Chalmers Test Turbine at Björkö today and at Hönö in the past

Förnyelsebar elproduktion och eltransporter (DAT460)

Wind Energy Assignment Part 2: Wind Turbine Control

Course Examiner : Ola Carlson
Tutors : Bowen Jiang, bowen.jiang@chalmers.se

Submission deadline : TBD

Original version of the exercise manual was prepared by Magnus Ellsén

Electric Power Engineering
Department of Electric Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, 2020

1. Introduction

The objective of this exercise is to gain understanding on how the wind turbine and its control system work. This is achieved by investigating some basic theories of wind turbine engineering, checking plots of some calculated values, and then analyzing measurement data. By looking at different plots of measurement data, it is possible to distinguish the different operation modes of the wind turbine controller. Finally, the theoretical and measured data is compared.

Q1: Read Appendix B, which type of wind turbine are we using in this exercise? Fix-speed wind turbine or variable-speed wind turbine?

2. Working with Excel file

The Excel file can be downloaded from the course web page. There are six sheets in the Excel file:

- Parameters
- Calculation1
- Calculation2
- Calculation3
- Calculation4
- Plots

3. Basic Theories of Wind Energy Conversion

The turbine mechanical power can be expressed as:

$$P_{mech} = \frac{1}{2}\rho \cdot C_p \cdot A \cdot {v_w}^3$$

The tip speed ratio (TSR) or λ is defined as:

$$\lambda = \frac{v_{tip}}{v_w}$$

Abbreviations of the variables can be found in Appendix A. From turbine data, a theoretical curve with power coefficient as a function of TSR can be derived. The same curve could also be experimentally measured. The power coefficient curve for this turbine is provided in Appendix C. The tasks and questions given in this exercise help you to understand on how the turbine mechanical power is affected by the TSR.

Q2: Observe the power coefficient curve in Appendix C, what is the optimal TSR of the turbine? What is the maximum power coefficient under the optimal TSR?

Write the optimal TSR in the Excel file “Parameter: Column D, Row 8”. Write the maximum power coefficient in the “Parameter: Column D, Row 7”.

Let us then look at the amount of power that is available from the turbine at different wind speeds. In this exercise it is assumed that the turbine speed is adapted to the wind speed in a way that gives maximum power from the turbine.

Q3: In the Excel file "Callculation1: Column F", calculate the theoretical maximum mechanical power on the turbine shaft under different wind speeds, assuming that the turbine is working at optimal TSR over the whole wind speed range. Observe the plot1 in the Excel file "Plots".

Note: the mechanical power should be calculated in kW.

The most straightforward strategy to keep the turbine running at optimal TSR is to measure the wind speed v_w and calculate the appropriate turbine speed and then assign a controller to achieve that speed. However, in practice this strategy is seldom used since it puts up some difficulties.

Q4: What are the difficulties of controlling turbine speed by measuring wind speed directly?

Rather than measuring wind speed directly by using anemometer, the turbine speed can be used as a wind speed sensor instead. The controller uses the turbine rotor speed as an input. Based on this speed input, the controller calculates an appropriate load torque. If this is done correctly, the rotor speed will adapt to the wind speed in a way that it keeps the TSR at its optimum value.

Q5: Derive the function that calculates the desired turbine shaft torque value which keeps the TSR at an optimum value, using turbine rotator speeds as the functions' only input.

$$T = f(n)$$

Calculated desired turbine shaft torque in the Excel file "Calculation2: Column H". Observe the Plot2 in the Excel file "Plots".

Hints:

$$\omega = \frac{2\pi n}{60}$$

$$P_{mech} = T \cdot \omega$$

$$v_{tip} = r \cdot \omega$$

4. Measurements

In order to measure the wind turbine power as a function of wind speed (power curve), the data must be averaged. The wind speed signal comes from an anemometer in a mast located in front of the wind turbine. In most weather conditions wind speed varies considerably from one second to the next, and from one position to another. This means there is a poor correspondence between a single instantaneous wind speed value and a power reading taken at the same time. An additional error source is that the wind with the measured speed hits the turbine with a slight delay depending on the distance between the anemometer mast and the turbine.

A common procedure is to measure instantaneous values of wind speed, turbine rotator speed and electrical power at a rate of 1 sample/second. These values are then averaged into 1-minute or 10-minute average values.

To have a complete power curve, the measurements must cover the whole wind speed range of interest. The wind must also blow from a limited sector where the anemometer mast is in front of the turbine. Normally it takes at least a month of measurements to build a complete and accurate database. Measurements in the correct wind sector must be sorted out, and the valid data from different measurements must be merged.

Just like in cooking programs on TV, all the data you need have been prepared in advance. The database available is collected from some of the measurements during the period June to November 2002. It consists of 5693 one-minute averages, which are listed in the Excel file "Calculation3"

Data Position	Data Name	Data Description
"Calculation3 Column B"	RSA: Rotor Speed Analog [RPM]	The turbine rotator speed
"Calculation3 Column C"	DCV: DC link Voltage [V]	Voltage from the rectifier.
"Calculation3 Column D"	DCC: DC link Current [A]	Current from the rectifier.
"Calculation3 Column E"	WS: Wind Speed [m/s]	Wind speed at hub height in the meteorological mast adjacent to the turbine.

Q6: Using the measured RSA and SW data, calculate the TSR in the Excel file "Calculation3: Column I".

The electrical power can be calculated by multiplying the DC link voltage and DC link current. Using the measured DCV and DCC data, calculate the electrical power (kW) in the Excel file "calculation3: Column J".

$$P_{elec} = DCC \cdot DCV$$

Calculate the mechanical power in the Excel file "Calculation3: Column K", assuming the total efficiency of the generator and rectifier is kept constant at 0.85.

$$P_{mech} = \frac{P_{elec}}{\eta}$$

Calculate the power coefficient in the Excel file "Calculation3: Column L".

The calculated turbine power coefficient is shown in Excel file "Plots: plot3". And the average line of the calculated turbine power coefficient is shown in "Plots: plot4". Does the plot4 match the curve given in the Appendix C?

5. Mechanical Power Calculation

The generator system is converting mechanical power into electrical power. In the generator system there are losses, so the output power should be less than the input power. The efficiency of the generator and rectifier is regarded to be 0.85 (as stated in exercise 4.1). The efficiency is the relation between the output power and the input power of the system. To calculate the mechanical power from the electrical power, the relation will be like this:

$$\eta = \frac{P_{elec}}{P_{mech}}$$

Two more plots are given in the Excel file "plots: plot5" and "plots: plot6". They are TSR as a function of wind speed based, and turbine rotator speed as a function of the wind speed on the measurement data.

Q7: The mechanical power against wind speed is shown in the Excel file "Plots: plot7". And the average mechanical power is shown in the Excel file "Plots: plot8".

Compare the plot8 and the plot 1, at higher wind speeds, the mechanical power calculated from the measurement data and theoretical mechanical power do not match very well, why?

Q8: Calculate the turbine shaft torque based on the measurement data in the Excel file "Calculation3: Column M".

The turbine shaft torque as a function of the turbine rotator speed is shown in the Excel file "Plots: plot9".

Compare the plot9 and plot2, Is the controller operating correctly?

6. Results Evaluation

Before you try to understand what is going on in the graphs of the measured values, first you must know the control principles of the generator. The control principles are described in Appendix D. Note that there are several different rotor speed regulator modes involved. The different regulator or controller modes are engaged one at a time.

Which controller that is selected for the moment depends on the rotor speed. When you study the various plots of the measured data, try to identify each control region as described in Appendix D, evaluate and give comments on them separately.

Q9: In the Excel file "Plots: plot5, plot6, plot9", identify different regions of the measured data that relates to the different controller modes.

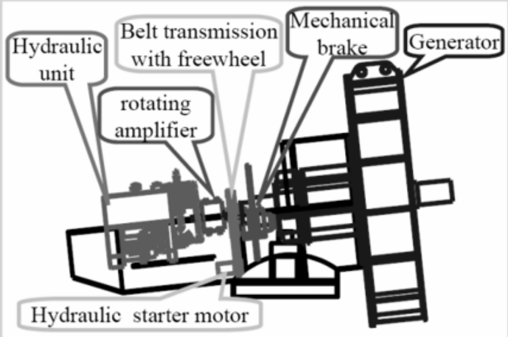
Appendix A: Abbreviations and Constant Values

ρ	air density = 1.225 $[kg/m^3]$
d	rotor diameter = 13.5 $[m]$
r	rotor radius = 13.5 ÷ 2 $[m]$
A	rotor swept area = πr^2 $[m^2]$
C_p	power coefficient (It is similar to turbine efficiency. Theoretical its max is 100% without any tube around it. It is 16/27 (about 59%) according to Betz's law. (Swedish: effektkoefficient)
v_{tip}	turbine tip speed $[m/s]$
v_w	wind speed $[m/s]$
λ	TRS, tip speed ratio (Swedish: löptal)
C_{pmax}	maximum power coefficient
λ_{opt}	tip speed ratio to get C_{pmax}
ω	turbine angular speed $[rad/s]$
n	turbine rotor speed = $\frac{\omega}{2\pi} \cdot 60[rpm]$
T	turbine shaft torque $[Nm]$ (Swedish: turbinaxelvridmoment)
P_{mech}	mechanical power on the turbine shaft $[W]$
P_{elec}	electrical power output from the generator rectifier $[W]$
η	efficiency of the generator and rectifier

Appendix B: Turbine Data and Components

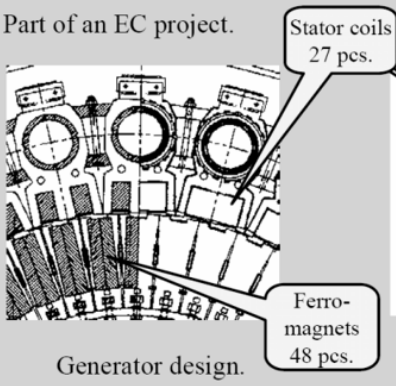
Data:

- Turbine diameter 13,5 m
- Teeter hub
- Direct driven (gearless)
- Steel tower, 18 m
- Variable speed
- Fixed pitch, stall control.

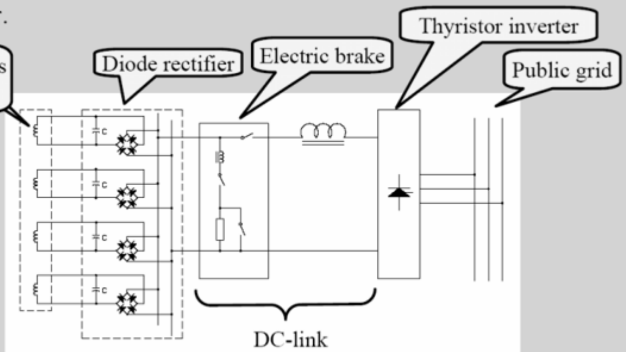


Direct driven Permanent Magnet Generator:

- Experimental generator designed by Prof. Ed Spooner, Univ. of Durham, Prof. Alan Williamsson, Univ. Of Manchester and Mr. Les Thompson, MEC Electrical Machines, UK
- Pre study for a large scale generator.
- Part of an EC project.



Generator design.

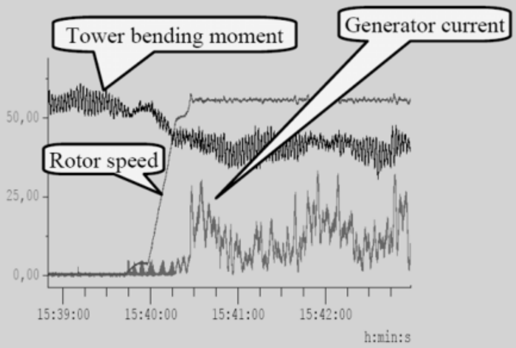


Electrical system for variable speed.

Rated power: 30 kW at 70 rpm.

Measurement and Control system

- Large number of transducers, e.g. Currents, voltages, tower forces, main shaft torque, generator temperature, meteorological parameters.
- Flexible
- Available for a large number of experiments, like active damping.
- PC-based system
- User friendly interface.



Rotor speed control test.

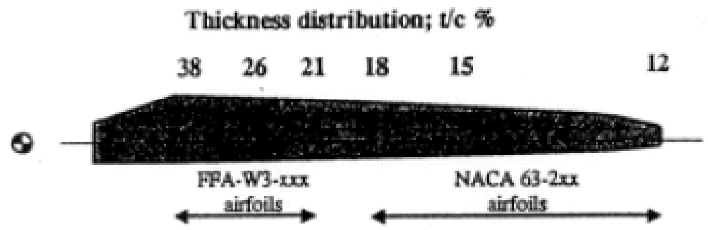
Appendix C: Turbine Blades and Cp-λ curve

The Hönö blades

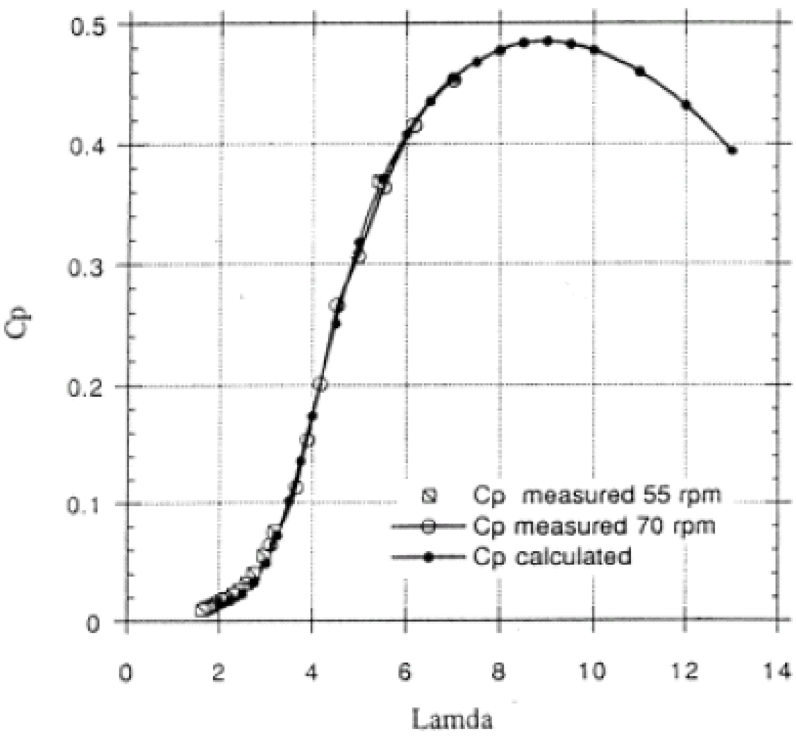
EEK225
Lab1
Appendix1.
page 1(1)

Manufactured in solid wood (Thuja Plicata)

NACA 63-2xx and FFA-W3-xxx airfoils



Cp-λ curve



Appendix D: Controller

Figure D1 shows the main controllers of the wind turbine system. The controllers operate according to the following sequence:

The control computer takes a generator speed and voltage measurement. It then calculates a current demand in one of the speed controller modes as described later on. There is an approximately linear relationship between the generator current and torque. The current demand is then sent to the thyristor inverter in the generator electrical system. Inside the thyristor converter there is another controller trying to achieve that current on the DC-link. This sequence occurs continuously with frequency at ten times per seconds.

The more current that is taken from the DC-link, the more loaded the generator will be, and more power will be sent out on the public grid. If the current is to high compared to the wind speed, the turbine will run too slow or even stop. The power to the grid then will drop because the voltage on the DC-link drops when the generator runs slower.

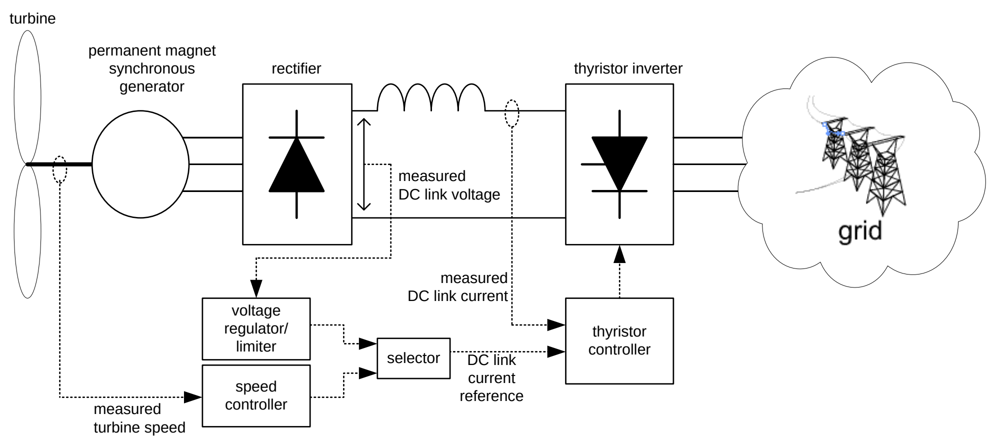


Figure D1. Overview of the WT control principle

Speed Control Modes

As shown in Figure D2 (clearer figure can be found in file Appendix.pdf), the speed controller has five different modes of operation as follows:

Standby mode: No load applied below 50 rpm. The objective is to prevent the turbine from stopping to often at low winds. If the wind dies completely for a few seconds the inertia in the turbine will be enough to prevent the rotor speed to drop below the parking speed limit. If the speed drops below the parking speed limit, the control system parks the turbine, and the starter motor must be engaged when the wind picks up again.

Ramp up mode: The objective of this controller is to act as a smooth transition between the Standby and optimal controller mode.

Optimal mode: In this mode, the controller tries to maximize the energy capture from the turbine by applying a torque dependent on the rotor speed in such a way that the turbine will operate at its optimal tip speed ratio. The idea is that if the wind speed changes, the incoming torque from the turbine will be affected. The speed of the turbine will then change. If the speed changes, the optimal controller adjusts the generator torque. When the turbine torque and the generator torque become equal, a new stable operation point is achieved. In reality the wind speed varies almost all the time, and the rotor speed tries to follow to keep the tip speed ratio constant.

Stall mode: This controller limits the maximum speed of the turbine. This mode is engaged when the turbine speed reaches the stall speed set point. In this exercise it was set to 72 rpm. The objective of the stall controller is to prevent over speeding of the generator and turbine. The turbine is designed to operate at maximum 75 rpm with some margin. At about 150 rpm the blades will break and fly off.

The generator voltage is dependent on the rotational speed. The generator and its electrical system (reactive power compensation capacitors, rectifier, thyristor converter) were designed to operate at a voltage level that is reached at no load and about 70 rpm. When the generator is loaded the voltage drops slightly. At full load the maximum voltage level is reached at about 80 rpm. So the maximum allowed speed of the generator is dependent on the load but should not exceed 80 rpm.

Another reason for limiting the turbine speed is to limit the incoming power and shaft torque from the turbine at high wind speeds. The maximum torque the generator can produce is approximately equal to the incoming torque from the turbine at 80 rpm. That is if the wind speed happens to give the optimal tip speed ratio at that point. If the generator speed is allowed any higher than that, only the mechanical brake can provide a torque that is big enough to bring the speed down.

On a normal induction generator, the peak torque is much higher than the rated torque. The problem for an induction generator would instead be overheating if it is operated for a long time at a power level higher than the rated level.

Retard mode: This mode is engaged manually, or by the supervisor program, and is the normal way to stop the turbine.

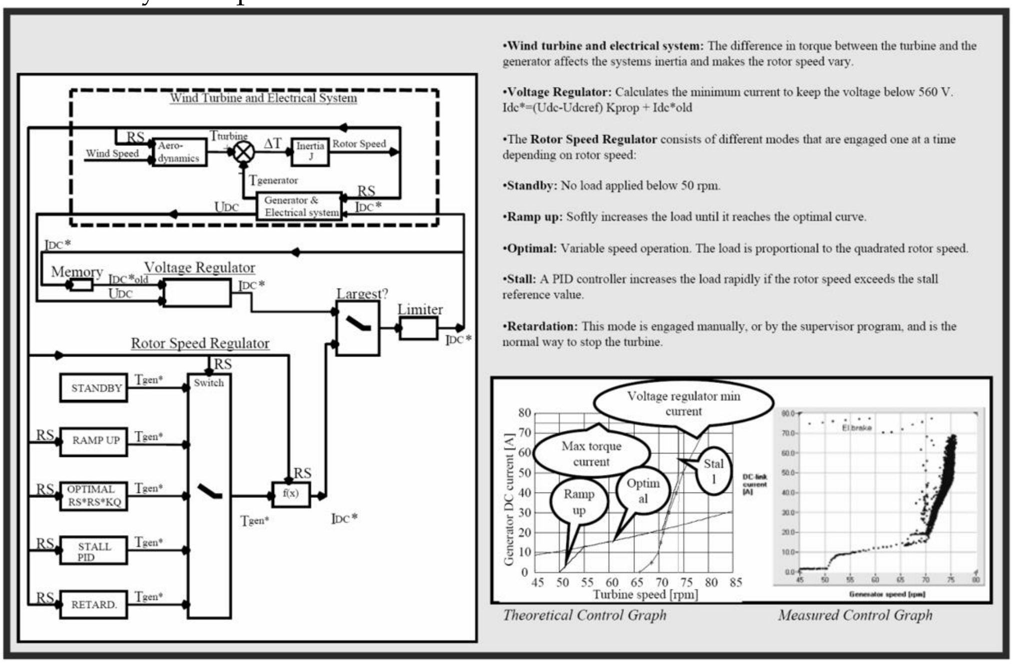


Figure D2. Different control modes and the associated operating region.

Voltage controller

If the stall controller set point is set higher than about 70 rpm there is a risk of over voltage if the load is not large enough. The voltage controller measures the voltage and adds an appropriate amount of current for the next control loop if the voltage approaches the maximum limit. The voltage controller is engaged all the time independent of the rotor speed. It works side by side with one of the rotor speed regulators above. Of course, only one control value can be sent to the electrical system each control loop. Therefore, the voltage controller value and the speed regulator value are compared. The highest value is sent to the electrical system. In this exercise the impact of the voltage controller is hardly visible in the graphs since the stall speed is set to 72 rpm.