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Application Article

Avoidance High-Frequency Chattering Second-Order Sliding Mode Controller Design: Buck Converter in Wind Power System

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This paper mainly discussed a method of high-frequency second-order sliding mode control for Buck converter in wind power systems. Because the wind energy of nature is always unpredictable and intermittent, the robust control such as sliding mode control is adopted in past literatures. In order to remove the high frequency chattering problem when the traditional sliding mode achieves convergence, the second order sliding mode algorithm is reviewed firstly. Meanwhile, the Buck converter taken as a step-down converter is usually adopted in wind power system, because of its simple structure and good linearity. Under those conditions, the second order sliding mode controller is designed based on Buck converter, especially in high-power wind generation system. The experimental results illustrate that the theory of second order sliding mode can be used in high-power Buck converter. It provides one novel avoidance high frequency chattering method for the technology development of new energy generation system.

1. Introduction

Conventional energy resources may run out of in the following few decades, especially from fossil energy could lead to the energy shortage in the world. Moreover, the energy consumption is increased dramatically in recent years. The renewable energy sources, such as solar, wind, or ocean wave energy, are considered to be the future energy solutions. Thanks to the extensive research in renewable energy field, those energies can be exploited more and more easily and properly [1–3].

Among the renewable resources, the wind energy is gaining greater visibility during the last several years as a convenient and promising energy source in the future [4]. The application of wind energy is divided into two aspects. One is off-grid wind power station with the battery as energy storage component, and the other is connect-to-grid wind turbine. In many applications, such as small villages or islands power station, the off-grid wind power generation system provides an excellent energy solution. The key problem of this kind of energy production systems is that they are unstable energy sources due to their primary source in nature.

Thus, an energy storage component is usually added to form a hybrid energy system. In such a system, the suitable power converter plays an important role in energy conversion and management system.

Generally speaking, these converters should be adaptive for wider wind speed range in order to improve the system performance. In a wind generation system, two types of converter can be usually found: a primary AC/DC converter connected directly to the wind turbine generator and a secondary DC/DC converter connected to the load. As known, the nonisolated DC/DC Buck converter is usually used in lower power system [5–7]. For robustness improvement, the sliding mode technology is widely used.

Well known to all is that the PI control has become classical method in engineering applications owing to its simple structure and universality. The switch property of power device in converter makes the converter becomes discrete time-variable system. Thus, the sliding mode control holds strong suitability for Buck converter [8]. However,

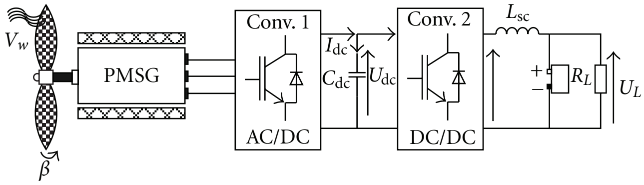

Figure 1: Off-grid wind power generation system.

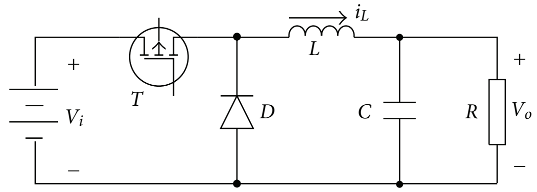

Figure 2: Buck converter topology.

traditional sliding mode control has the drawback of chattering phenomenon owing to its discrete control law. In order to overcome this disadvantage, a high frequency second order sliding mode control algorithm was proposed by Bartolini et al. [9] and Levant et al. [10].

A second sliding mode controller for Buck converter is designed in this paper when the system relative degree equals $r = 2$. By taking the derivative of sliding mode variable s continuously, until the control input u appears, it makes discrete control law acts on the second order sliding mode manifold $\dot{s}$, so that the lower sliding mode manifold s avoids high frequency chattering. The experiment results illustrate that the system holds good performance, especially in high-power Buck converter.

This paper is organized as follows. In Section 2, the related system structure and mode of Buck converter are given. In Section 3, the second order sliding mode method based on the Buck converter is presented. The experimental results of the algorithm proposed in this paper with Buck converter for wind power system are also presented in Section 4. Finally, our work of this paper is summarized in Section 5.

2. System Structure and Mode of Buck Converter

In general, six parts can be distinguished in an off-grid wind power generation system. They are wind turbine, permanent magnet synchronous generator (PMSG), AC/DC rectifier, DC/DC converter, storage battery, and load. The structure of the system is presented in Figure 1.

The wind energy in nature drives the turbine to whirl. From where the PMSG produces the AC electrical energy, whose frequency is variable, depends on the random wind speed in the nature under the external torque. Through the AC/DC rectifier, the DC electrical energy with alterable amplitude is obtained. In comparison with conventional Buck converter, the wider input voltage range is a novel challenge for the converter design. For system performance consideration, the maximum power point tracking (MPPT) technology control method is used [11, 12], in order to ensure a stable DC output for storage battery and load.

The topology of Buck converter is shown in Figure 1. T is switch, L is inductance, C is capacitance, D is freewheel diode, and R is load resistance. i_L is the current of inductance L, V_i is input voltage, and V_o is output voltage.

The Buck converter has double modes, which are conduction and shutoff of switch. From Figure 2, according to the KCL and KVL, there should be

$$\begin{aligned} C\frac{dV_o}{dt} + \frac{V_o}{R} &= i_L, \\ L\frac{di_L}{dt} + V_o &= V_i \cdot \Delta. \end{aligned} \tag{1}$$

The state function of Buck converter is rewritten by

$$\begin{bmatrix} \dfrac{dV_o}{dt} \\ \dfrac{di_L}{dt} \end{bmatrix} = \begin{bmatrix} \dfrac{-1}{RC} & \dfrac{1}{C} \\ \dfrac{-1}{L} & 0 \end{bmatrix} \begin{bmatrix} V_o \\ i_L \end{bmatrix} + \begin{bmatrix} 0 \\ \dfrac{\Delta}{L} \end{bmatrix} V_i, \tag{2}$$

where Δ is duty cycle. Let $x = [x_1, x_2]^T = [V_o, i_L]$, and let the control input of system $u = V_i$; then the above equation can be rewritten by

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} k_1 & k_2 \\ k_3 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ k_4 \end{bmatrix} u, \tag{3}$$

where $k_1 = -1/RC + \delta k_1$, $k_2 = 1/C + \delta k_2$, $k_3 = 1/L + \delta k_3$, and $k_4 = \Delta/L + \delta k_4$. In the expressions, the δk_i ($1 \le i \le 4$) represents the uncertainty part of system parameters.

3. Second Order Sliding Mode

It is necessary to review the principle of second order sliding mode. The sliding mode control is known to be a robust approach to solve the control problems of nonlinear systems. Robustness properties against various kinds of uncertainties such as parameter perturbations, external disturbances, and measurement errors can be guaranteed. However, this control strategy has a main drawback: the well-known chattering phenomenon [13]. In order to reduce the chattering, an approach called second order sliding mode (SOSM) has been proposed, whose convergence trajectory curve on s and s' is shown in Figure 3. Some literatures also call it as the dynamic sliding mode control (DSM) [14].

Without losing generality, considering a state equation of single input nonlinear system as

$$\begin{aligned} \dot{x} &= f(x) + g(x)u, \\ y &= s(x,t), \end{aligned} \tag{4}$$

where $x \in R^n$ is system state variable, t is time, y is output, and u is control input. Here, $f(x)$, $g(x)$, and $s(x)$ are smooth function. The control objective is making output function $s \equiv 0$.

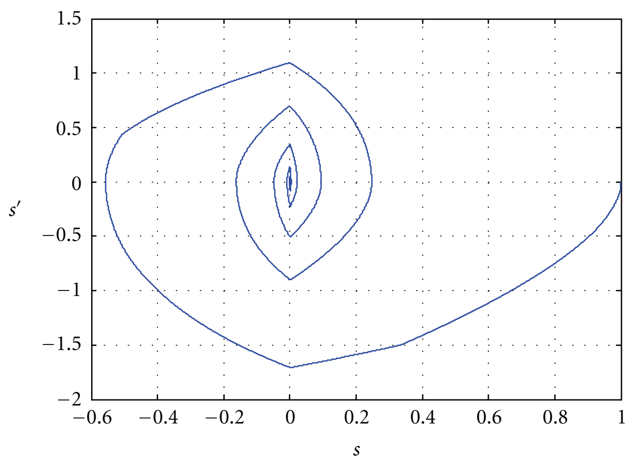

Figure 3: The convergence trajectory of twisting algorithm.

Differentiating the output variables continuously, we can get every order derivative of s. According to the conception of system relative degree, there are two conditions:

(I) Relative degree $r = 1$, if and only if $(\partial/\partial u)\dot{s} \neq 0$.

(II) Relative degree $r \geq 2$, if $(\partial/\partial u)s^{(i)} = 0$ $(i = 1, 2, \ldots r - 1)$ and $(\partial/\partial u)s^{(r)} \neq 0$.

If the relative degree $r = 1$, traditional sliding mode control can be used to design controller. Else, it needs to design a second order sliding mode controller. Second order sliding mode control is able to eliminate chattering.

Supposing system relative degree equals 1 and differentiating sliding mode variable twice continuously, then

$$\begin{aligned} \dot{s} &= \frac{\partial}{\partial t}s(x,t) + \frac{\partial}{\partial x}s(x,t)[f(x) + g(x)u], \\ \ddot{s} &= \underbrace{\frac{\partial}{\partial t}\dot{s}(x,t) + \frac{\partial}{\partial x}\dot{s}(x,t)[f(x) + g(x)u]}_{\varphi(x)} + \underbrace{\frac{\partial}{\partial u}\dot{s}(x,t)\dot{u}}_{\gamma(x)} \\ &= \varphi(x) + \gamma(x)\dot{u}. \end{aligned} \tag{5}$$

In order to achieve this aim of eliminating chattering, the $\dot{u}$ derivative of control input u is made as actual control variable. The discontinuous control law $\dot{u}$ will drive sliding mode variable $s = 0$ in the second order sliding mode surface S^2. In this way, chattering is eliminated [15].

Definition 1. Supposing given sliding mode variable is $s(x, t)$, second order sliding mode surface (or called sliding mode manifold) is defined as

$$S^2 = \{x \in X \mid s(x,t) = \dot{s}(x,t) = 0\} \quad x \in R^n. \tag{6}$$

To illustrate the tightness of control algorithm, the following conditions must be met u is continuous and bounded norm function:

$$\|f(x)\|_2,\ \|g(x)\|_2 \text{ are bounded}, \quad \gamma(x) > 0. \tag{7}$$

In meeting the above bounded conditions, there must be positive constants Γ_m, Γ_M, and Φ so that

$$\begin{gathered} 0 < \Gamma_m \leq \gamma(x) \leq \Gamma_M, \\ |\varphi(x)| \leq \Phi. \end{gathered} \tag{8}$$

A second order sliding mode algorithm is called twisting, which shuttle among the double differentiation manifold so that system can converge into zero within finite time [16]. If the relative degree of system equals 1, the detail control law is

$$\dot{v}(t) = \begin{cases} -u & |u| > u_{\max} \\ -V_m \operatorname{sign}(s) & s\dot{s} \leq 0;\ |u| \leq u_{\max} \\ -V_M \operatorname{sign}(s) & s\dot{s} > 0;\ |u| \leq u_{\max}. \end{cases} \tag{9}$$

Likewise, if the relative degree equals to 2,

$$v(t) = \begin{cases} -V_m \operatorname{sign}(s) & s\dot{s} \leq 0 \\ -V_M \operatorname{sign}(\dot{s}) & s\dot{s} > 0. \end{cases} \tag{10}$$

The sufficient condition of the sliding mode surface convergence into origin with finite time is

$$\begin{gathered} 0 < V_m < V_M, \\ \frac{\Phi}{\Gamma_m} < V_m, \\ \Gamma_m V_M - \Phi > \Gamma_M V_m + \Phi. \end{gathered} \tag{11}$$

The convergence trajectory of twisting algorithm is shown in Figure 2. It converges to origin with finite time asymptotically.

4. Controller Design

Suppose all the variables can be measured. The sliding mode surface is chosen as

$$s = x_1 - x_{1\text{ref}} = 0, \tag{12}$$

where $x_{1\text{ref}}$ is the reference of output voltage. Take the derivate of s, then

$$\dot{s} = \dot{x}_1 - \dot{x}_{1\text{ref}} = k_1 x_1 + k_2 x_2 - \dot{x}_{1\text{ref}}. \tag{13}$$

The control input u does not appear in (13). So take the derivative of $\dot{s}$ until u appears out.

$$\ddot{s} = (k_1^2 + k_2 k_3)x_1 + k_1 k_2 x_2 + k_2 k_4 u - \ddot{x}_{1\text{ref}}. \tag{14}$$

Thus, the system relative degree is 2. The twisting algorithm (10) is used now. Remarkably, the choice of sliding mode surface is not unique. For example, the following sliding mode surface is selectable:

$$s = \dot{x}_1 - \dot{x}_{1\text{ref}} + \lambda(x_1 - x_{1\text{ref}}) = 0. \tag{15}$$

In (15), λ is a positive constant, which should satisfy Hurwitz polynomial $P(z) = \dot{z} + \lambda z$. When we derive s, the control input u first appears in expression. So the relative degree equals 1. The corresponding algorithm (9) can be used. In this paper, the algorithm of the relative degree equaling 2 is adopted.

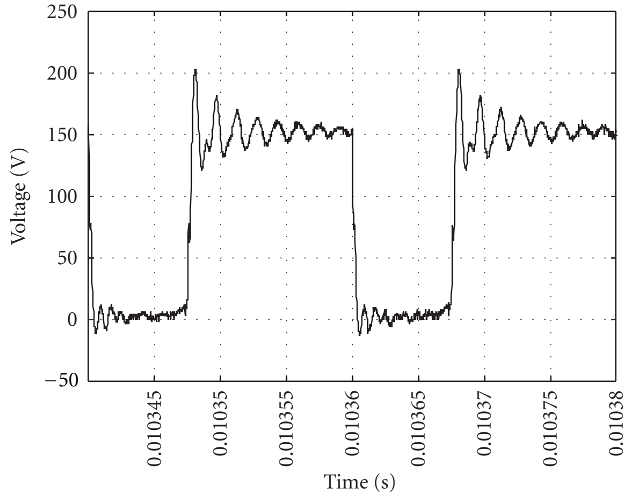

Figure 4: The voltage on MOSFETs with sliding mode.

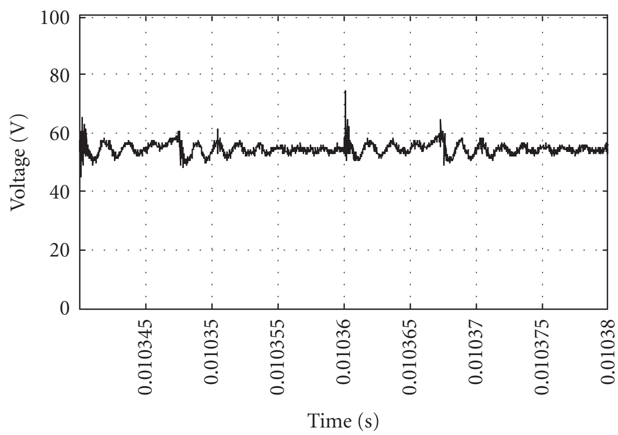

Figure 5: The output voltage of system with sliding mode.

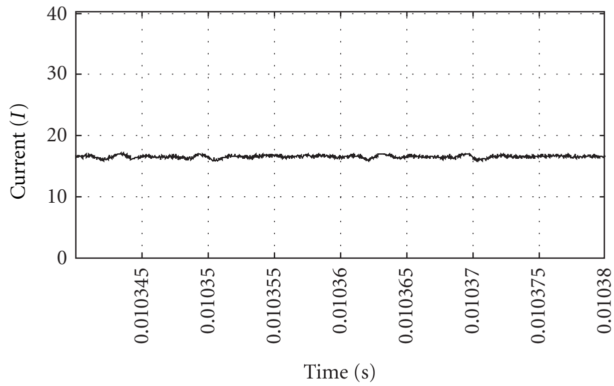

Figure 6: The output current of system with sliding mode.

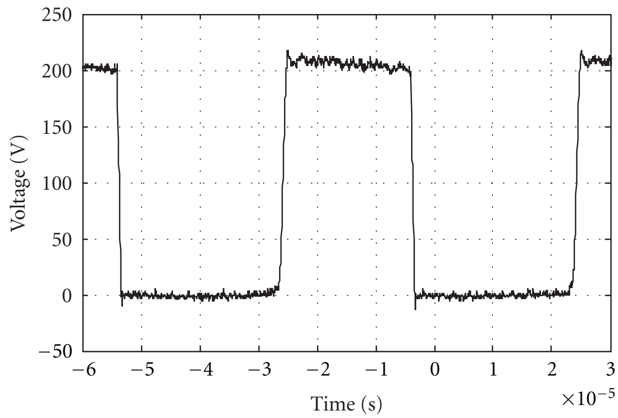

Figure 7: The voltage on MOSFETs with second order sliding mode.

Table 1: Experimental parameters.

Name	Notation	Value	Unit
Inductance	L	200	mH
Capacitance	C	470×4	uF
Input voltage	V_i	<300	V
Resistance	R	10	Ω
Switch freq.	f_s	20 k	Hz
Battery	Q	200×4	Ah

5. Experimental Result

In the experiment, the elements parameters of the Buck converter are displayed in Table 1. For testing the second sliding mode controller, in the model of Buck converter, the second order sliding mode controller's parameters are $V_m = 70$, $V_M = 200$. The experimental parameters of control platform are shown in Table 1 in detail.

Figure 4 shows the voltage between drain and source using traditional sliding mode control method. From this figure, the peak voltage is up to 200 V. When the MOSFET works in conducting state, there is obvious chattering due to the nonlinear stray parameters.

For the output voltage of system, high frequency PWM chopper produces a number of ripples, sometimes called chattering in control, in Figure 5.

From Figure 6, the charge current nearly achieves at 18A using the sliding mode control. In this case, the output power of system is about 1000 W.

Figure 7 shows the voltage between drain and source. From this figure, it can be inferred that the bus voltage is up to 200 V. It means the second order sliding mode works well in high-power system.

In comparison with the traditional control method in Figure 5, Figure 8 displays the output voltage of system using sliding mode control. It is easy to say that the ripple or chattering voltage is removed obviously.

Actually, the Buck converter is connected with a battery and the load usually. The output voltage and current are displayed in Figures 8 and 9. And the output voltage reaches over 70 V more than battery's rated voltage 48 V, owing to the float charge condition. Meanwhile, the output current is near to 23 A. In this way, the total power achieves 1600 W using this method.

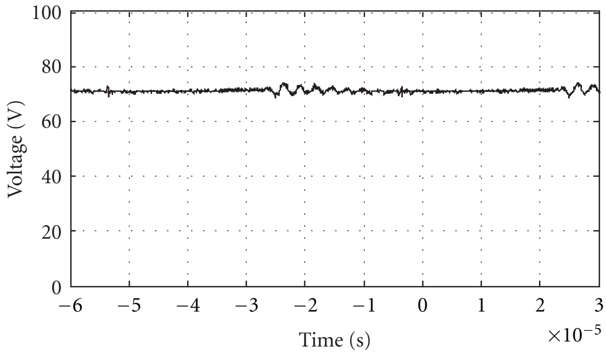

Figure 8: The output voltage of system with second order sliding mode.

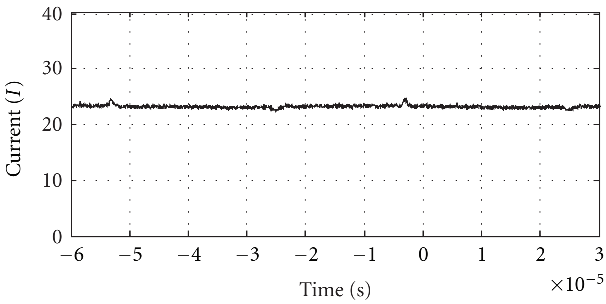

Figure 9: The output current of system with second order sliding mode.

6. Conclusions

Above all, the second order sliding mode control diverts the discrete control law onto the higher order sliding mode manifold, so that the first sliding mode surface becomes smoother. Thus, it removes the high frequency chattering phenomenon which exists in the traditional sliding mode.

In this paper, the proposed method is successfully used in high-power Buck converter for wind power system. The experimental results illustrate that the second order sliding mode can be applied in actual engineering project. This technology will propel the development of new energy generation systems.

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