PSO Based Adaptive Terminal Sliding Mode Controllers for a DC-DC Converter

H. Abderrezek and M. N. Harmas

***Abstract*—This paper presents an adaptive non-singular terminal sliding mode (ANTSM) tracking control design for DC-DC buck converter. An adaptive Terminal sliding mode control method is presented for nonlinear systems with parameter uncertainty and external disturbance. The method estimates the boundary of parameter uncertainty and external disturbance by adaptive law. The idea behind this strategy is to use the terminal sliding mode control (TSMC) approach to assure finite time convergence of the output voltage error to the equilibrium point and integrate an adaptive law to the TSMC strategy so as to achieve a dynamic sliding line during the load variations. The convergence rate is fast, and a strong robustness can be achieved. Control parameters are optimized using a Particles Swarm Optimization (PSO) algorithm to further enhance performances.**

***Index Terms*—DC-DC converter, sliding-mode (SM) control, terminal sliding mode controller (TSMC), adaptive, PSO.**

I. Introduction

DC-DC converters have been widely used in most of the industrial applications such as DC motor drives, computer systems and communication equipments. Design of high performance control is a challenge because of its nonlinear and time variant nature. Generally, linear conventional control fails to accomplish robustness under nonlinearity, parameter variation, load disturbance and input voltage variation.

Sliding mode control (SMC) is one of the most important approaches to handling systems with nonlinearities and uncertainties. Generally, the linear sliding mode has been widely used, that is, the system state variables reach the system origin asymptotically in linear sliding mode [1], [2]. However, the system states in the sliding mode cannot converge to zero in finite time. Recently, the terminal sliding mode control (TSMC) has been developed to achieve finite time convergence of the system dynamics in the terminal sliding mode. Instead of using linear hyper planes as the sliding surfaces, the terminal sliding mode control adopts nonlinear sliding surfaces.

The terminal sliding mode control has the advantage of finite time convergence and tiny steady state error [3]. But there exist singular points in conventional terminal sliding mode control [4]. Non-singular terminal sliding mode control can avoid the singularity, but the upper bounds of the disturbances usually must be known for calculating the switching gain [5], [6].

Adaptive control techniques have also successfully advanced in tackling control problems for uncertain nonlinear systems. To make the controlled system realize finite time convergence even in the condition of unknown boundary disturbance and overcome the singular problem in designing TSMC synchronously[7], [8], a kind of adaptive estimation method was integrated to non-singular terminal sliding mode control (ANTSMC) [9], [10]. To weaken the chattering caused by SMC, the switching item in controller was eliminated.

The selection of adaptive nonsingular terminal sliding mode coefficients affects the performance of the controller in terms of transient response. Proper selection of these coefficients causes the system to become robust, stable and achieve fast response. In this paper, a particle swarm optimization approach is presented and termed PSO. The coefficients optimized through such techniques are compared and shown to guarantee high dynamic performance over a wide range of operating points.

The outline of the paper is as follows. The mathematical model for a typical Buck DC-DC converter is described in Section II. Designing an adaptive non-singular terminal sliding mode controller is given in section III. In Section VI, This section presents modified PSO and its problem formulation. Simulation results are presented to confirm the effectiveness and the applicability of the proposed method in Section V.

II. Model of DC-DC Converter

A basic DC-DC converter circuit known as the buck converter is illustrated in Fig. 1, consisting of one switch, a fast diode and RLC components. The switching action can be implemented by one of three-terminal semiconductor switches, such as IGBT or MOSFET.

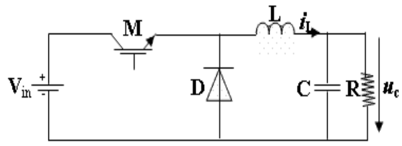

Fig. 1.Buck DC-DC converter.

When the converter works in the continuous conduction mode, the system can be described as in [4].

$$\begin{bmatrix} i_L \\ \dot{u}_C \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{L} \\ \frac{1}{C} & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ \dot{u}_C \end{bmatrix} + \begin{bmatrix} \frac{V_{in}}{L} \\ 0 \end{bmatrix} u \qquad (1)$$

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The authors are with the Electrical Engineering Department, University of Ferhat Abbas Setif1, setif, Algeria (e-mail1: hadjer_ji@ live.fr, mharmas@ univ-setif.dz).

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where u is the switching state, when u=1, the switch M is turned on, and when u=0, M is off.

Select the output voltage and its derivative as system state variables, that is

$$\begin{cases} x_1 = u_C \\ x_2 = \dfrac{du_C}{dt} \end{cases} \tag{2}$$

Then the state space model describing the system is derived as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -\dfrac{x_1}{LC} - \dfrac{x_2}{RC} + \dfrac{V_{in}}{LC} u \end{cases} \tag{3}$$

When the switching frequency is high enough and ripples are small, if we suppose the duty ratio of a switching period is ***d*** then the state space average model can be rewritten as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -\dfrac{x_1}{LC} - \dfrac{x_2}{RC} + \dfrac{V_{in}}{LC} d \end{cases} \tag{4}$$

Consider that disturbances caused by parametric variation may occur in running processes, the model of the converter can be amended as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -\dfrac{x_1}{LC} - \dfrac{x_2}{RC} + \dfrac{E}{LC} d + F \end{cases} \tag{5}$$

where F denotes the whole disturbances the system suffered. Other parameters such as L, C, R and E denote the given definite part.

III. Designing of Adaptive Nonsingular Terminal Sliding Mode Control

First a non-singular terminal SMC for DC-DC converter modeled as equation (5) It is assumed that F is bounded and $F \le l_g$, $l_g > 0$.

Suppose the expected tracking voltage is r, then the tracking error and its derivative are defined as

$$e = x_1 - r \,.\; \dot{e} = x_2 - \dot{r}\,.$$

The sliding surface of this nonsingular terminal SMC is chosen as

$$S = e + \frac{1}{\beta}\dot{e}^{\frac{p}{q}} = (x_1 - r) + \frac{1}{\beta}(x_2 - \dot{r})^{\frac{p}{q}} \tag{6}$$

where $\beta > 0$, p and q are positive odd constants, and

$$1 < p/q < 2 \tag{7}$$

To make the control system not rely on the disturbance boundary values, adaptive estimation to disturbance F is carried out, and then the nonsingular terminal sliding mode controller is amended [11]. The estimated error is defined as

$$\tilde{F} = F - \hat{F} \tag{8}$$

where $\hat{F}$ is the estimation of F .

Lyapunov function is defined as

$$V = \frac{1}{2}s^2 + \frac{1}{2\gamma}\tilde{F}^2 \tag{9}$$

Then the following relation can be derived

$$\dot{V} = s(x_2 - \dot{r} + \frac{1}{\beta}\frac{p}{q}(x_2 - \dot{r})^{\frac{p}{q}-1}(-\frac{x_1}{LC} - \frac{x_2}{RC} + \frac{E}{LC}d + \hat{F} - \ddot{r})) - \frac{1}{\gamma}\tilde{F}(\dot{\hat{F}} - \gamma s\frac{1}{\beta}\frac{p}{q}(x_2 - \dot{r})^{\frac{p}{q}-1}) \tag{10}$$

To eliminate the influence which the estimated error bring onto the system, the estimated controlled variable is selected as

$$\dot{\hat{F}} = \gamma s \frac{1}{\beta}\frac{p}{q}(x_2 - \dot{r})^{\frac{p}{q}-1} \tag{11}$$

The control input is designed as

$$d = -\frac{LC}{E}(-\frac{x_1}{LC} - \frac{x_2}{RC} + \hat{F} - \ddot{r} + \beta\frac{q}{p}(x_2 - \dot{r})^{2-\frac{p}{q}} + ws^{\frac{m}{n}} + hs) \tag{12}$$

where $w > 0$, $h > 0$, $m < n$, are positive odd constants. There is no switching item in this control law, and thereby system chattering is eliminated.

Substituting (11) and (12) into (10) leads to

$$\dot{V} = -\frac{1}{\beta}\frac{p}{q}(x_2 - \dot{r})^{\frac{p}{q}-1}(ws^{\frac{m+n}{n}} + hs^2) \tag{13}$$

Because (7) is satisfied, and meanwhile p and q are positive odd constants, so when $x_2 - \dot{r} \ne 0$ comes into existences, equation $(x_2 - \dot{r})^{\frac{p}{q}-1} > 0$ is satisfied.

On the other hand, because $m < n$, and m , n are positive odd constants, so when $s \ne 0$ comes into existences, the following condition is satisfied

$$s^{\frac{m+n}{n}} > 0 \tag{14}$$

With the condition of $x_2 - \dot{r} \ne 0$, we have

$$\dot{V} = -\frac{1}{\beta}\frac{p}{q}(x_2 - \dot{r})^{\frac{p}{q}-1}(ws^{\frac{m+n}{n}} + hs^2) \le 0 \tag{15}$$

So lyapunov stability can be satisfied.

IV. Particle Swarm Optimization (PSO)

Particle In 1995, particle swarm optimization (PSO), a swarm intelligence stochastic optimization algorithm which simulated searching food behavior of bird flock and fish school, was first presented by Kennedy and Eberhart [12].

In this algorithm, every particle represents a potential solution flying through problem space by following the current optimum particles with a velocity component that decides flying direction and distance. At each iterative, particles update themselves via two best values. One is individual best value named '*pbest*', which keeps track of its coordinates associated with the best solution that it has achieved so far in the problem space. Another one is global best value called '*gbest*', which can be found in the whole population [13].

Particles are evaluated through objective function at each iterative search. The flow chart in Fig. 6 explains process of PSO concisely.

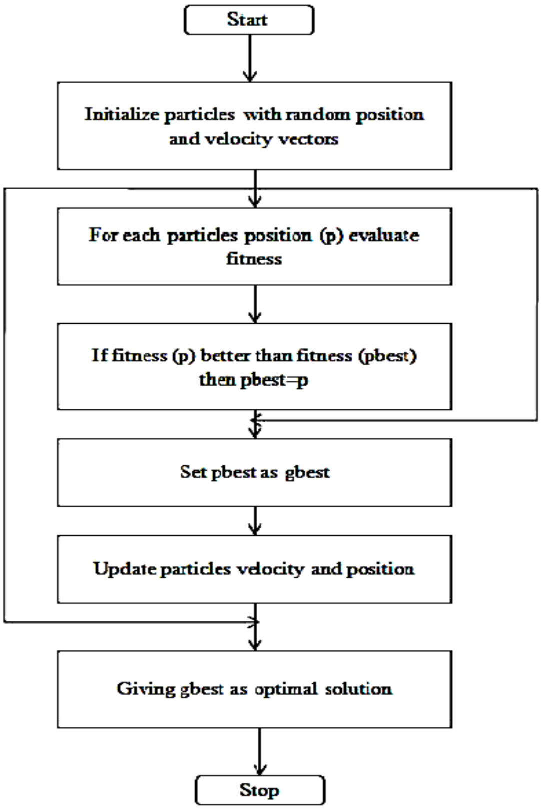


Fig. 2. Flow chart of PSO algorithm.

Each particle tries to modify its position using the following information:

- the current positions,
- the current velocities,
- the distance between the current position and pbest,
- the distance between the current position and the gbest.

The modification of the particle's position can be mathematically modeled according the following equation [13]:

$$V_i^{k+1} = wV_i^k + c_1.rand_1(..)(pbest_i - S_i^k) + c_2.rand_2(..)(pbest_i - S_i^k) \quad (16)$$

$$s_i^{k+1} = s_i^k + V_i^{k+1} \quad (17)$$

where

V_i^k Velocity of particle *i* at iteration *k*

w Weighting function

c_1, c_2 weighting factor are uniformly distributed random numbers between 0 and 1.

S_i^k Current position of the particle *i* at iteration *k* 'Pbest' of particle I 'gbest' value is obtained by any particle so far in the above procedure.

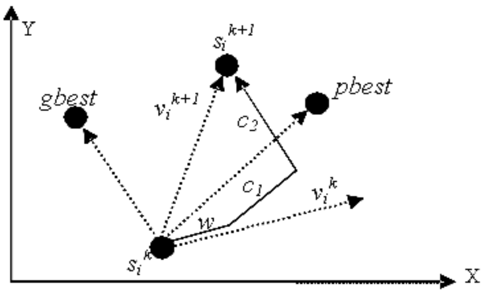


Fig. 3. The velocity and position updates in PSO.

The advantages of PSO compared to other evolutionary computational techniques are

- PSO is easy to implement.
- There are few parameters to be adjusted in PSO.
- All the particles tend to converge to the best solution rapidly.

The description of a PSO algorithm is introduced in [14] and is used in the present work to minimize an objective function described next.

The selected objective function to be minimized (ITAE) is defined by:

$$J = \int_0^t t.|e(t)|dt \quad (18)$$

where *t* is the time range of simulation and $|e(t)|$ the absolute value of the voltage error.

The proposed approach employs a PSO search for the optimum parameter settings of the proposed DC-DC converter ATSM control. Control parameters to be tuned through the optimization algorithm are $\alpha(p/q)$ and $\beta(m/n)$, with the aim to minimize the selected fitness objective function thus improving system response performance in terms of settling time and overshoot.

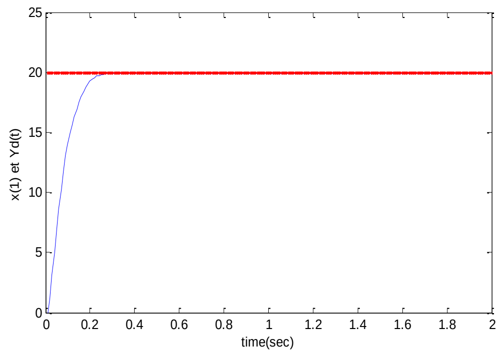
V. Simulation Results

The proposed controllers were used to DC-DC converter and simulation operation was carried out. Parameters of DC-DC converter are chosen as: $L = 80\mu H; E = 24V; R = 8\Omega; C = 2000\mu F$. The expected tracking voltage is $r = 20v$. The initial state of this system is $x = [0,0]^T$. The main parameters used in designing controller are: $p = 5, q = 3, m = 3, n = 5, \gamma = 50$.

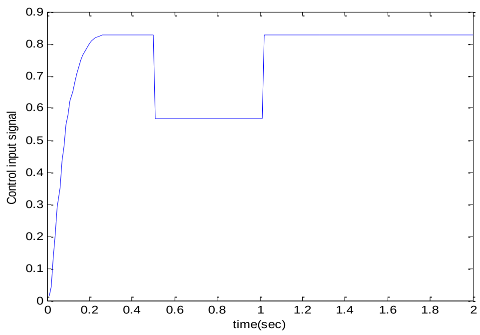
Fig. 4. shows the responding profiles of output voltage, control input, tracking error and inductor current corresponding to source variation. The source voltage varies from 24V to 35V at the time of 0.5s and returns to 24V at the time of 1s. It can be seen from these curves that the voltage output can tracking error is almost zero. Because the output

voltage is proportional to the product of duty cycle and source voltage, when the source voltage changes, the tracking output voltage keep steady by adjusting duty cycle d. chattering is eliminated from this system.

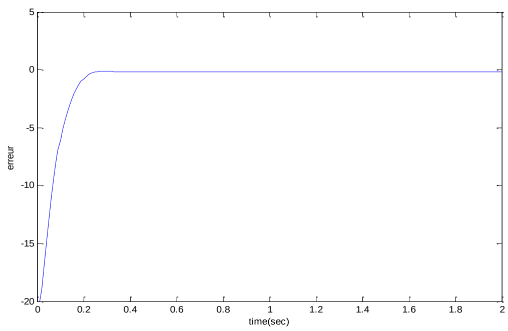
Fig. 5. shows the responding profiles corresponding to load fluctuation. The load resistance varies from 8 to 20 at the time of 0.5s and returns to 8 at the time of 1s. From these curves we can see that the tracking output voltage is with small rise time and nearly zero error, and also there is no chattering.



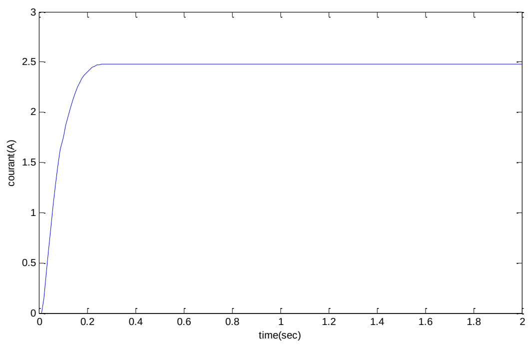
a) Output voltage



b) Control input signal



c) The tracking error

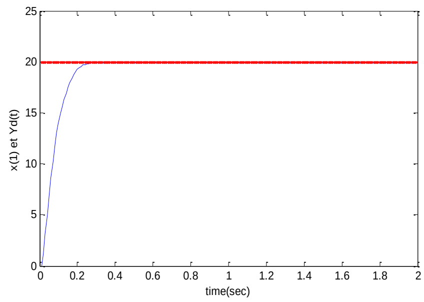


d) Inductor current

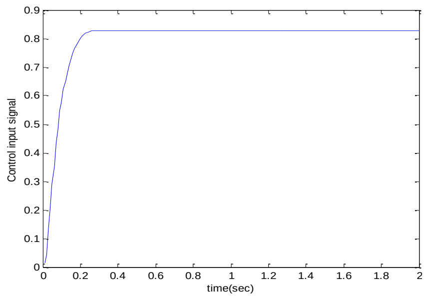
Fig. 4. Simulation results for converter with source fluctuation.

Fig. 6 Show the results of simulation using PSO.

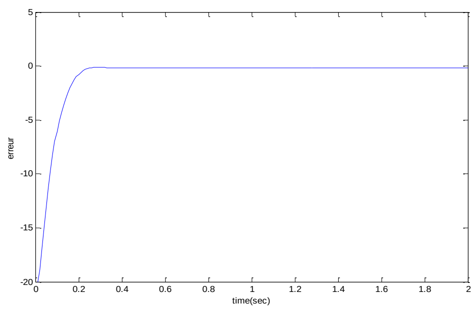
Optimized value for α, β is sought through PSO and optimal value was found to be equal to $\alpha = 1.5342$, $\beta = 0.8067$. Simulation results show better chatter free performances. The objective function (ITAE) is depicted in Fig. 7.



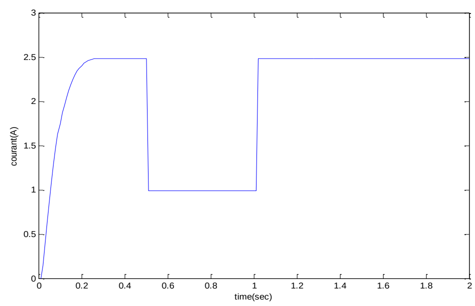
a) Output voltage



b) Control input signal

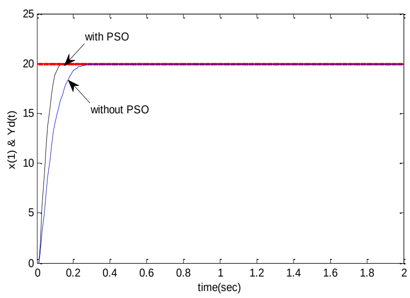


c) The tracking error

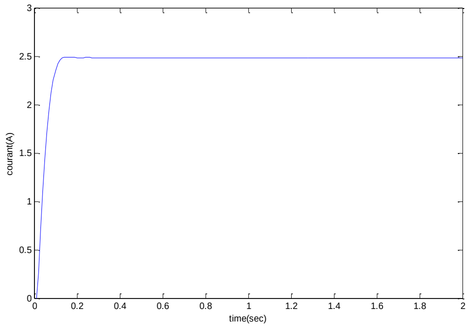


d) Inductor current

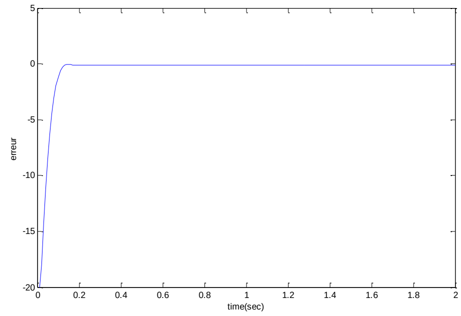
Fig. 5. Simulation results for converter with load fluctuation.



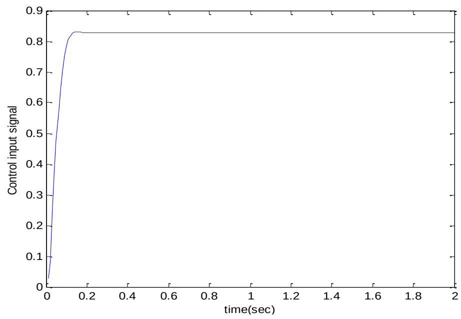
a) The output voltage



b) Inductor current



c) The tracking error



d) Control input signal

Fig. 6. Results of PSO-ANTSMC approach.

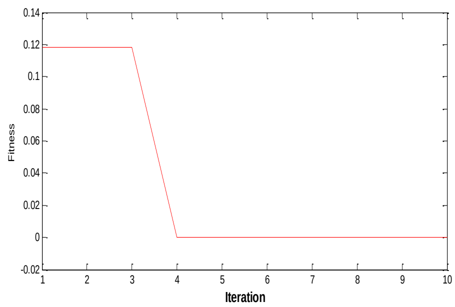


Fig. 7. The function objective (ITAE).

VI. Conclusion

Paper we have presented the development and simulation of Adaptive Terminal Nonsingular Sliding Mode Control of a DC-DC converter using PSO to optimize control parameters.

Terminal approach guarantees finite time convergence increasing therefore system robustness. The TSMC integrated with adaptive disturbance estimation can overcome the influence which unknown border disturbances bring about to control system and guarantee DC-DC converter keep good dynamic and steady performances even if it undergo arbitrary random disturbances. Global performances are up kept despite load variation or line disturbance. As an unexpected result is chattering decrease using PSO while fast convergence is reached thus empowering much sought invariance after a shorter time than the obtained with its classical counterpart.

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H. Abderrezek was born in Algeria in 1988. She received the degree of engineering in automatic from Electrical Engineering Department University of Setif1 in 2011. She is currently a M.Sc. student in the Electrical Engineering Department. She is interested in subjects of optimization techniques, control technique for power electronics.

M. N Harmas was born in Algeria. He received the degree of professor in Ferhat Abbas University of setif1, Department of Electronics, Algeria in 2013. He is currently a professor in the Electrical Engineering Department. He interested field is in control systems, power systems, power electronics