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AN APPROACH TO DESIGN OF DIGITAL SLIDING MODE CONTROL FOR BUCK-BOOST CONVERTER

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Abstract: *The paper deals with design of DC-DC buck-boost converter controlled by the combination of digital sliding mode control and generalized minimum variance control. This approach can also be implemented for different converter topologies operating in the continuous conduction mode. The converter switch is driven by PWM signal, generated by controller using only sensed output voltage. Simulation results shows that the proposed digital control algorithm provides a small voltage ripple in steady-state and good dynamic performances under different operation conditions, which include intensive load and parameter variations.*

Key Words***: DC-DC Converter, Buck-Boost Converter, Sliding Mode, Pulse Width Modulation.***

1. INTRODUCTION

DC-DC converters are circuits that convert DC voltage from one voltage level to another. These converters are nonlinear and time-variant plants. Buck-boost converter is one of these converters, used to generate an output voltage less than, greater than, or equal to the input voltage. The circuit usually consists of three stages: power-, controller-, and the pulse width modulation stage.

Choosing controller algorithms and design techniques, which can be applied in control of these converters, is a big challenge because each one has its own advantages and disadvantages, taking into account cost, size, switching speed, efficiency and flexibility. The controller should provide satisfactory dynamic performances as to be as simple as possible. In order to reduce costs and improve the converter robustness, we propose digital sliding mode (SM) controller.

SMcontrol is a nonlinear control method that alters the dynamics of a nonlinear system by applying a discontinuous control signal that forces the system to "slide" along a predefined hyper-surface [1, 2]. Its main advantage is its insensitivity to parameter variations, external disturbances and modeling errors [3, 4]. With the advent of digital computers and its widespread use in control systems, considerable efforts have been made in the study of digital SM control techniques [5, 6, 7].

Digital SM controller, proposed herein, is based on the generalized minimum variance control method [8] that enables the design of control law only on input-output plant model. This approach is therefore very suitable for the synthesis of buck-boost converter, since there is no need for additional current sensors. The similar control laws are implemented in the design of buck converter [9, 10], operating in continuous conduction mode (CCM) [11, 12].

The paper is organized as follows. In section 2 the topology of buck-boost converter is considered and a discrete-time model of the circuit is derived using the state-space equations [12]. The control law design procedure for this converter, using SM control strategy that is based on the generalized minimum variance control method, is given in section 3. The converter performances are checked by using digital simulation, and the results are discussed in section 4.

2. MODEL OF BUCK-BOOST CONVERTER

The topology of buck-boost converter is presented in Fig. 1. Its basic operational principle is described as follows. When the switch S_W is ON, the input voltage source V_i is directly connected to the inductor L. Thus the energy accumulates in L, whereas the output voltage is supplied to the load R_L by the capacitor C, as the diode D is inverse polarized. During the switch OFF-state, the inductor L is connected through the diode D to the output load R_L and capacitor C, so the energy is directly transferred from L to C and R_L. The converter output voltage has a polarity opposite to the input voltage and can vary continuously from 0 to $-\infty$ (theoretically in ideal case). There are three operational modes: (*i*) step-down mode with output voltage from 0 to V_i, (*ii*) step-up mode with output voltage above V_i, and (*iii*) inverter mode with output voltage equal to - V_i.

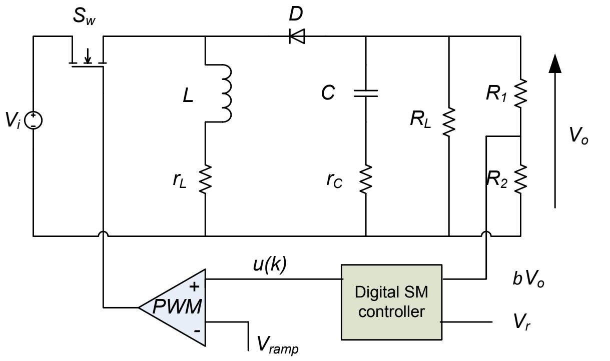


Fig. 1. *Buck-boost converter with digital SM controller*

During normal operation of the buck-boost power stage, the electric switch S_W is repeatedly switched on and off with the on- and off-times governed by the controller output. This switching action gives rise to a train of pulses at the junction of S_W, diode D and L. As the inductor L is connected to the output capacitor C only when the diode D conducts, an effective L/C output filter is formed when switch S_W is OFF. The PWM duty cycle ratio d defines the converter operational mode according to:

$$\frac{V_o}{V_i} = -\frac{d}{1-d}, \quad (1)$$

where $d \in (0,1)$, so the output voltage V_o can vary between lower or higher than the input voltage V_i in magnitude. When the duty cycle d is exactly 0.5, V_o is equal to $-V_i$.

The mathematical model of buck-boost converter in state space can be easily derived as [13]:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{1}{R_L C} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{\beta V_o}{LC} \end{bmatrix} \bar{u}, \quad (2)$$

with all elements considered ideal [13, 14, 15, 16]. β is a voltage divider ratio, and $x_1 = V_o$. The converter transfer function can be written now in the following form:

$$W_{bbc}(s) = \frac{Y(s)}{U(s)} = \frac{\frac{\beta V_o}{LC}}{s^2 + \frac{1}{R_L C} s}, \quad (3)$$

where $Y(s) = X_1(s)$. With the assumption that no external disturbance is affecting on the system under control, the input-output model of the system in z-domain is:

$$y(k) = \frac{z^{-1} B(z^{-1})}{A(z^{-1})} u(k), \quad (4)$$

and:

$$A(z^{-1}) = a_0 + a_1 z^{-1} + a_2 z^{-2}, \quad (5)$$

$$B(z^{-1}) = b_0 + b_1 z^{-1}. \quad (6)$$

z^{-1} is an unit delay i.e. $z^{-1} = e^{-pT}$, where p denotes a complex variable and T is a sampling period.

3. DIGITAL SLIDING MODE CONTROL

In this paper, the proposed controller for buck-boost converter is digital SM based GMV control [8] given in the following form:

$$u(k) = -\frac{F(z^{-1})y(k) - C(z^{-1})V_r(k+1) + \frac{\alpha T}{1-z^{-1}} \operatorname{sgn}(s(k))}{E(z^{-1})B(z^{-1}) + Q(z^{-1})}, \quad (7)$$

under an assumption that the reference input signal $V_r(k)$ is known in advance. $s(k)$ represents the switching function defined by:

$$s(k+1) = C(z^{-1})\left(y(k+1) - V_r(k+1)\right) + Q(z^{-1})u(k), \quad (8)$$

with:

$$C(z^{-1}) = c_0 + c_1 z^{-1} + c_2 z^{-2}, \quad (9)$$

$$C(z^{-1}) = (1 - e^{-2\pi f_c T} z^{-1})^2, \quad (10)$$

where f_c is a cut-off frequency. $C(z^{-1})$ is a polynomial with all zeros inside the unit disk of z-plane, and $Q(1) = 0$. The polynomials $E(z^{-1})$ and $F(z^{-1})$ are the solutions of Diophantine equation:

$$C(z^{-1}) = E(z^{-1})A(z^{-1}) + z^{-1}F(z^{-1}), \quad (11)$$

Notice that $s(k)=0$ is an equation of sliding hyper-surface in general case. Substituting (7) in (4), considering (8) and (11), gives:

$$s(k+1) = s(k) - \alpha T \operatorname{sgn}(s(k)), \quad (12)$$

Equation (12) defines the dynamics of switching function. If $\alpha > 0$, a quasi-sliding motion is established in Δ-vicinity of $s(k)=0$, i.e. $|s(k)| \le \Delta$ is always satisfied, where Δ is a function of αT [8].

In SM, the system is stable if the roots of:

$$B(z^1)C(z^1) + A(z^{-1})Q(z^{-1}) = 0, \quad (13)$$

lie inside the unit disk in the z-plane, and the pairs ($B(z^{-1})$, $Q(z^{-1})$),($C(z^{-1})$, $A(z^{-1})$) and ($C(z^{-1})$, $Q(z^{-1})$) do not have a common zeros outside this disk.

As the sensed output voltage βV_o is compared with the referent voltage V_r, resulting in an error signal that is only fed to the digital SM controller, there is no need for the use of current sensors. On the other side, a signal $u(k)$ is fed to the PWM stage, where is compared with the ramp signal, providing a PWM signal u that drives the switch S_W. It is proven in [12] that the average dynamics of system with digital SM control is equivalent to the average dynamics of PWM controlled system, implying that the equivalent control $u_{eq}(k)$ in SM corresponds to the duty cycle control signal d of PWM stage:

$$0 < d = \frac{u(k)}{V_{ramp}} < 1. \quad (14)$$

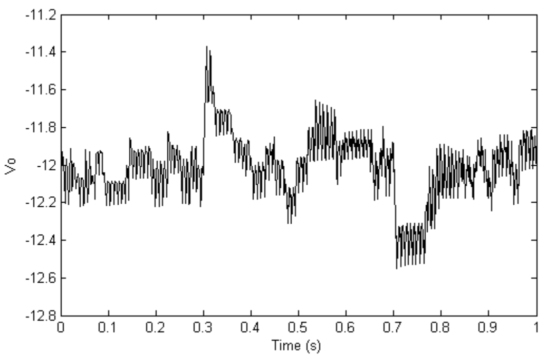
4. SIMULATION RESULTS

A validation of the proposed buck-boost converter with digital SM control is done by digital simulation. The values of converter parameters are listed in Table 1.

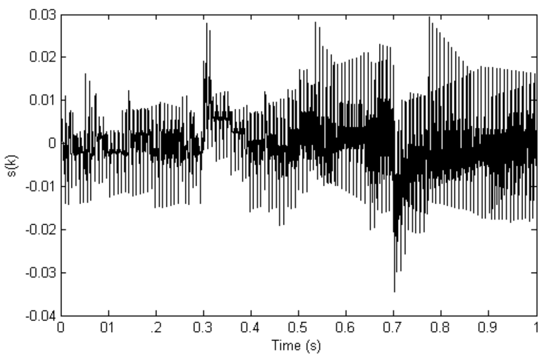
Table .1 *Buck-Boost converter parameter values*

Description	Parameter	Nominal Value
Input voltage	V_i	12 V
Capacitance	C	1470 μF
Capacitor resistance	r_c	0.001 Ω
Inductance	L	300 μH
Inductor resistance	r_L	0.14 Ω
Load Resistance	R_L	34 Ω
Specified output voltage	V_o	12 V
Sampling period	T	1 ms
Cut-off frequency	f_{cut}	100 Hz
PWM frequency	f_{pwm}	8 kHz
Controller gain	α	10
Voltage divider ratio	β	0.1

Figs. 2-4 present the simulation results of buck-boost converter in different operational modes. Each figure contains output voltage and switching function responses. As an external disturbance, we consider the load current 0.35 A, acting on the converter output between 0.3s and 0.7s. As far as parameter perturbations concern, on-line changing of operational modes can produce these variations.

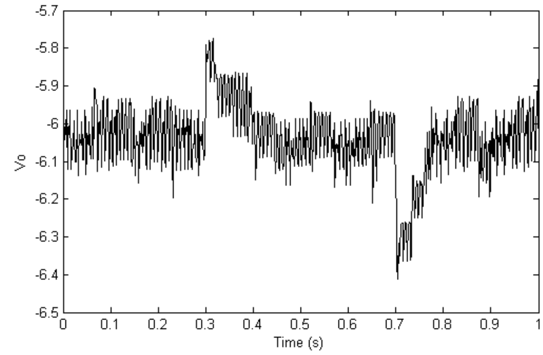


(a) *Output voltage*

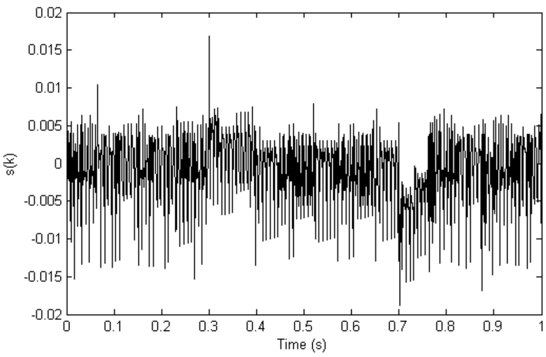


(b) *Switching function*

Fig. 2 *Buck-boost converter in inverter mode*

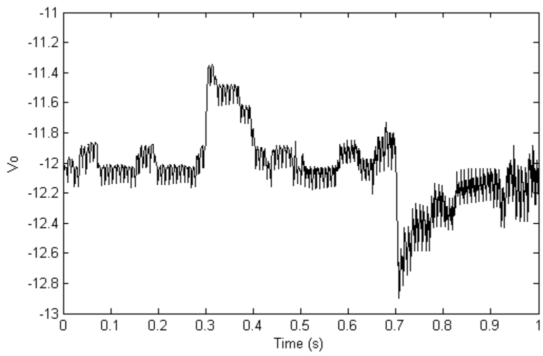


(a) *Output voltage*

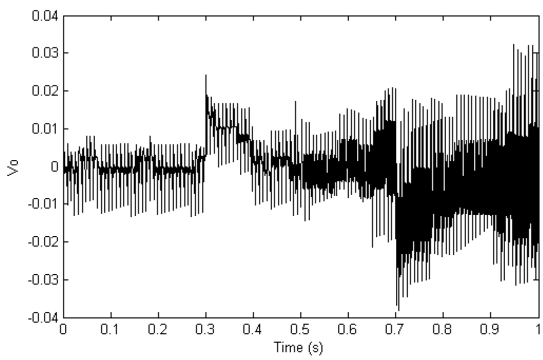


(b) *Switching function*

Fig. 3 *Buck-boost converter in step-down mode*



(a) *Output voltage*



(b) *Switching function*

Fig. 4 *Buck-boost converter in step-up mode*

Fig. 2 shows the response of converter in inverter mode when the output voltage is the same as the input one, but with inverse polarization. The performances when converter behaves as the buck one is presented in Fig. 3. The scenario when the input voltage has dropped from 12 V to 10 V is depicted in Fig. 4. In that case, the converter operates in the step-up mode. All presesented simulation results justify the implementation of the proposed digital SM control law in the design of buck-boost converter.

4. CONCLUSION

In this paper, we consider a buck-boost converter with digital sliding mode control based on the generalized minimum variance control method. The proposed control algorithm is applicable in different converter topologies, operating in continuous conduction mode (CCM). It guarantees improved robustness, faster transient response, low output ripple, and better steady-state accuracy of buck-boost converter. Furthermore, we achieve this measuring only output voltage signal. The converter performances are verified both theoretically and by means of digital simulation.

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