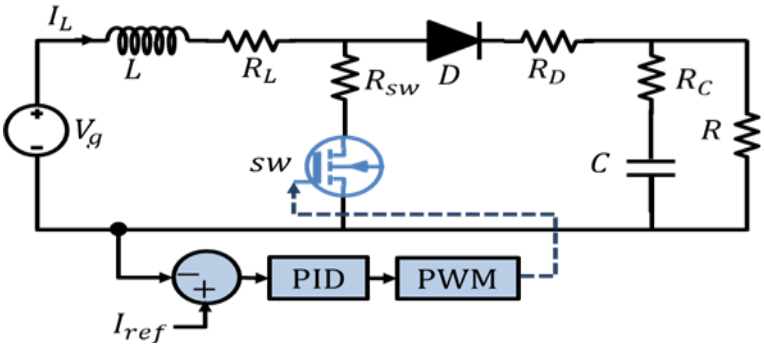

Figure 1 - Boost converter under current mode

In continues conduction mode (CCM), the inductor current never reaches zero as the Boost converter is running. There are two configurations associated with the switch position in this mode. The system state is expressed as:

$$\dot{X} = A_i X + B_i U \tag{1}$$

Where A_i and B_i present the state matrices in the i^{th} configuration

$$A_1 = \begin{bmatrix} -\frac{1}{C(R+rc)} & 0 \\ 0 & -\frac{r_L+r_{SW}}{L} \end{bmatrix} \quad A_2 = \begin{bmatrix} -\frac{1}{C(R+rc)} & \frac{1}{C(R+rc)} \\ -\frac{R}{L(R+R_C)} & -\frac{r_L+r_{VD}+\frac{R_{rc}}{R+r_C}}{L} \end{bmatrix} \quad B_{1,2} = [0\ \tfrac{1}{L}]^t \tag{2}$$

The state is $x = [v_c\, i_L]^t$, with v_c is voltage across capacitor, and i_L is the inductor current. The state can be expressed by:

$$X_i(t) = e^{A_i(t-t_0)}\left(X_i(t_0) + A_i^{-1} B_i \mathrm{V_g}\right) - A_i^{-1} B_i \mathrm{V_g} \tag{3}$$

By using equation (3) to describe the behavior of the converter in each of its configurations, the system model can be obtained. The final value of the state in the current configuration is then taken as the initial value for the next configuration, and this process is repeated until the system response for the entire time range is obtained.

3. Multi-Objective Aquila Optimizer

Aquila Optimizer (AO) is a nature-inspired algorithm inspired from the behavior of the Aquila, a bird of prey commonly found in the Northern Hemisphere. This species belongs to the Accipitridae group and is usually dark brown with a lighter golden-brown plumage on the back of its neck. Young Aquila often display white coloring on the tail and white markings on their wings. The Aquila uses its speed and agility, as well as its strong feet and sharp talons, to capture different prey, such as rabbits, hares, squirrels. (Abdualigah *et al.*, 2021).

Aquila is one of the most observed birds in the world due to its hunting bravery. Male Aquila tend to acquire more prey when hunting alone. It is known that Aquila employ four distinct hunting methods, which can be switched between quickly and intelligently depending on the situation. Similar to population based algorithms, the Aquila Optimization (AO) method begins with a population of candidate solutions (X). Each iteration will attempt to find the optimal solution, referred to as the best solution, with an upper bound and lower bound being established stochastically at the beginning.

The Aquila's behavior during hunting can be simulated by the AO algorithm, which is composed of four steps:

- Step 1: Increased exploration ($X1$). Here, the Aquila scans the surrounding environment from the sky to identify areas of potential prey. It then selects the most promising area for hunting.
- Step 2: Limited exploration ($X2$). Once the prey is located at a high altitude, the Aquila circles in the clouds to get into position for an attack.
- Step 3: Increased exploitation ($X3$). In this step, the Aquila is in a position of exploitation, meaning it is getting closer to the prey and preparing to attack.
- Step 4: Limited exploitation ($X4$). Finally, the Aquila gets close enough to the prey to attack it on the ground. It then walks on the ground and captures the prey at the last location.

Further information regarding the mathematical model of the Aquila optimizer (AO) algorithm can be discovered in the references (Abdualigah *et al.*, 2021; Zhao *et al.*, 2022; Aribowo *et al.*, 2022).

4. AO application

Figure 2 illustrates a closed-loop control system that uses an AO optimizer to minimize the difference between the inductor current and the reference current, as well as the error between the values of peaks of the inductor current. Tuning the parameters of the PID regulator is accomplished through the utilization of an AO optimization approach.

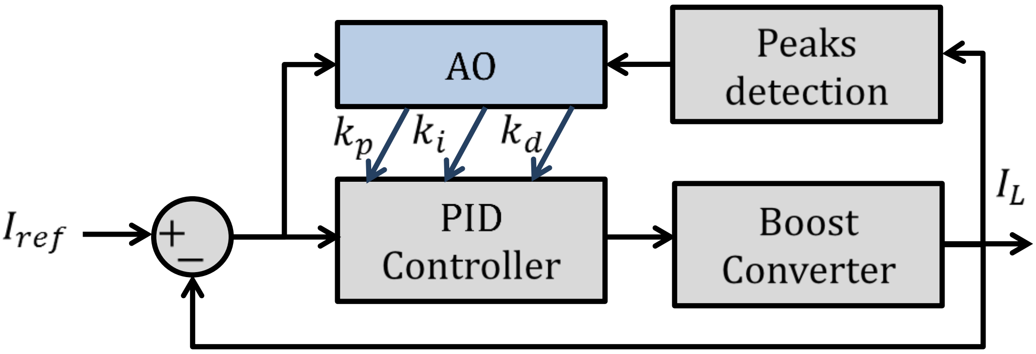

Figure 2 - Closed loop system with AO.

The equation in Equation 4 serves as the objective function for the optimization.

$$F(t) = w_1F_1 + w_2F_2 \tag{4}$$

$$F_1 = \sqrt{\frac{\sum_i^N (P_i - \mu)^2}{N}} \tag{5}$$

$$F_2 = \int_{t_0}^{t_f} |\varepsilon(t)|\, dt \tag{6}$$

Let F_1 and F_2 be two objective functions with weight coefficients w_1 and w_2 for assigning priority to each. N, P_i and μ can be determined from samples of inductor current, which respectively represent the number of current peaks in the sample, the the i^{th} value in the sample, and the mean of the sample.

The algorithm employed for optimization is outlined in the five steps below:

- Step 1: Generating random positions in the search space.
- Step 2: Computing the fitness of each position.
- Step 3: Identifying the fittest position.
- Step 4: Updating the positions of all search agents based on the fittest position.
- Step 5: Returning to Step 2 until the termination criterion is met, which is the final iteration in our case.

In the last iteration the algorithm will return the alpha wolf as the optimum solution for the problem

5. Results and discussion

The nonlinear dynamics of a DC-DC boost converter were explored using phase portraits, time-domain waveforms, and bifurcation diagrams. Bifurcation is a mathematical technique that allows for the investigation of qualitative changes in the system behavior when parameters are varied (input voltage, load, and reference current). The results obtained through phase portraits and time-domain waveforms were used to confirm the findings of the bifurcation diagrams.
The parameters of the used study circuit are presented in Table 1.

Table 1 – The parameters of the proposed circuit.

	Parameter		**Value**
Converter	V_g		24 V
	F		1000 Hz
	$R_{sw} = R_D$		0.23 V
	L		0.027 H
	R_L		1.2 Ω
	C		120 μF
	R_C		0.2 Ω
	R		30 Ω
Optimizer	w_1		1
	w_2		100
	iterations		120
	Nbr		15
Controller	K_p	**Original**	0.1
		Optimized	1.7
	K_i	**Original**	300
		Optimized	87
	K_d	**Original**	0.0000001
		Optimized	0

Figure 3 shows the bifurcation diagrams and phase plan representation (output voltage/inductor current) for different values of the input voltage. It is evident from the figure that when the input voltage Vg is greater than 20V, the converter exhibits periodic behavior. However, when Vg is less than 20V, the converter exhibits sub-harmonic and quasi-periodic oscillations similar to chaos. With the optimized PID controller, the undesirable phenomena are eliminated and the stable periodic behavior is widened in the entire operating region.

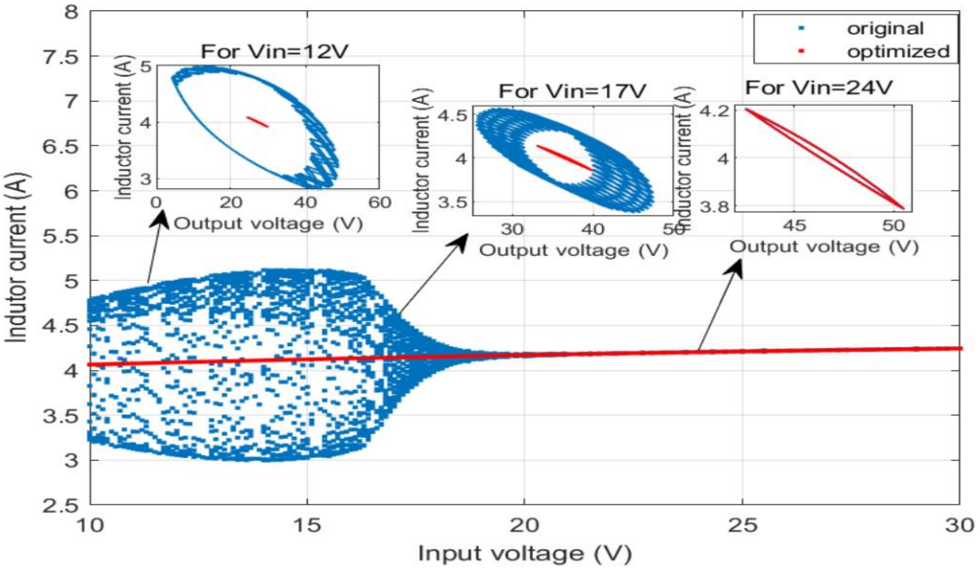

Figure 3 – Bifurcation diagram and phase-plan representation (varying the input voltage).

The figure illustrates the bifurcation diagrams and phase plan representations in response to load variations. It is observed that the converter exhibits periodic behavior when the load is lower than 22 Ω, followed by sub-harmonic and quasi-periodic phenomena when the load is greater than 22 Ω. Furthermore, the proposed regulator has improved the behavior of the converter, allowing for the desired behavior in a wide range, with complete suppression of abnormal phenomena in the operating region.

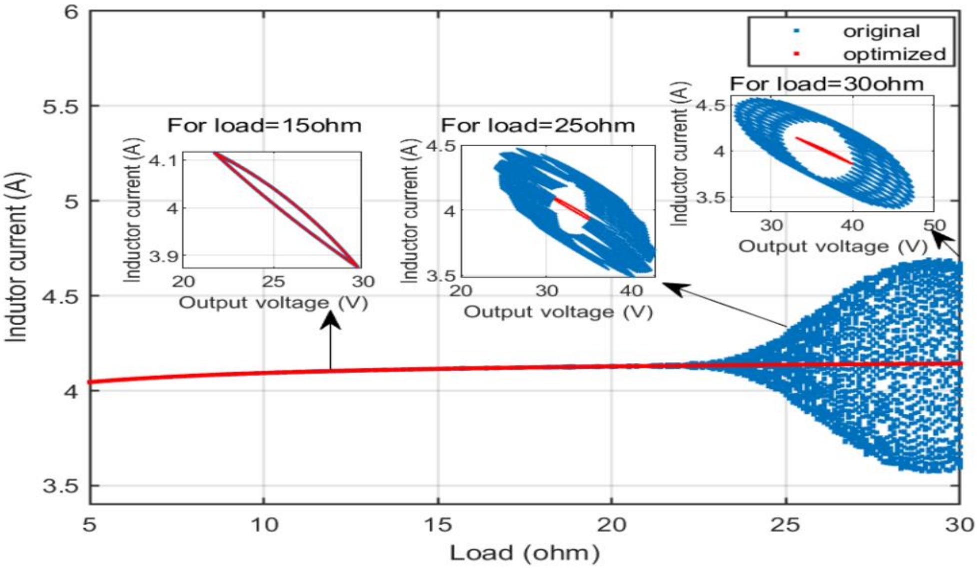

Figure 4 – Bifurcation diagram and phase-plan representation (varying the load)

Figure 5 shows the original and optimized bifurcation diagrams as well as the phase-plane representation for the case of varying reference current. It is seen that the converter exhibits periodic behavior for reference current lower than 5.5A, followed by quasi-periodic and chaotic behavior for reference current higher than 5.5A. However, the use of the optimized regulator suppresses the undesirable phenomena and a periodic behavior is obtained in a wider range of operation.

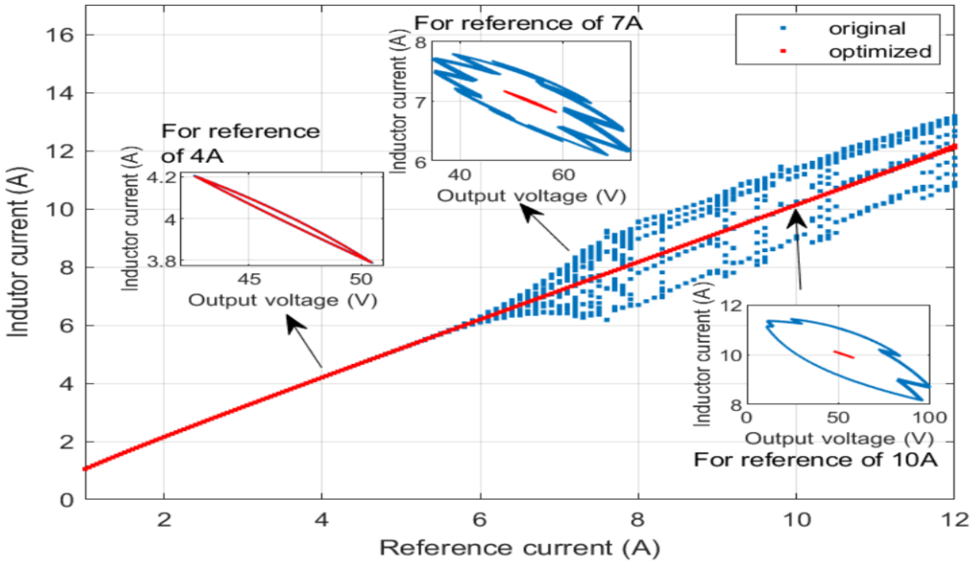

Figure 5 – Bifurcation diagram and phase-plan representation (varying the reference current).

Various tests were conducted to determine the performance of the optimized controller under different disturbances, including load, input voltage and reference current. Perturbations were introduced at different points to evaluate the controller's ability to handle these disturbances. The results of these tests provided a more accurate understanding of the controller's effectiveness.

The time response of the boost converter to a perturbation in load is presented in Figure 6. After the system attained its steady state, the load was abruptly changed from 15Ω to 25Ω at t=1 s. As observed in the time response, the converter remained stable and exhibited a periodic behavior. The perturbation caused some oscillations and chaotic behavior, but the system eventually returned to its equilibrium point. At t=1.5s, the load was increased from 25Ω to 30Ω. This change had no effect on the system's behavior when using the optimized controller, demonstrating its effectiveness in rejecting perturbations in the load. In contrast, the use of the original regulator caused the system to become increasingly chaotic as the load increased.

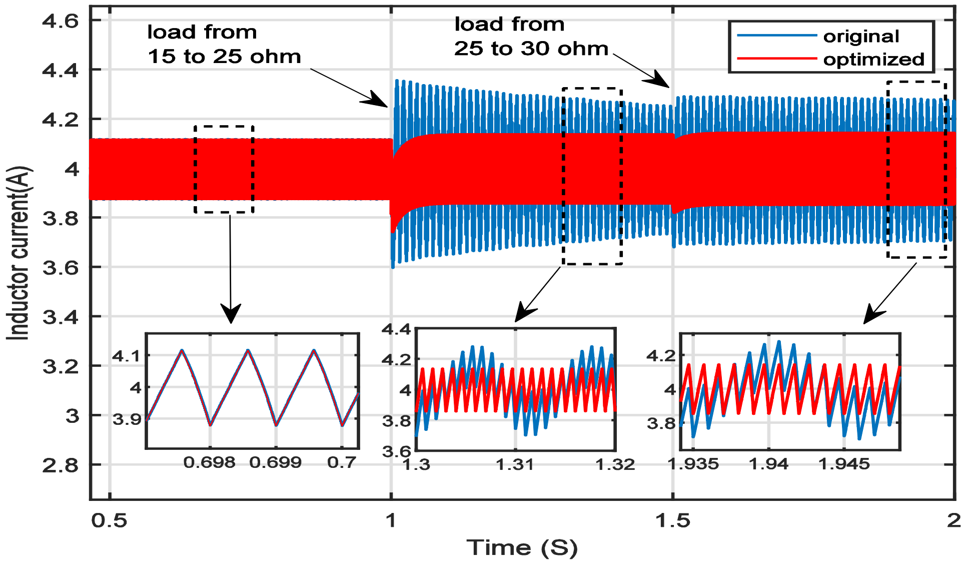

Figure 6 – Time response of the inductor current for a disturbance in the load

In Figure 7, it is shown how the time response of the converter to disturbances in reference current is affected by the use of an optimized regulator compared to an original regulator. When a perturbation of 2 A (from 4 A to 6 A) was induced in the reference current at t=1 s, the system with the optimized regulator exhibited some oscillations followed by the desired periodic behavior. However, when a sudden change of the reference current (from 6 A to 10 A) was induced at t=1.5 s, the optimized regulator was able to keep the system in a stable periodic behavior, while the original regulator caused the system to display a more chaotic behavior as the reference current increased.

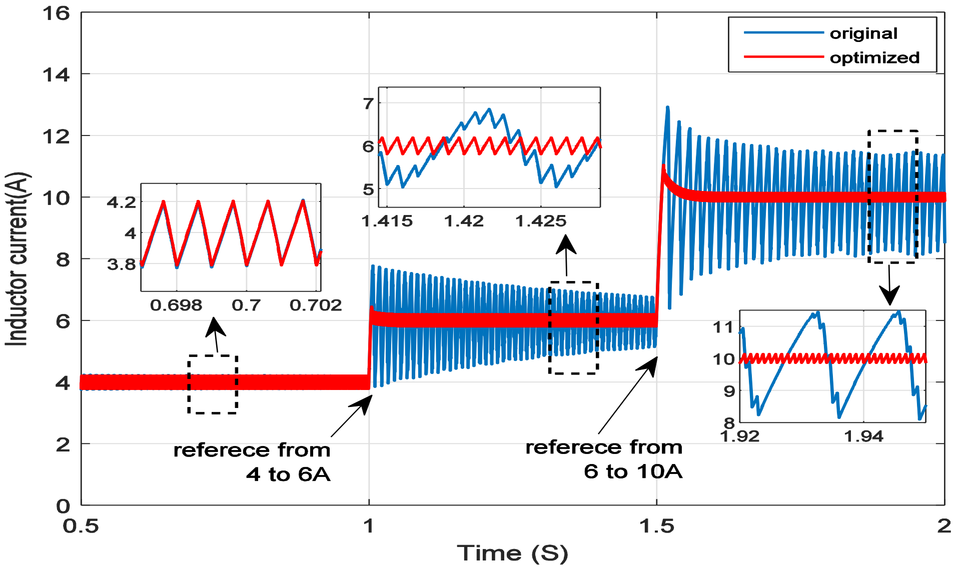

Figure 7 – Time response of the inductor current for a disturbance in the reference current

In Figure 8, the time response of the converter to disturbances in input voltage is depicted. At t=1 s, a perturbation of 8V (from 24 V to 17 V) was applied to the input voltage, followed by a sudden change at t=1.5s (from 17 V to 12V). The optimized regulator was able to keep the system in a stable periodic behavior, while the original regulator caused the system behavior to become more chaotic as the reference current increased.

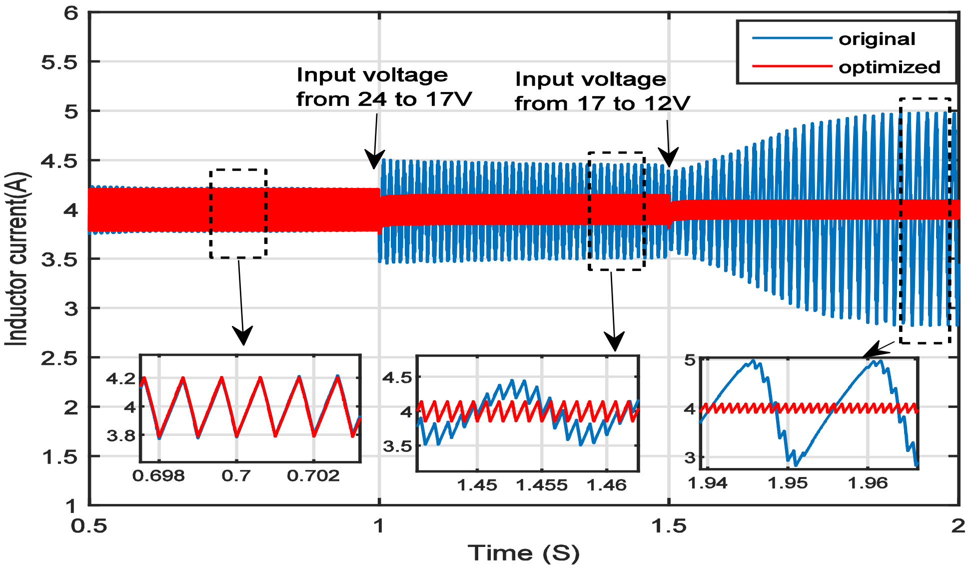

Figure 8 – Time response of the inductor current for a disturbance in the input voltage

6. Conclusion

This research paper is focused on PID controller gain tuning for current controlled DC-DC boost converters. The optimization process is designed to provide the most robust closed loop system possible. The effectiveness of the gains obtained through optimization is tested by the objective function, which is calculated by taking the difference between the reference current and the inductor current, as well as the difference between the peaks of the inductor current values. The optimization problem was solved with the help of Aquila optimizer.

To assess the controller's efficacy in moving nonlinear phenomena, we compared the diagram‘s bifurcation generated with the optimized controller to one found in the literature. Furthermore, we examined the controller's ability to reject disturbances in the converter parameters. The results demonstrate that the proposed resolution is highly efficient in shifting nonlinear phenomena and extends the range of the stable period 1 behavior. Additionally, the control circuit is straightforward and low-cost to implement without requiring extra circuits.

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