Multivariable Control Strategy for Variable Speed, Variable Pitch Wind Turbines

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Abstract

Reliable and powerful control strategies are needed for wind energy conversion systems to achieve maximum performance. A new control strategy for a variable speed, variable pitch wind turbine is proposed in this paper for the above-rated power operating condition. This multivariable control strategy is realized by combining a nonlinear dynamic state feedback torque control strategy with a linear control strategy for blade pitch angle. A comparison to existing strategies, PID and LQG controllers, is performed. The proposed approach results in better power regulation. The new control strategy has been validated using an aeroelastic wind turbine simulator developed by NREL for a high turbulence wind condition.

Key words: wind energy, variable speed wind turbine, power regulation, multivariable control

Nomenclature

v	Wind speed, $\mathrm{m \cdot s^{-1}}$
ρ	Air density, $\mathrm{kg \cdot m^{-3}}$
R	Rotor radius, m
P_a	Aerodynamic power, W
$P_{a_{opt}}$	Optimal aerodynamic power, W
T_a	Aerodynamic torque, N·m
λ	Tip speed ratio
β	Pitch angle, deg
λ_{opt}	Optimal tip speed ratio
β_{opt}	Optimal pitch angle, deg
C_p	Power coefficient
C_q	Torque coefficient
ω_r	Rotor speed, $\mathrm{rad \cdot s^{-1}}$

ω_g Generator speed, $\text{rad}\cdot\text{s}^{-1}$
T_{em} Generator (electromagnetic) torque, N·m
T_g Generator torque in the rotor side, N·m
T_{ls} Low speed shaft torque, N·m
T_{hs} High speed shaft torque, N·m
J_r Rotor inertia, $\text{kg}\cdot\text{m}^2$.
J_g Generator inertia, $\text{kg}\cdot\text{m}^2$.
J_t Turbine total inertia, $\text{kg}\cdot\text{m}^2$.
K_r Rotor external damping, $\text{N}\cdot\text{m}\cdot\ \text{rad}^{-1}\cdot\ \text{s}$.
K_g Generator external damping, $\text{N}\cdot\text{m}\cdot\ \text{rad}^{-1}\cdot\ \text{s}$.
K_t Turbine total external damping, $\text{N}\cdot\text{m}\cdot\ \text{rad}^{-1}\cdot\ \text{s}$.
K_{ls} Low speed shaft damping, $\text{N}\cdot\text{m}\cdot\ \text{rad}^{-1}\cdot\ \text{s}$.
B_{ls} Low speed shaft stiffness, $\text{N}\cdot\text{m}\cdot\text{rad}^{-1}$.
n_g Gearbox ratio.
P_a Aerodynamic power, W.
P_e Electrical power, W.

1 Introduction

Since the early 1990's wind power has enjoyed a renewed interest, particularly in the European Union where the annual growth rate is about 20%. This growth is attributed to wind power's inherent attribute of generating carbon emission-free electricity. In order to sustain such growth, wind turbine performance must continue to be improved. Advanced control is one research area where such improvement can be achieved.
This perspective of wind power production increase needs the developments of an efficient production tools. The research work presented in this paper is in line within this framework in the aim to improve the performance of the machines to get the best benefit from this energy source.
The controllers presented in this paper are designed for variable speed wind turbines operating at high wind speeds. The primary objective of the controllers is to reduce electrical power and rotor speed fluctuations while minimizing the control actuating loads. When the wind speed exceeds its nominal value, the control objective shifts from maximizing power capture to regulating power to the turbine's rated output. Two control inputs are available: the generator torque and the blade pitch angle.
The herein developed controllers are devoted for variable speed, variable pitch wind turbine control for high wind speeds. The main objective of the control system in this area is to reduce electrical power and rotor speed fluctuations while reducing the control loads.
Linear controllers have been extensively used for power regulation through

the control of blade pitch angle. One may find PI and PID pitch controllers in [1] and [2]. LQ and LQG control techniques have also been demonstrated in [3], [4], and [5]. Linear robust control has been introduced in [6] and used in [7], [8], and [9]. However, the performance of these linear controllers is limited by the highly nonlinear characteristics of the wind turbine.

Typical power regulation control schemes use blade pitch angle as the only controller input. Generator torque is sometimes controlled according to the method employed for the below-rated wind speed conditions known as the indirect control in torque technique. Most controllers hold the generator torque constant at its nominal value making the controller monovariable in pitch only [2], [10], [11], [12] and [13].

These monovariable controllers are unable to meet the multiple objectives of regulating electrical power and rotor speed. A multivariable controller is therefore presented in this work. Its principle is to combine a PID pitch controller with the non linear torque controller we have suggested in [14]. With some simplifications, a multivariable control scheme that results in a good compromise between the regulation of both outputs is demonstrated.

This paper is organized as follows: Section 2 provides a brief description of the wind turbine model requirements. A simplified mathematical model is derived, and a complicated aeroelastic simulator is described. The control objectives of this work are then specified. Section 3 starts with a brief description of some existing monovariable control techniques for blade pitch. The multivariable controller in pitch and torque is then presented. Section 4 first compares the performance of the monovariable controllers to that of the multivariable controller using the mathematical model. These results are then validated with the FAST [15] aeroelastic wind turbine simulator developed by NREL [1]. A high wind speed profile that pushes the limits of the monovariable controllers is used to demonstrate the ability of the multivariable controller to extend the turbine's operating regime.

2 Model Description

2.1 System modelling

A variable-speed wind turbine generally consists of an aeroturbine, a gearbox, and a generator. The aerodynamic power captured by the rotor is given by the non linear expression

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

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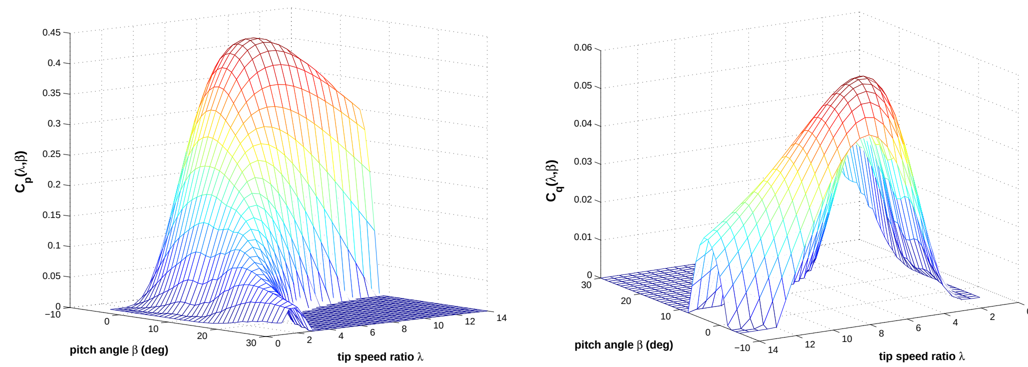


(a) power coefficient C_p curve (b) torque coefficient C_q curve

Fig. 1. CART wind turbine power and torque coefficients

where ω_r is the rotor speed; R is the rotor radius and ρ is the air density. The power extracted from the wind, P_a, is proportional to the cube of the wind speed v. The power coefficient, C_p, depends on the blade pitch angle, β, and the tip-speed ratio, λ, which is defined as the ratio between the linear blade tip speed and the wind speed v.

$$\lambda = \frac{\omega_r R}{v} \tag{2}$$

Thus, any change in the rotor speed or the wind speed induces change in the tip-speed ratio leading to power coefficient variation. In this way, the generated power is affected. The aerodynamic torque coefficient is related to the power coefficient as follows. Using the relationship:

$$P_a = \omega_r T_a \tag{3}$$

the aerodynamic torque expression is then

$$T_a = \frac{1}{2}\rho\pi R^3 C_q(\lambda,\beta)v^2 \tag{4}$$

where

$$C_q(\lambda,\beta) = \frac{C_p(\lambda,\beta)}{\lambda}$$

Power and torque coefficient surfaces for the wind turbine considered in this study are shown in figure 1. These surfaces are obtained using blade-element moment theory implemented in a wind turbine performance code, WT-PERF [16], developed by NREL. These surfaces are implemented in the mathematical model as look-up tables. A two mass model of a wind turbine is shown in figure 2.

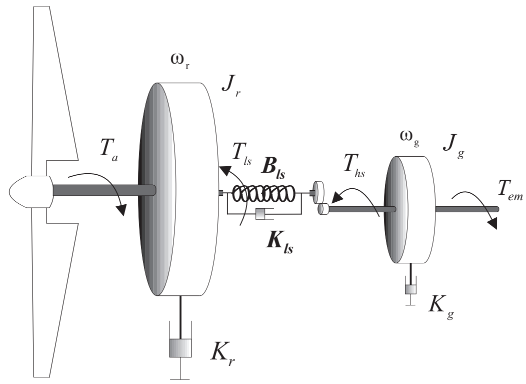


Fig. 2. Two mass model of a wind turbine

The dynamic response of the rotor driven at a speed ω_r by the aerodynamic torque T_a is shown to be

$$J_r\dot{\omega}_r = T_a - T_{ls} - K_r\omega_r \tag{5}$$

The low-speed shaft torque T_{ls} acts as braking torque on the rotor (see figure 2). It results from the torsion and friction effects due to the difference between ω_r and ω_{ls}

$$T_{ls} = B_{ls}(\theta_r - \theta_{ls}) + K_{ls}(\omega_r - \omega_{ls}) \tag{6}$$

The generator is driven by the high speed shaft torque T_{hs} and braked by the generator electromagnetic torque T_{em}.

$$J_g\dot{\omega}_g = T_{hs} - K_g\omega_g - T_{em} \tag{7}$$

Assuming an ideal gearbox with transmission ratio n_g, we have

$$n_g = \frac{T_{ls}}{T_{hs}} = \frac{\omega_g}{\omega_{ls}} \tag{8}$$

Transferring the generator dynamics to the low speed side and using Eq. (7) and Eq. (8), the generator dynamics can be written as

$$n_g^2 J_g\dot{\omega}_g = T_{ls} - (n_g^2 K_g)\omega_g - n_g T_{em} \tag{9}$$

If a perfectly rigid low-speed shaft is assumed, a single mass model of the turbine may then be considered

$$J_t\dot{\omega}_r = T_a - K_t\omega_r - T_g \tag{10}$$

where

$$J_t = J_r + n_g^2 J_g$$
$$K_t = K_r + n_g^2 K_g$$
$$T_g = n_g T_{em}$$

The scheme of the wind turbine one mass model is given in figure 3.

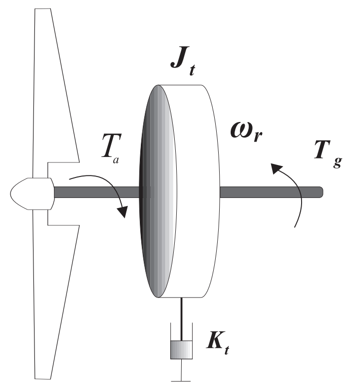


Fig. 3. One mass model of a wind turbine

2.2 Simulator description

The Fatigue, Aerodynamics, Structures and Turbulence (FAST) code developed by NREL is an aeroelastic WT simulator that is capable of modelling two- and three-bladed propeller-type machines. This code is used by WT designers to predict both extreme and fatigue loads. It uses an assumed mode method to model flexible blades and tower components. Other components are modelled as rigid bodies. In this study, seven degrees-of-freedom (DOFs) are simulated: the variable generator and rotor speed (2 DOFs), the blade teeter DOF, the first flapwise bending moment of the two blades (2 DOF) and the second flapwise bending moment of the two blades (2 DOF). The variable generator and rotor speed DOFs account for the variations in generator speed and the drive train flexibility associated with torsional motion between the generator and hub/rotor. The blade teetering DOF accounts for the teeter motion induced by asymmetric wind loads across the rotor plane.

2.3 Control objectives

Wind turbine operation can be divided into two regions :

- Above rated wind speed (full load) where $v_1 < v < v_2$.
- Below rated wind speed (partial load) where $v_2 < v < v_3$.

v is the mean wind speed. The wind turbine is stopped for $v < v_1$ or $v > v_3$.

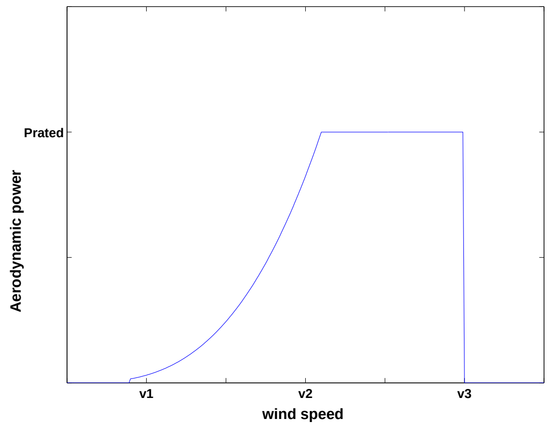


Fig. 4. Wind turbine aerodynamic power

Control system design objectives for each region can be specified by:

- Limitation and smoothing of electrical power in the above rated power area.
- Generation of maximum power in the below rated power area.
- Minimization of transient loads in all turbine components.

When power production is below the rated power for the machine, the turbine operates at variable rotor speeds to capture the maximum amount of energy available in the wind. Generator torque provides the control input to vary the rotor speed, and the blade pitch angle is held constant [17]. For high wind speeds, the primary objective is to maintaining constant the output power to its rated value. This is generally achieved by holding the generator torque constant and varying the blade pitch angle. In both control regimes, the turbine response to transient loads must be minimized. In this paper, the above-rated power operating regime is considered.
Monovariable baseline controllers are first described. In order to compensate their drawbacks, a new multivariable controller, using blade pitch and generator torque is proposed.

3 Multivariable controller

3.1 Baseline control strategies

For a variable speed, variable pitch wind turbine control, two means are possible: The blades pitching and the generator torque. Linear monovariable pitch controllers have been initially used with a PID and LQG regulators. Although

they led to acceptable results for the rotor speed regulation, these controllers showed limited performance for power regulation.
A classical approach of this control problem is a PID, controller for the rotor speed, while keeping the generator torque constant, as it can be found in [18]. The scheme of a PID controller is depicted in figure 5.

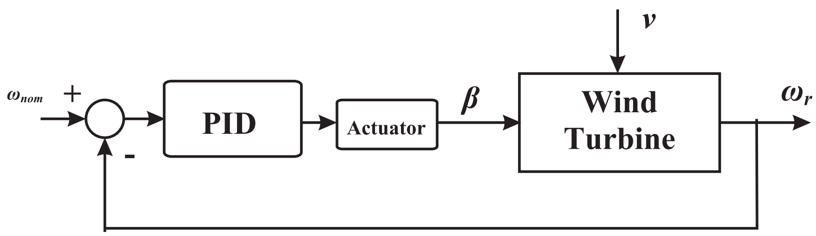


Fig. 5. PID controller scheme of the wind turbine

Another classical approach as described in [2] concerns an LQG controller. As above, the generator torque is also supposed to be constant, while the speed control scheme is as indicated in figure 6.

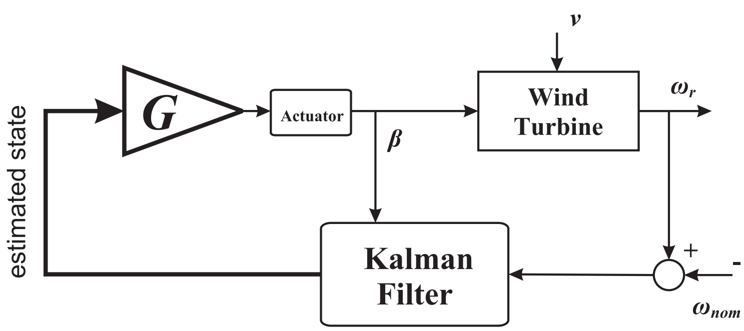


Fig. 6. LQG controller scheme of the wind turbine

From a linear state space representation of the wind turbine, a cost function J_{abv} of the state $\mathbf{x}$, and the control input u is to be minimized, such as follows:

$$J_{abv} = \lim_{0 \to T} \frac{1}{T} \; E \left\{ \int_0^T \left(\mathbf{x}^T \mathbf{Q} \mathbf{x} + Q_\beta (\Delta\beta)^2 \right) dt \right\} \tag{11}$$

resulting in a gain $\mathbf{G}$ for the linear state feedback.
The LQG control strategy ensures a better power tracking than the PID, but this turns out to be still insufficient.

3.2 Multivariable control strategy

In the aim of achieving some performance, a nonlinear torque controller have been proposed in [14]. This one allows a good regulation of the output power; however, the rotor speed unfortunately presents large variations.
The previous controllers are unable to achieve the double objective of wind turbine electric power regulation while maintaining the rotor speed around its nominal value. This is due to the fact that one control input only is used in both cases. To join the advantages of these two control techniques, our idea is to combine a fast torque controller and a slow pitch controller in order to minimize the actuator control loads, forming thus a multivariable controller.

3.2.1 Torque controller

In order to make the controller less complex and as the rotor speed regulation objective is partly guaranteed by the pitch controller, the torque controller presented in [14] is simplified. There is no dynamics imposed to the rotor speed in this case.
A slower first order dynamics are imposed to the power tracking error of the torque controller. The lack of quickness is compensated by the pitch action.
The electrical power tracking error is defined as

$$\varepsilon_p = P_{nom} - P_e \ .$$

Let us impose a first order dynamics to this error:

$$\dot{\varepsilon}_p + c_0 \varepsilon_p = 0, \quad c_0 > 0 \ . \tag{12}$$

Considering the following expression of the electric power

$$P_e = \omega_r \cdot T_g \tag{13}$$

and when (13) is replaced in 12, one obtains for a constant reference P_{nom}

$$-\dot{\omega}_r T_g - \omega_r \dot{T}_g + c_0 \varepsilon_p = 0 \ , \tag{14}$$

From the $\dot{\omega}_r$ expression deduced from 10, one can finally write

$$\dot{T}_g = \frac{1}{\omega_r} \cdot \left[c_0 \varepsilon_r - \frac{1}{J_t}(T_a \cdot T_g - K_t \omega_r \cdot T_g - T_g^2) \right] \ . \tag{15}$$

3.2.2 Pitch controller

In order to assist the torque controller to regulate the wind turbine electric power output, while avoiding significant loads and maintaining the rotor speed within acceptable limits, a proportional pitch controller is added upon the rotor speed tracking error

$$\Delta\beta = K_p \varepsilon_\omega \ , \tag{16}$$

where

$$\varepsilon_\omega = \omega_{ref} - \omega_r \ ,$$

The multivariable controller scheme is given in Figure 7.

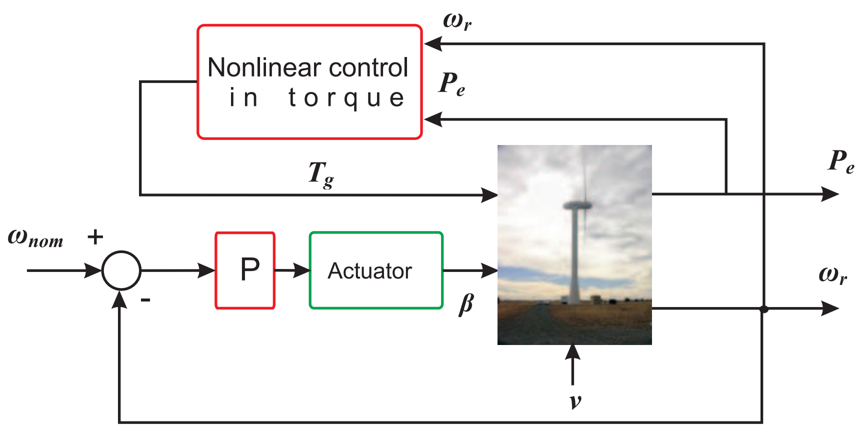


Fig. 7. Multivariable controller scheme

This control action does not have to strongly solicit the blades actuators, because contrary to the pitch controllers only, this action is helped by the generator torque.
The tests results have shown that a more complex action (PI, ,PID) will make the pitch control more turbulent without a significant improvement of the power regulation performance.

4 Simulation Results

The numerical simulations have been performed on a wind turbine whose characteristics are given in Table I.

Rotor diameter	43.3 m
gearbox ratio	43.165
Hub height	36.6 m
Generator system electrical power	650 kW
Maximum rotor torque	162 kN.m

TABLE I. Wind turbine characteristics

These parameters correspond to the Controls Advanced Research Turbine (CART) which is located at NREL's National Wind Technology Center nearby Boulder, CO.
The CART is a variable-speed, variable pitch WT with a nominal power rating of 600 kW and a hub height of 36 m. It is a 43-m diameter, 2-bladed, teetered hub machine. The gearbox is connected to an induction generator via the high-speed shaft, and the generator is connected to the grid via power electronics. This turbine has been modelled with the mathematical model and validated through the FAST aeroelastic simulator also developed by NREL.
The wind inflow for the simulations consists of 10-minutes data set of full-field turbulent wind. Figure 8 illustrates the hub-height wind speed variation.

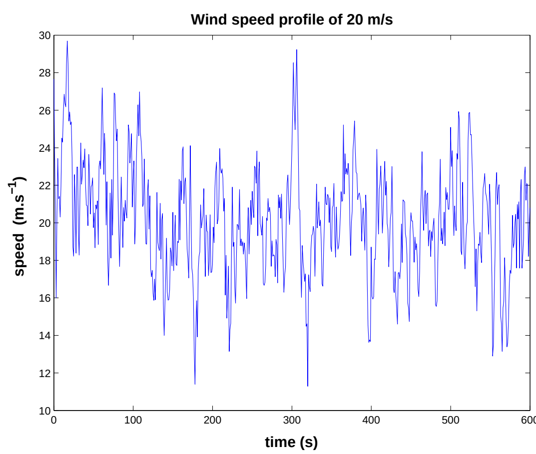


Fig. 8. Wind profile with a mean of 20 m/s

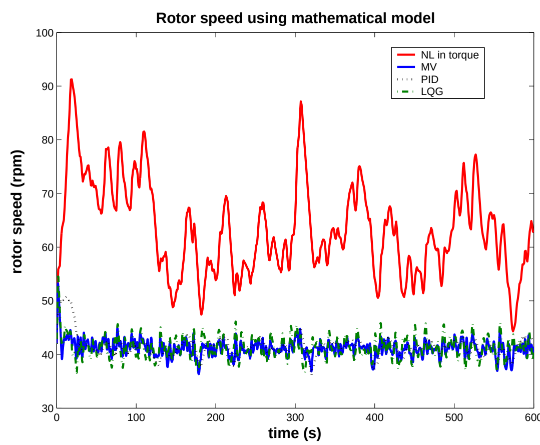
This turbulent wind data was generated using the Class A Kaimal turbulence spectra. It has a mean value of 20 m/s at the hub height and a turbulence intensity of 15 %.
This wind condition is at the limit of the turbine operating regime. Using this excitation, each of the discussed controllers is compared in order to keep the wind turbine in operation as long as possible while dealing with rotor speed, power regulation and transient loads reduction.

4.1 Using the mathematical model

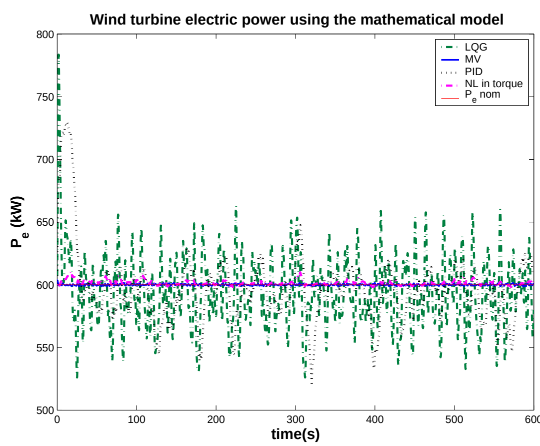
The test of the multivariable controller on the mathematical model has shown that it is possible to carry out a good compromise between the regulation of both outputs with acceptable control loads.
The simulations results using the different controllers with the mathematical model are shown in figures 9(a) and 9(b). According to figure 9(a), the PID and LQG pitch controllers achieve an acceptable rotor speed regulation. However, the electrical power regulation performance may be improved a little bit

more (figure 9(b)). That can be explained by the fact that these controllers are apart from their field of action as we imposed extreme wind conditions. In opposite, the nonlinear torque controller presented in [14] ensures a good power regulation (figure 9(b)), but the rotor speed fluctuations are very large (figure 9(a)). The multivariable controller achieves a good compromise between electrical power regulation and rotor speed one. As one may observe in figure 9(a), the rotor speed is well regulated close to its nominal value. ω_r varies between 36 and 48 rpm with a standard deviation of 1.50 rpm. The electrical power regulation performance are quite satisfactory. Figure 9(b) shows that the electrical power P_e remains very close to the nominal power. Its mean value is almost equal to the nominal power P_{nom}.
Because of the presence of a pitch action, the control torque standard deviation is reduced comparing to the nonlinear torque controller (Table II).

The pitch action remains acceptable. Its variations are similar to those ob-



(a) rotor speed using the mathematical model



(b) electrical power using the mathematical model

Fig. 9. Simulation results using the mathematical model

tained by the PID regulator, but solicit the pitch actuator less than the LQG controller. The use of both control actions has shown that one can achieve

Controller	$\bar{T}_g$	$std(T_g)$	$\bar{\beta}$	$std(\beta)$
PID	-	-	15.36	2.49
LQ	-	-	15.17	3.78
NL in torque	93.15	8.79	-	-
MV	139.38	4.88	15.38	3.38

TABLE II. Comparison of the control loads using the mathematical model

a good tracking of a power reference while keeping the rotor speed close to its nominal value. According to Table II, the control torque and pitch control loads remain acceptable.

4.2 Using FAST simulator

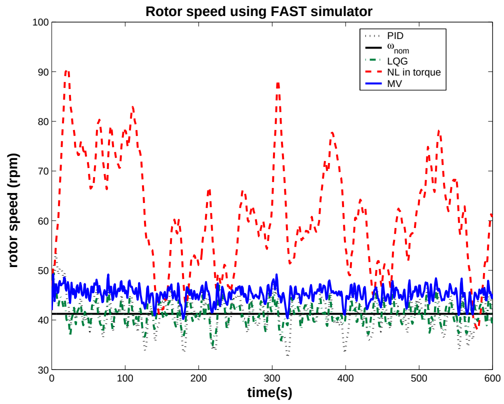
The proposed controllers performance have also been compared using FAST simulator described in section 2.2. This comparison has been realized with the SymDyn simulator too [14], which is faster but less performant than FAST. In spite of performance decrease in comparison with the mathematical model, the obtained results show that the multivariable control strategy allows to join the advantages of both monovariable pitch and torque controllers.

As one can notice in figure 10(a), the non linear control in torque does not succeed in to maintain the rotor speed near its nominal value. This variable reaches large values that can damage the wind turbine behavior. That proves the need of a pitch action for high winds to keep the rotor speed in a limited domain of variations.

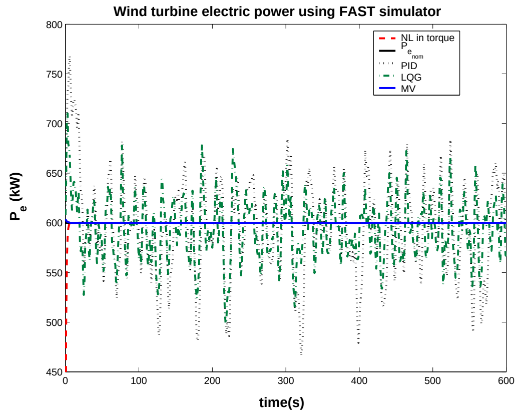
On the other hand, the nonlinear controller in torque realizes a good electric power regulation. The standard deviation of P_e exceeds 45 kW using the PID controller while it is about 1 kW for the nonlinear controller in torque.

One can also notice that there is a small deviation of the rotor speed from its nominal value. However, a more complex action in pitch (PI, PID) in the multivariable controller leads to reduce this deviation, but the control loads in pitch are more involved. In order to made a compromise between rotor speed regulation and control loads reduction, a proportional action in pitch is thus chosen. Therefore, the combination of the torque and pitch control inputs leads to a multivariable approach which can reach the double objective of regulating simultaneously the rotor speed (figure 10(a)) and the electrical power (figure 10(b)).

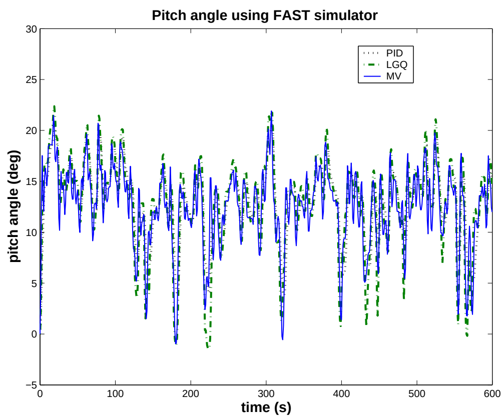
The association of both techniques gives rise to a less turbulent control loads. The generator torque T_g fluctuations with the multivariable controller are lower than those related to the nonlinear controller in torque. The T_g standard deviation is reduced by 13 kN.m. The pitch action remains acceptable with a standard deviation being between those of the LQG and PID controllers.



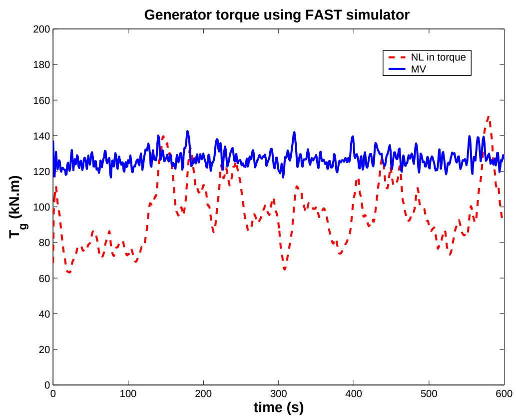
(a) rotor speed



(b) electrical power



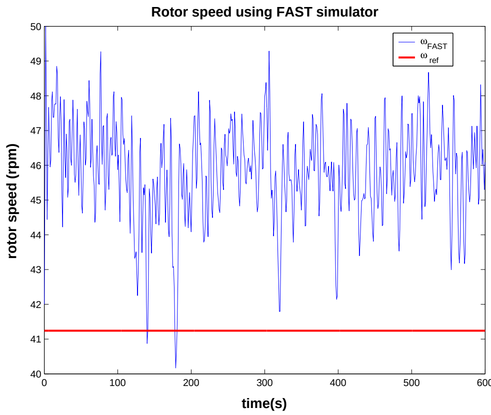
(c) pitch angle



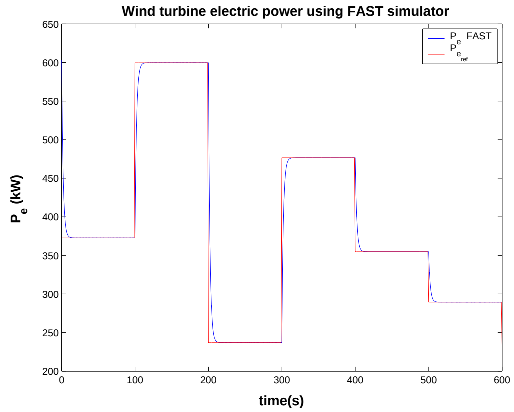
(d) Generator torque

Fig. 10. Validation results using the FAST simulator

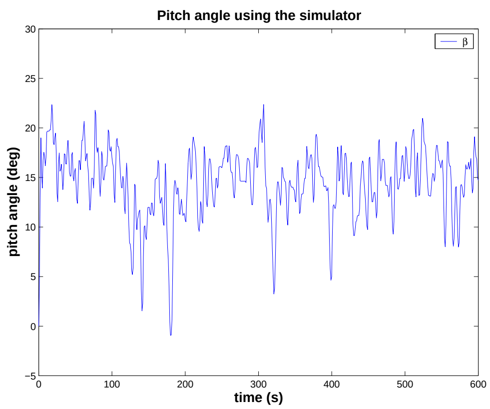
Figure 11 gives FAST simulators outputs when a variable reference set point is imposed to the WT output power using the same wind speed profile presented in figure 8. This is shown to be interesting; particularly when the wind park manager requires a given electrical power and that he must dispatch this reference over different wind turbines and impose a variable reference for each one in order to meet a specific request of the grid. The electrical power join its reference in some dozens of seconds. The generator torque action, while standing lower than its nominal value, shows less fluctuations. The blade pitch angle is all the time lied in the authorized variation domain without exceeding a variation of 10 deg/s. Finally, the rotor speed stands near to its nominal value in stand of a small deviation.



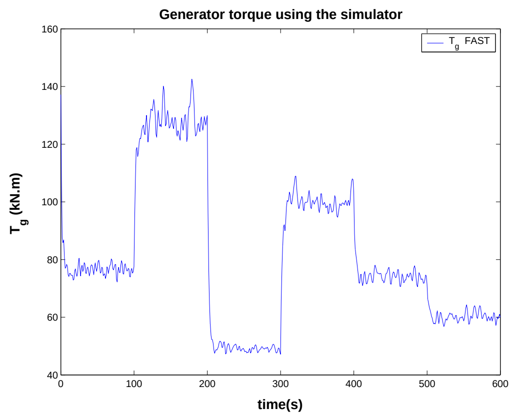
(a) rotor speed



(b) electrical power



(c) pitch angle



(d) generator torque

Fig. 11. Validation results using the FAST simulator with a variable reference

Controller	$\bar{T_g}$	$std(T_g)$	$\bar{\beta}$	$std(\beta)$
PID	-	-	15.36	3.40
LQG	-	-	15.17	4.63
NL in torque	98.13	17.51	-	-
MV	127.07	4.35	12.32	3.84

TABLE III. Comparison of the control loads using the FAST simulator

5 Conclusion

A multivariable wind turbine controller is presented in this paper. A comparative study with some existing monovariable controllers shows that the use of a single control input in pitch for wind turbine control allows to partially satisfy the fixed objectives only. The pitch controllers achieve a good performance in rotor speed regulation, but the power regulation is not satisfactory. Conversely, the nonlinear torque control technique leads to a good power regulation, however it has the drawback of generating large rotor speed fluctuations.
The multivariable control in torque and pitch we have proposed joins the advantages of the monovariable controllers while simplifying the formulation of each one. It leads to good performance even in rotor speed and electrical power regulation; with an acceptable control loads.

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