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Design of Adaptive Back-Stepping Controller for Chaos Control in Boost Converter and Controller Coefficients Optimization Using CHPSO Algorithm

Seyed Hamid Shahalami[1,†], Farzin Rajabnezhad[2]

[1,2]Department of Electrical Engineering, University of Guilan, Iran

ABSTRACT

In this paper, the DC-DC boost converter in chaos mode is controlled using the adaptive Back-stepping method. One of the main features of power electronic converters istheir nonlinear behavior due to existence of nonlinear elements such as diodes, switches, comparator and limiters in control circuits. Different types of non-linear behaviors such as bifurcation and chaos may occur in power electronic converters. These undesirable behaviors reduce efficiency of converters greatly and also cause dielectric losses, copper losses, undesirable sound noises and system failure. Back-stepping method is one of the common nonlinear techniques for controller design. This method is capable of generating an asymptotic and stabilizing control law in order to suppress chaos and synchronize chaotic systems. Also, optimal controller coefficients are determined using Chaotic Particle Swarm Optimization algorithm. By selecting an objective function, parameters of the back-stepping controller are determined using CHPSO algorithm. The system with adaptive Back-stepping controller is compared with the optimized adaptive back-stepping controller.

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Adaptive, Back-stepping Control, Chaos, CHPSO Algorithm, Nonlinear System.

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I. INTRODUCTION

Power electronic converters are used as intermediaries between energy producers and energy consumers. Switching power supplies are abundant in industry because of their low volume and cost. Due to nonlinear behavior such as switching properties and specific control loops, some chaotic conditions can be observed in power electronic converters [1,2]. In addition, other parameters such as parasitic elements can exacerbate the nonlinear behavior of the converters. Extensive use of DC switching power converters, nonlinear nature and chaotic behavior in these converters in some working conditions is attracted attention of many researchers to such circuits in recent years [3-10].

[†]Corresponding Author: shahalami@guilan.ac.ir
Tel: +98-1333690274, Fax: +98-1333690271, University of Guilan
Dept. of Electrical Engineering, Faculty of Engineering,
University of Guilan, Rasht, Iran

Back-stepping method is one of the common nonlinear techniques for controller design. This method is capableof generating an asymptotic and stabilizing control law in order to suppress chaos and synchronize chaotic systems. The concept of back-stepping design, the selection of appropriate functions of state variables as quasi-control inputs for sub-systems with smaller dimensions. Each back-stepping step leads to a new pseudo-control design, which is expressed in terms of pseudo-control design from the previous design steps. When this process is completed, a real control law and a final Lyapunov function were formed completely systematic.Back-stepping controller contains the positive parameters determined by trial and error method. The response of the system is different depending on the choice of these parameters. Inappropriate selection of the parameters causes inappropriate system performance. By selecting an objective function, parameters of the back-stepping controller

are determined using CHPSO algorithm.

II. Chaos in Boost Converter

Power electronic converters are susceptible in bifurcation and nonlinear phenomena [11], [12], [13]. Performance of the converter changes due to the variation in converter parameters such as predecessor inductance, capacitance, and input voltage or reference current. Therefore, converter may show chaos behavior. The boost converter gets into the chaotic mode with the following parameters:

$R = 20\Omega$, $C = 10\mu f$, $L = 1mH$, $E = 10V$, $f = 20kHz$.

Fig. 1 shows the circuit of the boost converter which is out of stable state and is in a chaotic behavior.

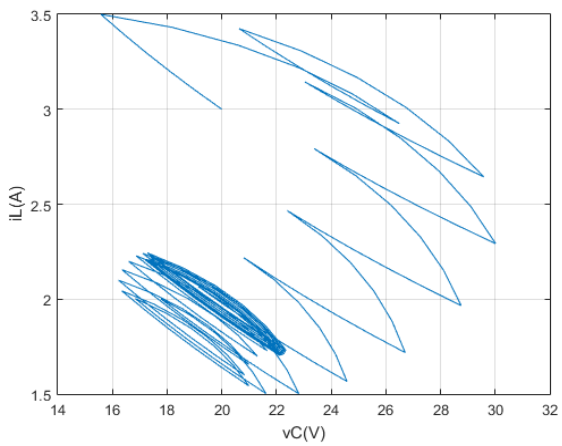

Fig. 1. Phase portrait of the boost converter in a chaotic mode

III. Back Stepping Controller

The boost converter circuit which contains the power electronic equipment is shown in Fig. 2. The operating mode of circuit is called Pulse Width Modulation (PWM). According to this principle, the time shared at this length distance "T" is called switching period. In each period, the switch turns on during the fraction of the period called μT, which is $0 \le \mu \le 1$.Therefore, the inductor's current increases and the diode is also turned off. At interval time of sampling $(1-\mu T)$, switch turns off and the stored energy of the inductor enters into circuit's output through the diode. Equation (1) represents the averaged state variable model of the Boost converter.

$$\begin{aligned} \dot{x}_1 &= -(1-\mu)\frac{x_2}{L} + \frac{E}{L} \\ \dot{x}_2 &= (1-\mu)\frac{x_1}{C} - \frac{x_2}{RC} \end{aligned} \tag{1}$$

where the state variable x_1 is the inductor current and the state variable x_2 is the capacitor voltage. The variation of parameter μ is in the range of 0 to 1, and μ is called the duty cycle.

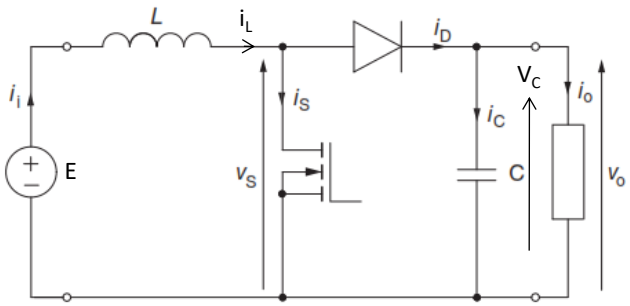

Fig. 2. Boost converter circuit

A. Nonlinear Back-stepping Controller in Boost Converter

1) *Direct Voltage Controller:* In the first method, a back stepping controller (called a direct voltage controller) is designed. A reference voltage should be followed by the voltage of capacitor $(V_d > E)$. The back-stepping method consists of two steps.

a) Step 1: The output voltage error is defined as in Equ. (2).

$$z_1 = x_2 - V_d \tag{2}$$

According to the above definition, the objective of back-stepping control is to regulate the capacitor voltage (i.e. state parameter of x_2). By inserting the derivation of Equ. (2) into Equ. (1), the Equ. (3) will be obtained:

$$\dot{z}_1 = \dot{x}_2 - \dot{V}_d = (1-\mu)\frac{x_1}{C} - \frac{x_2}{RC} - \dot{V}_d \tag{3}$$

where x_1 / C is considered as a virtual control input. Using the back-stepping control method, the number of state variables is equal to the design steps and, at each step, a stabilizer controller is designed for one of the state variables. With this description, if virtual control variable x_1 / C is selected as in Equ. (4), z_1 becomes stable and converges to zero.

$$\frac{x_1}{C} = \frac{\left(-k_1 z_1 + \frac{x_2}{(RC)} + \dot{V}_d\right)}{(1-\mu)} \tag{4}$$

The optimal value for x_1 / C can be calculated to be as in Equ. (5).

$$\alpha_1 = \frac{\left(-k_1 Z_1 + \frac{x_2}{(RC)} + \dot{V}_d\right)}{(1-\mu)} \tag{5}$$

Now, the actual control input of μ so should be used that x_1 / C converges to the value obtained by Equ. (4).

$$z_2 = \frac{x_1}{C} - \alpha_1 \tag{6}$$

As a result, the derivative of z_1 is obtained as in Equ. (7).

$$\dot{z}_1 = -k_1 z_1 + (1-\mu) z_2 \tag{7}$$

b) Step 2: Now, μ must be obtained in such a way that Equ.(6) converges to value of. z_2 Inserting the state variables of the system in Equ. (1) in the derivative of Equ. (6), one obtains Equ. (8).

$$\dot{z}_2 = -(1-\mu)\frac{x_2}{LC} + \frac{E}{LC} - \frac{\dot{\mu}\alpha_1}{(1-\mu)} - \frac{\left\{k_1^2 z_1 - (1-\mu)k_1 z_2 + \frac{(1-\mu)x_1}{(RC^2)} - \frac{x_2}{(RC)^2} + \ddot{V}_d\right\}}{1-\mu} \tag{8}$$

To demonstrate system stability, the positive definite function is proposed by Equ. (9).

$$V = 0.5 z_1^2 + 0.5 z_2^2 \tag{9}$$

Inserting z_2 from Equ. (8) and the state variables of system and virtual control input in the derivative of Equ. (9), Equ. (10) is obtained.

$$\dot{V} = -k_1 z_1^2 - k_2 z_2^2 + z_2\left[k_2 z_2 + (1-\mu) z_1 + \dot{z}_2\right] \tag{10}$$

Given that k_2 is the design parameter, the stability of Equ. (8) is ensured by selecting control input as shown in Equ. (11).

$$\dot{\mu} = \{[(1-\mu)^2 - k_1^2] z_1 + (1-\mu)(k_1 + k_2) z_2 - \frac{(1-\mu)x_1}{(RC^2)} + \left(\frac{1}{(RC)^2} - \frac{(1-\mu)^2}{(LC)}\right)x_2 + \frac{(1-\mu)E}{LC} + \ddot{V}_d\}/\alpha_1 \tag{11}$$

In equilibrium mode in which $z_1 = z_2 = 0$, Equ. (11) is simplified as shown by Equ. (12).

$$\dot{\mu} = R(1-\mu)^2 \frac{\left[E - (1-\mu)V_d\right]}{(LV_d)} \tag{12}$$

Equation (12) is the dynamic equation of duty cycle μ.In the state of equilibrium, the stability of this dynamic equation is studied. Equation (12) has two equilibrium points which are $\mu = \mu_1 = 1$ and $\mu = \mu_2 = 1 - \frac{E}{V_d}$.

Given the definition of duty cycle, the second value is only acceptable, which is in the range of 0 to 1. The stability of the system is verified for this value.

Near the second equilibrium point, by substitution of $1 - \mu_2 = \frac{E}{V_d}$ in Equ. (12), Equ. (13) is obtained as follows:

$$\dot{\mu} = \frac{R}{L}(1-\mu)^2(\mu - \mu_2) \tag{13}$$

Since Equ. (13) is positive for some $\mu > \mu_2$, results in $\dot{\mu} > 0$, this means that the derivative of a non-negative variable is non-decreasing and unstable. An indirect method has been used to solve this problem.

2) Indirect Voltage Controller: According to the fact that the direct voltage regulator has encountered a problem, the indirect method is used for controlling this state variable. In order to apply this method, firstly the following definition is presented in Equ. (14).

$$I_d = \frac{V_d^2}{(RE)} \tag{14}$$

Now, back-stepping controller must be designed in such a way that x_1 converges to the value of I_d.Similar to Equ. (2), inductor current error is defined as in Equ. (15).

$$z_1 = x_1 - I_d \tag{15}$$

By selecting x_2 / L as the virtual control input in the derivative of Equ. (15), the optimal value for stability of z_1 is obtained as in Equ. (16).

$$\alpha_1 = \frac{(k_1 z_1 + \frac{E}{L} - \dot{I}_d)}{(1-\mu)} \tag{16}$$

The value of α_1 in Equ. (16) causes the stability and convergence of z_1 to zero. This value is equal to the optimal value of x_2 / L, so that x_2 / L converge to its optimal value.

$$z_2 = \frac{x_2}{L} - \alpha_1 \tag{17}$$

The deriving of z_2 in Equ. (17) and obtaining μ in such a way that Equ. (17) becomes stable:

$$\dot{\mu} = \{[k_1^2 - (1-\mu)^2] z_1 + (1-\mu)(k_1 + k_2) z_2 - \frac{(1-\mu)^2 x_1}{(LC)} - \frac{(1-\mu)x_2}{(RLC)} + \ddot{I}_d\}/\alpha_1 \tag{18}$$

It means that Equ. (18) will lead to the stability of z_2. In order to prove the stability of the entire system, the Lyapunov candidate function in Equ. (9) is used.

To verify the dynamical stability of the whole system with the proposed controller, in the proximity of stable state values

$z_1 = z_2 = 0$, the derivative of control signal variable μ becomes as in Equ. (19).

$$\dot{\mu} = (1-\mu)\frac{\left[(1-\mu)^2 RI_d - E\right]}{(RCE)} \quad (19)$$

Equilibrium points of Equ. (19) are as follows: $\mu_1 = 1-\sqrt{E/(RI_d)}$, $\mu_2 = 1+\sqrt{E/(RI_d)}$ and $\mu_3 = 1$ .The only acceptable equilibrium point is $\mu_1 = 1-\sqrt{E/(RI_d)}$. Near to this equilibrium point μ_1 ,the Equ. (19) can be transformed to Equ. (20):

$$\dot{\mu} = \frac{2(\mu_1 - \mu)}{(RC)} \quad (20)$$

In this condition, when the value of μ is greater than $\mu_1 (\mu > \mu_1)$, the derivative value of μ is negative and μ is reduced and consequently converges to μ_1 .When the value of μ is smaller than $\mu_1 (\mu > \mu_1)$, the derivative value of μ is positive and μ increases and μ converges to μ_1 . Consequently it means that the system stables and converges to equilibrium point.

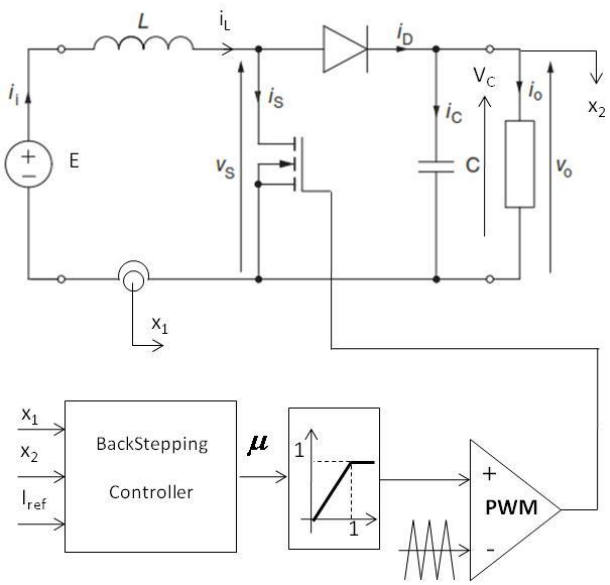

Fig. 3. Block diagram of the boost converter with Back-stepping controller

3) Proposed Back-stepping Controller Performance: As it is mentioned in circuit of Fig. 1, the boost converter was in chaos state with current mode controller. The back-stepping controller is designed and applied to the boost converter as shown in Fig. 3. The design parameters values are as follows:

$R = 20\Omega$, $C = 10\mu f$, $L = 1mH$, $E = 10V$,

$f = 20kHz$, $k_1 = 100$, $k_2 = 1000$

As shown in Fig. 4, the output voltage varies from 25 to 35 volts and the system has entered into the stability state using back-stepping controller.

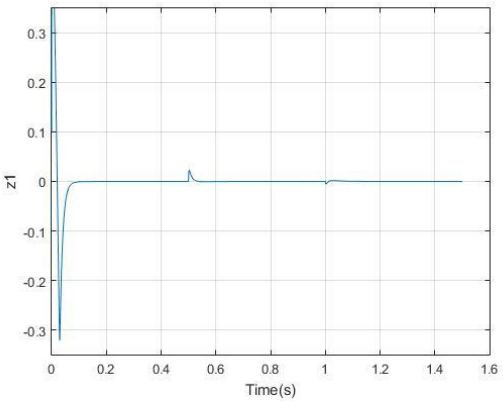

Fig.4(a)

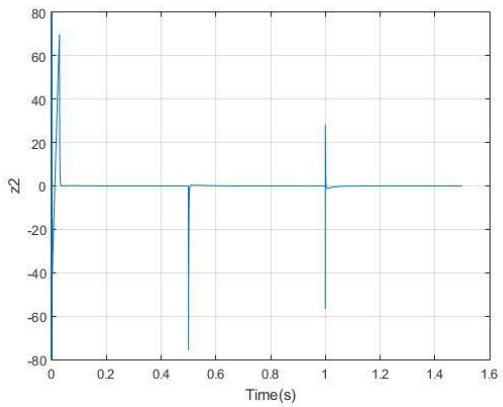

Fig.4(b)

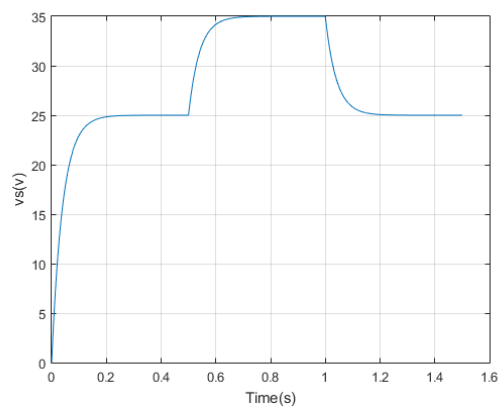

Fig.4(c)

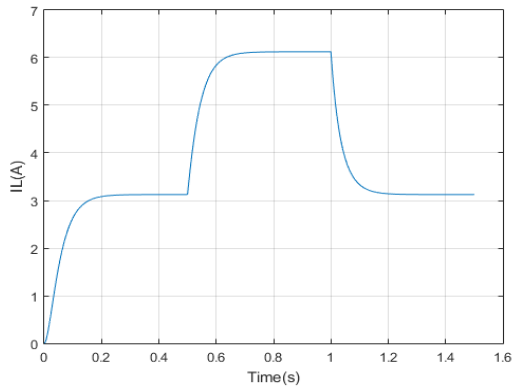

Fig.4. Back-stepping controller behavior and boost converter stabilization

4) Adaptive Back-stepping controller applied to Boost Converter: The back-stepping controller designed in the previous section was stable. The resistance R is the value of the load resistor, and this resistance is not always accurate and well-known. Therefore, this resistance must be estimated adaptively. The value of 1/R was considered as an unknown constant parameter θ and it can be estimated by the online adaptive rule.

$$\theta = \frac{1}{R} \tag{21}$$

All design steps are the same as the previous one, with the difference that instead of 1/R in all the equations, the estimated value was replaced.

$$I_d = \left(\frac{V_d^2}{E}\right)\theta \Leftrightarrow \hat{I}_d = \left(\frac{V_d^2}{E}\right)\hat{\theta} \tag{22}$$

a) Step 1: Like the previous one, the tracking error is defined as in Equ. (23):

$$z_1 = x_1 - \hat{I}_d \tag{23}$$

By deducing the Equ. (23) and selecting x_2/L as virtual control input, for the stability of z_1, the optimal value of x_2/L is obtained by Equ. (24):

$$\alpha_1 = \frac{(k_1 z_1 + \frac{E}{L})}{(1-\mu)} \tag{24}$$

and to guarantee the convergence of x_2/L to α_1, the tracking error is defined as in Equ. (25):

$$z_2 = \frac{x_2}{L} - \alpha_1 \tag{25}$$

b) Step 2: To ensure the stability of system, the actual control law Equ. (26) is obtained using derivative of Equ. (25).

$$\dot{\mu} = \{\left[k_1^2 - (1-\mu)^2\right] z_1 + (1-\mu)(k_1 + k_2) z_2 + \\ + (1-\mu) b_1 z_1 x_2 + \frac{(1-\mu)^2 x_1}{(LC)} - \frac{(1-\mu) x_2 \hat{\theta}}{(LC)} + C_1 \dot{I}_d\} / \alpha_1 \tag{26}$$

Verifying the stability of the whole system, the following Lyapunov candidate function is used:

$$\hat{\theta} + \dot{\theta} = \theta \tag{27}$$

$$V = 0.5\left(z_1^2 + z_2^2 + \frac{\theta^2}{\gamma}\right) \quad with \quad \gamma > 0 \tag{28}$$

The derivative of Lyapunov function of Equ. (28) is given by Equ. (29):

$$\dot{\theta} = -\frac{\gamma x_2 z_2}{(LC)} \tag{29}$$

From Equ. (22) and (28):

$$\dot{I}_d = -b_1 z_2 x_2 \tag{30}$$

In Equ. (29), the value of b_1 is as in Equ. (31):

$$b_1 = \frac{V_d^2 \gamma}{(ELC)} \tag{31}$$

To guarantee the overall stability of the system and to obtain the adaption law, the values of k_1, k_2 and γ are chosen as $k_1 = 100$, $k_2 = 1000$ and $\gamma = 10^{-9}$ where γ is training or adaptive gain. These parameters are extremely positive.

As shown in Fig. 5, by using adaptive back-stepping controller, the system is transformed from chaos state to the stable state, and uncertain value of θ is determined. In order to obtain the design parameters accurately, the algorithm CHPSO is used.

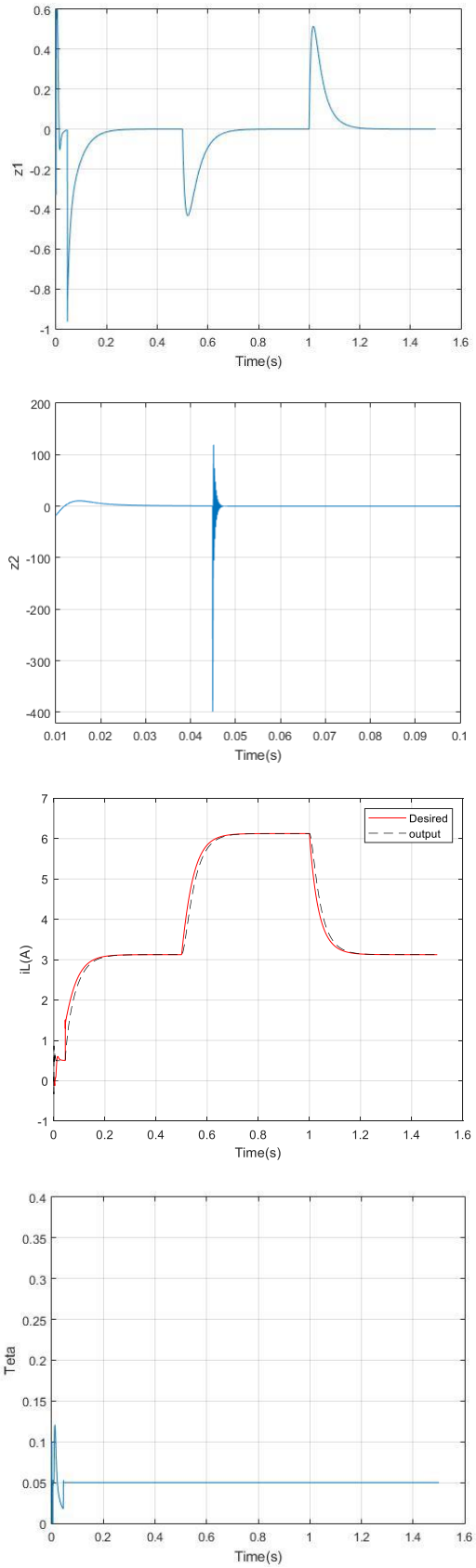

Fig. 5. Adaptive back-stepping controller behavior and boost converter stabilization

IV. PSO ALGORITHM

Particle Swarm Optimization (PSO) algorithm was introduced by Kennedy and Eberhart through the simulation of social behavior of birds in 1995 [11]. The PSO works with a whole batch of particles. Each particle can be an optimal solution of problem as a candidate solution and represented by a point or a vector of variables as $x_{ij} = (x_{i1}, x_{i2}, \ \ldots \ , x_{id})$ in a search space with dimension d, moving on to new points in the search space by adding the velocity vector of $V_{ij} = (V_{i1}, V_{i2}, \ \ldots \ , V_{id})$ to facilitate the search process. Initial positions and velocities of particles are randomly selected from the range $u \in [0,1]$. All particles in the search space move in order to optimize the objective function $f(x)$. Each member of particles, after being evaluated with the objective function $f(x)$ with a score, is considered as a weighted value. Each particle retains its previous position. During the search process, all particles move to the potential response areas using cognition and learning. This process continues until it reaches the stopping point. After each repetition, all the particles show their position and speed in order to achieve better value, according to Equ. (32):

$$V_i^{k+1} = w \times v_{ij}^k + C_1 \times r_1 \times (p_{best} - x_{ij}) + C_2 \times r_2 \times (g_{best} - x_{ij})$$
$$x_{ij}^{k+1} = x_{ij}^k + V_{ij}^{k+1} \quad (32)$$

Acceleration constants of C_1, C_2 represent the weighing unit that pulls each particle towards p_{best_i}, g_{best}. Parameters of r_1 and r_2 are a random function distributed uniformly between 0 and 1. The PSO algorithm is also very sensitive to inertia, w. The w modifies PSO's dynamic behavior during the search process. $w \leq 1$ ensures PSO convergence over multiple repetitions. A large amount of w causes the particle to not be caught in the local minima, and low amount of w increases the search precision in local are as typically, the value of decreases linearly with the increase of repetitions according to the Equ. (33), and its domain of variation is $w \in [0.4, 0.9]$.

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{iter_{\max}} \times iter \quad (33)$$

Where $w_{\max} = 0.9$ and $w_{\min} = 0.4$, $iter_{\max}$ is the maximum number of repetitions and $iter$ is the current repeat number.

V. CHPSO ALGORITHM

Depending on the initial condition of the system, chaos is a completely random and unpredictable phenomenon. This means that minor changes in the initial values lead to significant differences in the fate of the system process.

As a result, the r_1, r_2 values can be improved with randomness and chaotic state which is the chaotic local search process as in Equ. (34-36):

$$cx_i^{(k+1)} = 4cx_i^{(k)}\left(1-cx_i^{(k)}\right),\ i=1,2,\ldots,n \tag{34}$$

$$cx_i^{(k)} = \frac{x_i^{(k)} - x_{min,i}}{x_{max,i} - x_{min,i}},\ i=1,2,\ldots,n \tag{35}$$

$$x_i^{(k+1)} = x_{min,i} + cx_i^{(k+1)}\left(x_{max,i} - x_{min,i}\right),\ i=1,2,\ldots,n \tag{36}$$

where c_{xi} is a chaotic variable in step *i*.

Now, using the CHPSO algorithm and selecting the appropriate objective function, the Back-stepping controller parameters are optimized.

The objective function is represented by the Equ. (37):

$$\begin{cases} J = \int_0^{t_f}\left[w_1 t\left|E(t)\right| + w_2 u^2(t)\right]dt \\ \left|E(t)\right| = \sum_{i=1}^{n}\left|e_i(t)\right| \\ e_i(t) = x_i(t) - x_{di} \end{cases} \tag{37}$$

where t_f is the final time in sec, is time in sec, u is control signal and n is the degree of system. x_i is system state variables and, x_d is an optimal path of x_i. In accordance with the objective of stabilization and control of chaos, the x_d system is considered equal to zero. The optimized parameters in this problem are k_1, k_2 and γ.

With this optimized controller, the fastest response is achieved with minimal control effort, that is, system chaos is controlled in minimal time and minimal energy. In this optimization, the simulation time and the sampling time are 1.5sec and 20μsec respectively. Also, the search domains for k_1, k_2 is between $k_1, k_2 \in [1-5000]$ and the range of variation for γ is between $\gamma \in [0.99\times10^{-11}, 1.01\times10^{-11}]$. The number of iteration of CHPSO algorithm is 50. N represents the order of the system which is equal to 2. The population size is considered equal to 20.

The optimized values of k_1, k_2 verses number of iterations are given in Fig. 4.

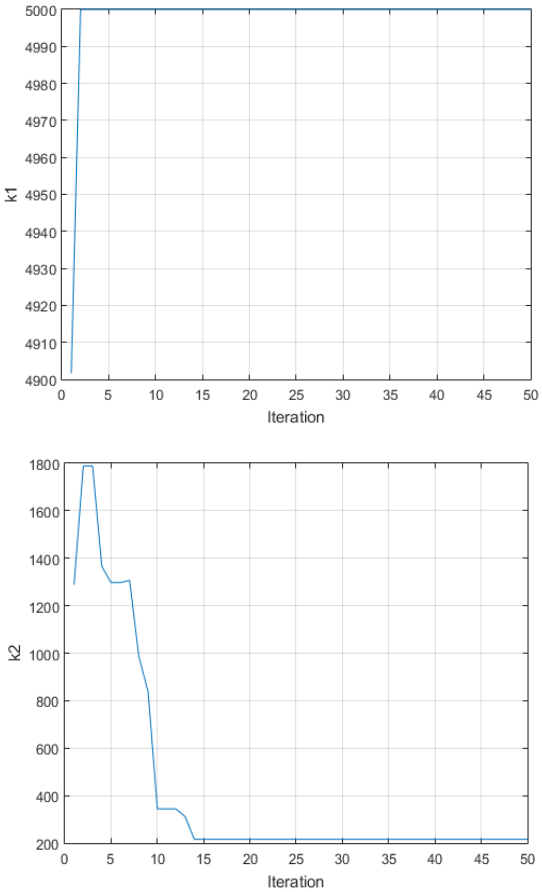

Fig. 6. Optimal values of k_1, k_2

In Fig. 7, the system with adaptive back-stepping controller is compared with the optimized adaptive back-stepping controller. With increasing the particles swarm and the number of repetitions, more optimal response will be resulted. The CHPSO algorithm optimizes the cost function and adjusts the system and its values in such a way that the cost function is minimized.

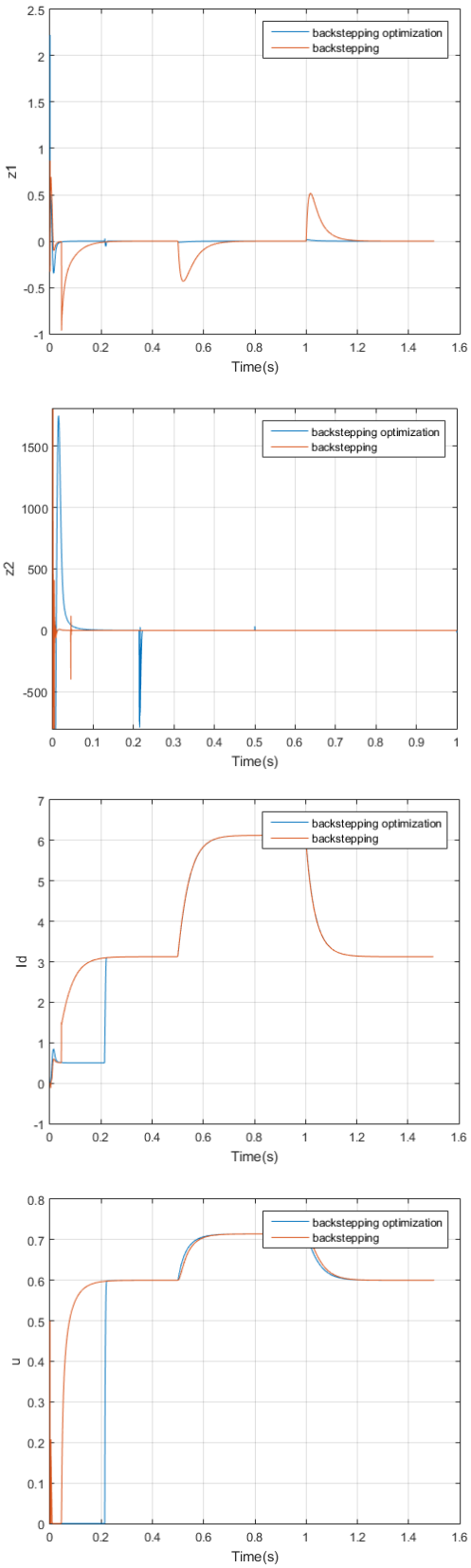

Fig. 7. Comparison of the adaptive Back-stepping with optimized adaptive Back-stepping controller

VI. Conclusions

In DC-DC converters, any sub-harmonic, quasi-periodic, and chaotic behaviors are not desirable and should be controlled. Therefore, the switching frequency of DC-DC converters should be used in the stable operation area. In this paper, an optimal adaptive Back-stepping controller was introduced which parameters are optimized by the CHPSO algorithm. The proposed controller is used to control chaos phenomenon in the DC-DC boost converter. In the proposed controller, parameters of the back-stepping method are chosen such that the chaos of the system is controlled in a short time. Therefore, a limited control signal is needed to stabilize system states and to control chaos conditions. Simulation results show that the adaptive Back-stepping controller has less sensitivity to design parameters and better performance in terms of accuracy and convergence.

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Farzin Rajabnejad born in Rasht, Iran, in 1992. He received his M.S. degree from the Faculty of Engineering, University of Guilan, Rasht, Iran, in 2018. He joined electrical engineer at the Power Distribution Company of Guilan from 2016 to 2020. His current research interests include power electronic converters, nonlinear control, the application of power electronics in renewable energy systems.

Seyed-Hamid Shahalami was born in Mashhad, Iran in 1964. He received the B.S.C. degree from Ferdowsi University of Mashhad-Iran, in 1989, M.S. degree from Sharif University of Technology, Tehran in 1992, D.E.A from SUPELEC and the University of Paris6, Paris in 1996 and PhD degree from the University of Henri Poincarre (Nancy I), Nancy-France in 2001, all in electrical engineering. Since 2003 he has joined the department of electrical engineering at the University of Guilan, Iran, where he is currently an Assistant Professor. His current research interests include all Drives, Active filters, Power Quality control and the FACTS.

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