

Torque- and Speed Control of a Pitch Regulated Wind Turbine

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Göteborg, Sweden 2003

THESIS FOR THE MASTER OF SCIENCE DEGREE

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Abstract

Variable speed operated wind turbines has the potential to reduce fatigue loads, compared to fixed speed wind turbines. With pitch controllable rotor blades limitation of the power at high wind speeds is obtained.

The thesis describes different controlling aspects concerning wind turbines and how these together can be used to optimize the system's performance. Torque control is used in order to achieve reduction on the mechanical loads on the drive-train for low wind speeds and limitation of power output for high wind speeds. In the high wind speed interval torque control is effective in order to limit the output power if a sufficiently fast pitch actuator is used. In the middle wind speed interval filter utilization can be used to give a reference signal to the controller in order to reduce speed and torque variations.

Keywords: *Wind turbine, variable speed operation, torque control, pitch control, energy capture, mechanical stresses.*

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Contents

Abstract	i
Acknowledgements	iii
Contents	iv
List of Symbols	vii
1 Introduction	1
1.1 Definition of the problem	1
1.2 Theoretical and historical background	1
1.3 The aim and the extent of the thesis	2
1.4 Thesis layout	2
2 Theory and Modelling	3
2.1 Wind Power Turbine	3
2.2 Wind Properties	4
2.2.1 Turbulence	4
2.2.2 Wind Model	5
2.3 Aerodynamics	7
2.3.1 Transformation from Kinetic Energy to Rotational Torque	7
2.3.2 Blade Element Theory	10
2.4 Drive-train and Generator	13
2.4.1 Moment of Inertia	14
2.4.2 Mechanical Conversion to Electrical	14
2.5 Different Operational Modes for a Wind Turbine	14
2.5.1 Constant Speed	15
2.5.2 Variable Speed	16
2.6 Turbine Operation	16
2.6.1 Steady State Operation	16
2.6.2 Steady State Control	17
2.7 Controlling	18
2.7.1 Low Wind Speed Interval	18
2.7.2 High Wind Speed Interval	21
2.7.3 Middle Wind Speed Interval	22

3	Analysis	25
3.1	Wind Turbine Operation at Different Wind Speed Intervals	25
3.2	Low Wind Speed Operation	25
3.2.1	Step Response	26
3.2.2	Simulations using Realistic Wind Input	28
3.2.3	Fixed Speed Wind Turbine	31
3.2.4	Energy Losses versus Mechanical Stresses	32
3.3	High Wind Speed Operation	33
3.3.1	Step Response for Pitch Regulation with Torque Estimator	33
3.3.2	Pitch Regulation with Torque Estimator for Simulations with Realistic Wind	35
3.3.3	Need for Pitching Capacity	37
3.3.4	Comparison with Measured Data	39
3.4	Middle Wind Speed Operation	40
3.4.1	Generator Model Evaluation	41
4	Conclusions	47
4.1	Future Work	47
A	Alsvik Wind Turbine Data	51
B	Simulated Wind Speed	53

List of Symbols

Abbreviations

A_d	rotor swept area
A_w	downstream area
A_∞	upstream area
C_P	power coefficient of rotor blades
C_T	torque coefficient of rotor blades
cut_{in}	cut in wind speed for turbine
cut_{off}	cut off wind speed for turbine
D	drag force on blade segment
F_{edge}	edge force on blade segment
F_{flap}	flap force on blade segment
F_{tot}	total force on blade segment
h	height above ground level
h_d	height at actuator disc
h_∞	height at down- and upstream distance
J_g	moment of inertia for generator
J_r	moment of inertia for rotor
J_{tot}	total moment of inertia on low speed side
K_i	integral part of PI controller
K_p	proportional part of PI controller
L	lift force on blade segment
P	power
P_e	electrical power from generator
P_n	rated power
P_r	power from rotor
p	pressure
p_d^+	pressure at actuator disc, incoming air
p_d^-	pressure at actuator disc, outgoing air
p_∞	pressure at down- and upstream distance
R	blade radius
r	distance to blade segment
TI	turbulence intensity
T_e	electrical torque from generator
T_n	nominal torque on generator
T_r	mechanical torque from rotor
T_{SF}	time constant for spatial filter

T_β	time constant for pitch-actuator
v	fluctuating wind speed component
W	relative wind speed acting on blade segment
WS	instantaneous wind speed
WS_d	wind speed at actuator disc
WS_m	mean wind speed
WS_w	wind speed at downstream distance
WS_∞	wind speed at upstream distance
z	height above ground level
z_0	reference height

Greek

α	angle of attack
β	pitch angle
β_{ref}	reference pitch angle
θ_g	angle of generator shaft
θ_r	angle of rotor shaft
λ	tip speed ratio
ρ	air density
ρ_d	air density at actuator disc
ρ_∞	air density at down- and upstream distance
σ_{WS}	standard deviation of wind speed
ϕ	angle between relative wind and rotor plane
ω	angular frequency
ω_g	angular speed for generator shaft
ω_r	angular speed for rotor shaft
ω_r	rotational speed of rotor
ω_{ref}	reference pitch angle

Chapter 1

Introduction

1.1 Definition of the problem

Wind turbine generators used all over the world today are mostly operated with constant speed operation. This is mainly due to their simplicity in order of connection to the utility grid with no need of frequency conversion [1]. However, constant speed operation implies that the mechanical structure of the turbine has to be strong as it is exposed to high loadings. Recently though, variable speed operation has gained interest, specially owing to their possibilities to lower stresses on the mechanical parts of the turbine. Control of a wind turbine is very complex since the energy input that comes from the wind is highly fluctuating. These fluctuations will also introduce variations in the produced electric power which causes a negative power quality impact. By using rotor speed control these disturbances can be reduced and thereby also the loadings on the mechanical system.

1.2 Theoretical and historical background

The use of wind energy has grown constantly during the last 10 years. This has led to an increase of research and development of larger and more effective wind turbine in order to offer renewable energy to the customers [2]. This has also lead to, as the sizes of the systems increase, that controlling of wind turbines are beginning to be more flexible and also crucial. The future promises a further increase in the use of control systems as new designs investigate controlling load and power excursions by using variable speed operation, and also aerodynamic controls and other devices in more complex schemes.

Early modern-era wind turbines used passive blade controls to regulate power, yawing and rotor braking. As the size of turbines and the knowledge of automation control systems increased, other passive devices became impractical and active control systems arose. Today a 1-2 MW wind turbine often has active pitch control [3].

1.3 The aim and the extent of the thesis

The aim of the work presented in this thesis is to evaluate how different strategies of controlling a variable speed- and pitch regulated wind turbine will effect the load transients on the turbine's shaft and how this control effects the efficiency and performance. These are then compared to results achieved for a constant speed stall controlled wind turbine.

The wind is described by a stationary Gaussian process and generated from a Kaimal frequency spectrum [4]. A non-linear model of the wind turbine where the incoming wind's influence on the drive-train dynamics, with no tower dynamics involved, is analyzed [5]. Only a simplified model of the generator and it's power converter system is employed [2].

Three different control strategies are utilized in each range of the wind speed interval. For each of these then different configurations for the control system is tested.

1.4 Thesis layout

Chapter 2 presents an overview of the most important theories behind the wind characteristics, rotor blade aerodynamics and energy conversion system. Furthermore it describes the model of the system that been used in the analysis and gives an overview of different control strategies used for wind turbine operation.

Chapter 3 describes the control strategy used for the evaluated system and analysis of simulations on with these implemented.

Chapter 4 gives a summary of the conclusions that could be done from the results of the simulations. Furthermore it gives aspects to what future work can be done within the area.

Chapter 2

Theory and Modelling

2.1 Wind Power Turbine

The wind turbine is a device for conversion of kinetic energy in the wind into electricity [6]. Although there are many different configurations of wind turbines systems they all work in the same way. The available power originates from the mass flow of the moving air, referred to as the wind speed. The transformation to mechanical torque is done by aerodynamical forces acting on the rotors blades, the actuator disc. The wind turbine shaft then transports the power to the generator which is connected to the electrical grid. Usually there is a gearbox between the slowly rotating turbine shaft and the more rapidly rotating generator shaft. This is described by the model shown in Figure 2.1.

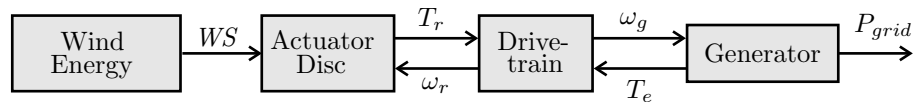


Figure 2.1: Power Extraction for a Wind Turbine

As the incoming wind contains the energy input to the system, the power output is dependent on the wind speed. A lowest and highest wind speed, $WS_{cut_{in}}$ respectively $WS_{cut_{out}}$, determines the range in which wind turbine can operate as shown in Figure 2.2.

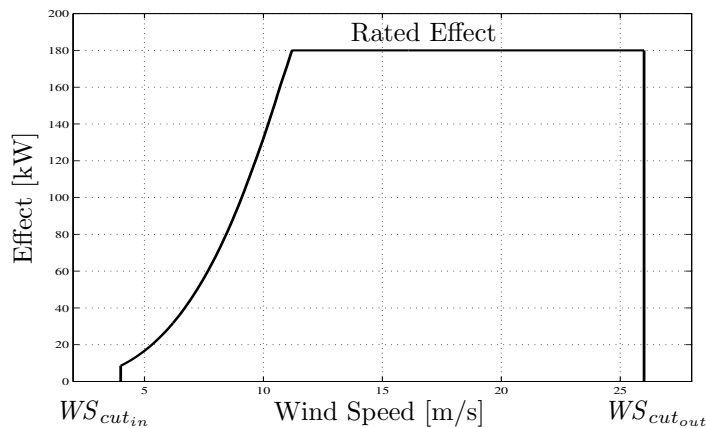


Figure 2.2: Wind Turbine Power Curve

2.2 Wind Properties

The wind is movement of air masses with different speeds in all the regions of the atmosphere. These movements are very difficult to characterize because of the highly variable behavior both geographically and in time. This means that this variability persists over a very wide range of scales in time. On a long-term scale, days and hours, the wind will vary from site to site mostly dependent on the general climate and the physical geography of the region [7]. Locally, the surface conditions at the ground, such as buildings, trees and areas of water will effect the sort-time behavior of the wind and introduce fluctuations in the flow, turbulence. The effect of the ground roughness will then decrease as a function of height over the ground. A measured wind speed with low turbulence intensity can be seen in Figure 2.3.

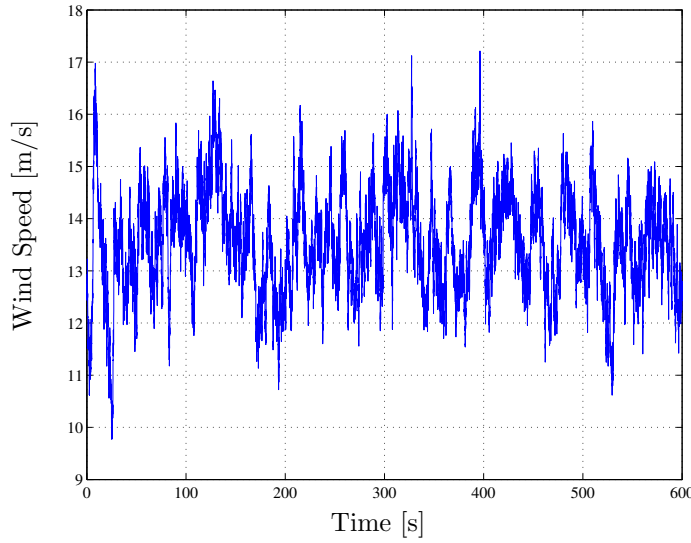


Figure 2.3: Measured Wind Speed sampled with 31,25Hz.

2.2.1 Turbulence

The instantaneous wind speed WS can be described as a mean wind speed WS_m , typically determined as a 10 minute average value, plus a fluctuating wind component v

$$WS = WS_m + v. \quad (2.1)$$

The turbulence intensity, TI , is defined by

$$TI = \frac{\sigma_{WS}}{WS} \quad (2.2)$$

where σ_{WS} is the standard deviation of the wind speed. This is also calculated over a time period of 10 minutes, with a sample rate at least 1 Hz [6]. The effect of the friction at the ground, the roughness, will decrease as the elevation increases. Also the wind speed increases with increasing height which is described by

$$WS(z) = WS_0 \left(\frac{z}{z_0} \right)^\alpha \quad (2.3)$$

where $WS(z)$ is the wind speed at height z above ground level, WS_0 the wind speed at the reference height z_0 and α is an exponent which depends on the roughness of the terrain [8]. Some parameters for α and z_0 for different types of terrain is shown in Table 2.1.

Type of terrain	Roughness class	Roughness, length z_0 (m)	Exponent, α
Water areas	0	0.001	0.01
Open country, few surface features	1	0.12	0.12
Farmland with buildings and hedges	2	0.05	0.16
Farmland with many trees, forest, villages	3	0.3	0.28

Table 2.1: Parameters for calculating vertical profile of wind speed

2.2.2 Wind Model

As described in the previous section the characteristics of the wind will vary dependent of factors such as turbulence and height above ground. In the model of the wind that is used for the simulations, based on [4], the wind speed is described by a periodic stochastic function

$$WS(t) = a_o + \sum_{k=1}^{\infty} a_k \cos(2\pi\Delta t) + b_k \sin(2\pi\Delta t). \quad (2.4)$$

Here Δ represents the sampling frequency, a_0 the mean wind speed and a_k, b_k independent, normal distributed random numbers in the interval $N(0,2)$, in this thesis. For the wind generation a frequency spectrum proposed by Kaimal is used

$$S(n) = \left(\frac{0.4}{\log(z/z_0)}\right)^2 \frac{105z\overline{WS}}{(1 + 33nz/\overline{WS})^{(5/3)}} \quad (2.5)$$

where n is the frequency, z the height above ground, z_0 the ground roughness factor and \overline{WS} the mean wind speed. This is then solved by the relation taken from the probability theory

$$Var[WS(t)] \approx \int_0^{n_{cut}} S(n)dn. \quad (2.6)$$

For values of n_{cut} in the range from 10 to 100 Hz this will, according to [4], give a very good approximation. This is the description of the wind characteristics in one dimension which is used in this work.

Wind Speed Characteristics

As the wind, which is both the systems energy input and main disturbance, is highly varying, it is very important to get a good picture of it's characteristics. This is best done by looking at it's frequency contents. The wind speed from Figure 2.3 is shown as function of frequency and compared with a simulated one in Figure 2.4.

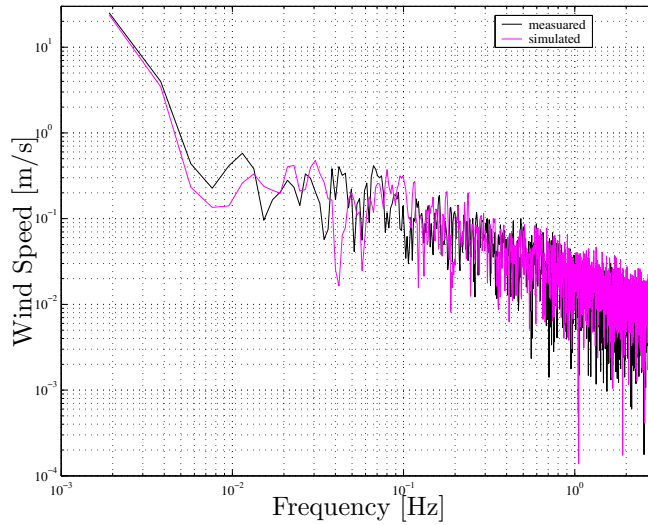


Figure 2.4: Wind Speed spectra for a measured and simulated wind, with mean wind speed 13.5m/s, 31.25Hz sampling frequency and 7.4% turbulence intensity.

As can be noted for Figure 2.4 both have similar characteristics which demonstrates that the wind model is accurately enough.

Turbulence Intensity

Turbulence in the wind is a measure of the disturbances on the input signal to the system. The crucial task for the system is therefore to react fast and compensate smoothly for these without making its operation unfeasible. The controller unit thereby directly reflects the systems possibility to compensate for these disturbances. The turbulence is given by the surface roughness factor and height over ground as described in equation 2.3 and its intensity with equation 2.2. In figure 2.5 a comparison between two wind series with different turbulence intensities is shown.

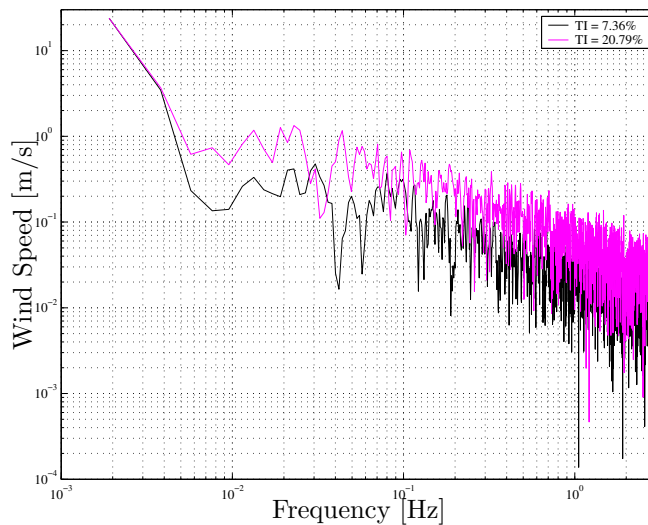


Figure 2.5: Wind Speed spectra for two different turbulence intensities

As can be seen higher turbulence results in larger values on the high frequency contents of the wind. This implies that higher turbulence leads to greater disturbances to be handled by the wind turbine system.

2.3 Aerodynamics

The wind turbine rotor is an energy converter which transforms kinetic energy from the moving air into mechanical energy in the rotating axis at the rotor. Since kinetic energy is a mass moving with a certain velocity, the extraction to mechanical energy will mean that the wind slows down. As volume is mass by density, this implies that the volume of the affected wind increases. Therefore there is a drop of static pressure such that the leaving air is below the atmospheric pressure level and the air from which the energy is extracted and passes through the rotor forms a stream-tube as shown in Figure 2.6 [9].

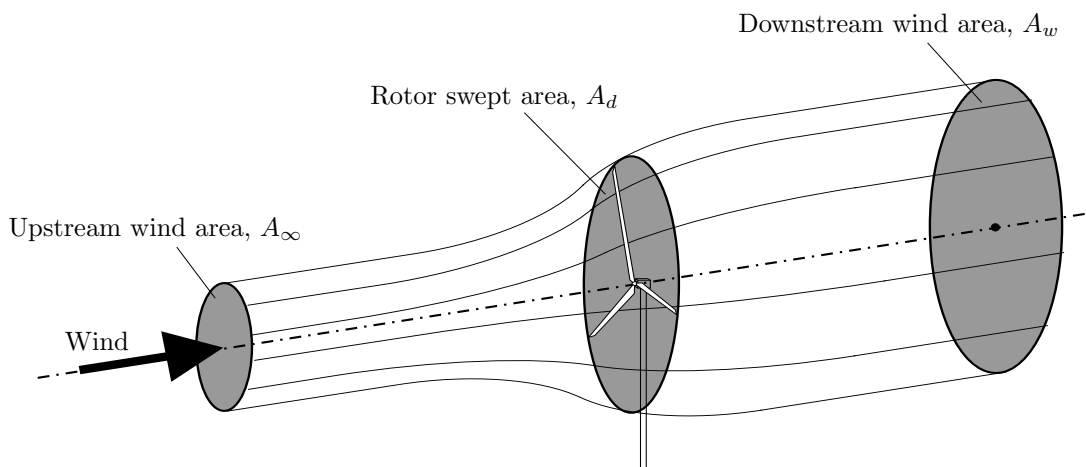


Figure 2.6: Energy Extracting Wind Stream-tube

2.3.1 Transformation from Kinetic Energy to Rotational Torque

The aerodynamics behavior of the wind turbines is described with mass flow rate which must be the same everywhere within the stream-tube. When kinetic energy is extracted from the wind at the actuator disc it slows down its velocity, which can be seen in Figure 2.7.

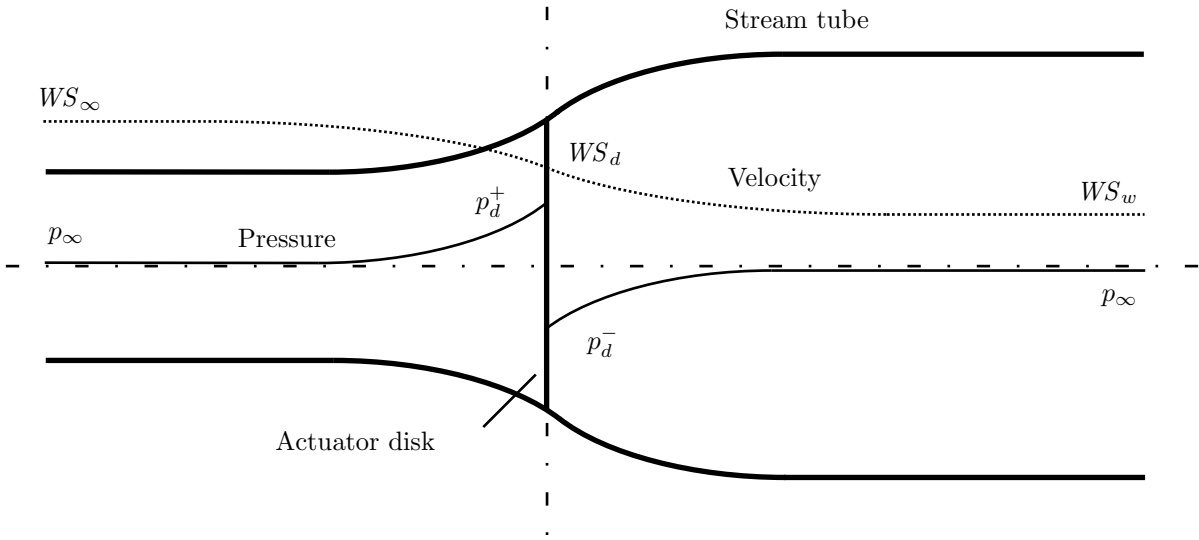


Figure 2.7: Stream-tube

The mass of air which passes through a given cross section of the stream-tube in a unit length of time is $\rho A WS$, where ρ is the air density, A the cross-sectional area and WS is the flow velocity. Because the mass flow rate must be the same everywhere along the stream-tube this gives the equation

$$\rho A_{\infty} WS_{\infty} = \rho A_d WS_d = \rho A_w WS_w. \quad (2.7)$$

The symbol ∞ refers to conditions far upstream, d to conditions at the disc and w to conditions in the far downstream, wake. It is usual to consider that the actuator disc induces a velocity variation which must be superimposed on the free-stream velocity. The stream-wise component of this induced flow at the disc is given by $-a WS_{\infty}$, where a is called the axial flow induction factor, or the inflow factor. At the disc therefore the net stream-wise velocity is

$$WS_d = WS_{\infty}(1 - a). \quad (2.8)$$

Momentum Theory

The air that passes through the disc undergoes an overall change in velocity, $WS_{\infty} - WS_w$ and a rate of change of momentum equal to the overall change of velocity times the mass flow rate

$$\text{Rate of change of momentum} = (WS_{\infty} - WS_w)\rho A_d WS_d. \quad (2.9)$$

The force causing this change of momentum comes entirely from the pressure difference across the actuator disc because the stream-tube is otherwise completely surrounded by air at atmospheric pressure, which gives zero net force.

$$(p_d^+ - p_d^-)A_d = (WS_{\infty} - WS_w)\rho A_d WS_d \quad (2.10)$$

To obtain the pressure difference $(p_d^+ - p_d^-)$ Bernoulli's equation is applied separately to the upstream and downstream sections of the stream-tube; separate equations are necessary because the total energy is different upstream and downstream. Bernoulli's equation states

that, under steady conditions, the total energy in the flow, comprising kinetic energy, static pressure energy and gravitational potential energy, remains constant provided no work is done on or by the fluid

$$\frac{1}{2}\rho WS^2 + p + \rho gh = \text{constant}. \quad (2.11)$$

Upstream, therefore, we have

$$\frac{1}{2}\rho_\infty WS_\infty^2 + p_\infty gh_\infty = \frac{1}{2}\rho_d WS_d^2 + p_d^+ + \rho_d gh_d. \quad (2.12)$$

Assuming the flow to be incompressible ($\rho_\infty = \rho_d$) and horizontal ($h_\infty = h_d$) then

$$\frac{1}{2}\rho WS_\infty^2 + p_\infty = \frac{1}{2}\rho WS_d^2 + p_d^+. \quad (2.13)$$

Similarly, downstream

$$\frac{1}{2}\rho WS_w^2 + p_\infty = \frac{1}{2}\rho WS_d^2 + p_d^-. \quad (2.14)$$

Subtracting these equations we obtain

$$(p_d^+ - p_d^-) = \frac{1}{2}\rho(WS_\infty^2 - WS_w^2). \quad (2.15)$$

Equation (2.10) then gives

$$\frac{1}{2}\rho(WS_\infty^2 - WS_w^2)A_d = (WS_\infty - WS_w)\rho A_d WS_\infty(1 - a) \quad (2.16)$$

and so

$$WS_w = (1 - 2a) WS_\infty. \quad (2.17)$$

That is, half the axial speed loss in the stream-tube takes place upstream of the actuator disc and half downstream.

Power Coefficient

The force on the air becomes, from Equation (2.10)

$$F = (p_d^+ - p_d^-)A_d = 2\rho A_d WS_\infty^2 a(1 - a). \quad (2.18)$$

As this force is concentrated at the actuator disc the rate of work done by the force is $F WS_d$ and hence the power extraction from the air is given by

$$\text{Power} = F WS_d = 2\rho A_d WS_\infty^3 a(1 - a)^2. \quad (2.19)$$

And the *power coefficient* is then defined as

$$C_p = \frac{\text{Power}}{\frac{1}{2}\rho WS_\infty^3 A_d} \quad (2.20)$$

where the denominator represents the power available in the air, in the absence of the actuator disc.

Thrust Coefficient

The force on the actuator disc caused by the pressure drop, given by Equation (2.18), can also be non-dimensionalized to give a *Coefficient of Thrust* C_T

$$C_T = \frac{\text{Thrust}}{\frac{1}{2}\rho WS_\infty^2 A_d} \quad (2.21)$$

This force is working on the rotor shaft in it's longitudinal direction and is mainly a burden on the gearbox and generator.

2.3.2 Blade Element Theory

The effect of the wind acting on the rotor blades will give rise to forces that will give the rotor it's rotation. For blade profiles two forces are generally used to describe the characteristics lift, L , and drag, D , with a resulting force, F_{tot} . Figure 2.8 illustrates this and how the incoming wind speed, WS_d , rotational speed of the rotor, $r\omega_r$, and the angle between them, ϕ , results in the actual wind speed component, W , that determines the size of this force [10].

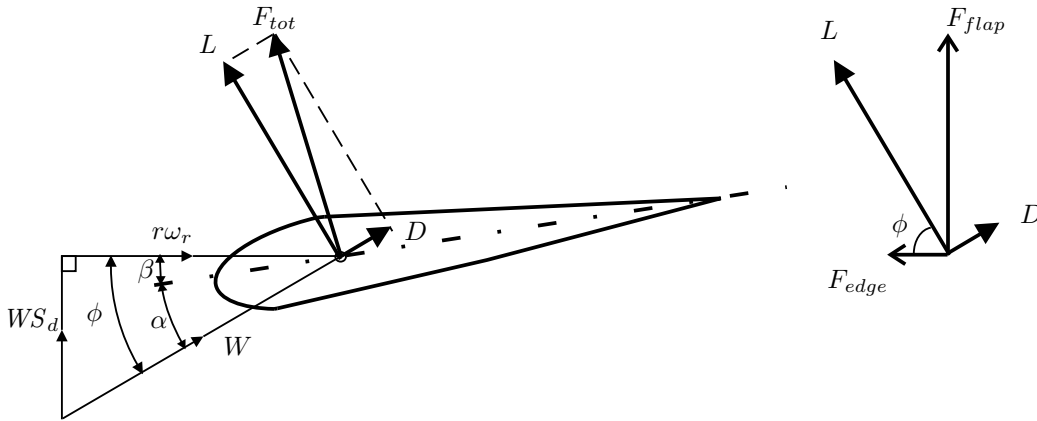


Figure 2.8: Blade Aerodynamics

The ϕ -angle is made up by the angle of attack, α , and pitch-angle, β . By varying β the size and direction of F_{tot} can be changed and it's components in rotor's rotational and charging direction, F_{edge} and F_{flap} , can be changed [11]. These relations are given by

$$F_{edge} = L \sin(\phi) - D \cos(\phi) \quad (2.22)$$

$$F_{flap} = L \cos(\phi) + D \sin(\phi). \quad (2.23)$$

Blade element theory is used to determine these parameters together with data for blade profiles for segments of each blade, consisting of for instance constants for lift and drag, blade length, shape and twist. To be able to calculate the total force from a rotor detailed data for each section is necessary. How coefficients for lift, C_D , and drag, C_L , changes due to pitch angle-changes for a rotor blade profile is shown in Figure 2.9.

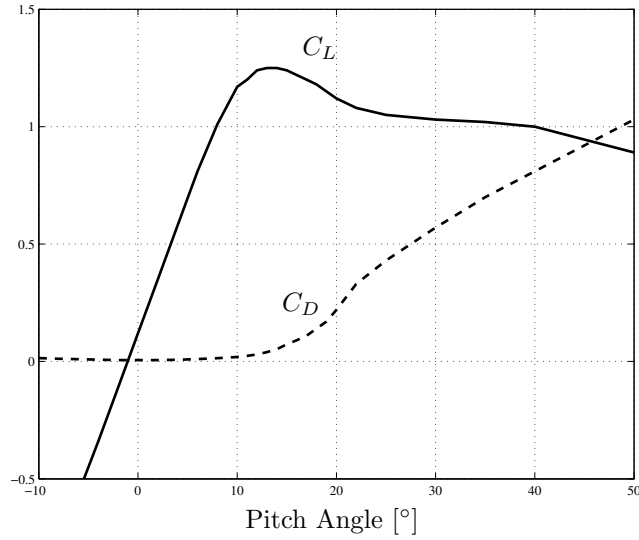


Figure 2.9: Coefficients of Lift and Drag for a Blade Profile

Actuator Disc

As the actuator disc is a highly non-linear part of the system, and the input to this is the highly fluctuating wind the characteristics has to be determined by dividing the blade into smaller parts. This is best described by the schematic model presented in Figure 2.10, which can be applied on every segment of each of the rotor blades [12].

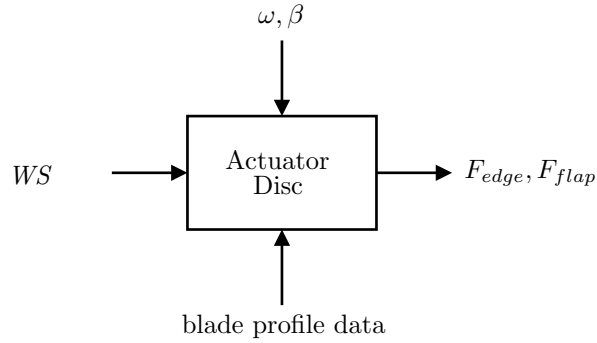


Figure 2.10: Actuator Disc

The forces that are formed by the incoming wind speed, WS , on every segmented blade profile on each rotor blade are summed up to a total driving force, F_{edge} , and a total thrust load, F_{flap} . These forces are also dependent on the rotor blades state variables for rotational speed, ω , and pitch angle, β . In this work profile data for 17 segments on each blade from a 180kW wind turbine at Alsvik on Gotland has been used. Blade element momentum theory has then been used on each segment to calculate the total power extracted from the wind according to

$$P_a = \sum_{blade=1}^3 \sum_{k=1}^{17} F_{edge_k} r_k \omega_{a_k} \quad (2.24)$$

as shown in Figure 2.11 [11].

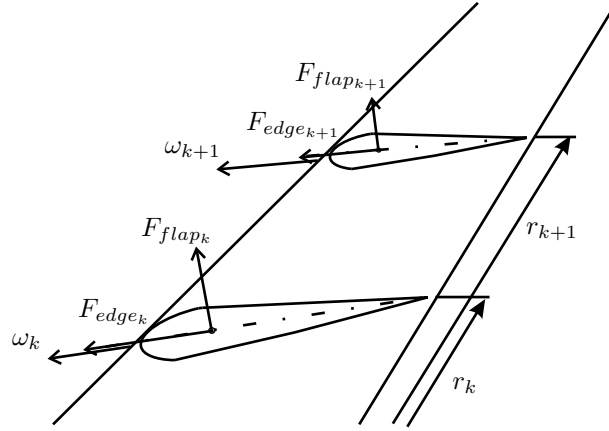


Figure 2.11: Blade Segments of Rotor Blade

In this work, all simulations have been done with the one dimensional wind, described earlier, applied on all blade segments which, of course, is a rough simplification. However, by using a lowpass filter the behavior of the wind over the whole rotor swept area can be approximated as shown in work by Vihriälä [13], Iqbal [14] and Leithead [15]. A comparison between an advanced wind model, with wind field calculations for three dimensional wind, and the filter utilization has been evaluated in a work by Petru [16] where the results show that there is no conspicuous difference. The filter described in those works is a spatial filter which averages the one point wind data over the rotor swept area and has a transfer function given by

$$G_{SF}(s) = \frac{\sqrt{2} + bs}{(\sqrt{2} + bs\sqrt{a})(1 + \frac{b}{\sqrt{a}}s)} \quad (2.25)$$

$$b = \gamma \frac{R}{WS} \quad (2.26)$$

where:

γ decay factor over rotor disc ($\gamma = 1.3$)

R rotor radius

WS wind speed at hub height

a $a = 0.55$ (empirical value).

This can be simplified to a first-order transfer function, without any significant affections on the filter, as

$$G_{SF}(s) = \frac{1}{sb + 1}. \quad (2.27)$$

Calculations with blade element momentum theory on the available blade profile data however doesn't give useful data for low wind speeds with low pitchangles. Therefore a model with the power coefficient C_p (Equation 2.20) as function of pitchangle, β , and tip speed ratio, λ given by

$$\lambda = \frac{\omega_r R}{WS} \quad (2.28)$$

is used, where R represent the rotor blade radius. Figure 2.12 shows the resulting characteristics for this model for some pitchangles.

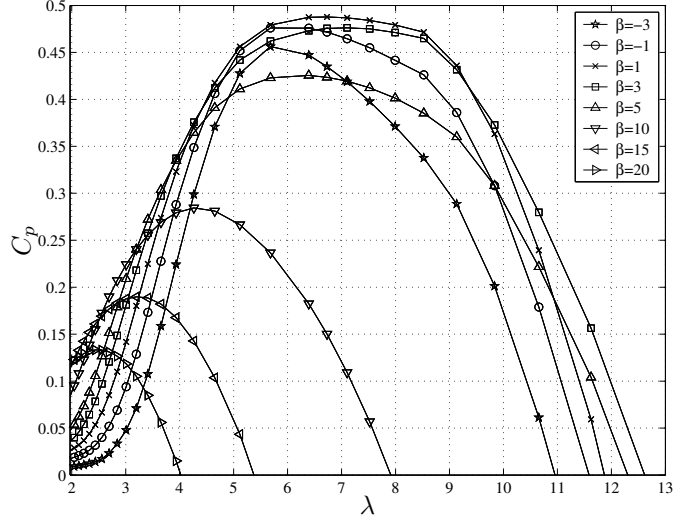


Figure 2.12: $C_p(\beta, \lambda)$ -curves

The curves for pitchangles between -3° and 5° and λ greater than 9 has been adjusted to curves shown in [12] to fit a more realistic characteristics of a rotor, as the available blade profile data doesn't give appropriate values in this range. Finally the power is then given by

$$P_a = \frac{\rho}{2} \pi R^2 C_p(\beta, \lambda) WS^3 \quad (2.29)$$

where ρ is the air density.

For the model of the actuator disc also often a rotational sampling filter is used [13], [16]. This filter describes how there is a variation in shaft torque when the blades sweeps over the rotor disc. These variations are periodic with multiples of the rotational speed of the turbine shaft. In this work this filter is not implemented as the rotational speed is allowed to vary and therefore these pulsations period will vary. However this effect is significant for fixed speed turbines [17], [18].

2.4 Drive-train and Generator

All the rotating parts in a wind turbine are summarized in the drive-train, which consists of a low-speed shaft, on the rotor side, a gearbox and a high-speed shaft, on the generator side. The gearbox is used to adapt the slow rotation of the rotor shaft to the much higher required by the generator. In wind turbines generators can be of either induction or synchronous type. For variable speed turbines induction generators with slip rings are the most common [19]. Synchronous generators though enables, together with a converter, a configuration without the gearbox.

2.4.1 Moment of Inertia

The rotor blades in a wind turbine are very large with lot of weight and create a significant moment of inertia into the system, specially in comparison to the generator. This inertia behaves like a capacitor in a electric circuit, storing energy when the turbine accelerates and restoring it during deceleration. It also accordingly prevent fast variations of the rotor speed on the turbine shaft meaning that it acts like a low-pass filter [2]. The rotor's moment of inertia is much larger than the generators.

Model of the Drive-train

The drive-train is described with mass inertias for the turbine blades, J_a , and the generator, J_g , as can be seen in the left in Figure 2.13, which also contains the gearbox, with ratio $1/n$ [6].

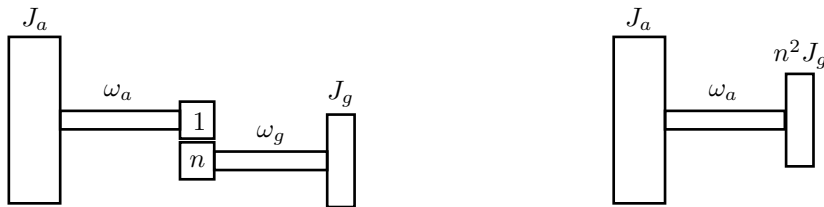


Figure 2.13: Drive-train

With all the parameters and quantities referred to at the low speed side of the turbine, as at the right in the figure, this gives the torque equation for the whole system [1], ignoring the shaft stiffness.

$$\frac{d\omega_a}{dt} = \frac{1}{J}(T_a - nT_e) \quad (2.30)$$

$$J = J_a + n^2 J_g. \quad (2.31)$$

The equation for the wind turbine, which will be referred to thereby becomes, on the low speed shaft,

$$\frac{d\omega}{dt} = \frac{1}{J}(T_a - T_e). \quad (2.32)$$

2.4.2 Mechanical Conversion to Electrical

The torque created by the wind is transmitted to the generator. As the incoming torque can be very fluctuating, different connections of the generator to the grid can be implemented. Variable speed operation is obtained by controlling the electrical torque of the generator. This is done by connecting a converter between the generator's rotor-circuit and the grid or between the generator's stator and the grid [11].

2.5 Different Operational Modes for a Wind Turbine

The characteristics of the wind turbine varies strongly with the wind speed. It is therefore necessary to develop different control strategies that are valid in different regions. The

most common operational modes will shortly be described here, and in addition also their advantages and disadvantages will be mentioned.

2.5.1 Constant Speed

In constant speed turbines, the generator’s stator circuit is directly connected to the grid and a cage rotor is used [20], [15] and [12]. The rotor shaft speed is thereby almost locked by the electrical frequency of the grid, admitting only small variations from it’s nominal value. Since λ is inversely proportional to the wind speed, se Equation 2.29, this means the turbine’s power is only optimized for one operating point.

The drawback of using fixed speed is that the fluctuations in the wind will lead to a fluctuating shaft torque. This has the consequence of voltage fluctuations on the electrical grid, specially when connected to a weak grid. The shaft pulsations will also result in high stresses on the rotor, shaft, gearbox and generator [13].

Stall Control

Stall-regulated turbines have blades that are designed to stall at higher wind speeds, and in this way the incoming power is limited close to the rated one. This concept is the most common used in turbines today [12].

The power characteristics for a stall controlled wind turbine can be seen at the left in Figure 2.14 for the pitch angle 0° .

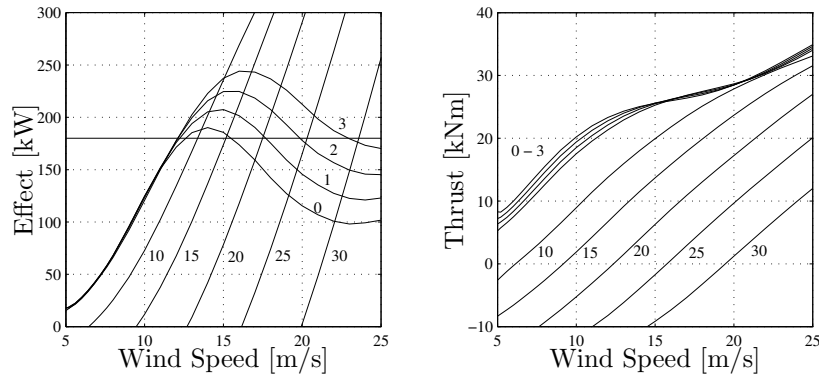


Figure 2.14: Effect and Thrust for Different Pitch Angles with Constant Speed Operation

Active Stall Control and Pitch Control with Constant Speed

If the turbine is pitched slightly at high wind speeds, to adjust the stalling, this is called active stall control. This is used to obtain rated power in the whole high wind speed region. In Figure 2.14 pitch angles between $0 - 3^\circ$ represents operation where this type of controlling is used. This is due to the fact that the power can be kept closer to the nominal, and as seen from the curves at right keeping the thrust at a similar level. However if the pitch angles are allowed to change in a broader interval this will lead difficulties for limiting the power for high wind speeds. This can be seen in the left plot in Figure 2.14, as large differences in power output occur between the different pitch angles [13].

2.5.2 Variable Speed

By using a variable rotor speed at low wind speeds it is possible to operate at a λ that results in maximal C_p and thereby run at it's highest efficiency [21], [22]. Variable rotational speed control gives due to this the opportunity to maximize energy capture in the low wind speed range. Other important advantages associated to operation in this mode are reduction of the drive-train mechanical stresses, improvement on output power quality and reduced noise emission, especially important with wind turbines located near occupied areas [20]. Variable speed requires control of the rotational speed by varying the electrical torque on the generator against the load torque from the wind.

When variable speed is used it is almost always in combination with pitch control as these are very suitable to use together.

2.6 Turbine Operation

The power versus wind characteristics have a highly non-linear relation for wind turbines. This together with the great variations with time for the wind speed makes the control design for a wind turbine a non-trivial task. To be able to control the system satisfactory, the correct state of the turbine has to be determined for each operating point. With adequate status of the system, suitable reference signals to the regulators can be determined. The most desirable operation for the wind turbine is to maximize it's energy capture throughout the whole wind speed interval. This requires that the systems steady state qualities are determined with high accuracy over the whole interval.

2.6.1 Steady State Operation

The turbine's operation is mainly determined by it's possibility to extract maximal power from the wind for each stationary wind speed. For the evaluated wind turbine therefore it's most optimal operation is examined, within the system's limitations, and with these a control strategy is determined.

Optimal Steady State Operation

For the lowest wind speeds most efficient operation for the wind turbine is to run at maximal C_p value with

$$\lambda_{max} = \frac{\omega R}{WS}. \quad (2.33)$$

The pitch angle will be kept fixed at it's most efficient position, around 1° . This can be achieved by using speed regulation until, with increasing wind speed, the nominal speed of the turbine has been reached. With increasing wind speed then, with the speed kept at nominal speed, the pitch angle is kept at the one giving the highest C_p value until rated power is reached. In the rest of the operating region then, with nominal speed, the pitch angle will be adjusted so that the rated power is held in the whole high wind speed area of the turbine. In Figure 2.15 power, torque, rotational speed, C_p , λ and pitch angle as function of the wind speed can be seen.

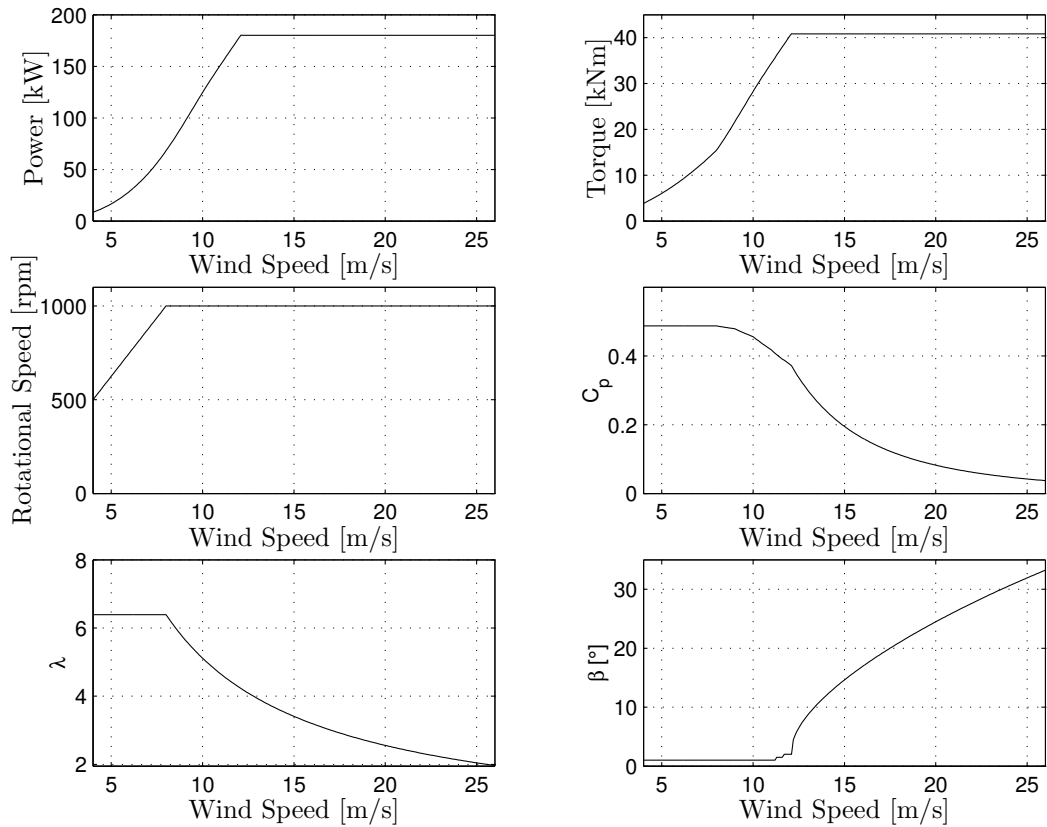


Figure 2.15: Most Effective Operation of the Wind Turbine

For the determination of these operating points, blade element theory have been used to get the most exact values for each parameter. These optimal operating points will be used as reference values by the controller to operate the wind turbine with right strategy over the whole wind speed interval.

2.6.2 Steady State Control

The power-curve from Figure 2.15 will now be used as a reference to state a proper control strategy for the turbine. This can be seen in Figure 2.16 where the three different controlling areas are shown.

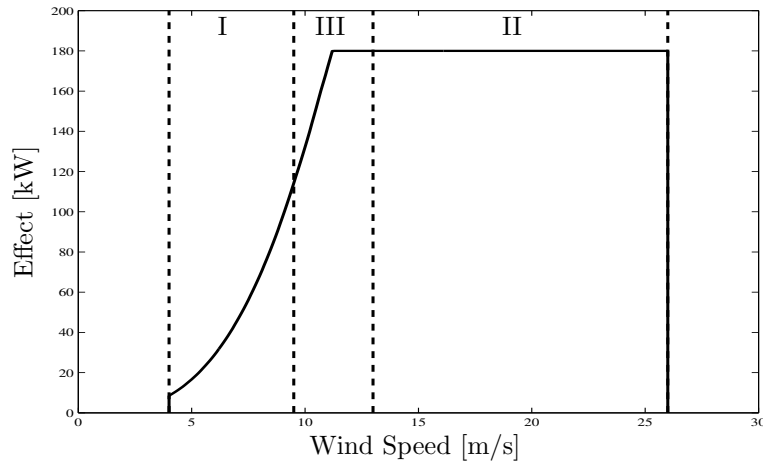


Figure 2.16: Areas for Different Control Operation

In the first interval, the low wind speed interval, variable speed regulation is used to keep the turbine at its most effective operation. Here the pitch angle is kept at 1° , which leads to that C_p is at the point which gives the best efficiency. This mode can be used up to 9.5 m/s where the nominal speed of the turbine is reached.

In the second interval, the high wind speed interval, the rotational speed is kept at the nominal and the pitch angle is regulated to give the rated effect. This interval will start at a wind speed around 13 m/s and end at a wind speed of 26 m/s.

For the third interval, the middle wind speed interval, the generator is controlled to keep nominal speed with a pitch angle kept at constant 1° .

2.7 Controlling

As already stated in previous section three different methods of controlling will be used in each of the wind speed intervals.

2.7.1 Low Wind Speed Interval

For the low wind speeds, variable speed control will be implemented to regulate the electrical torque of the generator. This is done in order to smooth out fluctuations on the electrical torque by slowly regulating the rotor speed.

Speed Regulator

The speed of the generator is controlled by regulating the electrical torque on the generator [5], [2], [22] and [23] as shown in Figure 2.22.

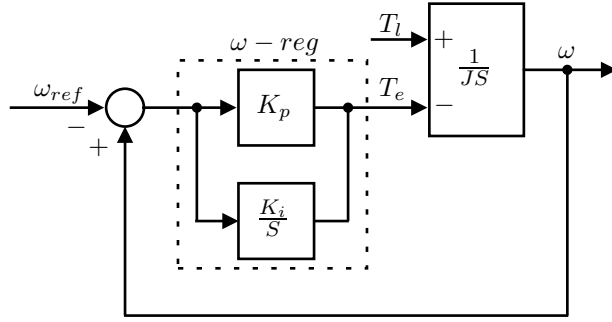


Figure 2.17: Rotational Speed Controller

The reference to the PI-regulator is

$$w_{ref} = \frac{\lambda_{max} WS}{R} \quad (2.34)$$

which results in maximal C_p for the rotor actuator. For this a good estimation of the wind speed is required. Wind measurements by an anemometer does not sense the same turbulence as the wind turbine and the gusts arrive with a time delay. If the systems characteristics are well known the wind speed can be estimated from Equation 2.29. For this work the estimated wind speed has been set the same as the spatial filtered wind speed. As the rotor blades contains a large moment of inertia changing the generator speed will actually imply high electrical torque outputs, especially if fast speed changes are commanded [24].

Generator Model

The generator is in this work assumed to be a induction machine controlled by a converter system. The total electrical generation for the system is modelled only as a static relation with $T_e^{ref} = T_e$ as the electrical dynamics, for the induction machine, are much faster than the mechanical. Instead of only being able to operate at the commonly known predestinated steady-state torque-speed characteristics, the turbine can now be operated in the whole shaded area shown in Figure 2.18.

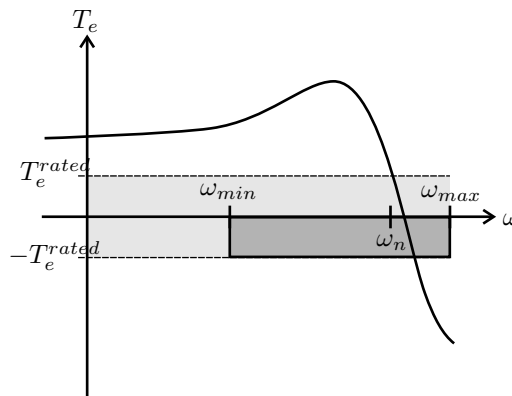


Figure 2.18: Induction Machine Model

The turbine is, however, only running in generator mode, i.e. the negative part of the shaded area. Moreover as the turbine isn't operating for low wind speeds the generator speed will start from ω_{min} and run up to maximal allowed speed ω_{max} . Therefore only the dark shaded area of the generator's operational region will be studied in this work.

Energy Flowchart

The energy input to the system is given by the kinetic energy of the wind flow. As this flow is highly varying and the turbine's rotor speed is variable a increase and decrease of the rotor's kinetic energy is caused, due to it's angular momentum. The inertia of the generator is neglected as it is much smaller than the rotor's. The relation is given by

$$W_{wind} = W_{rot} + W_{electric} \quad (2.35)$$

where W_{rot} is the kinetic energy extracted by the turbine and W_{wind} not the available but the captured energy form the wind as shown in Figure 2.19.

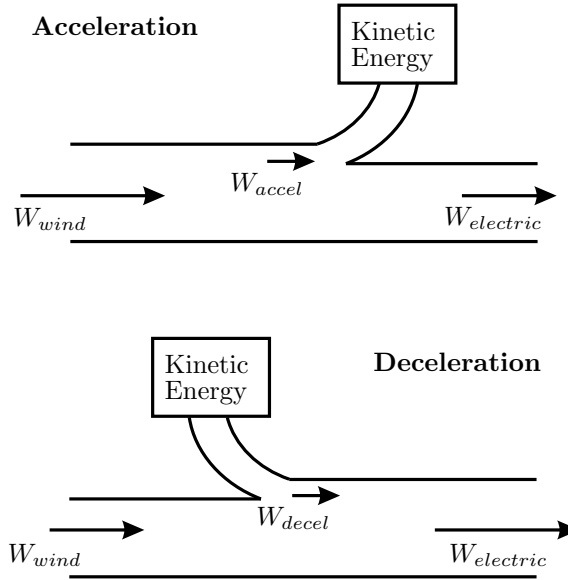


Figure 2.19: Energy Flows in Wind Turbine

When the wind speed increases energy is stored by the rotor and otherwise consumed when the speed decreases [2]. As the model of the wind turbine is only analyzed in respect to it's regulation, and full models of the generator and drive-train are not implemented, the only energy losses in the system occur due to it's possibility to track optimized reference signals. The deviation from this optimal reference will lead to the only energy losses of the system. Energy losses for simulations in the analysis chapter will therefore be calculated as

$$W_{loss} = W_{opt} - W_{wind} - \Delta W_{rot} \quad (2.36)$$

$$W_{wind} = \Delta t \sum_{k=1}^N P_{a_k} \quad (2.37)$$

$$\Delta W_{rot} = \frac{J_a}{2} (\omega_{init}^2 - \omega_{final}^2) \quad (2.38)$$

where W_{opt} is the optimal energy capture, Δt is the time step, N the number of samples and ω_{init} respectively ω_{final} the rotor speed at the first and last sample.

2.7.2 High Wind Speed Interval

For the high wind speeds the desired operation is to keep the turbine's power at the rated. This is achieved by regulation of the rotor blades pitch angles.

Pitch Regulator

As the pitch actuator has a performance limitation of $\dot{\beta}_{max}$, on the ramping speed, this prevents fast control of the regulator. The pitch regulator is thereby chosen to directly act on the torque signal from the loading torque. This requires a torque observer as this is a unknown parameter for the controller. Work by Cardenas, Asher [22] and Bossanayi [25] however shows that this can be achieved with god accuracy. The model of the pitch regulator therefore is as shown in Figure 2.20.

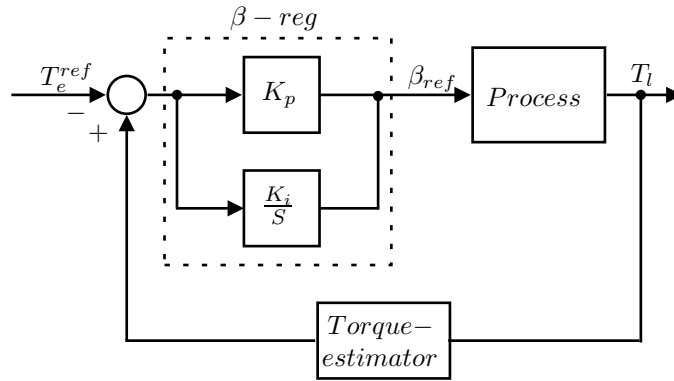


Figure 2.20: Pitch Controller

And the controlled process as shown in Figure 2.21.

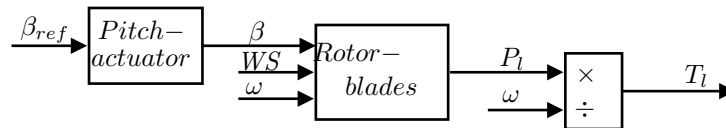


Figure 2.21: Process

The torque observer described by the authors uses determination of $\frac{d\omega}{dt}$ in Equation 2.32 to get estimation of the torque generated by the wind. Results in [22] shows that the torque observer gives very good characteristics for the regulation. In this work the torque observer has been set ideal, meaning that estimated torque and actual torque generated by the wind has been set the same.

Pitch Actuator

The pitch-actuator describes the possibility for the rotor blades to adjust to a given desired pitch angle. The actuator is modelled with as a first-order transfer function

$$B_{act}(s) = \frac{\alpha}{s + \alpha} \quad (2.39)$$

$$\alpha = \frac{1}{T_\beta} \quad (2.40)$$

where T_β is the time constant [1]. The actuator though has a maximal changing speed of the pitch angle which is modelled with a rate limiter as

$$\frac{d\beta}{dt} = \frac{1}{T_\beta}(\beta_{ref} - \beta), \quad \frac{d\beta}{dt} \leq \dot{\beta}_{max} \quad (2.41a)$$

$$\frac{d\beta}{dt} = \dot{\beta}_{max}, \quad \frac{d\beta}{dt} > \dot{\beta}_{max} \quad (2.41b)$$

β_{ref} representing the pitch demand and the pitching speed boundary $\dot{\beta}_{max}$. The pitch actuator will hereby limit the performance of the pitch control as if given poor specifications will make hindrance for the regulator.

2.7.3 Middle Wind Speed Interval

For the middle wind speed interval the operation of the turbine will controlled to, with pitch angle 1° , keep the nominal speed, which will be done by stalling the turbine.

Stall Regulator

This regulator is the same that is used for fixed speed turbines. The regulator scheme therefore results in the one seen in Figure 2.22 where K_p is the crucial parameter of control.

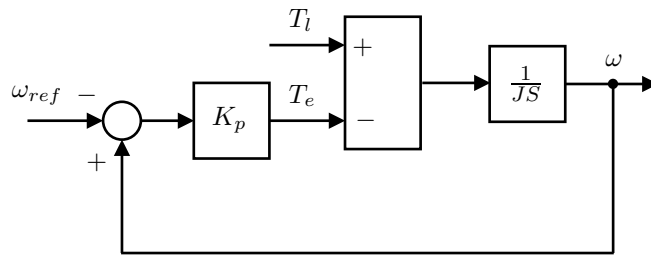


Figure 2.22: Speed Controller for Stall Regulations

Here the reference will be the nominal speed of the generator and the amplification K_p will be very high in order to keep the electrical torque near the loading torque from the wind. This is done in order to avoid that the generator speed is not allowed to differ from the nominal. This will however lead to fluctuations in the electrical torque when the turbine is exposed to a realistic wind input as the wind is highly varying.

In this interval also pitch regulation could be used to improve the performance of the regulation, but this not a investigated in this work.

Linearized Generator Model

To get a good regulation during this mode a proper value of K_p had to be found. This will be done by making a linear model of the generator around its synchronous speed [26], [22]

$$\Delta T_e = K \Delta \Omega_a. \quad (2.42)$$

By Laplacetransforming Equation 2.32 and using small signal analysis we get

$$Js \Delta \Omega_a = \Delta T_a - \Delta T_e. \quad (2.43)$$

Together with Equation 2.42 this results in

$$\frac{\Delta T_e}{\Delta T_a} = \frac{1}{1 + sK}. \quad (2.44)$$

The model from Figure 2.18 is enlarged as can be seen in Figure 2.22. K now represents the angle of inclination of the linearized model and further more the K_p -parameter of the controller shown earlier.

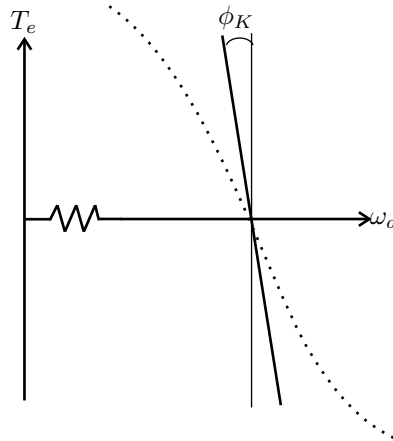


Figure 2.23: Linear Generator Model around Nominal Speed

With different values on K_p the regulator now can be operated to track the loading torque with varying capacity.

Chapter 3

Analysis

3.1 Wind Turbine Operation at Different Wind Speed Intervals

As already mentioned in the previous section the wind turbine is controlled with three different methods in the three wind speed intervals, low, middle and high. These regions will here be studied separately to get a proper picture of each controlling method.

The low wind speed interval, where the rotor speed is regulated, starts at 4 m/s and stops at 9.5 m/s when the nominal speed of the turbine has been reached. The middle wind speed interval then continues up to 11.2 m/s where rated power of the generator is reached. The last interval then proceeds up to 26 m/s where the load on the wind turbine is too high and it is therefore disconnected.

3.2 Low Wind Speed Operation

In this interval the turbine is controlled by the speed regulator which controls the electrical torque on the generator [5], [2], [22] and [23]. The reference speed is given by

$$w_{ref} = \frac{\lambda_{max} WS_{filt}}{R}. \quad (3.1)$$

Here WS_{filt} is the spatial filtered wind speed, seen by the rotor, and λ_{max} is the value that together with $\beta = 1^\circ$ is resulting in the highest efficiency-value for the rotor disc, as could be seen in on the $C_p(\beta, \lambda)$ -curves shown in Figure 2.12. For the controlling a PI-regulator circuit for the speed error is used as shown in Figure 3.1.

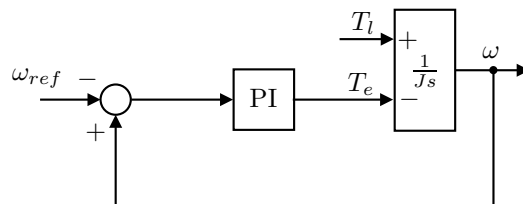


Figure 3.1: Speed Regulator.

The torque generated by the wind speed is given by

$$T_l = \frac{\rho}{2} \pi R^2 C_p(\beta, \lambda) \frac{WS_{filt}^3}{\omega}. \quad (3.2)$$

Various regulator settings are tested to get a picture of how the relation between speed and electrical torque is working. To obtain the stress reductions in the electrical torque, the strategy is to use a slow speed regulation. This will though lead to that the energy capture will decrease since the turbine now will operate with a lower efficiency.

Simulations with wind speed steps are shown to demonstrate the relation between the electrical torque and speed of the generator. How different settings on the regulator will effect the electrical torque of the generator is shown by simulations using a realistic wind speed input. These results are then compared with simulations on a fixed speed wind turbine.

3.2.1 Step Response

First the response to a wind speed step from 5 to 6 m/s with no limiter is studied. The response for the electrical torque is held in the generator's operating region modelled in Figure 2.18. The result is shown in Figure 3.2.

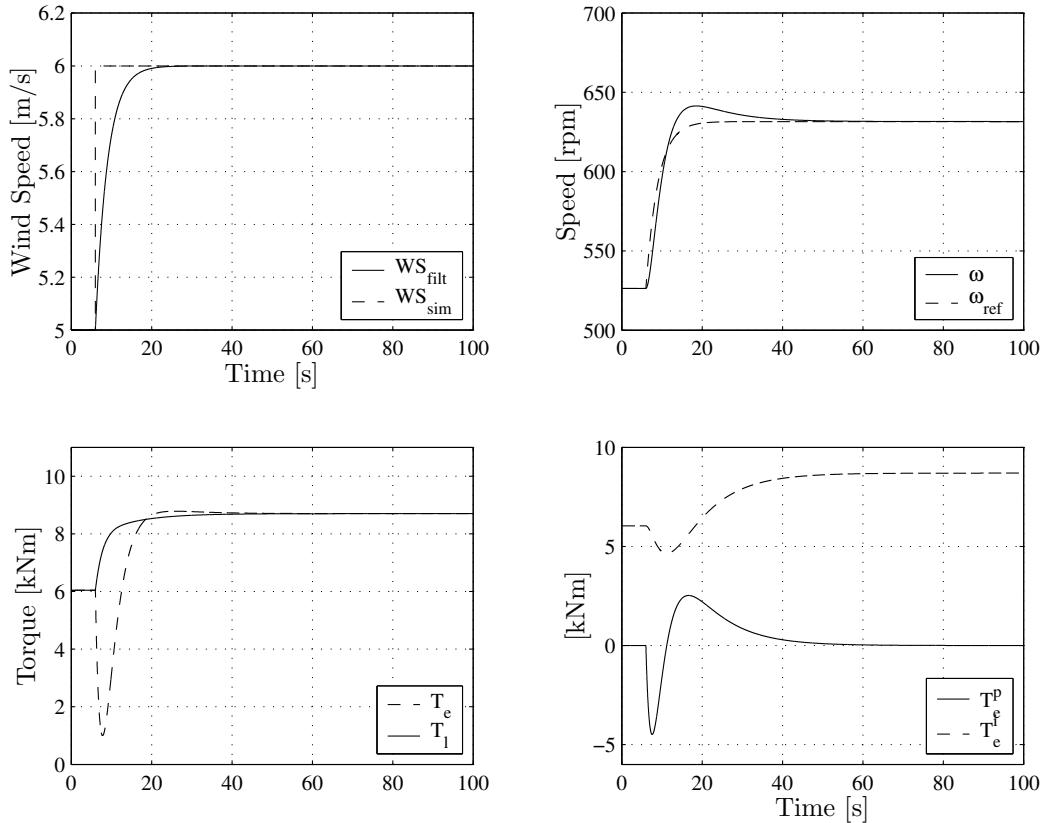


Figure 3.2: Steps in Wind Speed, $K_p = 2000$ and $K_i = 200$.

Here the first plot shows the realistic, simulated, wind speed against the spatial filtered. The second one presents the generator speed against the optimized speed reference. The

third displays the torque generated by the wind against the electrical torque from the generator, referred to the low speed shaft. And in the last the proportional and integral parts of the electrical torque are plotted separately. As can be seen the time responses for the speed- and torque steps are very long, several seconds. However, note that in spite of the slow speed response, the electrical torque is changed strongly to achieve this which is very crucial, especially if the reference changes fast. The integral part of the regulator adjusts the level but as it has very slow characteristics it will have no greater effect on the speed of the regulation, as the fast response is determined by the proportional part.

For a slower regulation on the same step signal, with same variables plotted, the results are seen in Figure 3.3.

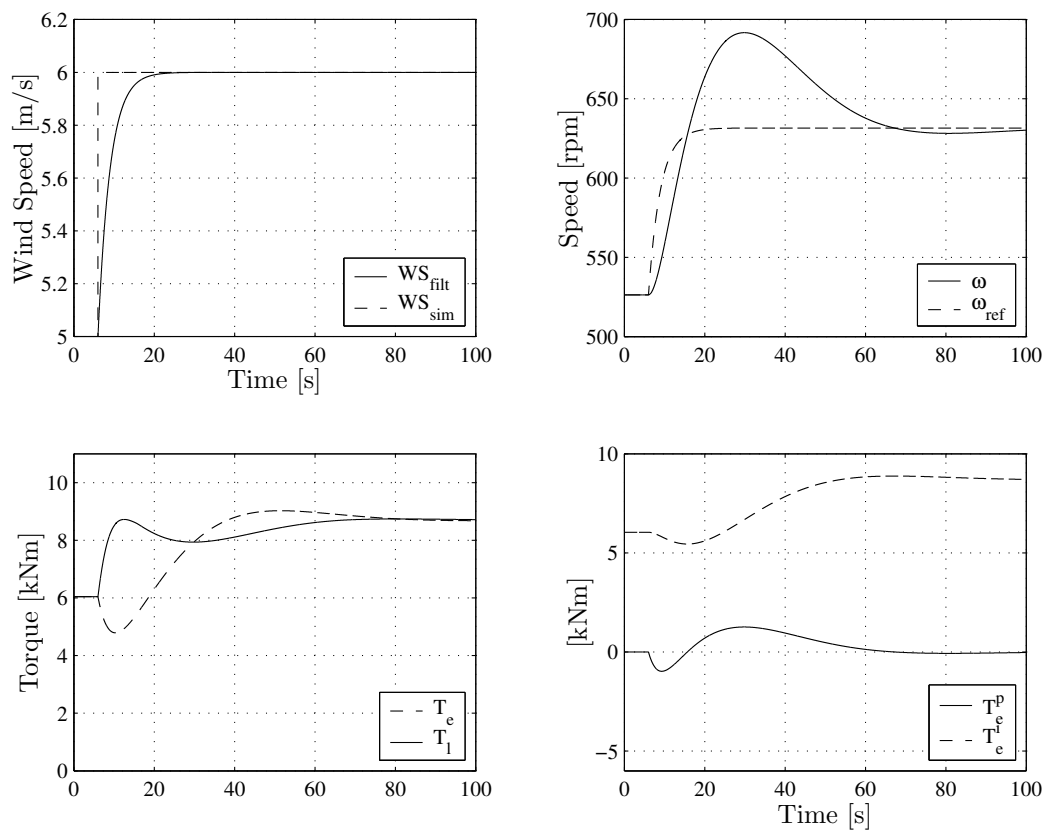


Figure 3.3: Steps in Wind Speed, $K_p = 200$ and $K_i = 20$.

This shows a great reduction on the electrical torque signal, but also how the speed follows the reference slower. For a strongly varying reference this slow tracking will lead to that the system may become unstable.

3.2.2 Simulations using Realistic Wind Input

For the evaluation of the systems restrictions, when exposed to different wind speeds, settings on the control system will be tested. This will imply changed values of the proportional and integral amplifications of the regulator and also the effects of different turbulence intensities will be evaluated. To put the effect of the changes on the regulator parameters, the same wind input has to be used to each tested set. The wind speed series is shown in Figure 3.4, where the dashed line represents the actual wind speed and the solid line the spatial filtered wind speed.

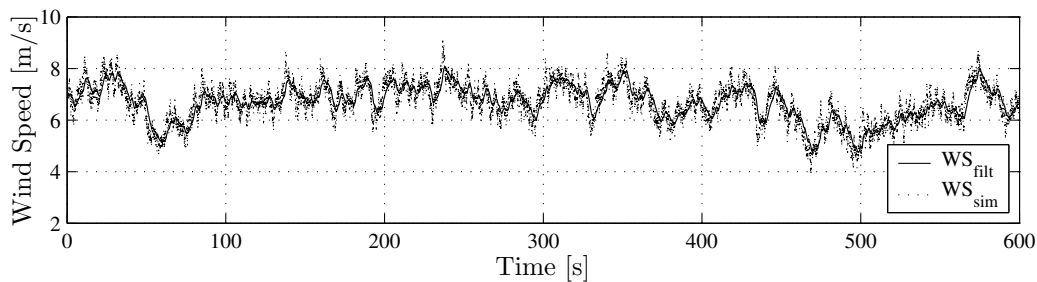


Figure 3.4: Stochastic Wind. Mean Wind Speed 7 m/s and Turbulence Intensity 10.8%.

Effect of changed Regulator Parameters

To get a good picture of the characteristics of the effect of the changed regulator parameters two sets with fast respectively slow parameter sets will be evaluated. The frequency spectrums of the electrical torque for these will then be compared. First to be presented is a simulation with the parameters from the faster of the previous step responses as Figure 3.5 shows.

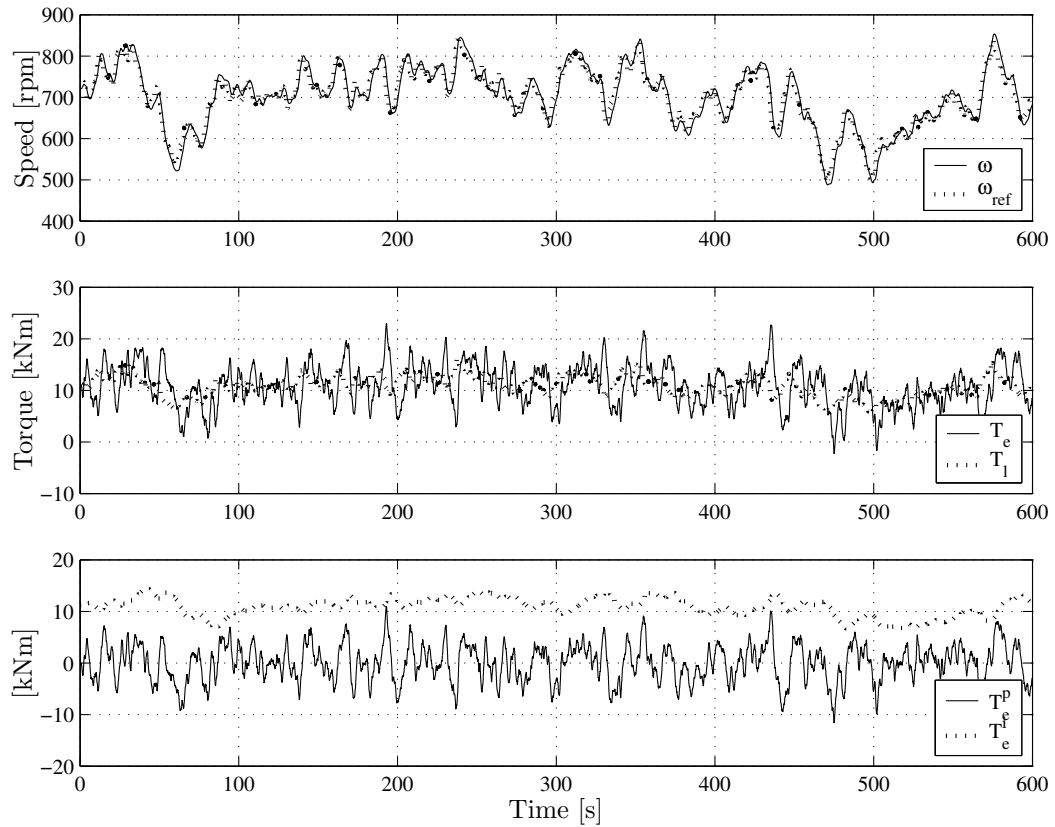


Figure 3.5: Stochastic Wind with Fast Regulation, $K_p = 2000$, $K_i = 200$.

The same variables as studied earlier are shown, speed, torque and the proportional and integral parts of the electrical torque. Here, it clearly can be seen that the speed is tracking the reference speed very well and thereby keeping a good efficiency for the turbine's energy capture. The electrical torque on the other hand shows high disturbances caused by the high strength of the speed regulation. The main reason for this is the high inertia of the rotor which requires very high energy outputs to quickly compensate for the speed variations. This is best shown from the previous plot of wind speed where the wind seen by the rotor isn't responding on the fast fluctuations in the wind. Here results also show that it is the proportional amplification in the regulator that achieves this effect of fast compensation. The integral part shows a more smooth compensation on the error between the reference and the actual signal. Therefore, now the proportional part is decreased strongly to get a slower parameter set which is tested in Figure 3.6.

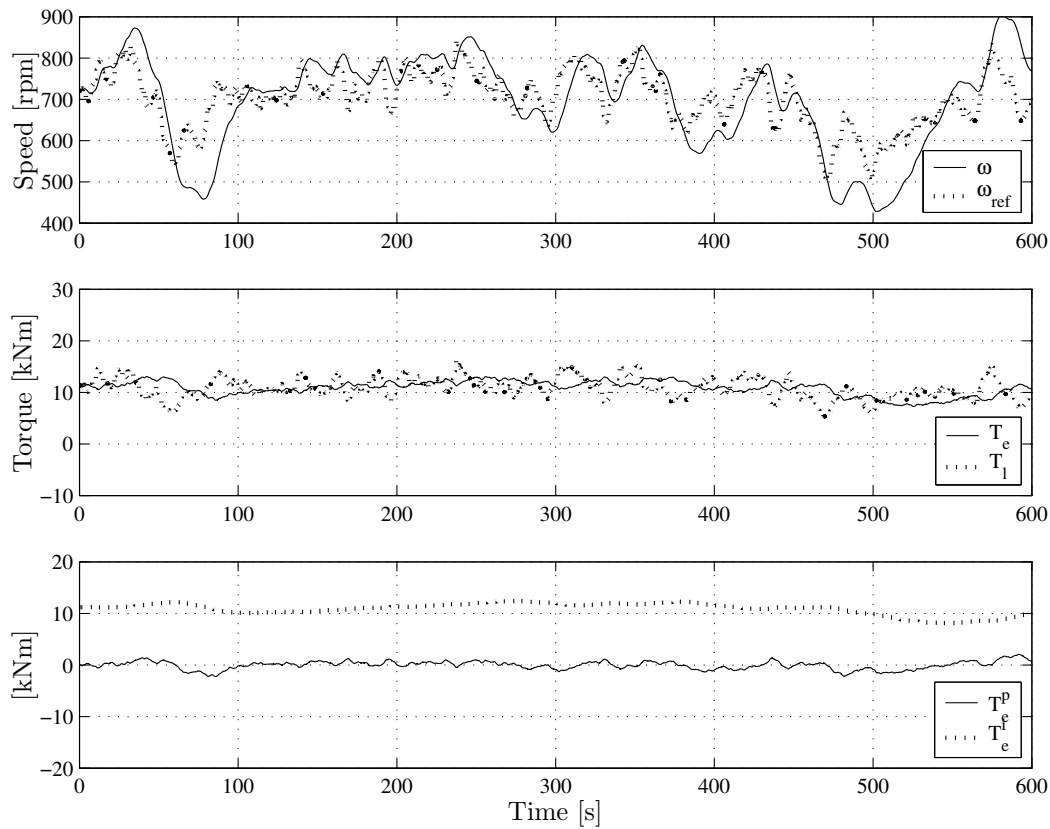


Figure 3.6: Stochastic Wind with Slow Regulation, $K_p = 100$, $K_i = 4$.

Here the relation between speed and the electrical torque can clearly be observed. Now the speed is allowed to both increase and decrease without fast compensation from the regulator. This leads to a great smoothness in the electrical torque and thereby a lower stress on the drive-train components.

Simulations with even slower regulation on the speed was tested, but for these the speed diverged from the reference and they didn't run for all the simulated time. This shows that too slow regulation can make the system unstable.

The effect is also pictured with a plot of the frequency contents of the electrical torques for the both simulated cases as shown in Figure 3.7.

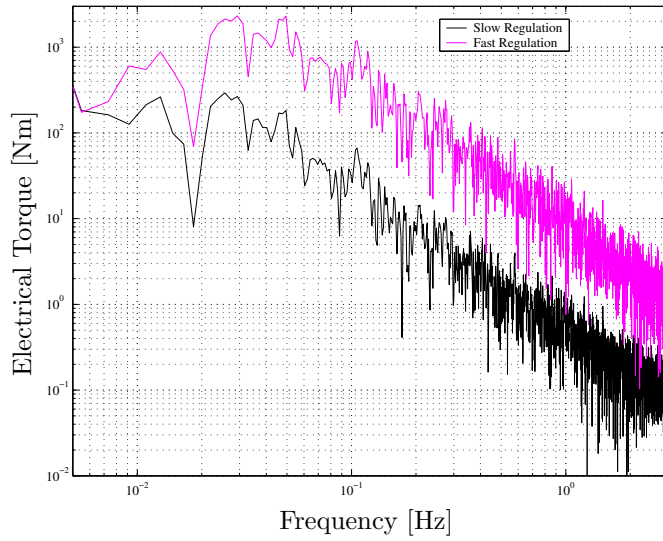


Figure 3.7: Frequency Spectra for the Fast and Slow Regulations

Except for the very lowest frequencies the slower regulation shows a great reduction of the frequency components of the electrical torque.

3.2.3 Fixed Speed Wind Turbine

The rotor speed, torque and energy capture are also determined for a classic fixed speed wind turbine. This can be seen in Figure 3.8.

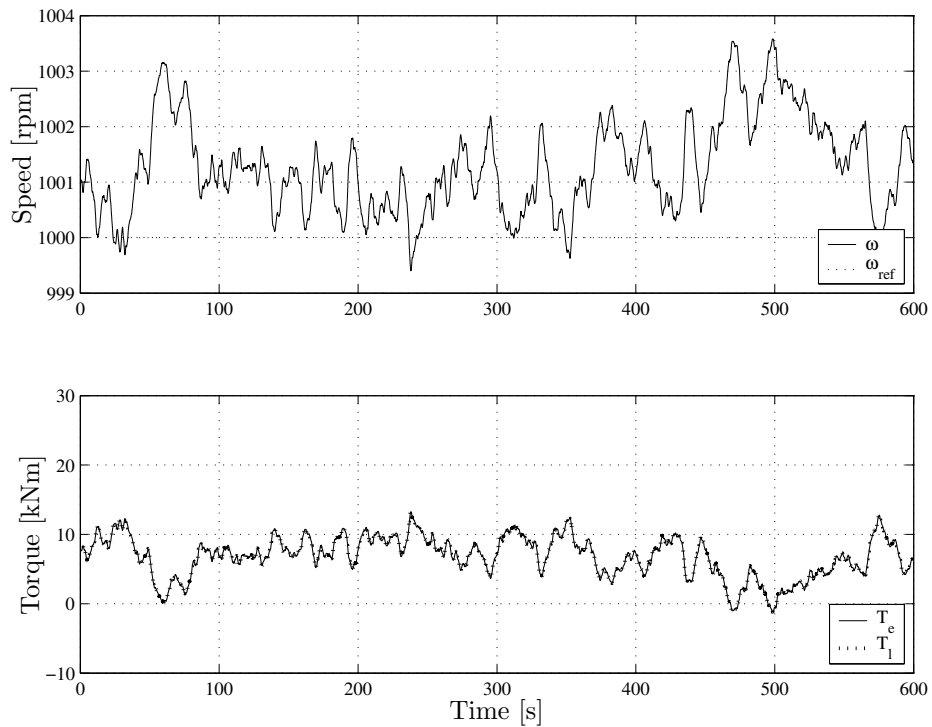


Figure 3.8: Stochastic Wind with Stall Controlled Wind Turbine with slope 1%

As the generator speed is almost fixed to the nominal, the variations in the electrical torque is directly responding to the loading torque generated by the incoming wind. This will apply that λ now is not fixed to the optimal value and the efficiency of the turbine is now directly determined by the value on $C_p(\lambda)$ -curve.

As there is no rotational sampling filter implemented for the model, the torque fluctuations will be to low in the fixed speed case and a proper comparison between fixed speed and variable speed operation can not be done.

3.2.4 Energy Losses versus Mechanical Stresses

To obtain how different settings on the speed regulator parameters and different turbulence intensities influences the mechanical stresses on the turbine's shaft, results from several simulations are evaluated.

The stresses of interest are the high-frequency components of the electrical torque. Therefore the electrical torque from all simulations are highpass filtered with a 9:th order Butterworth filter, with cut-off frequency of 0.5Hz. The standard deviation for the results are then presented in Figure 3.9. Energy losses are calculated with the deviation from the optimal mean energy, for C_p^{max} , and the mean energy for the wind generated torque for the simulated cases.

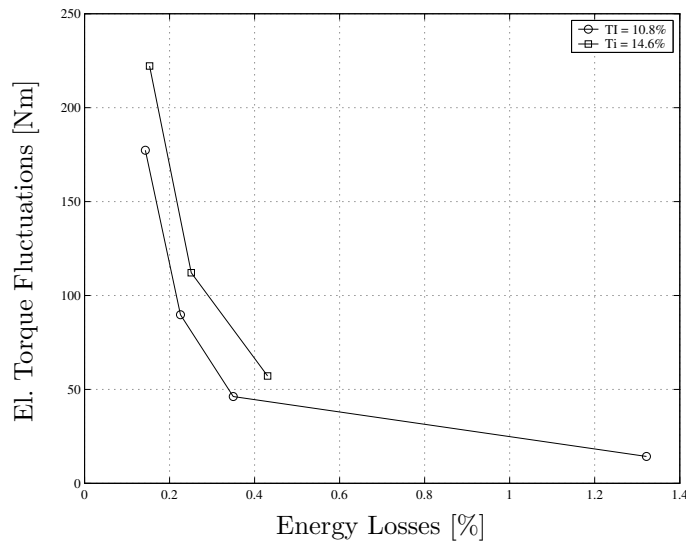


Figure 3.9: Standard Deviation on High Frequent Torque Fluctuations against Energy Losses

The lowest of the two curves is obtained for the wind speed in Figure 3.4, the curve above for a wind speed series with a higher turbulence intensity, 14.6%. For lower proportional amplifications the system became unstable and the speed diverged after some time, especially for the higher turbulence intensities. For this reason the regulator can't be made too slow. The point for the fixed speed wind turbine, for the lowest turbulence intensity, is not plotted in the figure but it was almost 30% on the energy loss and 31.3Nm on the electrical torque fluctuations. A reason why there is very small, and low, values on the energy losses for the variable speed turbine, is that the used blades are designed

for a fixed speed turbine. This has the consequence that the value for $C_p(\beta, \lambda)$ will not vary much for the simulated wind speed interval. Normally fixed speed turbines can be operated with 2 speed operation and thereby lower their energy losses [19].

3.3 High Wind Speed Operation

At the higher wind speeds, the desired operation of the turbine is to keep the turbine speed close to the nominal speed and also the output power close to the rated [1], [5]. Two different control methods will be tested. The first method is to estimate the torque generated by the wind, and regulate directly on the difference between this and the rated electrical torque of the generator [22], [25]. With a good estimation this gives a great advantage because the rotor inertia's slowing effect on the speed is avoided. In this work the estimation is assumed ideal. In order to achieve this, a pitch regulator as pictured in Figure 3.10 is used.

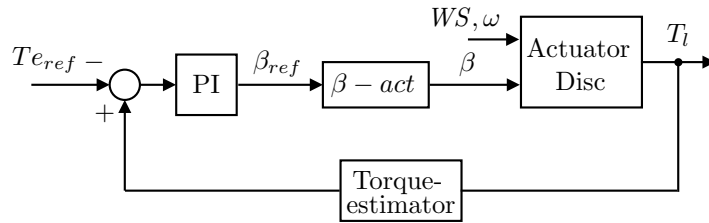


Figure 3.10: Pitch Regulator with Torque Estimator

With the other method the controlling is done by regulation on the speed error as seen in Figure 3.11 [2].

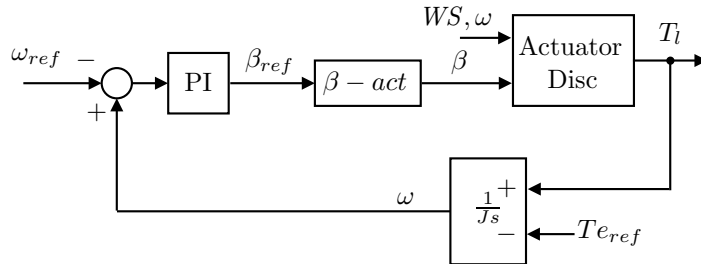


Figure 3.11: Pitch Regulator with Speed Reference

This gives a regulation with much slower characteristics and will be used to show similarities with measured data.

3.3.1 Step Response for Pitch Regulation with Torque Estimator

First the pitch-actuator is modelled with only a first-order transfer function with a time constant of 12ms [1]. The step response for a multistage wind speed signal is tested, which can be seen in Figure 3.12.

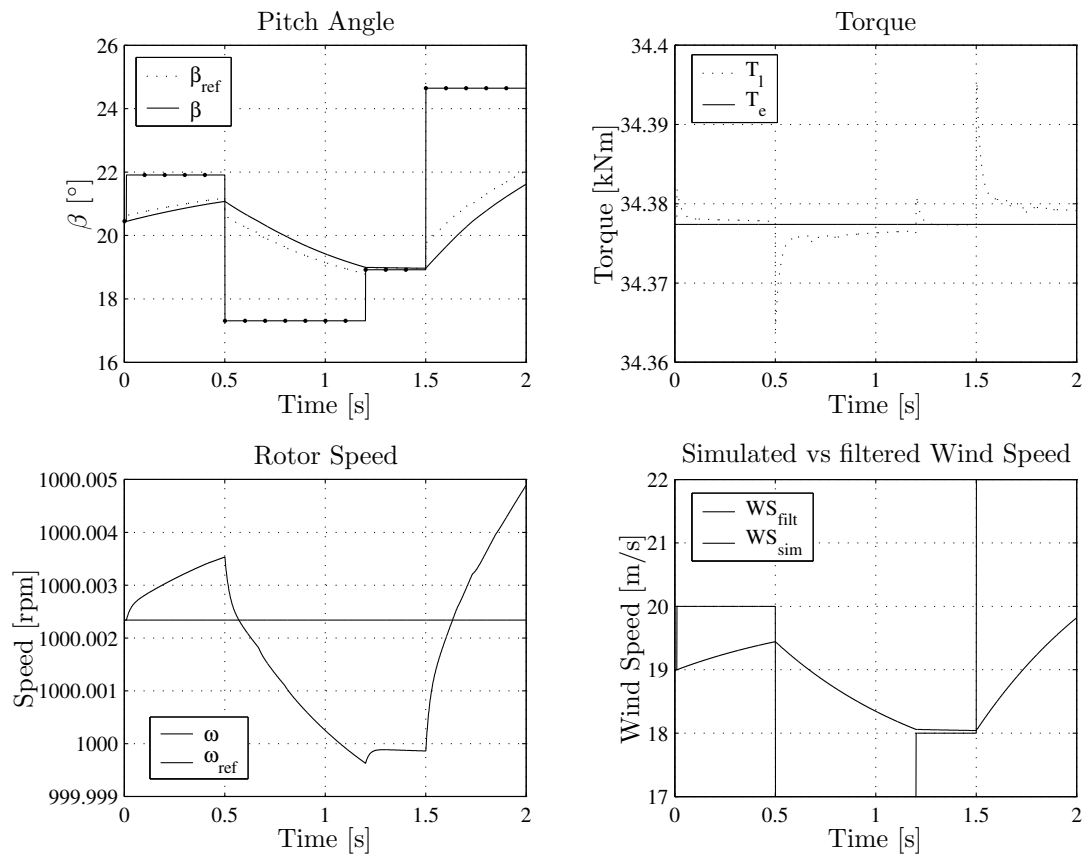


Figure 3.12: Steps in Wind Speed

The first plot shows the pitch angles where the pointed line shows the angle for the determined operation from the previous chapter. The second plot shows electrical torque and the torque generated by the wind. The third the rotor speed and the last simulated and filtered wind speeds. Note that both torque and speed shows insignificant variations due to the ideal torque reference used by the regulator. Moreover it can be seen that the reference pitch follows the characteristics of the filtered wind speed as this is the one seen by the actuator. Thus even though there is a small time delay implemented for the pitch actuator the results show that the PI-regulator is giving very good and fast response.

Ramp Limiter

The most crucial factor for the regulation is it's possibility to quickly respond to variations in the torque generated by the wind. This puts very high demands especially on the pitch actuator which tunes the blade angles to the desired position. In practice all pitch actuators has a limited capacity to change the pitch angles of the rotor blades. To imitate this a ramp limiter is used and step responses for some different ramping speeds are shown in Figure 3.13.

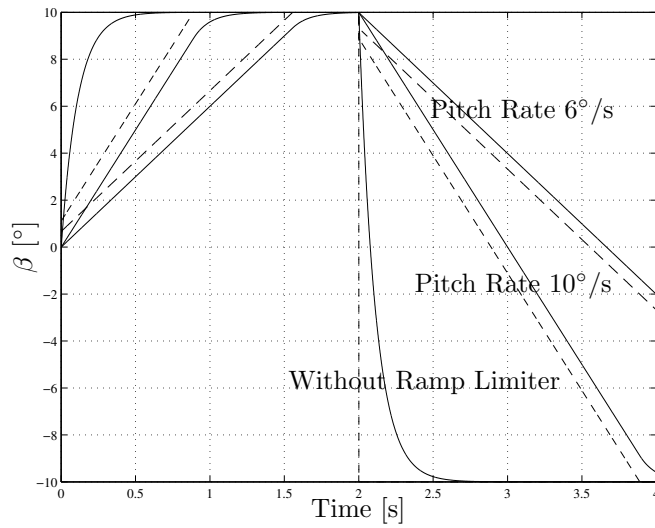


Figure 3.13: Responses for Pitch Actuator

The dashed lines represents the reference values for the actuator and the solid the actual pitch angle. Although the step signal is very large this clearly shows that the ramping speed is of high importance to be able to get a good controllability to the regulator.

3.3.2 Pitch Regulation with Torque Estimator for Simulations with Realistic Wind

The pitch regulators performance will now be evaluated when it is exposed to a realistic wind input. As already pointed out when the step response were tested, the regulator is handling the controlling very fast and reliably. Therefore the effect of different ramping speeds for the pitch actuator will be tested and how it's capability is affected. The wind speed used for these simulations is shown in Figure 3.14.

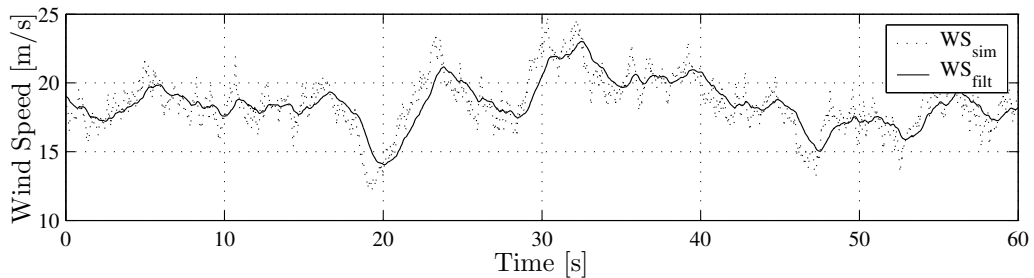


Figure 3.14: Stochastic Wind. Mean Wind Speed 18 m/s and Turbulence Intensity 11.3%.

Effects of Different Ramping Speed

First a pitch rate of $8^\circ/\text{s}$ both up and down is tested as shown in Figure 3.15.

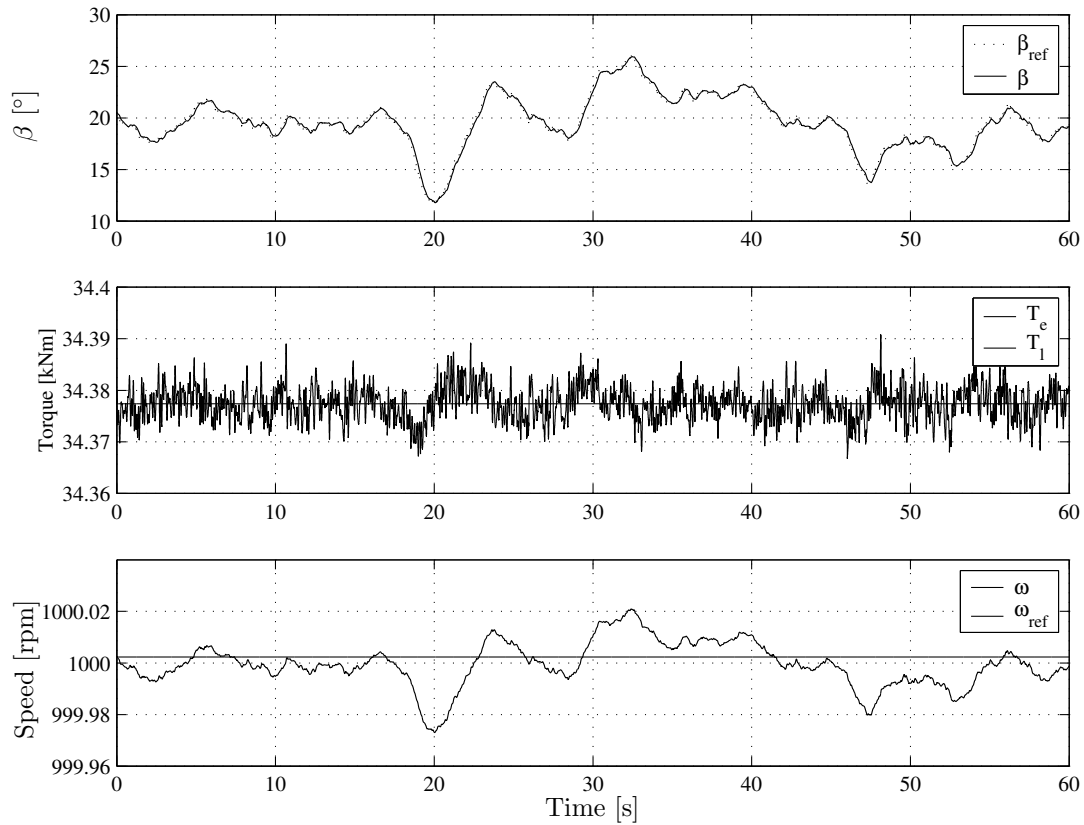


Figure 3.15: High Wind Speed Simulation, Pitch Rate = $8^\circ/s$

The first plot shows the pitch angle and its reference. The second the torque generated by the wind and the electrical torque which is held constant. The last plot shows the speed. As for the cases with the step responses, the torque and speed shows no notable deviation from their references. The pitch angle follows its reference without any restrictions from the pitch actuator. With a good estimation of the torque this gives an excellent performance for the controlling for the high wind speeds.

Now, a slower pitchrate of 4° both up and down is tested as shown in Figure 3.16.

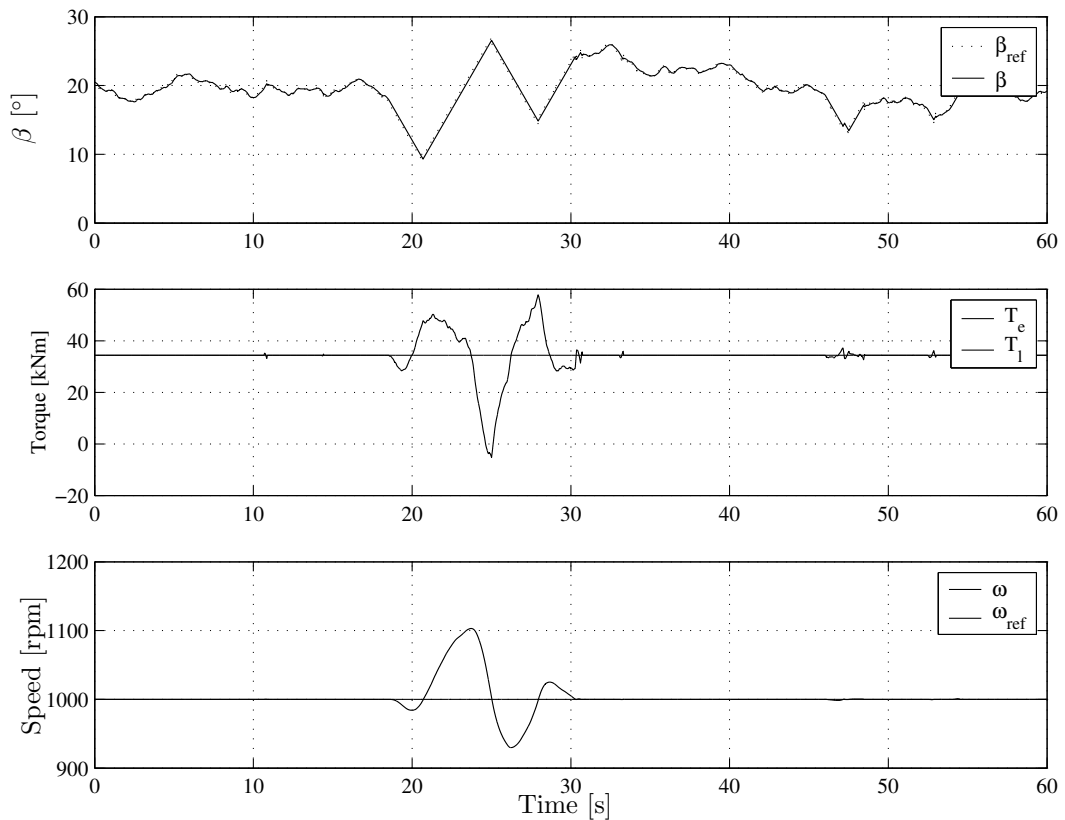


Figure 3.16: High Wind Speed Simulation, Pitch Rate = $4^\circ/\text{s}$

The same type of plots as in the previous case are shown. Here a large disturbance occurs when the wind speed is raising rapidly between about 20 to 30 seconds. As can be seen on the pitch angle in this interval the pitch actuator is running on it's maximal capacity to try to control the loading torque. This also has a great effect on the generator speed which is varying heavily for it's ideal range. This leads to the conclusion that a high pitch rate capacity is highly crucial to get a decent controlling for the high wind speeds.

3.3.3 Need for Pitching Capacity

To see how different pitching speeds affect the performance of the pitch regulator, six different ramping speeds are tested. First the effect on the mechanical torque stresses are simulated and the results are presented in figure 3.17.

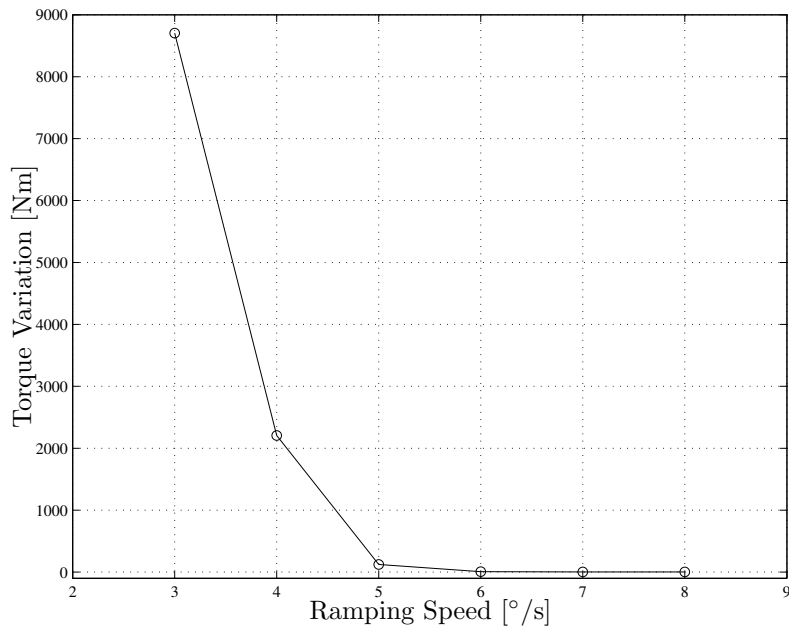


Figure 3.17: Mechanical Stresses against Pitching Speed

Here it can be seen that for pitch-rates over $5^\circ/s$ no effect is hardly seen but for the lower ones there is a distinct deterioration. This is also seen in Figure 3.18 where the speed variation is shown.

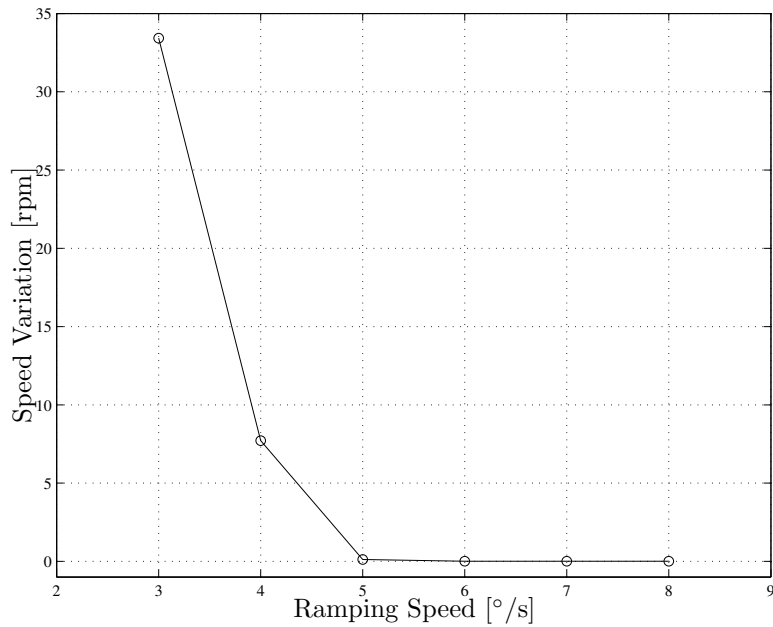


Figure 3.18: Speed Variation against Pitching Speed

The effect is the same as the rotational speed is controlled by the pitch regulator for this wind speed interval.

As already mentioned earlier, these simulations are done with a perfect torque estimator and therefore these results shows very low variations both for the torque and

speed variations for the fastest ramping speeds. These results clearly indicates that a slow capacity for the pitch actuator will make the controlling poor and unstable.

3.3.4 Comparison with Measured Data

Access to data from a 850 kW wind turbine located at Jung has been available and is presented in Figure 3.19.

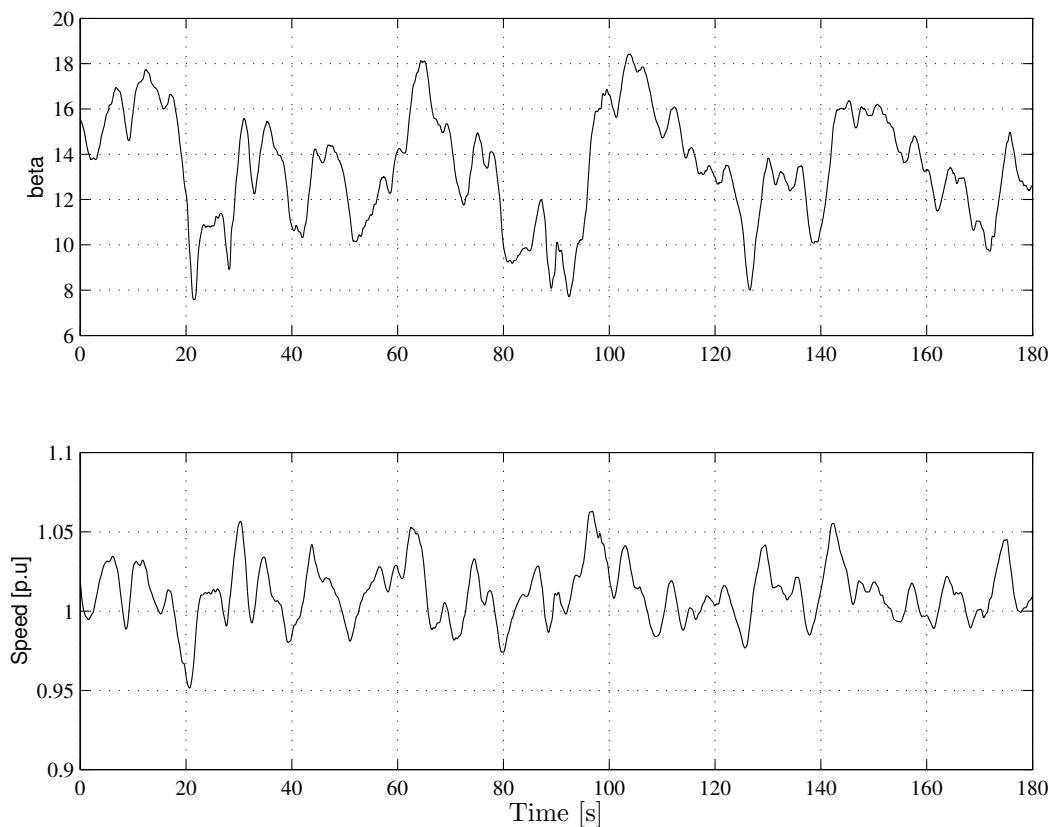


Figure 3.19: Measurements from Wind Turbine at Jung

No wind speed data is provided but this shows the characteristics of the pitch angle and generator speed for a real wind turbine. This will be compared with the second of the two regulators presented earlier as this shows more similar characteristics for the system. Results for these simulations are shown in Figure 3.20.

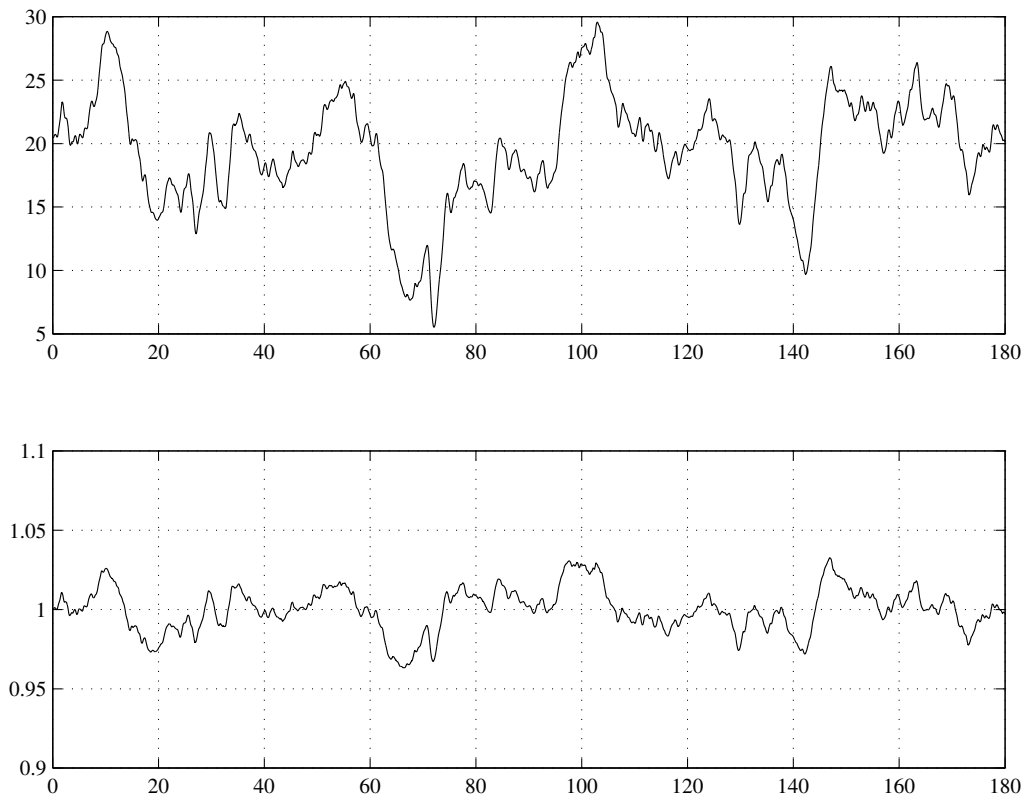


Figure 3.20: Measurements from Wind Turbine at Jung

Although the speed doesn't vary as much for the simulated case as for the measured the opposite effect is seen for the pitch angle. This probably due to different regulator settings for the two systems.

3.4 Middle Wind Speed Operation

The most difficult area for controlling the turbine is the middle wind speed interval. In this interval the best efficiency of the turbine is achieved by running the generator at nominal speed and keeping the pitch angle at 1° . This is achieved by control the generator to stall with regulator model in Figure 3.21.

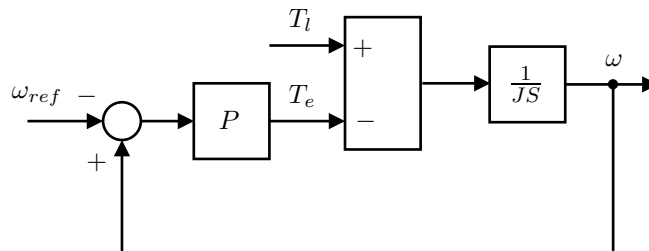


Figure 3.21: Stall Regulation with Speed Controller

The proportional amplification, P , is given by the angle of inclination chosen for the

evaluated model. The wind speed series that been used for these simulations is shown in Figure 3.22.

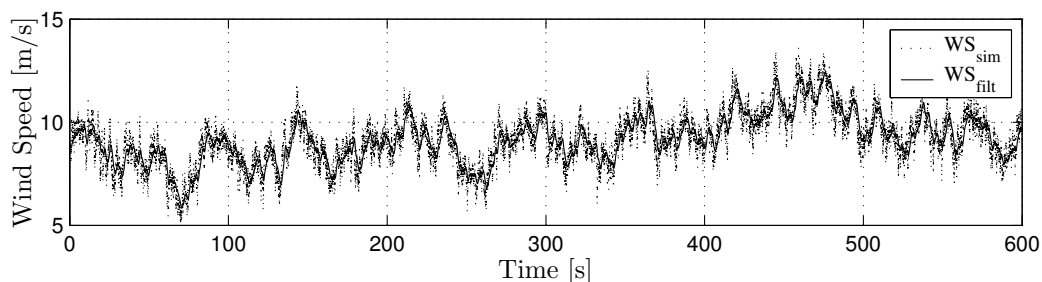


Figure 3.22: Stochastic Wind. Mean Wind Speed 9.5 m/s and Turbulence Intensity 15%.

3.4.1 Generator Model Evaluation

For the simulations three models with different angle of inclination is used. The are defined by their slope which are 1, 5 and 10%. Simulation with each of these are run separately to show their characteristics. In Figure 3.23 the 1 percent slope generator model is shown.

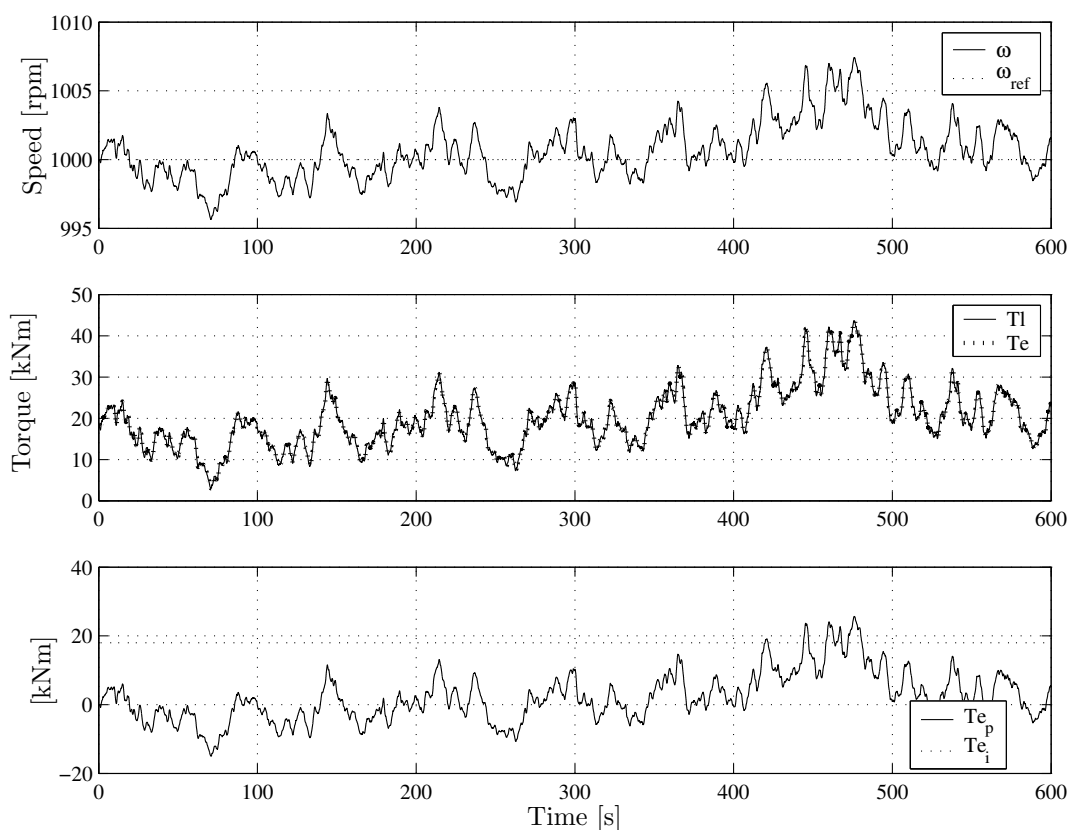


Figure 3.23: Generator Model with 1% Slope

The first plot shows the generator speed, the second loading resp. electric torque, the third proportional resp. integral parts of the electric torque and the last simulated resp.

filtered wind speed. For this model the response to the loading torque is very fast as the inclination-angle has a steep slope. This means that turbine is running at very high efficiency but on the other hand has great variations on the electrical torque. The variations on the generator speed though are marginal. To obtain wanted effect of reduction on the electrical torque variations the 10% slope results is shown in figure 3.23.

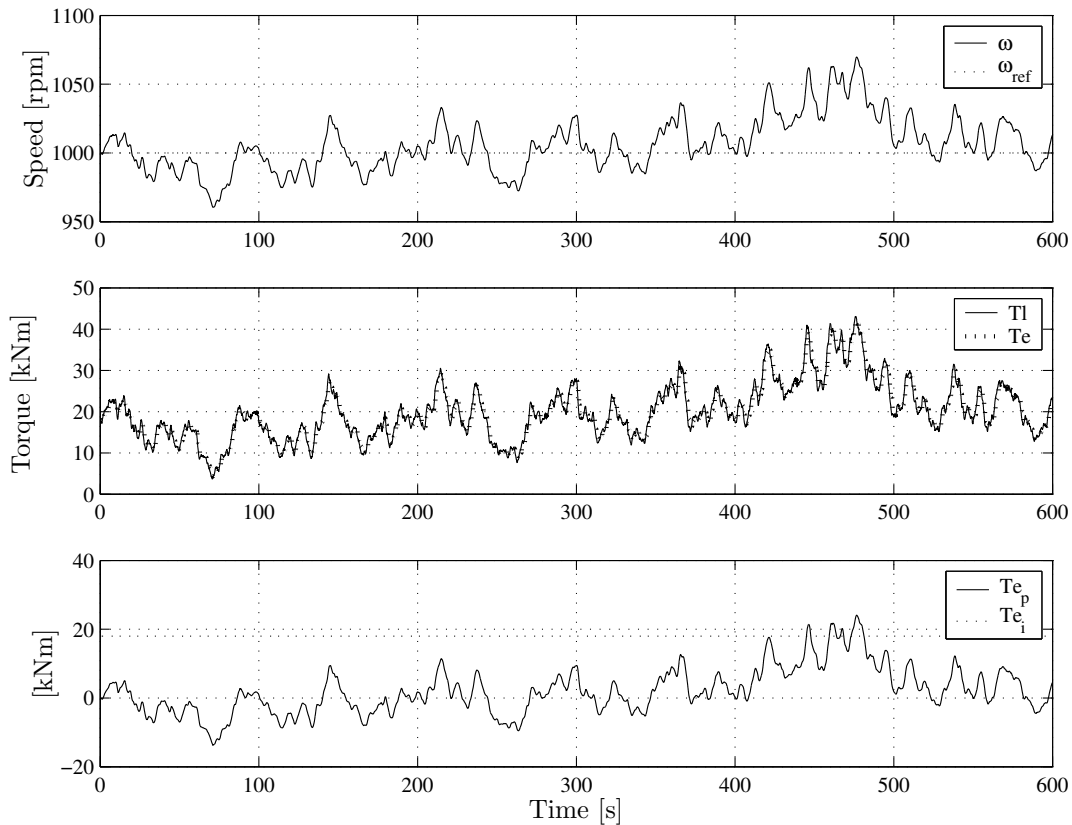


Figure 3.24: Generator Model with 10% Slope

Here the variations on the electrical torque has been reduced effectively, which is not visible in the figures, but as shown to the price of a great speed variation.

As the the wind speed, as shown earlier, consists of a great variety of frequency components a approach with filters separating fast and slow components is designed.

Filter Utilization

As earlier stated it is the high frequent contents of the wind speed input that is considered as the main disturbances and the low frequent contents as the energy input to the system. To minimize the effect of the disturbances without affecting to much on the energy input a first order lowpass and bandpass filter is tested. The results are shown in Figure 3.25.

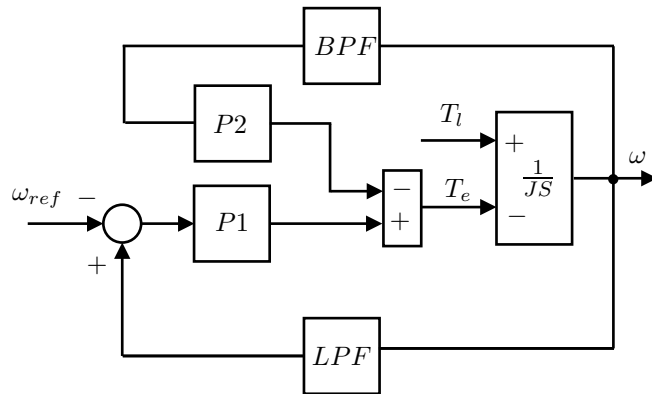


Figure 3.25: Stall Regulator with Lowpass and Bandpass Filters

The purpose is to get the low-frequency variations on the the speed from the 1% slope model but still get a good tracking of the torque generated by the wind. Therefore the low frequencies goes through the 1% slope generator model and are amplified with P1 in the figure and the high frequencies with the 10% slope generator model which are reduced with P2.

Results of this simulation with 0.05Hz switching frequency for the lowpass filter and 0.25Hz respectively 0.5Hz for the bandpass filter is shown in Figure 3.26.

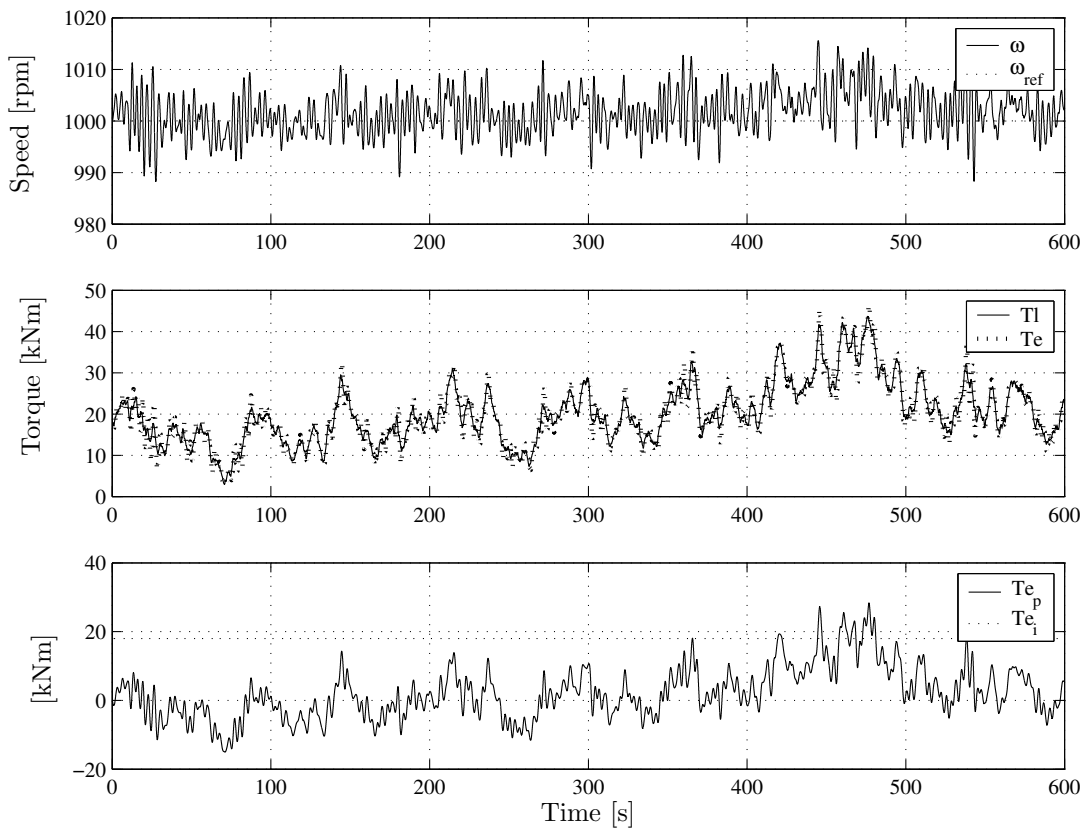


Figure 3.26: Generator Model with 10 percent Slope and Lowpass Filter

This shows that the torque variations are kept low and a good reduction on the

generator speed variation is also achieved. This is best seen by showing the frequency characteristics of the generator speeds for the 1% and 10% slope generator models together with the results from the filtered case are shown in Figure 3.27.

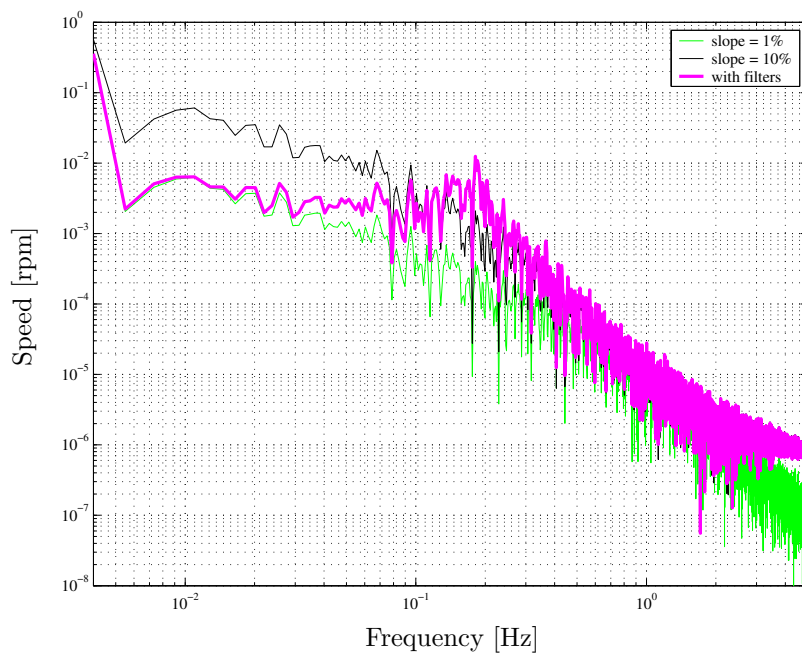


Figure 3.27: Frequency Spectra for the Speed with Generator Model with 1% and 10% Slope and Filter Utilization

As can be seen the amplifications for the lower frequencies stays with the 1% slope characteristics as for the higher it goes down to the 10% slope characteristics. The frequency characteristics of the electrical torque can be seen in Figure 3.28.

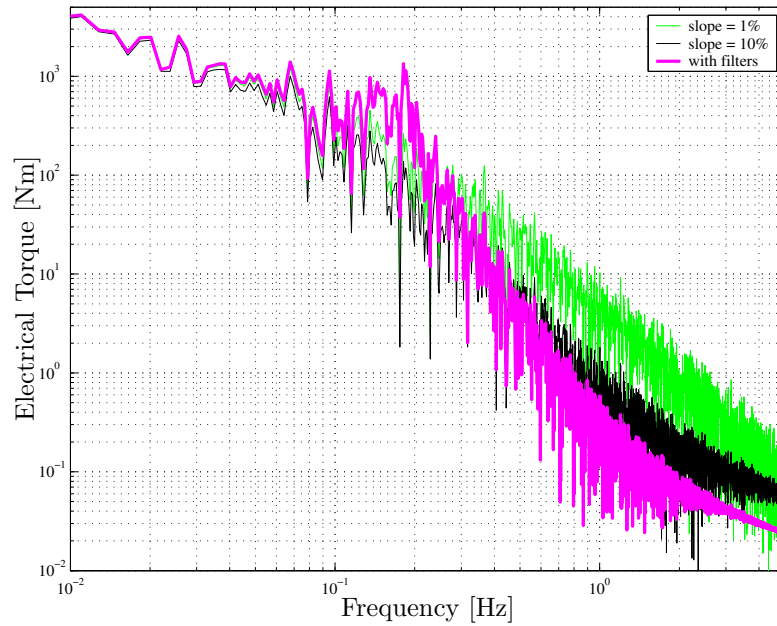


Figure 3.28: Frequency Spectra for the Speed with Generator Model with 1% and 10% Slope and Filter Utilization

Here the effect for the low frequencies are the same for all three models but the difference is clear for the higher ones even though some frequencies in the middle of the spectra peaks a bit. Although just first-order filters are used for these simulations a good characteristics is achieved with filters used. Speed variations are kept low and variations on the electrical torque do not differ remarkably much for these three cases.

Chapter 4

Conclusions

The purpose of this thesis has been to evaluate how variable speed control can reduce fatigue damage on mechanical parts of a wind turbine. With the implementation of a speed regulator for the lower wind speeds, results shows that this can be achieved but with a insecurity factor due to the systems stability. This is particularly important for highly turbulent winds where the reference to the regulator becomes a crucial parameter. By using lowpass filter on the reference this would improve the stability but the energy capture will be lowered, as the regulation would be slower.

For the high wind speeds the best controlling is achieved with regulation directly on the torque difference between electrical and wind generated torque. For this a good pitch actuator is crucial.

For middle wind speeds, a special approach makes it possible to reduce speed and torque variations. Pitch regulation in this interval would probably further improve the results.

4.1 Future Work

By using windfield for the simulations a better accuracy for the actuators behavior would be achieved mostly because the use of that the spatial filter would be avoided. As functions for evaluating the mechanical forces created by the wind already are available blade profile data for other types and larger wind turbines would be a great improvement. Estimation of the wind speed and torque observer for the torque generated by the wind are also tasks that was not implemented in this work but would make the results more adequate. Introduction of pitch regulation in the middle wind speed interval should also be tested. Evaluation of how a soft axis affects the turbine, and more accurate comparison between measured and simulated data, with a more extended wind turbine model, is also desired.

Bibliography

- [1] N. Horiuchi and T. Kawahito, "*Torque and Power Limitations of Variable Speed Wind Turbines Using Pitch Control and Generator Power Control*", Power Engineering Society Summer Meeting, vol. 1, pp 638-643, July 15-19 2001.
- [2] E. Muljadi and C. P. Butterfield, "*Pitch-Controlled Variable-Speed Wind Turbine Generation*", IEEE Transactions on Industry Applications, vol. 37, no. 1, pp 240-246, Jan. 2001.
- [3] K. Pierce and L. J. Fingersh, "Wind Turbine Control System Modeling Capabilities, American Controls Conference, report, June 24-26, 1998.
- [4] E. Persson, *One-dimensional Wind Simulation*, Mathematical Statistics, Chalmers University of Technology, Gothenburg, 1996.
- [5] M. A. M. Prats, J. M. Carrasco, E. Galván, J. A. Sánchez, L. G. Franquelo and C. Battista. "*Improving transition between power optimization and power limitation of variable speed, variable pitch wind turbines using Fuzzy control techniques*", Industrial Electronics Society, vol. 3, pp 1497-1502, 2000.
- [6] J. F. Manwell, J. G. McGowan and A. L. Rogers, "*Wind Energy Explained*", John Wiley and Sons LTD, Chichester, England, 2002.
- [7] L.L. Freris, *Wind Energy Conversion Systems*, Prentice Hall Int., Hertfordshire, UK, 1990.
- [8] J.F. Walker and N. Jenkins, *Wind Energy Technology*, John Wiley and Sons LTD, Chichester, England, 1997.
- [9] T. Burton, D. Sharpe, N. Jenkins and E. Bossanyi, *Handbook of Wind Energy*, John Wiley and Sons LTD, Chichester, England, 2001.
- [10] D.M. Egglestone and F.S. Stoddard, *Wind Turbine Engineering Design*, Van Nostrand Reinhold Company Inc., New York, USA, 1987.
- [11] E. Hau, *Windturbines: Fundamentals, Technologies, Application and Economics*, Springer-Verlag, Berlin, Germany, 2000.
- [12] S. Heier, "*Wind Energy Conversion Systems*", John Wiley and Sons LTD, Chichester, England, 1998.

- [13] H. Vihriälä, *Control of Variable Speed Wind Turbine*, Lic. thesis, Tampere University of Technology, Tampere, Finland, 1998.
- [14] M. T. Iqbal, A. H. Coonick and L. L. Freris, "Some Control Aspects of a Wind Turbine", IEE Colloquium on Two Decades of Fussy Control - Part 1, pp 6/1-6/3, 1993.
- [15] W. E. Leithead, S. A. de la Salle, D. Reardon and M. J. Grimble "Wind Turbine Modelling and Control", International Conference on Control, vol. 1, pp 1-6, 1991.
- [16] T. Petru, *Modelling of Wind Turbines for Power System*, Lic. thesis, Chalmers University of Technology, Gothenburg, Sweden, 2001.
- [17] T. Thiringer, "Periodic Pulsation from a Three-bladed Wind Turbine", IEEE Transactions on Energy Conversion, vol. 16, no. 2, pp. 128-133, June, 2001.
- [18] C. Skaug and C. Stranne, *HVDC Windpark Configuration Study*, MsC thesis, Chalmers University of Technology, Gothenburg, Sweden, 1999.
- [19] L. H. Hansen, L. Helle, F. Blaabjerg, E. Ritchie, S. Munk-Nielsen, H. Bindner, P. Sørensen and B. Bak-Jensen, *Conceptual survey of Generators and Power Electronics for Wind Turbines*, Report, Risø National Laboratory, Roskilde, Denmark, Dec., 2001.
- [20] S. A. Papathanassiou and M. P. Papadopoulos, "Dynamic Behaviour of Variable Speed Wind Turbines under Stochastic Wind", IEEE Transactions on Energy Conversion, vol. 14, no. 4, pp 1617-1623, Dec. 1999.
- [21] E. Muljadi, K. Pierce and P. Migliore, "Control Strategy for Variable-Speed, Stall-Regulated Wind Turbines", Proceedings of the American Control Conference, vol. 3, pp 1710-1714, June 24-26 1998.
- [22] R. Cárdenas, G. M. Asher, W. F. Ray and R. Pena, "Power Limitation in Variable Speed Wind Turbines with Fixed Pitch Angle", Conference on Opportunities and Advances in International Power Generation, Conf. Publ. no. 419, pp 44-48, March 18-20 1996.
- [23] B. Connor and W. E. Leithead, "Performance Assessment of Variable Speed Wind Turbines", Conference on Opportunities and Advances in International Power Generation, Conf. Publ. no. 419, pp 65-68, March 18-20 1996.
- [24] T. Thiringer and J. Linders, "Control by Variable Rotor Speed of a Fixed-Pitch Wind Turbine Operating in a Wide Speed Range", IEEE Transactions on Energy Conversion, vol. 8, No. 3, pp 520-526, Sept. 1993.
- [25] E. A. Bossanyi, "The Design of Closed Looped Controllers for Wind Turbines", Wind Energy 2000, no. 3, pp. 149-163, July, 2001.
- [26] T. Thiringer, "Measurements and Modelling of Low-Frequency Disturbations in Induction Machines", Lic. thesis, Chalmers University of Technology, Gothenburg, Sweden, 1993.

Appendix A

Alsvik Wind Turbine Data

Wind Turbine

(all data referred to the low speed shaft)

Hub height	30	[<i>m</i>]
Number of Blades	3	[]
Rotor Radius	11.6	[<i>m</i>]
Blade Profile	NACA-63200	
Turbine Inertia	55500	[<i>kgm</i> ²]

Gearbox

(a ratio of 20 has been used in this work to extend the low wind speed interval)

Gearbox Ratio	23.75	[]
---------------	-------	----

Generator

Generator Inertia	1800	[<i>kgm</i> ²]
Rated Effect	180	[<i>kW</i>]
Synchronous Speed	1000	[<i>rpm</i>]
Poles	6	[]
Frequency	50	[<i>Hz</i>]
Nominal Voltage	400	[<i>V</i>]
Stator Resistance	0.0092	[Ω]
Rotor Resistance	0.0061	[Ω]
(referred to the stator)		
Stator Leakage Inductance	186	[μH]
Rotor Leakage Inductance	427	[μH]
Magnetizing Inductance	6.7	[<i>mH</i>]

Appendix B

Simulated Wind Speed

```
function [ak,fik] = windrand(len)
%-----
% Output :
% ak = vector of Rayleigh distributed random numbers (length = len)
% fik = vector of random numbers uniformly dist. in [0, 2 $\pi$ ] (length = len)
% Input :
% len = the acquired length of random number vectors
%-----

n = rand(1,len);
m = rand(1,len);      % n,m = vectors of random numbers uniformly dist. in [0, 2 $\pi$ ]
ak = sqrt(2*(-log(n)));
fik = 2*pi*m;        % calculation of the outputs

function [ux,uy,tv] = windsim(t,fsamp,fcut,u,ak,fik)
%-----
% Output :
% ux = vector of windspeed sampled at a frequency fsamp over a total time t [m/s]
% uy = the timederivates of the windspeed in ux [m/s2]
% tv = the time vector according to ux and uy [s]
% Input :
% t = total time [s]
% fsamp = sampling frequency [Hz]
% fcut = the (upper) frequency at which to cut the spectrum [Hz]
% u = mean windspeed over the time t [m/s]
% ak = vector (length > t * fcut) of Rayleigh distributed random numbers
% fik = vector (length > t * fcut) of random numbers uniformly dist. in [0, 2 $\pi$ ]
%-----
```

```

len = round(t*fsamp); % the length of the output vectors
lenc = round(t*fcut); % the number of frequencies up to fcut at which to calculate the spectrum
ak = ak(1:lenc);
fik = fik(1:lenc); % cutting the vectors of random numbers to appropriate length
kdel = (1:lenc)/t; % vector of frequencies up to fcut at which to calculate the spectrum
z = 30; % the height of the point where the wind is simulated
z0 = 0.3; % a ground roughness factor

s = 16.8/(log(z/z0)^2)*z*u./((1+33*z/u*kdel).^5/3);
% the spectrum calculated at the frequencies of kdel

ex = sqrt(s/t).*ak.*exp(-i*fik);
% the expression to put into the FFT to calculate ux

ey = 2*pi*kdel.*sqrt(s/t).*ak.*exp(-i*(fik+2*pi/2));
% the expression to put into the FFT to calculate uy

n = 0; % n contains the indices of the output vector
len - 1;

cor1 = exp(-i*2*pi*n/len);
cor2 = kdel*t*pi*(1/len-1/(t*fsamp));
% correlation terms to make the FFT useble for our purposes

ux = u+real(cor1.*(fft(ex,len)+n.*fft(i*2*cor2.*ex,len)-n.^2.*fft(2*cor2.^2.*ex,len)));
% calculation of the output ux

uy = real(cor1.*(fft(ey,len)+n.*fft(i*2*cor2.*ey,len)-n.^2.*fft(2*cor2.^2.*ey,len)));
% calculation of the output uy

tv = n/fsamp; % calculation of the output tv

```