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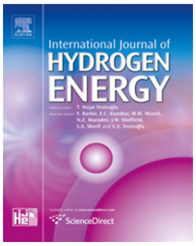

Wind turbine efficiency optimization. Comparative study of controllers based on second order sliding modes

C. Evangelista*, P. Puleston, F. Valenciaga

CONICET and LEICI, Faculty of Engineering, National University of La Plata, C.C.91, (1900) La Plata, Argentina

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A B S T R A C T

This paper studies the applicability of second order sliding mode control strategies to a wind energy conversion system aiming to optimise its power conversion efficiency. Four different controllers are designed and analysed, based on the ‘‘sub-optimal’’, ‘‘twisting’’, ‘‘super-twisting’’ and ‘‘with a prescribed law of variation’’ algorithms, which present finite-time convergence, robustness, chattering and mechanical stress reduction, and are of quite simple online operation and implementation. Representative simulation results are shown, using a complete model of the system under realistic operating conditions, where the performance of the controlled system can be appreciated for each of the controllers and some comparisons can be made.

1. Introduction

During the last decades, especially after the oil crisis in the 70s, global interest for clean and renewable energy sources has been growing intensely. Wind energy in particular, has received a strong impulse, reflected in great technology advances regarding reliability, cost-efficiency and integration to the grid of the wind energy conversion systems (WECS). These can inject their generated power directly into the grid or use it to feed small rural communities or isolated industries, frequently in hybrid systems complemented with other energy sources. Wind turbines generate about 1.5% of the world electricity consumption, with an installed capacity of 121 GW by the end of 2008 comprising more than 70 countries [1].

One of the main matters involved in WECS improvement is related to the inclusion of new control strategies, based on low computational cost algorithms capable of maximising the efficiency of the system while reducing structural loading. Research in this area must consider the exacting control challenges posed by these systems, e.g., the stochastic nature of the wind, the uncertainties in the parameters of the aerodynamic and electric models, external disturbances and the nonlinear behaviour of the whole system [2]. Among the known techniques available to control nonlinear systems under heavy disturbances, the sliding mode (SM) algorithms represent an attractive solution. In particular, controllers based on second order sliding mode (2-SM) algorithms have several interesting features [3–5]:

-robustness with respect to various internal and external bounded disturbances and to unmodelled dynamics, accurately regulating and tracking different kind of variables, with finite-time convergence.
-reduction of mechanical stresses and *chattering* (i.e., high-frequency vibrations of the controlled system), compared to standard SM strategies, given that the applied control actions are continuous.
-simple control laws, easy to implement, which can be designed based on nonlinear models.

The viability of 2-SM control applied to a grid-connected variable-speed WECS is explored in this paper. Specifically, four controllers are designed and analysed, based on four

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* *Corresponding author.*
E-mail address: cae@ing.unlp.edu.ar (C. Evangelista).

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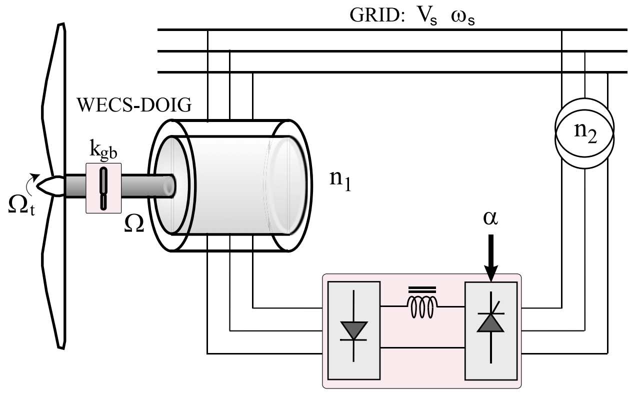

Fig. 1 – WECS-DOIG with slip power recovery.

selected algorithms: “with a prescribed law of variation”, “sub-optimal”, “twisting” and “super-twisting”.

2. Control objective

A grid-connected variable-speed WECS based on a double-output induction generator (DOIG) which uses a static Kramer drive topology (see Fig. 1) is employed in this paper for the analysis of the proposed controllers.

In this configuration, the system operates at variable speed while generating electricity at grid constant frequency. It is capable of generation above its rated power, given that it provides power from both stator and rotor circuits. Whereas the stator power is directly fed to the grid, rotor power is partially recovered through the electronic drive, comprised by an uncontrolled bridge rectifier, a line commutated inverter and a smoothing reactor. The generator torque, and hence the system operation speed and the operation points, can be controlled by modifying the inverter firing angle α [6–8]. A rigid drive train has been supposed and for mathematical simplicity every turbine variable in the paper has been referred to the fast shaft side (generator side) through the transmission relation k_{gb} of the speed multiplier (see appendix B).

Wind turbine operation can be divided into four zones depending on the wind speed ν, each requiring a different control objective (see Fig. 2) [9].

When $V < V_{\text{cut-in}}$, the wind is not strong enough to move the blades. In the *partial load zone*, range of speeds between the cut-in speed and the rated one, the control objective is maximising the energy conversion efficiency. In the *full load zone* the controller must limit the extracted power to its rated value. Finally, above $\nu_{\text{cut-out}}$ speed the turbine should be turned out of the wind to prevent damages, so the generated power is zero.

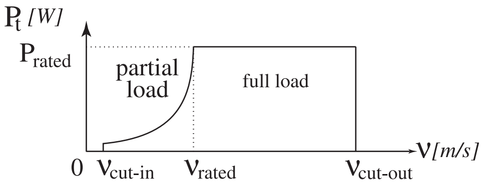

Fig. 2 – Wind turbine operation zones.

The mechanical power a real turbine can extract is only a fraction of the wind power and it can be written as [10]:

$$P_t = 0.5\pi\rho R^2 C_p(\lambda)\nu^3 \tag{1}$$

where ρ is the air density, R is the blades length and C_p is the conversion efficiency or power coefficient of the WECS, a nonlinear function of the tip speed ratio $\lambda = R\Omega/\nu$, with Ω the angular velocity of the blades. $C_p(\lambda)$ depends on the shape and geometrical dimensions of the rotor, presenting for a fixed pitch turbine a single maximum at λ_{opt} (see Fig. 3).

The 2-SM controllers studied here were designed to optimise the conversion efficiency within the *partial load zone*, considering fixed pitch. According to this, from (1) and given that $C_p(\lambda)$ is maximum uniquely for λ_{opt}, the control objective would be accomplished by tracking an optimum speed reference, variable with the wind speed, given by:

$$\Omega_{\text{ref}} = \frac{\lambda_{\text{opt}}\nu}{R} \tag{2}$$

3. Model for design

A reduced order model of the electromechanical system of the WECS is used for the control design process. The simplification is based on considering only the mechanical dynamics and neglecting the electrical, assuming them quite faster in comparison. Hence, the nonlinear equation which defines the dominant dynamics of the system can be straightforwardly obtained by applying Newton’s second law. Neglecting friction and higher order terms it can be written as:

$$\dot{\Omega} = \frac{1}{J}(T_t + T_e) \tag{3}$$

where T_t and T_e are the turbine and the electrical resistant torques ($T_e < 0$ as generator) and J is the inertia of the whole combined rotating parts, also referred to the fast shaft side (see appendix B). An expression for the turbine torque can be obtained from the quotient P_t/Ω:

$$T_t = 0.5\pi\rho R^3 C_t(\lambda)\nu^2 \tag{4}$$

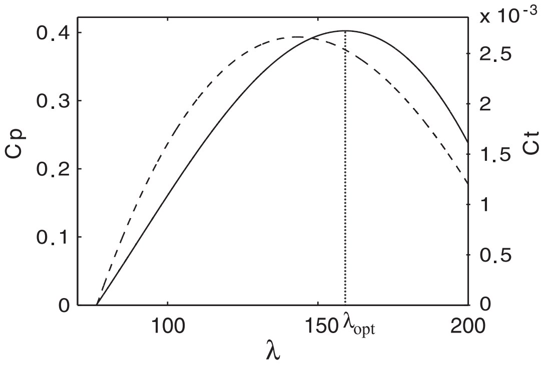

Fig. 3 – Power (solid line) and Torque (dotted line) coefficients versus tip speed ratio.