# Pitch and Torque Control Strategy for Variable Speed Wind Turbines

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***Abstract*-- This paper is dealing with a new control strategy for a variable speed wind turbine, operating above rated power in order to guarantee the power regulation. For this purpose, a multivariable control strategy is conceived, combining a nonlinear dynamic state feedback torque control with pitch linear based control. This resulting controller has not yet been described in the literature, at least to our knowledge. A high turbulence wind speed profile is used. The obtained simulation results have been performed using a wind turbine simulator. Significant improvements have been pointed out, in comparison with those presented in the literature.**

## I. NOMENCLATURE

| | |
|---|---|
| $v$ | wind speed (m/s). |
| $\rho$ | air density (kg /m$^3$). |
| $R$ | rotor radius (m)▷ |
| $P_a$ | aerodynamic power (W)▷ |
| $P_e$ | electrical power (W)▷ |
| $T_a$ | aerodynamic torque (N.m). |
| $\lambda$ | tip speed ratio. |
| $C_p(\lambda, \beta)$ | power coefficient. |
| $C_q(\lambda, \beta)$ | torque coefficient. |
| $\omega_r$ | rotor speed (rad /s). |
| $\omega_g$ | generator speed (rad /s). |
| $T_{em}$ | generator (electromagnetic) torque (N.m). |
| $T_g$ | generator torque in the rotor side (N.m). |
| $T_{ls}$ | low speed shaft (N.m). |
| $T_{hs}$ | high speed shaft (N.m). |
| $J_r$ | rotor inertia (kg .m$^2$). |
| $J_g$ | generator inertia (kg .m$^2$). |
| $J_t$ | turbine total inertia (kg .m$^2$). |
| $K_r$ | rotor external damping (Nm/rad/s). |
| $K_g$ | generator external damping (Nm/rad/s). |
| $K_t$ | turbine total external damping (Nm/rad/s). |
| $K_{ls}$ | low speed shaft damping (Nm/rad/s). |
| $B_{ls}$ | low speed shaft stiffness (Nm∝rad)▷ |

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## II. INTRODUCTION

Nowadays, the interest towards renewable forms of energy is becoming more and more stronger. In particular, the wind turbine farms construction is now a common fact. The advances in wind turbine technology made necessary the design of powerful control systems. This is in order to improve wind turbines behavior, namely to make them more profitable and reliable: a good regulation of the electrical power and reducing the loads on the different parts of the wind turbine will be the primary objectives.

Compared to fixed speed turbines, variable speed ones feature higher energy yields, lower component stress, and fewer grid connection power peaks. To be fully exploited, variable speed should be controlled in meaningful way.

Variable-speed wind turbines operate in two primary regimes, below-rated power and above-rated power. 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. In above-rated power conditions, the primary objective is to maintain a constant power output. 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.

Most of the research work in the wind energy conversion systems control deals with the power regulation in full load area. For this purpose, classical controllers have been extensively used, particularly the PI regulator [2], [3]. Optimal control has been applied in the LQ [8], and LQG forms [9], [10]. Linear robust control of wind energy conversion systems (WECS) has been introduced in [11] and also used in [12] - [13]. These control strategies use the pitch angle as a control input while the generator torque is generally maintained at its rated value.

In [1], it was shown that the generator torque alone is able to regulate the electrical power in an acceptable way. However, it generates large variations of the rotor speed that are not desirable for the wind turbine structure especially for those which reach values rather far away from the nominal rotor speed.

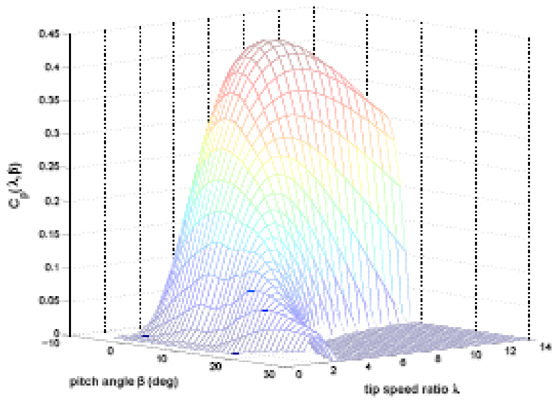


Fig. 1. Power coefficient $C_p(\lambda,\beta)$ curve

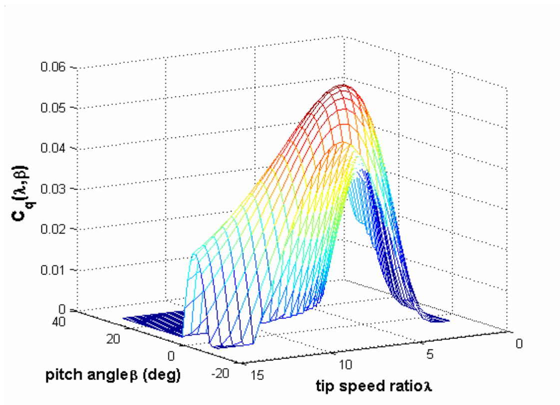


Fig. 2. Torque coefficient $C_p(\lambda,\beta)$ curve

The drawback of these methods lies in the fact that they are unable to attain the double objective of simultaneously regulating both rotor speed and electrical power.

In order to reach this double objective, a multivariable approach using generator torque and blades pitch is then herein developed. Its principle is to consider a PID pitch controller together with the nonlinear torque control approach presented in [1] while simplifying them leading thus to a multivariable control scheme. In doing so, one may manage to get a good compromise between power and rotor speed regulation with an acceptable control loads.

This study focuses on the different wind turbine control strategies attaining these objectives. A multivariable control strategy is conceived and its performance will be compared to existing control strategies. The results have been validated through a wind turbine simulator provided by NREL[2].

The paper is organized as follows: Section III describes the modeling of the wind turbine. Section IV briefly reviews existing control strategies and then passes to the multivariable nonlinear control one. Finally, in section V, the obtained results on the mathematical model as well as validation results upon the simulator are presented.

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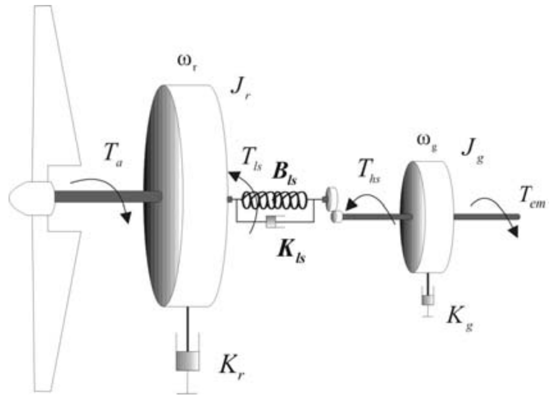


Fig. 3. Two mass model of the wind turbine scheme

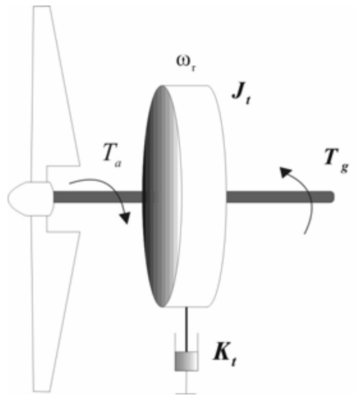


Fig. 4. One mass model of the wind turbine scheme

## III. WIND TURBINE MODEL

### A. Wind turbine Aerodynamics

The wind turbine may be, in general, represented as an electromechanical system, mainly composed by an aeroturbine, a gearbox and a generator.

The aerodynamic power has the following nonlinear expression [1]:

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

Where $\lambda = \dfrac{\omega_r R}{v}$ is the tip speed ratio. $C_p(\lambda,\beta)$ represents the power coefficient. It is given by a curve specific to each wind turbine.

A full list of notations is given at the beginning of the paper, for the reader convenience.

The power coefficient curve used is displayed in Figure 1.

Since $P_a = T_a \cdot \omega_r$, the aerodynamic torque is then given by

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

where

$$C_q(\lambda,\beta) = \frac{C_p(\lambda,\beta)}{\lambda} \tag{3}$$

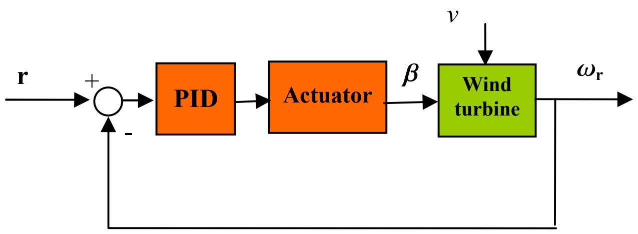


Fig. 5. PID control scheme

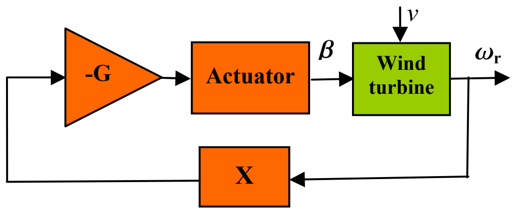


Fig. 6. LQ control scheme

is the torque coefficient. An example of $C_q$ is displayed in figure 2.

*B. Dynamical model*

The two mass model of the wind turbine is depicted in figure 3.

The following equations describe the rotor and generator dynamics:

$$\begin{aligned} J_r\dot{\omega}_r &= T_a - B_r\omega_r - T_{ls} \\ J_g\dot{\omega}_g &= T_{hs} - B_g\omega_g - T_{em} \\ T_{ls} &= K_{ls}(\omega_r - \omega_{ls}) + B_{ls}(\theta_r - \theta_{ls}) \end{aligned} \quad (4)$$

where the gearbox ratio $n_g$ is :

$$n_g = \frac{\omega_g}{\omega_{ls}} = \frac{T_{ls}}{T_{hs}} \quad (5)$$

If a perfectly rigid low-speed shaft is assumed, a single mass model of the turbine may be then considered (figure 4):

$$J_t\dot{\omega}_r = T_a - K_t\omega_r - T_g \quad (6)$$

with

$$\begin{aligned} J_t &= J_r + n_g^2 J_g \\ K_t &= K_r + n_g^2 K_g \\ T_g &= n_g T_{em} \end{aligned} \quad (5)$$

*C. Baseline control strategies*

The control objective to attain is the best tracking of rated power while regulating rotor speed. In the same time, it is desirable to solicit the wind turbine components as little as possible.

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 [2]. This approach has been considered for a long time quite satisfactory. The scheme of a PID controller is shown in figure 5.

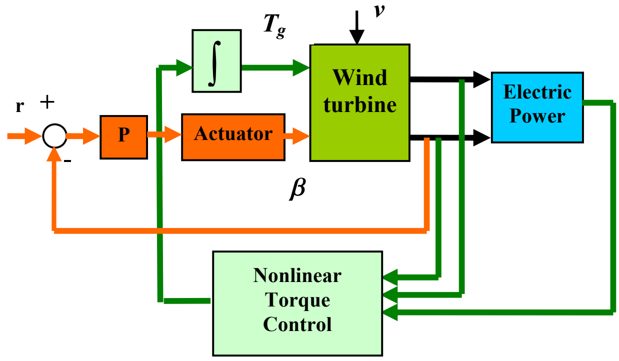


Fig. 7. Mutivariable control scheme

Another classical approach is the one described in [3]: an LQ controller. A cost function is to be minimized, such as follows:

$$J(t) = \int_0^t (x'Qx + u'Ru)dt \quad (7)$$

The generator torque is also supposed to be constant, while the speed control scheme is such as represented in figure 6.

An LQ control strategy ensures a better power tracking than the PID, but unfortunately this turns out to be still insufficient.

## IV. MULTIVARIABLE CONTROLLER

*A. Multivariable control strategy*

In order to minimize the tracking error, a multivariable control strategy has been conceived. Using a similar procedure as in [1], a nonlinear dynamic state feedback torque control law is obtained. As for the pitch control, a simple proportional strategy is shown to be sufficient.

The principle of the multivariable controller is to use a nonlinear torque controller while limiting the pitch control action. By the fact of imposing dynamics to the power tracking error, one manages better the control torque $T_g$ for power regulation. If a pitch action is added, the power regulation objective is shared considering that this action contributes to the rotor speed regulation.

The nonlinear control block is displayed in figure 7. It includes both speed and torque control schemes.

*B. 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 [1] 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 $\varepsilon_p = P_{nom} - P$. A first order dynamics are imposed

$$\dot{\varepsilon}_p + a_0 \varepsilon_p = 0, \qquad a_0 > 0 \tag{8}$$

Considering the expression of the electric power

$$P = \omega_r \cdot T_g, \tag{9}$$

and using equations (6) and (8), the following expression is obtained:

$$-\dot{\omega}_r \cdot T_g - \omega_r \cdot \dot{T}_g + a_0 \cdot \varepsilon_p = 0, \tag{10}$$

from which the control comes out

$$\dot{T}_g = \frac{1}{\omega_r} \cdot \left( a_0 \cdot \varepsilon_p - \frac{1}{J_r} \left( T_a \cdot T_g - K_t \omega_r \cdot T_g - T_g^2 \right) \right) \tag{11}$$

*C. Pitch controller*

Besides the torque control, speed control is also needed to limit the rotor speed. So, in order to reduce the generator torque fluctuations and regulate the rotor and generator speed, the torque control needs an assistance of the pitch action.

The pitch control allows keeping the rotor speed in an acceptable limit around its nominal value. For this, a simple proportional pitch action on the rotor speed error is used:

$$\Delta\beta = K \cdot \varepsilon_\omega \tag{12}$$

where $\varepsilon_\omega = \omega_{nom} - \omega_r$ is the rotor speed tracking error.

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.

## V. Simulation Results

The numerical simulations have been performed on a wind turbine whose characteristics are given in Table 1.

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 modeled with the mathematical model and validated through the SymDyn aeroelastic simulator also developed by NREL.

| | |
|---|---|
| **Rotor diameter** | 43.3 m |
| **Gearbox ratio** | 43.165 |
| **Hub height** | 36.6 m |
| **Generator system electrical power** | 600 kW |
| **Maximum rotor torque** | 162 kN.m |

Tab.1. CART wind turbine characteristics

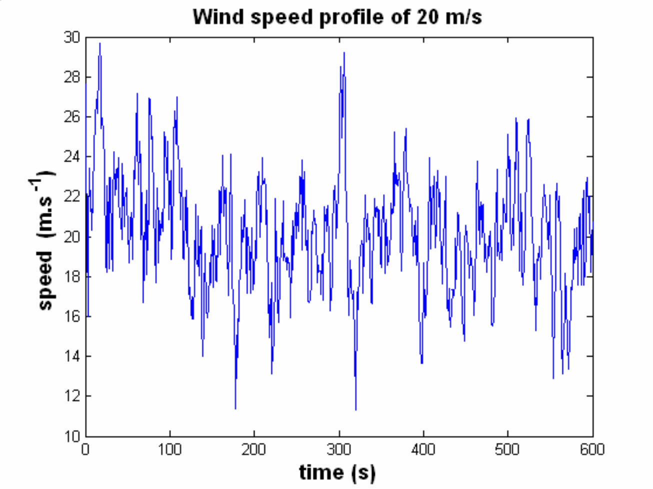


Fig. 8. Wind profile with a mean of 20 m/s

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. 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 %. Using this excitation, each of the discussed controllers is compared for rotor speed, power regulation and transient loads reduction.

*A. Using the mathematical model*

The simulation results using the different controllers with the mathematical model are shown in figures 9 and 10.

According to figure 9, the PID and LQG pitch controllers achieve an acceptable rotor speed regulation. However, the electrical power regulation performance are poor (figure 10). In opposite, the nonlinear torque controller presented in [1] ensures a good power regulation (figure 10), but the rotor speed fluctuations are very large (figure 9).

The multivariable controller achieves a good compromise between electrical power and rotor speed regulation. As one may observe in figure 9, the rotor speed is well regulated around its nominal value. $\omega_r$ varies between 36 and 48 rpm with a standard deviation of 1.50 rpm. The electrical power regulation performance are quite satisfactory. Figure 10 shows that the electrical power $P_e$ remains very close to the nominal power. Its mean value is almost equal to the nominal power $P_{nom}$.

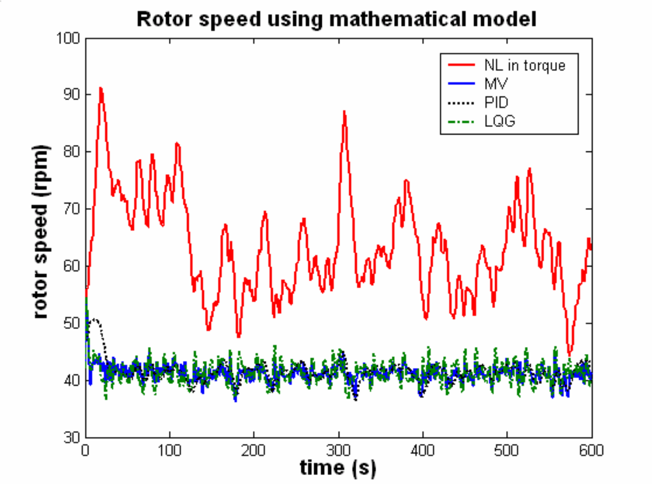


Fig. 9. Rotor speed using the mathematical model

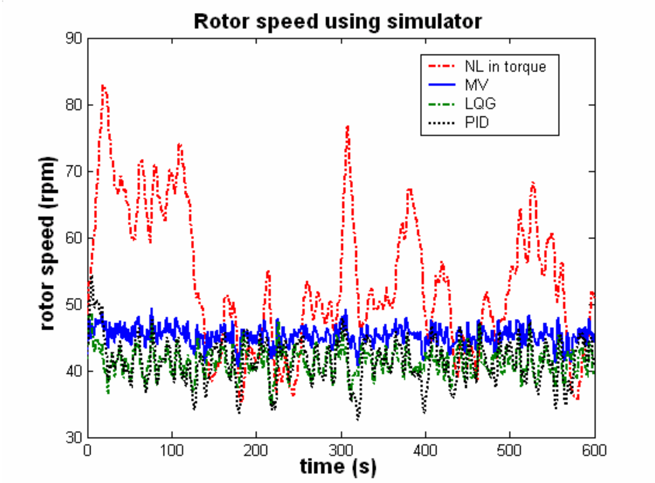


Fig. 11. Electrical power using the simulator

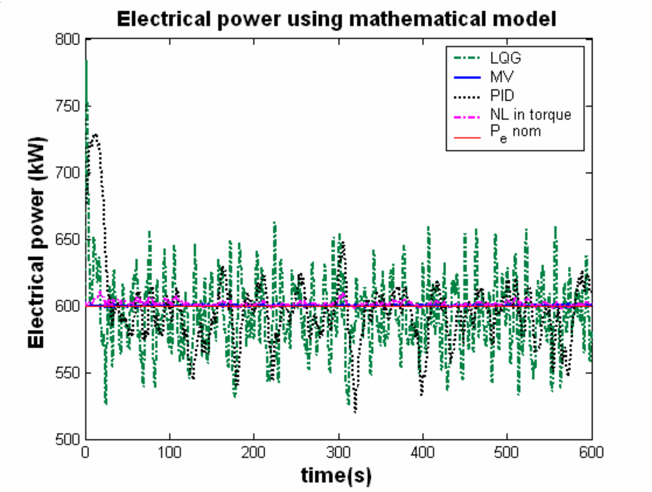


Fig. 10. Electrical power using the mathematical model

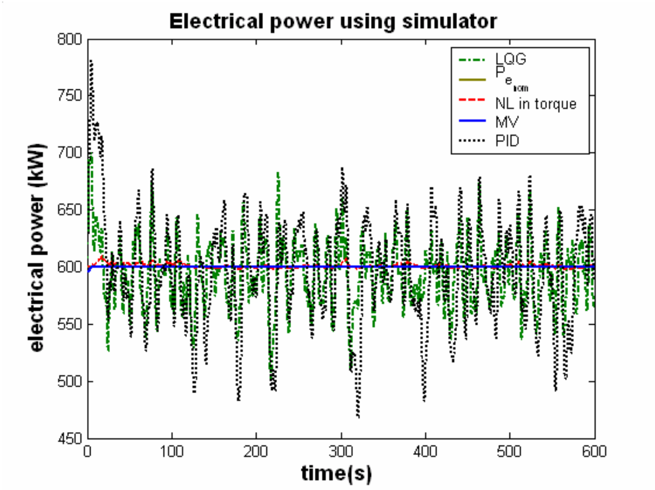


Fig. 12. Electrical power using the simulator

| Controller | $\overline{T_g}$ (kN.m) | $std(T_g)$ (kN.m) | $\overline{\beta}$ (deg) | $std(\beta)$ (deg) |
|---|---|---|---|---|
| **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 |

Tab.2. Comparison of the control loads using the mathematical model

| Controller | $\overline{T_g}$ (kN.m) | $std(T_g)$ (kN.m) | $\overline{\beta}$ (deg) | $std(\beta)$ (deg) |
|---|---|---|---|---|
| **PID** | - | - | 13.04 | 3.36 |
| **LQ** | - | - | 12.95 | 4.37 |
| **NL in torque** | 93.15 | 17.57 | - | - |
| **MV** | 139.38 | 4.03 | 12.58 | 3.57 |

Tab.3. Comparison of the control loads using the simulator

Because of the presence of a pitch action, the control torque standard deviation is reduced comparing to the nonlinear torque controller (Table 2).

The pitch action remains acceptable. Its variations are similar to those obtained by the PID regulator, but solicit the pitch actuator less than the LQG controller does.
The use of both control actions has shown that one can achieve a good tracking of a power reference (figure 10) while keeping the rotor speed close to its nominal value (fig 9).
According to Table 2, the control torque and pitch control loads remain acceptable.

## *B. Validation using SymDyn simulator*

A good regulation of the rotor speed is obtained using the MV controller (figure 11). The electrical power regulation presents also acceptable performance (figure 12) with a standard deviation less than 0.3 kW.
According to figures 13 and 14 and Table 3, the control loads are acceptable. The generator torque $T_g$ presents fewer oscillations to the non linear torque controller when used alone (Table 3). Concerning the pitch action, it remains close to the one developed by the PID controller when a pitch action is used only.

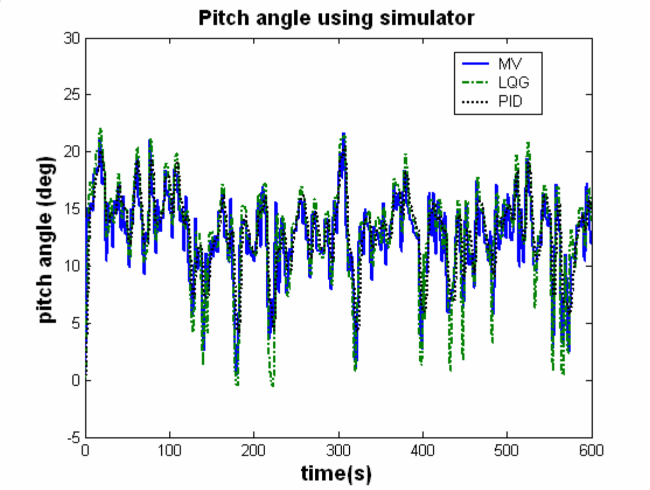


Fig. 13. Pitch angle using the simulator

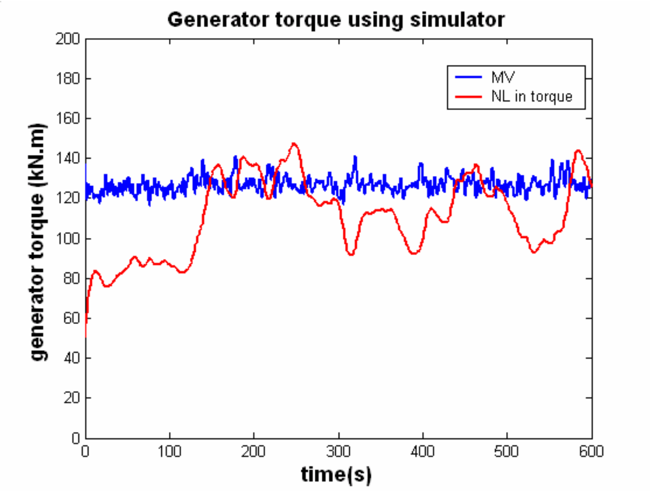


Fig. 14. Generator torque using the simulator

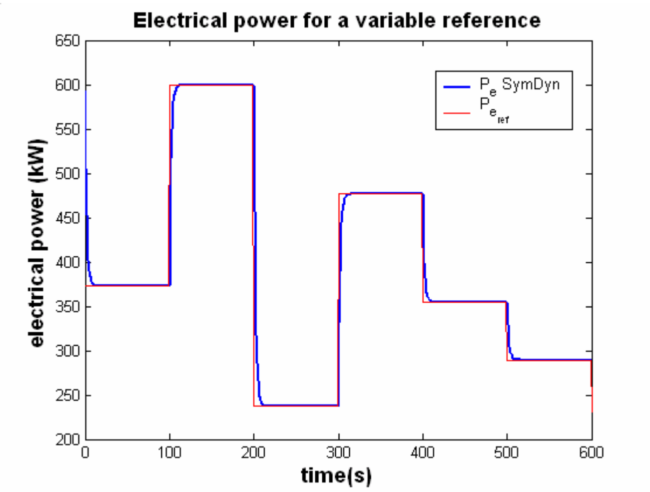


Fig. 15. Electrical power using the simulator with a variable reference

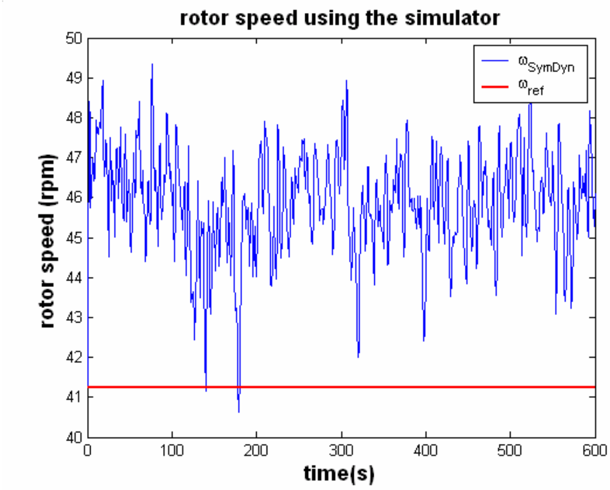


Fig. 16. Rotor speed using the simulator with a variable reference

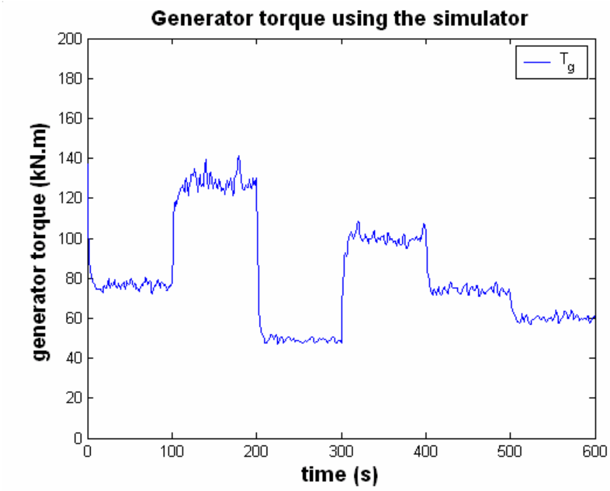


Fig. 17. Generator torque using the simulator with a variable reference

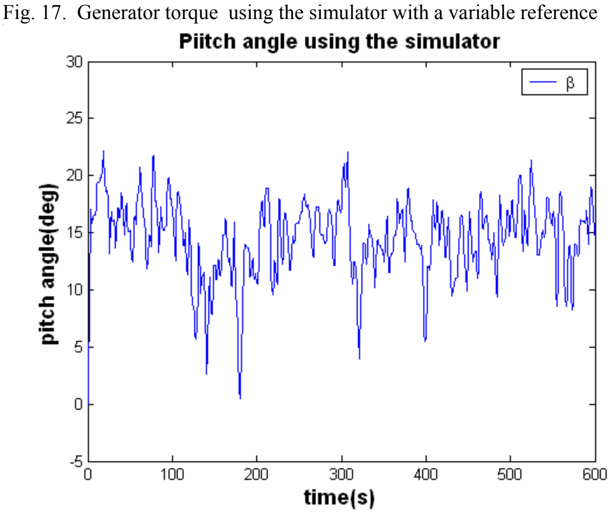


Fig. 18. Pitch angle using the simulator with a variable reference

One may also notice that the pitch actuator is less solicited using the MV controller than the LQ controller one. However, the multivariable control method achieves a better electrical power regulation. The electrical power fluctuations are significantly reduced (figure 12) compared to the LQ and PID controllers.

First simulations have been realized with constant power reference. A variable reference set point is also imposed to the WT output power using the same wind speed profile presented in figure 8. Results are shown in figures 15 to 18.
This is shown to be interesting; particularly when the wind park manager requires a given electrical power and that he must dispatch this reference between different wind turbines

and impose a variable reference for each one in order to meet a specific request of the grid.

The validation of the multivariable pitch and torque controller with the SymDyn simulator using a variable power reference confirms the efficiency of this controller in achieving power tracking (figure 15) while keeping the rotor speed close to its nominal value.

The pitch mechanism and generator torque are solicited in an acceptable way as one can notice it on the plots of $T_g$ (figure 17) and $\beta$ (figure 18).

## VI. CONCLUSION

This work shows that the use of a single pitch control allows achieving only partially the control objectives of a wind turbine, above rated wind speed. The pitch controllers give a good rotor speed regulation performance, but the electrical power regulation is not satisfactory and large power fluctuations can be shown.

The proposed multivariable controller allows the combination of both required objectives. It leads to good performance even in power and rotor speed regulation with an acceptable control loads.

Tests through a flexible wind turbine simulator have been performed with a variable power reference and have shown satisfactory results.

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