Sliding Mode Control for PMSG-based Wind Power System

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Abstract. Variable structure control has proven particularly suitable to variable speed wind energy conversion system control, being easy to implement by the already existing electronics. Its main drawback is an increase of mechanical stress due to chattering, which can however be alleviated by various methods. This paper proposes a sliding mode approach for tracking the energetic optimum of a variable speed permanent magnet synchronous generator PMSG. The sliding surface is systematically derived from imposing a desired reduced-order dynamics and allows the turbine operation more or less close to the optimal regimes characteristic, according to an imposed trade-off between the torque (control input) ripple and the optimum tracking. In this way, by torque controlling the generator, a multipurpose (energy-reliability) optimization is actually achieved.

1. Introduction
In recent decades, wind power becomes more interest as a source of electrical energy with minimal environmental impact. The variable wind speed turbine enables the operation over a wide speed range to extract the maximum power from wind. Recent trends indicate a move toward direct-drive turbine with permanent magnet synchronous generator PMSG. The PMSG have higher efficiency and power density as compared to wound rotor generators. Also, used to extract a maximum of energy by reducing mechanical stress by elimination of the speed multiplication (gear box), which improves system reliability and reduce maintenance costs [1]. Several research studies on wind control were conducted. Thanks to them, the latest generation of wind turbines operates at variable speed, which offers a higher yield of energy compared to fixed-speed turbines [1] [2]. The rotational speed of turbine varies with changing the wind speed, which makes command of control schemes for electrical generator hard with wind turbine, since the wind speed varies.

Figure 1. Wind energy conversion system based on PMSG [6].
Different studies of wind turbine were made, some use asynchronous motor, they have the advantage of having a low cost and easy maintenance. However, their speed control requires equipment in power electronics more expensive and more complex control [3] [4].

The purpose of wind energy systems is to maximize energy efficiency, and have a maximum power coefficient, and therefore extract maximum power from the wind speed. In this case, the MPPT control becomes important. To maintain, the operating point of maximum efficiency, different methods can be achieved. Optimum power/torque tracking is the most popular control strategy [5]. To realize this control, strategy conventional proportional and integral (PI) controller is usually used [5]. However, this strategy cannot achieve better performance. To solve this problem there are other control methods such as fuzzy logic, sliding mode control [6].

The sliding mode control is a control variable structure, which by its nature is a non-linear control. Proposed in the early 1950s, its success has been proven in control problems, since it is able to tackle system uncertainties and external disturbances with good robustness. This control is characterized by some advantages such as: high precision, rapid dynamic response, stability, simplicity of its design and its implementation [6].

Objective of this paper is propose a robust control to achieve better performance. This paper is organized as follows: describes The Wind Energy Conversion System (WECS). Sliding mode control is designed in develops control strategy and simulation results show the performance of the proposed approach and the conclusion is deducted in finally. The proposed strategy is compared with conventional PI controllers and confirmed superiorly in the MATLAB / Simulink environment.

2. Mathematical modelling of WECS

2.1. Turbine Model

The aerodynamic power $P$ captured by the wind turbine is given by [5]:

$$P_{col} = \frac{1}{2} C_p (\beta, \lambda) \rho S V_f^3$$

Where $\frac{R\Omega}{V_f}$ is the ratio of turbine blades tip speed to wind speed.

2.2. PMSG Model

Permanent magnet synchronous generator state model of the windings of the stator and the rotor according to the $d$-$q$ axes are given by the following relations [6]:

$$\dot{x} = \begin{bmatrix} x_1(t) \\
 x_2(t) \end{bmatrix} = \begin{bmatrix} -\frac{R}{L_d} x_1 + \frac{L_d}{L_q} x_2 \omega_h \\
 -\frac{R}{L_d} x_1 - \frac{L_d}{L_q} x_2 - \Phi_m \omega_h \end{bmatrix} + \begin{bmatrix} 0 \\
 0 \end{bmatrix} u$$

$$y = \Gamma_G = p \Phi_m x_2$$

Where:
- $p$: number of pole pairs.
- $R$: stator resistance.
- $L_d, L_q$: $d$ and $q$ inductances.
- $\Phi_m$: flux due to permanent magnets.
- $\Gamma_G$: electromagnetic torque.

The electromagnetic torque given by:

$$\Gamma_G = -\frac{3}{2} N_p \Phi_f i_{sq}$$
The mechanical equation for the PMSG is expressed as:

\[ J_{ef} \frac{d\Omega_h}{dt} = \Gamma_h - \Gamma_G - f \Omega_h \]  

(5)

3. Sliding mode control

Sliding mode control is divided into three parts; first step is to select a sliding surface, which models the desired closed-loop performance in the state variable space. Then, we impose the condition of convergence, and then the command must be designed so that the system state trajectories are directed towards the sliding surface and stay on it [7] [8]. The principle operation is based on three steps:

- Selection of the sliding surface is based on the mathematical model of the PMSG.
- Convergence condition is obtained by the Lyapunov function.
- Determine of the control strategy.

Considering the nonlinear system defined by the following form [9] [10]:

\[ X = g(X, t) + b(X, t)u(X, t) \]  

(6)

While: \( X \in R^n, u \in R^m, g(X, t) \in R^n, b(X, t) \in R^m \) and \( g(X, t) \) and \( b(X, t) \) are two non-linear functions, continuous, and limited.

The sliding surface is given by [8]:

\[ S(X) = \left( \frac{d}{dt} + \delta \right) e^n - e \]  

(7)

Where:

\[ e = X_{ref} - X, X_{ref} = [x_{ref}, k_{ref}, x_{ref}, \ldots]^T \]

\( e \) is the error, \( \delta \) is a positive constant, \( X_{ref} \) is the reference signal, and \( X \) is the state variable.

Convergence condition: Lyapunov functions define the convergence condition:

\[ S(X)S(X) \leq 0 \]  

(8)

Control calculation: The control is given by this equation:

\[ u = u^{eq} + u^n \]

Where \( u \) is the control signal, \( u^{eq} \) is the equivalent control, and \( u^n \) is the switching term which defined by the sign of the sliding surface multiplied by a positive constant:

\[ u^n = k_{sat}(S(X)) \]  

(9)

![Figure 2. Sliding mode controller diagram [7].](image)

3.1. Sliding control for wind speed turbine

The sliding surface and its derivative for the mechanical speed generator are given by:
Substituting (5) in (10), the new derivative of sliding surface is shown in (11).

\[ \frac{dS_\Omega}{dt} = \frac{d\Omega_{\text{h,eq}}}{dt} + \frac{d\Omega_h}{dt} \tag{10} \]

Substituting (5) in (10), the new derivative of sliding surface is shown in (11).

\[ \frac{dS_\Omega}{dt} = \frac{d\Omega_{\text{h,eq}}}{dt} = -1 J_{eq} (\Gamma_h - \Gamma_{eq} - f \Omega_h) \tag{11} \]

The Lyapunov function is defined by:

\[ \nu = \frac{1}{2} S_\Omega^2 \tag{12} \]

According to condition (8) we obtain:

\[ \frac{d\nu}{dt} = S_\Omega \frac{dS_\Omega}{dt} \leq 0 \tag{13} \]

In order to obtain the control strategy for \( \Omega_h \), the electromagnetic torque which is the variable command is composed of two components:

\[ \Gamma_h = \Gamma_{h,eq} - \Gamma_{h,n} \tag{14} \]

Where, \( \Gamma_{h,eq} \) is the equivalent command enables the pursuit of the trajectory on sliding surface, and it is deduced from \( S_\Omega = 0 \). The other component \( \Gamma_{h,n} \) is the discontinuous control which is responsible of the attractiveness of the variable command around the sliding surface, it is calculated by:

\[ \Gamma_{h,n} = \eta \Omega \text{sat} \left( \frac{S_\Omega}{\varepsilon} \right) \tag{15} \]

\( \eta \) is the gain of sliding mode controller, the saturation function of is given by (16), and is the width of boundary layer of the sliding surface.

\[ \text{sat} \left( \frac{S_\Omega}{\varepsilon} \right) = \begin{cases} \text{sign} \left( \frac{S_\Omega}{\varepsilon} \right) \left| \frac{S_\Omega}{\varepsilon} \right| & \left| \frac{S_\Omega}{\varepsilon} \right| \leq \varepsilon \\ \frac{S_\Omega}{\varepsilon} & \left| \frac{S_\Omega}{\varepsilon} \right| > \varepsilon \end{cases} \] \tag{16}

By solving \( S_\Omega = 0 \), it found that \( \Omega_{\text{eq}} = \Omega_h \). Then the equivalent command of electromagnetic torque is given by:

\[ \Gamma_{h,eq} = \Gamma_h - f \Omega_h - J_{eq} \dot{\Omega}_{h,\text{eq}} \tag{17} \]

Then, the electromagnetic torque command is expressed as (18) ; substituting (4) obtain the reference q-axis current in (18):

\[ \Gamma_{eq} = \Gamma_h - f \Omega_h - J_{eq} \dot{\Omega}_{h,\text{eq}} + \eta \Omega \text{sat} \left( \frac{S_\Omega}{\varepsilon} \right) \tag{18} \]

\[ l_{qr} = \frac{-2}{S_{\text{eq}} N_p \Phi_f} \left[ \Gamma_h - f \Omega_h - J_{eq} \dot{\Omega}_{h,\text{eq}} + \eta \Omega \text{sat} \left( \frac{S_\Omega}{\varepsilon} \right) \right] \tag{19} \]

The sliding surfaces for the dq-axis current control are:

\[ \begin{cases} S_{sd} = \text{sat} \left( \frac{S_\Omega}{\varepsilon} \right) = \frac{S_\Omega}{\varepsilon} - \frac{S_{sd}}{\varepsilon} \\ S_{sq} = \text{sat} \left( \frac{S_\Omega}{\varepsilon} \right) = \frac{S_\Omega}{\varepsilon} - \frac{S_{sq}}{\varepsilon} \end{cases} \tag{20} \]

By (10) and (19), we obtain:

\[ v_{dsd} = \Omega_h L_q i_{sq} - R_s i_{sd} \]

\[ v_{dqd} = -L_q \frac{di_{dq}}{dt} - R_s i_{dq} - \Omega_h L_d i_{sd} + \Omega_h \Phi_f \tag{21} \]

Then, \( v_{dsd} \) and \( v_{dqd} \) are given by the same method as shown by:
3.2. Sliding Control for Grid Side Converter

The following equations for Grid Side Converter are:

\[ V_{sd} = \Omega_h L_q i_{sq} - R_s i_{sd} + \eta_d \text{sat}\left( \frac{S_d}{e} \right) \]

\[ V_{sq} = -L_q \frac{di_{qg}}{dt} - R_s i_{sq} - \Omega_h L_d i_{sd} + \Omega_h \Phi_f + \eta_q \text{sat}\left( \frac{S_q}{e} \right) \]  

(22)

The sliding surfaces for the DC-bus voltage and dq-axis grid currents are expressed by:

\[ C \frac{dV_{dc}}{dt} = i_g - \frac{3}{2} \left( \frac{V_{gd}}{V_{dc}} \right) \]  

(23)

Where, \( V_{ud} \) is dq-axis inverter voltage components, \( i_{ph} \); \( V_{ph} \) are the dq-axis grid current and voltage components respectively, \( V_{dc}; i_d \) are the dc-bus voltage and current, \( i_g \) is the output current of the generator side converter, and \( R_c, L_c \) are resistance and inductance of \( R_c \) filter, \( \Omega_g \) is the grid frequency.

The active and reactive power is expressed by:

\[
\begin{align*}
\mathcal{P} &= \frac{3}{2}(V_{gd} i_{gd} + V_{gq} i_{gq}) - \frac{3}{2} V_{gd}^2 - i_{gq}^2 \\
\mathcal{Q} &= \frac{3}{2}(V_{gq} i_{gd} - V_{gd} i_{gq}) - \frac{3}{2} V_{gq}^2 - i_{gd}^2 
\end{align*}
\]  

(24)

\[ i_{dqr} = -\frac{2 \Omega_g}{3 V_{gd}} \]  

(25)

The sliding surfaces for the DC-bus voltage and dq-axis grid currents are expressed by:

\[ S_{dc} = V_{dcr} - V_{dc} \]

\[ S_{gd} = i_{gd} - i_{gq} \]  

(26)

\[ S_{gq} = i_{gqr} - i_{gq} \]

The convergence condition is expressed by:

\[ S_{dc} = V_{dcr} - V_{dc} \]

\[ S_{gd} = i_{gd} - i_{gq} \]  

(27)

\[ S_{gq} = i_{gqr} - i_{gq} \]

The expressions of variable command for different controllers are expressed by:

\[ i_{gdh} = \frac{2}{3} \frac{i_g V_{dc}}{V_{gd}} + \eta_d \text{sat}\left( \frac{S_{dc}}{e} \right) \]

\[ V_{sdh} = L_f \frac{di_{hdc}}{dt} + R_f i_{hdc} - \Omega_g L_f i_{hqr} + V_{gd} + \eta_d \text{sat}\left( \frac{S_{gd}}{e} \right) \]  

(28)

\[ V_{sqh} = R_f i_{hqr} - \Omega_g L_f i_{hdc} + \eta_q \text{sat}\left( \frac{S_{gq}}{e} \right) \]
Figure 3: Control scheme of the WECS [9].

Figure 4: WECS state space evolution by SMC [10].

4. Results and Discussion

MATLAB/Simulink numerical simulations have been performed in order to assess the sliding mode optimization approach detailed above. Simulations detailed have been done for 180 seconds time horizon, using a pseudo-random sequence of wind speed. Then, we compare the performance of the SMC controllers with the PI controller [11]. Initially, a wind speed profile with a maximum of 11 m/s and a minimum of 7 m/s was applied to the PMSG WECS in order to see the performance of the proposed controller. The wind speed, power coefficient, wind power, active power, reactive power, stator voltage and stator current are shown respectively in figures 5, 6, 7, 8, 9 and 10 where a good performance was observed. Power coefficient value it’s equal to 0.47 for SMC controller where it was found equal to 0.44 in PI controller \( C_{p_{max}} = 0.48 \), which shows good performance of SMC controller. The active power \( P \) and reactive power \( Q \) are regulated. In figure10, it can be seen that the current and voltage are in phase, which is established by controlling the power factor. It can therefore be concluded from the results of simulation that the SMC controller has good performance of tracking power points. The method also has good application potential in other types of wind energy conversion system.
Figure 5. Wind speed profile.

Figure 6. Power coefficient profile.

Figure 7. Wind turbine power profile.
Figure 8. Active power profile.

Figure 9. Reactive power profile.

Figure 10. Stator voltage and current by phase.
5. Conclusion

The sliding mode control law presented in this paper aims at maximizing the wind harvested power, while limiting the electromagnetic torque variations. Provided that ensuring the optimal tip speed ratio implies strong torque variations, the choice of an appropriate sliding surface is not a trivial task. Such a surface, having a non-empty intersection with the optimal regimes characteristic, variant with the wind speed and depending on a desired energy reliability trade off, has been systematically found. The possibility of driving the operating point in a conveniently sized neighborhood of the optimal regimes characteristic is thus ensured by imposing some desired reduced order dynamics, implicitly allowing the generator torque variations limitation in the high frequency range. The drive train mechanical fatigue induced by the generator control is alleviated with positive influence on the WECS overall reliability. The possibility of adjusting the trade-off coefficient, confers flexibility to the WECS, so that the wind energy conversion efficiency be significantly increased when the particular conditions of the site allow it.

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Annex

PMSG parameters are:
Rated power: $P_n = 1.4$MW; $V_n = 690$ V and $f_n = 50$Hz; Stator resistance: $R_s = 0.82$mΩ; $dq$-axis inductances: $L_d = 1.573$mH; Number of pole pair: $N_p = 26$; Rated mechanical torque: $T_{nom} = 848.826$ KN.m; PM flux: $\Phi_f = 5.8264$Wb