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Sliding Mode Power Control of Variable Speed Wind Energy Conversion Systems

B. Beltran, T. Ahmed-Ali and M.E.H. Benbouzid, *Senior Member, IEEE*

Abstract—This paper addresses the problem of controlling power generation in variable speed wind energy conversion systems (VS-WECS). These systems have two operation regions depending on wind turbines tip speed ratio. They are distinguished by a minimum phase behavior in one of these regions and a nonminimum phase in the other one. A sliding mode control strategy is then proposed to ensure stability in both operation regions and to impose the ideal feedback control solution despite of model uncertainties. The proposed sliding mode control strategy presents attractive features such as robustness to parametric uncertainties of the turbine and the generator as well as to electric grid disturbances. The proposed sliding mode control approach has been simulated on a 1.5-MW three-blade wind turbine to evaluate its consistency and performance. The next step was the validation using the NREL (National Renewable Energy Laboratory) wind turbine simulator FAST (Fatigue, Aerodynamics, Structures and Turbulence code). Both simulation and validation results show that the proposed control strategy is effective in terms of power regulation. Moreover, the sliding mode approach is arranged so as to produce no chattering in the generated torque that could lead to increased mechanical stress because of strong torque variations.

Index Terms—Wind energy conversion system, power generation control, sliding mode control.

NOMENCLATURE

v	= Wind speed (m/sec);
ρ	= Air density (kg/m ³);
R	= Rotor radius (m);
P_a	= Aerodynamic power (W);
T_a	= Aerodynamic torque (Nm);
λ	= Tip speed ratio;
$C_p(\lambda)$	= Power coefficient;
$C_q(\lambda)$	= Torque coefficient;
ω_r	= Rotor speed (rad/sec);
ω_g	= Generator speed (rad/sec);
T_g	= Generator electromagnetic torque (Nm);
T_{ls}	= Low speed torque (Nm);
T_{hs}	= High speed torque (Nm);

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K_r	= Rotor external damping (Nm/rad sec);
K_g	= Generator external damping (Nm/rad sec);
J_r	= Rotor inertia (kg m ²);
J_g	= Generator inertia (kg m ²);
J_t	= Turbine total inertia (kg m ²);
K_t	= Turbine total external damping (Nm/rad sec);
B_r	= Rotor external stiffness (Nm/rad sec);
B_g	= Generator external stiffness (Nm/rad sec);
B_t	= Turbine total external stiffness (Nm/rad sec).

I. INTRODUCTION

Wind energy conversion is the fastest-growing energy source among the new power generation sources in the world and this tendency should remain for some time. At the end of 2003 the installed wind energy capacity stands at over 40000 MW, doubling since 1999, and it could exceed 95000 MW by the end of 2008 (Fig. 1). A higher target would be achieving 12% of the world electricity from wind power by 2020. Harnessing wind energy for electric power generation is an area of research interest and nowadays the emphasis is given to the cost-effective utilization of this energy aiming at quality and reliability in the electricity delivery [1-2]. During the last two decades wind turbines sizes have been developed from 20 kW to 2 MW, while even larger wind turbines are being designed. Moreover, a lot of different concepts have been developed and tested [3].

Actually, VS-WECS 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 energy generation. The more VS-WECS are investigated, the more it becomes obvious that their behavior is significantly affected by the used control strategy. Typically, VS-WECS 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 an incentive to consider alternative control approaches.

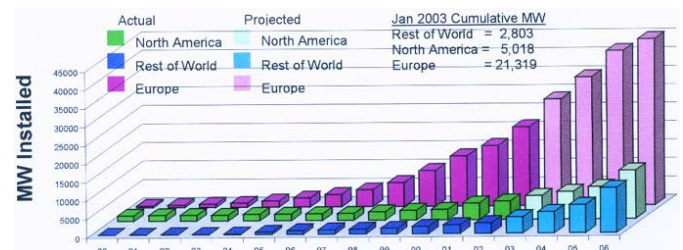


Fig. 1. Installed wind power [1].

The prime control objective of VS-WECS is power efficiency maximization. To achieve this goal the turbine tip speed ratio should be maintained at its optimum value despite wind variations. Nevertheless, control is not always aimed at capturing as much energy as possible. In fact, in above rated wind speed, the captured power needs to be limited. Although there are both mechanical and electrical constraints, the more severe ones are commonly on the generator and the converter. Hence, regulation of the power produced by the generator (i.e. the output power) is usually intended and this is the main objective of this paper.

II. WIND TURBINE MODELING

The global scheme for VS-WECS is given by Fig. 2. The system modeling is inspired from [4-5]. Moreover, a fixed pitch variable speed wind turbine, which is considered in this paper, could be schematically represented by Fig. 3.

The aerodynamic power P_a captured by the wind turbine is given by

$$P_a = \frac{1}{2} \pi \rho R^2 C_p(\lambda) v^3 \quad (1)$$

C_p represents the wind turbine power conversion efficiency. It is a function of the tip speed ratio λ , as well as the blade pitch angle β in a pitch controlled wind turbine. λ is defined as the ratio of the tip speed of the turbine blades to wind speed, and given by

$$\lambda = \frac{R \omega_r}{v} \quad (2)$$

The C_p - λ characteristics, for different values of the pitch angle β , are illustrated in Fig. 4. This figure indicates that there is one specific λ at which the turbine is most efficient.

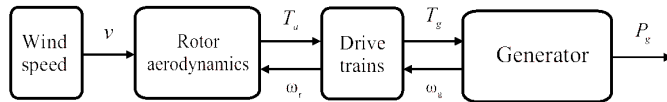


Fig. 2. VS-WECS global scheme.

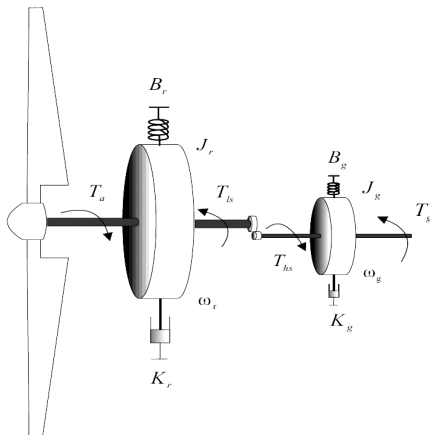


Fig. 3. WECS drive train dynamics.

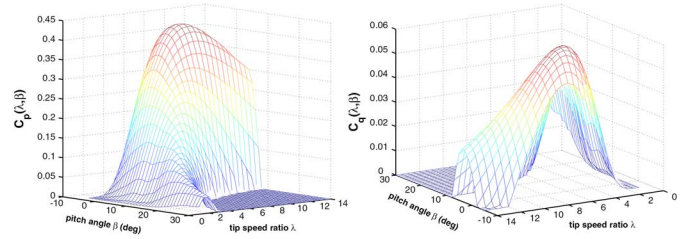


Fig. 4. Wind turbine power and torque coefficients [7].

Normally, a variable speed wind turbine follows the C_{pmax} to capture the maximum power up to the rated speed by varying the rotor speed to keep the system at λ_{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 [6].

The rotor power (aerodynamic power) is also defined by

$$P_a = \omega_r T_a \quad (3)$$

$$\text{Moreover } C_q(\lambda) = \frac{C_p(\lambda)}{\lambda} \quad (4)$$

It comes then that the aerodynamic torque is given by

$$T_a = \frac{1}{2} \pi \rho R^3 C_q(\lambda) v^2 \quad (5)$$

According to Fig. 3, the aerodynamic torque T_a will drive the wind turbine at the speed ω_r . The low speed torque T_{ls} acts as a braking torque on the rotor. The generator is driven by the high speed torque T_{hs} and braked by the generator electromagnetic torque T_g . Through the gearbox, the rotor speed is increased by the gearbox ratio n_g to obtain the generator speed ω_g while the low speed torque is augmented.

The rotor dynamics together with the generator inertia are characterized by the following differential equations.

$$\begin{cases} J_r \dot{\omega}_r = T_a - K_r \omega_r - B_r \theta_r - T_{ls} \\ J_g \dot{\omega}_g = T_{hs} - K_g \omega_g - B_g \theta_g - T_g \end{cases} \quad (6)$$

The gearbox ratio is defined as

$$n_g = \frac{\omega_g}{\omega_r} = \frac{T_{ls}}{T_{hs}} \quad (7)$$

It comes then that

$$J_t \dot{\omega}_r = T_a - K_t \omega_r - B_t \theta_r - T_g \quad (8)$$

where

$$\begin{cases} J_t = J_r + n_g^2 J_g \\ K_t = K_r + n_g^2 K_g \\ B_t = B_r + n_g^2 B_g \\ T_g = n_g T_{em} \end{cases} \quad (9)$$

Since the external stiffness B_t is very low, it can be neglected. We will then use the following simplified model for control purposes.

$$J_t \dot{\omega}_r = T_a - K_t \omega_r - T_g \quad (10)$$

The generated power will be finally given by

$$P_g = T_g \omega_r \quad (11)$$

III. ROBUST CONTROL DESIGN

A. Problem Formulation

Wind turbines are designed to produce electrical energy as cheaply as possible. Therefore, they are generally designed so that they yield maximum output at wind speeds around 15 m/sec. In case of stronger winds, it is necessary to waste part of the excess energy of the wind in order to avoid damaging the wind turbine. All wind turbines are therefore designed with some sort of power control. This standard control law keeps the turbine operating at the peak of its C_p curve.

$$T_g = k \omega^2, \text{ with } k = \frac{1}{2} \pi \rho R^3 \frac{C_{p \max}}{\lambda_{opt}^3}$$

where λ_{opt} is the optimal tip speed ratio.

There are two significant problems with this standard control. The first is that there is no accurate way to determine k , especially since blade aerodynamics can change significantly over time. Second, even when it is assumed that k can be accurately determined via simulation or experiments, wind speed fluctuations force the turbine to operate off the peak of its C_p curve much of the time, resulting in less energy capture.

The proposed control strategy will therefore reduce the negative effects of both the uncertainty regarding k and the change in optimal operating point due to turbulence.

Moreover, to effectively extract wind power while at the same time maintaining safe operation, the wind turbine should be driven according to the following three fundamental modes (regions) associated with wind speed, maximum allowable rotor speed, and rated power [4]: Region 1 – operating at variable speed/optimum tip-speed ratio.

Region 2 – operating at variable speed/variable tip-speed ratio. Region 3 – operating at variable speed/constant power. Figure 5 is then given for illustration in the case of a wind turbine producing a maximum power of 800-kW at a rated wind speed of about 14 m/sec, and it has a maximum power coefficient $C_{p \max} = 0.4$ [8].

A common practice in addressing the control problem of wind turbines is to use linearization approach. However, due to the stochastic operating conditions and the inevitable uncertainties inherent in the system, such a control methods comes at the price of poor system performance and low reliability [4]. So the need for nonlinear and robust control to take into account these control problems.

B. The Proposed Control Strategy

The proposed generator power control strategy that takes into account the above discussed problems is shown by Fig. 6. This strategy is based on a dynamical robust sliding mode controller. Indeed, sliding mode control is one of the effective nonlinear robust control approaches since it provides system dynamics with an invariant property to uncertainties once the system dynamics are controlled in the sliding mode [9]. It has been previously applied in the case of wind driven induction generators [10-11].

The adopted scheme uses an adaptive gain that increases as long as the power tracking error is not equal to zero.

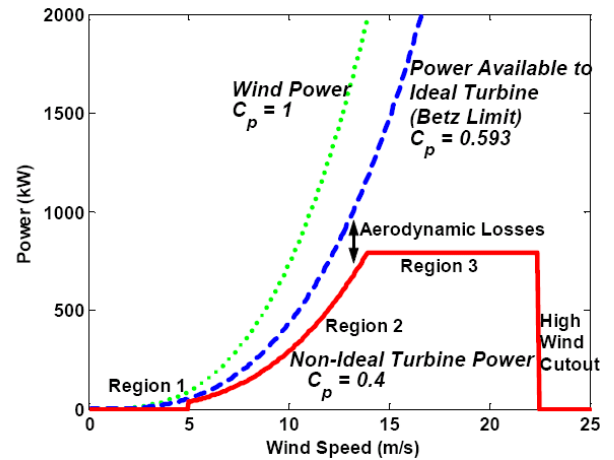


Fig. 5. Steady-state power curves [8].

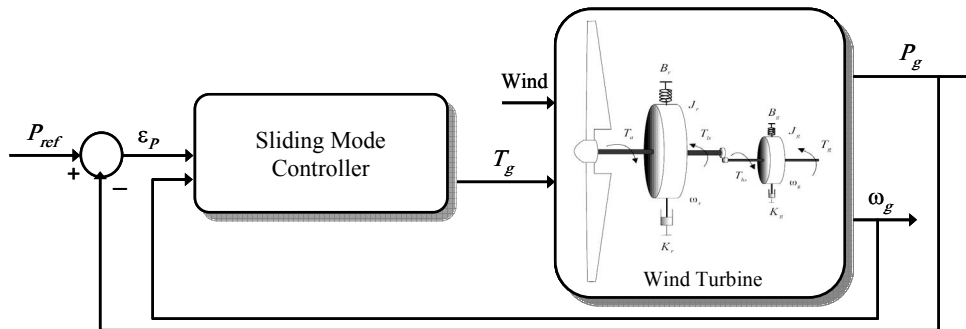


Fig. 6. The proposed control scheme.

Let us consider the tracking error

$$\varepsilon_p = P_{ref} - P_g \quad (12)$$

It follows that

$$\dot{\varepsilon}_p = \dot{P}_{ref} - T_g \dot{\omega}_r - \dot{T}_g \omega_r \quad (13)$$

If we choose the following dynamical sliding mode controller

$$\dot{T}_g = \frac{(B + \lambda) \text{sgn}(\varepsilon_p)}{\omega_r} \quad (14)$$

with $\dot{B} = |\varepsilon_p|$, then we obtain

$$\dot{\varepsilon}_p = \dot{P}_{ref} - T_g \dot{\omega}_r - (B(t) + \lambda) \text{sgn}(\varepsilon_p) \quad (15)$$

Now, if we suppose

$$d = \dot{P}_{ref} - T_g \dot{\omega}_r \quad (16)$$

as a perturbation that satisfies

$$|d| < B_1$$

where B_1 is a positive unknown constant. Then we can write

$$\dot{\varepsilon}_p = -(B(t) + \lambda) \text{sgn}(\varepsilon_p) + d \quad (17)$$

In order to proof the stability of our controller, let us consider the following Lyapunov function.

$$V = \frac{1}{2} \varepsilon^2 + \frac{1}{2} (B - B_1)^2 \quad (18)$$

It is not difficult to see that its time derivative will satisfies

$$\dot{V} \leq -\lambda |\varepsilon| \quad (19)$$

From this, and based on LaSalle theorem, we can conclude that the tracking error converges asymptotically to zero [12].

In order to avoid the chattering phenomena introduced by the function $\text{sgn}(\cdot)$, we will use the following approximation.

$$\text{sgn}(\varepsilon_p) = \frac{\varepsilon_p}{|\varepsilon_p| + a_0}$$

Where a_0 is small positive constant. A practical consequence of this approximation is that no chattering will be produced in the generated torque. This will prevent from increased mechanical stress due to strong torque variations.

IV. SIMULATION RESULTS

Numerical simulations, using Matlab-Simulink® [13] have been carried out on the NREL WP 1.5-MW wind turbine which ratings are summarized in Table 1 (Fig. 7) [14]. Moreover, the power coefficient is given by the following equation and illustrated by Fig. 8.

$$C_p(\lambda, \beta) = 0.22 \left(\frac{116}{\lambda} - 0.4\beta - 5 \right) e^{-\frac{12.5}{\lambda_i}}$$

$$\text{where } \frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}$$

Using the available blocks from the *Wind Turbine Blockset*, the proposed strategy has been implemented as schematically illustrated by Fig. 9. It should be noticed that for simulation convenience the gearbox ratio of about 84 was not taken into account.

Table 1. Wind Turbine Characteristics.

Number of blades	3
Rotor diameter	70 m
Hub height	84.3 m
Rated power	1.5 MW
Turbine total inertia	$4.4532 \times 10^5 \text{ kg m}^2$



Fig. 7. The simulated WP 1.5-MW wind turbine.

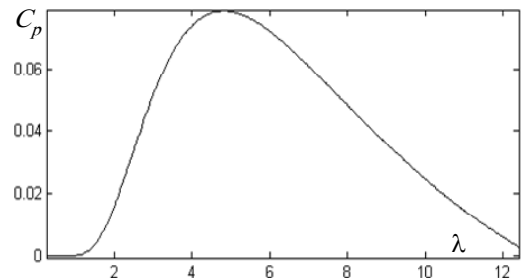


Fig. 8. Power coefficient of the simulated wind turbine.

Simulations wind inflow (Fig. 10) consists of 10 min data set of full-field turbulent wind. This turbulent wind data was generated using the Class A Kaimal turbulence spectra. It has a mean value of 16 m/sec [15].

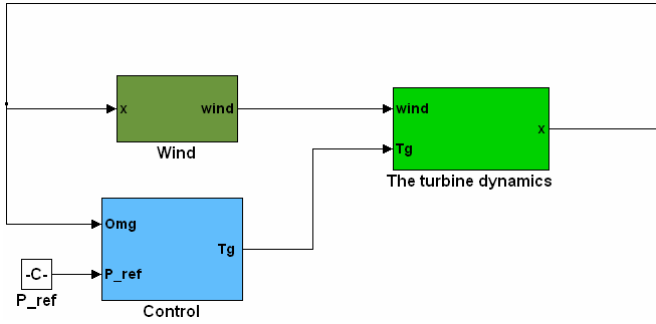


Fig. 9. Simulink basic scheme of the implemented control strategy.

Scanning the simulation results, one should conclude that the wind turbine control is satisfactory. Indeed, very good power tracking and regulation performances are achieved as clearly shown by Fig. 11. In this case, convergence is very fast to the power reference. Moreover, the generator torque is very smooth with no chattering (Fig. 12). In this case, the conclusion is that the proposed sliding mode control strategy does not induce increased mechanical stress as there are no strong torque variations. Figures 13 and 14 are given to illustrate the other wind turbine dynamics.

V. VALIDATION

To confirm the encouraging simulation results, the proposed sliding mode power regulation strategy has been tested for validation using NREL FAST code.

The FAST (Fatigue, Aerodynamics, Structures, and Turbulence) Code is a comprehensive aeroelastic simulator capable of predicting both the extreme and fatigue loads of two- and three-bladed horizontal-axis wind turbines [16]. This simulator has been chosen for validation because in 2005, it was evaluated by Germanischer Lloyd WindEnergie and found suitable for the calculation of onshore wind turbine loads for design and certification [17].

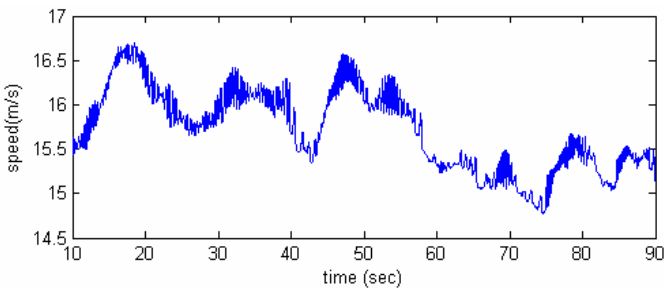


Fig. 10. Wind speed profile.

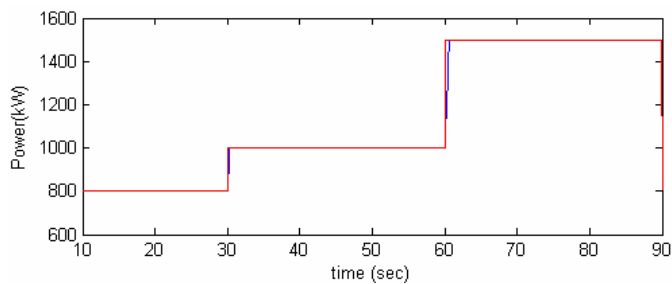


Fig. 11. The generator power and its reference.

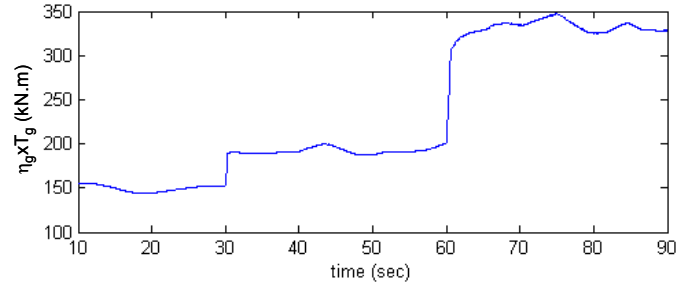


Fig. 12. The generator torque ($\eta_g \times T_g$).

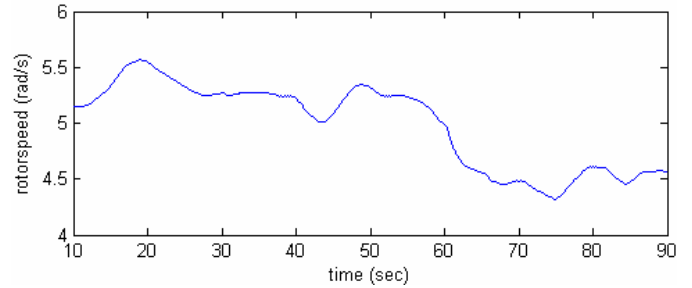


Fig. 13. The rotor speed.

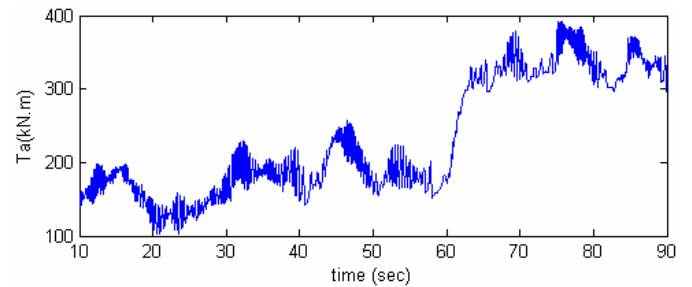


Fig. 14. The aerodynamic torque.

A. FAST Briefly

During time-marching analysis, FAST makes it possible to control the turbine and model specific conditions in many ways. Five basic methods of control are available: pitching the blades, controlling the generator torque, applying the HSS brake, deploying the tip brakes, and yawing the nacelle. The simpler methods of controlling the turbine require nothing more than setting some of the appropriate input parameters in the Turbine Control section of the primary input file. Methods of control that are more complicated (that is our case) require writing specific routines, compiling them, and linking them with the rest of the program [18].

B. Validation Results

The proposed control strategy has been validated on the same simulated WP 1.5-MW wind turbine.

The obtained performances are shown to be as expected: very good power tracking and regulation with fast convergence (Figs. 15 and 16). Moreover, as expected the torque generator remains smooth (Fig. 17). The rotor speed is shown by Fig. 18.

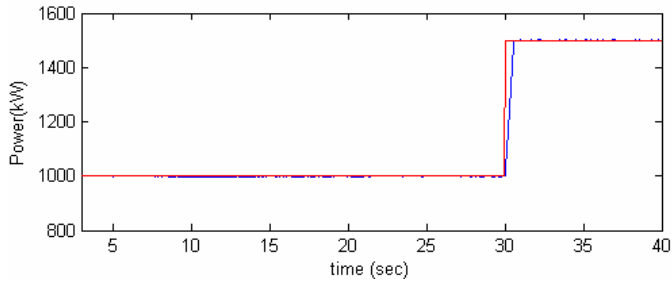


Fig. 15. The generator power and its reference.

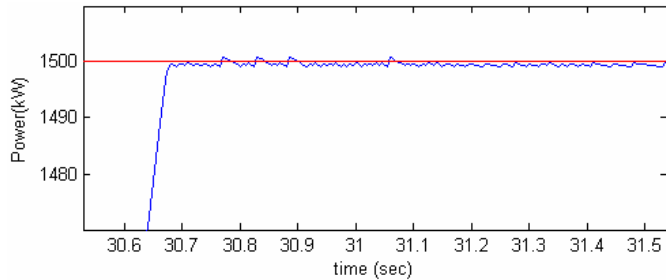


Fig. 16. Zoom on the generator power and its reference.

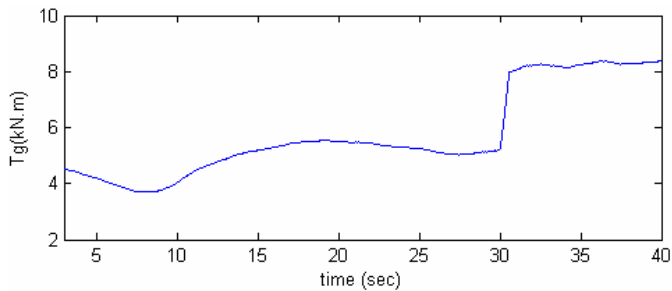


Fig. 17. The generator torque.

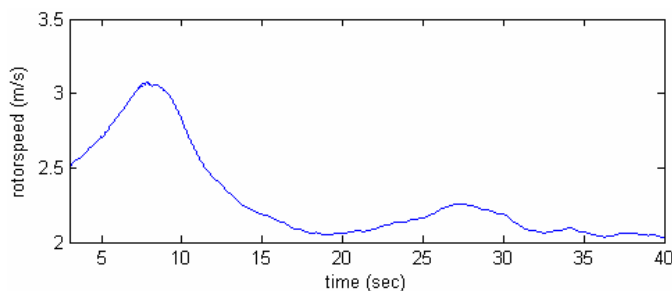


Fig. 18. The rotor speed.

VI. CONCLUSION

This paper dealt with the problem of controlling power generation in variable speed wind turbines. For that purpose, a sliding mode control strategy was proposed to ensure stability in both operation regions and to impose the ideal feedback control solution despite of model uncertainties. The proposed sliding mode control strategy presents attractive features such as robustness to parametric uncertainties of the turbine and the generator as well as to electric grid disturbances.

The proposed sliding mode control approach has been simulated on a 1.5-MW three-blade wind turbine to evaluate its consistency and performance. Then, it has been validated using the NREL wind turbine simulator FAST. Both simulation and validation results show that the proposed control strategy is effective in terms of power regulation. Moreover, the torque generator remains smooth. Indeed, the sliding mode approach was arranged so as to produce no chattering in the generated torque. The main advantages of the proposed control algorithm, according to the available literature [4-5], [8], are its simplicity and robustness against parameters uncertainties and modeling inaccuracies.

The states of the system (variable speed wind turbine) were supposed available. Next step of this work is to extend the control to the case of unmeasured states by combining the sliding mode controller to a nonlinear observer.

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