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Comparison between a PI and LQ-regulation for a 2 MW wind turbine

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Abstract This paper deals with the design of controllers for pitch regulated, variable speed wind turbines where the controller is used primarily for controlling the (rotor and generator) speed and the electric power through a collective pitch angle and the generator torque. However, other key parameters such as loads on the drive train, wings and tower are in focus. The test turbine is a 2 MW turbine used as a bench mark example in the project "Aerodynamisk Integreret Vindmøllestyring" partly founded by the Danish Energy Authority under contract number 1363/02-0017.

One of the control strategies investigated here in this report, is based on a LQ (Linear time invariant system controlled to optimize a Quadratic cost function) strategy. This strategy is compared to a traditional PI strategy. As a control object a wind turbine is a nonlinear, stochastic object with several modes of operation. The nonlinearities calls for methods dealing with these. Gain scheduling is one method to solve these types of problems and the PI controller is equipped with such a property. The LQ strategy is (due to project time limitations) implemented as a fixed parameter controller designed to cope with the situation defined by a average wind speed equal to 15 m/sec.

The analysis and design of the LQ controller is performed in Matlab and the design is ported to a Pascal based platform and implemented in HAWC.

In general a LQ controller can be designed as a compromise between minimizing several effects including the performance parameters as well as the control effort parameters. In this report, however (and due to project time limitiation), only the produced electric power has been in focus.

In the comparison between the two strategies the produced electric power for the LQ controller has indeed been kept within a more narrow interval than for the PI controller. One of the costs is however a high pitch angular speed. In one of the LQ designs this costs (in terms of the pitch angular speed) is unrealistic high. In a redesign the maximum pitch angular speed is reduced, but still higher that in the case of the traditionally PI controller.

For reducing the pitch speed, further development in connection the LQ design, should be directed i a direction where the pitch speed directly is included in the design cost function. Also for reducing the loads, these should be included in the design model and given a weight in the control objective function.

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Contents

1 Introduction

The work presented in this report is part of the EFP project titled "Aerodynamisk Integreret Vindmøllestryring" partly founded by the Danish Energy Authority under contract number 1363/02-0017.

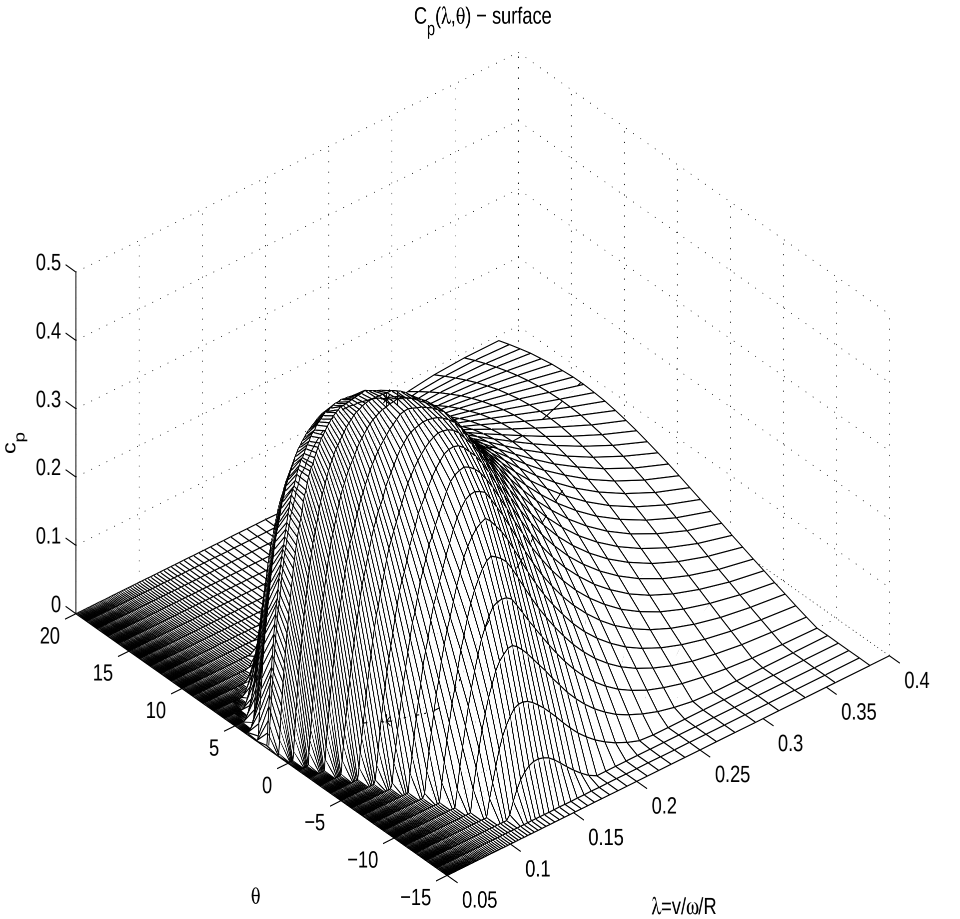

Figure 1. C_p as function of λ and θ

This paper deals with the design of controllers for pitch regulated, variable speed wind turbines where the controller is used primarily for controlling the (rotor and generator) speed and the electric power through a collective pitch angle and the generator torque. However, other key parameters such as loads on the drive train, wings and tower is in focus. The test turbine is a 2 MW turbine described in Appendix A in terms of HAWC input parameters.

The control strategies investigated here in this report, is based on the LQ (Linear time invariant system controlled to optimize a Quadratic cost function) strategies and compared to a traditional PI strategy. Traditional shall here be understood in an extended meaning (see e.g. Figure 20). It is a PI based controlled equipped with components and filters to cope with the characteristics of the wind turbine to be controlled. The design of a PI controller can be model based or other principles as well. The actual design can be found in [1]. The PI controller is based on gain

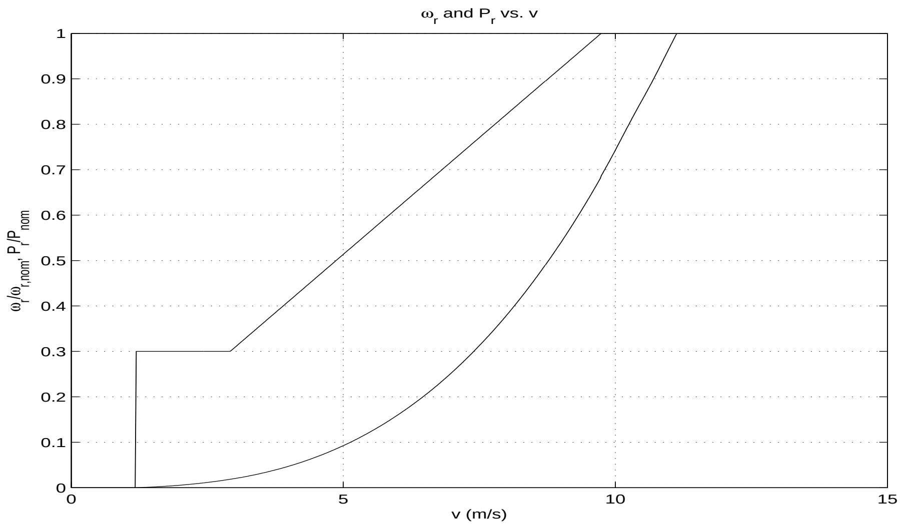

Figure 2. P_r *and* ω_r *as function of wind speed* v*.Notice the 5 modes of operation, the stop mode, the low mode, the mid mode, the high mode and the high mode.*

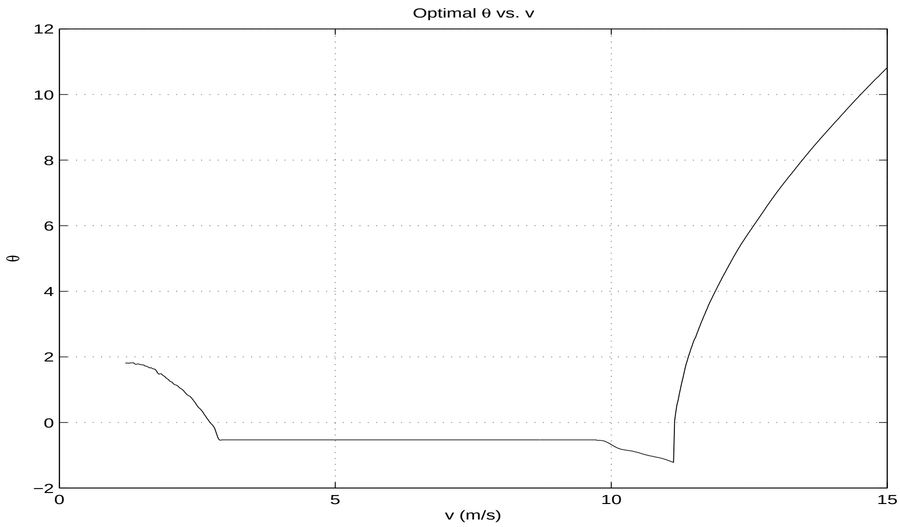

Figure 3. Stationary θ *as function of wind speed.*

scheduling, which is a type of (so called open loop) adaptive strategy enabling the controller to operate at different wind speed.

The design of the LQ controller is a model based design in which the controller can be designed to optimize a certain cost function reflecting the objective of the control. It can also be designed to obtain certain locations of poles describing the closed loop. In this report the first approach is applied. The analysis and design is performed in a Matlab based platform and the design is ported to a Pascal based platform and implemented in HAWC.

As a control object a wind turbine is a nonlinear, stochastic object with several modes of operation. Some of these are quite classical with one or two set points. Other mode of operations are untraditional. The nonlinearities calls for methods dealing with these. Gain scheduling is one method to solve these types of problems.

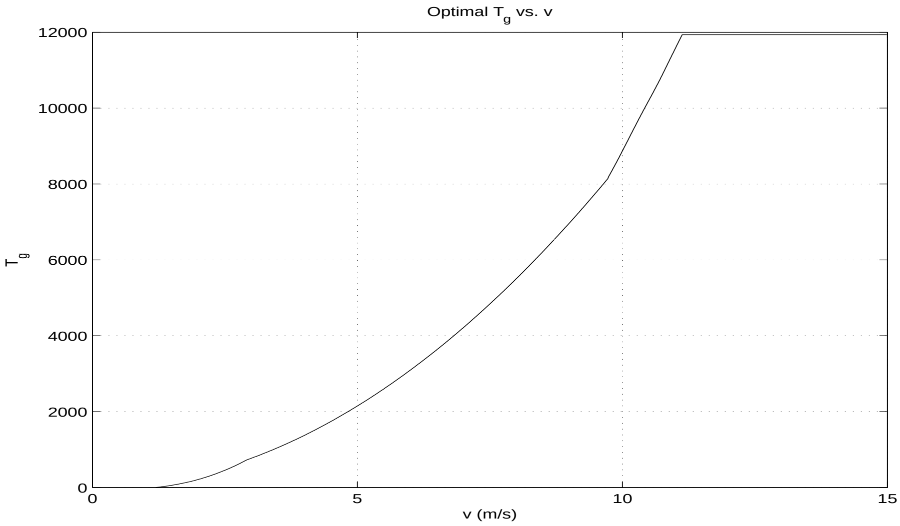

Figure 4. Stationary T_g as function of wind speed.

In the first section, section 2, a simplified LQ control strategy is outlined. It is based on the most simple model of a wind turbine and only includes the rotational degree of freedom. In this context several different mode of operation depending of the wind speed is outlined.

In the next section, section 3, a more realistic model including the flexibility in the drive train is investigated. The control task i however narrowed and is only focusing on the problem of controlling the wind turbine in a region with average wind speed equal to 15 m/sec. The resulting controller is fixed parameter controller

In section 4 the PI controller and its components is described in details. The core of the controller is basically a PI-regulator that adjust the pitch angles and generator on basis of measured rotational speed.

The comparison between the two strategies is described in section 5. To test the performance of the two controller a series of load calculations at 15 m/sec has been performed. The wind speed of 15 m/s is chosen since the LQ-regulator has only been tuned to this wind speed. To test the robustness some parameter variations with respect to turbulence seed, turbulence intensity and yaw error. A representative number of load sensors has been compared.

2 Basic model (WT_0)

In connection to control, design models are often of lower order and complexity than models used for process design and understanding. The most basic model of a wind turbine includes only the rotation. The rotor speed, ω_r, is given by

$$J_t\dot{\omega}_r = T_r - T_{gr}$$

where:

$$T_r = \frac{P_r}{\omega_r} \qquad P_r = \frac{1}{2}\rho\pi R^2 v^3 C_p(\theta, \lambda)$$

and

$$\lambda = \frac{v}{\omega_r R} \qquad T_{gr} = N_g T_g$$

The wind turbine can be controlled by means of the generator torque, T_g, and the pitch angle, θ, i.e. the control vector is:

$$u = \begin{bmatrix} \theta \\ T_g \end{bmatrix} \qquad x = \omega_r$$

and the state of the system is the rotational speed ω_r.

The C_p has a maximum at θ^* and λ^* (see Figure 1). This optimum can only be obtained in a region of operation (mid mode). Both the produced power and the speed is limited. Due to the generator the speed is limited both from above and below. For a fixed speed mode operation (high and low mode) the optimal θ is a function of λ. In the top mode both the speed and produced electric power is limited.

In this report we will only focus on a comparison in the top mode in which the produced power (P_e) and speed (ω_r) are controlled. The resulting controller:

$$u_t = \begin{bmatrix} \theta_o \\ Tg_o \end{bmatrix} - L \begin{bmatrix} \omega_r - \omega_{ro} \\ z \end{bmatrix}$$

where z is an integral state, i.e. obey

$$\dot{z} = \omega_{ro} - \omega_r$$

Notice, this in fact is a PI controller. The design of the controller, i.e. the determination of the gain L, can be carried out using a LQ design in which the cost function

$$J = \mathbf{E}\left\{ \int \varepsilon^T Q \varepsilon \ \ dt \right\}$$

is minimized. Here the (extended) error vector ε is given by

$$\varepsilon = \begin{bmatrix} NTg_o & 0 & 0 & N_g\omega_{ro} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \omega_r - \omega_{ro} \\ z \\ \theta - \theta_o \\ Tg - Tg_o \end{bmatrix} \tag{1}$$

and the weight matrix, Q, reflects the compromise between reducing the errors in P_e (first row), the integral of the speed error (second row) and the control activities in θ and T_g (third and fourth row).

In this design a linearized model has to be used. Let

$$x = \omega_r - \omega_{ro}, \qquad u = \begin{bmatrix} \theta - \theta_o \\ Tg - Tg_o \end{bmatrix}$$

The linearized model

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

is valid in a region around the point of linearization (see Figure 5 and 6). In the comparison shown later the point of linearization is for a wind speed equals 15 m/s.

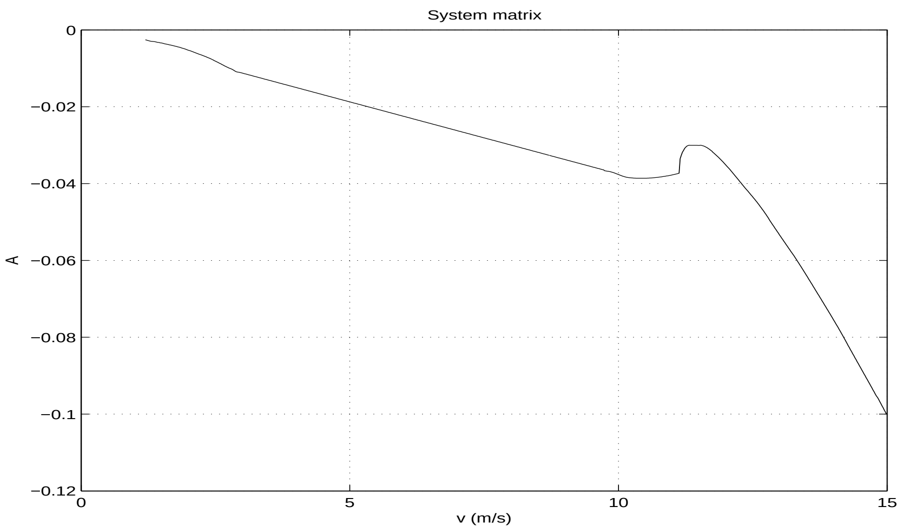

Figure 5. The A matrix from the linearized model as function of wind speed.

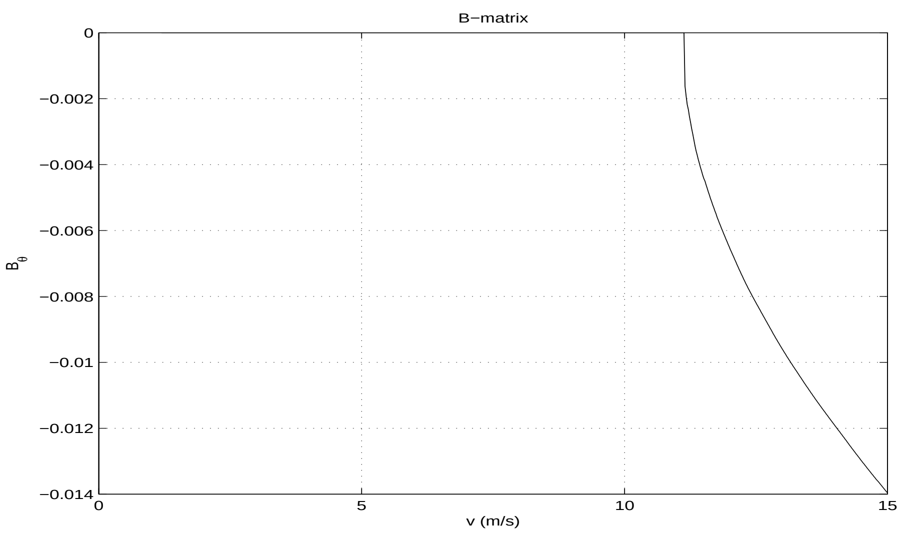

Figure 6. The B vector from the linearized model as function of wind speed.

3 Flexibility in drive train (WT_1)

If the flexibility in the drive train is included then the model is described by the following tree differential equations:

$$J_r \dot{\omega}_r = T_r - T_{gr}$$
$$J_g \dot{\omega}_g = T_{rg} - T_g$$
$$\dot{\delta} = \omega_r - \frac{1}{N_g}\omega_g$$

where as previous

$$T_r = \frac{P_r}{\omega_r} \qquad P_r = \frac{1}{2}\rho\pi R^2 v^3 C_p(\theta, \lambda)$$

and

$$\lambda = \frac{v}{\omega_r R} \quad T_{rg} = \frac{1}{N_g} T_{gr} \quad T_{gr} = K_s \delta + C_s \dot{\delta}$$

In this situation the state vector is augmented to

$$x = \begin{bmatrix} \tilde{\omega}_r \\ \tilde{\omega}_g \\ \tilde{\delta} \end{bmatrix} \qquad u = \begin{bmatrix} \tilde{\theta} \\ \tilde{T}_g \end{bmatrix}$$

as well as the system matrices A and B (which are determined for $v_o = 15\ m/s$). The linearized description is

$$\dot{x} = Ax + Bu + B_v v$$

where the signals are deviation away from stationary values.

Besides the dynamics of the wind turbine a model of the wind speed variations is included. From the simulation data obtained from HAWC, a model

$$\dot{x}_w = \begin{bmatrix} -\frac{1}{\tau_1} & 1 & 0 \\ 0 & -\frac{1}{\tau_2} & 1 \\ 0 & 0 & -\frac{1}{\tau_2} \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} e_t$$
$$v = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} x_w$$

can be obtained. The wind variations are modelled as driven by white noise e_t. The time constants are estimated to be 3.1 sec, 0.6 sec and 0.02 sec. This model is of course only valid in a region around $v_o = 15\ m/sec$.

The total system can then be described by:

$$\dot{\bar{x}} = \begin{bmatrix} A & B_v C_w & 0 \\ 0 & A_w & 0 \\ -1 & 0 & 0 \end{bmatrix} \bar{x} + \begin{bmatrix} B \\ 0 \\ 0 \end{bmatrix} u$$

Here the augmented state vector is

$$\bar{x} = \begin{bmatrix} x \\ x_w \\ z \end{bmatrix}$$

and the design of the controller

$$u = u_0 - L\bar{x}$$

is based on the cost functions (1) in which

$$\varepsilon = \begin{bmatrix} 0 & Tg_o & 0 & 0 & 0 & 0 & 0 & 0 & \omega_{go} \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \tilde{\omega}_r \\ \tilde{\omega}_g \\ \tilde{\delta} \\ x_{w1} \\ x_{w2} \\ x_{w3} \\ z \\ \theta \\ Tg \end{bmatrix} \tag{2}$$

Notice, the first row in the extended error signal reflects the focus on P_e, the second on the integral state, the third (which has zeros weight) reflects the deformation of the drive train and the fourth row reflects the control activity in θ.

With a weight matrix Q equals

$$Q = vv \qquad v = diag(\begin{bmatrix} \frac{1}{P_0} & \frac{500}{P_0} & 0 & \frac{5e-5}{\theta_0} \end{bmatrix})$$

the resulting gain matrix is:

```
L =
   -1.3036   -0.0019    0.0200   -0.0305   -0.0105   -0.0002    0.9301
   -0.0001   71.2415    0.0000   -0.0000   -0.0000   -0.0000    0.0001
```

Let us denote this design as WT_{1a}. The gain (i.e. the `2,2` element in L) from the error on ω_g to the generator torque, T_g, can be compared to the non linear strategy

$$T_g = \frac{P_0}{\omega_g} \simeq -71.24(\omega_g - \omega_0)$$

The control design show above focus to a large degree on keeping the produced electric power P_e constant. The flexibility in the drive train has not been given any attention. This can easily be changed by given this error a weight different from zero. If other effect are considered to be minimized then the extended error in (2) has to include this effect (i.e. the matrix has to be extended with additional row(s) and some elements in v. The results are illustrated in Figure 8-17

The focus in the design og WT_{1a} is primarily on P_e which results in a quite active control especially seen in the variation in θ (see Figure 8 and Table 3.

In order to reduce the large control activity in θ the weight has changed to:

$$Q = vv \qquad v = diag(\begin{bmatrix} \frac{1}{P_0} & \frac{500}{P_0} & 0 & \frac{5e-4}{\theta_0} \end{bmatrix})$$

the resulting controller (denoted as WT_{1b}) has a gain matrix which is:

```
L =
  -0.3813   -0.0006   -0.0142   -0.0205   -0.0106   -0.0002    0.0940
  -0.0041   71.2415   -0.0002   -0.0002   -0.0001   -0.0000    0.0010
```

Besides that the controller has been equipped with a device for limiting the pitch rate. In the actual case the slev rate has been set to 6 deg/sec. The results are illustrated in Figure 18-19

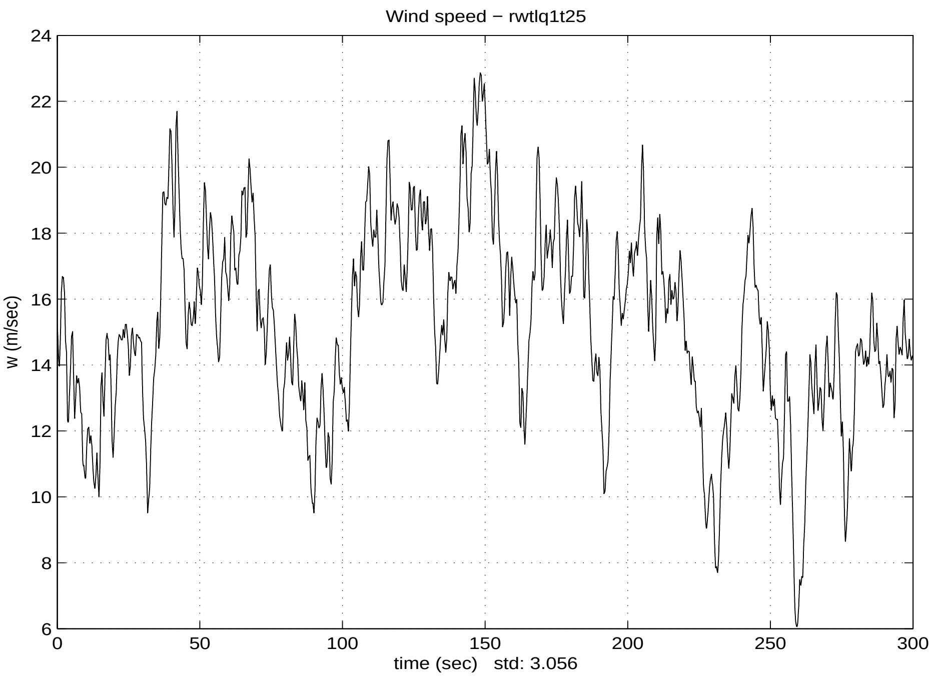

Figure 7. Wind speed variation

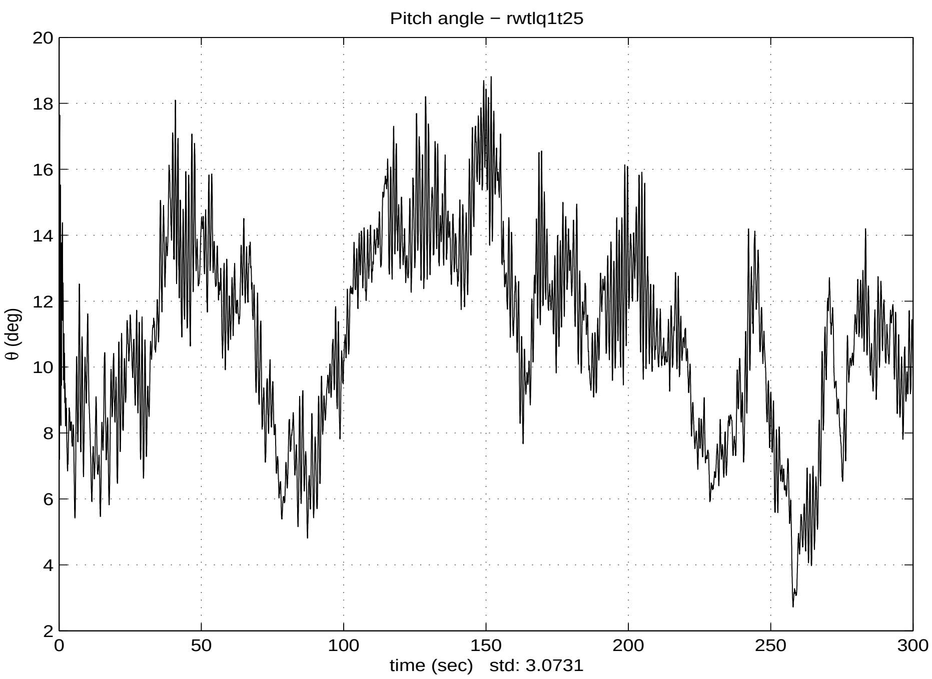

Figure 8. Variation in θ for the WT_{1a} design.

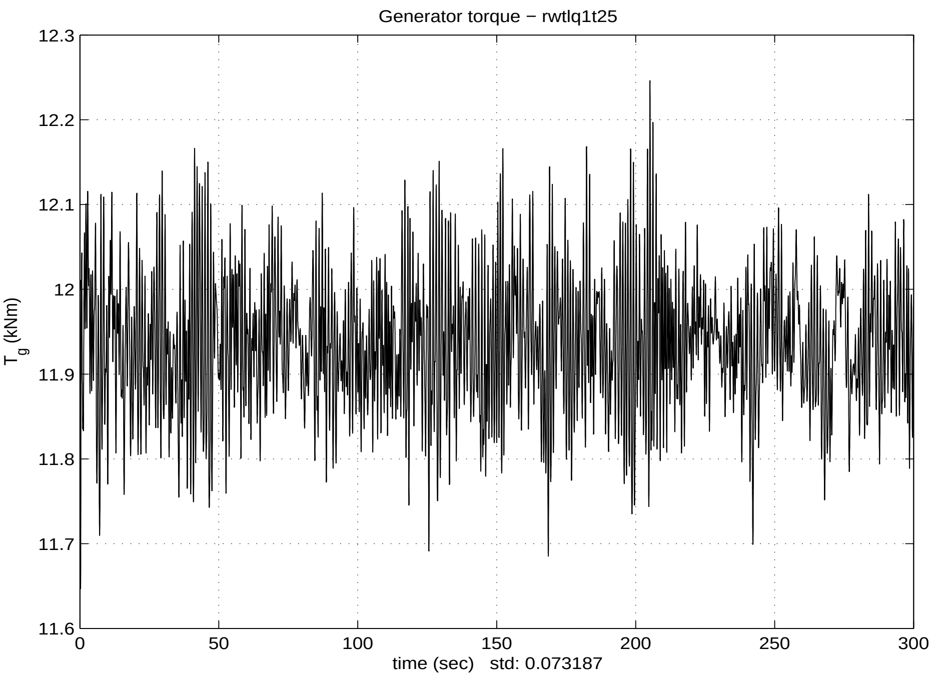

Figure 9. Variation in T_g for the WT_{1a} design.

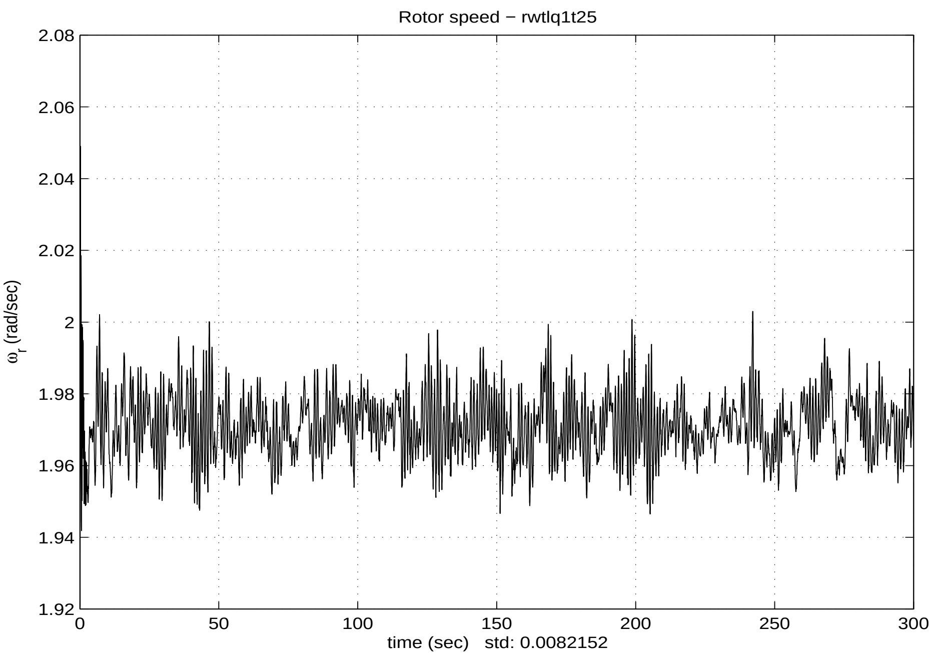

Figure 10. Variation in ω_r for the WT_1a design.

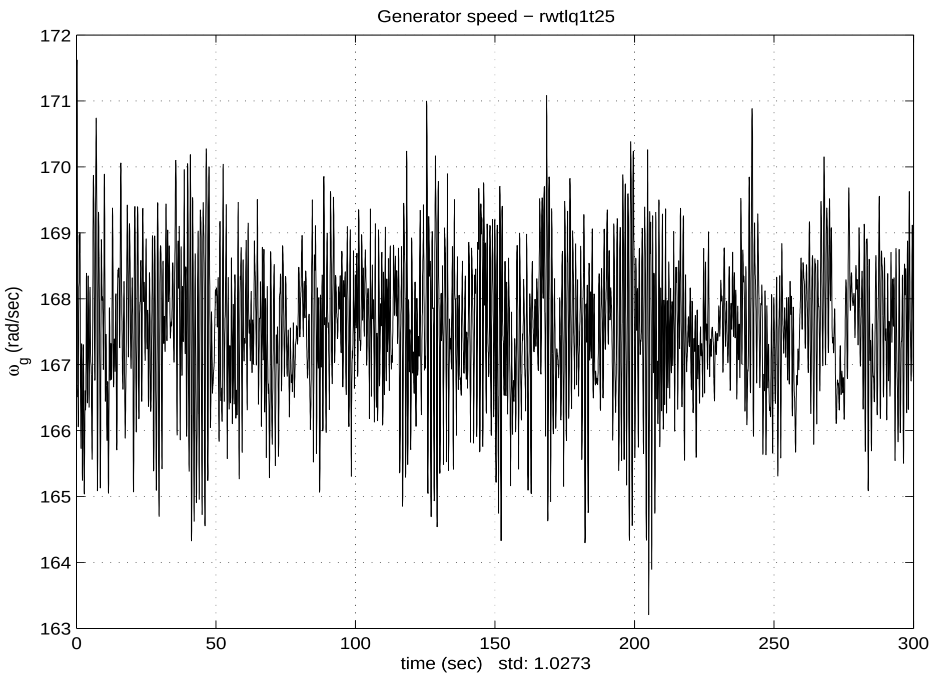

Figure 11. Variation in ω_g for the WT_1a design.

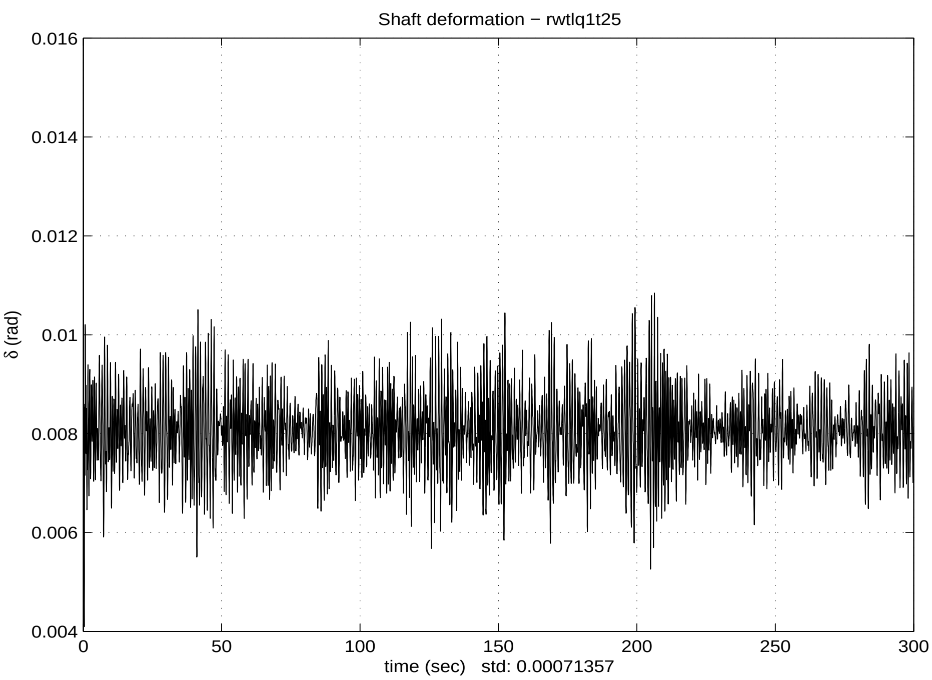

Figure 12. Variation in δ for the WT_1a design.

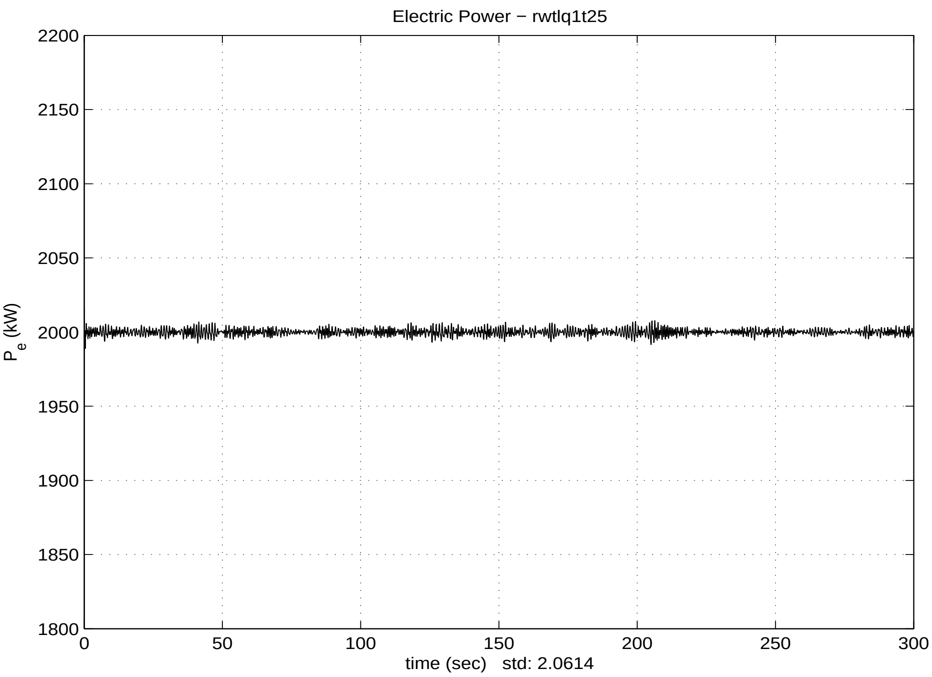

Figure 13. Variation in P_e for the WT_1a design.

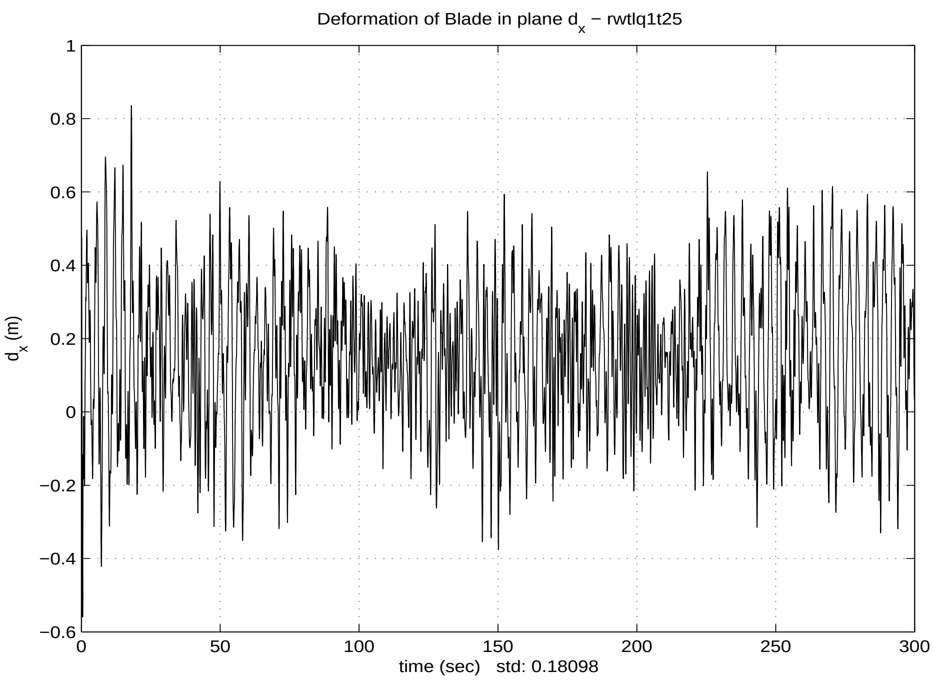

Figure 14. Deformation of blade in plane for the WT_{1a} design.

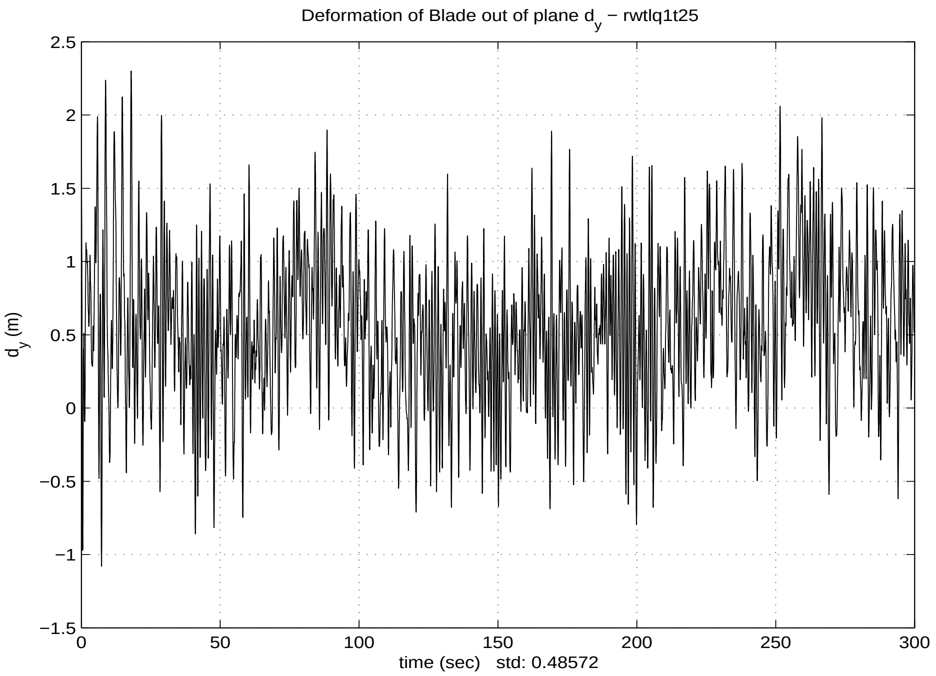

Figure 15. Deformation of blade out of plane for the WT_{1a} design.

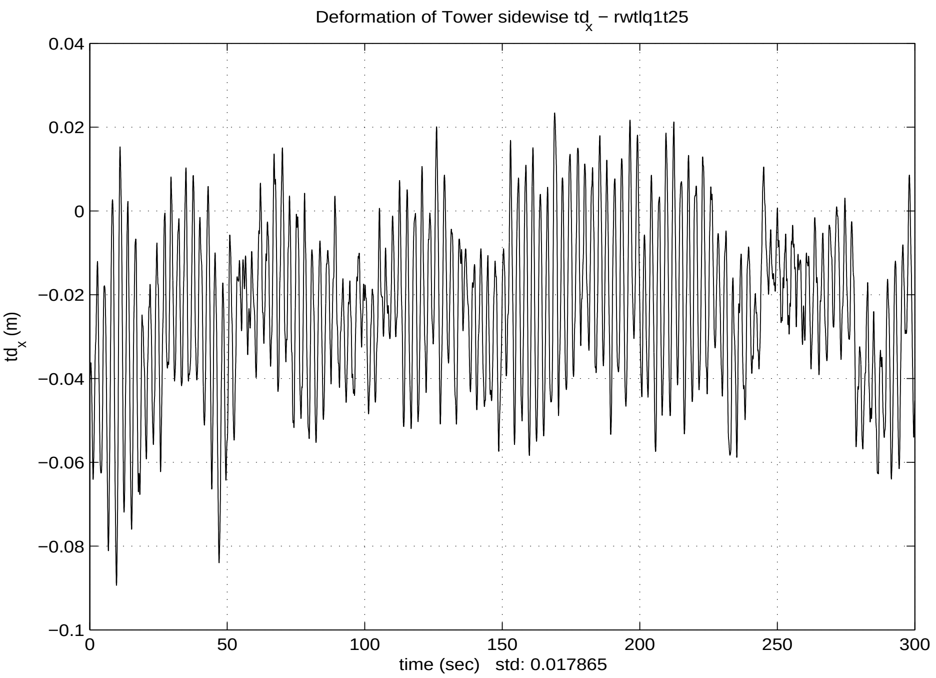

Figure 16. Deformation of tower sidewise for the WT_{1a} design.

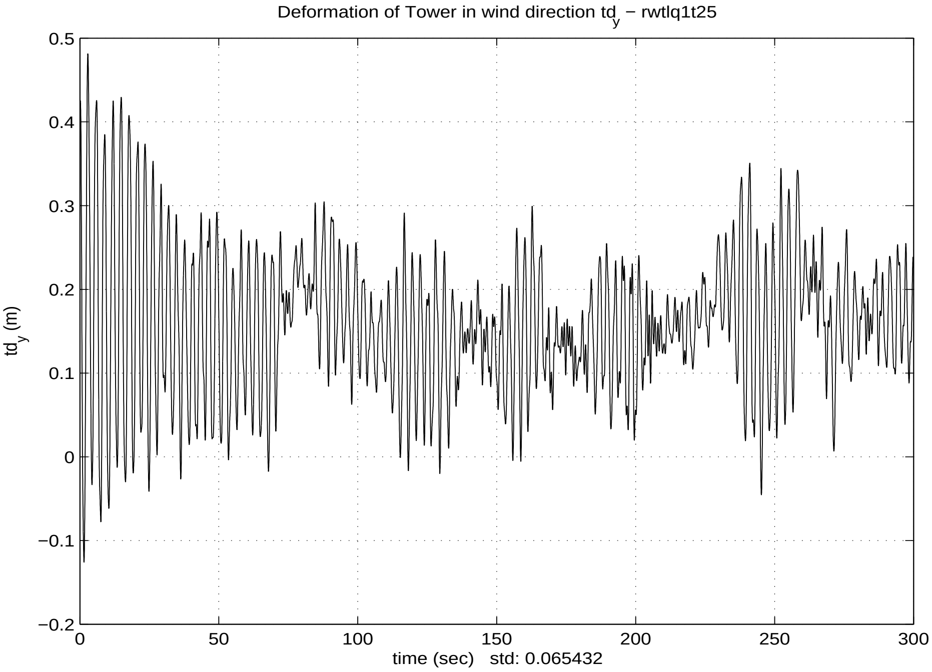

Figure 17. Deformation of tower in the wind direction for the WT_{1a} design.

			PI	WT_{1a}	WT_{1b}
std.	θ	(deg)	2.9946	3.0731	3.0383
std.	$\dot{\theta}$	(deg/sec)	0.7723	5.6336	1.8372
	$max(\|\dot{\theta}\|)$	(deg/sec)	2.5800	24.7720	6.0000
std.	T_g	KNm	0.2277	0.0732	0.1905
std.	ω_r	(rad/sec)	0.0369	0.0082	0.0304
std.	ω_g	(rad/sec)	3.1667	1.0273	2.6743
std.	δ	(rad)	0.0005	0.0007	0.0007
std.	P_e	(kW)	10.9046	2.0614	2.1270
std.	d_x	(m)	0.1838	0.1810	0.1721
std.	d_y	(m)	0.4771	0.4857	0.4370
std.	t_x	(m)	0.0289	0.0179	0.0219
std.	t_y	(m)	0.0505	0.0654	0.0484

Table 1. Standard deviation (over the last $3/4$ of the series) for key signals. The third line contains however maximum values. The standard deviation is also shown for the defomation of the blades in the plane (d_x) and out of plane (d_y) and deformation of the tower sidewise (t_x) and in the wind direction (t_y).

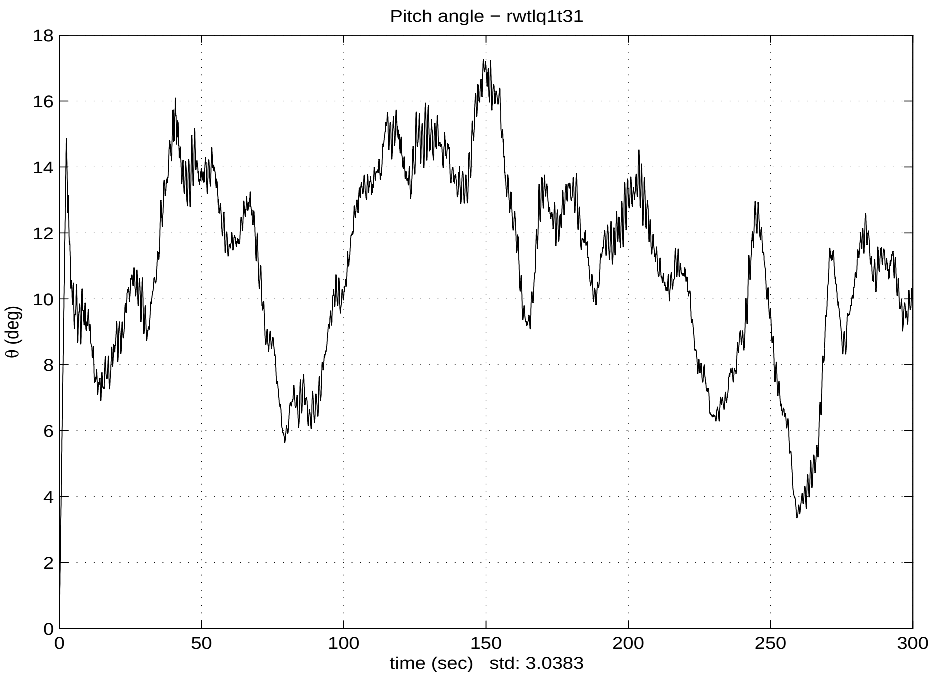

Figure 18. Variation in θ for the WT_{1b} design.

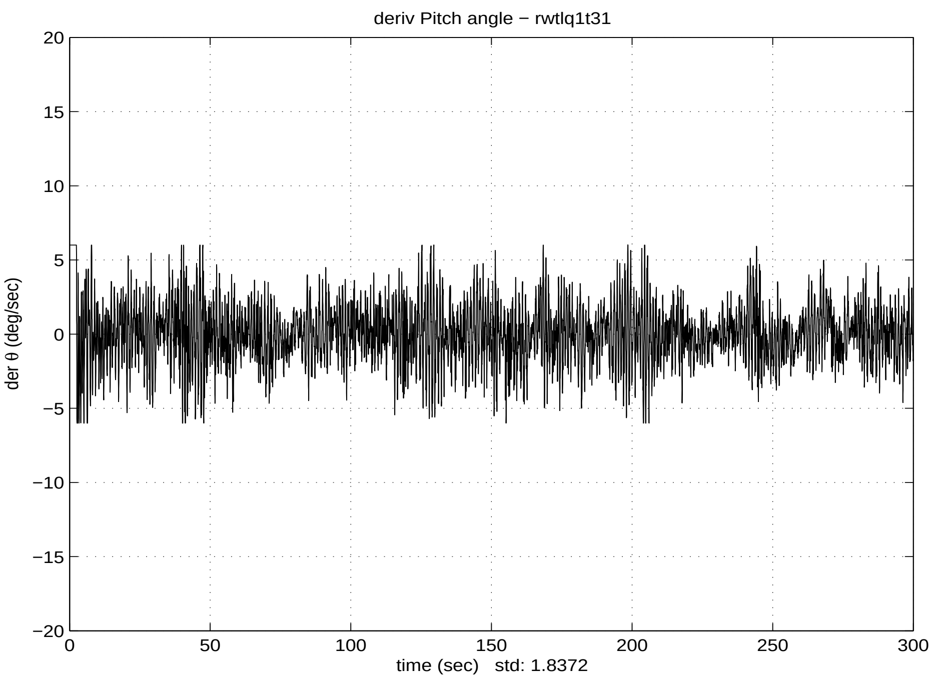

Figure 19. Variation in $\dot{\theta}$ for the WT_{1b} design.

4 Standard PI Control

The turbine controller is basically a PI-regulator that adjust the pitch angles and generator on basis of measured rotational speed. The controller diagram can be seen in Figure 20. In this Figure different parts of the regulation can be seen. In basic the regulator consist of a power controller and a pitch controller. The power controller is adjusting the reference power of the generator based on a table look up (2) with input of the rotor speed. This table has been created on basis on quasi static power calculations. In this table the overall characteristics of the turbine control regarding variable speed, close to rated power operation and power limitation operation are given.

In the power regulation it is important to avoid too much input of especially the free-free drive train vibration. If not taken into consideration this vibration could very well be amplified through the power control creating very high torque oscillations. Therefore a special band stop filter (1) has been applied to filter out this vibration frequency. For the current turbine the filter is implemented as a 2^{nd} order Butterworth filter with center frequency at the free-free eigenfrequency.

To limit the aerodynamic power to the turbine a PI-regulator (3) is applied that adjusts the reference pitch angle based on the error between rotational speed and rated speed. The PI-regulator has a minimum setting of zero deg, which makes the turbine operate with zero pitch angle at low wind speeds. The proportional and integral constants Kp and Ki are set to respectively 1.33 and 0.58, which corresponds to an eigenfrequency of 0.1 Hz and a damping ratio of 0.6.

A special gain scheduling (5) to adjust for increased effect of pitch variations at high wind speed compared to lower speeds is applied. This gain scheduling handles the linear increasing effect of $\frac{\partial P}{\partial \theta}$ with increasing wind speed and pitch angle. This gain function is implemented following the expression $gain(\theta) = \frac{1}{1+\frac{\theta}{KK}}$ where the value KK is the pitch angle where the gain function shall be 0.5.

To increase the gain when large rotor speed error occurs another gain function (4) is applied to the PI-regulator. This gain function is simply 1.0 when the rotor speed is within 10% of rated speed and 2.0 when the error exceeds 10%. This very simple gain function seems to limit large variations of the rotational speed at high wind speed.

The pitch servo is modeled as a 1^{st} order system with a time constant of 0.2 sec. The maximum speed of the pitch movement is set to 20 deg/sec.

The generator is modeled as a 1^{st} order system with a time constant of 0.1 sec, which means that the reference torque demand from the regulator has a little phase shift before executed. A drive train filter has been included in the generator model to decrease response at the free-free drive train frequency. This filter makes sure that any torque demand at the free-free frequency is counter phased before entering the structural model.

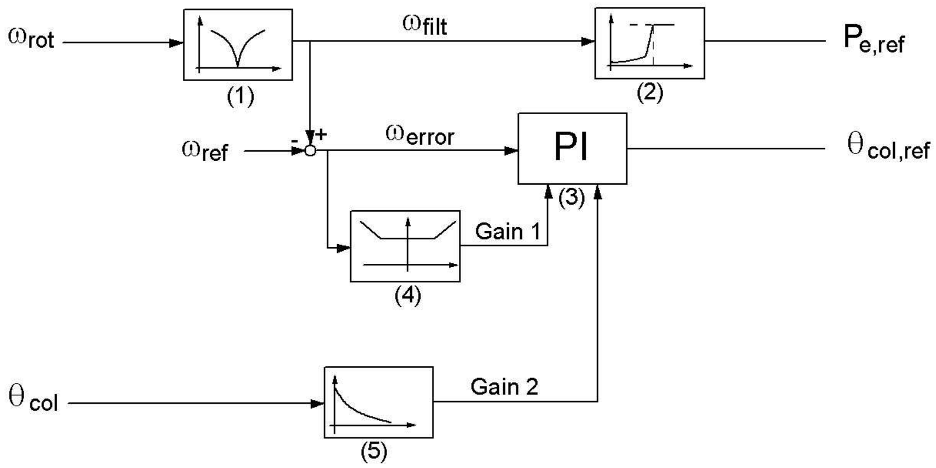

Figure 20. Control diagram of regulator. Input is measured rotational speed and output is reference electrical power to generator and reference collective pitch angle to pitch servo.

5 Comparison between $\mathbf{WT}_{1a}$ and PI

To test the performance of the two controllers against each other a series of load calculation at 15 m/s has been performed. The wind speed of 15 m/s is chosen since the LQ-regulator has only been tuned to this wind speed. To test the robustness some parameter variations with respect to turbulence seed, turbulence intensity and yaw error. A representative number of load sensors has been compared.

I general the LQ-regulator is adjusted to very fast pitch angle variations and reaches pitch angle speed up til 60 $°/s$, which is way more than achievable in praxis. This is however a result of the optimization procedure of the regulator where no limit in the pitch angle speed has been included. In this optimization the main effort has been to keep the fluctuations in power and rotational speed small. These two parameters has indeed been kept within a more narrow interval than for the PI-regulation, but on the cost of pitch angle speed. The turbine loads for the two concepts are in general very similar, but for the tower loads a increase in loads has been seen for the LQ-regulator.

In the calculations performed with the PI-regulator a first order filter with a time constant of 0.2 s has been used to represent the dynamic behavior of the pitch servo, whereas no dynamics has been included in the LQ-regulator simulations.

5.1 Effect of different wind track realizations

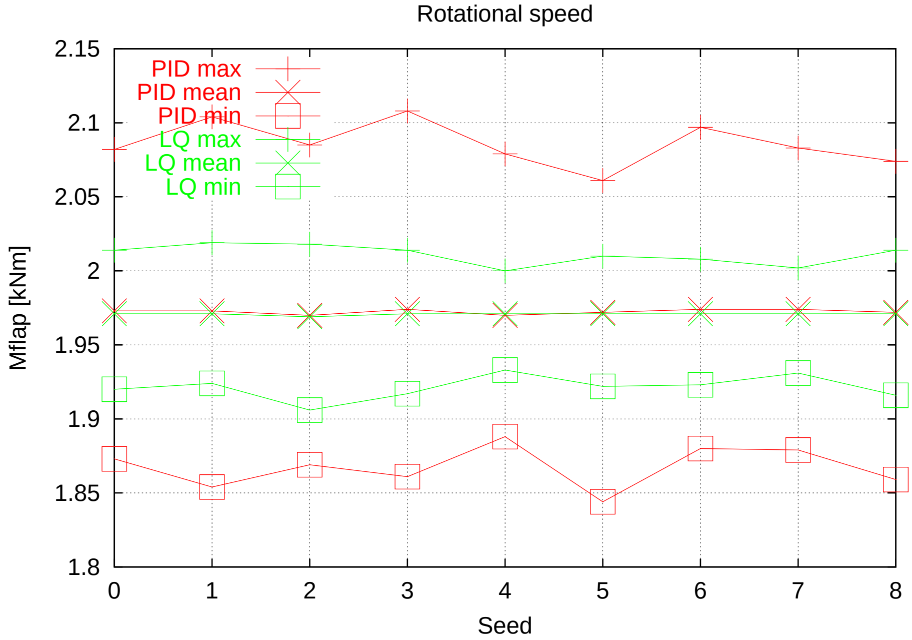

Figure 21. Comparison of rotational speed..

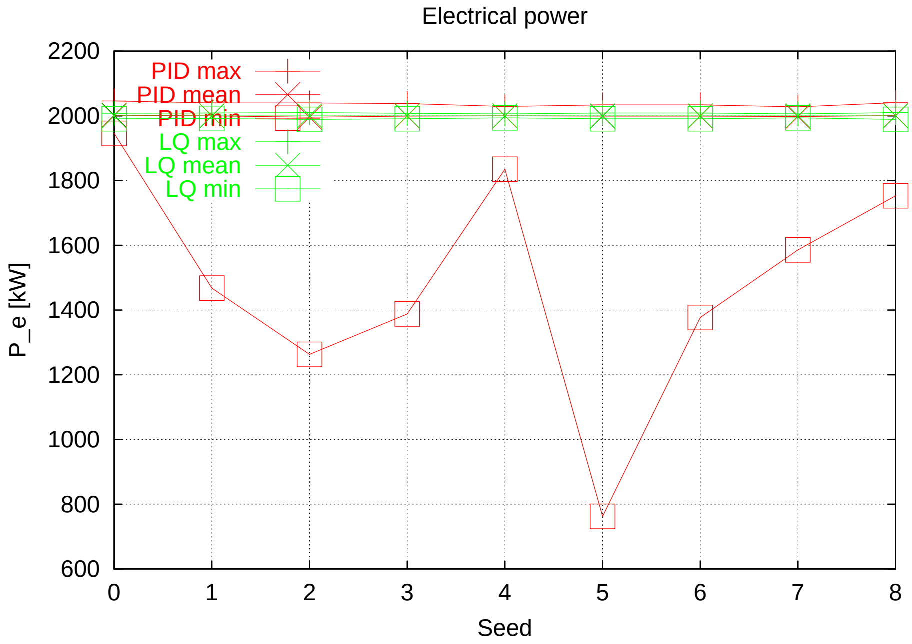

Figure 22. Comparison of electrical power.

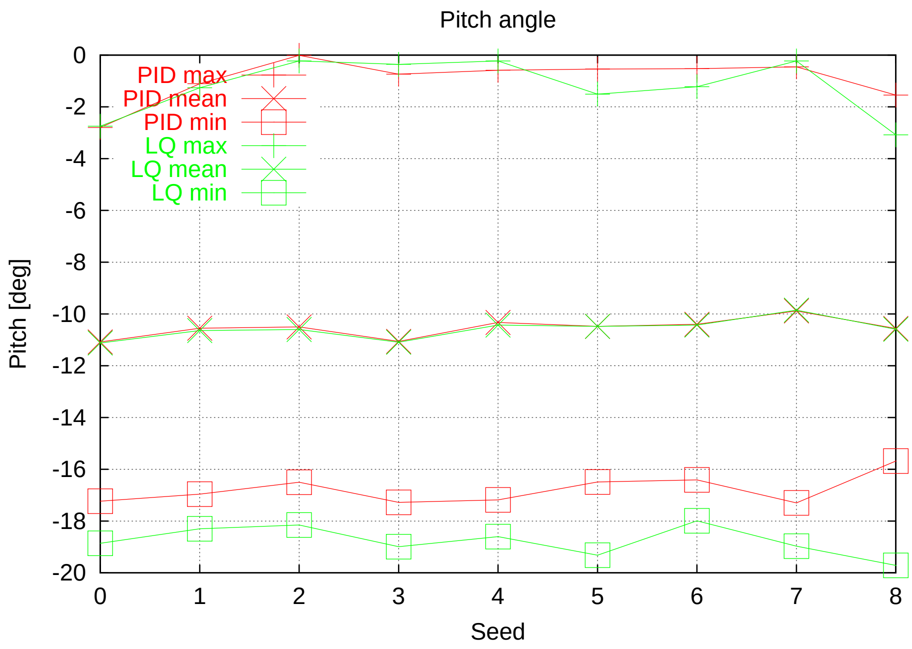

Figure 23. Comparison of pitch angle.

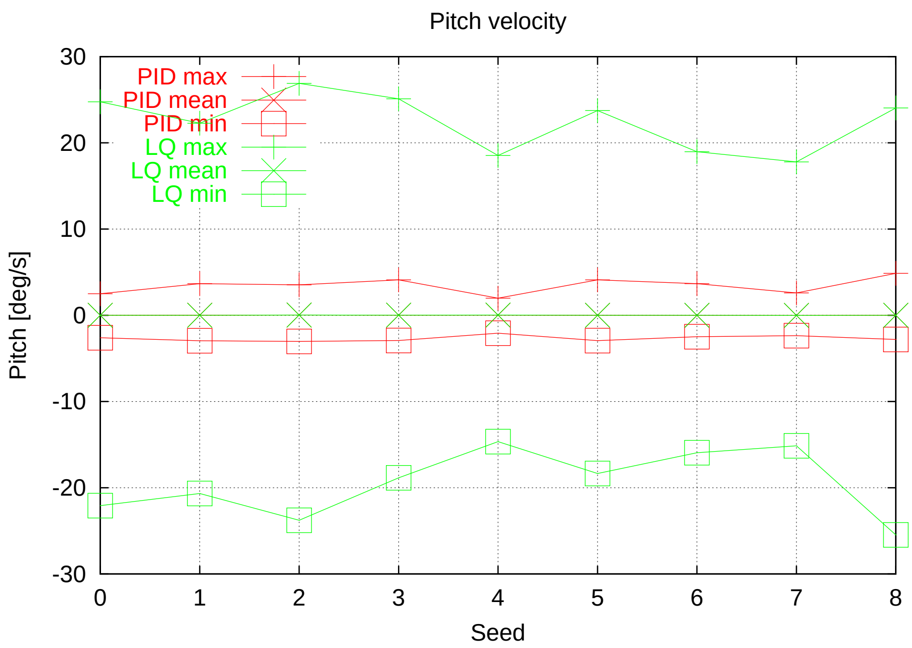

Figure 24. Comparison of pitch angle velocity.

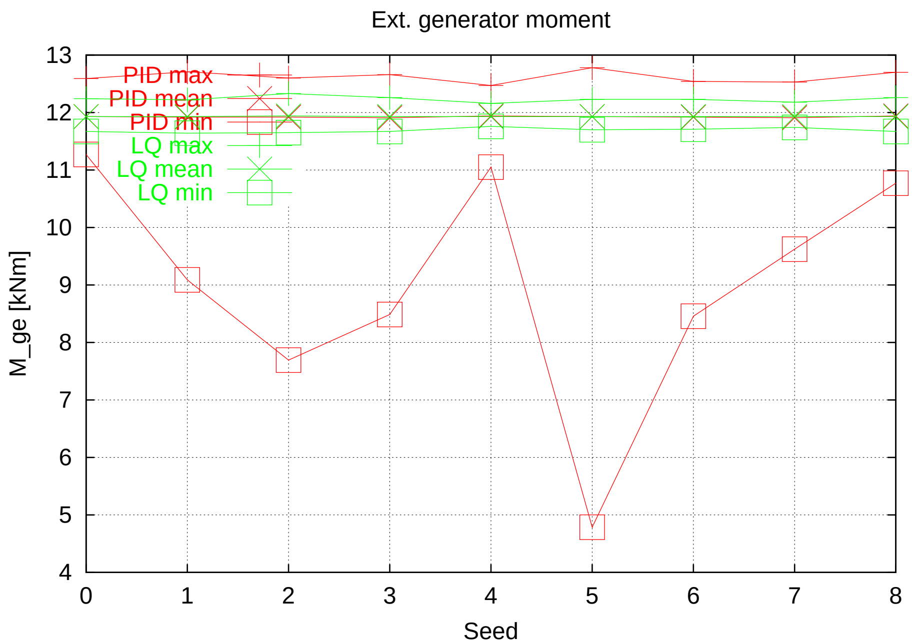

Figure 25. Comparison of generator torque.

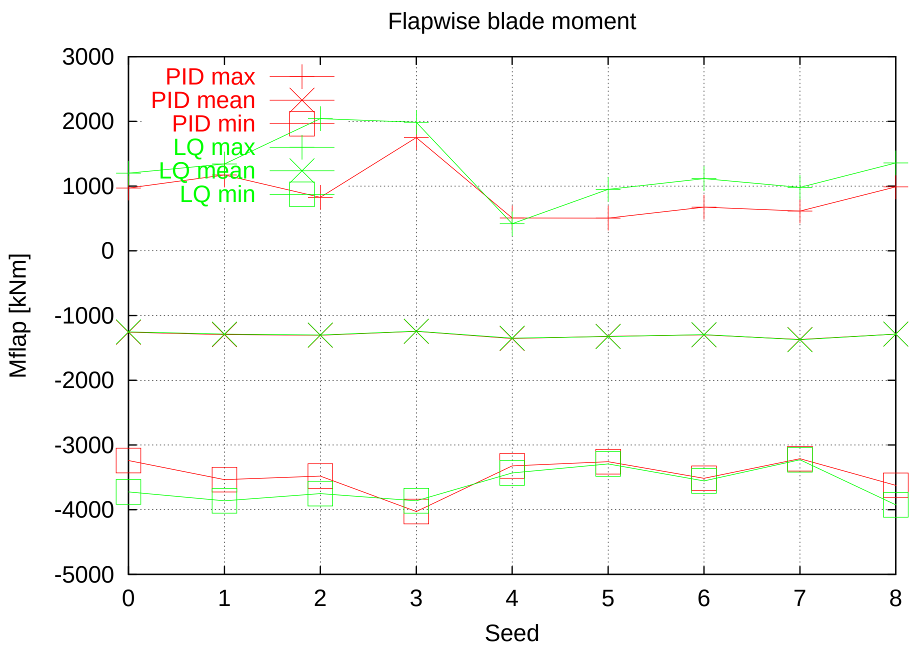

Figure 26. Comparison of flapwise blade root bending moment.

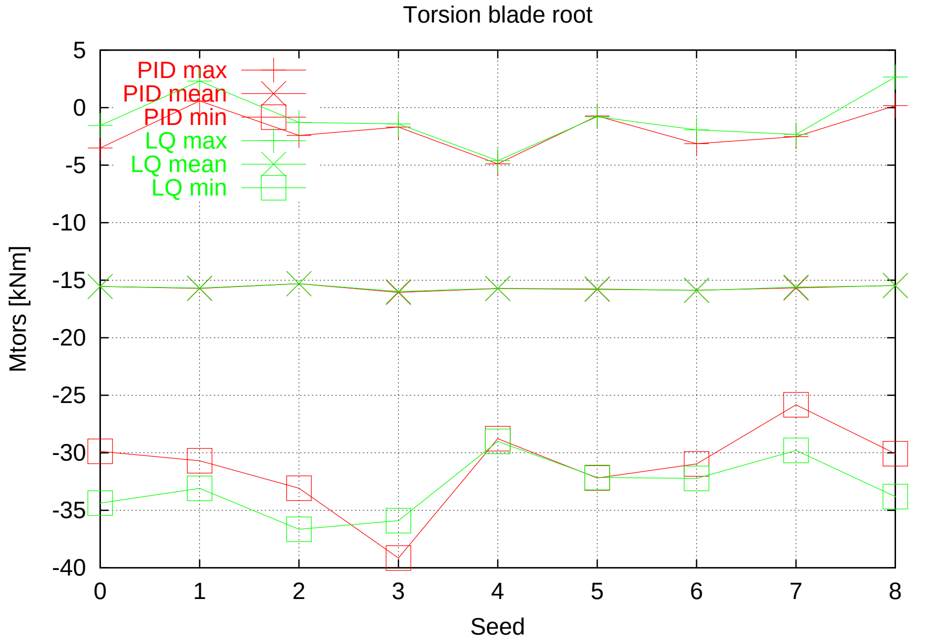

Figure 27. Comparison of pitch moment in blade root. No effects of acceleration forces include.

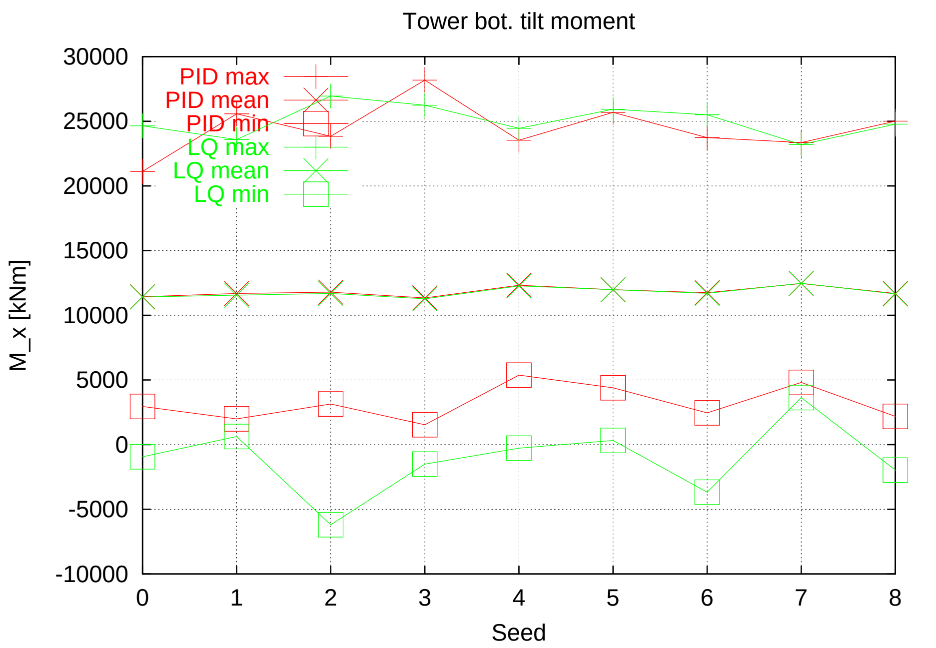

Figure 28. Comparison of tower bottom tilt moment.

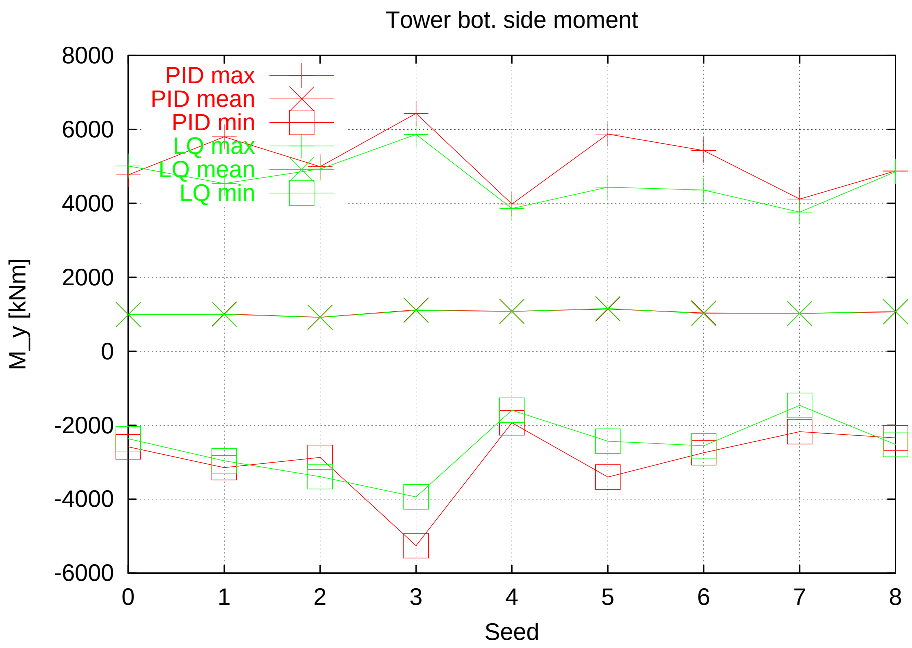

Figure 29. Comparison of tower bottom side moment.

5.2 Effect of different turbulence intensity

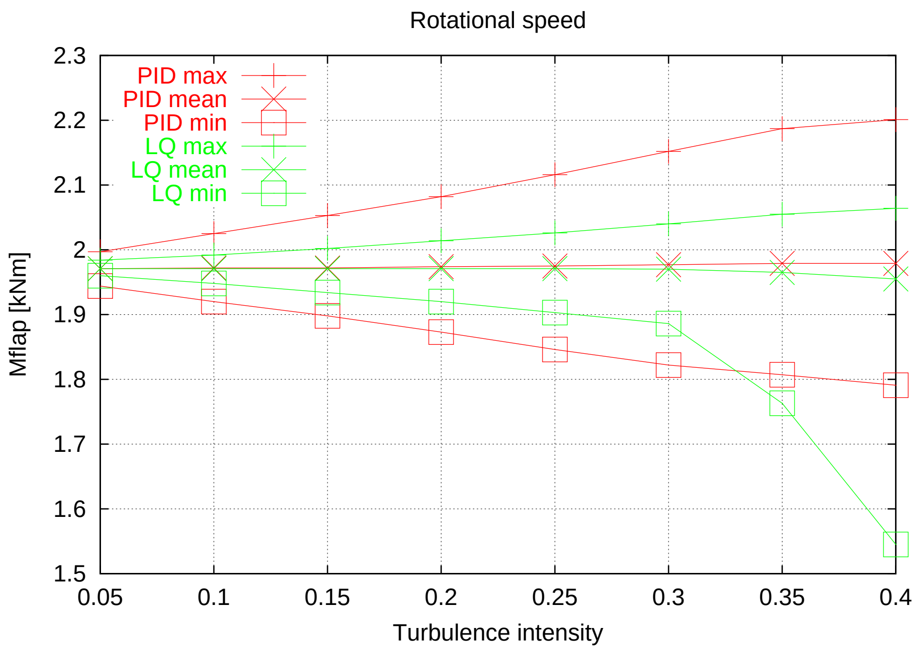

Figure 30. Comparison of rotational speed..

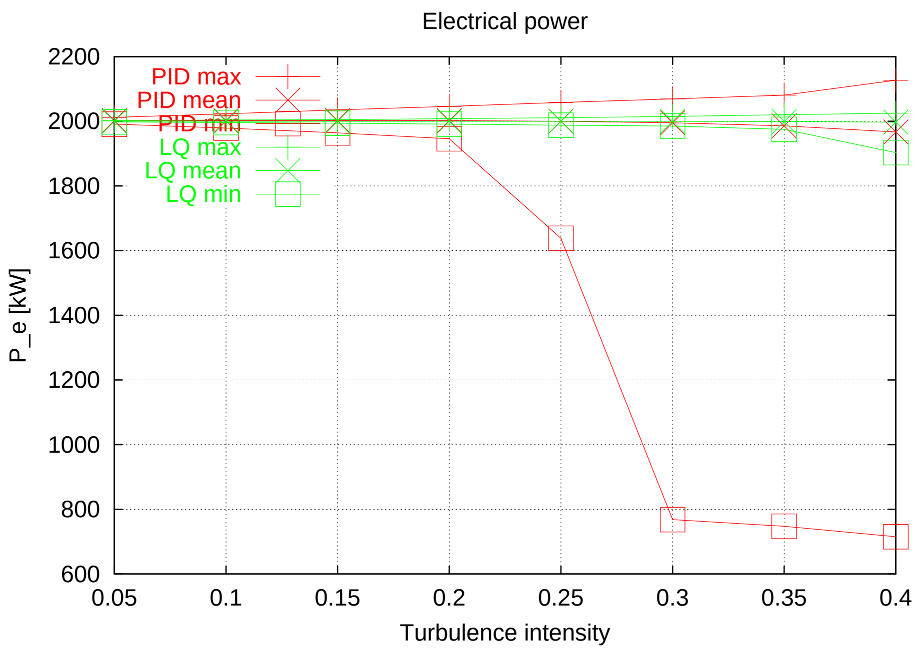

Figure 31. Comparison of electrical power.

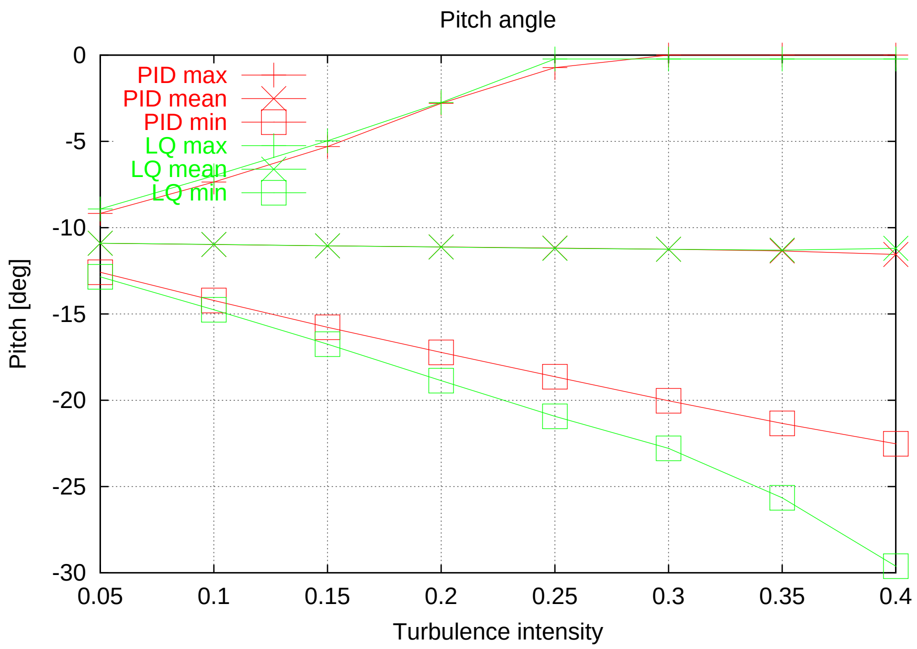

Figure 32. Comparison of pitch angle.

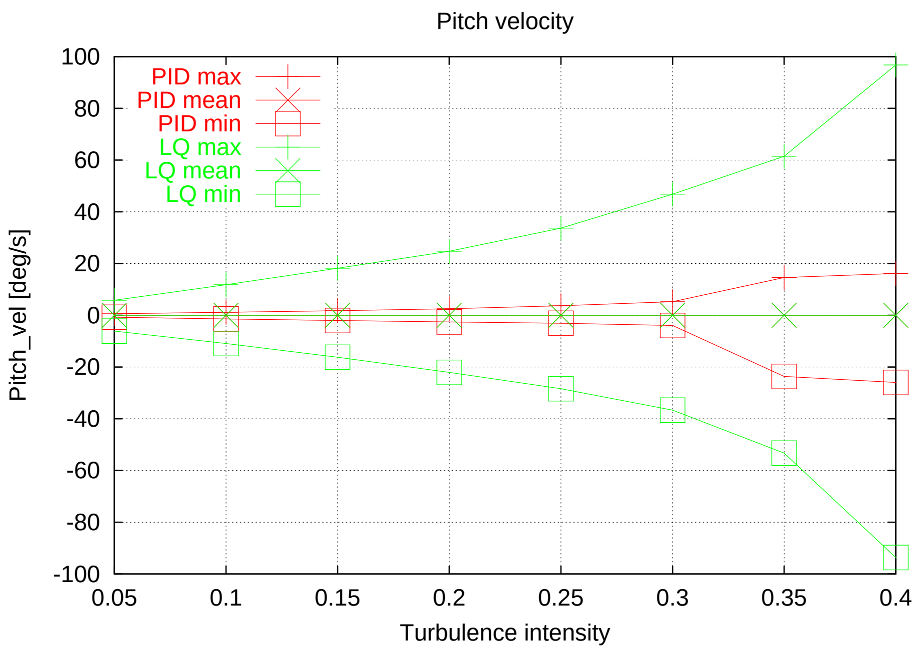

Figure 33. Comparison of pitch angle velocity.

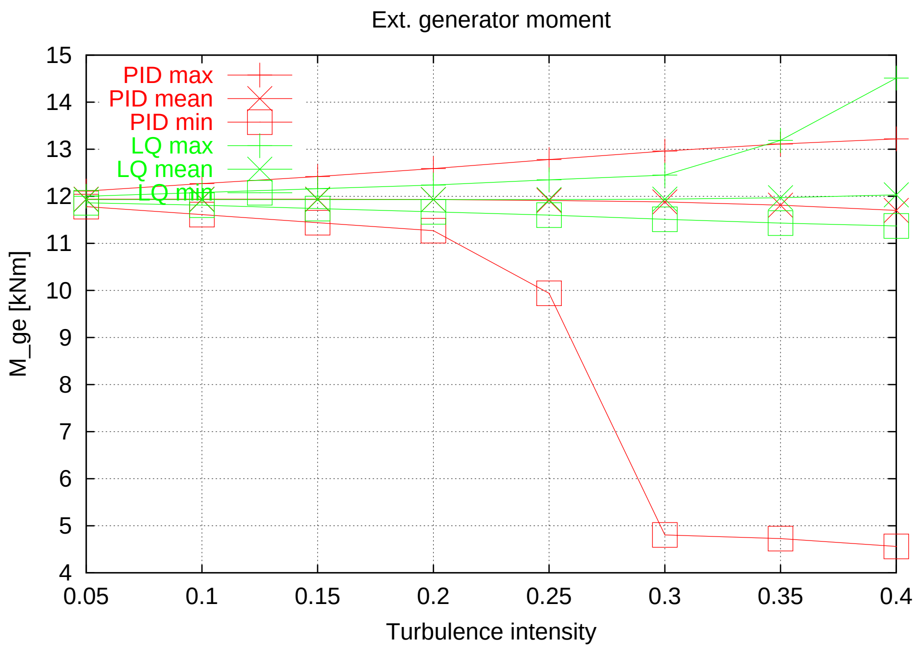

Figure 34. Comparison of generator torque.

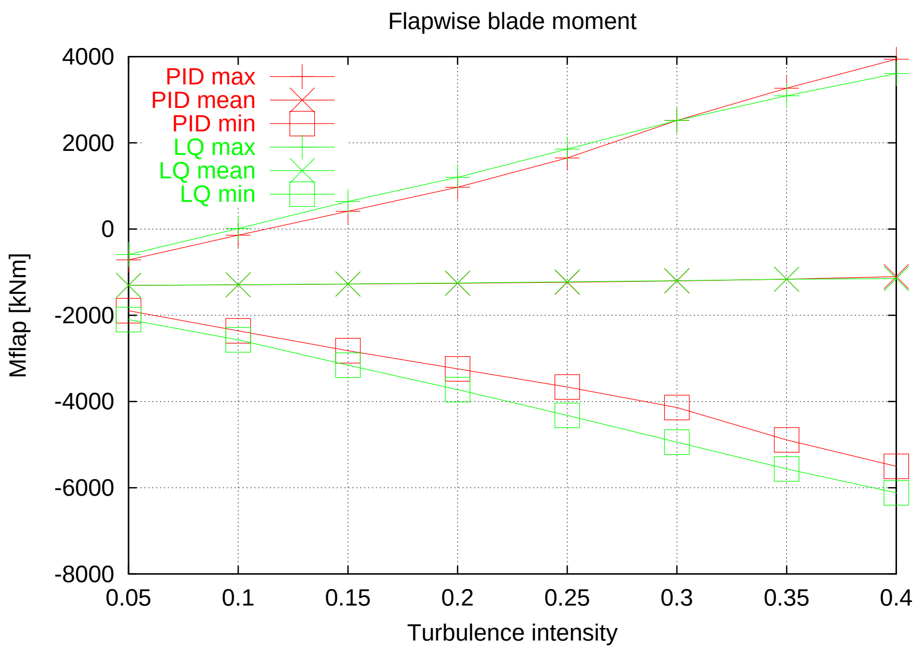

Figure 35. Comparison of flapwise blade root bending moment.

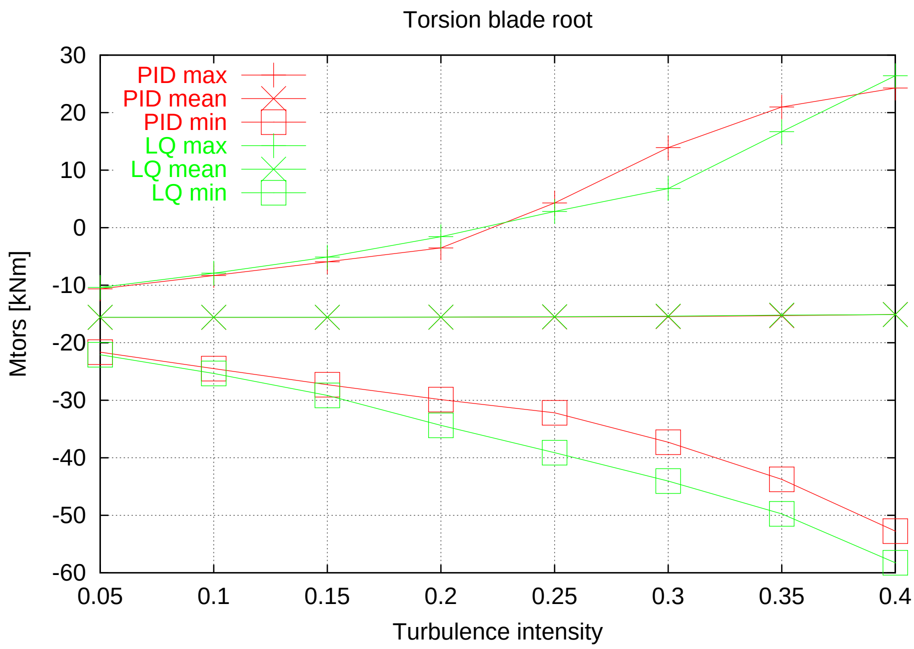

Figure 36. Comparison of pitch moment in blade root. No effects of acceleration forces include.

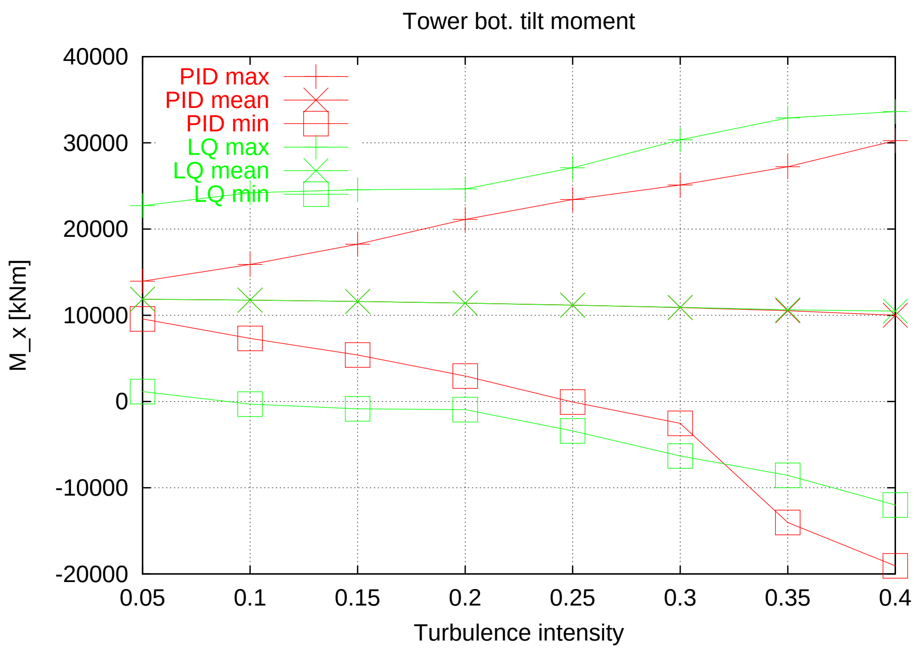

Figure 37. Comparison of tower bottom tilt moment.

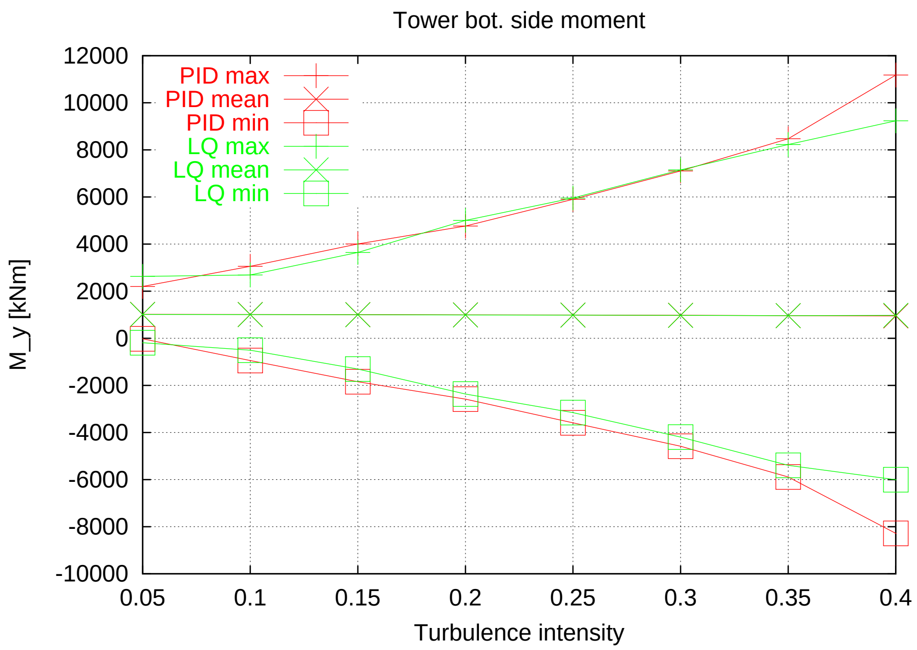

Figure 38. Comparison of tower bottom side moment.

5.3 Effect of error in yaw angle

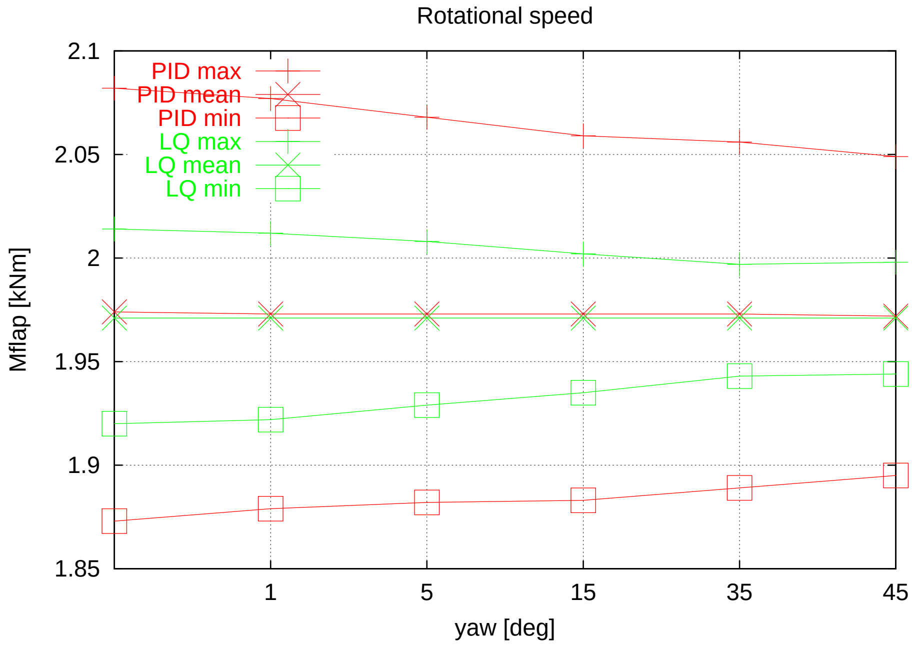

Figure 39. Comparison of rotational speed..

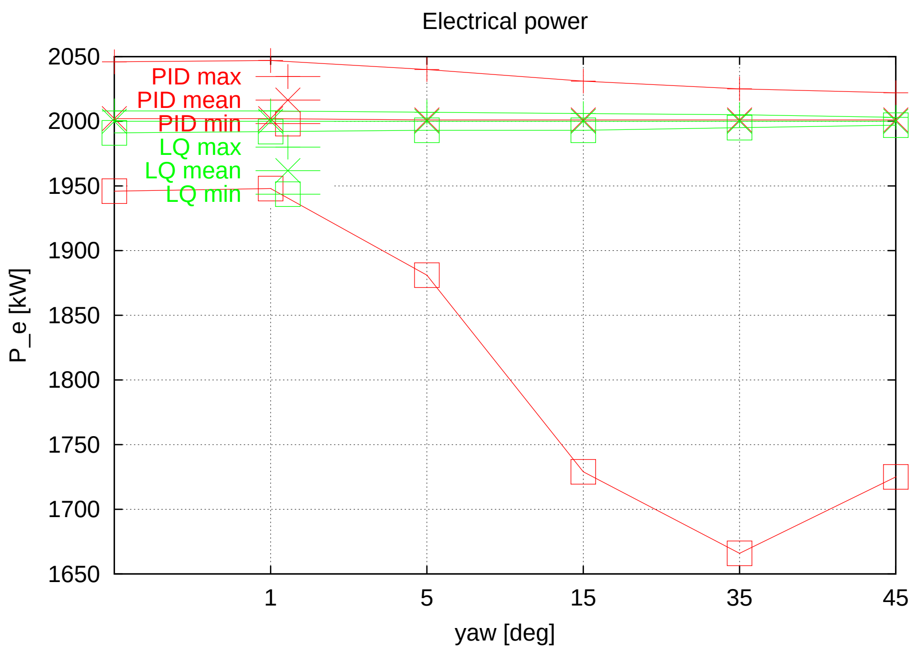

Figure 40. Comparison of electrical power.

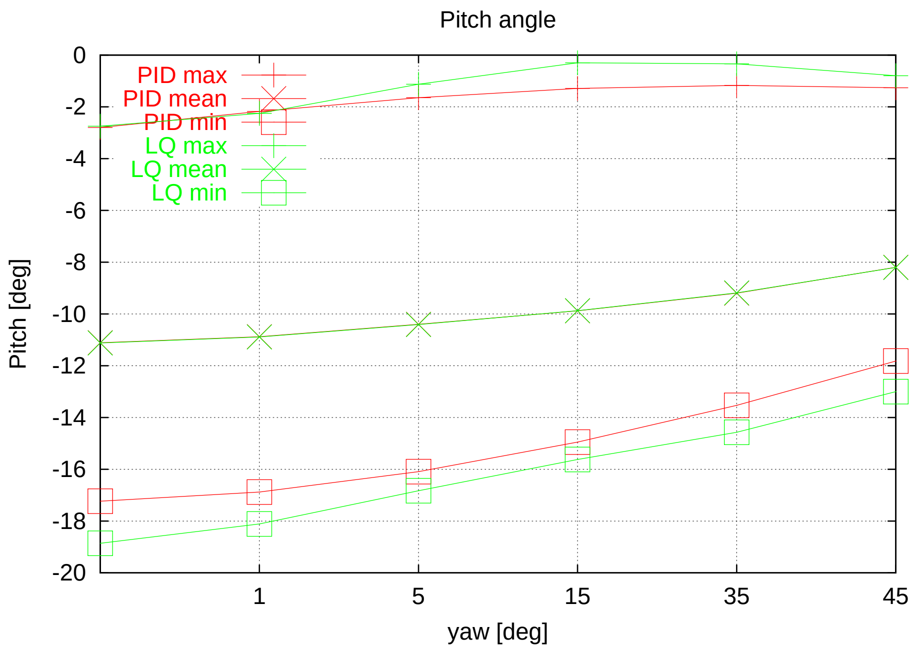

Figure 41. Comparison of pitch angle.

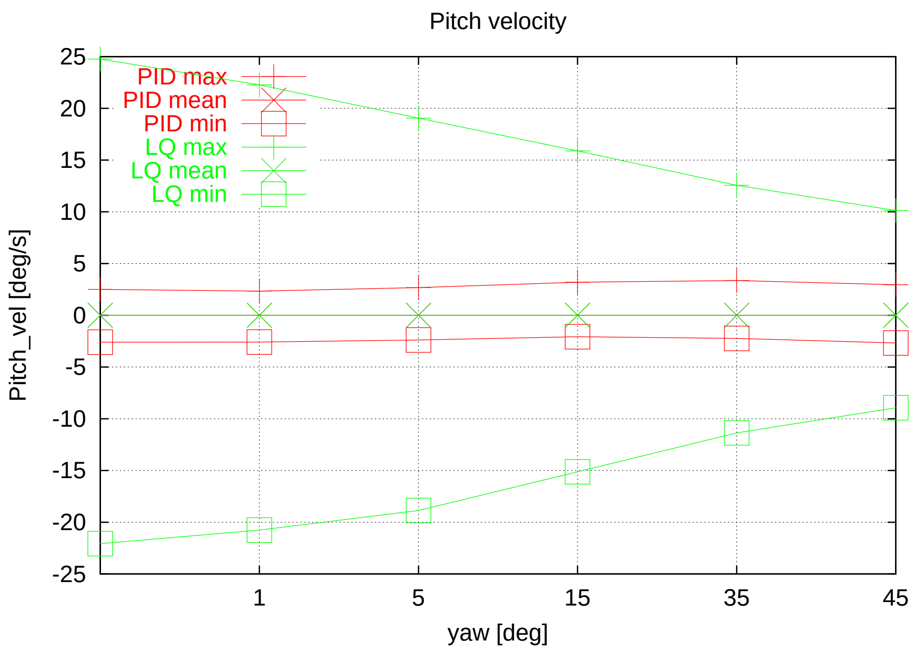

Figure 42. Comparison of pitch angle velocity.

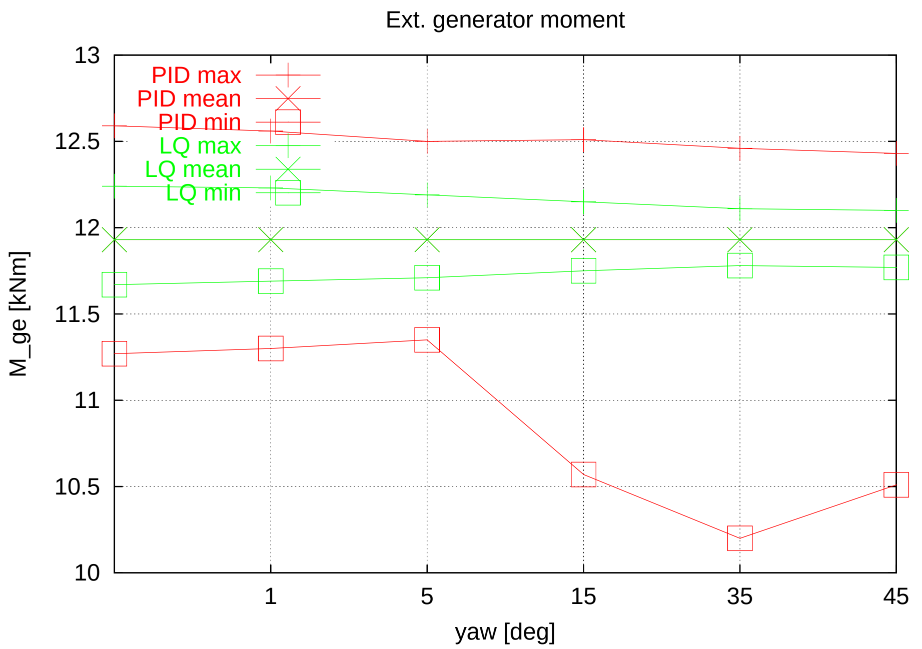

Figure 43. Comparison of generator torque.

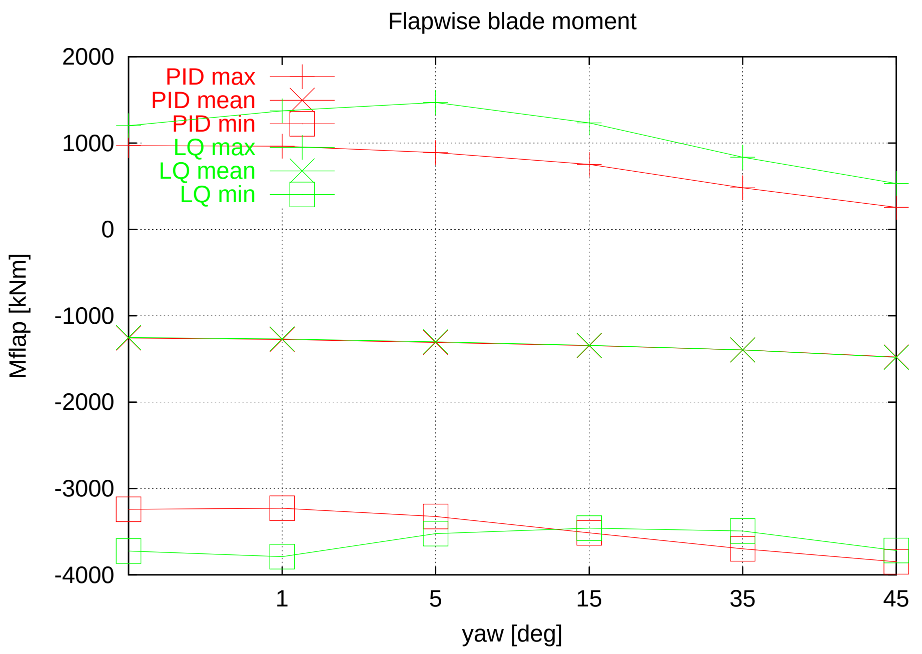

Figure 44. Comparison of flapwise blade root bending moment.

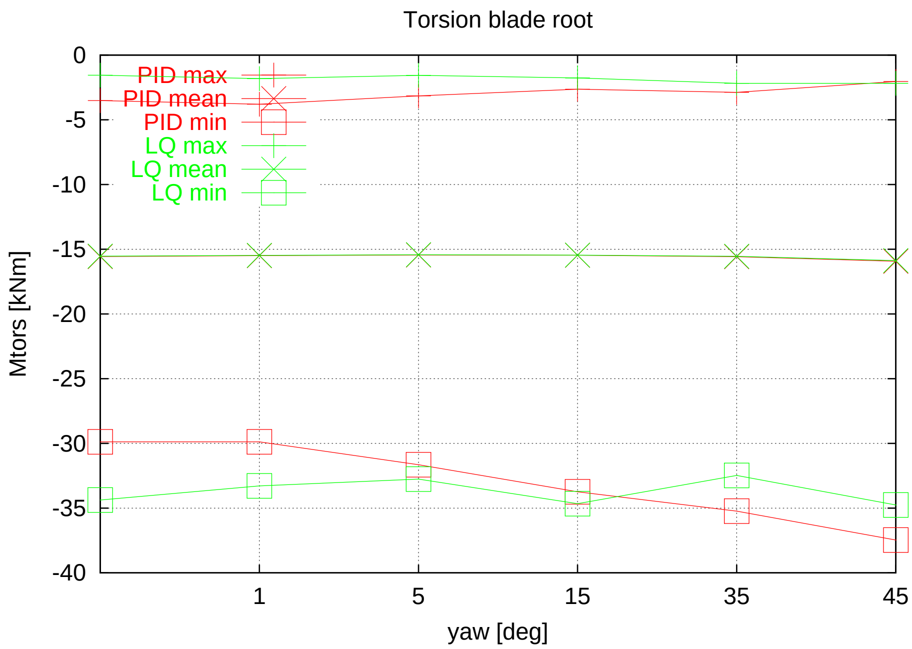

Figure 45. Comparison of pitch moment in blade root. No effects of acceleration forces include.

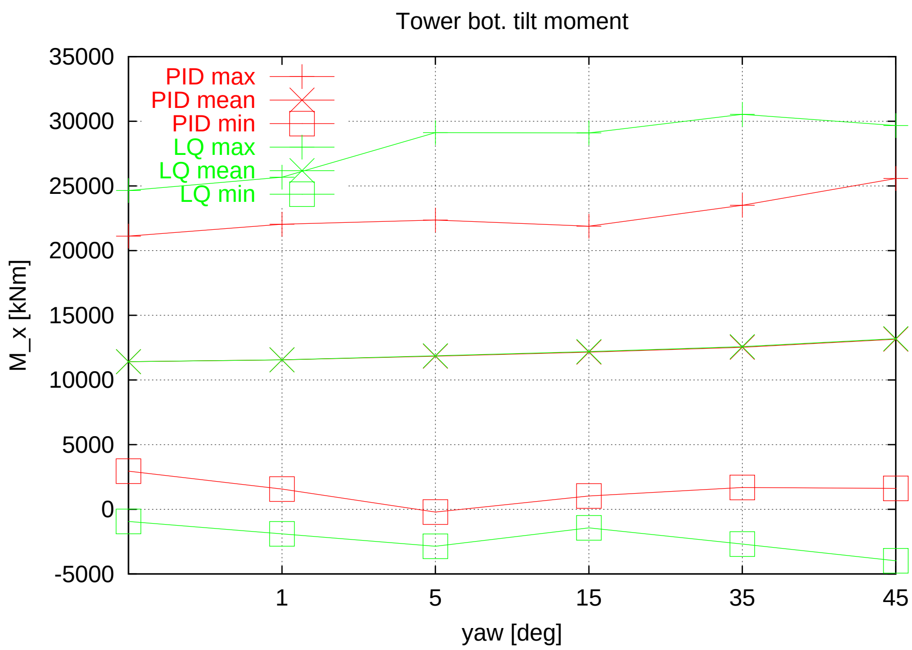

Figure 46. Comparison of tower bottom tilt moment.

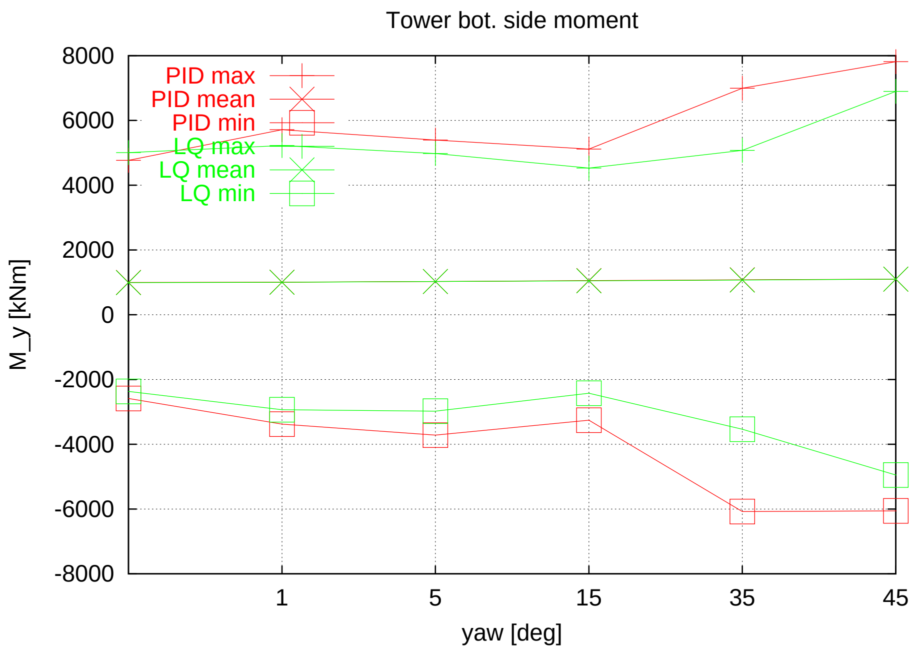

Figure 47. Comparison of tower bottom side moment.

6 Conclusion

In this paper two control strategies has been investigated and compared. One strategy, which in some sense consists the base line for comparison, is a PI based controller equipped with Butterworth filters, mode switching and gain scheduling. The last property has been incorporated in order to deal with the nonlinear effects involved in connection to wind turbine control. The other strategy is a LQ based controller which due to time limitation has (only) been implemented as a fixed parameter controller and designed for operating in a region around a wind speed equal to 15 m/sec. In other words there has not been take any measures in the design to cope with nonlinearities except for the ridge limitation. The resulting controller, WT_{1a}, is equipped with a Kalman filter for estimating the state in the wind model.

In general a LQ controller can be designed as a compromise between minimizing several effects including the performance parameters as well as the control effort parameters. In this report, however (and due to project time limitiation), only the produced electric power has been in focus.

In the comparison between the two strategies the produced electric power for the WT_{1a} has indeed been kept within a more narrow interval than for the PI controller. The cost is however a higher pitch angular speed, and thereby larger forces on the pitch actuator system. For the two strategies the variation in control inputs, i.e. the pitch and generator torque, are measured as standard deviation or variance quite similar. However, the pitch activitiy in the WT_{1a} design has a large component in the high frequency region, which can be seen as previously mentionend a high pitch angular speed. In the WT_{1b} design the weight on the pitch activity has been increased slightly which result in a slightly larger variation in P_e but a huge reduction in the pitch speed. However, not less than the PI control strategy. The WT_{1b} design has in this report been tested for one wind speed realization with a average wind speed equal to 15 m/sec.

For reducing the pitch speed, further development in connection to the LQ design, should be in a direction where the pitch speed directly is included in the design cost function. Also for reducing the loads, these should be included in the design model and given a weight in the control objective function.

References

[1] M. H. Hansen, A. Hansen, T. J. Larsen, S. Øye, P Sørensen, and P Fuglsang. Control design for a pitch-regulated, variable speed wind turbine. Technical report, Risø-R-1500(EN),Risø National Laboratory, 2005.

[2] B.D.O. Anderson and J.B. Moore. *Optimal Control, Linear Quadratic Methods.* Prentice Hall, 1990.

[3] T. J. Larsen. Description of the DLL regulation interface in HAWC. Technical report, Risø-R-1290(EN),Risø National Laboratory, September 2001.

[4] J. T. Petersen and T. J. Larsen. HAWC wind turbine simulation code, users guide. Technical report, Risø-I-1408(EN),Risø National Laboratory, 2001.

[5] K. J. Åström. *Introduction To Stochastic Control Theory.* Academic Press, 1970.

A HAWC input file

```
 HEAD HAWC input for "Aeroelastisk int. styring"    /*
          80m trnhjde.        nkp 15 m/s        /*
          Ris testcase                          ;
 DEFINE_STRING CASE_IDENTIFICATION           wtlq1t31;
 DEFINE_STRING STRUCTURE_FILE_EXT            001 ;
 DEFINE_STRING AERODYN_FILE_EXT              001 ;
 DEFINE_STRING PROFILE_FILE_EXT              001 ;
 DEFINE_STRING GENERATOR_EFFICIENCY_FILE_EXT 001 ;
 DEFINE_STRING GEAR_BOX_EFFICIENCY_FILE_EXT  001 ;
 DEFINE_STRING EXTERNAL_REGULATION_NAME  wtlq1t.dll ;
 DEFINE_STRING TURB_FILE_PATH  .\turb\ ;
 DEFINE_STRING MANN_TURB_FILE_EXT            1 ;
 PARAMETERS TURBINE  3  2  4  2 ;
 PARAMETERS GEAR_BOX   85.0  2  1 ;
 PARAMETERS GENERATOR  150.0  9.99E3  2000.0  0.75  1600.0  1 ;
 PARAMETERS TILT   6.00 ;
 PARAMETERS HAM_DYNAMIC_STALL  1.50  6.00  0.75  0.14  *
                               0.53  0.30  0.70  0.95  1  12 ;
;
 PARAMETERS EXTERNAL_REGULATION 0.025 ; Ts
 EXT_CONTR_SENS HUB_SPEED 1;
 EXT_CONTR_SENS GENERATOR_SPEED 2;
 EXT_CONTR_SENS SHAFT_DEFORMATION 4 0 0 0 0 1 0 *
                                    0 0 0 0 3 0 ;
 EXT_CONTR_SENS PITCH_BEARING_ANGLE 1 1 1 *
                                    4 5 6 ;
 EXT_CONTR_SENS SIMULATED_TIME 15 ;
;
 PARAMETERS PITCHABLE_BLADE_PART 2 3 0.0 0.0 0.0 ;
 ROTOR BASIC_LAYOUT       3   2 0.00 0.00 0.00 *
                                0.00 0.00 0.00 *
                                0.00 0.00 0.00 0.0 ;
 DAMPING TOWER  0.0 0.0 0.0  3.06E-3 3.06E-3 1.45E-3 ;
 DAMPING SHAFT  0.0 0.0 0.0  1.00E-3 1.00E-3 3.20E-3 ;
 DAMPING BLADE  0.0 0.0 0.0  1.39E-3 9.00E-4 1.39E-3 ;
 DEFINITION AEROCAL_INDUCTION 32  1.0  1.0  1.0  0.1  1.0 *
                                  4.0  4.0  4.0  0.4  4.0 *
                                  2.0  2.0  2.0  2.0  1.0 ;
; DEFINITION AEROCAL_MODIFICATIONS 1 1 15 ;
;                         rho    u0    h0      slope   yaw  sigma/u0 r0  shear
 DEFINITION WIND_FIELD   1.25  15.00 80.00   0.00    0.00   0.20  0.55 4 ;
; DEFINITION WIND_FIELD   1.25  5.00  80.00   10.00   0.00   0.20   0.55 4 ;
DEFINITION TURBULENCE_MANN 80.0 32 4096 80 1 1.0 0.8 1.0 0.5 1 2; Stoch.wind.
; DEFINITION TOWER_AERODYNAMIC_LOAD 0.6;
; DEFINITION TOWER_SHADOW  1.200  2.150  1.5  1;
; Blade nodes
 NODE BLADE  1      1     0.000     0.000     0.000 ;
 NODE BLADE  1      2     0.000     0.000     2.000 ;
 NODE BLADE  1      3     0.000     0.000     7.000 ;
 NODE BLADE  1      4     0.000     0.000    12.000 ;
 NODE BLADE  1      5     0.000     0.000    20.000 ;
 NODE BLADE  1      6     0.000     0.000    25.000 ;
 NODE BLADE  1      7     0.000     0.000    28.000 ;
 NODE BLADE  1      8     0.000     0.000    31.000 ;
 NODE BLADE  1      9     0.000     0.000    34.000 ;
 NODE BLADE  1     10     0.000     0.000    36.000 ;
 NODE BLADE  1     11     0.000     0.000    38.000 ;
 NODE BLADE  1     12     0.000     0.000    40.000 ;
 NODE BLADE  2      1     0.000     0.000     0.000 ;
 NODE BLADE  2      2     0.000     0.000     2.000 ;
```

```
 NODE BLADE  2      3     0.000     0.000     7.000 ;
 NODE BLADE  2      4     0.000     0.000    12.000 ;
 NODE BLADE  2      5     0.000     0.000    20.000 ;
 NODE BLADE  2      6     0.000     0.000    25.000 ;
 NODE BLADE  2      7     0.000     0.000    28.000 ;
 NODE BLADE  2      8     0.000     0.000    31.000 ;
 NODE BLADE  2      9     0.000     0.000    34.000 ;
 NODE BLADE  2     10     0.000     0.000    36.000 ;
 NODE BLADE  2     11     0.000     0.000    38.000 ;
 NODE BLADE  2     12     0.000     0.000    40.000 ;
 NODE BLADE  3      1     0.000     0.000     0.000 ;
 NODE BLADE  3      2     0.000     0.000     2.000 ;
 NODE BLADE  3      3     0.000     0.000     7.000 ;
 NODE BLADE  3      4     0.000     0.000    12.000 ;
 NODE BLADE  3      5     0.000     0.000    20.000 ;
 NODE BLADE  3      6     0.000     0.000    25.000 ;
 NODE BLADE  3      7     0.000     0.000    28.000 ;
 NODE BLADE  3      8     0.000     0.000    31.000 ;
 NODE BLADE  3      9     0.000     0.000    34.000 ;
 NODE BLADE  3     10     0.000     0.000    36.000 ;
 NODE BLADE  3     11     0.000     0.000    38.000 ;
 NODE BLADE  3     12     0.000     0.000    40.000 ;
;  Nacelle nodes
 NODE NACELLE    1  0.0    0.000  0.000 ;  Tower top
 NODE NACELLE    2  0.0   -0.600  0.000 ;  Gearbox
 NODE NACELLE    3  0.0   -2.186  0.000 ;  Main shaft flange
 NODE NACELLE    4  0.0   -3.486  0.000 ;  Rotor centre
; Tower nodes
 NODE TOWER    1     0.000     0.000     0.000 ;
 NODE TOWER    2     0.000     0.000   -25.000 ;
 NODE TOWER    3     0.000     0.000   -50.000 ;
 NODE TOWER    4     0.000     0.000   -80.000 ;
 ;                             1  3  2  m0       Ix        Iy(axel)   Iz
 DEFINITION CONCENTRATED_MASS  1  3  2  75.3E+3  409.4E+3  20.0E+3  367.7E+3 ;
 TYPES BLADE_AERODYN_3    1    1    1 ;
 TYPES BLADE_STRUCTURE_3  1    1    1 ;
 TYPES SHAFT_STRUCTURE    1 ;
 TYPES TOWER_STRUCTURE    1 ;
 TYPES USE_CALCULATED_BEAMS ;
 INITIAL AZIMUTH     0.000     1.9712   0.000 ;

 ;
 WRITE BEAM_DATA_TO_RDA_DIRECTORY ;
;
 RESULTS BLADE_CO_SYS_FORCE  2 ;
 RESULTS BLADE_CO_SYS_DEFORM  1 ;
 RESULTS FORCE_MOMENT_SIGN 4 ;
;
 RESULTS TIME ;
; RESULTS AZIMUTH  0.0 ;
 RESULTS ROTOR_SPEED ;
 RESULTS GENERATOR_SPEED ;
 RESULTS EXTERNAL_GENERATOR_MOMENT ;
 RESULTS HUB_SPEED ;
 RESULTS ELECTRICAL_POWER ;
 RESULTS WIND_SPEED_AT_HUB   0 1 0  1 1 1 ;
 RESULTS PITCH_BEARING_ANGLE  1 1 1 ;
; RESULTS SHAFT_FORCE_MOMENT 1 0 0 0 0 1 0 ;
; RESULTS ELEMENT_CL_CD_CM_DATA 3 0 0 0 0 0 0 1 ;
; RESULTS ELEMENT_CL_CD_CM_DATA 5 0 0 0 0 0 0 1 ;
; RESULTS ELEMENT_CL_CD_CM_DATA 7 0 0 0 0 0 0 1 ;
; RESULTS ELEMENT_AERODYNAMICS 1 7 1.0 1 0 0 0 0 0 0;
RESULTS BLADE_FORCE_MOMENT  1  1  0 0 0  1 1 0 ;  Rotor centre
; RESULTS BLADE_FORCE_MOMENT  1  2  0 0 0  1 1 0 ;  R=1.2m
```

```
; RESULTS BLADE_FORCE_MOMENT  1  5  0 0 0  1 1 0 ;  r=20m
; RESULTS BLADE_FORCE_MOMENT  1  9  0 0 0  1 1 0 ;  r=34m
RESULTS SHAFT_FORCE_MOMENT     4  0 1 0  1 1 1 ;  Rotor centre
RESULTS TOWER_FORCE_MOMENT     1  1 1 0  1 1 1 ;  Tower base
; RESULTS TOWER_FORCE_MOMENT     2  1 1 0  1 1 1 ;  Tower h=25m
; RESULTS TOWER_FORCE_MOMENT     4  1 1 0  1 1 1 ;  Tower top
 RESULTS BLADE_DEFORMATION   1 12  1 1 0  0 0 0 ;  Tip
 RESULTS SHAFT_DEFORMATION      4  0 0 0  0 1 0 ;  Rotor centre
 RESULTS TOWER_DEFORMATION      4  1 1 0  0 0 0 ;  Tower top
 DEFINITION RESPONSE_CALC_LIMITS  1.0E-3  1.0E-3  0.0  5.0E-1  1  10 ;
 RESULTS RESPONSE_TIME_OFFSET  0.0;  40.0;
; WRITE POWER   7.0  25.0   1.0    4    1   0.10   0.10   0.10   8 ;
 WRITE RESPONSE 300.0  0.025  1  1  0  1  2  1  5  1 ;
 STOP ;
```

Bibliographic Data Sheet **Risø-I-2320(EN)**

Title and author(s)

Comparison between a PI ad LQ-regulation for a 2 MW wind turbine

Niels K. Poulsen, Torben J. Larsen, Morten H. Hansen

Dept. or group	Date
Wind Energy Department	Februar 2005

Groups own reg. number(s)

1110039-00

Pages	Tables	Illustrations	References
43	1	47	5

Abstract (Max. 2000 char.)

This paper deals with the design of controllers for pitch regulated, variable speed wind turbines where the controller is used primarily for controlling the (rotor and generator) speed and the electric power through a collective pitch angle and the generator torque. However, other key parameters such as loads on the drive train, wings and tower are in focus. The test turbine is a 2 MW turbine used as a bench mark example in the project "Aerodynamisk Integreret Vindmøllestyring" partly founded by the Danish Energy Authority under contract number 1363/02-0017.

One of the control strategies investigated here in this report, is based on a LQ (Linear time invariant system controlled to optimize a Quadratic cost function) strategy. This strategy is compared to a traditional PI strategy. As a control object a wind turbine is a nonlinear, stochastic object with several modes of operation. The nonlinearities calls for methods dealing with these. Gain scheduling is one method to solve these types of problems and the PI controller is equipped with such a property. The LQ strategy is (due to project time limitations) implemented as a fixed parameter controller designed to cope with the situation defined by a average wind speed equal to 15 m/sec.

The analysis and design of the LQ controller is performed in Matlab and the design is ported to a Pascal based platform and implemented in HAWC.

In general a LQ controller can be designed as a compromise between minimizing several effects including the performance parameters as well as the control effort parameters. In this report, however (and due to project time limitiation), only the produced electric power has been in focus.

In the comparison between the two strategies the produced electric power for the LQ controller has indeed been kept within a more narrow interval than for the PI controller. One of the costs is however a high pitch angular speed. In one of the LQ designs this costs (in terms of the pitch angular speed) is unrealistic high. In a redesign the maximum pitch angular speed is reduced, but still higher that in the case of the traditionally PI controller.

For reducing the pitch speed, further development in connection the LQ design, should be directed i a direction where the pitch speed directly is included in the design cost function. Also for reducing the loads, these should be included in the design model and given a weight in the control objective function.