Nonlinear Power Control Strategies for Variable-Speed Wind Turbines

Abdiddaim KATKOUT*, Ahmed ESSADKI*, Tamou NASSER**

*Electrical engineering department, at the Ecole Normale Supérieure de l'Enseignement Technique, Mohammed V University, Rabat-Morocco

** The communication networks department, at the Ecole Nationale Supérieure d'Informatique et d'Analyse des Systèmes, Mohammed V University, Rabat-Morocco

abdiddaim.katkout@um5s.net.ma, ahmed.essadki1@gmail.com

*Abdiddaim KATKOUT, Tel: +212 628923419
abdiddaim.katkout@um5s.net.ma

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Abstract- These last years, several important researches are about the controls of a variable-speed wind turbines. The objectives of these controls are the optimization of power in the zone of lows winds and the regulation of the power in the zone of intense winds and reduction of the mechanical constraints applied to the wind turbines. The productivity of the wind turbines is limited by available linear controls. In this paper, we will have developed nonlinear controls that satisfy the control objectives of variable-speed wind turbines. The nonlinear controls are tested and compared between them for lows and intense winds. The simulation results on Matlab software show that the nonlinear controls satisfy the desired objectives.

Keywords Variable speed wind turbines, the optimization, the regulation, the mechanical constraints, nonlinear controls.

1. Introduction

The acceleration of social and technical development is accompanied by the unlimited increase of needs to electric energy, much of this energy is produced from fuels [1]. The decline in the natural resources of fuels and the environmental challenges that guide global energy policy towards the exploitation and development of renewable energy sources such as wind power [2] [3].

The wind turbine is the basic element in the wind power production chain. The wind turbine is a set of subsystems interact with each other [4] [5]. The primary element of the wind turbine is the blades that interact with the wind; the kinetic energy of the wind is converted to an electrical energy by an electric machine [6]. This energy injected into the electrical network directly or through static converters for adapted the energy with that required by the electrical network [7] [8].

There are two main wind turbine families: horizontal axis wind turbines and vertical axis wind turbines [9]. The control is considered to be the major factor for the efficiency of the system whatever the type of wind turbine [10] [11].

The wind turbine is a nonlinear system. Most of the available controls are linear controls which limits the electrical power produced by the wind turbine [10]. The present study aims at developing nonlinear controls for lows and intense winds and achieving a good compromise between the production of electric power and the mechanical constraints undergone by the wind turbine [12].

The difference of the constant of time between the turbine and the electric machine allows the dissociation of the control between them and allows defining two levels of control [10]:

- A control level 1 applied to the machine through the power converters;
- A control level 2 which provides the two input parameters β and T_{em} of control level 1.

In this study, the control of the turbine is dissociated at the control of the electrical system and the control laws have been developed in control level 2. First, we present the models of the turbine and the blade angle control system. Then we define the objective of the control of wind turbines and the nonlinear controls in every zone of functioning. Finally, we test the validity of the used models and we make the comparison between the simulations results of the used nonlinear controls.

2. Systems Models

2.1. Modelling the turbine

The theoretical power stored in the incident wind is [13] [14]:

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

Where R is the Radius of blades [m], ρ is the density of the air (1.225 Kg/m^3 at atmospheric pressure) and v is the wind speed [m/s].

The power extracted by the blades of the wind turbine is:

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

The coefficient C_p is defined as the aerodynamic efficiency of the wind turbine [13]. The coefficient C_p used in this study is the expression suggested by Heier [10].

The dynamics of the turbine shaft is governed by the following differential equation [15] [16]:

$$J_t\dot{\omega}_t = T_{aer} - T_{em} - f\omega_t \quad (3)$$

And:

$$T_{aer} = \frac{P}{\omega_t} \quad (4)$$

Where T_{aer} is the aerodynamic torque produced by the wind turbine, T_{em} is the electromagnetic torque of the electric machine, J_t is the turbine's inertia, f is the coefficient of friction and ω_t is the angular velocity of the rotor.

2.2. Modelling the blade angle control system

The structure of the blade angle control system is constituted by two imbricate buckles of regulation: a buckle of position and a buckle of speed of positioning of blades [17]. The simplified block diagram of this system is illustrated in Fig. 1.

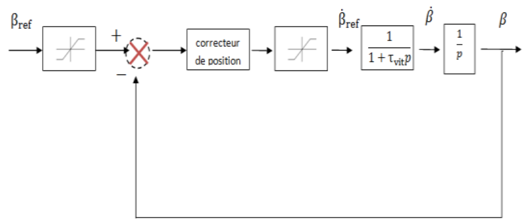


Fig. 1. Structure of the blade angle control system

Where τ_{vit} represents the equivalent time constant for the buckle of speed.

3. The Control of the Turbine

The turbine can be controlled by acting on two inputs: the angle of the blade and the electromagnetic torque of the electric machine. The wind speed is considered as a disruptive input to this system [18] [19].

The objectives of the control are defined for every zone of functioning [10] [20]:

- $v_{min} \le v \le v_{nom}$: The main objective in this zone is the maximization of the produced electric power: the optimization [21].
- $v_{nom} \le v \le v_{max}$: The main objective in this zone is kept the electric power produced around its nominal value: the regulation.

The common objective between the two zones is the reduction of the mechanical constraints applied to the wind turbine.

3.1. The optimization of the power

In the zone of lows winds the control keeps the blade angle at an optimal value β_{opt} and the control acts on the electromagnetic torque T_{em}.

The specific speed:

$$\lambda = \frac{\omega_t R}{v} \quad (5)$$

The control of the wind turbine must keep the coefficient λ at its optimum value:

$$\lambda_{opt} = \frac{\omega_{topt} v}{R} \quad (6)$$

ω_{topt} is the speed to be followed by the wind turbine to optimize power production [22].

The power of a variable-speed wind turbine is optimized if the variations of the speed of the turbine followed the variations of the wind speed [23].

The error between the speed of the turbine and the optimum speed:

$$e_\omega = \omega_{topt} - \omega_t \quad (7)$$

This error must be maintained at a null value. We use two dynamics of pursuit of this error which is defines two controls. The electromagnetic torque is calculated from equation 3.

3.1.1. Nonlinear control by static state-feedback NCSSF

On this control the dynamics imposed on the error of pursuit of the rotor speed is a dynamics of the first order [10]:

$$\dot{e}_\omega + a_0 e_\omega = 0 \quad (8)$$

This control is sensible to perturbations.

3.1.2. Nonlinear control by dynamic state-feedback NCDSF

If we suppose that a constant perturbation p acts on the system, we have:

$$J_t\dot{\omega}_t = T_{aer} - T_{em} - f\omega_t + p \quad (9)$$

To remove the constant perturbation on the system we impose a dynamics of the second order on the error of pursuit of the rotor speed [10]:

$$\ddot{e}_\omega + a_1\dot{e}_\omega + a_0 e_\omega = 0 \qquad (10)$$

3.2. *The regulation of the power*

3.2.1. Torque control TC

This technique of control maintains a fixed angle of blades and acts only on the torque of the electric machine T_{em} for the regulation of the power [24].

The dynamics imposed on the error of pursuit of the rotor speed is a dynamics of the first order, according to equation 3 and equation 8 we have [10]:

$$T_{em} = T_{aer} - f\omega_t - a_0 J_t e_\omega - J_t\dot{\omega}_{ref} \qquad (11)$$

Where ω_{ref} is the reference speed.

The generated power is written:

$$P = T_{em}.\omega_t \qquad (12)$$

The error between the generating power and the reference power:

$$e_p = P_{ref} - P \qquad (13)$$

We impose a dynamics of the first order on the error of pursuit of the power:

$$\dot{e}_p + b_0 e_p = 0 \qquad (14)$$

3.2.2. Torque and blade angle control TBAC

The principle is to use a torque control and limiting the efforts of control using the blade angle.

- *Torque control*

We consider equation 13 and equation 14 with a constant power reference:

$$\dot{T}_{em} = \frac{1}{\omega_t}\left[b_0 e_p - \frac{1}{J_t}\left(T_{aer}T_{em} - f\omega_t T_{em} - T_{em}{}^2\right)\right] \quad (15)$$

- *Blade angle control*

We use a proportional blade angle control to avoid intense torque controls.

4. Simulation Results

4.1. *Simulation parameters*

The Table. 1 shows the wind turbine Parameters.

4.2. *Validation of the turbine model*

To validate the mathematical model of the turbine two tests are realized: One with a wind profile with an average speed of 7 m/s, Fig. 2, and the other with an average speed of 20 m/s, Fig. 3.

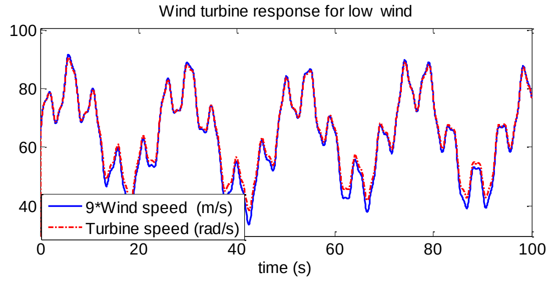


Fig. 2. Wind turbine response for low wind

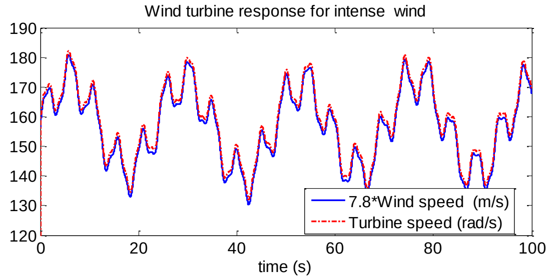


Fig. 3. Wind turbine response for intense wind

Whether in low or intense wind, the variations of the speed of the turbine follow the variations of the wind speed.

These results prove the validity of the model that is chosen.

4.3. *Validation of the model of the blade angle control system*

The validation of model of the blade angle control system shows that the blade angle is followed the variations of the reference blade angle, Fig. 4.

Table. 1. The wind turbine Parameters

System	Parameters	Values
Wind turbine	•Nominal power •Blade radius •Turbine inertia •Coefficient of friction •Gain of the speed multiplier •Nominal wind speed	P_n=300 Kw R=14 m J_t=50 kg. m^2 f=7. 10^{-3} G=28 v_n=12 m/s
blade angle control system	• Equivalent time constant • Maximal angle of blades • Maximum speed of variation of the blade angle	τ_{vit}=0.01 25° 19°/s

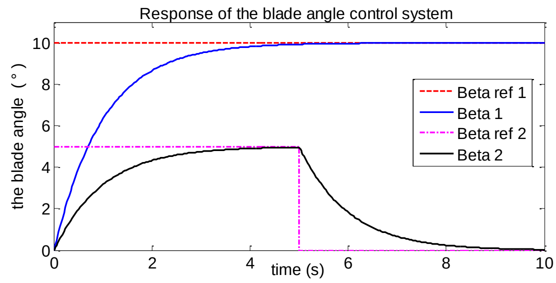
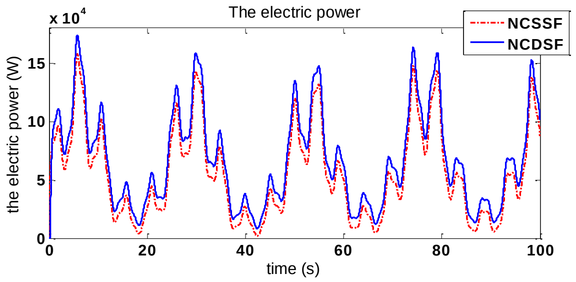


Fig. 4. Response of the blade angle control system to the reference angle

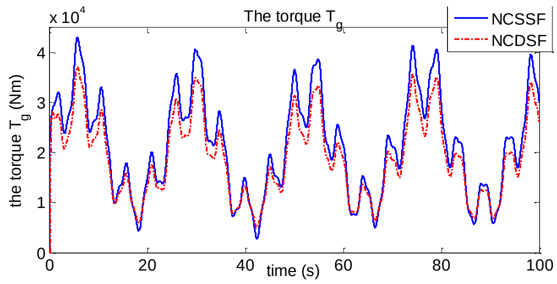
4.4. *Comparison of different control strategies for power optimization*

We realized the simulations by acting on the torque T_{em} and keeping the blade angle β at its optimum value $\beta_{opt} = 0°$, with a profile of wind of average value $v_m = 7\ m/s$ and a constant disturbance p=1000 Nm.

The curves of the electrical power P_e and the torque T_{em} are combined on the same graph represented on Fig. 5 for each of the controls applied.



(a)



(b)

Fig. 5. The electric power P_e (a) the torque T_g (b)

The produced electric power P_e and the electromagnetic torque T_{em} follow the variations of the wind speed, the Table. 2 shows the extreme values of P_e and T_{em} obtained for each command applied:

We notice that the power produced by the NCDSF control is superior to that produced by the NCSSF, Fig. 5 (a). The mechanical constraints undergone by the wind turbine in the case of the NCDSF is more important than those of the NCSSF, Fig. 5 (b).

Table. 2. The extreme values of P_e and T_{em}

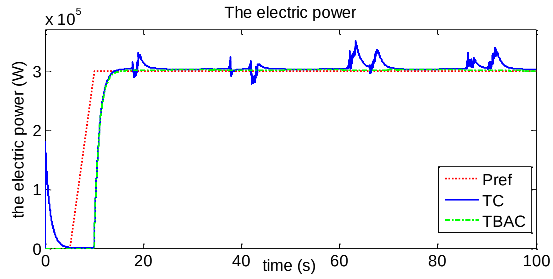
The measures	NCSSF	NCDSF
$P_{e\ max}$	$1,577.10^5$	$1,7388.10^5$
$P_{e\ min}$	1962	8400
$T_{em\ max}$	$4,3125.10^4$	$3,7221.10^4$
$T_{em\ min}$	2822	5000

4.5. *Comparison of the different control strategies for power regulation*

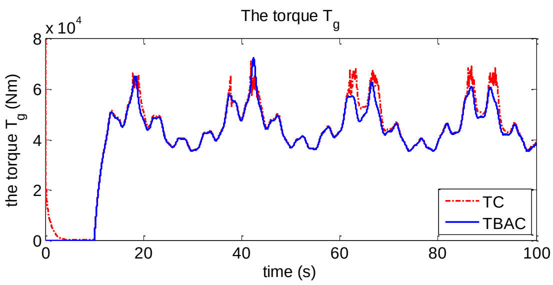
We realized the simulations with a profile of wind of average value $v = 21\ m/s$. For the TC, the blade angle β is kept at its maximum value of 25° and we act on the electromagnetic torque T_{em}.

For the TBAC the two variables of the wind turbine control are affected: blade angle β and the electromagnetic torque T_{em}.

Two references of power are used: one constant of 300 KW, Fig. 6, and the other variable of 200 KW, 300 KW and 250 KW in order to meet a specific demand of the electricity network, Fig. 7.

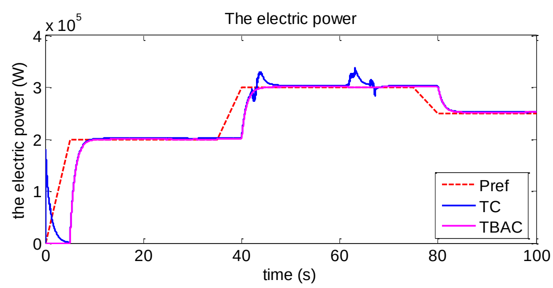


(a)

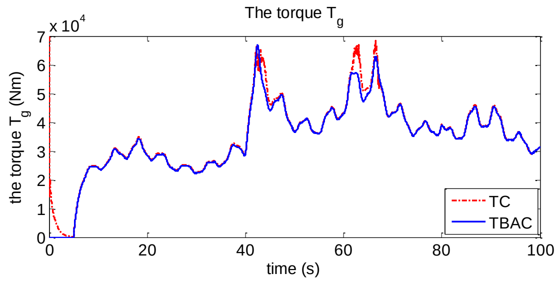


(b)

Fig. 6. Electric power P_e (a) the torque T_{em} (b) with a reference P_{ref} constant



(a)



(b)

Fig. 4. Electric power P_e (a) the torque T_{em} (b) with a reference P_{ref} variable

The main difference between the two controls is the quality of the power produced by the turbine. For both types of power references, the performance of the power control is unsatisfactory for the TC, the produced electric power diverted in the desired reference and this deviation corresponds to the maximum values of the electromagnetic torque, Fig. 6 (a) and Fig. 7 (a). On the other hand, in the case of the TBAC, the power produced followed its reference value, Fig. 6 (a) and Fig. 7 (a).

The mechanical constraints undergone by the wind turbine are very important for the TC compared to TBAC, Fig. 6 (b) and Fig. 7 (b). In the case of the TC control, the passage of the torque by its maximum values is accompanied by disturbances due to the fast variations in speed of the turbine.

5. Conclusion

The main contribution of the paper is the development of the nonlinear controls of variable speed wind turbines for lows and intense winds. The entire system and controls is designed and simulated in Matlab software. The simulation results illustrate that the nonlinear controls are more profitable and stable than the existing controls.

For lows winds, the nonlinear control by dynamic state-feedback makes it possible to obtain the maximum electrical power with reduced forces. In the case of the intense winds, the controls are tested in different reference power and the torque and blade angle control produces an electrical power around the desired reference and reduces the disturbances of the electromagnetic torque.

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