DC-DC CONVERTER FINITE TIME ROBUST CONTROL

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***Abstract**: As unavoidable power electronic devices, DC-DC converters seem to be used in so many different scientific, industrial, space and military domains for their versatility and efficiency. It is understandable therefore to grasp the great emphasis put on the control community to develop robust control schemes able to handle line and load variations as well as perturbations alike.*

Thus many controllers were developed for DC-DC converters but mostly with asymptotic convergence. Sliding mode control, a proven robust control approach, will be used here in an effort to achieve finite time convergence thus enhancing the already established technique robustness. Furthermore a PSO algorithm will be used to optimize controller parameters using an ITAE criterion. Simulation of terminal sliding mode control of a buck DC-DC converter is carried out for different operating conditions and results compared to classic sliding mode control showing good performance of the proposed approach. .

***Key words:** dc-dc converter, sliding mode, terminal, PSO.*

1. Introduction

As inevitable power electronic devices, DC-DC converters are everywhere from desk computers to space vehicle and seem to be always conquering new domains. Very versatile converters require robust control algorithms to handle unknown load values and/or line variation efficiently. Great emphasis realizing this task has been put on the control community. A myriad of sound work has been published on the subject []for a variety of applications including DC motor drives, computer systems and communication equipment. Converter design control with high performance 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. Thus nonlinear approaches such as SMC, one of the most effective nonlinear robust control approaches have been extensively used [1-3]. This technique provides system dynamics with an invariance property to uncertainties once the system dynamics are controlled in the sliding mode, making it very reliable despite the inherent chattering drawback [1-3,8-10]. Its major advantages are guaranteed stability and robustness against parameter, line, and load variations. Moreover, being a controller that has a high degree of flexibility in its design choices, SMC is relatively easy to implement as compared with other types of nonlinear controllers. Such properties make it highly suitable for control applications in nonlinear systems. Robustness of SMC plays a very important role in guaranteeing the normal operation of DC converter despite parameters variations and uncertainties. Furthermore SMC can make DC-DC converter provide stable voltage output even on load or line voltage variations. Nonetheless it only provides asymptotic convergence.

Terminal sliding mode control has the advantage of providing finite time convergence and tiny steady state error[1-3,10]. However there exist singular points in conventional terminal sliding mode control [3]. Recent work [8] has given emergence to nonsingular terminal sliding mode control which can avoid the singularity problem but the upper bounds of the disturbances usually must be known for calculating the switching gain. We intend to apply this new technique to a DC-DC buck converter control in which PSO is used to improve overall performance.

The rest of the paper starts with an introduction of the mathematical model for a typical Buck DC-DC converter followed by a section which presents a brief recall of sliding mode control scheme. Design of a terminal sliding mode controller is given on the ensuing section. Finally the last two sections present the PSO algorithm used, followed by a discussion of simulation results presented to confirm the effectiveness and the applicability of the proposed method.

2. 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 R,L,C components. The switching action can be implemented by one of three-terminal semiconductor switches M, such as IGBT or MOSFET switch.

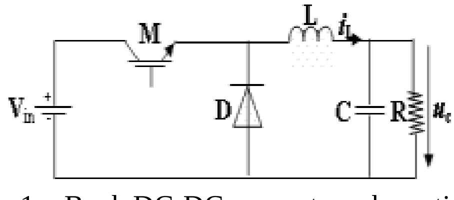


Fig.1. Buck DC-DC converter schematics.

When the converter works in the continuous conduction mode, the system can be described as in[1].

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

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

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

$$\begin{cases} x_1 = u_C \\ x_2 = \frac{du_C}{dt} \end{cases} \qquad (2)$$

leads to the state space model describing the system, derived as:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -\frac{x_1}{LC} - \frac{x_2}{RC} + \frac{V_{in}}{LC} u \end{cases} \qquad (3)$$

If the switching frequency is high enough and if we suppose the duty ratio of a switching period is ***d*** then the state space average can be rewritten as in (4):

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -\frac{x_1}{LC} - \frac{x_2}{RC} + \frac{V_{in}}{LC} d \end{cases} \qquad (4)$$

3. Sliding Mode Control of Buck Converter

The sliding mode control is widely used in the literature [2, 3]. Its success is based on its simplicity of implementation and its robustness to parameter variations and external disturbances. The synthesis of the control law is done in two steps.

First a so called sliding surface S is defined having the desired dynamics and can be designer chosen as follows:

$$S = \dot{e} + \lambda e \qquad (5)$$

Where e designates the error and $\dot{e}$ its derivative supposing *r* is the expected tracking voltage:

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

To guarantee the existence of sliding mode, the control must satisfy the condition:

$$S\dot{S} < 0 \qquad (6)$$

In the second step, a control law is developed so as to force the system to reach the sliding surface and to maintain state trajectories on it until it reaches the origin of the phase plane. This control law consists of two parts: continuous term called the equivalent control and a discontinuous component.

The equivalent control is obtained by the conditions of invariance of the surface given by:

$$S = 0 \quad ; \quad \dot{S} = 0$$

Therefore, the expression of the equivalent command is easily derived as:

$$u_{eq} = \frac{LC}{V_{in}} \left[\frac{x_1}{LC} + \frac{x_2}{RC} + \lambda \dot{e} + \ddot{r} \right] \qquad (7)$$

The discontinuous term u_s guarantees the hitting condition and provides robustness vis-à-vis the external disturbances. The discontinuous portion of the command is generally chosen as:

$$u_s = -k.sign(S) \; , \; k > 0 \qquad (8)$$

Therefore, the overall control law can be defined as:

$$u = \frac{LC}{V_{in}} \left[\frac{x_1}{LC} + \frac{x_2}{RC} + \lambda \dot{e} + \ddot{r} + k.sign(S) \right] \qquad (9)$$

Nevertheless the control elaborated guarantees only an asymptotic convergence, to have a faster convergence, it is necessary to modify the sliding surface.

4. Terminal sliding mode control of a buck DC-DC converter.

Terminal sliding mode control design is based on a particular choice of the sliding surface and the determination of a control law permitting to drive the system on a terminal sliding surface, a terminal sliding mode is established and a fast finite convergence is granted.

Towards this goal, one defines a nonlinear sliding surface as in (10):

$$S = e + \frac{1}{\beta} \dot{e}^{\frac{p}{q}} = (x_1 - r) + \frac{1}{\beta} (x_2 - \dot{r})^{\frac{p}{q}} \qquad (10)$$

Where $\beta > 0$, *p* and *q* are positive odd constants, such that this condition is satisfied:

$1 < p/q < 2$.

Let t_r designate the time it takes to move from $S(0) \neq 0$ to $S = 0$ and t_s the time to reach the origin of the phase plane that is when the tracking error is zero.

When the system reaches the sliding surface, we thus have:

$$S = e + \frac{1}{\beta} \dot{e}^{\frac{p}{q}} = 0 \qquad (11)$$

Which can rewritten as (12)

$$\dot{e} = -\beta^{\frac{p}{q}} e^{\frac{p}{q}} \quad (12)$$

Then t_s can be obtained as follows [11]

$$t_s = \frac{p}{\beta^{\frac{q}{p}}(p-q)} \left| e(t_r) \right|^{1-\frac{p}{q}} \quad (13)$$

By adjusting p, q and β, the system can reach steady state in a limited time t_s.

Let us consider the stability aspect using the classic Lyapounov function candidate:

$$V = \frac{1}{2} S^2 \quad (14)$$

Ae sufficient condition for the existence of the terminal sliding mode is

$$\dot{V} = \frac{1}{2}\frac{dS^2}{dt} < -\eta |S| \quad ;\eta > 0 \quad (15)$$

condition (15) leads to:

$$S\dot{S} < -\eta |S| \quad (16)$$

Differentiating (10) with respect to time and using (16), one obtain the following result

$$\dot{V} = S(x_2 - \dot{r} + \frac{1}{\beta}\frac{p}{q}(x_2 - \dot{r})^{\frac{p}{q}-1}(\frac{-x_1}{LC} - \frac{x_2}{RC} + \frac{V_{in}}{LC} d - \ddot{r})) \quad (17)$$

The terminal sliding mode controller is designed as

$$d = -\frac{LC}{V_{in}}(-\frac{x_1}{LC} - \frac{x_2}{RC} - \ddot{r} + \beta\frac{p}{q}(x_2 - \dot{r})^{2-\frac{p}{q}} + ... + (\eta + k) sign(S)) \quad (18)$$

where k is a positive design constant.

Substituting (18) into (17) leads to:

$$\dot{V} = S\dot{S} = \frac{1}{\beta}\frac{p}{q}(x_2 - \dot{r})^{\frac{p}{q}-1}(-(\eta + k)|S|) \quad (19)$$

Because of the following inequality

$$1 < p/q < 2$$

One may write :

$$0 < \frac{p}{q} - 1 < 1 \quad (20)$$

Because p and q are positive odd constants, when $(x_2 - \dot{r}) \neq 0$, we do have

$$(x_2 - \dot{r})^{\frac{p}{q}-1} > 0 \quad (21)$$

Such that:

$$\dot{V} \le \frac{1}{\beta}\frac{p}{q}(x_2 - \dot{r})^{\frac{p}{q}-1}(-\eta|S|) = $$

$$= \frac{-1}{\beta}\frac{p}{q}(x_2 - \dot{r})^{\frac{p}{q}-1}\eta|S| = -\eta'|S| \quad (22)$$

where:

$$\eta' = \frac{1}{\beta}\frac{p}{q}(x_2 - \dot{r})^{\frac{p}{q}-1}\eta > 0 \quad (24)$$

Therefore the controller can meet Lyapounov stability.

5. Particle Swarm Optimization (PSO)

Particle swarm optimization (PSO) is one among many nature based optimization method. PSO is a population based optimization tool first proposed by Eberhart and Kennedy in 1995[11]. In PSO inspired by flocks of birds and schools of fish, a number of simple particles (entities) are placed in the parameter space of problem or function, and each evaluates the fitness at its current location.

The advantages of PSO compared to other evolutionary computational techniques are:

- ✓ ease in implementation.
- ✓ fewer parameters to be adjusted.
- ✓ all the particles tend to converge to the best solution rapidly.

The mathematical equations for the searching process are[11]:

$$V_i^{k+1} = wV_i^k + c_1.rand_1(..)(pbest_i - S_i^k) + c_2.rand_2(..)(pbest_i - S_i^k) \quad (25)$$

(25)

$$x_i^{k+1} = x_i^k + V_i^{k+1} \quad (26)$$

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*

$pbest_i$ of particle *i* 'gbest' value is obtained by any particle in the above procedure.

The flow chart of PSO algorithm is shown in figure 2.

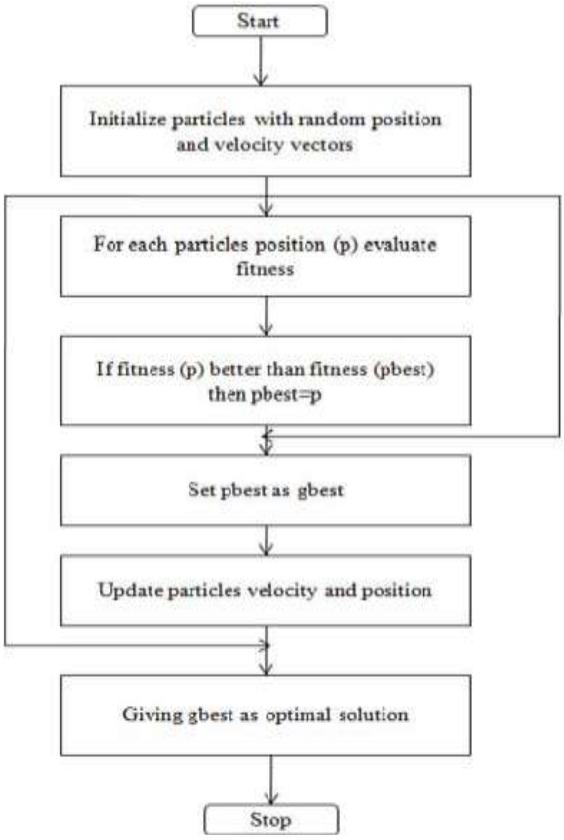


Fig.2. PSO algorithm flowchart

The objective function considered is based on absolute value of the error. The performance of a controller is best evaluated in terms of an error criterion as many such criteria are available. In the proposed work, controller performance is evaluated in terms of integral time absolute of error (ITAE) as in (27):

$$J = \int_0^t t\left|e(t)\right|dt \qquad (27)$$

ITAE criterion weighs the error with time and hence emphasizes the error values over a range of 0 to t, the latter is the expected settling time.

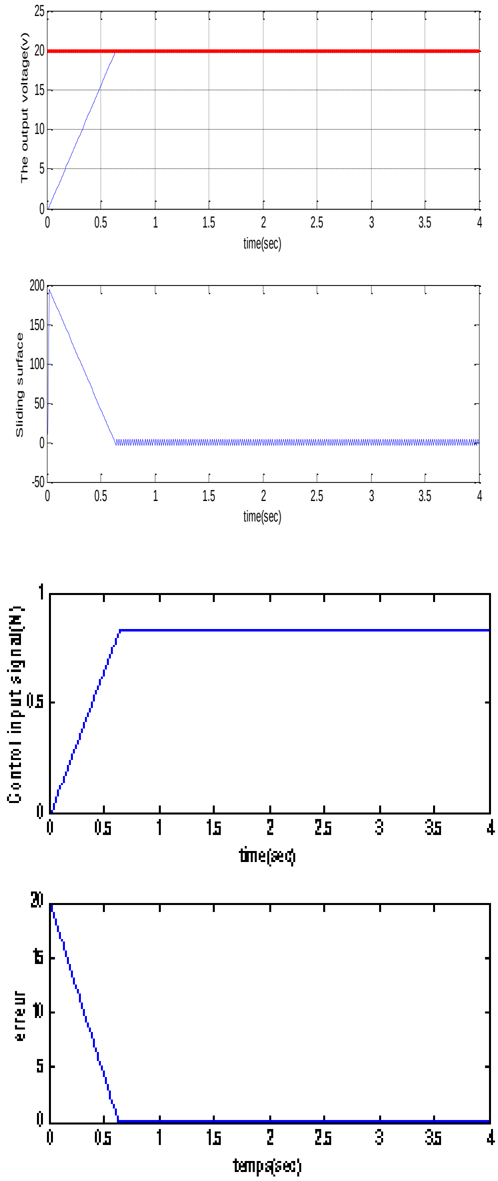
The proposed approach employs a PSO search for the optimum parameter settings of the proposed DC-DC converter terminal sliding mode control.

Control parameter to be tuned through the optimization algorithm is *(p/q)*, with the aim to minimize the selected fitness objective function thus improving system response performance in terms of settling time and overshoot.

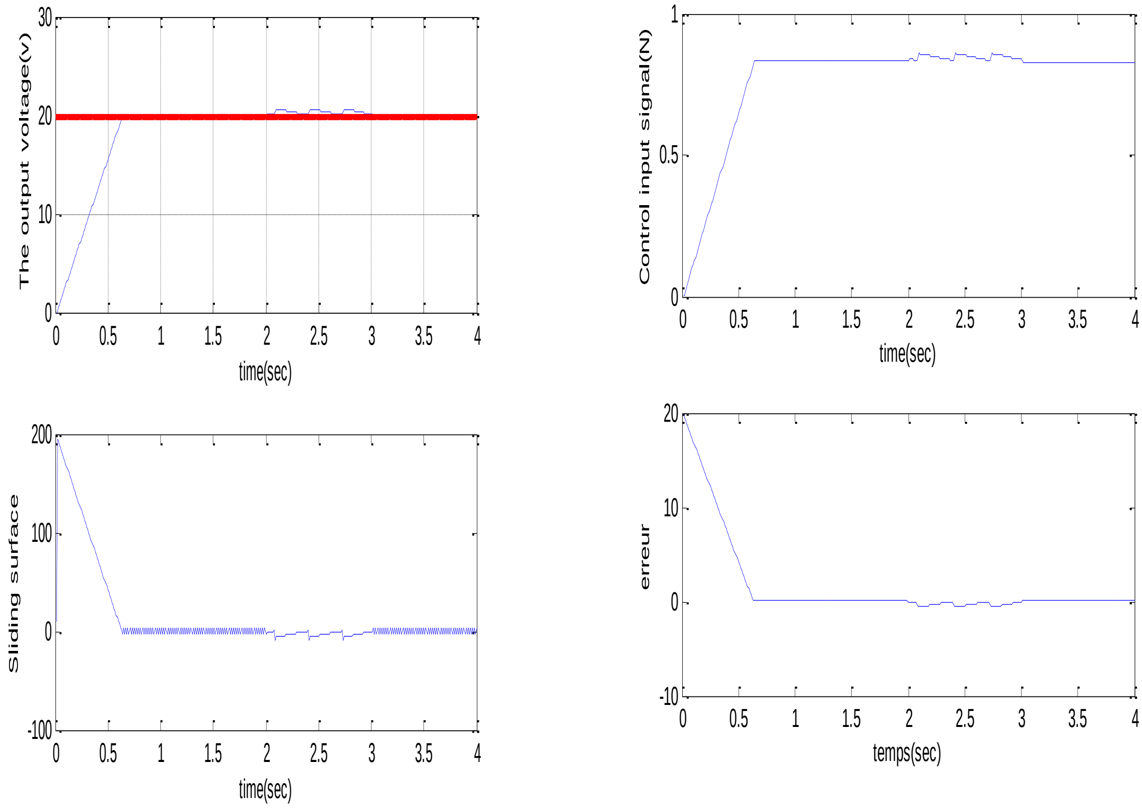
parameters used in design of the proposed controller are: p=5 *and* q=3.

6. Simulation Results

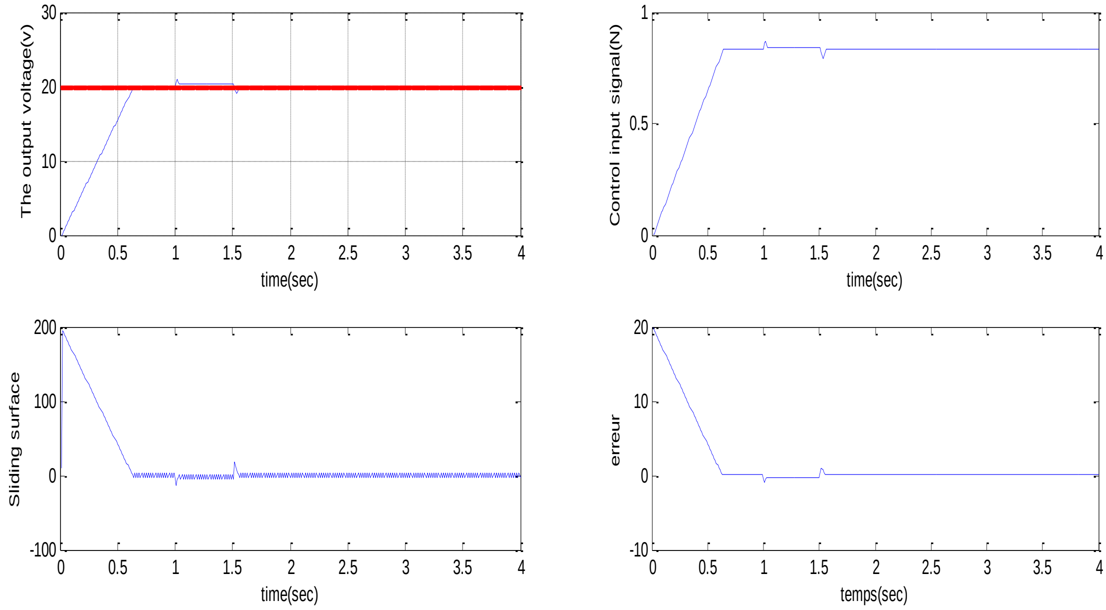
The proposed controller was used for a DC-DC buck converter and simulation operation was carried out. Parameters of DC-DC converter are chosen as $L = 80\mu H; E = 24V; R = 8\Omega; C = 2000\mu F$ .The expected tracking voltage is $r = 20v$. The initial state of this system is x=[0,0]. The starting main parameters used in design of the proposed controller are: p=5 *and* q=3.



a) normal operation for r=20v

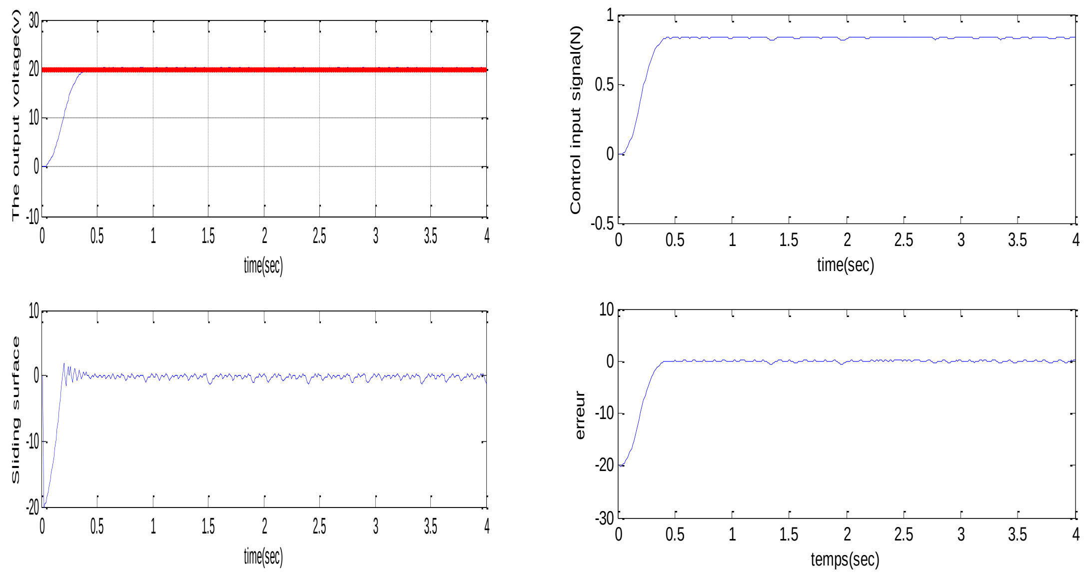


b) Application of a disturbance in the [2- 3 s] time range

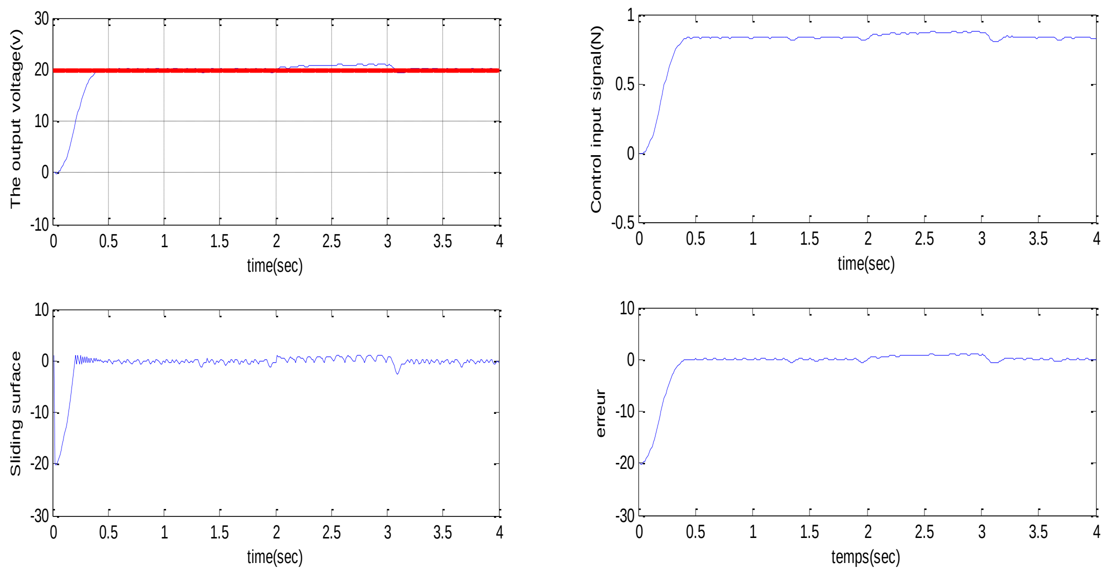


c) Periodic change of load resistor from R=8 to 20 Ω in the [1 1.5sec] time frame.

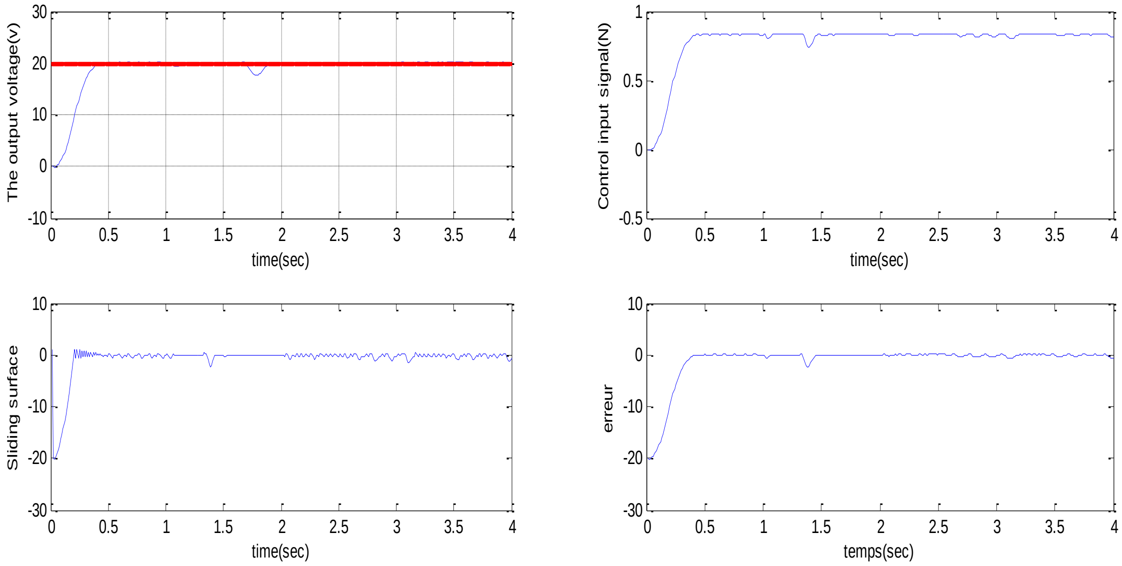
Fig.3. *Simulation signals for SMC control.*



a) Normal operation for r=20V

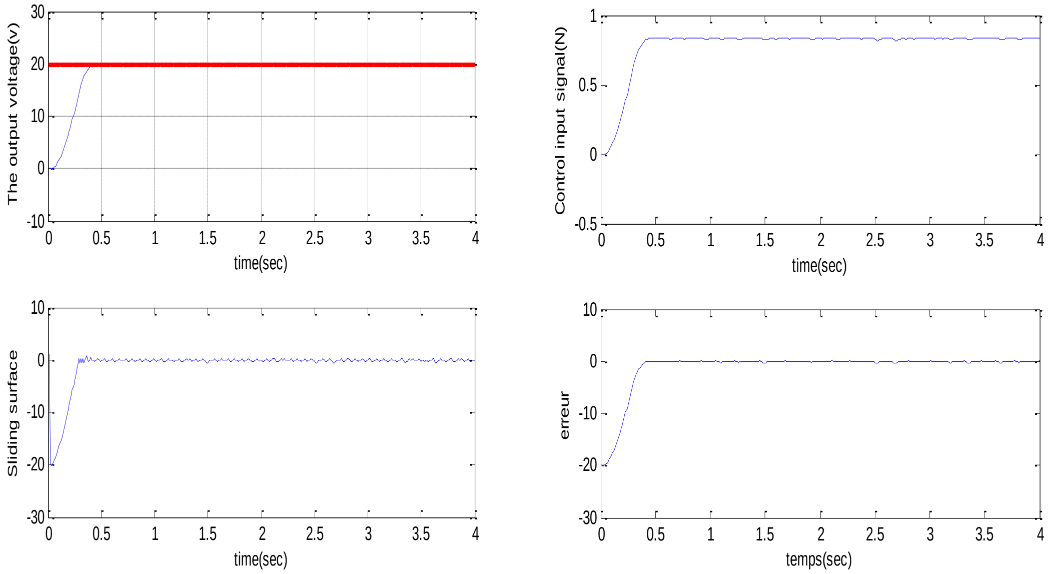


b) Application of a disturbance in the [2- 3.2 s] time range.

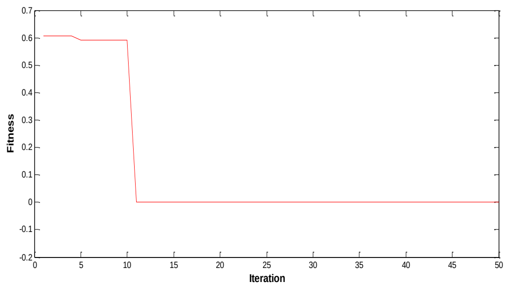


c) Periodic change of the load resistor from 8to 20 ohms in the [1-1.5 s] time frame.

Fig.4. *Simulation signals for TSMC control.*



1. Simulation results with PSO



2. *The objective function*

Fig.5. *Results of PSO-TSMC approach.*

Figures 3 and 4 show the responses profiles of output voltage, sliding surface, control input and tracking error for the two controllers.

The obtained results in regulation mode for the sliding mode control (SMC) and the terminal sliding mode control (TSMC) are shown in figures3.a and 4.a. These results show that the TSMC presents a faster convergence to the desired state than SMC's. Indeed the position error reaches zero in a time nearly equal to 0.6s by SMC whereas TSMC reaches zero in a time of the order of 0.4s.

In order to test the robustness of the two control laws, a perturbation is introduced at the instant 2s, obtained results are shown in figures 3.b and 4.b for the two controllers developed SMC and TSMC. The obtained simulation results show that the two controls laws verify the robustness property to disturbances in both approaches.

Figures 3.c and 4.c show the respective corresponding responses to load fluctuation. The load resistance varies from 8Ω to 20Ω at the time of 1s and returns to 8Ω at the time of 1.5s. From these results, one can see that tracking output voltage indicates a small rise time and nearly zero error.

Figure 5 shows the results of simulation using PSO. Optimized value for (p/q) was found to be equal to 1.5772. Simulation results show better chatter free performances.

VII. CONCLUSION

We have presented the development and simulation of terminal sliding mode control of a DC-DC converter using PSO to optimize control parameters. Terminal approach guarantees finite time convergence therefore increases system robustness. Global performances are up kept despite load variation or line disturbance. As an unexpected and most welcomed result, chattering decreases while using PSO with fast convergences after a shorter time than obtained with its classical counterpart.

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