# PERFORMANCES IMPROVEMENT AND STABILITY ANALYSIS OF MULTIMODEL LQ CONTROLLED VARIABLE-SPEED WIND TURBINES

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Abstract: In this paper, a linear quadratic (LQ) control law combined with a multimodel approach is designed for variable-speed, variable-pitch wind turbines. The presented technique is based on an optimal control method in order to improve the system global dynamic. A set of linear local models (sub-models) is then defined for different operating points corresponding to high wind speeds. Thereafter, a global asymptotic stability analysis is developed by solving a bilinear matrix inequality (BMI) feasibility problem based on the local stability of the sub-models.

## 1 INTRODUCTION

Nowadays, the growth of the utilization of the wind turbines is more and more important since they are producing carbon-emission-free electricity. Until today, only classic control laws, such as P, PI or PID controllers, are used in the wind turbines. However, the performance of these controllers is limited by the high nonlinear characteristics of the wind turbine and by the appearance of new control objectives required by the grid-codes; the reason why advanced control research area is improving every day.

In the first axis of this paper, an LQ controller, which had been advocated by many researchers, is designed with a multimodel approach, for pitch regulated variable speed wind turbines operating at high wind speeds, in order to guarantee an optimal behavior for the studied process. However, this technique still presents some limits to satisfy all the control objectives especially those concerning the system global dynamic. This paper aims then to present an issue for this problem by adding an exponential term in the quadratic cost function.

The second section deals with the asymptotic stability analysis of the global system by solving a set of BMI according to the Lyapunov theorems. In fact, the stability study is necessary and important to illustrate the effectiveness of the presented strategy.

Finally, the simulation results realized on Matlab Simulink are presented and discussed.

## 2 WIND TURBINE MODELLING

### 2.1 Wind Turbine Description

The considered wind turbine (Figure 1) is modeled as 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*. This model is widely used in the literature (Bianchi *et al.*, 2004; Camblong *et al.*, 2002).

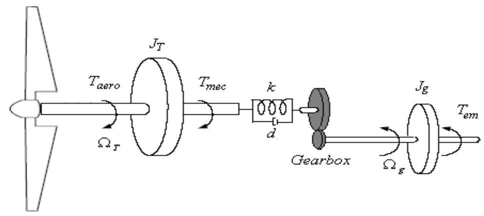


Figure 1: Wind turbine dynamic model.

where $\Omega_T$ and $\Omega_g$ are the turbine and the generator rotational speeds, $T_{em}$ is the generator torque, $T_{mec}$ is the drive train mechanical torque and $T_{aero}$ is the torque caught by the wind turbine which is expressed by:

$$T_{aero} = \frac{1}{2} \cdot \frac{\rho \cdot \pi \cdot R^5 \cdot \Omega_T^2}{\lambda^3} . c_p(\lambda, \beta) \qquad (1)$$

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where $\rho$ is the air density and $R$ is the turbine radius.

The power coefficient $c_p$ (Figure 2) is a non linear function of the blade pitch $\beta$ and the tip speed ratio $\lambda$ depending on the wind speed value $v$ and given by:

$$\lambda = \frac{\Omega_T \cdot R}{v} \tag{2}$$

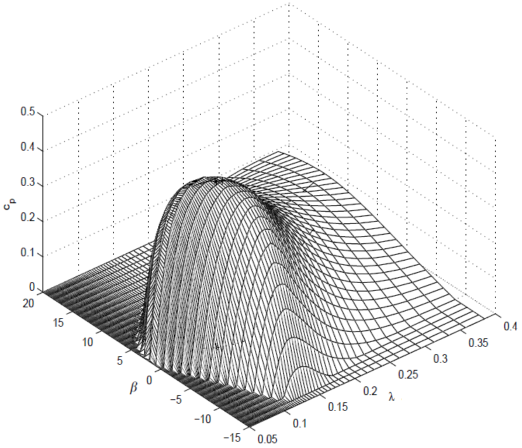

Figure 2: Power coefficient curves.

The dynamic response of the rotor is given by:

$$J_T.\dot{\Omega}_T = T_{aero} - T_{mec} \tag{3}$$

The generator is driven by the mechanical torque and braked by the electromagnetic torque. Reported to the low speed shaft, the characteristic equation is the following:

$$J_{g-ls}.\dot{\Omega}_{g-ls} = T_{mec} - G.T_{em} \tag{4}$$

where $G$ is the gearbox gain and:

$$\begin{aligned} &- \quad \Omega_{g-ls} = \frac{\Omega_g}{G} \\ &- \quad J_{g-ls} = G^2.J_g \end{aligned} \tag{5}$$

And the low speed shaft torque $T_{mec}$ results from the torsion and friction effects due to the difference between the generator and the rotor speeds (Boukhezzara *et al.*, 2007). It's defined by the following equation reported to the low speed shaft:

$$\dot{T}_{mec} = k.(\Omega_T - \Omega_{g-ls}) + d.(\dot{\Omega}_T - \dot{\Omega}_{g-ls}) \tag{6}$$

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

$$\dot{\beta} = \frac{1}{\tau_\beta}(\beta_{ref} - \beta) \tag{7}$$

$\beta_{ref}$ represents the control value of the blade-pitch angle $\beta$ and $\tau_\beta$ is the time constant of the pitch actuator.

## 2.2 Linearization and State Representation

The wind turbine is a complex non linear system presenting several difficulties in study and control. It seems then more suitable to describe it with a set of linear local models valid in different operating points corresponding to different levels of wind speed values. The principle of this method is used in several techniques. In this paper, we use the multimodel approach which was the subject of many research works (Kardous *et al.*, 2006, 2007).

For the studied system, we define a multimodel base made of four local models. The equivalent instantaneous model, as described in Figure 3, is obtained by a fusion of only two valid successive models. The choice of these models depends on the wind speed value.

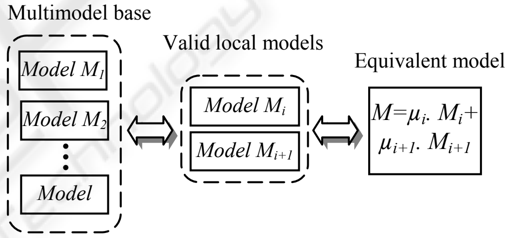


Figure 3: Wind-turbine multimodel description.

The weighting coefficient $\mu_i$ is the validity value of the model $M_i$ and it can be expressed by:

$$\mu_i = 1 - r_i \tag{8}$$

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

$$r_i = \frac{|v_i - v|}{v_i + v_{i+1}} \tag{9}$$

Thus, the validities satisfy the convex sum, such that: $\mu_i + \mu_{i+1} = 1$

To obtain the local models, the system should be then linearized around the operating point. The non-linearity of the system is due to the $c_p$ characteristic which is used in the expression of the aerodynamic torque. We need then to linearize the expression (1) of $T_{aero}$ around an operating point ($o.p$) defined by the wind speed value $v_i$ (Bianchi *et al.*, 2007; Munteanu *et al.*, 2005). We can define:

$$\Delta T_{aero} = \left.\frac{\partial T_{aero}}{\partial \Omega_T}\right|_{o.p} .\Delta\Omega_T + \left.\frac{\partial T_{aero}}{\partial \beta}\right|_{o.p} .\Delta\beta = a_i.\Delta\Omega_T + b_i.\Delta\beta \qquad (10)$$

where:

$$\begin{cases} a_i = \frac{1}{2}.\rho.\pi.R^3.\frac{v_i^2}{\Omega_{T\_nom}}.\left[\frac{\partial c_p(\lambda,\beta)}{\partial\lambda} - \frac{c_{p_{i\_nom}}}{\lambda_{i\_nom}}\right] \\ b_i = \frac{1}{2}.\rho.\pi.R^2.\frac{v_i^3}{\Omega_{T\_nom}}.\frac{\partial c_p(\lambda,\beta)}{\partial\beta} \end{cases} \qquad (11)$$

and:

$$c_{p_{i\_nom}} = c_p\left(\lambda_{i\_nom}, \beta_{i\_nom}\right) = \frac{2.\Omega_{T\_nom}.T_{aero\_nom}}{\rho.\pi.R^2.v_i^3} \qquad (12)$$

The symbol Δ represents the deviation from the chosen operating point corresponding to ($\Omega_{T\_nom}$, $\Omega_{g\text{-}ls\text{-}nom}$, $\beta_{i\text{-}nom}$, $T_{mec\text{-}nom}$, $T_{em\text{-}nom}$ and $P_{nom}$) where: $T_{em\text{-}nom}$ and $T_{mec\text{-}nom}$ are respectively the nominal values of the electromagnetic and the mechanical torques.

Thereafter, the linearization of the non-linear system expressed in equations (3), (4), (6) and (7) around an operating point gives a state space representation of the form below:

$$\begin{cases} \dot{x} = A_i.x + B_i.u \\ y = C_i.x + D_i.u \end{cases} \qquad (13)$$

where *x, u* and *y* are respectively the state, control and output vectors defined as:

$$x = \begin{bmatrix} \Delta\Omega_T \\ \Delta\Omega_{g-ls} \\ \Delta\beta \\ \Delta T_{mec} \end{bmatrix}, \; y = \begin{bmatrix} \Delta\Omega_T \\ \Delta P \end{bmatrix} \text{ and } u = \begin{bmatrix} \Delta\beta_{ref} \\ \Delta T_{em} \end{bmatrix} \qquad (14)$$

Notice that $P = T_{em}.\Omega_g$ designates the generated electrical power. This leads to write around an operating point:

$$\Delta P = G.\left(T_{em\_nom}.\Delta\Omega_{g-ls} + \Delta T_{em}.\Omega_{g-ls\_nom}\right) \qquad (15)$$

Hence, $A_i$, $B_i$, $C_i$ and $D_i$, which are respectively the state, input, output and feedthrough matrices, are defined as follows:

$$\begin{cases} A_i = \begin{pmatrix} \frac{a_i}{J_T} & 0 & \frac{b_i}{J_T} & -\frac{1}{J_T} \\ 0 & 0 & 0 & \frac{1}{J_{g-ls}} \\ 0 & 0 & -\frac{1}{\tau_\beta} & 0 \\ k + \frac{a_i.d}{J_T} & -k & \frac{d.b_i}{J_T} & -d.\left(\frac{1}{J_T} + \frac{1}{J_{g-ls}}\right) \end{pmatrix} \\ B_i = \begin{pmatrix} 0 & 0 \\ 0 & -\frac{G}{J_{g-ls}} \\ \frac{1}{\tau_\beta} & 0 \\ 0 & \frac{d.G}{J_{g-ls}} \end{pmatrix}, C_i = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & G.T_{em\_nom} & 0 & 0 \end{pmatrix} \\ \text{and } \; D_i = \begin{pmatrix} 0 & 0 \\ 0 & G\Omega_{g-ls\_nom} \end{pmatrix} \end{cases} \qquad (16)$$

# 3 CONTROLLER DESIGN

The control task is based on the objective of regulating the rotor rotational speed and the generated power by acting on two control variables: the electromagnetic torque $T_{em}$ and the regulating pitch angle $\beta_{ref}$.

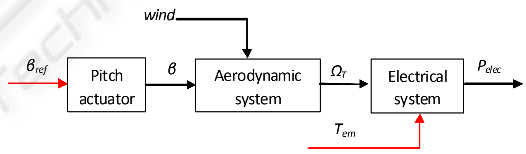


Figure 4: Wind turbine block diagram.

The LQ control strategy had been advocated by many research works (Boukhezzara *et al.*, 2007; Khezami *et al.*, 2009; Poulsen *et al.*, 2005; Hammerum et al., 2007; Cutululis *et al.*, 2006). This technique presents a good compromise between the performances optimization and the minimization of the control signals by the use of a quadratic cost function. However, it also presents the disadvantage of the non possibility of controlling the global system dynamic. In this paper, a solution that can partially solve this problem is presented.

This controller aims to minimize the following quadratic criterion $J$ :

$$J = \frac{1}{2}\int_0^{+\infty} \left(y^T.Q.y + u^T.R.u\right).e^{2\alpha t} dt \qquad (17)$$

where Q and R are diagonal positive definite matrices.

The term $y^T.Q.y$ expresses the performances optimization, the term $u^T.R.u$ expresses the minimization of the control signals and the term $e^{2\alpha t}$ allows the performances improvement of the classic quadratic criterion. It leads to the placement of the system poles on the left of $-\alpha$.

The criterion can be rewritten as follows with an input-state cross term:

$$J = \frac{1}{2}\int_0^{+\infty}\left(x^T.Q_1.x + 2.x^T.N.u + u^T.R_1.u\right).e^{2\alpha t}dt \quad (18)$$

where $Q_1$, $R_1$ and $N$ are defined as :

$$\begin{cases} Q_1 = C^T.Q.C \\ R_1 = R + D^T.Q.D \\ N = C^T.Q.D \end{cases} \quad (19)$$

For this criterion, the optimal gain can be calculated from the following Riccati equation:

$$\begin{cases} A_{i\alpha}^T.L + L.A_{i\alpha} - (L.B_i + N_1).R_1^{-1}.(B_i^T.L + N_1^T) \\ \quad + Q_1 = 0 \\ A_{i\alpha} = A_i + \alpha.I \\ K_i = R_1^{-1}.(B_i^T.L + N_1^T) \end{cases} \quad (20)$$

where $I$ is the identity matrix.

Since the dynamic of the pitch actuator should not be changed, the controller is designed in two steps. In the first step, we consider the blade pitch angle $\beta$ and the electromagnetic torque $T_{em}$ as control variables instead of $\beta_{ref}$ and $T_{em}$. The state representation becomes then:

$$\begin{cases} \dot{x}_1 = A_{i1}.x_1 + B_{i1}.u_1 \\ y = C_{i1}.x_1 + D_{i1}.u_1 \end{cases} \quad (21)$$

where:

$$\begin{cases} x_1 = \begin{bmatrix} \Delta\Omega_T \\ \Delta\Omega_{g-ls} \\ \Delta T_{mec} \end{bmatrix},\ y = \begin{bmatrix} \Delta\Omega_T \\ \Delta P \end{bmatrix} \text{ and } u_1 = \begin{bmatrix} \Delta\beta \\ \Delta T_{em} \end{bmatrix} \\ A_{i1} = \begin{pmatrix} \frac{a_i}{J_T} & 0 & -\frac{1}{J_T} \\ 0 & 0 & \frac{1}{J_{g-ls}} \\ k + \frac{a_i.d}{J_T} & -k & -d.\left(\frac{1}{J_T} + \frac{1}{J_{g-ls}}\right) \end{pmatrix} \\ B_{i1} = \begin{pmatrix} \frac{b_i}{J_T} & 0 \\ 0 & -\frac{G}{J_{g-ls}} \\ \frac{d.b_i}{J_T} & \frac{d.G}{J_{g-ls}} \end{pmatrix}, \\ C_{i1} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & G.T_{em-nom} & 0 \end{pmatrix} \\ \text{and} \quad D_{i1} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \end{cases} \quad (22)$$

From this representation, the optimal gain $K_{i1} = \begin{bmatrix} K_{i1\_\beta} \\ K_{i1\_Tem} \end{bmatrix}$ is calculated such that:

$$u_1 = \begin{bmatrix} \Delta\beta \\ \Delta T_{em} \end{bmatrix} = -K_{i1}.x_1 \quad (23)$$

The relation (23) leads to the following optimal control law using the global state vector as shown in Figure 5:

$$\begin{cases} u = -K_i.x \\ K_i = \begin{bmatrix} K_{i\_\beta ref} \\ K_{i\_Tem} \end{bmatrix} \end{cases} \quad (24)$$

with:

$$\begin{cases} K_{i\_\beta ref} = \left(K_{i1\_\beta} + \tau_\beta.K_{i1\_\beta}.A_1\right).T_1 + \tau_\beta.K_{i1\_\beta}.B_{i1\_\beta}.T_2 - \\ \qquad \tau_\beta.K_{i1\_\beta}.B_{i1\_Tem}.K_{i1\_Tem}.T_1 \\ K_{i\_Tem} = K_{i1\_Tem}.T_1 \end{cases} \quad (25)$$

and:

$$\begin{cases} \begin{bmatrix} B_{i1\_\beta} & B_{i1\_Tem} \end{bmatrix} = B_{i1} \\ T_1 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \\ T_2 = \begin{bmatrix} 0 & 0 & 1 & 0 \end{bmatrix} \end{cases} \quad (26)$$

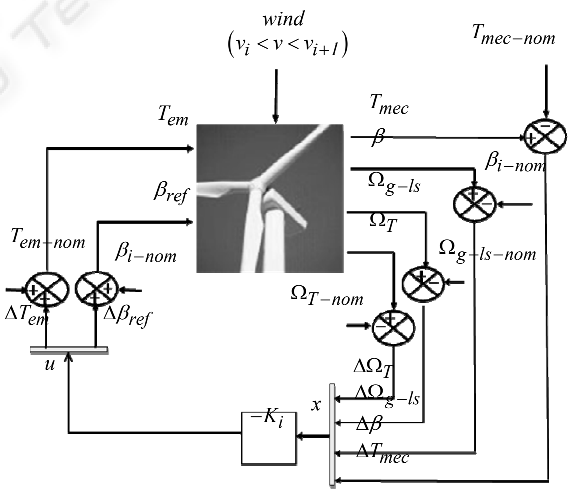


Figure 5: The LQ controller design.

## 4 STABILITY STUDY

The quantum advance in stability theory that allowed one the analysis of arbitrary differential equations is due to Lyapunov, who introduced the

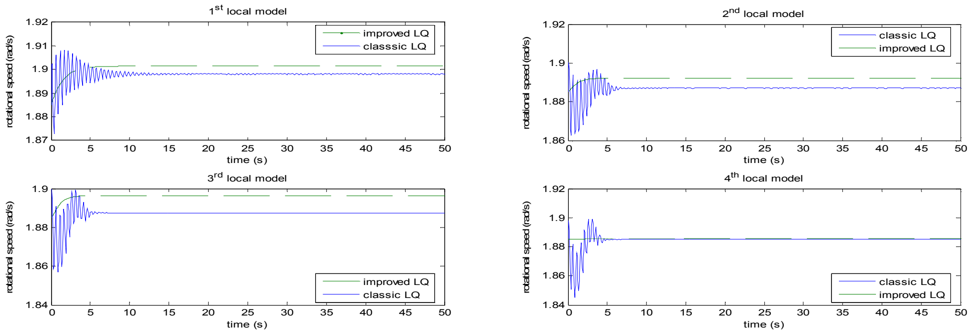


Figure 6: Comparison simulation between classic and improved LQ control laws.

basic idea and the definitions of stability that are in use today. The concept of Lyapunov stability plays an important role in control and system theory.

As we define a global model $M$ by fusion of two successive local models $M_i$ and $M_{i+1}$, the characteristic matrices of the system (13) can be obtained by:

$$\begin{cases} A_i = \mu_k.A_k + \mu_{k+1}.A_{k+1} \\ B_i = \mu_k.B_k + \mu_{k+1}.B_{k+1} \\ C_i = \mu_k.C_k + \mu_{k+1}.C_{k+1} \\ D_i = \mu_k.D_k + \mu_{k+1}.D_{k+1} \end{cases} \tag{27}$$

The input vector is calculated by:

$$u = -\left(\mu_k.K_k + \mu_{k+1}.K_{k+1}\right).x \tag{28}$$

Hereafter, the state vector can be represented as:

$$\begin{aligned} \dot{x} &= \sum_i \sum_j \mu_i.\mu_j.\left(A_i - B_i.K_j\right).x \\ &= \sum_i \mu_i^2.G_{ii}.x + 2.\sum_{j=i+1} \mu_i.\mu_j.\left(\frac{G_{ij} + G_{ji}}{2}\right).x \end{aligned} \tag{29}$$

where: $G_{ij} = A_i - B_i.K_j$

To study the global asymptotic stability of the above system supplied by the multimodel LQ control, the first necessity is to analyze the stability of every local model. As we focus here especially on the closed-loop system, the criterion of stabilization consists then in finding, for a local model $M_i$, a positive definite matrix $P$ that satisfies the following LMI (Chedli, 2002; Liberzon and Morse, 1999):

$$G_{ii}^T.P + P.G_{ii} < 0 \tag{30}$$

In the case of the multimodel systems, an extra condition is to add to the LMI (30) in order to guarantee the global stability (Chedli, 2002; Liberzon and Morse, 1999; Kardous *et al.*, 2003) and it consists in:

$$Q_{ij}^T.P + P.Q_{ij} < 0, \quad i < j \tag{31}$$

where $Q_{ij} = \dfrac{G_{ij} + G_{ji}}{2}$

And in our case, only two successive local models are valid at a time, which means that this condition will be considered for *i=1 to 3* and *j=i+1*.

## 5 SIMULATION RESULTS

The proposed control approach and the stability analysis of the controlled system have been illustrated through simulations on Matlab Simulink.

The simulated wind turbine parameters are presented in Table 1.

To calculate the linearization coefficients $a_i$ and $b_i$, the following $c_p$ empiric expression relative to 2MW wind turbines is used:

$$c_p = 0.18 \times \left(\frac{90}{0.4+0.5\lambda} - 6.8 - 0.115\beta^2\right) \times e^{\frac{-8}{0.4+0.5\lambda}+0.16} \tag{32}$$

Table 1: Wind turbine parameter values.

| *Parameters* | | *Values* |
|---|---|---|
| *Air density* | $\rho$ | *1,22 Kg/m³* |
| *Turbine radius* | $R$ | *40m* |
| *Nominal power* | $P_{nom}$ | *2MW* |
| *Nominal speed* | $\Omega_{T\text{-}nom}$ | *18 rpm* |
| *Optimal power coefficient* | $c_{p\text{-}opt}$ | *0.4775* |
| *Optimal speed ratio* | $\lambda_{opt}$ | *9* |
| *Gearbox gain* | $G$ | *92.6* |
| *Turbine inertia* | $JT$ | $4.9\times10^6$ *N.m.s²* |
| *Generator inertia* | $Jg$ | $0.9\times10^6$ *N.m.s²* |
| *Mechanical coupling damping coefficient* | $d$ | $3.5\times10^5$ $N.m^{-1}.s$ |
| *Mechanical coupling stiffness coefficient* | $k$ | $114\times10^6$ $N.m^{-1}$ |

Table 2 describes the four local models multimodel base used for the simulations.

Table 2: Multimodel base parameters.

| *Local model Mi* | *Wind speed vi (m/s)* | *Pitch angle* $\beta_{i\text{-}nom}$ *(°)* |
|---|---|---|
| *M1* | *11.6* | *1.1* |
| *M2* | *14* | *8* |
| *M3* | *17* | *11.1* |
| *M4* | *25* | *15.4* |

From this base, four optimal gains are calculated.

And thus, the stability feasibility problem consists in solving 8 LMI as shown after:

$$\begin{cases} P>0 \quad (1\,LMI) \\ G_{ii}^T.P+P.G_{ii}<0, i=1..4 \quad (4\,LMI) \\ Q_{ij}^T.P+P.Q_{ij}<0, i=1..3, j=i+1 \quad (3\,LMI) \end{cases} \tag{33}$$

The simulation leads to the following result:

$$P=\begin{pmatrix} 8.848 & -8.335 & -0.008 & 0.298 \\ -8.335 & 8.101 & 0.007 & -0.258 \\ -0.53 & 0.523 & 0.026 & -0.001 \\ 0.298 & -0.258 & -0.001 & 0.084 \end{pmatrix}$$

Finding this positive definite matrix $P$ is a sufficient condition proving the global stability of the control technique presented above.

For the simulations, we had chosen to place the closed loop poles for the local models at the left of -α=-0.5. This gives the following poles for each local model:

- *1st local model:* $P_1=\begin{bmatrix} -1.032+12.24i \\ -1.032-12.24i \\ -1 \\ -1.069 \end{bmatrix}$
- *2nd local model:* $P_2=\begin{bmatrix} -1.032+12.24i \\ -1.032-12.24i \\ -1 \\ -1.06 \end{bmatrix}$
- *3rd local model:* $P_3=\begin{bmatrix} -1.033+12.24i \\ -1.033-12.24i \\ -1 \\ -1.049 \end{bmatrix}$
- *4th local model:* $P_4=\begin{bmatrix} -1.037+12.24i \\ -1.037-12.24i \\ -1 \\ -1.046 \end{bmatrix}$

Thus, we can see that the pitch system pole (-1) is invariant for the four local models, and that all the other poles have their real parts less than –α.

To test the performance of this control strategy, a series of simulation for several wind steps has been performed to show the improvement of the studied controller against a classic multimodel LQ controller (Khezami *et al.*, 2009).

The Figure 6 presents a comparison simulation between the two control laws. For this simulation, only the turbine rotational speed response for a wind step of 0.5 m/s is presented for the four local models.

The local models poles for the classic LQ strategy have the following values:

- *1st local model:* $P_1=\begin{bmatrix} -0.346+12.25i \\ -0.346-12.25i \\ -1.162+0.868i \\ -1.162-0.868i \end{bmatrix}$
- *2nd local model:* $P_2=\begin{bmatrix} -1.2+12.401i \\ -1.2-12.401i \\ -2.693+2.013i \\ -2.693-2.0128i \end{bmatrix}$
- *3rd local model:* $P_3=\begin{bmatrix} -1.62+12.587i \\ -1.62-12.587i \\ -3.417+2.287i \\ -3.417-2.287i \end{bmatrix}$
- *4th local model:* $P_4=\begin{bmatrix} -2.148+12.845i \\ -2.148-12.845i \\ -4.108+2.418i \\ -4.1081-2.418i \end{bmatrix}$

In the comparison between both strategies, the system response for the proposed controller has indeed kept almost the same response time (about 4s), unlike the case with the classic LQ where the response times are varying from 12s for the 1st local model to 2s for the 4th local model.

Compared to the proposed strategy, the classic multimodel LQ control law shows responses with a more oscillating transient mode.

The improvements of the multimodel LQ controller consist in a more damped oscillatory mode and a faster dynamic than the classical control mode with an almost fixed response time for all the local models.

The simulation of the system with the proposed control strategy for a variable wind speed between 12m/s and 25m/s leads to the results presented in the curves of Figure 7.

The Figure 7 (a) illustrates a realistic aspect of the wind speed as described in a method elaborated by *C. Nichita* in (Nichita *et al.*, 2003). From this aspect, the controller allowed a good regulation of the generated electrical power (Figure 7 (d)) and the rotation speeds of both the rotor (Figure 7 (b)) and the generator (Figure 7 (c)) around their rated values with taking into account the fatigue damage since the mechanical torque (Figure 7 (e)) maintains an almost constant value which thereby leads to have alleviated mechanical loads.

The variations of the electromagnetic torque presented in Figure 7 (g) are smooth. However, the price paid for these performances is shown in Figure 7 (h) by a large activity of the pitch actuator.

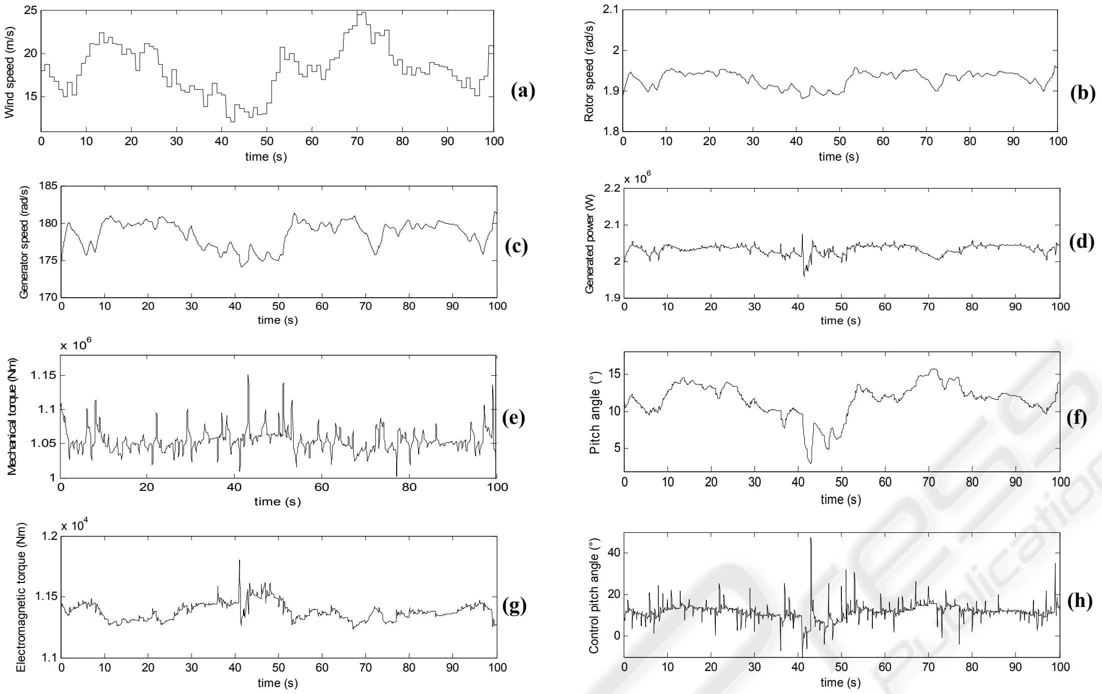


Figure 7: Variation of the system variables.

# 6 CONCLUSIONS

This paper dealt with a technique of designing a multimodel LQ regulator allowing to partially control the process global dynamic, and with a study of the global asymptotic stability of the controller by means of a set of LMI. The proposed strategy presented a compromise between different control objectives: optimizing the performances of the different system variables especially generating an electrical power of a good quality, minimizing the control efforts, alleviating the drive train dynamic loads and controlling the global dynamic of the studied process. The simulations results showed good performances of the controller with acceptable mechanical stress. But, satisfying such a trade-off between all these objectives is indeed difficult and the cost is however some high forces on the pitch actuator. These effects brought more challenges in the system analysis to improve the obtained results in order to control actively the system dynamic and to totally damp the oscillatory mode.

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