LUND UNIVERSITY

Analysis of the Control Problem for Horizontal Axis Wind Turbines

Mattsson, Sven Erik

1983

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):
Mattsson, S. E. (1983). *Analysis of the Control Problem for Horizontal Axis Wind Turbines*. (Technical Reports TFRT-7258). Department of Automatic Control, Lund Institute of Technology (LTH).

Total number of authors:
1

LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

CODEN:LUTFD/(TFRT-7258)/(1-052)/(1983)

Analysis of the Control Problem for Horizontal Axis Wind Turbines

Final Report
NE project 5061 621

Sven Erik Mattsson

DEPARTMENT OF AUTOMATIC CONTROL
LUND INSTITUTE OF TECHNOLOGY, AUGUST 1983

LUND INSTITUTE OF TECHNOLOGY
DEPARTMENT OF AUTOMATIC CONTROL
Box 725
S 220 07 Lund 7 Sweden

Document name
INTERNAL REPORT

Date of issue
August 1983

Document number
CODEN: LUTFD2/(TFRT-7258)/1-052/(1983)

Author(s)
Sven Erik Mattsson

Supervisor

Sponsoring organization
The National Swedish Board for Energy Source Development

Title and subtitle
ANALYSIS OF THE CONTROL PROBLEM FOR HORIZONTAL AXIS WIND TURBINES
Final Report, NE project 5061 621

Abstract

This report considers control of large horizontal axis wind power plants connected to utility grids. The objective is to give a global picture of the control problem.

The system dynamics and the wind characteristics are investigated first to find which properties that are basic to all horizontal axis wind turbines and which properties that can be influenced by process design and regulator design. Control objectives, measurements and other control issues are then discussed. The interaction between process design and regulator design is also discussed.

Key words
Horizontal axis wind turbines; Automatic Control

Classification system and/or index terms (if any)

Supplementary bibliographical information

ISSN and key title

ISBN

Language
English

Number of pages
52

Recipient's notes

Security classification

Distribution: The report may be ordered from the Department of Automatic Control or borrowed through the University Library 2, Box 1010, S-221 03 Lund, Sweden, Telex: 33248 lubbis lund.

TABLE OF CONTENTS

SUMMARY

This report considers control of large horizontal axis wind power plants connected to utility grids. The objective is to give a global picture of the control problem.

The system dynamics and the wind characteristics are investigated first to find which properties that are basic to all horizontal axis wind turbines and which properties that can be influenced by process design and regulator design. Control objectives, measurements and other control issues are then discussed. The interaction between process design and regulator design is also discussed.

The variation of the wind speed in space and time is a complex phenomenon. For control purposes the wind speed sensed by the wind turbine can be viewed as being the sum of one constant part representing the mean wind speed over 10 minutes and one stochastic part representing the turbulence. A simple and useful model for the turbulence is a first order lag driven by white noise and with a time constant of the order of 10 seconds. The standard deviation of the turbulence is of the order of 5 - 20% of the mean wind speed. The quality of the control depends on how well the wind speed is known and on how well its behaviour can be predicted. In some weather conditions the correlation between the wind speed in a point in the rotor disc and the mean wind speed over the rotor disc is low. This indicates that an anemometer may be of little use for feedforward compensation. However, it may be possible to use the wind turbine itself as wind gauge by measuring other quantities. An interesting idea to measure the wind is to put strain gauges on the blades. This appears promising because the average wind force is measured rapidly.

The dynamics of the drive train with the large turbine and the electrical coupling to the grid give the wind turbine generator its basic dynamic characteristics. If a synchronous or short-circuited asynchronous generator is used, the turbine inertia and the stiffness of the connection between turbine and generator give a torsional mode in the range 1 - 10 rad/s. It acts as a second order filter and filters out the rapid variations in the driving torque caused by wind shear and tower blockage. By making the connection between

the turbine and the generator torsionally soft, it is possible to lower the demands on the bandwidth of the pitch angle control. If a synchronous generator is used the mode has low damping and becomes a major design problem for pitch control. If a short-circuited asynchronous generator is used it possible to design the system so that the mode is better damped, at the expense of reactive current and with no means of controlling the terminal voltage.

If a fed asynchronous generator is used, the excitation control can handle the rapid variations in the driving torque and the filter effect of the soft shaft is not important. A fed asynchronous generator combine the operational advantages of variable speed with the possibility of reactive power generation.

Besides the demands on terminal voltage and produced power emanating from the desire to have a stable utility grid, internal demands due to the limited capability of the system to withstand heat, loads, deflections and fatigue are important. Today when most of the large wind power plants are prototypes, it is important to get safe and reliable systems so that breakdowns are avoided. So it seems recommendable to play for safe and put the efforts on keeping the loads inside the tolerable limits instead of trying to maximize the power output and thereby risking to get large loads on the system. Fast pitch angle control makes it possible to alleviate the loads on the turbine. However, fast pitch angle control must not entice the designer to to reduce weight of the turbine system too much. A fast pitch angle control has a high bandwidth and a weak system has low natural frequencies. If a natural frequency of a mode is lower than or close to the desired cross over frequency of the pitch angle control system, this causes large difficulties when designing the pitch angle control. It may even be impossible to achieve an acceptable performance. For reasons of safety it is recommendable to avoid these problems if possible.

SAMMANFATTNING

Denna rapport betraktar problemet att reglera stora horisontalaxlade vindkraftverk som är kopplade till elnätet. Målet är att ge en global bild av reglerproblemet.

Vindens egenskaper och systemets dynamik studeras först för att undersöka vilka egenskaper som är gemensamma för alla horisontalaxlade vindkraftverk och vilka som kan påverkas vid konstruktionen. Reglermålen, mätsignaler och andra reglertekniska aspekter diskuteras sedan. Beroendet mellan konstruktionen av systemet och konstruktionen av reglersystemet diskuteras också.

Vindens variation i rum och tid är ett komplext fenomen. För reglertekniska ändamål kan vinden som vindkraftverket känner av betraktas som en summa av en konstant del som representerar tiominuters medelvärden och en stokastisk del som representerar turbulensen. En enkel och användbar model för turbulensen ges av ett första ordningens system som matas med vitt brus och som har en tidskonstant i storleksordningen 10 sekunder. Standardavvikelsen är i storleksordningen 5 - 20% av medelvindhastigheten. Resultatet av regleringen beror på hur väl man känner vindhastigheten och hur bra man kan förutse dess beteende. Vid vissa vädertyper är korrelationen mellan vindhastigheten i en punkt i turbinarean och medelvindhastigheten över turbinarean låg. Detta indikerar att en vindmätare kan vara till föga nytta för framkoppling. Emellertid kan det vara möjligt att använda vindkraftverket självt som vindmätare genom att mäta andra storheter. Det är en intressant idé att placera trådtöjningsgivare på bladen. Idén är lovande eftersom medelvindstyrkan mäts snabbt.

Den grundläggande dynamiken ges av den stora turbinen, transmissionen och den elektriska kopplingen till nätet. Om en synkrongenerator eller kortsluten asynkrongenerator används, så ger turbinen och kopplingen mellan turbinen och generatorn en torsionsmod i området 1 - 10 rad/s. Den verkar som ett filter och filtrerar bort de snabba variationerna i det drivande momentet, som orsakas av vindprofilen och tornskuggan. Genom att göra förbindelsen mellan turbin och generator torsionsmjuk, är det möjligt att minska

bandbreddskravet på bladvinkelregleringen. Om en synkrongenerator används får moden en låg dämpning och blir en av de större svårigheterna vid bladvinkelreglering. Om en kortsluten asynkrongenerator används kan systemet konstrueras så att moden blir bättre dämpad, men det kostar reaktiv effekt och det är inte möjligt att reglera klämspänningen.

Om en matad asynkrongenerator används, så kan exciteringsregleringen eliminera de snabba variationerna i drivmomentet och den mjuka axelns filtereffekt är inte betydelsefull. En matad asynkrongenerator kombinerar fördelarna med variabel hastighet och möjligheten till att producera reaktiv effekt.

Förutom kraven på klämspänning och elektrisk effekt som kommer från önskan att ha ett stabilt nät så är de interna kraven som beror på systemets begränsade kapacitet att motstå värme, laster och utmattning viktiga. Idag när de flesta vindkraftverk är prototyper, är det viktigt att få ett säkert och tillförlitligt system och undvika krascher. Så det verkar vara rekommendabelt att köra försiktigt och lägga ner ansträngningarna på att hålla lasterna inom tolerabla gränser istället för att försöka maximera energiproduktion och därmed riskera att få stora laster på systemet. Snabb bladvinkelreglering gör det möjligt att minska på lasterna. Emellertid får inte en snabb bladvinkelreglering förleda konstruktören att minska vikten hos turbinen för mycket. En snabb bladvinkelreglering har hög bandbredd och ett vekt system har moder med låga resonansfrekvenser. Om en resonansfrekvens är lägre eller nära den önskade bandbredden hos bladvinkelregleringen innebär det stora svårigheter vid konstruktionen av bladvinkelregulatorn. Det kan till och med vara omöjligt att åstadkomma ett acceptabelt resultat. Av säkerhetsskäl är det om möjligt rekommendabelt att undvika problemen.

1. INTRODUCTION

This report considers control of large horizontal axis wind power plants connected to utility grids. The objective is to give a global picture of the control problem. The following questions are investigated:

> Which properties and limitations are basic and common to all horizontal axis wind turbines?
>
> Which properties and limitations are design dependent?
>
> Which properties can be influenced by control system design?
>
> What are the control objectives and is it possible to fulfil them?

The dynamics of horizontal axis wind turbines are considered in Chapter 2. There are a number of different types in operation and more are under construction. A survey is given in Koeppl (1982). The characteristics of the wind power systems MOD-2, WTS-3 (WTS-4), WTS 75 and Growian I are referenced in the discussion. A listing of their basic characteristics is given in Appendix A.

The wind is a source of both joy and sorrow. This power source cannot be controlled in any way and it is the major source of disturbances. The variations in the wind are large, rapid and random. The characteristics of the wind are considered in Chapter 3.

The control problem is considered in Chapter 4.

2. SYSTEM DYNAMICS

A suitable characterization of the system dynamics of horizontal axis wind turbines should tell how energy is transferred from the wind to the utility grid. For reasons of safety it is also necessary to consider the structural dynamics.

A characterization of the system dynamics can be given in different ways. Mathematical simulation models for the complete system can be found in for example Hwang and Gilbert (1978), Kos (1978), Hinrichsen and Nolan (1980), Krause and Man (1981) (also in Wasynczuk, Krause and Man (1981)) and Bergman, Mattsson and Östberg (1981) (also in Mattsson (1982), Bergman and Mattsson (1983)). These reports and papers also contain simulation plots. Here a more informal presentation is given with the intention of explaining the dynamics.

Several modes of operation can be identified: startup mode, power production mode, shutdown mode and emergency modes. In the startup mode the turbine is accelerated and the generator is connected to the utility grid. In the power production mode power is extracted from the wind and transferred to the utility grid. In the shutdown mode the generator is disconnected and the turbine is decelerated. The system is in an emergency mode if malfunctions have been detected. In an emergency mode backup systems are invoked to provide a safe shutdown. Mainly the power production mode will be considered here. It is the most difficult part and a plant will hopefully be operating in this mode in the major part of its lifetime.

The system may be viewed as consisting of an aerodynamical part and a electrical part, which are connected by a drive train. The aerodynamical part is influenced by the wind and consists of the wind turbine, the nacelle and the tower. The electrical part is connected to the utility grid and consists of the generator and possibly an excitation system. The drive train which connects the turbine and generator consists of shafts and gearboxes.

The investigation of the system dynamics starts in Chapter 2.2 by considering simple models in order to understand the behaviour of wind turbine generators. Higher order dynamics and the validity of the simple models for the aerodynamical part are discussed in Chapter 2.3 and for the electrical part in Chapter 2.4.

2.1 Preliminaries

Per Unit Systems

In a system with rotating masses like a wind turbine, resonance occurs at frequencies nearly equal to integer multiples of the rotational speed. To describe the structural modes it is natural to use a frequency scale related to the rotational speed;

1 P = "rated rotational turbine speed"

It is also natural to use this frequency scale when describing the disturbances caused by wind shear, gravity and tower blockage.

To facilitate comparisons between different wind power systems and also to other kinds of power systems, it is convenient to reduce inertias, stiffnesses and dampings to the electrical side and express quantities in a per unit system based on the electrical machine base. A spring coefficient K and a damping coefficient D of a component with a rated rotational speed ω are reduced as

$$K_{pu} = \frac{K}{(S_B/\omega_0)(\omega_0/\omega)^2} \tag{2.1 a}$$

$$D_{pu} = \frac{D}{(S_B/\omega_0)(\omega_0/\omega)^2} \tag{2.1 b}$$

where S_B is the rated apparent power of the generator and ω_0 the electrical angular frequency. S_B/ω_0 is the base for the torque and ω_0/ω is the step-up gear ratio from the rotating component to the electrical system. An inertia J with the rotational speed ω is represented by an inertia constant H defined as

$$H = \frac{0.5 \cdot J\omega^2}{S_B} \tag{2.1 c}$$

A Simple Wind Model

The variation of the wind speed in space and time is a complex phenomenon and is discussed in Chapter 3. Here it will be assumed that the wind speed sensed by the wind turbine consists of a constant part and stochastic part. The constant part represents the mean wind speed over 10 minutes and the stochastic part the turbulence. The stochastic part is assumed to be the output from a timeinvariant and linear system driven by Gaussian white noise with zero mean and unit variance. The transfer function of the system is assumed to be

$$G(s) = \frac{\sigma\sqrt{(2T)}}{1 + Ts} \tag{2.2}$$

with the time constant T being of the order of 10 seconds and the standard deviation σ being in the order of 5 - 20% of the mean wind speed.

Tower Blockage

The tower blocs the airflow in the rotor disc. The effect is most significant on turbines operating downwind of the tower. The wake depends critically on the aerodynamical properties of the tower. For WTS-3 Hamilton Standard calculated a velocity defect of 30% and a wake width of 1.4 times the tower diameter in the rotor disc. This means that the major part of the driving torque on a blade is lost as it swings behind the tower. Seidel (1977) reports that the MOD-0 wind turbine (The ERDA-NASA 100 kW wind turbine near Sandusky, Ohio) momentarily loses more than 60% of the rotor torque as a blade swings behind the tower.

The disturbance has bad spectral properties. For a turbine with n blades the disturbance caused by the tower blockage occurs with a frequency of nP. It is of short duration, because a blade is in the wake only a few per cent of the time. This means that at least 3 - 4 of the first harmonics have amplitudes of the same magnitude. The power spectrum in Figure 2.1 for the electrical power from WTS-3 shows the impact of the tower blockage. The spectrum is calculated from data collected on 1st February 1983 at 12.20. The measurements were filtered with a sixth order Bessel filter with a cut-off frequency of 25 Hz (60 P) and sampled with 100 Hz. The mean wind speed was

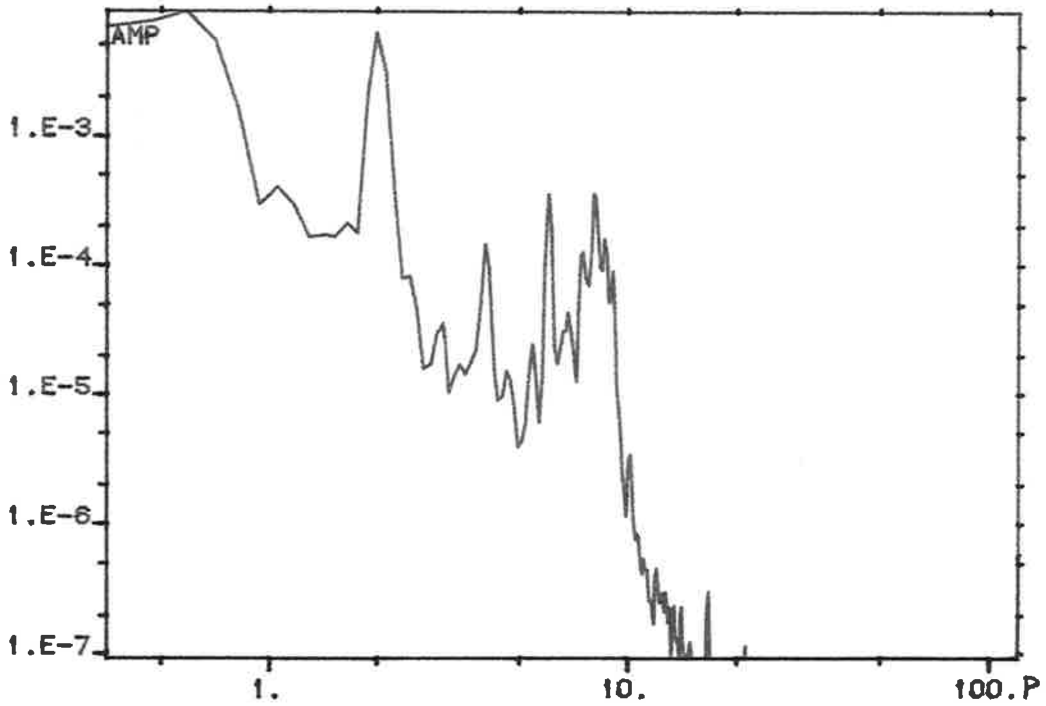

Figure 2.1: A power spectrum for the electrical power (in MW) produced by WTS-3 (1 P = 2.618 rad/s = 25 rpm).

15.4 m/s and the standard deviation 0.9 m/s. A two minutes series containing 12 000 data point were used. The series was blocked into six groups containing 2000 data points each. A spectrum for each of these blocks was calculated and the resulting spectrum in Figure 2.1 is the mean of these six spectra. IDPAC's DFT-command (with a Blackman-Harris time window) for calculating Discrete Fourier Transform (Wieslander (1980)) was used to calculate the spectrum of a data block.

2.2 Basic System Dynamics

The dynamics of the drive train with the large turbine and the electrical coupling to the grid give the wind turbine generator its basic dynamic characteristics.

A Simple Inertia-Stiffness Model

The equations of motion for the turbine rotor and the generator rotor give

$$\frac{2\ H_{turb}}{\omega_0}\ddot{\phi} = T - K_{shaft}(\phi - \delta) - D_{shaft}(\dot{\phi} - \dot{\delta}) \qquad (2.3\ a)$$

$$\frac{2\ H_{gen}}{\omega_0}\ddot{\delta} = K_{shaft}(\phi - \delta) + D_{shaft}(\dot{\phi} - \dot{\delta}) - T_E \qquad (2.3\ b)$$

ϕ is the position of the turbine rotor and δ the position of the generator rotor. T represents the driving aerodynamical torque and T_E the developed electrical torque. The drive-train is represented by an equivalent stiffness with the spring coefficient K_{shaft} and the damping coefficient D_{shaft}.

T is a nonlinear function of the incoming wind, the pitch angle and the turbine speed. The properties of T are discussed in Chapter 2.3. The aerodynamical damping is low, because the blades are designed to give minimum losses. For WTS-3 the aerodynamical damping coefficient is 0.002 pu torque/(el rad/s) at 14 m/s and increases to 0.01 pu torque/(el rad/s) at 26 m/s; D_{shaft} is 0.02 pu torque/(el rad/s). The aerodynamical damping of the turbine oscillation will be neglected in this chapter.

In the model (2.3) the inertia of the gearbox is neglected. For MOD-2, WTS-3 and WTS 75 the inertia constant of the gearbox is less than 0.05 s. Hinrichsen and Nolan (1980) report that for MOD-2 there are a natural mode where the rotating part of the gearbox oscillates through the high speed shaft against the generator rotor with 550 rad/s. They mean that this mode can be neglected because it is hard to excite it. Simulations made by ASEA (1980) show that this is also the case for WTS-3.

Table 2.1: Numerical values for some wind power systems.

Wind power system	H_{turb} [s]	H_{gen} [s]	K_{shaft} [pu torque/ el rad]	D_{shaft} [pu torque/ (el rad/s)]
MOD-2	15.7	0.53	0.065	0.020
WTS-3	5.2	0.60	0.050	
WTS 75	10.5	0.55	6.2	

Turbine Inertia

Hinrichsen (1981) points out that wind turbines have a very high per unit turbine inertia because

1. The low energy density of wind leads to a large rotor diameter.
2. The tip speed/wind speed ratio must lie within a narrow range to achieve good efficiency. This leads to turbine speeds between 15 and 50 rpm.

Typically the inertia constants are 5 - 15 seconds (See Table 2.1), which are about ten times more than for typical hydro, steam or diesel turbines.

With Synchronous Generator

MOD-2 and WTS-3 have a synchronous generator with four poles. For a synchronous generator the electrical torque can be modelled as (linearized around a stationary operating point)

$$T_E = K_E \delta + D_E \dot{\delta} \tag{2.4}$$

This means that the electrical coupling to the grid is equivalent to a mechanical coupling consisting of a spring and a damper. With $K_E = 2.3$ pu torque/el rad and $D_E = 0.017$ pu torque/(el rad/s), (2.3) and (2.4) give for WTS-3 poles in $-0.3 \pm 1.4i$ and $-4.8 \pm 24i$. The relative damping is 0.25 and 0.20. Note, that more than half of the damping of the second mode is due to D_{shaft}. The transfer function from T to T_E given by the model for WTS-3 is plotted in Figure 2.2.

If the damping is neglected, there is one natural mode where the turbine oscillates against the electrical system with 1.4 rad/s (0.53 P) and one mode where the generator oscillates against the synchronous power system with 25 rad/s (9.5 P). MOD-2 has the same modes and their frequencies are 0.88 rad/s and 26 rad/s (Hinrichsen and Nolan (1980)).

The first torsional mode is called the soft shaft mode. This mode is important. It gives MOD-2 and WTS-3 their basic dynamic characteristics. It is excited

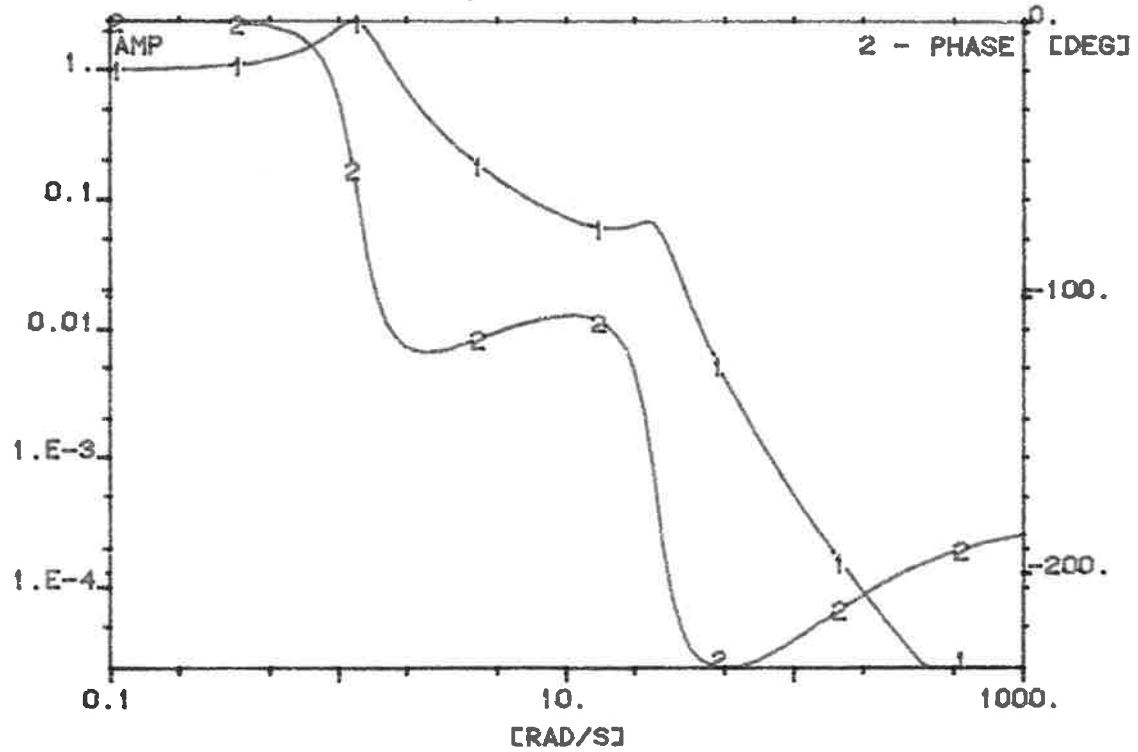

Figure 2.2: The transfer function from T to T_E for WTS-3 given by (2.3) and (2.4).

by the wind and blade angle changes and, since it has low damping, it becomes a major design problem for pitch control. However, the soft shaft also has its merits. The large turbine and the soft shaft act as a second order low pass filter with a bandwidth of about 2 rad/s = 0.76 P. Rapid wind variations are prevented from going through the system into the utility grid. This filter effect is important. Gravity, wind shear and tower blockage introduce disturbances with frequencies being multiples of 2 P, since the turbine has two blades. The 2 P frequency of WTS-3 is 3.8 times the torsional frequency of the soft shaft so 2 P disturbances are attenuated drastically by the soft shaft.

Small electrical disturbances like frequency-, voltage- and impedance fluctuations in the utility grid are prevented in the same way from influencing the turbine.

The electrical mode is the second mode. In conventional turbine generators this is generally the lowest mode and the only considered. This mode is also of great importance. It dominates the response to small and rapid electrical disturbances.

The study by Hinrichsen and Nolan (1980) shows that a well designed wind turbine generator with a soft shaft will perform equally well in single and multi-machine applications, since turbine and generator are decoupled transiently by the soft shaft.

From Table 2.1 it can be seen that the coupling between the turbine and the generator is 100 times stiffer for WTS 75 than for MOD-2 and WTS-3. MOD-2 and WTS-3 have deliberately designed soft shafts. MOD-2 has a quill shaft and WTS-3 has a softly mounted planetary gearbox which is equivalent to a torsionally soft shaft. The root-locus with respect to K_{shaft} for WTS-3 in

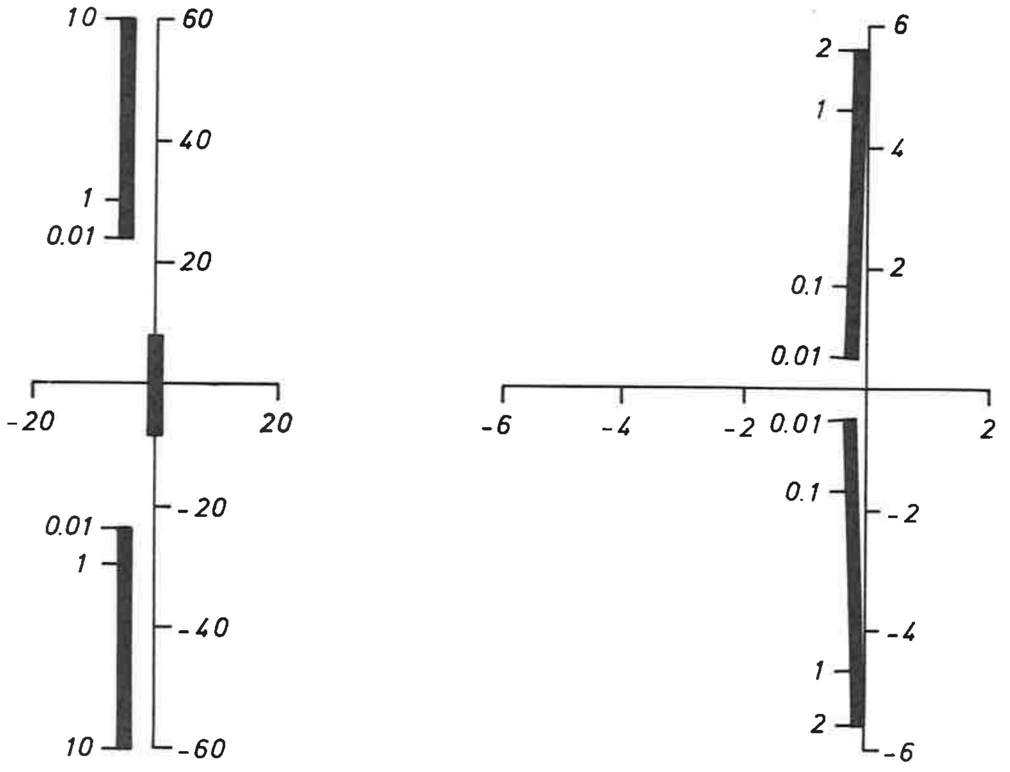

Figure 2.3: Root-locus with respect to K_{shaft} (in pu torque/el rad) for WTS-3 given by (2.3) and (2.4).

Figure 2.3 shows that such a stiff shaft would have been disastrous for MOD-2 and WTS-3. For $K_{shaft} = 5$ pu torque/el rad WTS-3 has poles in $-0.14 \pm 6.7i$ and $-5 \pm 45i$ which means that there is no filter effect for the 2 P (5.2 rad/s) disturbances.

With Short-Circuited Asynchronous Generator

The WTS 75 wind power system has an asynchronous generator with four poles. The asynchronous generator influence the first torsional mode in a more complex way than the synchronous generator. Statically the electrical torque is proportional to $\dot{\delta} - \omega_0$, with the mechanical interpretation of the coupling to the grid being a damper. This appears promising because it indicates a better damping of the soft shaft mode than with a synchronous case. However, dynamically the situation is somewhat more complex. The electrical dynamics cannot be neglected. The electrical torque can be modelled as (linearized around a stationary operating point)

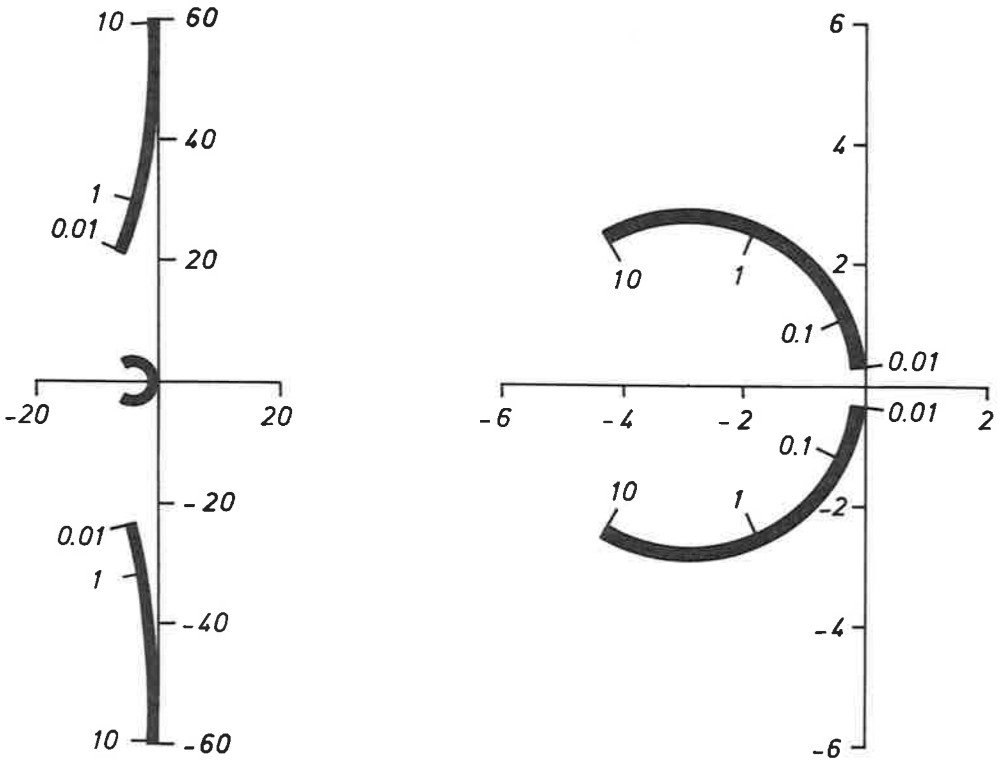

Figure 2.4: The root-locus with respect to K_{shaft} (in pu torque/el rad) for WTS 75 given by (2.3) and (2.5) when $K_{TE} = 0.2$ pu torque/(el rad/s) and $T_{TE} = 0.1$ s.

$$T_{TE}\dot{T}_E + T_E = K_{TE}\dot{\delta} \qquad (2.5)$$

T_{TE} and K_{TE} varies with the operating point and the are typically halved when produced power is increased from zero to rated. They also depend on the generator resistances and inductances. Typical values are T_{TE} = 0.1 - 0.2 s and K_{TE} = 0.1 - 0.4 pu torque/(el rad/s).

The root-locus with respect to K_{shaft} for different pairs of T_{TE} and K_{TE} can be found in Figures 2.4 - 2.6 (D_{shaft} = 0).

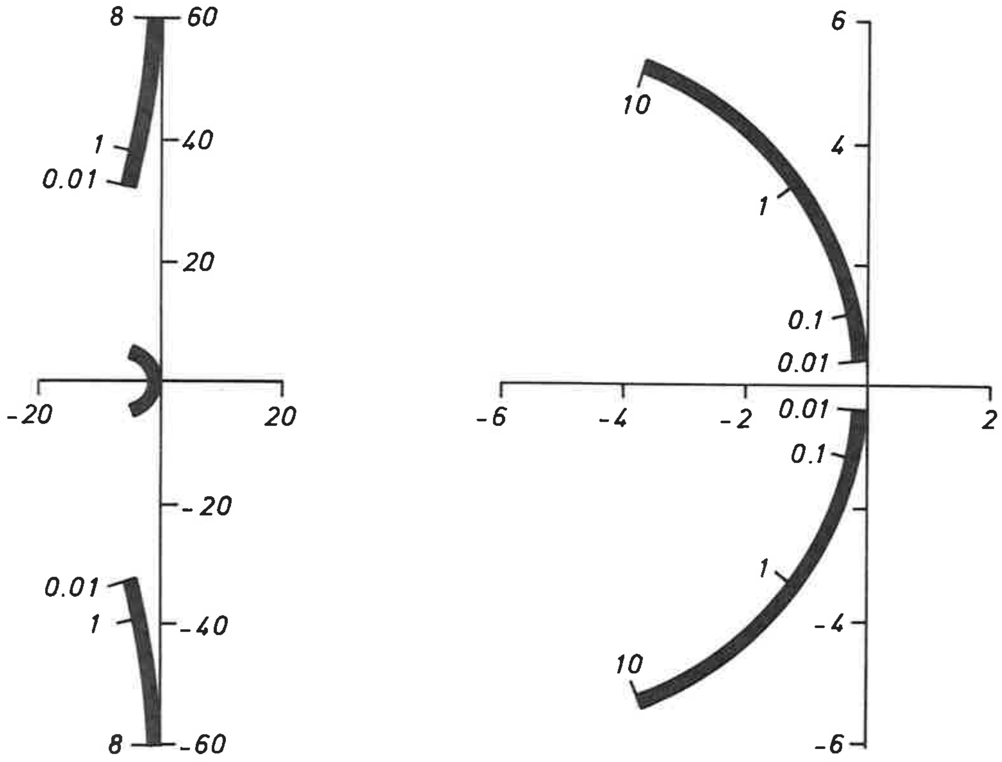

Figure 2.5: The root-locus with respect to K_{shaft} (in pu torque/el rad) for WTS 75 given by (2.3) and (2.5) when K_{TE} = 0.4 pu torque/(el rad/s) and T_{TE} = 0.1 s.

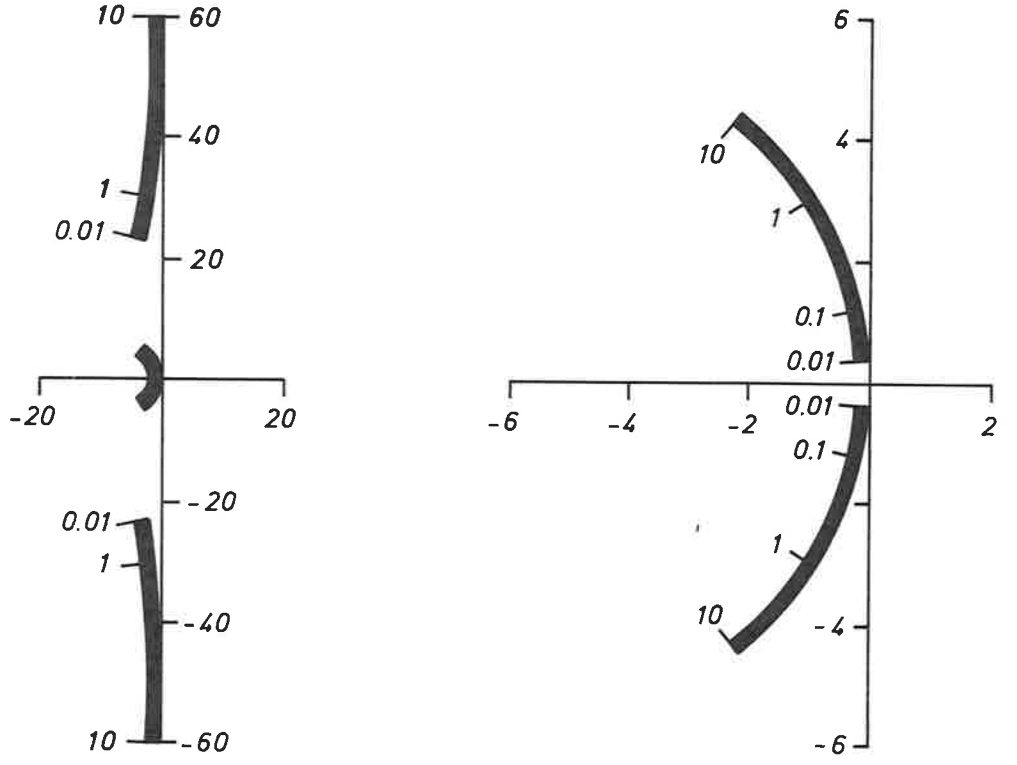

Figure 2.6: The root-locus with respect to K_{shaft} (in pu torque/el rad) for WTS 75 given by (2.3) and (2.5) when $K_{TE} = 0.4$ pu torque/(el rad/s) and $T_{TE} = 0.2$ s.

With Fed Asynchronous Generator

For MOD-2, WTS-3 and WTS 75 the the generator works at a nearly constant speed so the possibility to use the rotor as a storage of kinetic energy is negligible. The same can be said about the use of the windings as storages of electrical and magnetical energy. It is neither possible to get rid of energy. This means that the power output of the generator follows the power input of the generator closely. Hence, the power production must mainly be controlled by control of the power input to the turbine.

Growian I has a variable speed - fixed frequency generator. The generator speed is allowed to vary ±15% of synchronous speed. By allowing the turbine to perform limited speed excursions transient wind power can be absorbed by the turbine as kinetic energy and the demands on the blade angle control to respond to changing wind conditions may be lowered.

With Low Speed Generator

The generators of MOD-2, WTS-3, WTS 75 and Growian I have four poles and gearboxes are used to step-up the turbine speed. However, the gearbox is an expensive part; typically 7 - 10% of the costs for a delivered unit. Nygren, Grop and Pettersson (1981) suggest a low speed generator with 216 poles. This means that H_{gen} is in the magnitude of 10^{-4}s. Unfortunately, I have not been successful in getting typical data for low speed generators. If low speed generators are assumed to have similar electrical properties as those discussed above, the poles of the first mode will remain unchanged. Then the simple model gives poles with a modulus greater than 60, which indicates that other models are needed to compute the second mode.

The property that the first mode is insensitive to H_{gen} indicates that the pitch control is independent of if the generator has few or many poles and this is also stated by Nygren, Grop and Pettersson (1981). The value of K_{shaft} and the generator type are more important factors when designing pitch angle control.

2.3 The Aerodynamical Part

A wind turbine is a complex mechanical construction with several degrees of freedom. The rotation of the turbine around its axis is the main motion. The rotation of the nacelle and the turbine around the axis of the tower is called yawing. The blades may or may not move out of plane of rotation depending on how they are attached to the turbine shaft. To allow pitch control, the blades or parts of them can be turned around their longitudinal axes.

Below the dynamics of these motions are discussed perspicuously. The structural dynamics and stability of wind turbine generators are considered thoroughly in Stoddard (1978).

Aerodynamical Torque and Thrust

The driving aerodynamical torque T and the thrust F acting on the turbine can be obtained by applying static and two-dimensional airfoil theory to each cross section of the blades (Hultgren (1979)). If profile drag is neglected the driving aerodynamical torque acting on a cross section on blade i at the distance s from the rotor axis can be expressed as

$$dT_i = 0.5\ \varrho\ s\ c\ \left\{(1-a)^2 U_\infty^2 + s^2 \dot{\phi}^2\right\} \sin\alpha\ C_L(\alpha-\beta)\ ds \qquad (2.6\ a)$$

$$\alpha = \arctan\ (1-a)U_\infty/(s\dot{\phi}) \qquad (2.6\ b)$$

where ϱ is the density of air and c the local cord length. U_∞ is the incoming wind speed, the wind speed in the rotor disc is $(1-a)U_\infty$ and a is called the interference factor. It can be calculated by using momentum theory (e.g. Shepherd (1978)). If maximum energy is extracted $a \approx 1/3$. C_L is the lift coefficient and is a function of the angle of attack $\theta = \alpha-\beta$. β is the pitch angle and can be varied by the pitch servo. If the blade is twisted, β is also a function of s. C_L is typically increasing almost linearly to a maximum and then there is an abrupt decrease. This phenomenon is called stalling. The flow goes from laminar to turbulent flow. The different cross sections do not stall simultaneously so the the effect is smoother when looking on the driving torque from the whole blade. If the system is operating at the maximum point an increase in wind will give a decrease in torque, because an increase in wind speed means an increase in α.

The aerodynamical driving torque can be controlled by turning the blades or parts of them around their longitudinal axes. The servos can be electric or hydraulic.

For WTS-3 the servo is designed as a position servo with a time constant of 0.4 s. However, the servo speed is limited to 4°/s (Svensson and Ulen (1982)). The inertia of the blade about the pitch angle change axis, in combination with the linkage and hydraulic actuator spring rate yields a resonance around 9 Hz; it may vary depending on how much air there is in the system.

WTS-3 is able to produce rated power already at about a wind speed of 13.5 m/s, but is not allowed to do that until the wind speed is over 14.2 m/s. If extracted power is equal to rated power, the thrust F decreases with increasing wind speed. Thus by not extracting maximum power excessive blade loads are avoided. The method is called thrust clipping.

Orientation

The turbine can be designed for upwind or downwind operation. In upwind operation the rotor must be aligned against the wind by an active yaw mechanism. In downwind operation the free yaw behaviour may be stable. The WTS-3 turbine was designed for free yaw operation, but it turned out to be unstable. WTS-3 is now provided with an active yaw mechanism which can turn the nacelle with a maximum speed of 1.2°/s. The existing methods are deficient in their ability to predict free yaw behaviour in horizontal axis wind turbines (Thresher (1981) p. 445). Ganander and Olsson (1983) are currently considering these problems.

The turbine axis may be tilted out of the horizontal plane. One reason is to make the turbine disc more orthogonal to the streamlines. Another reason is to increase the clearance between blades and tower so that the effect of the tower blockage is minimized. For this reason the axis of WTS 75 is inclined 10°.

The blades can be attached to the turbine shaft in different ways. Three typical cases are

1. Hinged hub. The blades are hinged to the main shaft, so that each blade independently of the other can move out of the plane of rotation.

2. Teeter (pendulum) hub. The blades are rigidly mounted to each other and hinged to the main shaft by means of a teeter shaft. The teeter shaft may be inclined an angle δ_3 from the axis orthogonal to the longitudinal blade axis. It makes the pitch angle vary with the teeter angle.

3. Rigid hub. The blades are rigidly mounted to the main shaft.

The hinged hub and teeter hub give extra degrees of freedom of orientating the rotor disc in an optimal way. It is important to decrease the loads on the blades and the hub. The heavy bending moments in the root sections of the blades are critical. The bending moments due to thrust and centrifugal forces depend on the angle between the blade and the plane of rotation, the cone angle. Fortunately, they are in opposition and there is a specific cone angle for which they balance one another. For the hinged hub the the bending moment at the blade root is zero. For the teeter and rigid hub the bending moments are substantially relieved if the angle between the blades are chosen such that the wind force and centrifugal force are in balance at the design wind speed.

Gravity, wind shear, tower blockage and turbulence generate forces and torques on the blades that vary considerably over the rotor area. A hinged or teeter hub allows the blades to yield and thus relieves them of extreme loads resulting from wind variations over the rotor area. Variations in the driving torque are also attenuated.

The δ_3 hinge makes the pitch angle vary with the teeter angle. It is typically employed to stabilize lifting rotors by increasing the teetering stiffness and reduce teetering. The stiffness increase also increases the teetering frequency, thereby allowing flexibility in blade tuning to avoid possible structural resonances. The effect of δ_3 is discussed by Perkins and Jones (1981).

Rasmussen and Pedersen (1982) report that skew wind may cause high dynamical loads on a stalled turbine.

Elastic motions.

The bending motions of the blades have several names. The bending motion out of plane of rotation is called flapping, flapwise, flatwise etc. and the bending in plane is called lead-lag, chordwise, edgewise etc. Sullivan (1981) discusses blade resonance responses. He makes the following conclusions.

1. High aerodynamical damping prevents resonance in the blade flatwise direction at all frequencies.

2. Odd harmonic excitations up to and including 5 P can cause significant blade edgewise resonance response; teetering the rotor will reduce this response substantially.

Friedmann (1976) states that the blades in a typical wind turbine system are torsionally rigid.

Sullivan (1981) classifies towers with first bending frequencies over 2 P as "stiff" towers and those with bending frequencies between 1 P and 2 P as "firm" towers. He does not discuss towers with bending frequencies below 1 P. Hence, the tower of WTS-3 must be considered as "soft".

A pitch angle controller may have an injurious effect on the tower. Assume that we have an "ideal" pitch angle controller that eliminates all variations in the driving aerodynamical torque above rated wind speed. Furthermore, assume that the tower is moving forward in the wind direction. The effect on the driving torque of a turbine motion in the wind direction is identical to a decrease in wind and the pitch angle controller will compensate to keep the driving torque constant. The control actions do not eliminate the variations in thrust. The thrust may increase or decrease; it depends on the blade parameters and the operating point. If the thrust increases, this means that the aerodynamical damping on the tower is negative. The aerodynamical damping is added to the structural damping giving the total tower damping. Since the structural damping is low, typically a few per cent, the risk of instability is impending. This indicates that the tower bendings must be considered when designing the control system. It is especially important to do this if the frequency of the first tower bending mode is less than or near the desired cross over frequency of the pitch angle control.

Table 2.2: Natural frequencies (in P) for some elastic blade and tower modes.

	MOD-2	WTS-3	WTS 75	Growian I
1st blade flatwise	3.3	2.6	4.2	3.5
1st blade edgewise	6.7	4.7	6.7	4.3
1st blade torsional	20	19		20
1st tower bending, thrusting direct.	1.3	0.85	2.7	1.5
1st tower bending, side direction		0.90	2.6	

2.4 The Electrical Part

The Synchronous Generator

Modelling of the synchronous generator is extensively covered in the literature and there are many good textbooks. Elgerd (1971) gives an excellent introduction. Anderson and Fouad (1977) discuss synchronous machine modelling thoroughly and give many references. Excitation systems are modelled by standard representations developed by IEEE (IEEE Committee Report (1968)).

Models of different complexities exist. This discussion will be based on a complex one. The model can be found in for example Oliver (1968) and is used by Hwang and Gilbert (1978) when simulating synchronization against an infinite bus. Kirchhoff's law equations and the equation of motion for the rotor (the swing equation) constitute the model. The stator is considered to have three identical, symmetrically placed, lumped windings a, b and c. On the rotor there are three windings f, x and g, placed in the direction of two orthogonal axes d (direct axis) and q (quadrature axis). The rotor winding f represents the field winding, while windings x and g are fictitious windings inserted to account for the effects of currents in the iron parts of the rotor or in damper windings. It is assumed that all self- and mutual inductances are independent of current (saturation is handled in other ways) and that they may be represented as constants plus a simple sine variation of the rotor angle θ or 2θ.

Since the inductances are dependent on the rotor angle θ, Kirchhoff's law equations describing this model contain time-varying parameters. This complication can be avoided by relating stator quantities like currents, voltages and flux linkages to the rotating d, q reference system instead of the normal stator fixed reference system. This transformation is called Park's transformation (Park (1929)).

The equations describing the rotor motion and the windings give a seventh order model, which contain both fast modes in the millisecond range and slow modes in the second range. The linearized model for the generator of WTS-3 gives at zero power the following poles

$$-19.6 \pm 313i,\ -72.8,\ -2.65 \pm 21.6i,\ -16.2,\ -1.16$$

and at the rated operating point

$$-19.6 \pm 313i,\ -74.5,\ -2.23 \pm 24.6i,\ -15.9,\ -0.64$$

The two fastest poles ($-19.6 \pm 313i$) are due to the stator windings. In the literature they are referenced as the stator dynamics. The poles in -74.5 and -15.9 are due to the damper windings and the pole in -0.64 are due to the field winding. The time constant of the field winding is normally 10 to 100 times longer than the time constants of the equivalent damper time constants. The poles in $-2.23 \pm 24.6i$ give the basic oscillative mode of the rotor motion. In Chapter 2.2 the synchronous generator was modelled by the swing equation with T_E given by (2.4). The transfer function from mechanical torque T_m to electrical torque T_E given by the seventh order model linearized at the rated operating point are shown in Figure 2.7. The zeros are $-9.8 \pm 313i$, -51.4, -15.7

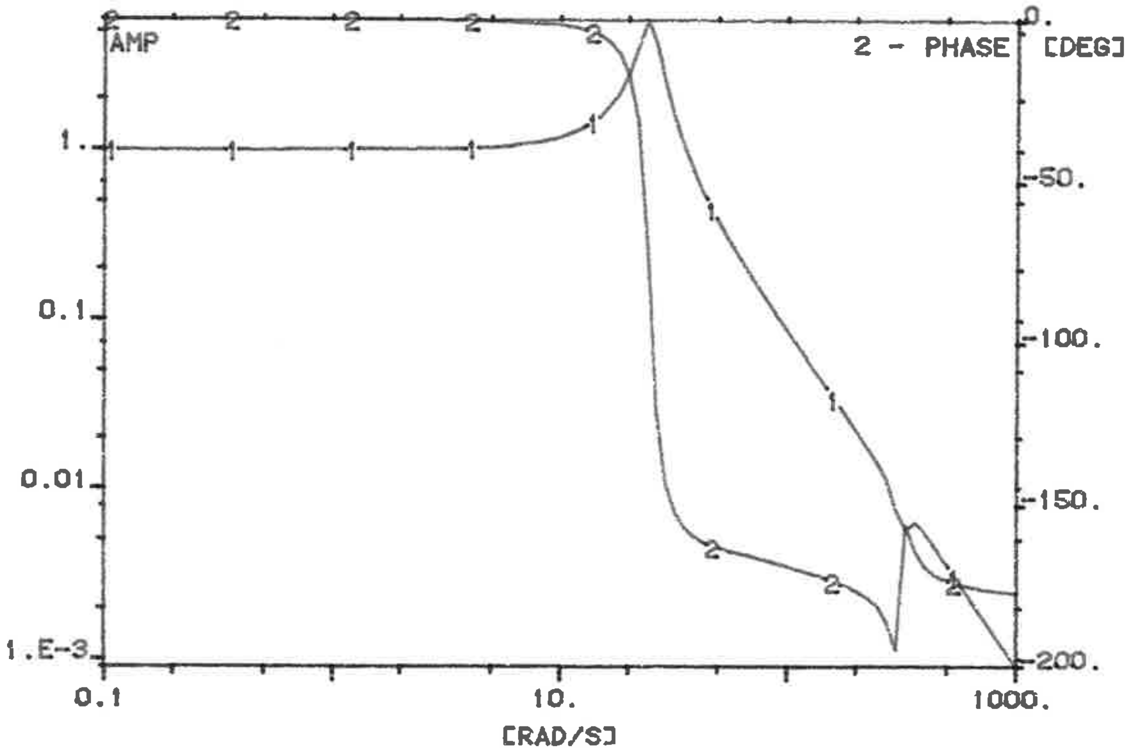

Figure 2.7: The transfer function from T_m to T_E for the synchronous generator of WTS-3 given by the seventh order model linearized at the rated operating point.

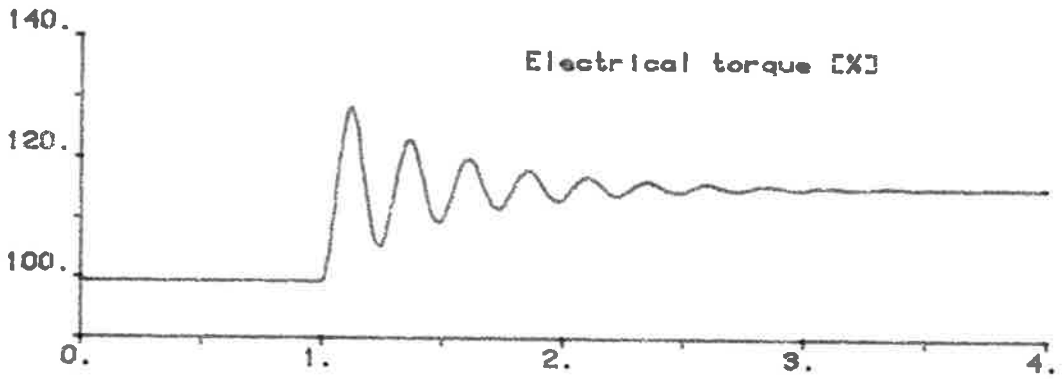

Figure 2.8: The response to a step in T_m at $t = 1$ s given by the nonlinear seventh order model for the generator of WTS-3.

and -0.64. A simulation of the response to a step in T_m using the nonlinear seventh order model is shown in Figure 2.8. As seen, the approximation (2.4) is very good when studying the influence from wind on the power production.

The stator dynamics and the dynamics of the windings are important when electrical properties like the response to faults in the grid are studied. The implications of neglecting the stator dynamics are discussed by Olive (1968). It means that second and higher harmonics in flux linkage and stator currents are neglected.

The Asynchronous Generator

The asynchronous generator is also modelled using Kirchhoff's law equations and the equation of motion for the rotor (for example Leonhard (1974) or Nordanlycke, Paulsson and Wredenberg (1974)). The rotor is considered to have two orthogonal windings.

To make the equations timeinvariant, the stator quantities are transformed to a synchronous rotating system in the same way as for the synchronous generator. The rotor quantities are transformed to a rotating system with the rotational speed $\dot{\delta} - \omega_0$. The equations give a sixth order model. The complex pole pair giving the stator dynamics is of the same magnitude as in the synchronous case.

If the the generator is short-circuited the integration giving δ can be

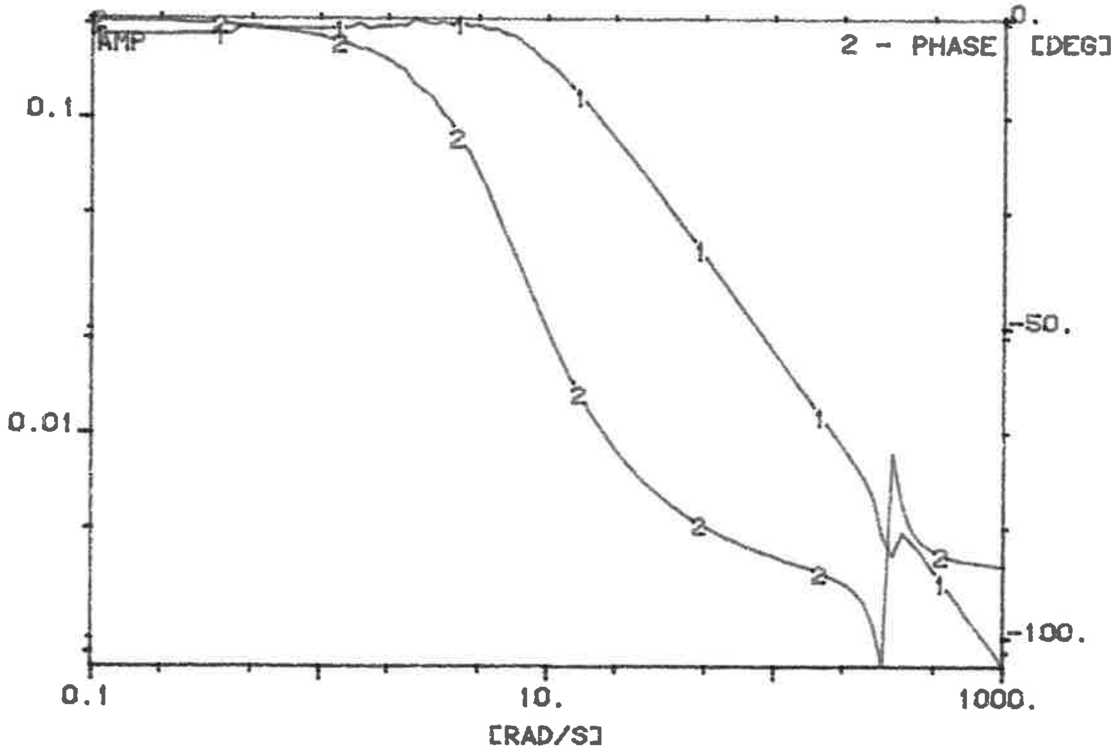

Figure 2.9: The transfer function from $\dot{\delta}$ to T_E for a typical asynchronous generator with a short-circuited rotor given by the linearized sixth order model.

eliminated from the model. The transfer function from $\dot{\delta}$ to T_E for an asynchronous generator with a short-circuited rotor is shown in Figure 2.9. It justifies the expression (2.5) for T_E.

Growian I has a double fed asynchronous generator. Leonhard (1979) describes the control scheme in the following way

> "Since it is based on the magnitude and direction of a flux vector, established by direct or indirect measurement, it is called field-oriented control. The magnitude, frequency and phase of the input currents (in this case the rotor currents) are generated in such as to give the rotor MMF-vector a prescribed orientation in relation to the main flux vector (which itself is a function of the rotor currents). The longitudinal component of the rotor current vector changes the terminal voltage, hence the reactive power, and through a substantial lag the magnitude of the

> main flux; the quadrature component of the rotor current vector immediately affects the torque and active power."

Loss of Load

Electrical faults may change the dynamic behaviour drastically. If the load is lost this corresponds to $T_E = 0$. WTS-3 has under full load the gearbox mounting twisted 1000 electrical degrees. If the load is lost, the untwisting of the spring between the turbine and the generator will accelerate the rotor of the generator. The behaviour can be estimated by the model (2.3). If damping is neglected the power angle δ can be estimated by

$$\delta(t) - \delta(0) = 1000° \cdot (1 - \cos 3.8 \cdot t) \tag{2.7}$$

For example $\delta(0.1) - \delta(0) = 75°$. A rigorous calculation shows that synchronism is lost if the load is lost more than 0.16 s. This is also a typical value for conventional turbine generators.

If the synchronous generator is connected and the bus voltage is greater than zero during the fault, it is possible to increase the electrical torque by increasing the excitation voltage. The synchronism can be maintained, if the excitation voltage can be increased so much that the electrical torque can be restored in stationary. The dynamics of the excitation system can be made fast enough.

It is not possible to prevent loss of synchronism at electrical faults by controlling the pitch angle even if the shaft is stiff. Hau (1982) reports that battery storage units weighing 2.5 tonnes were installed to fulfil the demand on Growian I to be able to bridge grid interruptions of up to 20 s. For WTS-3 the blade angle must be changed more than ten degrees to achieve zero driving aerodynamical torque at rated wind speed. In Figure 2.10 a simulation of the turbine rotor speed of WTS-3 at loss of load at different emergency pitch rates is shown. The simulation model described in Bergman and Mattsson (1983) was used. It is assumed that the wind speed is 14 m/s and that the system is in stationarity. At $t = 1$ s the generator is disconnected and the emergency system is activated.

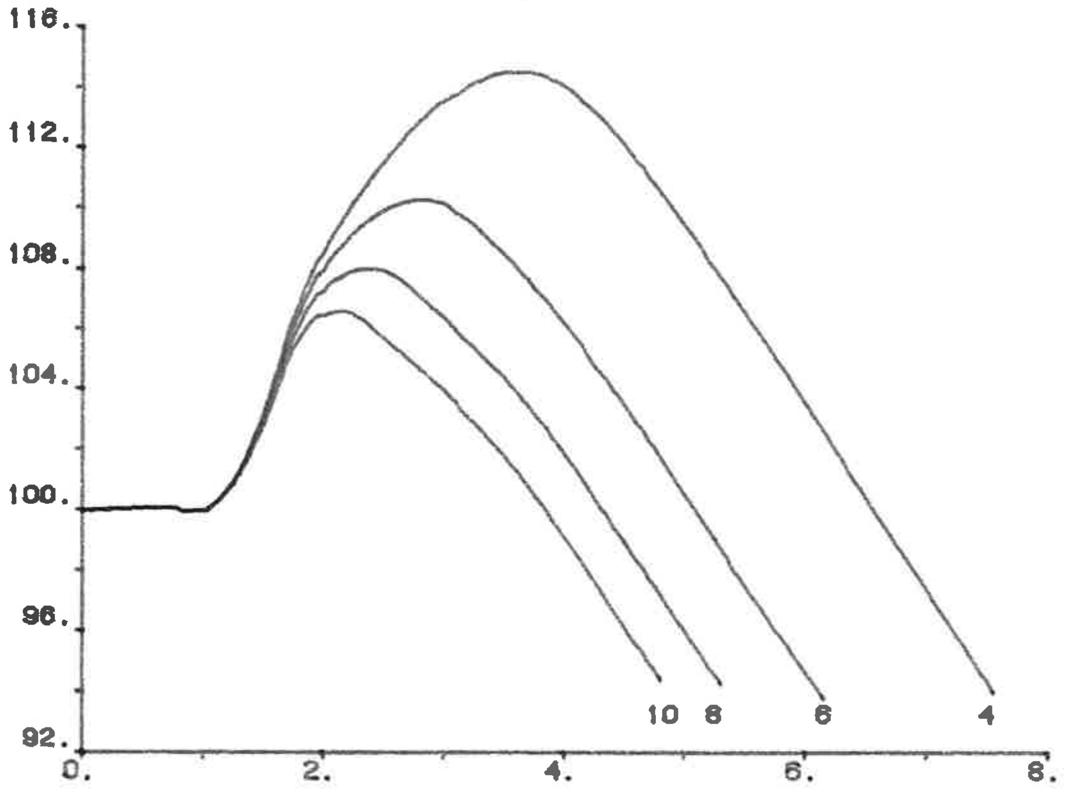

Figure 2.10: Simulated turbine rotor speed [%] of WTS-3 at different emergency pitch rates.

3. WIND CHARACTERISTICS

The variation of the wind speed in space and time is a complex phenomenon. The wind turbulence gives it a stochastic behaviour.

The power spectrum of horizontal wind speed near ground level ranges over several decades of frequencies. The spectrum has two major eddy-energy peaks in the spectrum; one peak occurs at a period of about 4 days, and a second peak occurs at a period of about 1 minute. The former peak is due to wind speed fluctuations caused by migratory pressure systems of synoptic weather-map scale. The latter peak is in the micrometeorological range and is a mechanical and convective type of turbulence. Between the two peaks, a broad spectral gap is centered at a period ranging from 10 minutes and 1 hour (van der Hoven (1957)). When considering blade angle control, it is the high frequency part that is of interest. The low frequency part gives the mean wind speed. This means that it is convenient to model a wind speed component in a point $\vec{x}$ as

$$U_i(\vec{x}, t) = \bar{U}_i(\vec{x}) + u_i(\vec{x}, t) \qquad (3.1)$$

where $\bar{U}_i$ is the mean value of U_i and u_i is the turbulence part having zero mean.

In Chapter 3.1 the variations of the mean wind speed in space are discussed. The turbulence is discussed in Chapter 3.2.

3.1 Wind Shear

Different analytic expressions for the variation of the mean wind speed with the altitude for an airflow over a horizontal and homogeneous terrain are suggested in the literature; Shepherd (1978) gives a survey. The influence of ridges and hills are discussed in Jackson and Hunt (1975) and Bradley (1980). Frost, Long and Turner (1978) give detailed computational procedures intended for fatigue strength analysis or structural strength analysis under extreme wind shear. Since, it is only the wind profile over the rotor disc that are of interest, it is reasonable to assume a linear wind profile when calculating variations in power output or when designing cyclic pitch control.

3.2 Wind Turbulence

Wind turbulence is a complex and not completely understood phenomenon. An introduction can be found in Lumley and Panofsky (1964). Etkin (1972) gives a nice summary of basic concepts and relations. Engineering Sciences Data (1974) and Frost, Long and Turner (1978) give detailed computational procedures.

Several analytical expressions for the power spectrum of the horizontal wind speed in a fixed point are given in the literature. They are typically of the form

$$S(\omega) = \frac{K \cdot |\omega|^{\gamma}}{\left[1 + (\omega T)^{\alpha}\right]^{\beta}} \tag{3.2}$$

where K and T depend on the surface roughness, mean wind speed and height over ground level. Mathematical models and also most spectra obtained from measurements indicate that there is a range (the inertial subrange) where $S(\omega) \sim \omega^{-5/3}$, which means that in (3.2) $\alpha\beta - \gamma = 5/3$. Engineering Sciences Data (1974) recommends the von Karman spectrum. It has $\alpha = 2$, $\beta = 5/6$ and $\gamma = 0$. A detailed description on how to calculate K and T is given. Also many references are given. Etkin (1972) uses also the von Karman spectrum. Davenport (1961) suggests a spectrum with $\alpha = 2$, $\beta = 4/3$ and $\gamma = 1$. In the Swedish Specification for WTS-3 a spectrum with $\alpha = 1$, $\beta = 5/3$ and $\gamma = 0$ is given. Frost, Long and Turner (1978) and Spera and Richards (1980) use a spectrum with $\alpha = 5/3$, $\beta = 1$ and $\gamma = 0$. Unfortunately, these spectra are not rational and this makes it complicated to use them for control design.

The Dryden spectrum (Powell and Conell (1980)), which has $\alpha = 2$, $\beta = 1$ and $\gamma = 0$, is rational. A stochastic process with the Dryden spectrum can be modelled by the output of a first order system driven by white noise with zero mean and unit variance. The system has the transfer function

$$G(s) = \frac{\sigma\sqrt{\left(2\ \bar{U}/L\right)}}{s + \bar{U}/L} \tag{3.3}$$

where $\bar{U}$ is the mean wind speed and σ is the standard deviation of the output and has the form

$$\sigma = T_F\bar{U} \tag{3.4}$$

T_F (the turbulence factor) and L depend on surface roughness and height over ground level. For Maglarp at hub height typical values are $T_F = 0.1 - 0.2$ and $L = 100 - 300$ m.

The wind spectra discussed above are spectra for the wind speed in a fixed point. However, the turbine senses some kind of an average value over the rotor area. Davenport (1977) suggests a nonrational filter to account for the averaging over rectangular walls.

Holley, Thresher and Lin (1981) approximate a component of the undisturbed turbulent velocity in a point in the rotor disc with the polar coordinates (r,ϕ) as

$$u_i(r,\phi,t) = u_{i0}(t) + u_{i1}(t)\ r\sin\phi + u_{i2}(r)\ r\cos\phi \qquad i = 1,\ 2,\ 3 \tag{3.5}$$

The uniform terms u_{i0} and the gradient terms u_{i1} and u_{i2} are stochastic processes. At any time they are chosen as the least square approximation over the rotor disc. $u_{i0}(t)$ is the mean value over the rotor disc of $u_i(r,\phi,t)$.

Models for u_{i0}, u_{i1} and u_{i2} assuming a stationary, homogeneous and isotropic turbulence and with the spatial correlation transformed to time τ using Taylor's frozen field hypothesis

$$x = -\bar{U}\tau \tag{3.6}$$

are given as a linear combination of nine uncorrelated stochastic processes which are outputs of first order systems driven by white noise. The model is based on the von Karman covariance functions and is parameterized by the mean wind speed $\bar{U}$, the rotor radius R and the integrale scale L defined as

$$L = \int_0^\infty f(\xi)\, d\xi \tag{3.7}$$

where $f(\xi)$ is the longitudinal correlation function. Intuitively L can be interpreted as the size of typical eddies.

If it is assumed that the mean wind direction is z, the uniform term u_{z0} is of special interest. It is modelled by the output of a first order system driven by white noise with zero mean and unit variance. The system has the transfer function

$$G(s) = \frac{b_* \sigma \sqrt{\left[2a_* \bar{U}/L\right]}}{s + a_* \bar{U}/L} \tag{3.8}$$

Holley, Thresher and Lin (1981) give a_* and b_* as functions of the quotient R/L. The standard deviation of the output is $b_* \sigma$. If $a_* = b_* = 1$ the spectrum is equivalent to the the point spectrum (compare with (3.3)) and that is approximately the case if $R/L < 0.1$. For $R/L = 1$ $a_* = b_* = 0.5$, which give a spectrum that differ significantly from the point spectrum.

If the flow is assumed to be incompressible and the turbulence is assumed to be homogeneous and isotropic the correlation between $u_{z0}(t)$ and $u_z(0,0,t)$ is $f(R)$, where $f(\xi)$ is the longitudinal correlation function. The von Karman correlation functions imply that for $R/L > 0.5$, $f(R) < 0.6$ (a plot of f can be found in for example Frost, Long and Turner (1978)). This indicates a low correlation between the wind speed in a point in the rotor disc and the mean value over the rotor disc.

Engineering Sciences Data (1974) states that it is reasonable in many applications to assume that wind turbulence is a Gaussian process, but in practice it contains 'patches' of a significantly non-Gaussian nature when larger gusts and longer lulls occur more frequently than indicated by the Gaussian distribution.

Spectral models are not well-suited for modelling extreme events like large gusts. Events of this kind can be modelled by discrete gust models. Powell and Conell (1980) define gusts as

> "any series of discrete velocity-time events that can be defined from a turbulence time series according to some extrinsic criterion."

For example the extrinsic criterion may be chosen as adjacent crossings of the mean value and the velocity-time events as the amplitude and duration.

A discrete gust model gives the statistics for the velocity-time events. Powell and Conell (1980) review a number of discrete gust models suggested in the literature. A report on this subject by Linde is to appear in the near future (See also Linde (1981)).

4. THE CONTROL PROBLEM

In this chapter the control problem is considered. In Chapter 4.1 control objectives are presented. The possibilities to measure different quantities are discussed in Chapter 4.2. The interaction between process design and regulator design is discussed in Chapter 4.3. Some control issues are discussed in Chapter 4.4.

4.1 Control Objectives

A wind turbine system connected to an electrical network is supposed to produce power by transforming wind energy into electrical form with an optimal overall efficiency. It is of course desirable that the plant extracts much energy, but it is not sure that a strategy that gives maximum power at every instance gives the best economic result. A safe and reliable operation must be guaranteed to give the system a long lifetime of 20 - 30 years with low maintenance and repair costs.

The operation is constrained by a number of demands from both the environment and the system itself. Most of the environmental demands emanate from the desire to have a stable utility grid, but there are others like that the acoustic noise should be low. The internal demands are due to the limited capability of the system to withstand heat, loads, deflections and fatigue.

Terminal Voltage

The Swedish norm for what is acceptable voltage variations in a low-voltage system is based on the sensitivity of the eye to light flickering. The eye is most sensitive to voltage variations at 15 - 20 Hz. In this range the acceptable variations is as low as 0.3%. At frequencies around 1 Hz the acceptance level is 0.8%. For occasional voltage fluctuations such as starting-ups a few times a day, the norm accepts a 2.5% voltage fluctuation.

Electrical Power

Since the wind is a unreliable power source, it is not possible to guarantee a certain production and it is not possible to fulfil usual unit commitments on the generation changes. This implies that is not reasonable to have more then 10 - 20% of the total electrical power coming from wind turbines (Larsson (1978)).

Demands on the power quality are contrary to the desire to produce much power. A maximal power extraction means that the produced power must follow the variations in the wind, since a wind power plant cannot store larger amounts of energy. Probably it is the demands emanating from the mechanical parts that are decisive for pitch angle control during normal operation and not those emanating form the utility grid. It is favourable for a mechanical system to operate smoothly and to avoid excessive dynamic loads. A wind turbine is not supposed to take part in the control of the utility grid, but if possible not make the situation worse. However, it is a basic demand that the generator remains in synchronism with the grid. As indicated in Chapter 2.4 electrical faults may cause loss of synchronism. A loss of the synchronism caused directly by the wind should not be possible. It should mean that produced power is in the magnitude of twice rated power. Such high power production cannot be tolerated for reasons of safety.

The generator itself puts constraints on the power output. If produced power is greater than rated power for longer times, the generator may be overheated and damaged.

Loads

Strain and stress put limits on the power production. As pointed out in Chapter 2.3 the bending moments in the root sections of the blades are critical. The shaft torque are also critical. The supervisory system of WTS-3 disconnects the generator and initiates an emergency shutdown, if produced power exceeds 140% of rated power.

For a wind turbine system with a soft shaft, mechanical stiffness is much lower than electrical stiffness and this implies that shaft torque amplification during electrical switching and faults is less severe than in conventional turbine generators. The limitation during electrical disturbances is bracing of generator windings, not strength of shafts. The soft shaft also reduces the accuracy required for matching voltage, speed and phase angle during synchronization.

Fatigue is a serious problem. The parts of the turbine are typically supposed to withstand 10^8 load cycles during the lifetime of the plant.

4.2 Measurements

Electrical quantities like power and voltage can all be measured easily.

Blade motions and blade loads can be measured by accelerometers and strain gauges. These measurements are of special interest if the blade loads should be controlled by active cyclic pitch control. See Liebst (1981).

Tower motions can be measured by accelerometers in the nacelle. These measurements are of interest in systems having soft towers for which the frequency of the first tower bending is lower than the desired cross over frequency of the pitch angle control. They make it possible to separate variations in the power production due to wind variations from those caused by tower motions. The possible instability discussed in Chapter 2.3 caused by interactions between the tower bendings and the pitch angle control can in this way be avoided.

Rotational Speed

Rotational speed at primary and secondary shaft can also be measured.

At on-line operation it is the rotor speed deviation from synchronous speed that is of interest. Svensson and Ulen (1982) report that it is not quite simple to measure the turbine rotor speed with required accuracy at on-line operation. They state that it is a limiting factor for the performance of WTS-3. The turbine speed varies typically ±1% of rated speed at on-line operation. The quantization in the rotor speed measurements is about 0.1% of rated speed. This means that the rotor speed measurement typically can give only about 20 different values. Furthermore, the signal is rather noisy. Their specification for the noise level was 0.25%.

The deviation of the turbine rotor speed from synchronous speed can for WTS-3 be inferred from the gearbox motions. However, this implies that an extra device is needed; the turbine rotor speed sensor is needed for startup, synchronization and shut-down.

Preliminary investigations indicate that in on-line operation the turbine rotor speed can be reconstructed from generator power measurements. The two following observations are important. First, the generator power varies typically ±10% of rated value compared to ±1% of the rated value for the rotor speed. The specified accuracy for the electrical power sensor is ±0.5% of the rated value. Second, in the frequency range of interest for pitch angle control (< 3 rad/s) the electrical power can be modelled by

$$\Delta P_E = (P_{E0}/\dot{\phi}_0 + D_{shaft}\dot{\phi}_0)\Delta\dot{\phi} + K_{shaft}\dot{\phi}_0\Delta\phi \qquad (4.1)$$

where Δ denotes deviation from the operating point given by the actual mean wind speed, $\dot{\phi}_0$ is the synchronous rotor speed and P_{E0} is the produced power at the operating point. Above rated wind speed WTS-3 has ΔP_E=(1.1+7.9) $\Delta\dot{\phi}$ MW/(rad/s) + 20.1 $\Delta\phi$ MW/rad so that in the frequency range around 1 rad/s $\Delta\dot{\phi}$ gives a significant contribution to ΔP_E.

Wind Speed

The quality of the control depends on how well the wind speed is known and on how well its behaviour can be predicted. In Chapter 3.2 it was shown that in some weather conditions the correlation between the wind speed in a point in the rotor disc and the mean wind speed over the rotor disc is low. This indicates that an anemometer may be of little use for feedforward compensation. However, it may be possible to use the wind turbine itself as wind gauge by measuring other quantities. An interesting idea to measure the wind is to put strain gauges on the blades. This appears promising because the average wind force is measured rapidly.

4.3 Interaction Between Process Design and Regulator Design

In a presentation at the Wind Energy Symposium at the Aeronautical Research Institute of Sweden, March 14 - 15, 1983, Anders Ulfvarsson from Swedyards Wind Turbine Systems Corp. stated that it is their design philosophy to have a fast pitch angle control since it simplifies the strength calculations. Kos (1978) states that "rapid modulation of blade angle will also reduce the peak blade and tower loads resulting from wind gusts and is therefore helpful in reducing the weight of the wind turbine system". This indicates a possible conflict between process design and regulator design. The desire to have a fast pitch angle control system means that a fast servo needed. Simulations in for example Kos (1978) indicate that pitch rates of the order of 10°/s is desirable. However, the pitch rates of both MOD-2 and WTS-3 are limited to 4°/s. For WTS-3, which has full span pitch control the speed is limited for reasons of safety. Fast turnings of a blade cause large loads in the blade root. Furthermore, a fast modulation means that a high bandwidth of the pitch angle control is needed. A lighter system means a softer system, which in turn means that the natural frequencies of the blades and the tower become lower. If a natural frequency of a mode is lower than or close to the desired cross over frequency of the pitch angle control system, this causes large difficulties when designing the pitch angle control. Additional sensors like accelerometers and strain gauges giving information about the state of the mode may be needed. It may even be impossible to achieve an acceptable performance. For reasons of safety it is recommendable to avoid these problems if possible.

However,if a synchronous or short-circuited asynchronous generator is used, it is desirable to have the first natural frequency of the drive train below the cross over frequency of the pitch angle control. The rapid variations in driving torque are then filtered out by the soft shaft and the demands on the bandwidth of the pitch angle control can be lowered. The designer has the freedom to chose the first torsional frequency in the range 1 - 10 rad/s. However, it is not quite easy to design a torsionally soft shaft that can stand the bending torques. A soft mounting of the planetary gearbox as done in WTS-3 is one solution to the problem. If a synchronous generator is used the mode has low damping and becomes a major design problem for pitch control. If a short-circuited asynchronous generator is used it is as demonstrated possible to design the system so that the mode is better damped, at the expense of reactive current and with no means of controlling the terminal voltage.

If a fed asynchronous generator is used, the excitation control can handle the rapid variations in the driving torque and the filter effect of the soft shaft is not important. A fed asynchronous generator combine the operational advantages of variable speed with the possibility of reactive power generation.

Different ways of designing the turbine in order to have passive alleviation of the cyclic loads were discussed in Chapter 2.3. The cyclic loads can also be alleviated by active pitch control. See Liebst (1980, 1981). Sensors like accelerometers and strain gauges are needed to measure blade motions and blade loads. It must be possible to control the blade angles individually. Liebst (1981) states that preliminary investigations for MOD-2 showed that pitch rates of the order of 12°/s would be necessary to obtain significant vibration reductions.

4.4 Control Issues

Chapter 4.1 indicates a complex, constrained dynamic optimization problem. Even if there were no constraints on the loads, it would be a very hard task to design a control scheme such that maximum power were extracted. One reason is that it is so difficult to get adequate information about the large, rapid and random variations in the wind speed. It is important to know the wind speed, because if the system is extracting maximum power, then both an increase and a decrease in the wind speed would give a decrease in extracted power.

Today when most of the large wind power plants are prototypes, it is important to get safe and reliable systems so that breakdowns are avoided. So it seems recommendable to play for safe and put the efforts on keeping the loads inside the tolerable limits instead of trying to maximize the power output and thereby risking to get large loads on the system.

As pointed out in Chapter 4.3, one important task for the control system is to reduce peak blade and tower loads resulting from wind gusts. The rated power is chosen so that the actual control system should be able to keep the loads inside tolerable limits. For WTS-3 this limit is 4.2 MW. Consequently, it would be possible to raise the power production above rated wind speed if the peak loads could be decreased by better control. However, the warning given in Chapter 4.3 must not be forgotten. Since the peak loads are caused by large wind gusts, it would be interesting to investigate if it is possible to detect or predict large wind gusts in advance.

There is a number of control signals like the orientation of the turbine, the pitch angle and the excitation of the generator. The system has many outputs like orientation relative to the wind, electrical power, terminal voltage, tower deflections and loads in blades and tower, that are of interest when controlling the system. It is an important task to find out if coordination of the control actions is necessary. The control problem is simplified considerably if the control actions can be done independently of each other. The need of coordination is discussed below.

The control problem is nonlinear. This implies that many design procedures cannot be used directly, but has to be modified or extended. The nonlinearities are considered below in order to see if they can be neglected or eliminated by transformations.

Coordination of Control Actions

Both the control of the orientation of the turbine rotor and the control of the pitch angle influence the driving aerodynamical torque. The purposes of the two control actions are different. The purpose of the yaw control is to have the turbine oriented correctly to achieve high efficiency and to avoid large dynamical loads caused by cross winds; yaw control should eliminate the effects of variations in wind direction, not the effects of variations in wind speed. It is the task of the pitch angle controller to handle the variations in wind speed sensed by the turbine rotor. Since the wind speed sensed by the rotor depends on the orientation, the pitch angle controller can be more effective if the control of the yaw controller is known. However, as seen from Table A.1 the maximum rates of the yaw drives are low so probably no coordination is needed.

As found in Chapter 2.2 the synchronous generators of MOD-2 and WTS-3 have a low damped oscillative mode at 25 rad/s. To excite this mode a high frequency disturbance around 25 rad/s is needed. Due to the low pass filter effect of the large turbine and the soft shaft, this mode is hardly not influenced by the wind variations or the blade servo. For WTS-3 such large and rapid disturbance as the loss of driving torque, when a blade passes behind the tower, causes only few small oscillations that dies out before the other blade passes behind the tower. The mode is excited by variations and faults in the grid and can be influenced by excitation control. Consequently, the damping and control of this mode is an internal problem of the electrical part and can be neglected when designing the pitch blade control. There is a possible conflict between the use of the excitation system for voltage control and damping of the rotor oscillations. Probably it is a good approach to assume that pitch and excitation control in normal operation can work independently of each other when a synchronous generator is used.

The situation is somewhat different when a fed asynchronous generator is used. In order to take advantage of the allowed variations in generator speed it it is natural to let the pitch angle controller and the excitation controller share the responsibility of keeping the the generator speed inside the allowed interval. Below rated wind speed the objective of the pitch angle control could be to extract maximum power (under given constraints on loads) and the objective of the excitation control could be to improve the power quality by smoothing out the rapid power variations under the constraint that the generator rotor speed should lie inside the allowed interval. Above rated speed the objective of both the pitch angle control and the excitation control could be to keep the power production constant. A high power quality could be achieved if the main responsibility of keeping the speed inside the allowed interval is put on the pitch angle controller. However, if the pitch angle controller fails due to for example an extreme wind gust the excitation controller must assist in keeping the speed inside the allowed interval.

Nonlinearities

Fortunately, only a few nonlinearities in the system are of importance in normal operation. They are found in the dynamics from wind speed and pitch angle to driving torque.

As shown in Chapter 2.3 the driving aerodynamical torque T is a nonlinear function of wind speed, turbine speed and pitch angle. To get a good understanding of T, its variation with rotor speed will be neglected, since the aerodynamical damping torque is small compared to desired damping torque. With an angle of attack below stalling angle, T is almost linear in the pitch angle. We can now write T as $T = f(U) \cdot \beta + g(U)$, where f(U) and g(U) are nonlinear functions. From the pitch angle controllers view this means that process gain varies with wind speed as well as the bias. Since the nonlinearity can be parameterized with one parameter, it seems suitable to use gain-scheduling. It is probably sufficient and most robust to have a gain-schedule based on the mean wind speed and base the design on models linearized at the operating point given by the mean wind speed.

The limitation in servo speed is an important nonlinearity when designing the pitch angle control system. The impact of the limitation on the performance depend on the wind speed, since the process gain varies with the wind speed. It also depends on the spectral properties of the turbulence and especially the variance.

ACKNOWLEDGEMENTS

This work has drawn upon results and experiences from a number of projects in the wind energy area since 1980. I want to express my sincere gratitude for the valuable discussions I have had during this time with the manufacturers of wind power plants, the Swedish utilities, the Aeronautical Research Institute of Sweden, the Swedish National Defence Research Institute and the Department of Electric Machinery, Chalmers University of Technology.

The support for this particular project by the National Swedish Board for Energy Source Development (NE) under contract 5061 621 is gratefully acknowledged. I also want to thank Professor Karl Johan Åström and Sten Bergman for many valuable discussions during the project.

REFERENCES

Anderson, P.M. and Fouad, A.A. (1977). Power Systems Stability and Control. Iowa State University Press.

ASEA (1980). Karlskronavarvet AB WTS-System Studies, Final Report. ASEA ref FKG 9519.2003, ASEA, Västerås, Sweden.

Bergman, S., Mattsson, S.E. and Östberg, A.B. (1981). A Modular Simulation Model for a Wind Turbine System. AIAA-81-2558. AIAA 2nd Terrestrial Energy Systems Conference, December 1-3, 1981/Colorado Springs, Colorado.

Bergman, S. and Mattsson, S.E. (1983). Wind Power Plant Modelling and Simulation. The Fifth Power Plant Dynamics, Control and Testing Symposium, March 21-23, 1983, Knoxville, Tennessee. pp. 7.1-7.27.

Bradley, E.F. (1980). An Experimental Study of the Profiles of Wind-Speed, Shearing Stress and Turbulence at a Crest of a Large Hill. Quart. J. Roy. Met. Soc. 106, pp. 101-123.

Davenport, A.G. (1961). The Spectrum of Horizontal Gustiness Near the Ground in High Winds. Quarterly J. Roy. Met. Soc., Vol 87, pp. 194-211.

Davenport, A.G. (1977). The Prediction of the Response of Structures to Gusty Winds. International Research Seminar on Safety of Structures under Dynamic Loading.

Elgerd, O.I. (1971). Electric Energy Systems Theory, An Introduction. Mc Graw-Hill, Inc.

Engineering Sciences Data (1974). Characteristics of atmospheric turbulence near the ground. Part II: single point data for strong winds (neutral atmosphere), Item No. 74031, London.

Etkin, B. (1972). Dynamics of Atmospheric Flight. Wiley, New York.

Friedman, P.R. (1976). Aeroelastic Modeling of Large Wind Turbines. J. Am Helicopter Soc. 21(4), 17-27.

Frost, W., Long, B.H. and Turner, R.E. (1978). Engineering Handbook on the Atmospheric Environmental Guidelines for Use in Wind Turbine Generator Development. NASA Technical Paper 1359.

Ganander, H. and Olsson, B. (1983). Variations of winddirections and their influences on horizontal axis windturbines. Notice of research project, NE, National Swedish Board for Energy Source Development, Stockholm, Sweden.

Hau, E. (1982). GROWIAN, design manufacturing, latest state of the project. 4th International Symposium on Wind Energy Systems, Sweden (September 21 - 24, 1982). Organized by BHRA Fluid Engineering, Cranfield, Bedford, England. Vol. 1, pp. 317-335.

Hinrichsen, E.N. and Nolan, P.J. (1980). MOD-2 Wind Turbine Stability Study, DOE/NASA/0134-1, NASA CR-165156. A summary is given in Dynamics and Stability of Wind Turbine Generators. IEEE Trans. on Power Apparatus and Systems, Vol. PAS-101, August 1982, pp. 2640-2648.

Hinrichsen, E.N. (1981). Discussion of the paper 'Methods of resynchronizing wind turbine generators' by Krause P.C. and Wasynczuk O. IEEE Trans. on Power Apparatus and Systems, Vol. PAS-100, October 1981, p. 4308.

Holley, W.E., Thresher, R.W. and Lin, S-R. (1981). Wind Turbulence Inputs for Horizontal Axis Wind Turbines. In Thresher (1981), pp. 101-112.

van der Hoven, I. (1957). Power spectrum of horizontal wind speed in the frequency range from 0.0007 to 900 cycles per hour. J. Meteoral., 14 pp. 160-164.

Hultgren, L.S. (1979). Torsional Oscillations of the Rotor Disc for Horizontal Axis Wind Turbines with Hinged or Teetered Blades. Technical Note AU-1499 part 12, The Aeronautical Research Institute of Sweden, Stockholm, Sweden.

Hwang, H.H. and Gilbert, L.J. (1978). Synchronization of Wind Turbine Generators Against an Infinite Bus under Gusting Wind Conditions. IEEE Trans. on Power Apparatus and Systems, Vol. PAS-97, March/April 1978, pp. 536-544.

IEEE Committee Report (1968). Computer Representation of Excitation Systems. IEEE Trans. on Power Apparatus and Systems, Vol. PAS-87, June 1968, pp. 1460-1464.

Jackson, P.S. and Hunt, J.C.R. (1975). Turbulent Wind Flow Over a Low Hill. Quart. J. Roy. Met. Soc. 101, pp. 929-955.

Koeppl, G.W. (1982). Putnam's Power from the Wind, Second Edition. Van Nostrand Reinhold Company, New York.

Kos, J.M. (1978). On-Line Control of Large Horizontal Axis Energy Conversion System and Its Performance in a Turbulent Wind Environment. Proceedings of the 13th Intersociety Energy Conversion Engineering Conference, August 1978, pp. 2064-2073.

Krause, P.C. and Man, D.T. (1981). Transient Behavior of a Class of Wind Turbine Generators during Electrical Disturbances. IEEE Trans. on Power Apparatus and Systems, Vol. PAS-100, May 1981, pp. 2204-2210.

Larsson, L. (1978). Large-Scale Introduction of Wind Power Stations in the Swedish Grid: A Simulation Study. Wind Engineering, Vol. 2, No. 4, 1978.

Leonhard, W. (1974). Regelung in der elektrischen Antriebstechnik. Teubner.

Leonhard, W. (1979). Field Oriented Control of a Variable Speed Alternator Connected to the Constant Frequency Line. Implementing Agreement for Co-Operation in the Development of Large Scale Wind Energy Conversion Systems, Second Meeting of Experts - Control of LS-WECS and Adaptation to the Network, July 1979, pp. 121-125. Zentralbibliothek der Kernforschungsanlage Julich GmbH, Julich, West Germany.

Liebst, B.S. (1980). Optimized Pitch Controller for Load Alleviation on Wind Turbines. Technical Note HU-2189 part 1, The Aeronautical Research Institute of Sweden, Stockholm, Sweden.

Liebst, B.S. (1981). A Pitch Control System for Large Scale Wind Turbines. Technical Note HU-2262 part 6, The Aeronautical Research Institute of Sweden, Stockholm, Sweden.

Linde, M. (1981). Analysis of Gust Structure in the Atmospheric Boundary Layer by Using Conditional Sampling. Technical Note HU-2262 part 1, The Aeronautical Research Institute of Sweden, Stockholm, Sweden.

Lumley, J.L. and Panofsky, H.A. (1964). The Structure of Atmospheric Turbulence. John Wiley & Sons, Inc.

Mattsson, S.E. (1982). Development of a Modular Simulation Model for a Wind Turbine System. Department of Automatic Control, Lund Institute of Technology, Lund, Sweden. CODEN: LUTFD2/(TFRT-7239)/1-033/(1982)

Mets, V. and Hermansson, O. (1983). Status and Experience with the 2 MW WTS 75 at Näsudden, Gotland. KaMeWa AB, Box 1010, S-681 01 Kristinehamn, Sweden.

Miller, D.R. (1978). Wind Turbines Structural Dynamics. NASA-CP-2034, A workshop held at Lewis Research Center, Cleveland, Ohio, Nov 15-17, 1977.

NE (1982). The National Swedish Wind Energy Program. NE, The National Swedish Board for Energy Source Development, Stockholm, Sweden.

Nordanlycke, I., Paulsson, E. and Wredenberg, L. (1974). Solution Methods of Power System Dynamics. The Royal Institute of Technology, Power Systems Research Group, Sweden.

Nygren, I., Grop, S. and Pettersson, B. (1981). Vindkraftverk med lågvarvig generator (Wind power plant with low speed generator). NE/WIND 81/7. NE, The National Swedish Board for Energy Source Development, Stockholm, Sweden.

Olive, D.W. (1968). Digital Simulation of Synchronous Machine Transients. IEEE Trans. on Power Apparatus and Systems, Vol. PAS-87, August 1968, pp. 1669-1675.

Park, R.H. (1929). Two-Reaction Theory of Synchronous Machines, Generalized Method of Analysis, pt. I. AIEE Trans., vol 48, July 1929, pp. 716-730; pt. II. AIEE Trans., vol 52, June 1933, pp. 352-355.

Perkins, F.W. and Jones, R. (1981). The Effect of δ_3 on a Yawing HAWT Blade and on Yaw Dynamics. In Thresher (1981), pp. 295-304.

Powell, D.C and Conell, J.R. (1980). Definition of Gust Model Concepts and Review of Gust Models. PNL-3138, Pacific Northwest Laboratory, Richland, Washington.

Rasmussen, F. and Pedersen, T.F. (1982). Measurements and calculations of forces on the blades of a stall regulated HAWT. 4th International Symposium on Wind Energy Systems, Sweden (September 21 - 24, 1982). Organized by BHRA Fluid Engineering, Cranfield, Bedford, England. Vol. 2, pp. 59-69.

Seidel, R.C. (1977). Power Oscillation of the Mod-0 Wind Turbine. NASA-CP-2034, for a Workshop: Wind Turbine Structural Dynamics held at NASA Lewis Research Center, Cleveland, Ohio, Nov 15-17, 1977, In Miller (1978), pp. 151-156.

Shepherd, D.G. (1978). Wind Power. In Auer, P.: Advances in Energy Systems and Technology, Vol 1. Academic Press, pp. 1-124.

Spera, D.A. and Richards, T.R. (1980). Wind Gust Analysis for Wind Turbine Design. Appendix A in Powell and Conell (1980).

Stoddard, F.S. (1978). Structural Dynamics and Control of High Aspect Ratio Wind Turbines. Energy Alternatives Program, University of Massachusetts, Amherst, Massachusetts.

Sullivan, T.L. (1981). A Review of Resonance in Large, Horizontal-Axis Wind Turbines. In Thresher (1981), pp. 235-244. Also in Solar Energy, Vol. 29, No. 5, pp. 377-383, 1982.

Svensson, J.E. and Ulen, E. (1982). The Control System of WTS-3, instrumentation and testing. 4th International Symposium on Wind Energy Systems, Sweden (September 21 - 24, 1982). Organized by BHRA Fluid Engineering, Cranfield, Bedford, England. Vol. 2, pp. 195-215.

Swedyards (1981). Swedish wind power. Swedyards Wind Turbine Systems Corp., Göteborg, Sweden.

Swedyards (1982). A milestone for wind power. Swedyards Wind Turbine Systems Corp., Göteborg, Sweden. March/April 1982.

Thresher, R.W. (1981). Wind Turbine Dynamics. NASA-CP-2185, DOE CONF-810226, A workshop held at Cleveland State University, Cleveland, Ohio, February 24-26, 1981.

Wasynczuk, G., Man, D.T. and Sullivan, J.P. (1981). Dynamic Behavior of Wind Turbine Generators during Random Wind Fluctuations. IEEE Trans. on Power Apparatus and Systems, Vol. PAS-100, June 1981, pp. 2837-2845.

Wieslander, J. (1980). Idpac Commands - User's Guide. Department of Automatic Control, Lund Institute of Technology, Lund, Sweden. CODEN: LUTFD2/(TFRT-3157)/1-108/(1980)

Appendix A

MOD-2, WTS-3, WTS 75 and Growian I

In this appendix some technical data of MOD-2, WTS-3, WTS 75 and Growian I are listed in Table A.1. References to reports and papers containing descriptions, simulation models, simulation plots and experiences are also given. All these four wind power systems are described in Koeppl (1982).

MOD-2

MOD-2 is designed and built by Boeing Engineering and Construction Company for DOE-NASA. Three plants have been installed at Goodnoe Hills, Washington and the are operated by the Bonneville Power Administration. References are Hinrichsen and Nolan (1980), Krause and Man (1981), Sullivan (1981) and Wasynczuk, Man and Sullivan (1981).

WTS-3

WTS-3 is designed and built by Karlskronavarvet AB, Sweden and Hamilton Standard, a division of United Technologies Inc, USA for the National Swedish Board for Energy Source Development (NE). Karlskronavarvet AB is a part of Swedyard Group and the their activities have now been transferred to Swedeyards Wind Turbine Systems Corp. One plant is installed at Maglarp, near the city of Trelleborg, in southern Sweden. The South Swedish Power Company Ltd. (Sydkraft AB) is engaged as NE's agent for operation and evaluation. A 4 MW plant (WTS-4) of the same design is installed in Medicine Bow, Wyoming, USA. References are Bergman, Mattsson, and Östberg (1981), Bergman and Mattsson (1983), Kos (1978), Mattsson (1982), NE (1982), Svensson and Ulen (1982), Swedyards (1981) and Swedyards (1982).

WTS 75

WTS 75 is designed and built by KaMeWa AB, Kristinehamn, Sweden for the National Swedish Board for Energy Source Development (NE). A plant is installed at Näsudden in the south-west of Gotland, Sweden. The Swedish State Power Board (Vattenfall) is NE's agent for operation and evaluation. References are NE (1982) and Mets and Hermansson (1983).

Growian I

Growian I (Grosse Windenergie Anlage) is designed and built by Mashienenfabrik Augsburg-Nurnberg Aktiengesellschaft (MAN-Neue Technologie) for the West German Ministry for Research and Technology. A plant is installed at Kaiser-Wilhelm-Koog which is located at the mouth of the river Elbe near the North Sea. References are Hau (1982) and Leonhard (1979).

Table A.1: Technical data of MOD-2, WTS-3, WTS 75 and Growian I

	MOD-2	WTS-3	WTS 75	Growian I
Rated power, MW	2.5	3	2	3
Wind speeds				
cut-in, m/s		7.2	6	5.4
rated, m/s	12.3	14.2	12.5	12.0
cut-out, m/s	20	27.2	21	24
Rotor				
blades	2	2	2	2
	steel	GRP-Epoxy[*]	steel[1]	steel[2]
location	upwind	downwind	upwind	downwind
yaw control	hydraulic	hydraulic	hydraulic	el.-mech
max rate, °/s	0.25	1.2		0.5
hub type	teetered[3]	teetered[3]	rigid	teetered
hub height, m	100	80	80	100
diameter, m	100	78	75	100
speed, rpm	17.5	25	25	18.5±15%
pitch control	hydraulic outer 30%	hydraulic full span	hydraulic full span	el.-mech full span[4]
Generator	synch	synch	asynch	asynch
speed, rpm	1800	1500	1500	1500
frequency, Hz	60	50	50	50
Tower	cyl steel shell	cyl steel shell	reinforced concrete	cyl steel shell

*) Glass-Fibre Reinforced Plastic

1) with GRP-Epoxy leading and trailing edges

2) with a GRP-shell

3) with δ_3 hinge

4) double fed

The electrical mode is the second mode. In conventional turbine generators this is generally the lowest mode and the only considered. This mode is also of great importance. It dominates the response to small and rapid electrical disturbances.

The study by Hinrichsen and Nolan (1980) shows that a well designed wind turbine generator with a soft shaft will perform equally well in single and multi-machine applications, since turbine and generator are decoupled transiently by the soft shaft.

From Table 2.1 it can be seen that the coupling between the turbine and the generator is 100 times stiffer for WTS 75 than for MOD-2 and WTS-3. MOD-2 and WTS-3 have deliberately designed soft shafts. MOD-2 has a quill shaft and WTS-3 has a softly mounted planetary gearbox which is equivalent to a torsionally soft shaft. The root-locus with respect to K_{shaft} for WTS-3 in

Figure 2.3: Root-locus with respect to K_{shaft} (in pu torque/el rad) for WTS-3 given by (2.3) and (2.4).

Figure 2.3 shows that such a stiff shaft would have been disastrous for MOD-2 and WTS-3. For K_{shaft} = 5 pu torque/el rad WTS-3 has poles in -0.14 ± 6.7i and -5 ± 45i which means that there is no filter effect for the 2 P (5.2 rad/s) disturbances.

With Short-Circuited Asynchronous Generator

The WTS 75 wind power system has an asynchronous generator with four poles. The asynchronous generator influence the first torsional mode in a more complex way than the synchronous generator. Statically the electrical torque is proportional to $\dot{\delta} - \omega_0$, with the mechanical interpretation of the coupling to the grid being a damper. This appears promising because it indicates a better damping of the soft shaft mode than with a synchronous case. However, dynamically the situation is somewhat more complex. The electrical dynamics cannot be neglected. The electrical torque can be modelled as (linearized around a stationary operating point)

Figure 2.4: The root-locus with respect to K_{shaft} (in pu torque/el rad) for WTS 75 given by (2.3) and (2.5) when K_{TE} = 0.2 pu torque/(el rad/s) and T_{TE} = 0.1 s.

$$T_{TE}\dot{T}_E + T_E = K_{TE}\dot{\delta} \quad (2.5)$$

T_{TE} and K_{TE} varies with the operating point and the are typically halved when produced power is increased from zero to rated. They also depend on the generator resistances and inductances. Typical values are T_{TE} = 0.1 - 0.2 s and K_{TE} = 0.1 - 0.4 pu torque/(el rad/s).

The root-locus with respect to K_{shaft} for different pairs of T_{TE} and K_{TE} can be found in Figures 2.4 - 2.6 (D_{shaft} = 0).

Figure 2.5: The root-locus with respect to K_{shaft} (in pu torque/el rad) for WTS 75 given by (2.3) and (2.5) when K_{TE} = 0.4 pu torque/(el rad/s) and T_{TE} = 0.1 s.

Figure 2.6: The root-locus with respect to K_{shaft} (in pu torque/el rad) for WTS 75 given by (2.3) and (2.5) when $K_{TE} = 0.4$ pu torque/(el rad/s) and $T_{TE} = 0.2$ s.

With Fed Asynchronous Generator

For MOD-2, WTS-3 and WTS 75 the the generator works at a nearly constant speed so the possibility to use the rotor as a storage of kinetic energy is negligible. The same can be said about the use of the windings as storages of electrical and magnetical energy. It is neither possible to get rid of energy. This means that the power output of the generator follows the power input of the generator closely. Hence, the power production must mainly be controlled by control of the power input to the turbine.

Growian I has a variable speed - fixed frequency generator. The generator speed is allowed to vary ±15% of synchronous speed. By allowing the turbine to perform limited speed excursions transient wind power can be absorbed by the turbine as kinetic energy and the demands on the blade angle control to respond to changing wind conditions may be lowered.