Improvement of Buck Converter Performance Using Artificial Bee Colony Optimized-PID Controller

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***Abstract*—In this study, Artificial Bee Colony (ABC) algorithm is proposed to determine gain parameters of the PID algorithm for controlling a designed buck converter. Study aims to improve the performance of buck converter via ABC-PID. Genetic Algorithm (GA) based PID is used also to control the converter in order to investigate the performance of the proposed algorithm on the system. Experiments with different cases are done via simulations. In the simulations, settling time, steady-state error and readjustment time of output voltage in cases of load variation are analyzed in order to determine the performance of the proposed algorithm. Results obtained from simulations are shows that ABC-PID controlled converter has superior performance than GA-PID controlled buck converter.**

***Index Terms*—artificial bee colony algorithm, PID, buck converter**

I. Introduction

Dc-dc converters are widely used power electronics components in industrial area like switching mode power supply (SMPS), personal computer, dc motor drives, etc. The input of the dc-dc converters is unregulated dc voltage obtained by the rectifying line-voltage and a converter converts this input into a regulated dc output voltage at a desired level. Buck converter is used to decrease the output voltage level in proportion to input and so it is called or known as step-down converter also. Since dc-dc converters have power devices, effect of switching and passive components like inductors and capacitors, they are non-linear systems [1], [2]. Therefore, control methods used to control the converters directly affect the performance of the converter.

Various control methods have used to control the output voltage of dc-dc converters such as pole placement [3], LQR [4], feedback loop [5], state space control [6]. A powerful method to control the converters is PID control. Since it is easy to design and implementation to a system, most of the time chosen by practitioners. However, choosing of PID gain parameters is hard because of dc-dc converters contains parasitic components and changes in input voltage and output load by the time [7]. Therefore, PID gain parameters must be designed effectively by using strong methods in order to obtain a robust transient response. First time, various classical methods [8], [9] or Ziegler-Nichols (ZN) [10] are used to perform this operation. These classical methods have some disadvantages such as the necessity of complex mathematical computation, producing huge overshoot and unsatisfactory phase and gain margins.

In recent years, artificial intelligence and optimization techniques have been used frequently in designing of PID depending on development of these methods. Algorithms like Fuzzy Logic (FL) [11], [12], Particle Swarm Optimization (PSO) [13], [14], Bacterial Foraging Optimization (BFO) [15], [16] or Genetic Algorithm (GA) [17], [18] have been implemented to determining the PID gain parameters successfully. However, they have had inadequate in some solution process due to reasons like difficulty of creating fuzzy rules in fuzzy logic, premature convergence or long computing time.

Artificial Bee Colony (ABC) which was proposed by Karaboğa [19] has a simple structure, less control parameters and gives strong solutions for different fitness functions when compared to other optimization algorithms like GA and PSO [20]. Therefore, in this study, ABC is used to determine the PID gain parameters for controlling the Buck Converter. The performances of the controller optimized by ABC are compared in simulation in accordance with overshoot, undershoot, rise time, settling time, and steady state error. Results obtained from ABC are compared the GA in order to evaluate the performance of proposed algorithm.

The rest of the paper organized as follows. In Section 2, the mathematical model of the buck converter is presented. In Section 3, ABC-PID control schema of the converter is expressed. Experimental results are given in Section 4, and Section 5 contains conclusion of the study.

II. Mathematical Model of the Buck Converter

As the simplest form of a SMPS circuit, a Buck Converter converts the unregulated input voltage into

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regulated output voltage which is lower level than input. A basic Buck Converter model is shown In Fig. 1. A buck converter contains a switch, a diode, an inductor, a capacitor and a load resistance. According to Fig. 1, the switch (S) choppers the input voltage at high frequency and converts the input voltage with constant amplitude to rectangular waveform. Then average DC output voltage V_o is obtained from this rectangular waveform by passing through low-pass filter formed from inductor and capacitor. The turning-on time of the switch *(t_{on})* during one switching period *(T_s)* is called duty ratio *(D)* and V_o is controlling by changing D. These formulations are illustrated in Eq. 1.

A buck converter circuit has two operating mode according to cases of the switch. In first mode, when the switch is on, the input source provides energy to the L, C and R and the input current passing through these components.

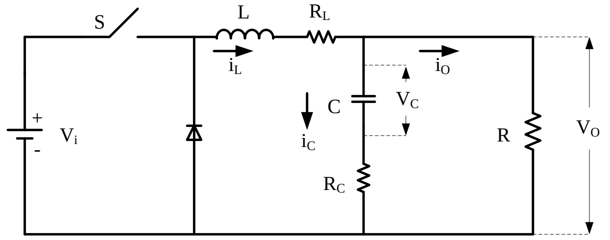


Figure 1. The equivalent circuit of the buck converter

$$D = \frac{t_{on}}{T_s} \text{ and } V_o = D \times V_i \tag{1}$$

The inductor current is equal to the input current and shows an increasing tendency. In second mode, when the switch is off, the inductor provides the own energy stored at previous mode to the L, C and R and the inductor current passing through these components. The inductor current shows a decreasing tendency at this mode. Mathematical model of the buck converter can be defined as follows according to both modes.

When the switch is on:

$$\frac{di_L}{dt} = \frac{V_i}{L} - i_L \frac{1}{L}\left(R_L + \frac{R \times R_C}{R + R_C}\right) - v_C \frac{1}{L}\left(1 - \frac{R_C}{R + R_C}\right) \tag{2}$$

$$\frac{dv_C}{dt} = i_L \frac{1}{C}\left(\frac{R}{R + R_C}\right) - v_C \frac{1}{C}\left(\frac{1}{R + R_C}\right) \tag{3}$$

When the switch is off:

$$\frac{di_L}{dt} = -i_L \frac{1}{L}\left(R_L + \frac{R \times R_C}{R + R_C}\right) - v_C \frac{1}{L}\left(1 - \frac{R_C}{R + R_C}\right) \tag{4}$$

$$\frac{dv_C}{dt} = i_L \frac{1}{C}\left(\frac{R}{R + R_C}\right) - v_C \frac{1}{C}\left(\frac{1}{R + R_C}\right) \tag{5}$$

where V_i is the input voltage, R_L is the inductor resistance, R_c is the capacitor resistance, i_L is the inductor current, v_c is the capacitor voltage, L is the inductor, C is the capacitor and R is the load resistance.

III. ABC-PID Based Control of the Buck Converter

The output voltage of the buck converter can be kept at a stable value by using the PID controller structure. A basic diagram of PID control model for buck converter is shown in Fig. 2. Difference between the output voltage of the converter and a desired voltage value are known as error (in Eq. 6) and it is input of the PID controller. Controller computes a control variable value (PID output, in Eq. 7) by using its gain parameters and error value and this control variable value feds the Pulse Width Modulation (PWM) generator. PWM generator produces the switching signal for switch located on the converter by comparing the PID output and a saw-tooth waveform. This process can be modeled mathematically as described in Eq. 6 and Eq. 7.

$$e(t) = V_{ref} - V_o(t) \tag{6}$$

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \tag{7}$$

where *e(t)* is the error, V_{ref} is the reference voltage, $V_o(t)$ is the converter output voltage, K_p is the proportional parameter, K_i is the integral parameter, K_d is the derivative parameter and *u(t)* is the output (control variable) of the PID controller .

In the PID control, K_p effects the rise time, K_i reduce the steady state error and K_d is used to reduce the overshoot and improve the stability.[14, 15].These controller parameters are defined optimally in the control system to make the system stability and obtain an effective or robust transient response. As can be seen from Fig. 2, in this study, ABC algorithm is used to define the PID parameters optimally. This optimization process is explained below.

A. Application of Artificial Bee Colony Algorithm to Optimize the PID Controller

ABC is a robust optimization method proposed by Karaboğa [19] inspiring by foraging behavior of honey bees. In the ABC, algorithm artificial bees which are employed, onlooker and scout search the food source which has the highest nectar amount by modifying the food positions by time. In the ABC, while a possible solution of the problem corresponds to position of a food source, fitness of the association solution corresponds to nectar amount of this source. ABC algorithm works at 10 steps described below [21].

TABLE I. LIMITS OF THE PID PARAMETERS

PID controller parameters	Range	
	Minimum	Maximum
Kp	0	200
Ki	0	10
Kd	0	0.01

Step1: Input data

Limits of PID parameters are read at this step. In this study used limits belong to PID parameters are given in Table I.

Step 2: Initialization

ABC parameters like colony dimension, maximum cycle number, number of variables and limit parameter are initialized.

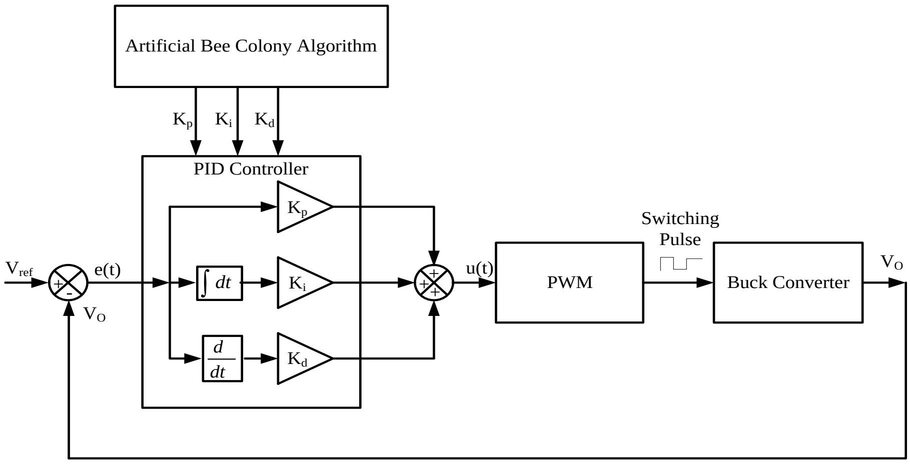


Figure 2. ABC-PID control model the buck converter

Step 3: Initialization of population

A set of initial population with N solutions *xi* *(i=1,2,…N)* is produced randomly and their fitness are determined. Here each solution of *xi* represented by *D*-dimensional vector corresponded to number of PID parameters optimized.

Step 4: Fitness evaluation of the population

Fitness values obtained from the fitness function belong to each solution is evaluated at this step. The fitness function used in this study is described as follows.

$$fit_i = \sum_{t=1}^{k} e^2(t) \tag{8}$$

where e(t) is the error value described in Eq. 6 and k is the maximum iteration number in simulation of operating buck converter for determined PID parameters at one cycle of ABC algorithm.

Step 5: Set the cycle counter to 1

Step 6: Modification of food source positions (solutions)

Food sources are modified and replaced by a new one via employed bees. Then the nectar amounts of the new sources are tested. If the nectar amount of the new source is better than old one, the new food source are kept the memory, otherwise it discards. This modification process of food sources are described as follows.

$$v_{ij} = x_{ij} + \beta_{ij}\left(x_{ij} - x_{kj}\right) \;\; k \in (1,2,...,N) \;\; and \;\; j \in (1,2,...,D) \tag{9}$$

where v_{ij} is the new food source position, *k* and *j* are randomly determined indexes, β_{ij} is a number determined randomly interval of [-1,1].

Step 7: Employing of onlookers and calculation of probabilities

Employed bees share the nectar amount and position information of food sources with onlookers waiting at the dance area after completing the search process. Onlooker bees prefer a food source according to a probability value Pi described as follows.

$$P_i = \frac{fit_i}{\sum_{j=1}^{N} fit_j} \tag{10}$$

where fit_i is the fitness value of the *i*-th solution described in Eq. 8 and *N* is the total number of food sources. Then, at this step, onlooker bees modify the food sources given in Eq. 9 and test the nectar amount as in the case of Step 6.

Step 8: Abandoning from the exploited source

At this step, if a food source is not improved further that source is abandoned and it replaced with a new one by scout bees. In the ABC, this process is done according to the "limit" parameter which is predetermined number of cycles for abandoning the food source. Discovering a new food source by a scout is described as follows.

$$x_i^j = x_{\min}^j + rand(0,1) \times \left(x_{\max}^j - x_{\min}^j\right) \tag{11}$$

x^j_{min} and x^j_{max} are minimum and maximum limits of the parameter to be optimized.

Step 9: Memorize the best solution so far

Step 10: Increase the cycle counter

Step 11: Stopping the algorithm

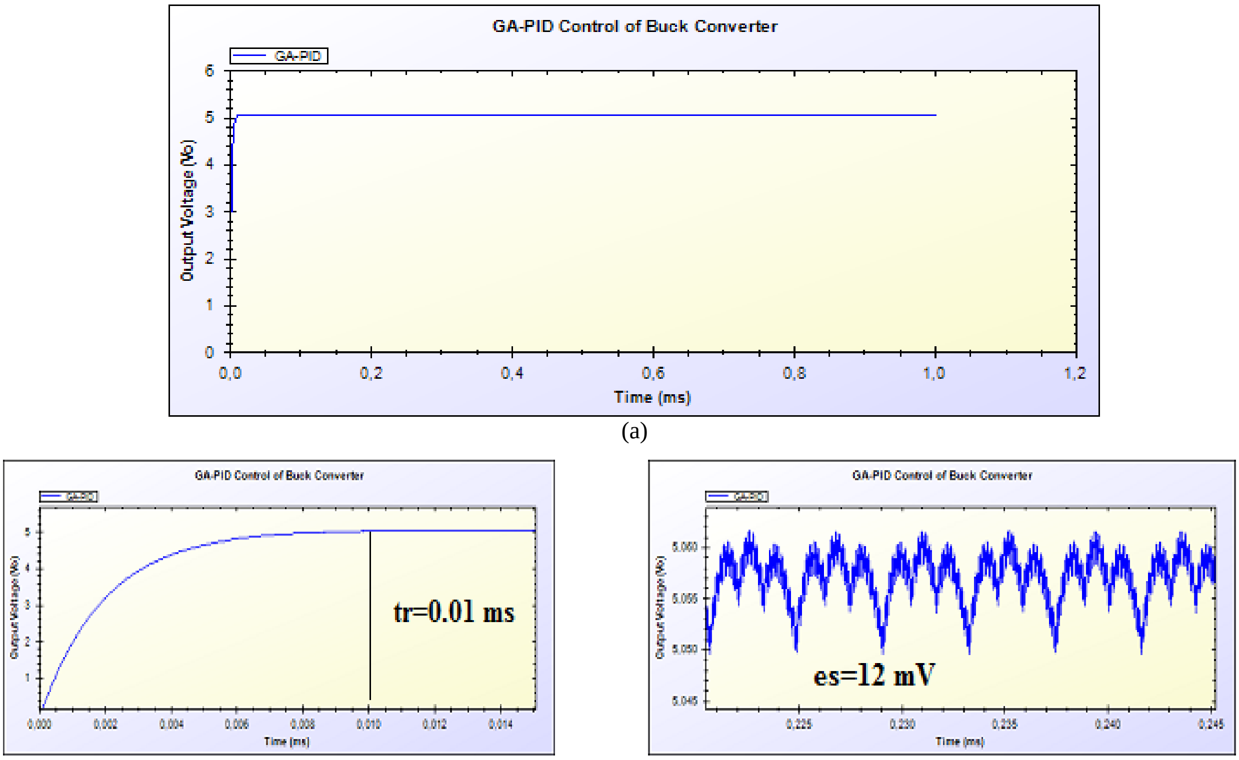
Steps between 6 and 10 are repeated until reach the Maximum Cycle Number (MCN) determined before. Then, the searching process is stopped.

IV. EXPERIMENTAL RESULTS

In this study, control of the buck converter is simulated by using ABC-PID algorithm in order to investigate performance of the proposed algorithm. GA based PID algorithm is also implemented on the same converter and obtained results are compared with GA-PID algorithm to show the effectiveness of the ABC-PID. Simulation of experiments is done via C# language in Visual Studio. Buck converter parameters used in simulation are listed in Table II, ABC parameters used in simulation are given in Table III and PID parameters produced by ABC and GA are given in Table IV.

TABLE II. PARAMETERS OF THE BUCK CONVERTER

Parameter	Value
V_i	12 V
R_L	0.13 Ω
R_C	0.03 Ω
R	2 Ω
L	270 µH
C	1000 µF



(a)

(b)

(c)

Figure 3. Simulation results of the GA-PID controlled buck converter

TABLE III. ABC PARAMETERS

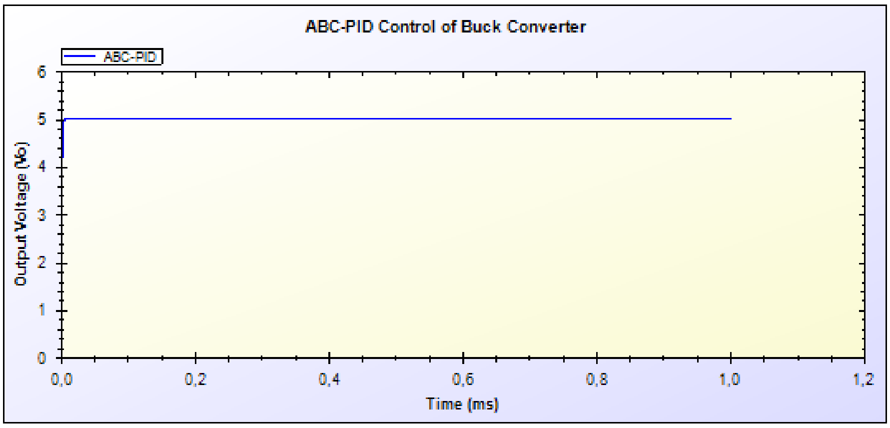
ABC Parameters	Values
Colony dimension	86
Maximum cycle number	5000
Number of variables	3
Limit parameter	0.006

TABLE IV. PID PARAMETERS OBTAINED FROM OPTIMIZATION ALGORITHMS

Algorithms	Gain Parameters		
	P (Proportional)	D (Derivative)	I (Integral)
GA	26	0.055	0.0037
ABC	94	0.097	0.0051

In Fig. 3(a), output waveform of GA-PID controlled buck converter is given. Fig. 3(b) and Fig. 3(c) are zoomed version of Fig. 3(a). The settling time is 0.01 ms as seen in Fig. 3(b) and steady-state error is 12 mV as seen in Fig. 3(c) for GA-PID control. In Fig. 4(a) output waveform of ABC-PID controlled buck converter is given. Fig. 4(b) and Fig. 4(c) are zoomed version of Fig. 4(a) also. The settling time is 0.0045 ms as seen in Fig. 4(b) and steady-state error is 3.9 mV as seen in Fig. 4(c) for ABC-PID control. It is clearly seen that these results ABC-PID algorithm produces more robust results to control the buck converter from the point of settling time and steady-state error.

In the experiment, the load resistor is changed 2 Ω to 10 Ω at 0.5 ms. Fig. 5(a) shows the output waveform of GA-PID controlled converter in this case. Fig. 5(b) is zoomed version of Fig. 5(a). The GA-PID controller regulates the voltage increase with 0.14 V in 0.009 ms for this case. Fig. 6(a) shows the output waveform of ABC-PID controlled converter for the same case.



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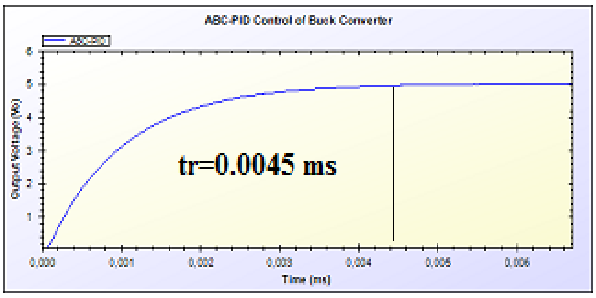

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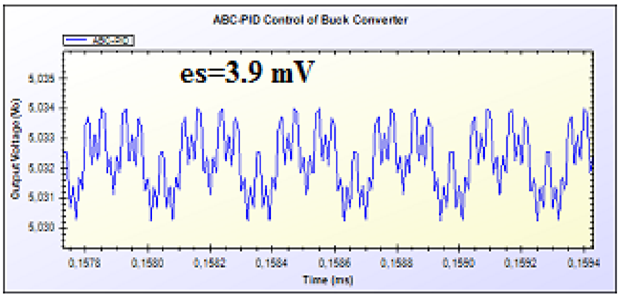
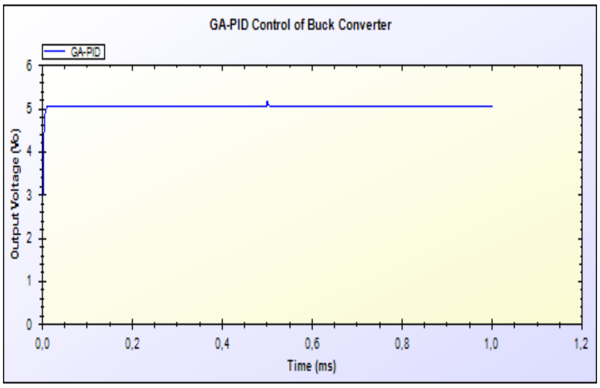
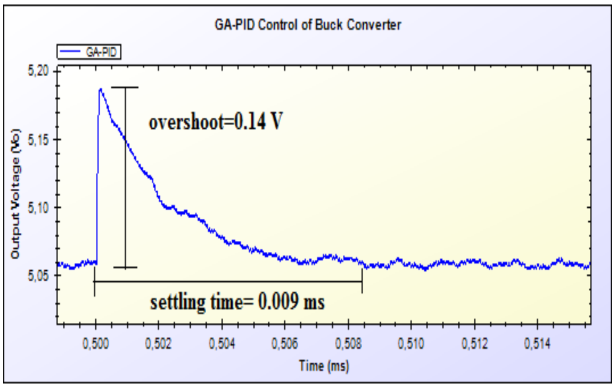


(c)

Figure 4. Simulation results of the ABC-PID controlled buck converter

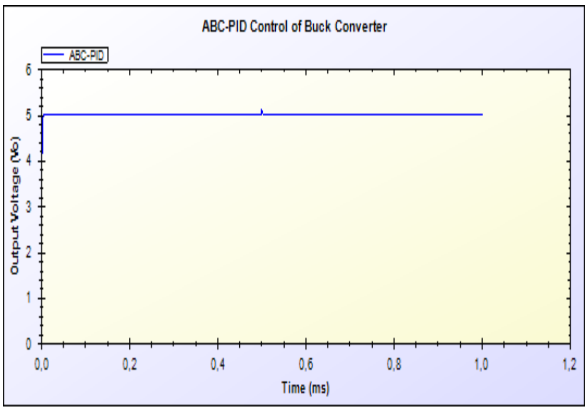


(a)

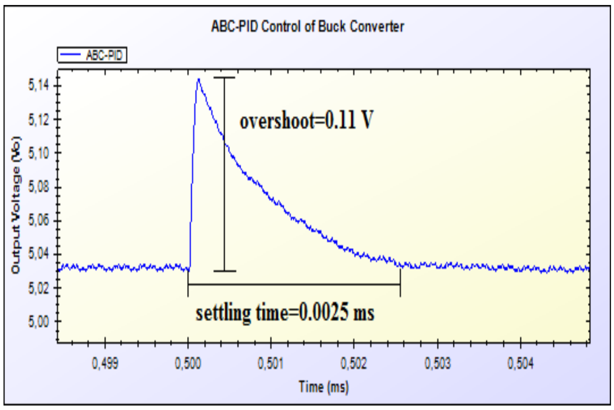


(b)

Figure 5. Simulation results of the GA-PID controlled buck converter; R=2 Ω to R=10 Ω at 0.5 ms



(a)



(b)

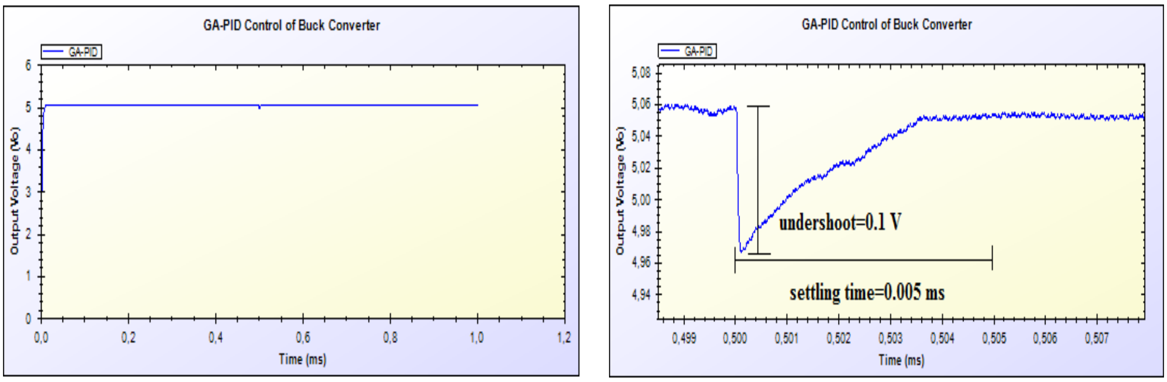
Figure 6. Simulation results of the ABC-PID controlled buck converter; R=2 Ω to R=10 Ω at 0.5 ms

Fig. 6(b) is zoomed version of Fig. 6(a). The ABC-PID control regulates the voltage increase with 0.11 V in 0.0025 ms for this case. As can be seen from these results, ABC-PID gives superior results than GA-PID in the case of being an increase in the output load.

In an another experimental case, the load resistor is changed 10 Ω to 2 Ω at 0.5 ms. Fig. 7(a) shows the output waveform of GA-PID controlled converter for this case. Fig. 7(b) is zoomed version of Fig. 7(a). The GA-PID controller regulates the voltage decrease with 0.1 V in 0.005 ms. Fig. 8(a) shows the output waveform of ABC-PID controlled converter for the same case. Fig. 8(b) is zoomed version of Fig. 8(a). The ABC-PID control regulates the voltage increase with 0.09 V in 0.004 ms for this case. ABC-PID controller gives better solution again than GA-PID for this case also.

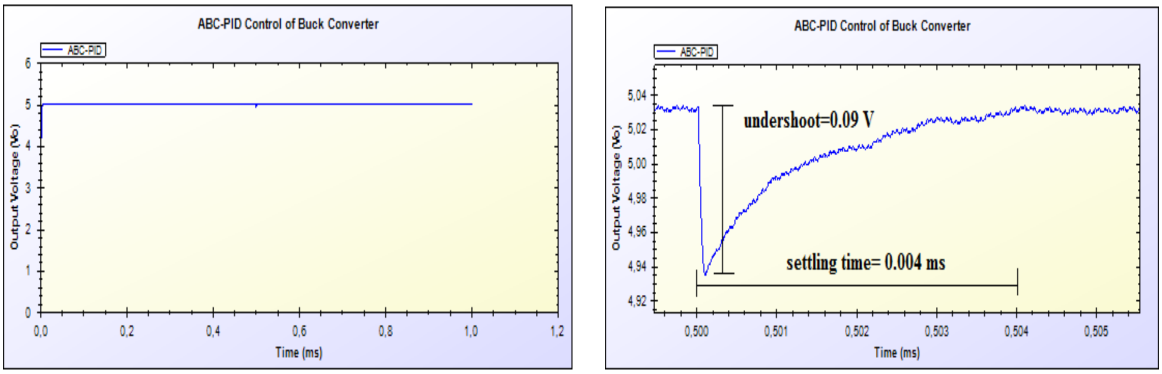
V. Conclusion

ABC-PID controller algorithm is designed and implemented to buck converter in this study.



(a) (b)

Figure 7. Simulation results of the GA-PID controlled buck converter; R=10 Ω to R=2 Ω at 0.5 ms



(a) (b)

Figure 8. Simulation results of the ABC-PID controlled buck converter; R=10 Ω to R=2 Ω at 0.5 ms

The effects of the proposed algorithm on system performance of the buck converter are investigated. Experiments are done via simulations to analyze the responses obtained. In order to verify the effectiveness of the proposed algorithm, GA based PID is used to control the same converter for same experimental cases. Results show that ABC-PID produces better results than GA-PID to control the buck converter in the way of settling time, steady-state error and load change cases. When ABC-PID compared to GA-PID, ABC-PID improves the settling time with 0.005 ms and steady-state error with 8.1 mV. Moreover, in the cases of load change, ABC-PID has a faster dynamic response with 0.0065 ms.

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