Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Variable speed wind turbine control by discrete-time sliding mode approach

Borhen Torchani [a,*], Anis Sellami [a], Germain Garcia [b]

[a] Unit of Research LESIER, ENSIT, Tunis, Tunisia
[b] Unit of Research LAAS, CNRS, Toulouse, France

ARTICLE INFO

Article history:
Received 29 June 2015
Received in revised form
12 December 2015
Accepted 6 January 2016

Keywords:
Discrete-time sliding mode control
Saturation constraint
Mechanical modeling
Wind turbine

ABSTRACT

The aim of this paper is to propose a new design variable speed wind turbine control by discrete-time sliding mode approach. This methodology is designed for linear saturated system. The saturation constraint is reported on inputs vector. To this end, the back stepping design procedure is followed to construct a suitable sliding manifold that guarantees the attainment of a stabilization control objective. It is well known that the mechanisms are investigated in term of the most proposed assumptions to deal with the damping, shaft stiffness and inertia effect of the gear. The objectives are to synthesize robust controllers that maximize the energy extracted from wind, while reducing mechanical loads and rotor speed tracking combined with an electromagnetic torque. Simulation results of the proposed scheme are presented.

1. Introduction

Wind energy was proved being an important source of clean and renewable energy because no fossil fuels are burnt in electrical energy production. Nowadays, the renewable energy industry is intensively accelerating the concerns about natural recourses exhaustion and climate change. Advances in wind turbine technology made necessary the design of more powerful control systems [1–5]. It is to improve as much as possible the performances with cost reduction for wind turbines and to make them more profitable and more reliable. Many works in wind energy conversion control systems deal with the optimization of extracted aerodynamic power in partial load area [6,7].

For this purpose, classical controllers have extensively used PI regulator. Then, optimal and adaptive control has large-scale applications [8–14]. Among the greatest interests of control application, we distinguish saturation constraint procedure. In fact, this phenomenon is due to inherent physical limitations of devices. Though often ignored as in classical control theory, it cannot be avoided in practice. Unfortunately, failure in accounting for saturation constraint may lead to severe deteriorations of closed loop system performance, and even to instability. Many rigorous design methods are available to provide guaranteed proprieties on stability of systems. Let us quote from these methods including the anti-windup design [15–18]. All of them introduce conditions on systems containing saturation functions [19–21]. In robustness terms, sliding mode is a very significant transitory mode for the variable structure control [22,23]. Early work was mainly done by soviet control scientists [24–26]. In recent years, we find more research and many successful applications [27,28]. Recently, a sliding mode control in the discrete-time domain is attracting the attention. Many previous works have used discretized version of continuous-time design schemes for systems [29–32]. By using microprocessors provided via computers, controllers of current systems are totally implemented in discrete-time domain. This fact surpasses the old threats of control system instability after sampling in continuous-time domain.

This paper is organized as following: as a start, we present discretized system and we introduce the structure of saturation constraint reported in control vector and its implementation in the discrete system. Then, we describe wind turbine modeling. After that, we validate the theoretical concepts of this work; by treating a variable speed wind turbine application.

2. Problem statement

2.1. Discrete-time systems

Consider the continuous system:

$$\dot{x}(t) = Ax(t) + Bu(t). \quad (1)$$

$x(t) \in \Re^n$ is the state vector.

* Corresponding author.
E-mail addresses: bourhen@gmail.com (B. Torchani), anis.sellami@esstt.rnu.tn (A. Sellami), Garcia@laas.fr (G. Garcia).

http://dx.doi.org/10.1016/j.isatra.2016.01.001
0019-0578/

$u(t) \in \Re^m$ is the control input.
$A \in \Re^{n \times n}$ is the state matrix.
$B \in \Re^{n \times m}$ is the input matrix.

Assumption 1. The pair (A, B) is controllable, B has full rank m, and $n > m$. The continuous system time response is given by

$$x(t) = e^{A(t-t_0)}x(t_0) + \int_{t_0}^{t} e^{A(t-t_0)}Bu(\tau)d\tau, \tag{2}$$

Let $t_0 = kT$ and $t = (k+1)T$ for integer k. defining the sampled state function as $x_k = x_{kT}$. Assuming that the control input $u(t)$ is reconstructed from the discrete control sequence u_k by using a zero-order hold, $u(t)$ have constant values of $u_{kT} = u_k$, over the integration interval. The equivalent discrete form of the system is then:

$$x_{k+1} = \Phi x_k + \Gamma u_k, \tag{3}$$

where

$$\Phi = e^{AT} = I + AT + \frac{A^2T^2}{2!} + \dots, \tag{4}$$

$$\Gamma = \int_0^T e^{A\tau}Bd\tau = BT + \frac{ABT^2}{2!} + \dots \tag{5}$$

where $k = 0, 1, 2, \dots$
$x_{(.)} \in \Re^n$ is the state vector.
$u_{(.)} \in \Re^m$ is the control input.
$\Phi \in \Re^{n \times n}$ is the state matrix.
$\Gamma \in \Re^{n \times m}$ is the input matrix.

2.2. Saturation structure

In the literature, various forms of saturation function structure are available.

Assumption 2. The control vector is subject to constant limitations in amplitude.

It is defined by

$$u_k = \left\{ u_k \in \Re^m / -u^i_{\min} \le u^i_k \le u^i_{\max}; u^i_{\min}, u^i_{\max} > 0, \forall i = 1 \dots m \right\}. \tag{6}$$

The term of saturation has the following form:

$$sat(Kx_k) = \begin{cases} u^i_{\max} & \text{if} \quad (Kx_k)^i > u^i_{\max} \\ (Kx_k)^i & \text{if} \quad -u^i_{\min} \le (Kx_k)^i \le u^i_{\max} \\ -u^i_{\min} & \text{if} \quad -(Kx_k)^i < -u^i_{\min} \end{cases}, \forall i = 1, \dots, m. \tag{7}$$

We can write:

$$sat(Kx_k) = \Lambda(\varsigma(x_k))Kx_k. \tag{8}$$

where the elements $\varsigma^i(x_k)$ of the diagonal matrix $\Lambda(\varsigma(x_k))$ are expressed as follows:

$$\varsigma^i(x_k) = \begin{cases} \frac{u^i_{\max}}{(Kx_k)^i} & \text{if} \quad (Kx_k)^i > u^i_{\max} \\ 1 & \text{if} \quad -u^i_{\min} \le (Kx_k)^i \le u^i_{\max} \\ -\frac{u^i_{\min}}{(Kx_k)^i} & \text{if} \quad -(Kx_k)^i < -u^i_{\min} \end{cases}, \forall i = 1, \dots, m. \tag{9}$$

with

$$0 < \varsigma^i(x_k) \le 1. \tag{10}$$

The saturated system can be written as

$$x_{k+1} = \Phi x_k + \Gamma\Lambda(\varsigma(x_k))u_k. \tag{11}$$

To simplify, we consider $\Lambda(\varsigma(x_k)) = \Lambda(x_k)$ and we can write:

$$x_{k+1} = \Phi x_k + \Gamma\Lambda(x_k)u_k. \tag{12}$$

3. Sliding mode control

3.1. Discrete sliding surface

The sliding mode occurs when the state reaches and remains in the surface:

$$S = \cap_{j=1}^{m} S_j = \left\{ x_k \in \Re^n : s_k = Fx_k = 0 \right\}, \tag{13}$$

Assumption 3. $(F\Gamma)$ is non-singular, with $F^T \in \Re^n$.

The following sliding dynamics is globally, uniformly and asymptotically stable:

$$s_k \equiv 0, \tag{14}$$

Differentiating with respect to incrementing in time, the sliding dynamics (14) can be rewritten as

$$\begin{aligned} S_{k+1} = Fx_k &= F\Phi x_k + F\Gamma\Lambda(x_k)u_k, \\ &= S_k, \\ &= Fx_{k+1}, \\ &= 0. \end{aligned} \tag{15}$$

where $k = 0, 1, 2, \dots$
If $(FB)^{-1}$ exists and using the equivalent control input $u_k = u_{eq,k}$. Then we obtain:

$$\begin{aligned} u_{eq,k} &= -(F\Gamma\Lambda(x_k))^{-1}F\Phi x_k, \\ &= -K_{eq}x_k, \end{aligned} \tag{16}$$

with

$$K_{eq} = (F\Gamma\Lambda(x_k))^{-1}F\Phi. \tag{17}$$

For the nominal system, therefore, the dynamics in the sliding mode can be expressed as

$$x_{k+1} = \Phi x_k + \Gamma\Lambda(x_k)u_{eq,k}, \tag{18}$$

$$x_{k+1} = [I_n - \Gamma\Lambda(x_k)(F\Gamma\Lambda(x_k))^{-1}F\Phi]x_k, \tag{19}$$

$$x_{k+1} = \Phi_{eq}x_k, \tag{20}$$

$$\Phi_{eq} = [I_n - \Gamma\Lambda(x_k)(F\Gamma\Lambda(x_k))^{-1}F\Phi]. \tag{21}$$

Φ_{eq} describes the motion on the sliding surface and depends only on the choice of F and $\Lambda(x_k)$.

3.2. Design of the discrete sliding mode

In this part, we will prove the existence of sliding mode. Indeed the canonical form can be extended to saturated systems to select the gain matrix F.

Assumption 4. There exists an $(n \times n)$ orthogonal transformation matrix T such that $y_k = Tx_k$.

with $y^T_k = \begin{bmatrix} y^T_{1,k} & y^T_{2,k} \end{bmatrix}$, $y_{1,k} \in \Re^{n-m}$ and $y_{2,k} \in \Re^m$.
The transformed system can be rewritten as

$$\begin{aligned} y_{1,k+1} &= \Phi_{11}y_{1,k} + \Phi_{12}y_{2,k}, \\ y_{2,k+1} &= \Phi_{21}y_{1,k} + \Phi_{22}y_{2,k} + \Gamma_2\Lambda(y_k)u_k. \end{aligned} \tag{22}$$

Then

$$T\Phi T^T = \begin{bmatrix} \Phi_{11} & \Phi_{12} \\ \Phi_{21} & \Phi_{22} \end{bmatrix}. \tag{23}$$

and

$$T\Gamma = \begin{bmatrix} 0 \\ \Gamma_2 \end{bmatrix}. \tag{24}$$

where Γ_2 is $(m \times m)$ and non-singular. The new defining sliding