Real-Time Implementation of Sliding Mode Controller for Buck Power Converter using DSpace 1104

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Abstract. This paper deals an experimental validation of a nonlinear controller using a sliding mode control (SMC) with integral action for a dc-dc buck power converter. The main control objectives are: i) perfect regulation of inductor current with unknown load resistance variation, ii) and ensure the asymptotic stability of the closed-loop system. To this end, a SMC with integral action is elaborated. Using Matlab-Simulink software, numerical simulations are carried out to show the effectiveness of the proposed approach. Furthermore, using an experimental test bench, the real-time controller is developed based on the Dspace 1104 card in real time (RT). It was shown, using formal analysis, simulations and experiments, that the controller achieves all desired performances.

Keywords: Buck power converter, real-time control (RTC), Non-linear control, Sliding mode controller (SMC), Dspace 1104 card, Matlab-Simulink.

1 INTRODUCTION

In the course of the last few years, electronic systems have grown exponentially in performance while circuits have become more compact. These developments now make it possible to integrate even complex and sophisticated technical features into portable housings. The technological development of power switches and control algorithms has made power converters more reliable in terms of efficiency, power density, and dynamic performance. A dc-dc power buck converter is one of the most used in several applications, such as switched power supplies, photovoltaic panels, electrical vehicles, batteries, PEM electrolyzer, etc.[1–3]
The choice of control technique for DC-DC power converters must follow for their intrinsic characteristic of non-linearity [4] and between measurement and large input voltage variations while maintaining stability in all operating conditions and providing fast transient response[5, 6].
DC-DC power converters are known to be structure variable systems; therefore, the sliding mode (SM) technique is more suitable for their control. This technique is characterized by the discontinuity of the control at the vicinity of the switching surface also called the sliding surface. The advantage of the variable structure control with the sliding mode is the robustness against changing parameters or system disturbances, [7]. Much research has proved that sliding mode control (SMC) has become a robust and efficient control with power electronics converters,[8,16,17].
The present paper aims to develop a SMC for controlling the inductor current of the buck converter in order to protect the load from strong currents and bad use, especially in the case of charging the battery or supercapacitor. The theoretical results have been analyzed and investigated by simulation software and experimental validation using Dspace 1104.

This document is organized as follows: firstly, a presentation of the buck converter and its modeling. secondly is dedicated to the controller design. The experimental validation of elaborating control law has been carried out in section three. in section four the robustness of the control law is checked and illustrated by a numerical simulation and practical validation. Finally, is a general conclusion to the document.

2 Buck converter presentation and state space modeling

Figure 1 shows a circuit structure of a DC-DC buck power converter, the system parameters are defined as follows: i_l is the inductor current, v_c is the voltage of the output capacitor, L is the inductance of filtering, C the filtering capacitor, R_{ch} represents the resistance load of the circuit, E is the voltage of the input source and u the binary input signal. The converter is controlled by a PWM technique whose duty cycle μ [0, 1].

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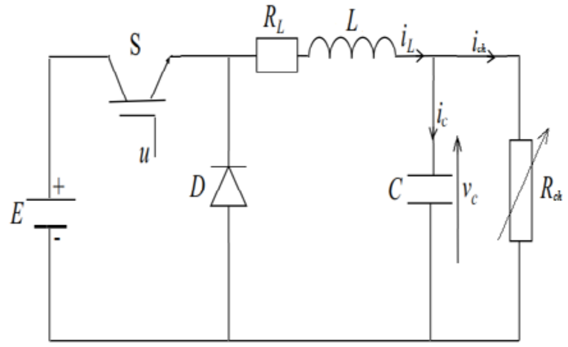

Fig 1: buck power converter circuit

The bilinear switching model of the buck power converter is obtained as follows:

$$\frac{di_L}{dt} = -\frac{v_c}{L} - \frac{R_L}{L} i_L + \mu \frac{E}{L} \quad (1a)$$

$$\frac{dv_c}{dt} = \frac{i_L}{C} - \frac{v_c}{R_{ch}} \quad (1b)$$

While it's averaged model is given by the following [9, 10]

$$\dot{x}_1 = -\frac{x_2}{L} - \frac{R_L}{L} x_1 + \mu \frac{E}{L} \quad (2a)$$

$$\dot{x}_2 = \frac{x_1}{C} - \frac{x_2}{R_{ch}} \quad (2b)$$

Where x_1 and x_2 denote the average values, let's define the state space variables as $[x_1, x_2]^T = [i_l, v_{dc}]^T$,and μ is the control signal PWM which $\mu \in [0,1]$ (the duty ratio of the signal).

3 Sliding mode control design

We recall the main control objectives, which are defined in the abstract which formulated as follows:

i) Robustness of the controller in the presence of load resistance variation, (Monitoring of inductance current i_l to its reference I_{Lref}).
ii) Ensuring the asymptotic stability.

According to the SMC technique, the following sliding surface with integral action is defined as [11–13]:

$$S = K_1 e + K_2 \int_0^t e\,dt \quad (3)$$

where $e = x_1 - x_{1ref}$ and $x_{1ref} = I_{Lref}$, I_{Lref} is the current reference, K_1 and K_2 are conception parameters.
The derivative of the equation (3) is given by:

$$\dot{S} = K_1 \dot{e} + K_2 e = K_1 \left(-\frac{x_2}{L} - \frac{R_L}{L} x_1 + \mu \frac{E}{L} \right) + K_2 e \quad (4)$$

Based on the SMC technique, the control law μ as a function of two components: first is an equivalent component μ_{eq} and second μ_n is nonlinear.

$$\mu = \mu_{eq} + \mu_n \quad (5)$$

the system moves on the surface following the excitation produced on its input by the control component each time the system is on the sliding surface. The existence of the sliding mode implies that $\dot{S} = 0$,[14, 15].
It follows that μ_{eq} can be deduced by using (4) and the invariance condition in sliding mode $\dot{S} = 0$, as follows:

$$\mu_{eq} = \frac{1}{E} \left(x_2 + R_L x_1 - L \frac{K_2}{K_1} e \right) \quad (6)$$

The second term μ_n is to ensuring the equilibrium $S = 0$ to be globally asymptotically stable. Let's us define now the following positive Lyapunov function shown in (7).

$$V = \frac{1}{2} S^2 \quad (7)$$

Its time derivative of (7) becomes:

$$\dot{V} = \dot{S} S \quad (8)$$

This equation gives, using (4) and (5)

$$\dot{V} = \left(-K_1 \frac{x_2}{L} - K_1 \frac{R_L}{L} x_1 + (\mu_{eq} + \mu_n) K_1 \frac{E}{L} + K_2 e \right) S \quad (9)$$

Combining now the equations above, (8) could be rewritten as follows:

$$\dot{V} = \mu_n K_1 \frac{E}{L} S \quad (10)$$

Accordingly, to this equation the nonlinear component μ_n can be chosen as follows:

$$\mu_n = -\frac{L}{EK_1} \lambda S \quad (11)$$

Where λ is a positive coefficient parameter.
with this choice, (10) becomes

$$\dot{V} = -\lambda S^2 \quad (12)$$

which is a negative definite. This ensures that the equilibrium $S = 0$ is globally asymptotically stable. It follows that the tracking error $e = x_1 - x_{1ref}$ is exponentially vanishing, which in turn shows that the inductor current perfectly tracks its reference.

Finally, combining (5), (6), and (11), the obtained sliding mode control law is given as follows

$$\mu = \frac{1}{E}\left(x_2 + R_L x_1 - L\frac{K_2}{K_1}e - \frac{L}{K_1}\lambda S \right) \tag{13}$$

4 Simulation and Experimental results

This Subsection aims to illustrate the effectiveness of the proposed SMC given by simulation and experimentation validation. The simulation bench of the Buck converter control is described by Fig. 3 and is simulated using the MATLAB/simulink software. The experimental bench is illustrated in Fig. 4. The controller is elaborated in RT using a Dspace 1104 card with the Control Desk software. The experimental test bench consists of a digital oscilloscope, a power supply from BK Precision, a dc-dc buck power converter, a Hall Effect voltage and current sensors, a DSpace 1104 with Control Desk software, a 300W Programmable DC Electronic Load from BK Precision operated under multiple modes such as constant current (CC), constant voltage (CV), constant power (CW), and constant resistance (CR). The parameters system is listed in Table 1.

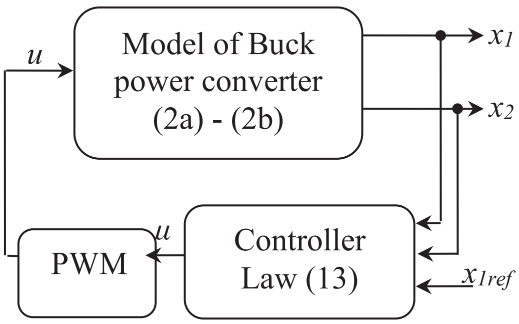

Fig. 3: bench of the Buck converter

Table 1. Simulation Parameters

Paramètre	Value
Inductance *L*	4mH
Resistor R_L	620mΩ
Resistor, R_{ch}	6Ω - 12Ω
Source, E	24V
Capacitance, C	220µF
Design parameter K_1	500
Design parameter K_2	1000
Design parameter Landa	1000
Switching frequency, f_{sim}	15kHz
Switching frequency, f_{exp}	25kHz

The power card consists of an IGBT transistor IRG4PH50S, an IGBT driver HCPL3101, and a power diode STTA 3006.

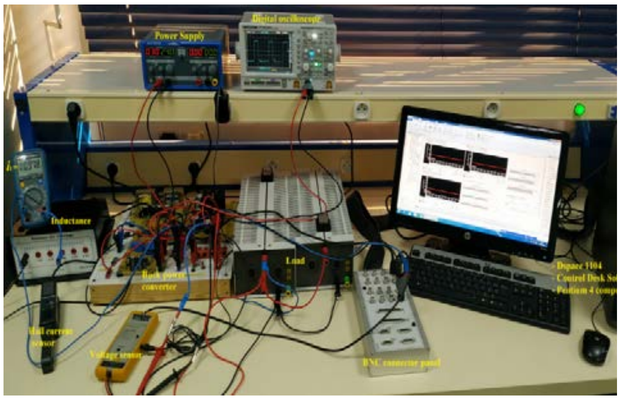

Fig 4: View of the experimental test bench.

4.1 Controller performances in the presence of time-varying reference

This Subsection is devoted to evaluate the tracking performances while the load resistance is kept constant. Fig. 5 shows that the measured current I_L tracks perfectly its reference signal, while Fig. 6 shows the tracking error between the reference current I_{Lref} and the measured current I_L. This figure illustrates a good tacking behavior of the controller. Fig.7 shows the resulting output voltage.

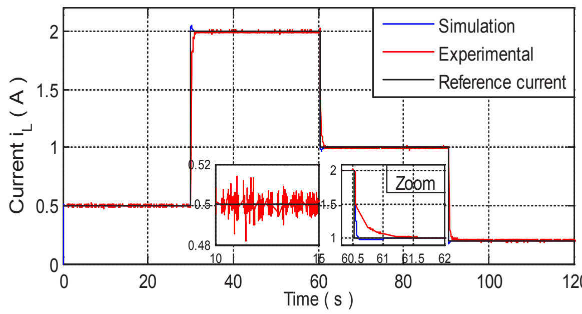

Fig. 5: The measured current i_l and its reference with a zoom.

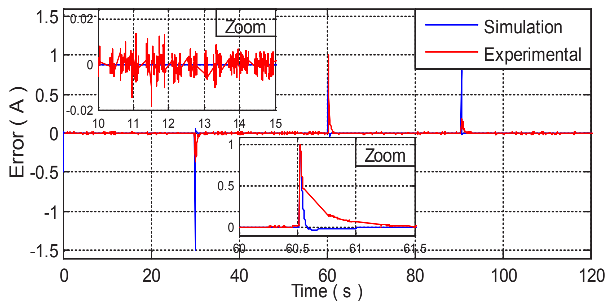

Fig. 6: The tracking error

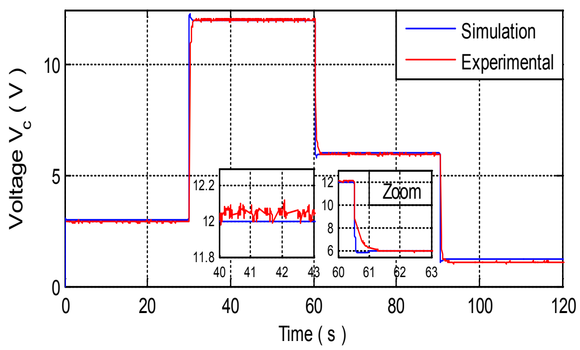

Fig. 7: The output voltage

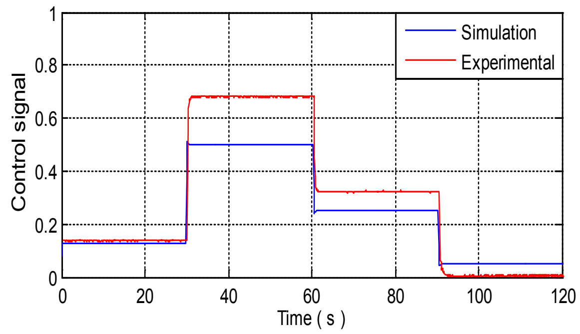

Fig. 8: The control signal

4.2 robustness in the presence of load resistance variations

In this Subsection we will show the robustness of the technique chosen in the presence of a varying load resistance while the current reference signal I_{Lref} is kept constant. The resistance varies from R = 6Ω to R = 12Ω at the instant t = 30s, and returns to R = 6Ω at time t = 60s. Fig. 9 and Fig. 10 illustrate a good tracking performance. Fig. 11 and Fig.12 show, respectively the output voltage and the control signal.

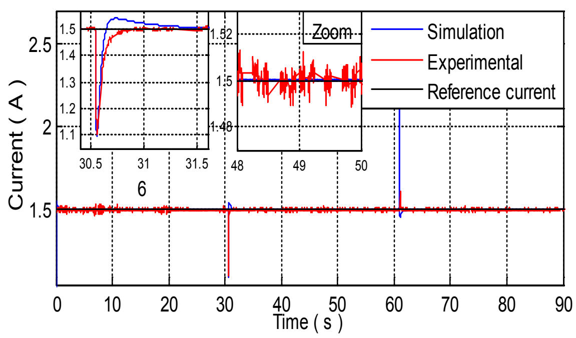

Fig. 9: The measured current iL and its reference in the presence of load resistance variations.

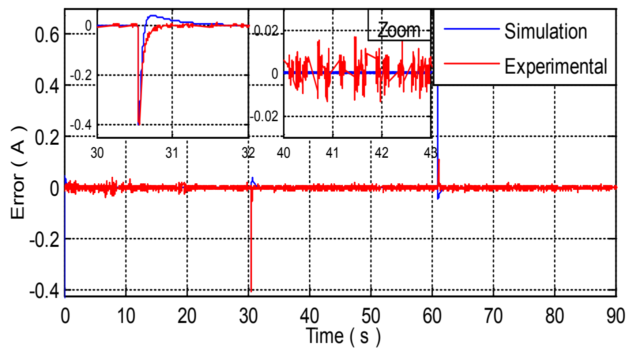

Fig. 10: The tracking error in the presence of load resistance variations.

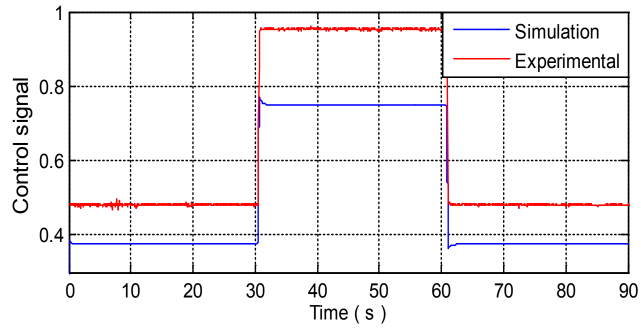

Fig.12: The control signal in the presence of load resistance variations

5 Conclusion

In this study, a SMC with integral action for a dc-dc Buck power converter has been deal with. The controller is elaborated based on an averaged model of the converter to ensure two objectives, namely: i) a tight regulation of the inductor current in presence of large load resistance variations, ii) and global asymptotic stability of the closed-loop system. It was shown, using formal analysis, simulations and experiments, that all controller objectives desired performances have been achieved.

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