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HAL Id: hal-00598996
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Submitted on 8 Jun 2011

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A Combined High Gain Observer and High-Order Sliding Mode Controller for a DFIG-Based Wind Turbine

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Abstract—This paper deals with the power generation control in variable speed wind turbines. In this context, a control strategy is proposed to ensure power extraction optimization of a DFIG-based wind turbine. The proposed control strategy combines an MPPT using a high gain observer and second-order sliding mode for the DFIG control. This strategy presents attractive features such as chattering-free behavior, finite reaching time, robustness and unmodeled dynamics (generator and turbine).

The overall strategy has been validated on a 1.5-MW three-blade wind turbine using the NREL wind turbine simulator FAST.

Index Terms—Wind turbine (WT), Doubly Fed Induction Generator (DFIG), high gain observer, high-order sliding mode.

I. INTRODUCTION

Variable speed wind turbines are continuously increasing their market share, since it is possible to track the changes in wind speed by adapting shaft speed and thus maintaining optimal power generation. The more variable speed wind turbines are investigated, the more it becomes obvious that their behavior is significantly affected by the used control strategy. Typically, they use aerodynamic controls in combination with power electronics to regulate torque, speed, and power. The aerodynamic control systems, usually variable-pitch blades or trailing-edge devices, are expensive and complex, especially when the turbines are larger. This situation provides a motivation to consider alternative control approaches and to introduce more intelligence [1].

Therefore, this paper deals with power generation control in variable speed wind turbines. A control strategy is proposed to ensure power extraction optimization and reduce mechanical stresses in the drive train of a DFIG-based wind turbine. The proposed control strategy combines an MPPT using a high gain observer and second-order sliding mode for the DFIG control. This strategy presents attractive features such as chattering-free behavior, finite reaching time, robustness and unmodeled dynamics (generator and turbine).

The overall control strategy, illustrated by Fig. 1, has been validated on a 1.5-MW three-blade wind turbine using the NREL wind turbine simulator FAST.

II. WIND TURBINE MODELING

The global scheme for a grid-connected wind turbine is given in Fig. 2. The wind turbine modeling is inspired from [2]. In the following, the wind turbine components models are briefly described.

A. The Turbine Model

In this case, the aerodynamic power \( P_a \) captured by the wind turbine is given by

\[
P_a = \frac{1}{2} \rho \pi R^2 C_p(\lambda) v^3
\]
normally, a variable speed wind turbine follows the $C_{p_{max}}$ to capture the maximum power up to the rated speed by varying the rotor speed to keep the system at $\lambda_{opt}$. Then it operates at the rated power with power regulation during high wind periods by active control of the blade pitch angle or passive regulation based on aerodynamic stall.

the rotor power (aerodynamic power) is also defined by

$$P_a = \omega T_a$$

(3)

according to [4], the following simplified model is adopted for the turbine (drive train) for control purposes.

$$J\dot{\omega} = T_s - K\omega - T_g$$

(4)

**b. the generator model**

the WT adopted generator is the DFIG. DFIG-based WT will offer several advantages including variable speed operation ($\pm33\%$ around the synchronous speed), and four-quadrant active and reactive power capabilities. Such system also results in lower converter costs (typically 25% of total system power) and lower power losses compared to a system based on a fully fed synchronous generator with full-rated converter. Moreover, the generator is robust and requires little maintenance [3].

the control system is usually defined in the synchronous $d-q$ frame fixed to either the stator voltage or the stator flux. for the proposed control strategy, the generator dynamic model written in a synchronously rotating frame $d-q$ is given by (5).

$$\begin{align*}
  V_d &= R_d I_d + \frac{d\phi_d}{dt} - \omega \phi_{eq} \\
  V_q &= R_q I_q + \frac{d\phi_q}{dt} + \omega \phi_{eq} \\
  V_d &= R_d I_d + \frac{d\phi_d}{dt} - \omega \phi_{eq} \\
  V_q &= R_q I_q + \frac{d\phi_q}{dt} + \omega \phi_{eq} \\
  \phi_{eq} &= L_d I_d + M I_q \\
  \phi_q &= L_q I_q + M I_d \\
  \tau_m &= pM (\dot{I}_d I_q - I_d \dot{I}_q)
\end{align*}$$

(5)

for simplification purposes, the $q$-axis is aligned with the stator voltage and the stator resistance is neglected [4]. these will lead to (6).
\[
\begin{align*}
\frac{dL_s}{dt} &= \frac{1}{\sigma L_s} \left( v_{em} - R_s I_{em} + s_0 \sigma L_s I_n - \frac{M d\phi_d}{L_s} \right) \\
\frac{dI_n}{dt} &= \frac{1}{\sigma L_s} \left( v_n - R_n I_n - s_0 \sigma L_s I_n - s_0 \frac{M}{L_s} \phi_d \right) \\
T_{em} &= -p \frac{M}{L_s} \phi_d I_n
\end{align*}
\] (6)

III. THE MPPT STRATEGY

A. Problem Formulation

The reference torque of the MPPT block must address two problems: the captured power maximization and be driven according to the three fundamental operating regions illustrated by Fig. 3.

In practice, there are two possible regions of turbine operation, namely the high- and low-speed regions. High speed operation (III) is frequently bounded by the speed limit of the machine. Conversely, regulation in the low-speed region (II) is usually not restricted by speed constraints. However, the system has nonlinear nonminimum phase dynamics in this region. This adverse behavior is an obstacle to perform the regulation task [5].

In region II, the control objective is to optimize the capture wind energy by tracking the optimal torque \( T_{opt} \).

\[ T_{opt} = k \omega^2, \quad \text{with} \quad k = \frac{1}{2} \pi \rho R^2 \frac{C_{p,max}}{\lambda_{opt}} \] (7)

The standard strategy neglect the dynamic of the drive train, which means that the aerodynamic torque is supposed to be equal to the generator torque. It is obvious that in many cases, and especially for turbulent winds, this assumption will not be realistic. The proposed control strategy relies then on the aerodynamic torque estimation using a high gain observer [6]. This estimate is then used to derive a high-order sliding mode controller that ensures \( T_{opt} \) tracking in finite time.

\[ \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} \omega \\ \frac{T}{J} \end{bmatrix} \]

Thus we have \( x = \begin{bmatrix} \dot{x}_1 = x_2 - \frac{K}{J} x_1 - \frac{T_{em}}{J} \\ \dot{x}_2 = f(t) \end{bmatrix} \) (10)

where

\[ A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \quad C = \begin{bmatrix} 1 & 0 \end{bmatrix}, \quad \varphi(x,u) = \begin{bmatrix} -\frac{Kx_1 - u}{J} \\ 0 \end{bmatrix}, \quad \varepsilon(t) = \begin{bmatrix} 0 \\ f(t) \end{bmatrix} \]

or in matrix form

\[ \begin{bmatrix} \dot{x} \\ y \end{bmatrix} = \begin{bmatrix} A & \varphi(x,u) + \varepsilon(t) \\ y & y C \end{bmatrix} \]

A candidate observer could be [6]

\[ \dot{\hat{x}} = A\hat{x} + \varphi(\hat{x},u) - \theta \Delta_n^{-1} S^{-1} C^T(\hat{x} - x) \] (11)

where \( \Delta_n = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \), \( S = \begin{bmatrix} 1 & -1 \\ -1 & 2 \end{bmatrix} \)

Let \( S \) be the unique solution of the algebraic Lyapunov equation

\[ S + A^T S + S A - C^T C = 0 \] (12)

Let us define \( \tau = \Delta_n(\hat{x} - x) \)

then \( \ddot{\tau} = \theta(A - S^{-1} C^T C)\tau + \Delta_n \left( \varphi(\hat{x}) - \varphi(x) \right) - \Delta_n \varepsilon(t) \) (13)

Consider the quadratic function

\[ V = \tau^T \Delta \tau \] (14)

then
\[
\begin{align*}
\dot{V} &= 2x^T \dot{x} \\
\dot{V} &= -\theta V - x^T C^T C x + 2x^T S \Delta g (\varphi(\dot{x}) - \varphi(x)) - 2x^T S \Delta \varphi(t)
\end{align*}
\]

Therefore
\[
\dot{V} \leq -\theta V + 2 \|x\| \lambda_{\max}(S) \left( \|\Delta g (\varphi(\dot{x}) - \varphi(x))\| + \|\Delta \varphi(t)\| \right)
\]

We can assume that (triangular structure and the Lipschitz assumption on \( \varphi \))
\[
\begin{cases}
\|\Delta g (\varphi(\dot{x}) - \varphi(x))\| \leq \xi \frac{K}{J} \\
\|\Delta \varphi(t)\| \leq \delta
\end{cases}
\]

It comes that
\[
\dot{V} \leq -\theta V + 2 \|x\| \lambda_{\max}(S) \xi + 2 \|x\| \lambda_{\max}(S) \delta
\]

then
\[
\dot{V} \leq -\theta V + c_1 V + c_2 \delta \sqrt{V}
\]

Now taking
\[
\begin{align*}
0_0 &= \max \{1, c_1\} \\
\lambda &= \frac{\lambda_{\max}(S)}{\|x\| \lambda_{\max}(S)} \\
\kappa &= \frac{\theta - c_1}{2} \\
\mu &= 2 \frac{\lambda_{\max}(S)}{\lambda_{\max}(S)(\theta - c_1)} \\
M_0 &= 2 \lambda_{\max}(S)
\end{align*}
\]

and \( \theta > \theta_0 \), we obtain
\[
\|e(t)\| \leq \theta_0 \exp(-\mu_0 t) \|e(0)\| + M_0 \delta
\]

With \( \tilde{T}_a = J \dot{\kappa} \), it comes that
\[
\tilde{T}_a = \tilde{T}_a - T_a \leq J \left[ \theta \exp(-\mu_0 t) \|e(0)\| + M_0 \delta \right]
\]

A practical estimate of the aerodynamic torque is then obtained as \( M_0 \) decreases when \( \theta \) increases. The asymptotic estimation error can be made as small as desired by choosing high enough values of \( \theta \). However, very large values of \( \theta \) are to be avoided in practice since the estimator may become noise sensitive.

Now, the control objective can be formulated by the following tracking errors
\[
e_r = T_{opt} - T_a
\]

where \( T_a \) is observed. Then we will have
\[
\dot{e}_r = 2k_{opt} \omega (T_a - K, \omega - \dot{T}_a) - \dot{T}_a
\]

If we define the following functions
\[
\begin{align*}
F &= 2k_{opt} \omega \\
G &= 2k_{opt} (T_a - K, \omega - \dot{T}_a)
\end{align*}
\]

then
\[
\dot{e}_r = -F \dot{T}_a + \dot{G}
\]

Let us consider the following observer based on the super twisting algorithm \[7\].

\[
\begin{align*}
T_a &= y + B_1 |e_r| \text{sgn}(e_r) \\
y &= +B_2 \text{sgn}(e_r)
\end{align*}
\]

The gains \( B_1 \) and \( B_2 \) are chosen as
\[
\begin{align*}
B_1 &\geq \frac{\Phi_2}{\Gamma_u} \\
B_2 &\geq \frac{4\Phi_1 \Gamma_v}{\Gamma_u} \left( A_1 + \Phi_1 \right) \\
|G| &< \Phi_2 \\
0 < \Gamma_u \leq F \leq \Gamma_M
\end{align*}
\]

Thus we will guaranty the convergence of \( e_r \) to 0 in a finite time \( t_c \). The aerodynamic torque estimation is then deducted.
\[
T_a = T_{opt}, \quad t > t_c
\]

V. CONTROL OF THE DFIG-BASED WIND TURBINE

The DFIG-based WT control objective is to optimize the extracted power by tracking the optimal torque \( T_{opt} \) (7). The control is a compromise between conversion efficiency and torque oscillation smoothing \[8\].

The reactive power is expressed as follows.
\[
Q = V_s q I_{sd} - V_d I_{sq}
\]

Adapting (25) to our hypotheses, it comes then
\[
Q = \frac{V_s}{L_s} - \frac{V}{L_s} I_{sd}
\]
As the stator reactive power reference is zero, then
\[
\phi_s = \frac{V_s}{\omega_s} \rightarrow I_{rd\_ref} = \frac{V_s}{\omega_s M}
\] (27)

Let us consider the following tracking errors.
\[
\begin{align*}
\dot{e}_{i_d} &= I_{ad} - I_{rd\_ref} \\
\dot{e}_{i_m} &= T_{em} - T_{ref}
\end{align*}
\] (28)

Then we will have
\[
\begin{align*}
\dot{e}_{i_d} &= \frac{1}{\sigma L_c} \left( V_{eq} - R_{i_d} I_{rd} + g_0 L_c \sigma I_{iq} - \frac{M}{L_s} \frac{d \phi_{ad}}{dt} \right) - I_{rd\_ref} \\
\dot{e}_{i_m} &= -p \frac{M}{\sigma L_c L_r} \phi_i \left( -g_0 L_c \sigma I_{rd} - g_0 \frac{M}{L_s} \phi_{ad} \right) - \dot{T}_{ref}
\end{align*}
\] (29)

If we define the functions \( G_1 \) and \( G_2 \) as follows.
\[
\begin{align*}
G_1 &= \frac{1}{\sigma L_c} \left( g_0 \sigma L_c I_{iq} - \frac{M}{L_s} \frac{d \phi_{ad}}{dt} \right) - I_{rd\_ref} \\
G_2 &= -p \frac{M}{\sigma L_c L_r} \phi_i \left( -g_0 \sigma L_c I_{rd} - g_0 \frac{M}{L_s} \phi_{ad} \right) - \dot{T}_{ref}
\end{align*}
\]

Thus we have
\[
\begin{align*}
\dot{e}_{i_d} &= \frac{1}{\sigma L_c} \hat{V}_{rd} + \dot{G}_1 - R_{i_d} \dot{I}_{rd} \\
\dot{e}_{i_m} &= -p \frac{M}{\sigma L_c L_r} \phi_i \hat{V}_{rq} + G_2 + p \frac{M}{\sigma L_c L_r} \phi_i R_{i_d} \dot{I}_{rq}
\end{align*}
\] (30)

Now, let's consider the following high-order sliding mode controller based on the super twisting algorithm.
\[
\begin{align*}
V_{eq} &= y_1 + B_1 e_{i_m} + \frac{1}{\sigma L_c} R_{i_d} I_{rd} \\
y_1 &= +B_2 Sgn(e_{i_m}) \\
V_{rd} &= y_2 - B_4 e_{i_d} + \frac{p M}{\sigma L_c L_r} \phi_i R_{i_d} I_{rd} \\
y_2 &= -B_4 Sgn(e_{i_d})
\end{align*}
\] (31)

Where the constants \( B_1, B_3, B_4, \Phi_1, \) and \( \Phi_2 \) satisfy (32).

Thus, we can assert that there exist finite times \( T_{em} \) and \( T_{rd\_ref} \) leading to (33).

This means that the control objective is achieved.

VI. VALIDATION RESULTS WITH FAST

The proposed SOSM control strategy has been tested for validation using the NREL FAST code [2], [9]. An interface has been developed between FAST and Matlab-Simulink enabling users to implement advanced turbine controls in Simulink convenient block diagram form.

Numerical validations, using FAST with Matlab-Simulink have been carried out on the NREL WP 1.5-MW wind turbine using turbulent FAST wind data shown by Fig. 3 [10]. The wind turbine, the DFIG ratings, and control parameters are given in the Appendix.

The observer validation is clearly illustrated by Fig. 4. Indeed, the aerodynamic torque tracks efficiently the optimal torque. As shown in Figs. 6 and 7, very good tracking performances are achieved in terms of DFIG rotor current and WT torque with respect to wind fluctuations. The proposed control strategy does not induce increased mechanical stress as there are no strong torque variations.

The proposed control strategy that combines a high gain observer-based MPPT and a second-order sliding mode has been compared to classical techniques used in wind power industry. The first one is that using the active power as reference and leading to the following control reference [11].

![Fig. 3. Wind speed profile.](image)

![Fig. 4. Aerodynamic torque: \( T_{opt} \) (blue), \( T_r \) real (red), \( T_s \) observed (green).](image)
This approach supposes that the active power is equal to the generator power. This approximation drives a difference between the desired torque and the generated one (Fig. 8).

The second classical approach is the one using the following reference [12].

\[ I_{rq\_ref} = -\frac{L_s}{pM\Phi_s} T_{ref} \]  

(34)

In this case, bad tracking performances are also achieved (Fig. 9).

VII. CONCLUSION

This paper dealt with a second-order sliding mode control of a doubly-fed induction-based wind turbine combined with a high gain observer-based MPPT. The proposed control strategy has been tested using the NREL FAST simulator on a 1.5-MW wind turbine.

APPENDIX

CHARACTERISTICS OF THE SIMULATED WIND TURBINE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Number of blades</td>
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</tr>
<tr>
<td>Rotor diameter</td>
<td>70 m</td>
</tr>
<tr>
<td>Hub height</td>
<td>84.3 m</td>
</tr>
<tr>
<td>Rated power</td>
<td>1.5 MW</td>
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<tr>
<td>Turbine total inertia</td>
<td>4.4532×10^5 kg m²</td>
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PARAMETERS OF THE SIMULATED DFIG

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<tr>
<td>( L_s )</td>
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</tr>
<tr>
<td>( R_r )</td>
<td>0.0089 ( \Omega )</td>
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<td>( L_r )</td>
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<td>( M )</td>
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CONTROL PARAMETERS

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<tr>
<td>( B_4 )</td>
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<tr>
<td>( k_{opt} )</td>
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</tr>
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REFERENCES