SWITCHING MULTIMODEL LQ CONTROLLERS FOR VARIABLE SPEED AND VARIABLE PITCH WIND TURBINES*

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ABSTRACT
This paper deals with the design of two gain scheduled linear quadratic (LQ) controllers for variable speed, pitch regulated wind turbines in the whole plant operating area. Depending essentially on the wind speed, the wind turbine operating range can be divided into two different zones. Each LQ controller is then valid in a specific operating zone and has different control objectives. And the system switches between them during the transitions from one operating zone to another in order to ensure a good level of performances in the whole plant operating area. The design of the LQ controllers is based on a multimodel description of the nonlinear plant. The good performances of the proposed approach are illustrated on a 2MW wind turbine.

Keywords: Wind turbines, LQ regulators, multimodel approach, switching system.

1. INTRODUCTION

Variable-speed wind turbines are being more and more popular between the commercial ones. Actually, in contrast to constant-speed turbines, variable-speed wind turbines are designed to follow wind-speed variations in low winds to maximize aerodynamic efficiency (Johnson *et al.*, 06; Bianchi *et al.*, 2007). In this scheme, variable-speed wind turbine controller design has become an area of increasing interest.

The wind turbine operating area can be divided into two different zones: the partial-load zone (PL) and the full load zone (FL). We can define two partial-load zones: PL1 and PL2, corresponding respectively to low and medium wind speed values. The control objectives are different for each zone. Indeed, in the PL operating zone, the turbine operates at fixed pitch and the regulator aims to control the rotor speed and the generated electrical power through acting on the electromagnetic torque. In the FL operating zone – corresponding to high wind speeds- the pitch is variable and the controller uses then two control variables which are: the electromagnetic torque and the pitch angle to regulate the rotor speed and the electric power around their rated values. Other issue can be added to the control objectives: it deals with reducing the dynamic loads of the mechanical structure, which can affect wind turbine lifetime. The control problem is then to ensure a trade-off between these objectives, by taking into account the high nonlinearity of the plant and the stochastic nature of the main component acting on it: the wind speed.

In response to this multi-objective control problem, we propose in this paper two linear quadratic (LQ) controllers (for each operating zone) calculated from a linearization of the model around several operating points depending on the wind speed. Then, a multimodel strategy is considered with the controllers to handle the problem of the nonlinearity of the system.

This paper is organized as follows: the second section deals with the description of the considered plant, then, in the third section, we develop the proposed control laws for the two wind-turbine operating zones, and finally, simulation results are presented for a 2MW wind turbine showing the transition between the different zones.

2. SYSTEM DESCRIPTION

The wind turbines convert a part of the kinetic energy of the wind into mechanical energy first, and then electrical energy. The wind affects the main shaft by a driving aerodynamic torque T_{aero} expressed as:

$$T_{aero} = \frac{\rho \pi {R_T}^5 \Omega_T^2}{2\lambda^3} c_p(\lambda, \beta) \tag{1}$$

where ρ is the air density, R_T is the turbine radius, Ω_T is the turbine rotational speed, and c_p is the power coefficient which is a non linear

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function (as presented in Figure 1) of the blade pitch β and the tip speed ratio λ depending on the wind speed value w and given by:

$$\lambda = \frac{\Omega_T \, R_T}{w} \tag{2}$$

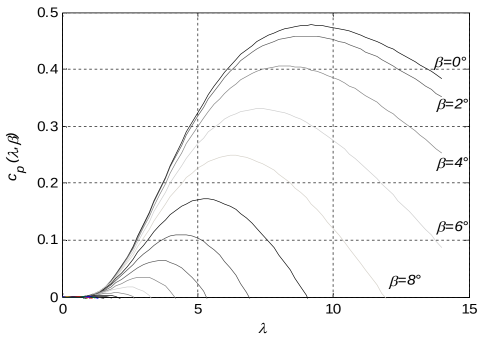


Figure 1: Illustration of the Power Coefficient (c_p) Curves

The aerodynamic torque is an input to the transmission system, modeled as a two mass system. This model considers two inertias (the generator and the turbine inertias respectively J_g and J_T) linked to a flexible shaft with a mechanical coupling damping coefficient d and a mechanical coupling stiffness coefficient k (Bianchi *et al.*, 2004; Camblong *et al.*, 2002). The drive train mechanical behavior is then characterized by the following equations reported to the low speed shaft:

$$\begin{cases} J_T \dot{\Omega}_T = T_{aero} - T_{mec} \\ J_{g-ls} \dot{\Omega}_{g-ls} = T_{mec} - G T_{em} \\ \dot{T}_{mec} = k\left(\Omega_T - \Omega_{g-ls}\right) + d\left(\dot{\Omega}_T - \dot{\Omega}_{g-ls}\right) \end{cases} \tag{3}$$

where T_{mec} and T_{em} are respectively the mechanical and the electromagnetic torques, G is the gearbox ratio, J_{g-ls} and Ω_{g-ls} are respectively the generator inertia and rotational speed reported to the low speed shaft, defined as:

$$\begin{cases} \Omega_{g-ls} = \dfrac{\Omega_g}{G} \\ J_{g-ls} = G^2 . J_g \end{cases} \tag{4}$$

The interconnection between the previously mentioned wind turbine components is illustrated in the block diagram of the Figure 2.

The pitch actuator dynamic is described by a first order system:

$$\dot{\beta} = \frac{1}{\tau_\beta}\left(\beta_{reg} - \beta\right) \tag{5}$$

β_{reg} is the control value of the blade-pitch angle β and τ_β is the time constant of the pitch actuator.

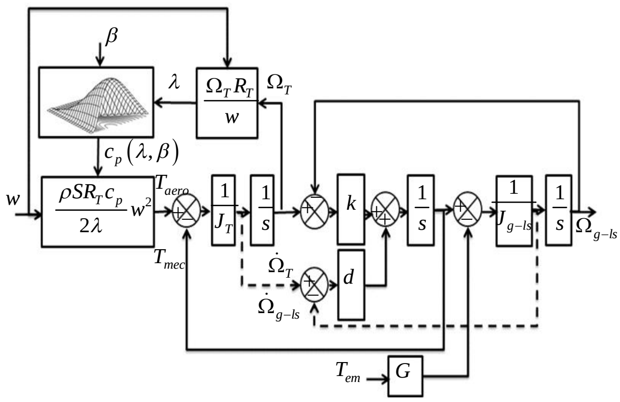


Figure 2: Block Diagram of Wind Turbine Model

The plant model, as it has been described, is highly nonlinear, mostly because of the nature of the wind seed and the coupling through the aerodynamics. It seems then appropriate to use linearized models where the wind is the gain scheduling variable. The linearization of the expression (1) of T_{aero} around an operating point (*o.p*) defined by the wind speed value w_i (Munteanu *et al.*, 2005; Bianchi *et al.*, 2007; Khezami *et al.*, 2009) leads to:

$$\begin{aligned} \Delta T_{aero} &= \left.\frac{\partial T_{aero}}{\partial \Omega_T}\right|_{o.p} \Delta\Omega_T + \left.\frac{\partial T_{aero}}{\partial \beta}\right|_{o.p} \Delta\beta \\ &= a_i \Delta\Omega_T + b_i \Delta\beta \end{aligned} \tag{6}$$

The symbol Δ presents the deviation from the chosen operating point.

3. MULTIMODEL APPROACH

The multimodel approach is an effective method to solve the control problem of strong nonlinear and parameter varying systems. For this reason, a multimodel strategy is considered in this study to describe the wind turbine. The core idea is to represent the nonlinear dynamical system by a set of locally valid sub-models across the whole operating range (Kardous *et al.*, 2006, 2007; Chedli *et al.*, 2002). The equivalent model is obtained by a weighted sum of these valid sub-systems. We will only valid two successive local models at once as described in Figure 3.

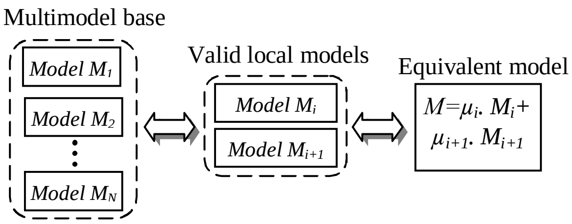


Figure 3: Wind Turbine Multimodel Description

The weighting coefficient μ_i is the validity value of the local model M_i and is calculated using the residue method as expressed in the following equation (Khezami *et al.*, 2009):

$$\mu_i = 1 - r_i \tag{7}$$

where r_i is a normalized residue measuring the error between w and w_i which are the wind speed values of respectively the instantaneous model and the valid local model (respectively M and M_i). When M_i and M_{i+1} are the valid models, the residue can be expressed as:

$$r_i = \frac{\left|w_i - w\right|}{w_i + w_{i+1}} \tag{8}$$

4. CONTROL TASK

The control objectives are to ensure good performances of the selected outputs, i.e. energy conversion and alleviation of the mechanical loads affecting the plant structure. The wind turbine operating area can be divided into two partial load zones and one full load zone as defined in the Figure 4.

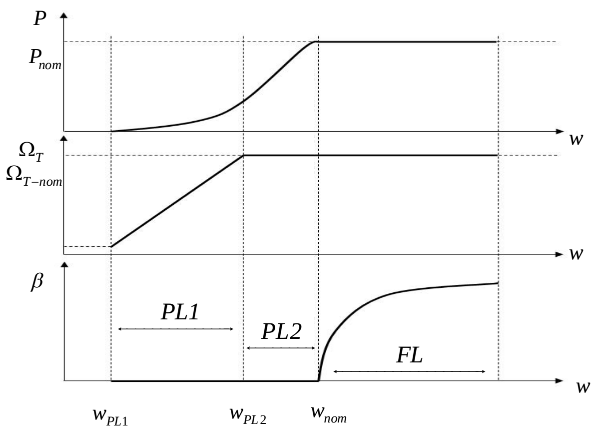


Figure 4: Evolution of the Plant Main Variables (Power P, rotor speed Ω_T and pitch angle β) in function of the wind speed

4.1. PL zone control law

In the partial load zones, the wind turbine operates at variable speed, fixed pitch in PL1 zone and at fixed speed, fixed pitch in PL2 zone. For low wind speeds ($w \le w_{PL2}$: PL1 zone), the main objective is to maximize the system energy conversion by maintaining the power coefficient at its optimal value $\left(c_p = c_{p-opt} = c_p\left(\lambda_{opt}, 0\right)\right)$. This supposes to regulate the rotor around a given reference Ω_{T-ref} calculated as follows:

$$\Omega_{T-ref} = \frac{\lambda_{opt} w_i}{R_T}; \forall w_i \le w_{PL2} \tag{9}$$

For medium wind speeds ($w_{PL2} \le w \le w_{nom}$: PL2 zone), the turbine speed reaches its nominal value and the control aim is to regulate it around this rated value.

The PL zones control objectives could be satisfied by acting on only the electromagnetic torque.

We define:

$$\begin{cases} \Omega_{T-ref} = \begin{cases} \dfrac{\lambda_{opt} w_i}{R_T}; \forall w_i \le w_{PL2} \\ \Omega_{T-nom}; \forall w_i \ge w_{PL2} \end{cases} \\ T_{aero-ref} = \begin{cases} \dfrac{1}{2}\rho\pi R_T^5 \Omega_T^2 \dfrac{c_{p-opt}}{\lambda_{opt}}; \forall w_i \le w_{PL2} \\ \dfrac{1}{2}\rho\pi R_T^5 \Omega_{T-nom}^2 \dfrac{c_{p-i}}{\lambda_i}; \forall w_i \ge w_{PL2} \end{cases} \\ T_{em-ref} = \dfrac{T_{aero-ref}}{G} \\ T_{mec-ref} = T_{aero-ref} \end{cases} \tag{10}$$

with:

$$\forall w_i \ge w_{PL2} : \begin{cases} \lambda_i = \dfrac{\Omega_{T-nom} R_T}{w_i}; \\ c_{p-i} = c_p\left(\lambda_i, 0\right) \end{cases} \tag{11}$$

The linearization of the aerodynamic torque as presented in equation (6), leads to write:

$$\begin{cases} \Delta T_{aero} = a_{1i}\Delta\Omega_T \\ a_{1i} = \dfrac{-\rho\pi R_T^4 w_i\, c_{p-opt}}{2\lambda_{opt}^2}; \forall w_i \le w_{PL2} \\ a_{1i} = \dfrac{\rho\pi R_T^4 w_i^2}{2\Omega_{T-nom}}\left[\dfrac{\partial c_p\left(\lambda, 0\right)}{\partial\lambda} - \dfrac{c_{p-i}}{\lambda_i}\right]; \forall w_i \ge w_{PL2} \end{cases} \tag{12}$$

The system could be now presented in the following state space representation:

$$\begin{cases} \dot{\widehat{\Delta x_1}} = A_{1i}\Delta x_1 + B_{1i}\Delta u_1 \\ \Delta y_1 = \Delta x_1 \end{cases} \tag{13}$$

where:

$$\begin{cases} \Delta x_1 = \begin{pmatrix} \Delta\Omega_T \\ \Delta\Omega_{g-ls} \\ \Delta T_{mec} \end{pmatrix}; \Delta u_1 = \left(\Delta T_{em}\right); B_{i} = \begin{pmatrix} 0 \\ -\dfrac{G}{J_{g-ls}} \\ \dfrac{dG}{J_{g-ls}} \end{pmatrix} \\ A_{1i} = \begin{pmatrix} \dfrac{a_{1i}}{J_T} & 0 & -\dfrac{1}{J_T} \\ 0 & 0 & \dfrac{1}{J_{g-ls}} \\ k + \dfrac{a_{1i}d}{J_T} & -k & -d\left(\dfrac{1}{J_T} + \dfrac{1}{J_{g-ls}}\right) \end{pmatrix} \end{cases} \tag{14}$$

The proposed control law aims to minimize the following quadratic criterion (Boukhezzara *et al.*, 2007; Hammerum et al., 2007; Cutululis *et al.*, 2006):

$$J_1 = \frac{1}{2}\int_0^{\infty}\left[\Delta x_1^T Q \Delta x_1 + \Delta u_1^T R \Delta u_1\right]dt \tag{15}$$

where Q and R are diagonal positive definite matrices.

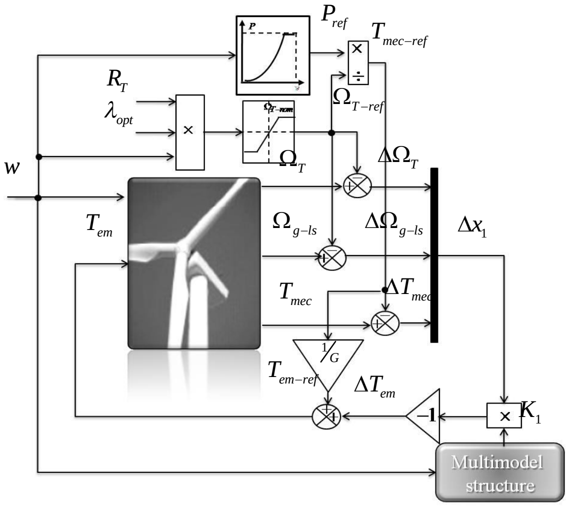
By solving a Riccati equation, an optimal gain is calculated such that:

$$\Delta u_1 = -K_1 \Delta x_1 \tag{16}$$

Then, we can write:

$$\begin{cases} u_1 = \left(T_{em}\right) = -K_1\left(x_1 - x_{1-ref}\right) + u_{1-ref} \\ x_1 = \begin{pmatrix} \Omega_T \\ \Omega_{g-ls} \\ T_{mec} \end{pmatrix}; x_{1-ref} = \begin{pmatrix} \Omega_{T-ref} \\ \Omega_{g-ls-ref} = \Omega_{T-ref} \\ T_{mec-ref} \end{pmatrix} \\ u_{1-ref} = \left(T_{em-ref}\right) \end{cases} \tag{17}$$

The Figure 5 presents the block diagram of the controlled system.



in PL Operation

To illustrate the good performances of the proposed control law, simulations have been runned on the basis of a dynamic model implemented on Matlab-Simulink of a three blades 2MW wind turbine.

The wind is generated with the method elaborated by C. Nichita in (Nichita *et al*, 2002).

For a variable wind with a speed mean value of 8m/s, the evolution of the different wind turbine variables are represented in Figure 6.

A preferential choice was taken on the regulation of the generated power with regard to the rotor speed regulation.

As shown in Figure 6, all the wind turbine variables follow nearly perfectly their reference signals while the wind varies and that by acting only on the electromagnetic torque (the pitch angle is maintained null).

4.2. FL zone control law

In the FL operation, the electrical power reaches its rated value. The main objective of the controller is then to regulate the generated power and the rotor speed at their rated values.

The linearization of the aerodynamic torque as presented in equation (6), leads to write:

$$\begin{cases} \Delta T_{aero} = a_{2i}\Delta\Omega_T + b_{2i}\Delta\beta \\ a_{2i} = \dfrac{1}{2}\rho\pi R_T^3 \dfrac{w_i^2}{\Omega_{T-nom}}\left[\dfrac{\partial c_p(\lambda,\beta)}{\partial\lambda} - \dfrac{c_{p_{i-nom}}}{\lambda_{i-nom}}\right] \\ b_{2i} = \dfrac{1}{2}\rho\pi R_T^2 \dfrac{w_i^3}{\Omega_{T-nom}} \dfrac{\partial c_p(\lambda,\beta)}{\partial\beta} \end{cases} \tag{18}$$

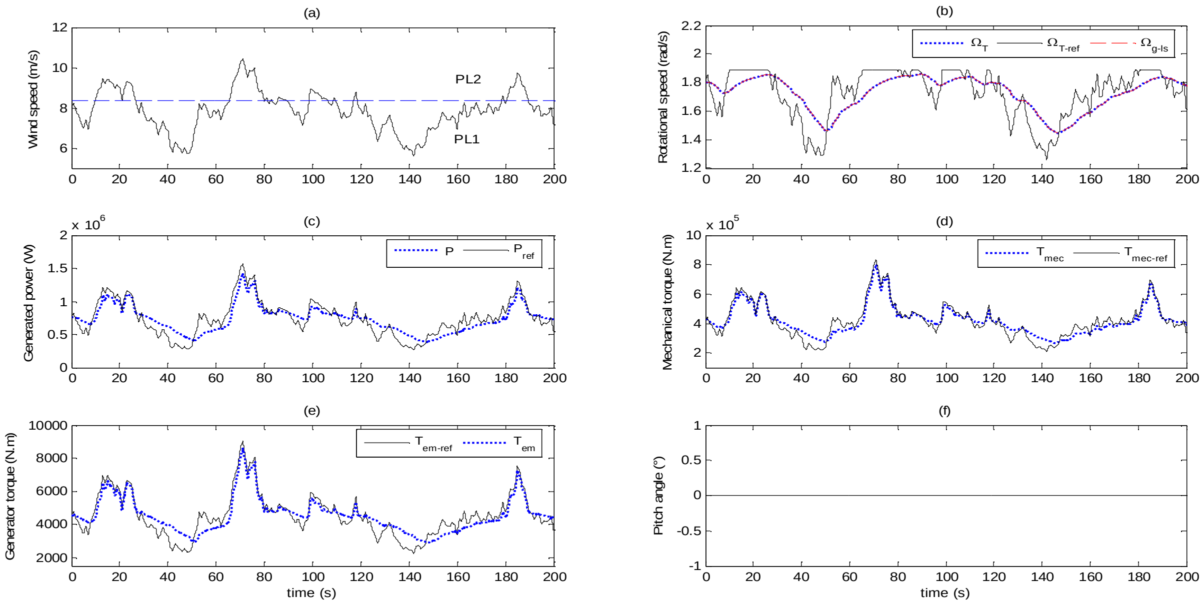


Figure 6: Evolution of the Wind Turbine Variables for a Partial Load Operation

where:

$$c_{p_{i-nom}} = c_p\left(\lambda_{i-nom}, \beta_{i-nom}\right) = \frac{2\Omega_{T-nom} T_{aero-nom}}{\rho \pi R_T^2 w_i^3} \tag{19}$$

For the wind turbine FL operation, we choose to use a linear quadratic controller combined to reference model and an integral action. With two control variables: the electromagnetic torque and the regulating pitch angle, the state space representation is as follows:

$$\begin{cases} \dot{\widehat{\Delta x_2}} = A_{2i}\Delta x_2 + B_{2i}\Delta u_2 \\ \Delta y_2 = C_{2i}\Delta x_2 + D_{2i}\Delta u_2 \end{cases} \tag{20}$$

where Δx_2, Δy_2 and Δu_2 represent the deviation of respectively the state vector x_2, the output vector y_2 and the input vector u_2 from the operating point at the wind speed w_i characterized by x_{2i-ref}, y_{2i-ref} and u_{2i-ref}:

$$\begin{cases} \Delta x_2 = x_2 - x_{2i-ref};\ \Delta y_2 = y_2 - y_{2i-ref}; \\ \Delta u_2 = u_2 - u_{2i-ref} \\ x_2 = \begin{pmatrix} \Omega_T \\ \Omega_{g-ls} \\ \beta \\ T_{mec} \end{pmatrix};\ u_2 = \begin{pmatrix} \beta_{reg} \\ T_{em} \end{pmatrix};\ y_2 = \begin{pmatrix} \Omega_T \\ P \end{pmatrix} \\ x_{2i-ref} = \begin{pmatrix} \Omega_{T-nom} \\ \Omega_{g-ls-nom} = \Omega_{T-nom} \\ \beta_{i-nom} \\ T_{mec-nom} \end{pmatrix} \\ y_{2i-ref} = \begin{pmatrix} \Omega_{T-nom} \\ P_{nom} \end{pmatrix};\ u_{2i-ref} = \begin{pmatrix} \beta_{i-nom} \\ T_{em-nom} \end{pmatrix} \end{cases} \tag{21}$$

The matrices of this state representation are given by:

$$\left\{\begin{array}{l} A_{2i}=\begin{pmatrix} \frac{a_{2i}}{J_T} & 0 & \frac{b_{2i}}{J_T} & -\frac{1}{J_T} \\ 0 & 0 & 0 & \frac{1}{J_{g-ls}} \\ 0 & 0 & -\frac{1}{\tau_\beta} & 0 \\ k+\frac{a_{2i}d}{J_T} & -k & \frac{db_{2i}}{J_T} & -d.\left(\frac{1}{J_T}+\frac{1}{J_{g-ls}}\right) \end{pmatrix} \\ B_{2i}=\begin{pmatrix} 0 & 0 \\ 0 & -\frac{G}{J_{g-ls}} \\ \frac{1}{\tau_\beta} & 0 \\ 0 & \frac{dG}{J_{g-ls}} \end{pmatrix};D_{2i}=\begin{pmatrix} 0 & 0 \\ 0 & G\Omega_{T-nom} \end{pmatrix} \\ C_{2i}=\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & G.T_{em-nom} & 0 & 0 \end{pmatrix} \end{array}\right. \qquad (22)$$

The proposed approach is developed in (Khezami *et al*, 2010), and the derived control law has the following form:

$$u_2=-\gamma_1 x_2-\gamma_2 v-\gamma_3 s+\gamma_4\eta_i+\gamma_5\xi_i+\gamma_6 y_o \qquad (23)$$

where:

- v is the integral action,
- s is the reference model on the outputs,
- y_o is the order signals (the input of the reference model),
- η_i and ξ_i give information on the chosen operating point, they are given by:

$$\left\{\begin{array}{l} \xi_i=\dot{x}_{2i-ref}-A_{2i}x_{2i-ref}-B_{2i}u_{2i-ref} \\ \eta_i=y_{2i-ref}-C_{2i}x_{2i-ref}-D_{2i}u_{2i-ref} \end{array}\right. \qquad (24)$$

The Figure 7 presents the block diagram of the system with the proposed control law.

To illustrate the good performances of the proposed controller, simulations have been carried on a 2MW wind turbine operating at a variable wind with a speed mean value of 18m/s. the Figure 8 presents the evolution of the wind turbine variables in a full load operation.

As one can see in Figure 8, the main control objectives are satisfied: the generated power and the rotor speed are maintained very close to their rated values with admissible control signals.

To prevent the mechanical fatigue damage, the alleviation of the drive train loads has been taken into consideration. Indeed, the mechanical torque keeps an almost constant value with acceptable fluctuations.

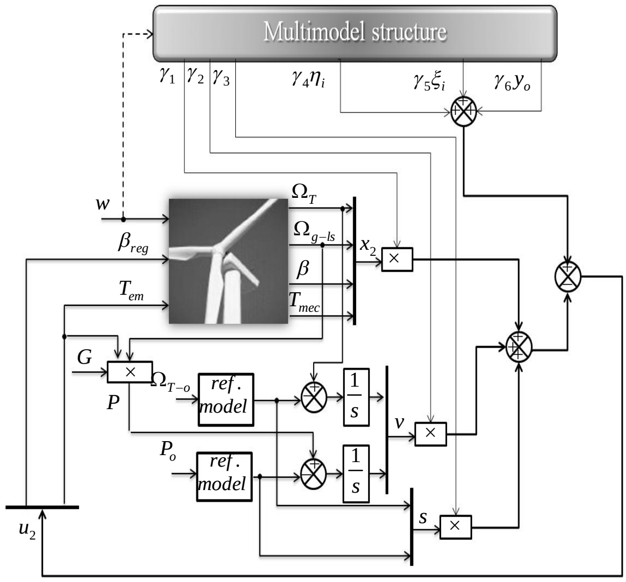


Figure 7: Block Diagram of the Controlled System in FL Operation

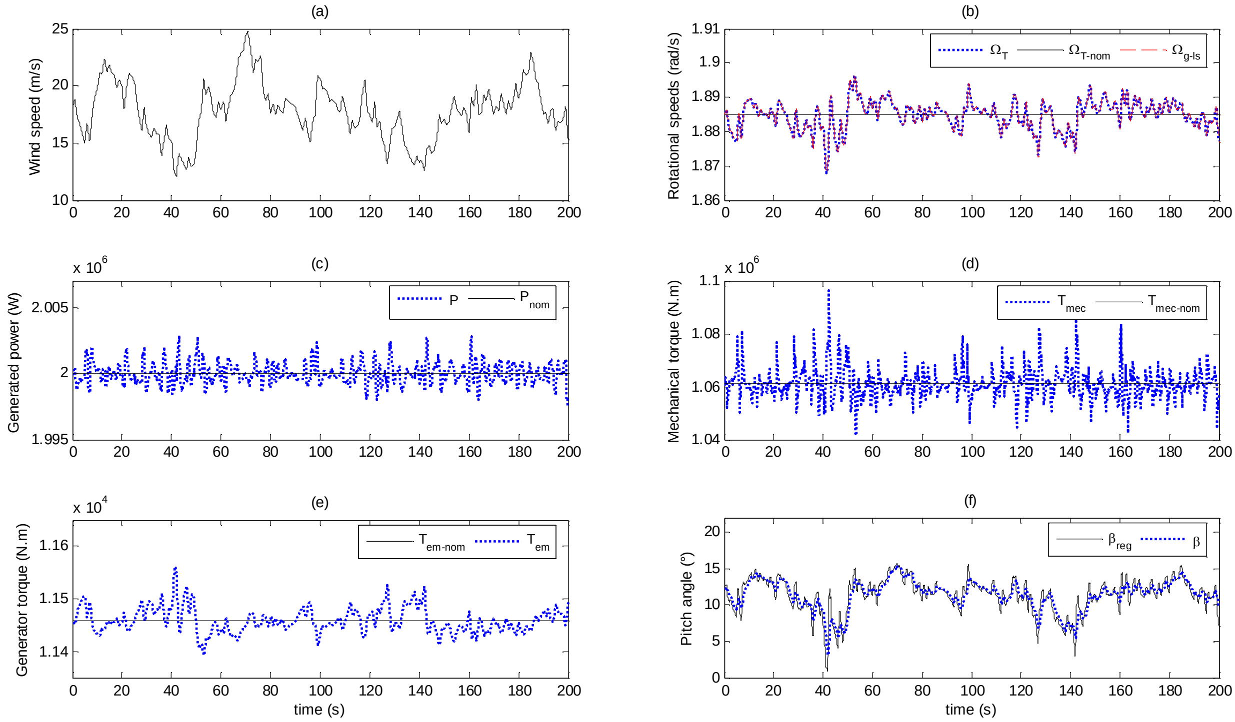


Figure 8: Evolution of the Wind Turbine Variables for a Full Load Operation

4.3. Switching controllers

On the basis of the measured wind speed, an algorithm allows to switch from one multimodel base to another during the transitions between the wind turbine operating zones. This is explained in Figure 9.

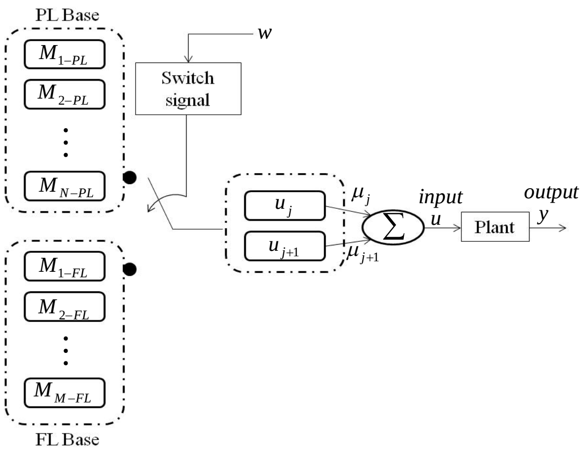


Figure 9: General Structure of a Multimodel Switching System

The efficiency of the proposed approach has been illustrated in the sight of simulation results obtained for a variable wind with a speed mean value of 11m/s, and transients between the three wind turbine operating zones: PL1, PL2 and FL zones as shown in Figure 10.

The transitions between these different operating zones have been efficiently handled by the control system in a smooth manner, which avoids the generation of large transients that could have damaging effects on the plant structure.

The rotor speed was kept slightly over its reference characteristic in order to get a better regulation and a better quality of the generated electrical power.

5. CONCLUSION

In this paper, two LQ controllers have been proposed for the whole operating range of a variable speed, pitch regulated wind turbine. The proposed strategy presented a compromise between different control objectives. The simulation results showed good performances of the controllers with acceptable mechanical stress. Furthermore, the presented approach handled successfully and efficiently the transitions between the different operating zones.

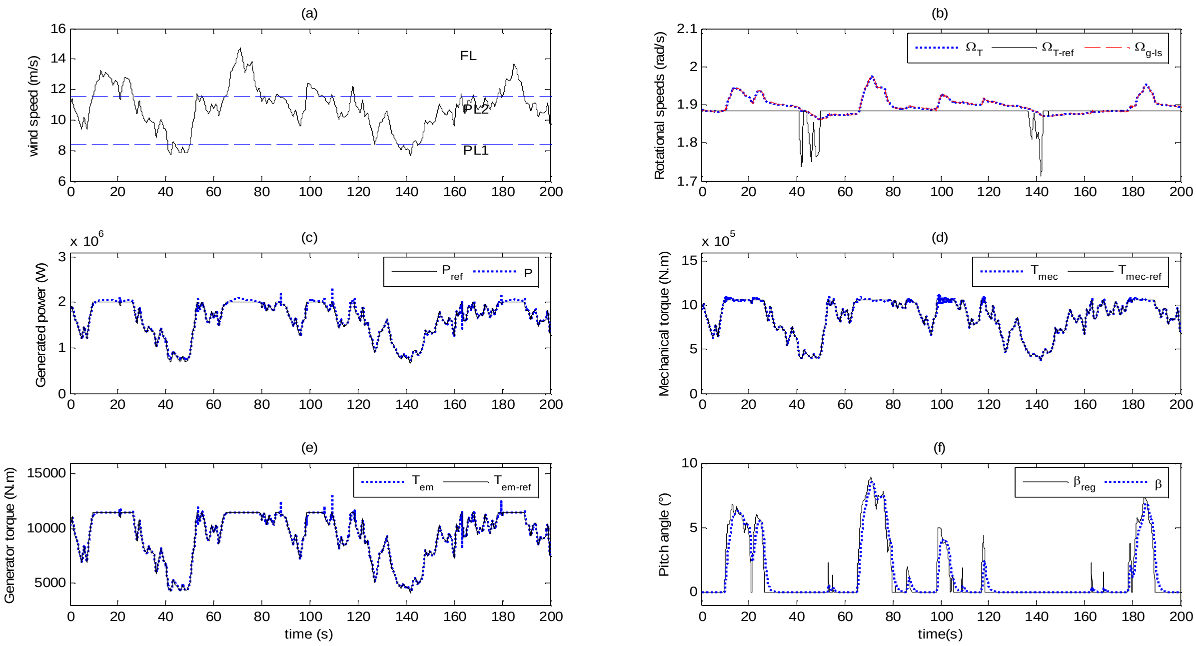


Figure 10: Evolution of the Wind Turbine Variables in Case of Switching Controllers Between PL and FL Operations

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