HORIZONTAL AXIS WIND TURBINE DYNAMIC SIMULATION BASED ON LQG CONTROLLER

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Abstract: Nowadays the energy production by wind turbines has been increasing because its production is environmentally friendly; therefore the technology developed for the production of energy through wind turbines brings great challenges in the investigation. The system is studied under nominal conditions by means nominal wind power and maximum pitch angle. A sensitivity analysis is implemented to study the system performance at the design margins of different parameters like wind speed, tip speed ratio and pitch angle.

The paper deals with the modeling and power control of horizontal variable speed wind turbines using an enhanced LQG controller. The proposed LQG controller is designed to realize a compromise between the maximum-power-point generations under randomized wind energy condition changes. The effectiveness and robustness of the proposed control approach are proven by numerical simulations. LQR is a conventional controller is built and the system performance is studied and compared with LQG. The results confirms that the proposed LQG controller success to maintain the output power equal or close to the rated value at different operating conditions while LQR is not. The LQG protects the wind turbine system from wind storms and force the system for shuts down.

Key-Words: Wind Turbines, Modelling, Dynamic Simulation, LQR, LQG, Intelligent Controller, Horizontal Axis Wind Turbine, MIMO Systems

1. introduction

An increasing amount of research and development has been directed towards variable-speed control of wind turbines (WT), where the aim is to benefit from increased aerodynamic efficiency and decreased mechanical loads in the drive system. Another key area is the design of a control system that optimizes the above benefits. A prerequisite of this is a reliable drive-system model of reasonable complexity. Physical modeling of the drive train will result in models of different orders, depending on the number of rotating masses. Variable-speed control of wind turbines requires good knowledge of the dynamics to be controlled. This is particularly important when combined with the increasingly common soft concept resulting in structural Eigen frequencies within the closed-loop bandwidth.

Most literature on wind turbine control has established an objective in the maximization of the power produced when the wind speed is in the range between the cut-in and the cutout wind speed. This goal is usually achieved by controlling the electromagnetic torque of the generator in order to obtain the optimal rotor speed for optimum power coefficient [1], [16].

Classical techniques such as PID and PI controllers of blade pitch are typically used to limit power and speed for turbine operating above rated wind speed. Many researchers have also developed other methods reducing loads using adaptive control method.

The purpose of this work is to design a multi-model LQG. Furthermore, because of the high non linearity of the wind turbine behavior, the LQG approach is based on a linearization of the system around different operating points corresponding to the subsystems of the multi-model base, and then a state feedback is tuned in order to satisfy the different control objectives: regulating the rotational speed and the electrical power around their nominal values by acting on two control variables which are the blade pitch angle and the electromagnetic torque.

1.1. Power in the Wind and Wind Turbines

The power of motion (kinetic energy) contained in a moving air stream can be calculated by the following formula [2]:

$$KP = \frac{1}{2} \rho A V^3$$

Eq. 1

Where:
KP   kinetic power (watts)
ρ   Air density (1.225kg/m3 at standard Condition)
V   wind speed.

It should be noted that, the kinetic power depends on the cube of the wind speed, so if the wind speed doubles, the amount of kinetic power in the wind increases by eight. Thus, wind speeds higher than the average wind speed contain much more power than those below the average wind speed do. For typical variation of wind speed, the average kinetic power can be calculated from the average speed by the formula:

1.2. Average kinetic power

The energy available on site, produced by the wind (without considering the limitations of the physical system that produces the energy) in a time unit, can be computed using the following mathematical expression [3]:

$$KP_{av} = 6/\pi * ½ \rho.A.V_{av}^3$$

$$= 1.17 \rho.A.V_{av}^3$$

Eq. 2

Where:
$6/\pi$ Multiplier accounts for the distribution of wind speed, and therefore kinetic power, with time.
Vav   Average wind speed at the center of the rotor   (m/s)

A wind turbine cannot capture al the kinetic power in the wind. A well suited, designed properly for the wind conditions at the site, will convert about 25% of the kinetic power in the wind into useful power. So, the average power output of a good wind turbine is:

$$P_{av} = 0.25 * 1.17 A V_{av}^3$$

Eq. 3

Where:
Pav   average power output from the wind turbine (Watt),
A   Swept area by the wind turbine rotor (m^2)

The specific energy of the wind-turbine Generator power is also modeled by the following formula [4]:

$$\begin{cases} PW = 0 & V < V_{CI} \\ PW = a.V^3 - b.P_r & V_{CI} < V < V_{CO} \\ PW = P_r & V_R < V < V_{CO} \\ PW = 0 & V > V_{CO} \end{cases}$$

Eq. 4

Where
a $= P_r / (V_r^3 - V_{CI}^3)$,
b $= V_{CI}^3 / (V_r^3 - V_{CI}^3)$,
P_r rated power,
V_r rated wind speed,
V_{CI} cut-in wind speed, and
V_{CO} cut-out wind speed.

The relation between the wind turbine output power and the wind speeds for 2000W rated wind turbine (f.e.) is shown in Figure 1. The cut-in speed is 3m/s, rated speed is 9m/s while cut-out speed is 20m/s.

2. Dynamic Modeling of the Wind Turbine

The wind turbine is characterized by no dimensional curves of the power coefficient (Cp) as a function of both the tip speed ratio (λ) and the blade pitch angle (β). In order to fully utilize the available wind energy, the value of (λ) should be maintained at its optimum value. Therefore, the power coefficient corresponding to that value will become maximum also.

The model is based on the steady-state power characteristics of the turbine. The stiffness of the drive train is infinite and the friction factor and the inertia of the turbine must be combined with those of the generator coupled to the turbine [5], [6].
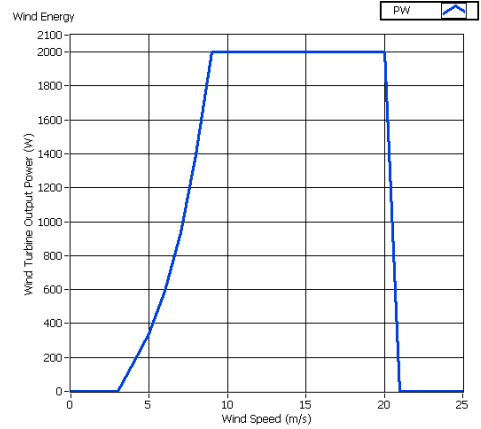

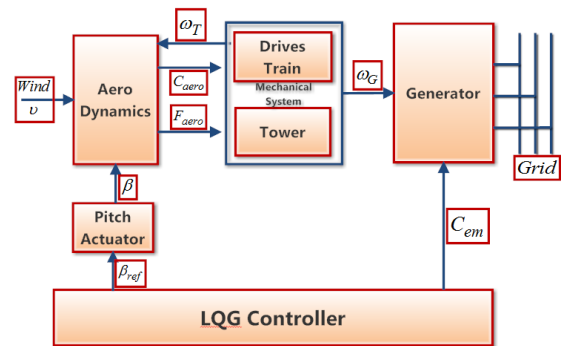Figure 1, Wind turbine Power to Wind speed curve

Figure 2, WTS and its corresponding control scheme [7]

The tip speed ratio (λ) can be defined as the ratio of the angular rotor speed of the wind turbine to the linear wind speed at the tip of the blades. It can be expressed as follows [8]:

$$\lambda = \omega_t R / V_\omega$$

Eq. 5

Where

R   is the wind turbine rotor radius,

V_ω is the wind speed and ω_t is the mechanical angular rotor speed of the wind turbine.

A generic equation is used to model $C_p(\lambda,\beta)$. This equation, based on the modeling turbine characteristics of [5], is:

$$C_p(\lambda,\beta) = C_1 * \left(C_2/\lambda_i - C_3*\beta - C_4\right)*e^{(-C_5/\lambda_i)} + C_6*\lambda$$

Eq. 6

Where the coefficients c1 to c6 are:

c1 = 0.5176,   c2 = 116,   c3 = 0.4,
c4 = 5,   c5 = 21 and   c6 = 0.0068.

In addition to Eq. 6, the relation between λ and β can be found in the following relation [5]:

$$1/\lambda_i = \frac{1}{\lambda + 0.08*\beta} - \frac{0.035}{\beta^3 + 1}$$

Eq. 7

The Cp-λ characteristics, for different values of the pitch angle β, are illustrated below. The maximum value of Cp (Cpmax = 0.48) is achieved for β = 0 degree and for λ = 8.1. This particular value of λ is defined as the nominal value (λ_nom).

The instantaneous values of Cp as a function of rotor speed and angle of attack is shown in Eq. 6. Wind turbine is designed to have low cut-in and cut-out speed (2-3m/s: 7-9m/s) to suit Jazan wind condition. The power output equation [8] of wind turbine can be described in Eq. 8:

$$P_t = \tfrac{1}{2}\rho\pi R^2 . C_p(\lambda,\beta).V^3$$

Eq. 8

Where:

PT   is wind power (W)

ρ is air density (kg/m3)

V   is wind speed (m/s)

R   is radius of turbine blades (m2)

CP   is wind power coefficient.

From (Eq. 8), the power that can be produced is proportional with the cube of the wind speed, thus it is necessary to define the wind speed. The wind speed is a non-stationary random process which can be described by the following equation:

$$\upsilon_w(t) = \upsilon_s(t) + \upsilon_t(t)$$

Eq. 9

Where:

$\upsilon_s(t)$ Low frequency component (wind currents and their long term variations) and

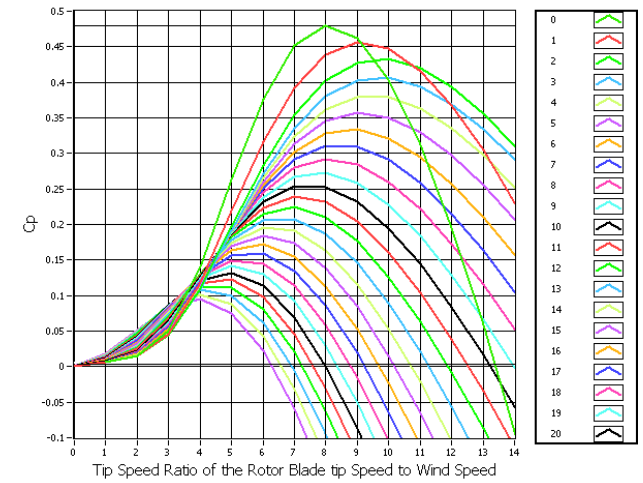$\upsilon_t(t)$ Turbulent component, (the fast, high frequency variations).

Figure 3, Wind turbine Cp-λ characteristics

It is easily understood that the wind speed components play a very important role in the energy production process and their influence must be considered in the design of the controller in order to obtain satisfactory results.

3. Mechanical Equations Of Wind Turbine Components

The wind turbine is an assembly of subsystems interconnected: aerodynamic, mechanical, electrical and pitch actuator [9]. In order to continue with the mathematical model definition the Lagrange equation will be used:

$$\frac{d}{dt}\left(\frac{\partial E_C}{\partial \dot{q}_t}\right) - \frac{\partial E_C}{\partial q_t} + \frac{\partial E_D}{\partial \dot{q}_t} + \frac{\partial E_P}{\partial q_t} = Q$$

Eq. 10

Where:

EC   is the kinetic energy,

EP   is the potential energy,

ED   is the dissipated energy of the system, and

Q   is the vector of the forces acting on the system, and

q   is the vector of generalized coordinates.

The three energies can be expressed as sums of energies specific to the wind turbine components considered for the model, see equation (11),

$$E_c = \frac{J_T}{2}\omega_T^2 + \frac{J_G}{2}\omega_G^2 + \frac{M_T}{2}\gamma_T^2 + M(\gamma_T^\square + r_P\zeta^\square)^2$$

$$E_p = \frac{k_A}{2}(\theta_T - \theta_G)^2 + k_p(r_P\zeta)^2 + \frac{k_T}{2}\gamma_T^2$$

$$E_D = \frac{d_A}{2}(\omega_T - \omega_G)^2 + d_p(r_P\zeta^\square)^2 + \frac{d_T}{2}\gamma_T^{\square2}$$

Eq. 11

Where:

$J_T, J_G, M_T, M_P, K_A, K_P, d_A, d_P$ and d_T are coefficients specific to the wind turbine components,

ωG is the generator angular speed and

Pr is the distance from the rotor hub to the point on the blade where the generalized thrust force is applied.

As the wind turbine can be considered a mechanical system, the following motion equation will be used:

$$M\ddot{q} + C\dot{q} + Kq = Q(\dot{q}, q, t, u)$$

Eq. 12

Where:

M, C and K are the mass, damping, and the stiffness matrices [10].

For the wind turbine model, the generalized coordinate's vector is:

$$q = (\theta_T, \theta_G, \zeta_1, \zeta_2, \gamma_T)$$

Eq. 13

Where:

θT is the angular position of the rotor,

θG represents the angular position of the generator,

$\zeta 1$ and $\zeta 2$ are the flaps of the blades, while

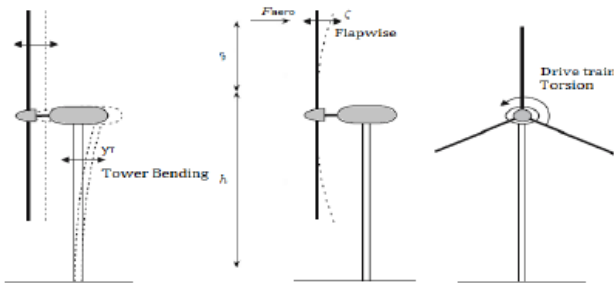yT represents the horizontal movement of the tower.

Figure 4, flaps of the blades (ζ) and tower horizontal movement (yT) [7]

The vector Q representing the forces acting on the system is:

$$Q = (C_{aero} - C_{em}, F_{aero,1}, F_{aero,2}, 2F_{aero})$$

Eq. 14

Where:

C_{aero} is the aerodynamic torque,

C_{em} represents the electromagnetic torque and

F_{aero} stands for the thrust force acting on the blades.

As stated previously some simplifying hypotheses were made in order to decrease the model order. The thrust forces acting on the blades can be considered equal, thus it can be written $F_{aero1} = F_{aero2} = F_{aero}$.

The mathematical model design starts with the definition of the two important factors of a wind turbine: the power coefficient and thrust coefficient, both depending on two variables specific to the wind turbine the tip speed ratio and the pitch angle of the blades. In consequence, as the blades are similar, it can be assumed that the blade flaps are equal under the action of the same thrust force, $\zeta 1 = \zeta 2 = \zeta$. Having the two factors $C_a(\lambda, \beta)$ and $C_P(\lambda, \beta)$ defined, and considering equations (1) and (3), the mathematical expressions for the aerodynamic torque and the thrust force can be written as follows:

$$C_{aero} = 0.5\rho \, \pi R^2 \frac{v^3}{\omega_T} C_P(\lambda, \beta)$$

$$F_{aero} = 0.5\rho \, \pi R^2 v^2 C_a(\lambda, \beta)$$

Eq. 15

As the mathematical expressions of C_{aero} and F_{aero}, described by equations (15), introduce a certain level of nonlinearity to the system, it is necessary to perform a linearization on the model, around an operating point:

$$P_{op}(\omega_{T,op}, \beta_{op}, \upsilon_{med}).$$

Thus the equations (15) can be written

$$\Delta C_{aero} = D_{c\omega}\Delta\omega_T + D_{c\beta}\Delta\beta + D_{cv}\Delta v_w$$

$$\Delta F_{aeo} = D_{f\omega}\Delta\omega_T + D_{f\beta}\Delta\beta + D_{fv}\Delta v_w$$

Eq. 16

Where:

Δ operator describes a small deviation from the optimal value $(e.g. \Delta\omega_T = \omega_T - \omega_{Top})$

and D_{xy} are the first order partial derivative coefficients of the equations (11) with respect to ωT, β and

v: $(e.g. D_{cw} = \partial C_{aero} / \partial\omega_T)$

Another important component of the mathematical model is the behavior of the servomotor which controls the pitch angle and also the limitations imposed for this angle (i.e. maximum value and variation speed of pitch angle) [11]. This component is described as follows:

$$\frac{\beta}{\beta_{ref}} = \frac{1}{1+T_\beta s}$$

Eq. 17

Where:
βref   is the pitch angle reference and
Tβ   is the time constant which illustrates the block constraints.

The servomotor limitations were also considered. In order to move forward in the model design, the wind speed will be represented according to reference [10]:

$$\dot{v}_w = -\frac{1}{T_v} v_w(t) + v(t)$$

Eq. 18

Where:
Tv   is the time constant, calculated in [7], and
v(t) is the turbulent component of the wind speed.

The last parameter used is the electric power generated by the turbine, one of the output vector components. The mathematical expression used to compute the power produced by the wind turbine is:

$$P_{el} = \omega_G C_{em}$$

Eq. 19

Based on the equations and the mathematical expressions defined so far, the state space representation of the wind turbine can be obtained.

The command vector is represented by $u(t) = (BC_{em})$, the state vector is represented by:

$$X_m(t)^T = (\theta_T - \theta_G \, \xi \gamma_T \, \omega_T - \omega_G \, \xi \dot{\gamma}_T \, \beta v_w)$$

Eq. 20

While the output vector is represented by:

$$y(t) = (P_{el})$$.

The system linear state space continuous-time model is illustrated in equation (16),

$$\dot{x} = A.x(t) + B.u(t) + M.m_v(t)$$

$$y = C.x(t) + D.u(t) + w(t)$$

Eq. 21

4. LQG Controller Design

In control theory, the linear-quadratic-Gaussian (LQG) control problem is one of the most fundamental optimal control problems. It concerns uncertain linear systems disturbed by additive white Gaussian noise, having incomplete state information (i.e. not all the state variables are measured and available for feedback) and undergoing control subject to quadratic costs. Moreover the solution is unique and constitutes a linear dynamic feedback control law that is easily computed and implemented. Finally the LQG controller is also fundamental to the optimal control of perturbed non-linear systems.

The LQG controller itself is a dynamic system like the system it controls. Both systems have the same state dimension. Therefore implementing the LQG controller may be problematic if the dimension of the system state is large. The reduced-order LQG problem (fixed-order LQG problem) overcomes this by fixing a-priori the number of states of the LQG controller. This problem is more difficult to solve because it is no longer separable. Also the solution is no longer unique. Despite these facts numerical algorithms are available[2][3][4][5] to solve the associated optimal projection equations[6][7] which constitute necessary and sufficient conditions for a locally optimal reduced-order LQG controller.

The LQG controller is simply the combination of a Kalman filter i.e. a linear-quadratic estimator (LQE) with a linear-quadratic regulator (LQR). The separation principle guarantees that these can be designed and computed independently. LQG control applies to both linear time-invariant systems as well as linear time-varying systems. The application to linear time-invariant systems is well known. The application to linear time-varying systems enables the design of linear feedback controllers for non-linear uncertain systems.

In traditional LQG Control, it is assumed that the plant dynamics are linear and known and that the measurement noise and disturbance signals (process noise) are stochastic with known statistical properties as shown in Figure 5.
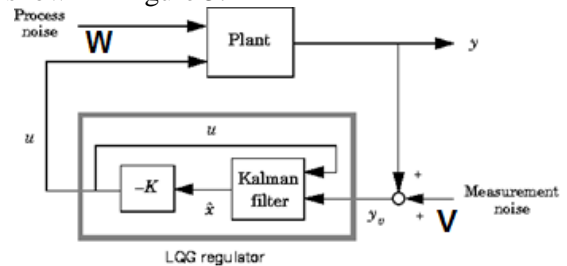

Figure 5, Block diagram of the optimal LQG-compensator.

$$\dot{x} = Ax + Bu + \Gamma w$$

$$y = Cx + v$$

Eq. 22

That is, W and V are white noise processes with covariance

$$E\left(ww^T\right) = w \ge 0, \quad E\left(vv^T\right) = v \ge 0 \quad \text{and}$$

$$E\left(wv^T\right) = 0, \quad E\left(vw^T\right) = 0$$

The problem is then to devise a feedback-control law which minimizes the 'cost'

$$J = E\left\{ \lim_{T \to \infty} \frac{1}{T} \int_0^T \left(z^T Q z + u^T R u\right) dt \right\} \qquad \text{Eq. 23}$$

Where:

$$z = Nx, \quad Q = Q^T \ge 0 \quad \text{and} \quad R = R^T > 0$$

The solution to the LQG problem is prescribed by the separation theorem, which states that the optimal result is achieved by adopting the following procedure:

1st, Obtain an optimal estimate of the state x Optimal in the sense that:

$$E\left\{ (x - \hat{x})^T (x - \hat{x}) \right\}$$

2nd, Use this estimate as if it were an exact measurement of the state to solve the deterministic linear quadratic control problem.

4.1. Optimal State Feedback LQR

The optimal control problem consists of solving for the feedback gain matrix, K, such that the scalar objective function, J(u), is minimized if all state variables can be measured [12], [13].

$$J_r = \int_0^\infty \left(z^T Q z + u^T R u\right) dt \qquad \text{Eq. 24}$$

Where:

$$z = Mx, \quad Q = Q^T \ge 0 \quad \text{and} \quad R = R^T > 0$$

The optimal solution for any initial state is

$$u(t) = -K_r x(t) \qquad \text{Eq. 25}$$

Where:

$$K_r = R^{-1} B^T P \qquad \text{Eq. 26}$$

We shall write:

$$K_r = LQR(A, B, Q, R, N) \qquad \text{Eq. 27}$$

Where:

P=PT ≥ 0 is the unique positive-semi-definite solution of the Algebraic Riccati equation

$$A^T P + PA - PBR^{-1}B^T P + N^T QN = 0 \qquad \text{Eq. 28}$$

Conditions for achieving a stable LQ system are as follows:

R > 0, Q ≥ 0, (A, B) controllable (stabilizable).

Choosing the weight matrices Q and R usually involves some kind of trial and error, and they are usually chosen as diagonal matrices, so that for a system with n states and m controls we have n+m parameters to choose.

4.2. Kalman Filter

The Kalman filter has the structure of an ordinary state-estimator or observer, as

$$\dot{\hat{x}} = A\hat{x} + Bu + K_f(y - c\hat{x}) \qquad \text{Eq. 29}$$

We need to choose the matrices W, V, which appear in and obtain the Kalman-filter gain Kf. The optimal choice of K_f which minimizes:

$$E\left\{ [x - \hat{x}]^T [x - \hat{x}] \right\} \text{ is:}$$

Where

$$K_f = PC^T V^{-1}$$

P=PT ≥ 0is the unique positive-semi-definite solution of the algebraic Riccati equation

$$A^T P + PA - PBR^{-1}B^T P + N^T QN = 0$$

We shall write Kalman filter as:

$$K_f = LQE(A, B, C, W, V) \qquad \text{Eq. 30}$$

It is generally advisable to start with simple choices of W, V, inspect L4. Then adjust W, V accordingly, and so gradually improve L4. One of the simplest possible choices is W=BT*B, V=C*CT, where L4 is the loop transfer function and it is equal to:

$$L_4(s) = C(sI - A)^{-1} K_f.$$

In short, the optimal LQG compensator design process is the following [14], [15]:

Design an optimal regulator for a linear plant using full-state feedback.

Design a Kalman filter for the plant assuming a known control input, u(t), a measured output, y(t), and white noises, W & V,

Combine the separately designed optimal regulator and Kalman filter into an optimal compensator LQG.

LQG is more stabilizer than LQR is sensitive of fast damping and small setting time.

Figure 6, Block diagram of Combined LQR and Kalman Filter

Referee to Figure 6 we can write the LQG controller as:

$$K_{LQG}(s) \cong \begin{bmatrix} A - BK_r - K_f C & K_f \\ -K_r & 0 \end{bmatrix} \quad \text{Eq. 31}$$

$$K_{LQG}(s) = \begin{bmatrix} A - BR^{-1}B^T X - YC^T V^{-1} C & YC^T V^{-1} \\ -R^{-1}B^T X & 0 \end{bmatrix} \quad \text{Eq. 32}$$

5. Simulation Results And Discussions

A. Nominal Values Results

Figure 7 and Figure 8 presents the angular velocity of wind turbine (ωg) rotor and the output power at nominal value of wind speed 13m/s and pitch angle 450.

The LQG controller affects the system to reach the nominal value of ωg that equal to 4rad/s while LQR reach only 2.4 rad/s. The power output is proportional to the value of ωg and multiplied by the factor Cem. Also, the LQG controller is better than LQR.
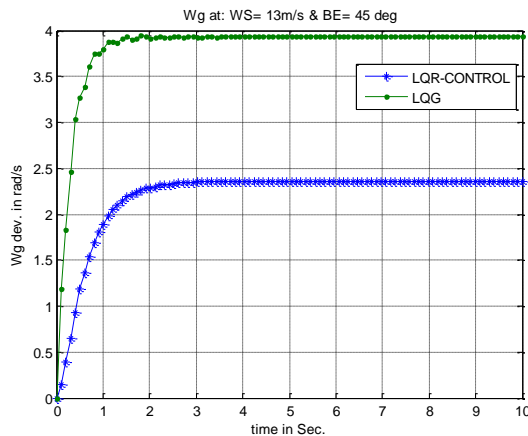
Figure 7, output rotor speed at nominal wind speed 13m/s and pitch angle 45^0
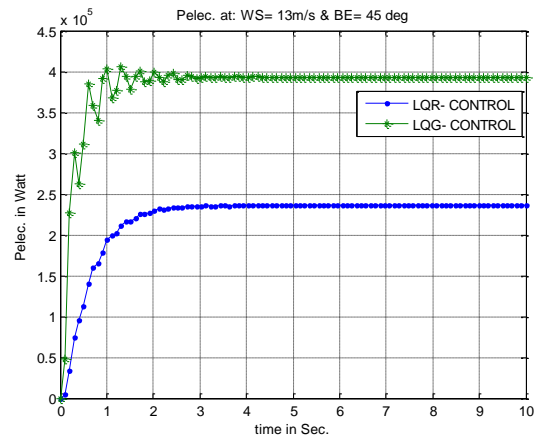
Figure 8, output power at nominal wind speed 13m/s and pitch angle 45^0

Figure 9 and Figure 10 presents the flaps of the blades "ζ"and movement of the tower "γt" at nominal value of wind speed 13m/s and pitch angle 450. The results show that both LQR and LQG success to damp the transient oscillation and the LQG settling time is shorter than LQR.
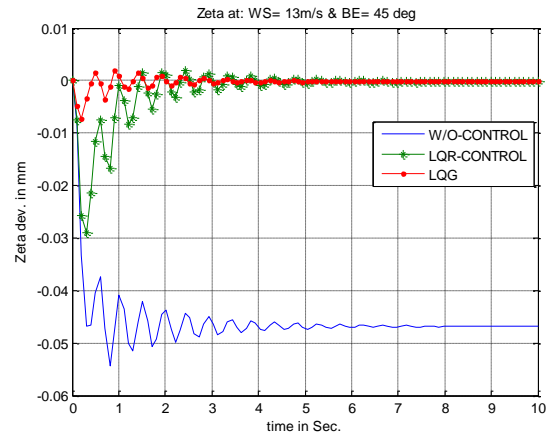
Figure 9, flaps of the blades at nominal wind speed 13m/s and pitch angle 45^0
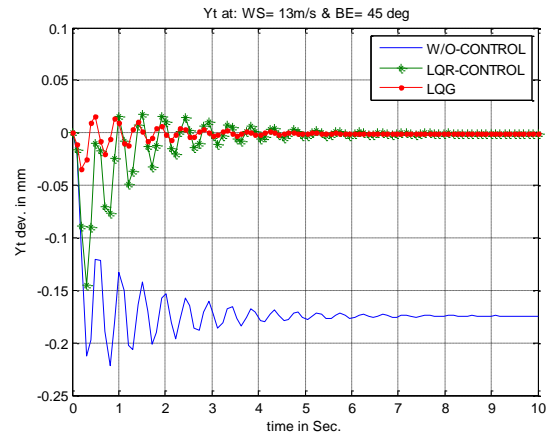
Figure 10, Movement of the tower at nominal wind speed 13m/s and pitch angle 45^0

B. Change of Wind Speed and Pitch Angle Values Results

Figure 11, Figure 12 and Figure 13 present the system response at 5m/s wind speed and 00 Pitch angle.
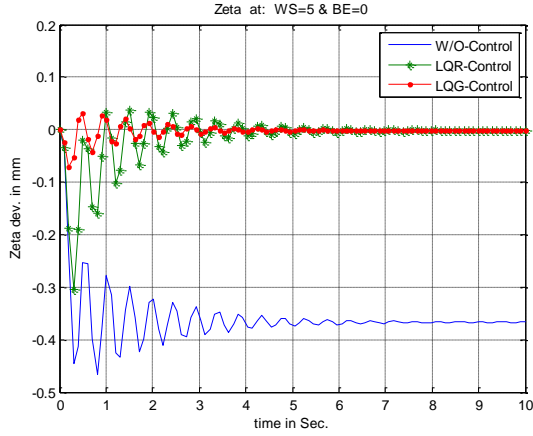

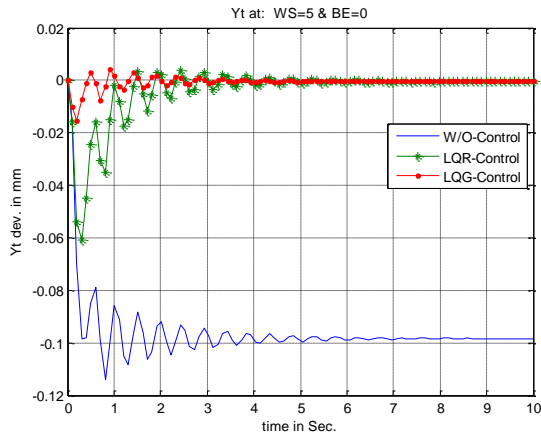Figure 11, flaps of the blades at wind speed 5m/s and pitch angle 0^0

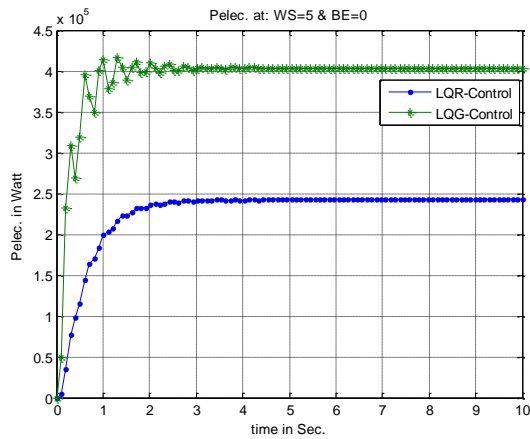Figure 12, Movement of the tower at wind speed 5m/s and pitch angle 0^0

Figure 13, output power at wind speed 5m/s and pitch angle 0^0

The controller acts to maintain the power at rated value while the wind speed is reduced by controlling the pitch angle to be minimum value. It should be noted also that the values of the flaps of the blades and movement of the tower is a little bit higher than the nominal value results because the minimum value of pitch angle that reflects maximum resistivity for the wind and hence higher resultant force. Figure 14, Figure 15 and Figure 16 show the system response at 5m/s wind speed and 300 Pitch angle. The output power is reduced from nominal value to be 350kW because of increasing the pitch angle to 300. Also the values of the flaps of the blades and movement of the tower is reduced compared to the previous case because the lower resistivity for the wind and hence lower resultant force. The most important factor that is the LQG controller success to damp the system oscillation to reach zero whatever the values are in nominal or offnominal conditions.
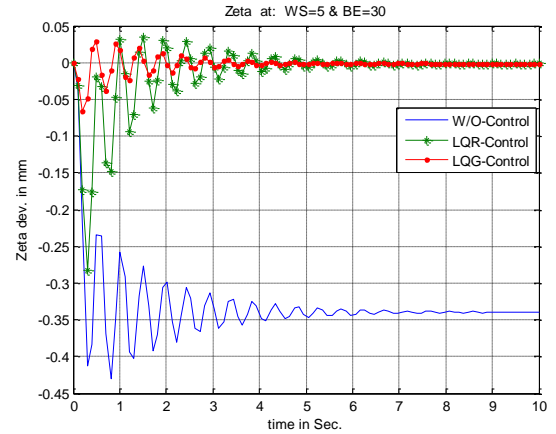

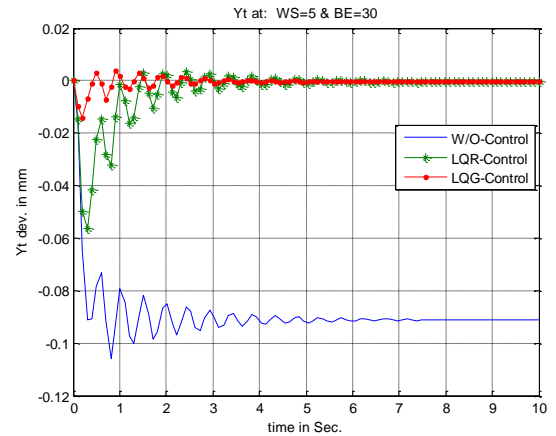Figure 14, flaps of the blades at wind speed 5m/s and pitch angle 30^0

Figure 15, Movement of the tower at wind speed 5m/s and pitch angle 30^0

The next figures from 17-22 illustrate the dynamics of the wind turbine system at different operating condition.
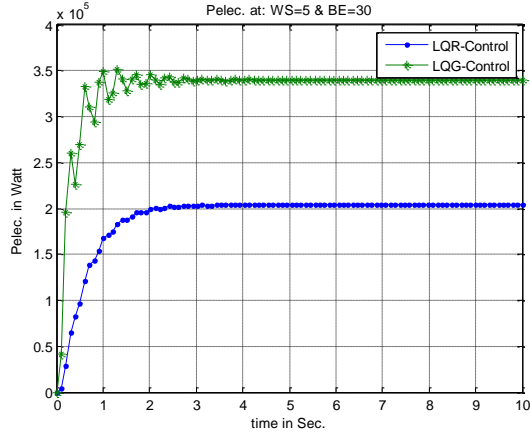

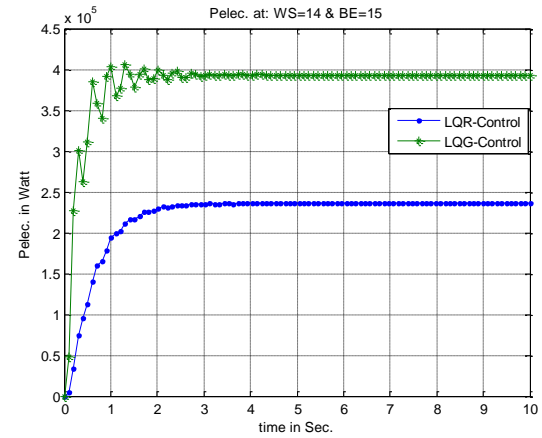Figure 16, output power at wind speed 5m/s and pitch angle 30^0

Figure 17, flaps of the blades at wind speed 14m/s and pitch angle 15^0

Figure 18, Movement of the tower at wind speed 14m/s and pitch angle 15^0

Figure 19, output power at wind speed 14m/s and pitch angle 15^0

In last three curves 23-25, the output power is zero watt because the wind speed exceeds the cut-out value 25m/s and controller acts to protect the system.

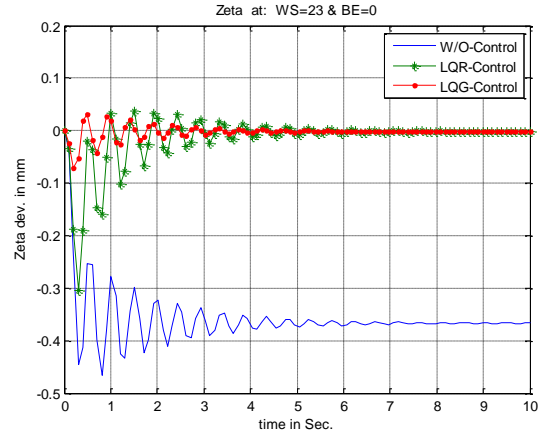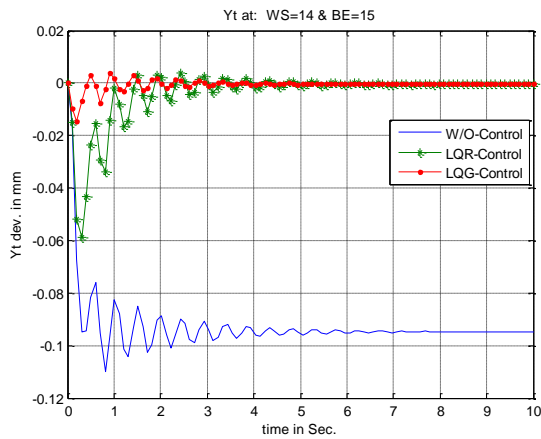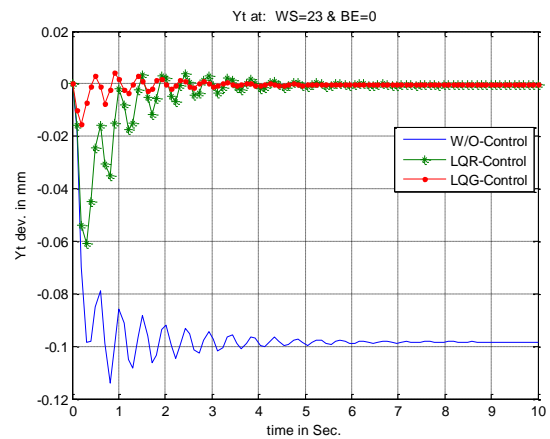Figure 20, flaps of the blades at wind speed 23m/s and pitch angle 0^0

Figure 21, Movement of the tower at wind speed 23m/s and pitch angle 0^0

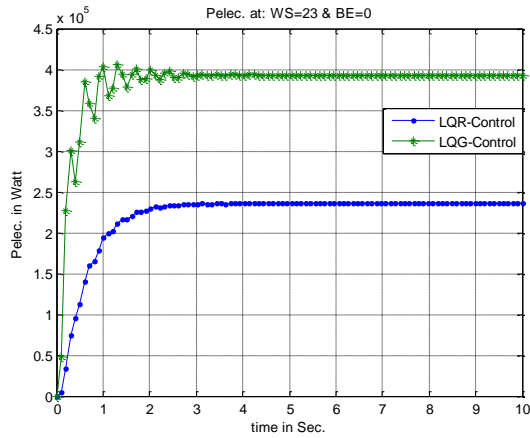Figure 22, output power at wind speed 23m/s and pitch angle 0^0

Figure 23, flaps of the blades at wind speed 32m/s and pitch angle 15^0

Figure 24, Movement of the tower at wind speed 32m/s and pitch angle 15^0

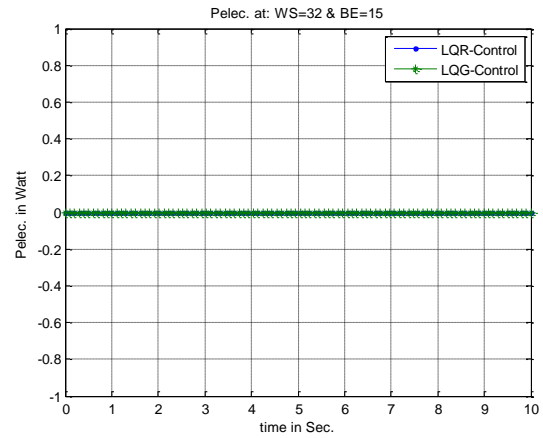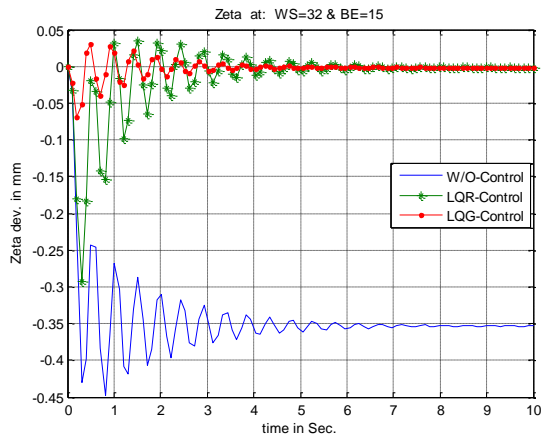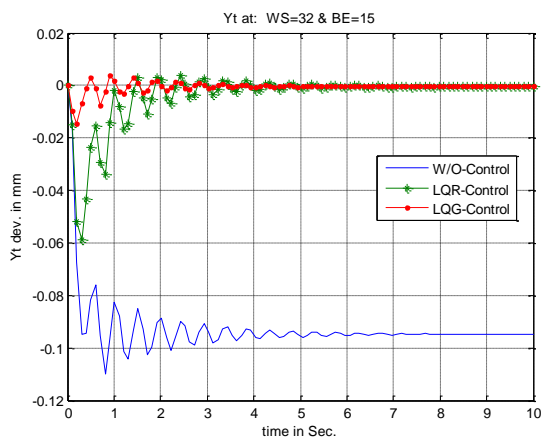Figure 25, output power at wind speed 32m/s and pitch angle 15^0

6. Conclusions

LQG compensated system is more robust with respect to measurement noise than the full state feedback system of the same LQR controller. The optimal control technique is presented for designing linear regulators for multi input plants that minimized a quadratic objective function.

Kalman filter is used as an optimal observer for multioutput plants in the presence of process and measurement noise. The results show that LQG controller is more robust than LQR in sense of small settling time, lower over/under shots and minimum steady state error.

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