TU/e technische universiteit eindhoven

Wind Turbine Study

Investigation into CVT application in wind turbines

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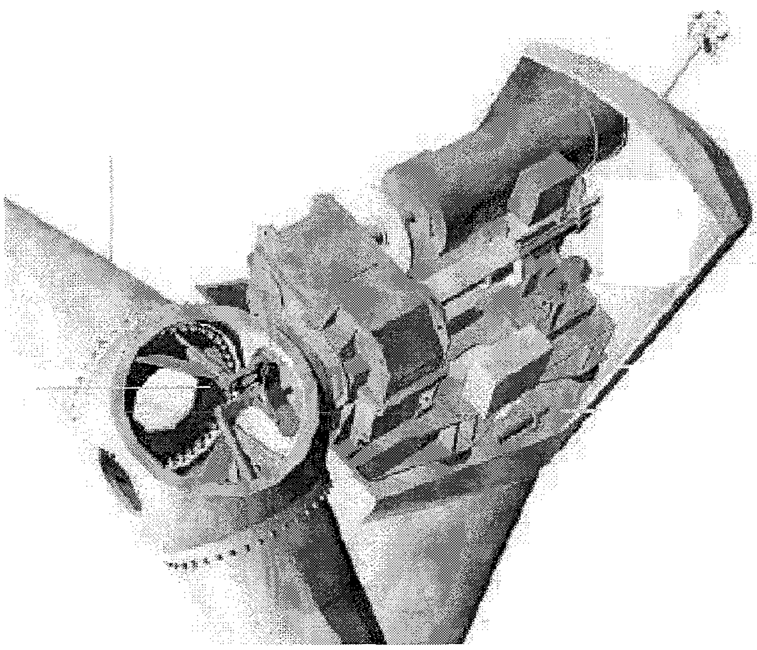

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Introduction

Wind turbines that operate at a constant speed attain the greatest aerodynamic efficiency levels only when the wind speed is the same as the design wind speed. In variable speed wind power systems, the turbine runs at a tip speed ratio which ensures its maximum efficiency. Variable speed systems have more advantages such as that the turbine is less sensitive to the wind pattern of a given location and emits less noise at low speeds.

Current variable speed systems generally utilize electric generators, which are rigidly fitted to the turbine and are coupled to an inverter, which adjusts the electric current generated to the frequency required. Systems equipped with inverters present a number of drawbacks. They are particularly expensive and complex and the inverter and variable speed electrical machine are not very efficient or reliable.

The goal of this internship is to investigate the possibility of using a continuous variable transmission (CVT) between a wind turbine and an electric generator in the design of a variable speed wind turbine. Such a solution will have the following advantages:

- Maximum efficiency of the wind device even with sudden changes in wind speed.
- The generator produces electric current at a constant frequency.

Before a simulation can be made of the turbine first the specifications of the ingoing side and outgoing side of the CVT should be know. With the ingoing side the wind profile is meant and by the outgoing side the kind of generator and it's properties. Further it is useful to know what the influences are of these two aspects with respect to the design of a wind turbine.

The goal of this internship is to investigate what the advantages and disadvantages are of a CVT wind turbine application.

Contents

1 Why incorporate a CVT?

The first classic way of generating electricity with wind turbines is shown in figure 1.1. The rotor of the generator is fed by the electrical grid or is a permanent magnet. When the rotor is rotated from the outside, instead of letting the current from the grid move it, it will work like a generator. The more torque you apply to the turbine, the more electricity you generate, but the generator will still run at the same speed dictated by the frequency of the electrical grid.

It is also possible to feed the synchronous generator from its own separated grid. In this case you will have to crank the generator/ rotor at a constant speed in order to produce alternating current with a constant frequency. Consequently, with this type of generator you will normally want to use an indirect grid connection of the generator. Now it is possible to run the generator at different frequencies and the AC-DC-AC inverter will match the current to the electrical grid.

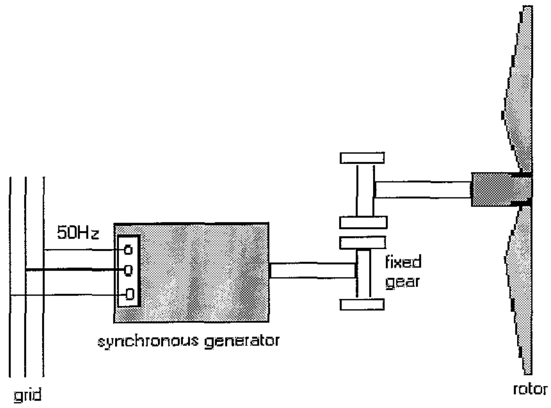


Figure 1.1: constant speed wind turbine

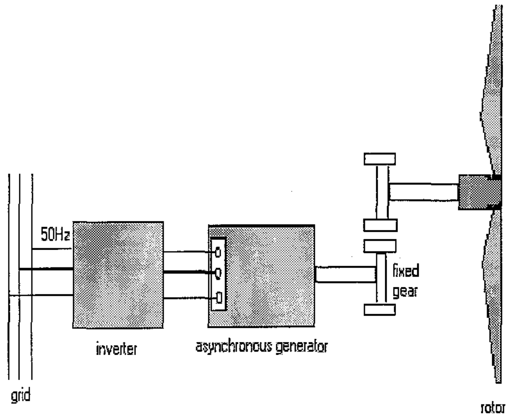


Figure 1.2: variable speed wind turbine with inverter

The second possibility (figure 1.2) is to use an asynchronous generator in combination with an inverter. At lower wind speed, the inverter sends a lower frequency to the asynchronous generator. Now it is possible for the generator to rotate with a slower speed and as a consequence the rotor can rotate at lower speeds. This is shown in figure 3.5 (see chapter 3). One of the disadvantages of this system is the wear and tear of the fixed gear, caused by the differences in torque acting on the rotor as function of the wind speed. Especially when the wind is turbulent there are huge fluctuations on the rotor and thus on the fixed gear. But the main disadvantages are the costs for the inverter and the generator. This will result in the third option for a wind turbine construction.

The third solution for a variable speed wind turbine is shown in figure 1.3. Now a continuous variable transmission (CVT) has been placed between the fixed gear and the asynchronous generator. Purpose of this CVT is to keep the tip speed ratio of the rotor on a constant value (see chapter 2). It is also possible that the CVT will take over a couple of tasks of the inverter. This is a great advantage because the inverter costs are high in comparison with the CVT. The biggest problem here is also the need of gears, and thus wear and tear.

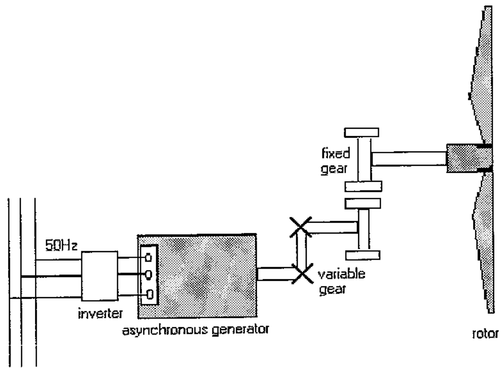


Figure 1.3: variable speed wind turbine with CVT

2 Wind characteristics

§2.1 Wind distribution

Wind is the movement of air in comparison to the earth surface. The geostrophic winds are largely driven by temperature differences, and thus pressure differences, and are not very much influenced by the surface of the earth. The geostrophic wind occurs at altitudes above 1000 metres above ground level. Another force that causes air to move is the coriolis force which is caused by the rotation of the earth.

The wind speed at the usual measurement height of 10 meter is approximately twice as small as the wind speed at the geostrophic height. This is because the friction of the earth surface slows the airflow down. The wind speed at a certain height can be approximated by the following equation.

$$V_{(z)} = V_{ref} \ln\left(\frac{z}{z_0}\right) \ln\left(\frac{z_{ref}}{z_0}\right), \qquad \textit{(eq. 2.1)}$$

With V_{ref} a known wind speed at a certain height z_{ref} and z_0 is the roughness length in the current wind direction. The roughness length may be found in certain reference manuals.
For the design of a wind turbine wind is considered to consist of a constant part and a fluctuating part. The constant part of the wind is of importance when determining the place of a turbine site. It determines the quantity of energy that can be extracted from the wind over a long period of time. The fluctuating part of the wind (turbulent effects) is considered when investigating the forces acting on a turbine. If a wind turbine is designed for a certain site, detailed information is needed to calculate the energy present in the wind at that site at the turbine height. In general a wind turbine is designed to deliver sufficient energy over a whole range of sites that satisfy a certain wind class. To show the information about the distributions of wind speeds, and the frequency of the varying wind directions, one may draw a so-called wind rose on the basis of meteorological observations of wind speeds and wind directions. An example of a wind rose is given in figure 2.1.

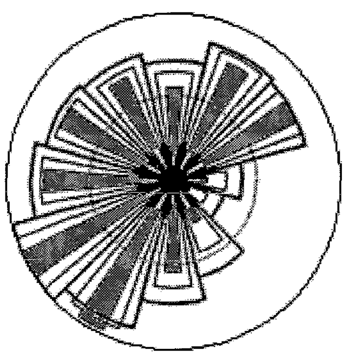


Figure 2.1: Example of a wind rose.

For this particular wind rose de wind direction is divided in twelve sections each covering thus 30 degrees of wind direction. The radius of the 12 outermost, wide wedges gives the relative frequency of each of the 12 wind directions, i.e. how many percent of the time is the wind blowing from that direction. The second wedge gives the same information, but multiplied by the average wind speed in each particular direction. The result is then normalised to add up to 100 per cent. This tells you how much each sector contributes to the average wind speed at our particular location.

The innermost (red) wedge gives the same information as the first, but multiplied by the cube of the wind speed in each particular location. The result is then normalised to add up to 100 per cent. This tells you how much each sector contributes to the energy content of the wind at our particular location.

When choosing a suited site for your wind turbine meteorology data, ideally in terms of a wind rose calculated over 30 years is probably your best guide, but these data are rarely collected directly at your site, and here are many reasons to be careful about the use of meteorology data. If there are already wind turbines in the area, their production results are an excellent guide to local wind conditions.

A more accurate reproduction of the wind speed distribution in a certain direction and height is the so-called Weibull distribution. The Weibull distribution is a statistical distribution of the wind speed.
The wind speed probability function is given by:

$$H(V \geq V_p) = 8760 \exp\left[-\left(\frac{V_p}{c}\right)^k\right], \qquad \textit{(eq. 2.2)}$$

This is the probability that the wind speed is equal or larger than wind speed V_p in hours per year. In this equation the parameters 'c' and 'k' are used for fitting the distribution to a certain wind field.
The wind speed distribution density is given by:

$$H(V < V_p < V + dV) = 8760(k/c)(V/c)^{k-1} \exp\left[-(V/c)^k\right] dV, \qquad \textit{(eq. 2.3)}$$

This is the probability that the wind speed is actually between V and $V+dV$ in hours per year. The relation with the annual average wind speed $\overline{V}$ is given by:

$$\overline{V} = c\Gamma\left[1 + \left(\frac{1}{k}\right)\right] \textit{ with } \Gamma\left[1 + \left(\frac{1}{k}\right)\right] = \textit{The gamma function of the argument}\left[1 + \left(\frac{1}{k}\right)\right]$$

(eq. 2.4)

The Weibull parameters 'c' and 'k' have to be corrected for the height at which the hub of the wind turbine is located. With these formulas it is thus possible to calculate how many hours per year the wind blows with a certain speed in a certain direction. This information is needed for the calculation of the energy income of the turbine per year.
A important detail is the number of hours per year that the wind speed is between the 'cut in wind speed' and the 'cut out of wind speed' of the turbine. Below the cut in wind speed the wind speed is to low for the turbine to operate and above the cut out of wind speed of the turbine the wind speed is to high for the turbine to operate safely. At that certain wind speed the turbine is shut down.

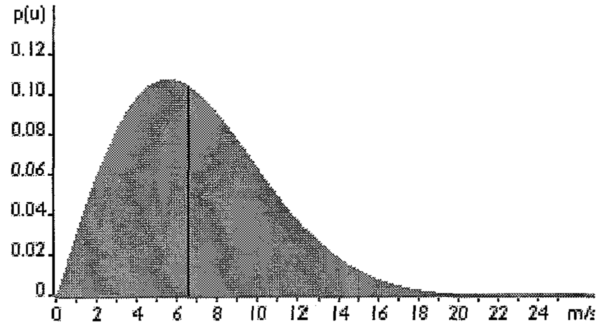


Figure 2.2: Example of a Weibull distribution with an average wind speed of approximately 7m/s.

§2.2 Turbulence

All time variations in wind speed and direction with a period smaller than 0.1 hour are considered as turbulence. Wind acting on a turbine can be divided in two categories. The first one is caused by a constant wind speed and is also called quasi-static or time averaged. The second one is caused by turbulence or wind gusts and is called dynamic. For the description of a turbulent airflow a number of different models are available varying in complexity.

The true efficiency of a wind turbine depends on its behavior in a turbulent wind flow field. For the description of a turbulent flow field in this thesis the spectral model of continues turbulence by Kaimal [1973] has been used. This model is based on a per hour average wind speed $\overline{V}$ with a standard deviation σ. The frequency behavior of the wind speed fluctuations is described by a model of the spectral power density S(n) with n the frequency.

$$nS(n) = \frac{(n\frac{z}{\overline{V}})\sigma^2}{f_m(1+\frac{1.5}{f_m}(n\frac{z}{\overline{V}}))^{5/3}}, \qquad \text{(eq. 2.5)}$$

With z the height above ground level and the coefficient f_m equal to 0.06 for the longitudinal component of the wind and equal to 0.2 for the lateral component of the wind.
Lateral (V_x) and longitudinal (V_y) components of the wind speed fluctuations can be calculated with:

$$V_i(t) = \sqrt{2}\sum_{k=1}^{m}\left[S_i(n_k)\Delta n\right]^{1/2}\cos(2\pi t+\beta), \qquad \text{(eq. 2.6)}$$

With i=x,y (lateral, longitudinal direction), m is the number of frequencies, Δn the frequency spacing and β a random phase angle.

§2.3 Wind gusts

Wind patterns are considered to be wind gusts when their speed grows to one and a half times their average speed in maximum time span of three seconds. A wind gust is said to be heavy when the wind speed during the gust rises to 21-29 m/s. Very heavy wind gusts have a minimum wind speed of 29 m/s. A discrete wind gust is characterized by its amplitude (the deviation from the average wind speed), its time span and a certain shape function which gives the variation of wind speed as a function of time during the gust. A commonly used shape function is the so-called 'one minus cosine' shape function:

$$v(t) = V + 0.5\Delta v\left[1-\cos(2\pi t/\tau)\right], \qquad \textit{(eq. 2.7)}$$

With Δu the amplitude of the wind gust, τ the period and t the time since the beginning of the wind gust.

A discreet wind gust model is a very idealized reproduction of the reality. They are useful for a wind turbine analyses if the gust is heavy enough to comprehend the entire rotor of the turbine. In such a case it can be said that the wind speed changes uniform over the total area of the turbine rotor. The minimum time that is needed for a gust to apply to the entire rotor is given by:

$$\tau = -\frac{d_\alpha \Delta l_\alpha}{V_r \ln(coh_\alpha)}, \qquad \textit{(eq. 2.8)}$$

With coh_α is the coherence between two points that are situated from each other in the α direction. It approaches 1 for small fluctuations over a long period and approaches 0 for big fluctuations over a short period. d_α Is the decay coefficient in the α direction and Δl_α is the distance between two point in the α direction. Suitable values for the decay coefficient based on measurements are $d_x = 4.5$, $d_{xy}=d_z=7.5$. For the calculation of Δv two empirical factors (F_g, F_s) are needed.

$$\Delta v = (F_g F_s - 1)V, \qquad \textit{(eq. 2.9)}$$

These factors are calculated on the basis of 17 years of measurement of the horizontal wind peaks at the coast of Cape Kennedy Florida by Kaufman [1977]. These factors can be used for wind over a smooth surface. In the Netherlands wind gusts with a wind speed of 200 km/h seldom occur. A wind gust that is sufficiently big to comprehend a rotor of 6 m has the following shape:

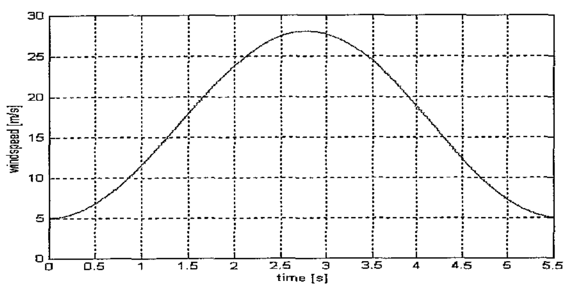


Figure 2.3: Wind gust of 200 km/h (56m/s) with a τ of 5.5 sec. and a constant speed of 5 m/s.

The maximum acceleration with such a wind gust is 27.5 m/s^2. Due to the very large inertia of the turbine rotor this acceleration will not be totally felt by the turbine.

§2.4 Wind energy

The power in wind is equal to the kinetic energy of the wind multiplied by the wind speed.

$$P_w = 0.5\rho V^3, \qquad \textit{(eq. 2.10)}$$

Herein P_w is the power density $[W/m^2]$, ρ is the air density and V is the horizontal wind speed. The maximum power that can be extracted from the wind is equal to the power density multiplied by the turbine rotor area.

$$P = 0.5\rho U^3 \pi R^2, \qquad \textit{(eq. 2.11)}$$

With P the wind power [W] and R the rotor radius.
The power coefficient (C_p) determines which part of the wind energy is extracted by the wind turbine.

$$C_p = \frac{P}{0.5\rho U^3 \pi R^2}, \qquad \textit{(eq 2.12)}$$

The power coefficient depends on the design of the turbine and the wind speed. According to Betz law the coefficient has a maximum of 16/27. Thus the maximum mechanical energy that can be extracted from the wind is 16/27 times the energy in wind. Because many design variables of a turbine influence the power coefficient it is very useful to make a quick approximation of the power coefficient with a particular turbine design. A empirical equation that gives an approximation of the maximum power coefficient is the equation of Wilson:

$$C_{p,\max} = 0.593\left[\frac{\lambda B^{0.67}}{1.48 + (B^{0.67} - 0.04)\lambda + 0.0025\lambda^2} - \frac{1.92\lambda^2 B}{1 + 2\lambda B} D/L\right], \qquad \textit{(eq 2.13)}$$

With D/L the lift to drag ratio, λ the tip speed ratio, B the number of rotor blades and ω the rotor speed [rad/s].

$$\lambda = \frac{R\omega}{V}, \qquad \textit{(eq. 2.14)}$$

Calculation of the ideal tip speed ratio demands detailed information of the turbine design. A rough estimation of the optimum tip speed ratio for the number of rotor blades, the ratio at which most energy is extracted from the wind, is given in table 2.1:

Table 2.1: Estimation optimum tip speed ratio

λ	B
1	6-20
2	4-12
3	3-6
4	2-4
5-8	2-3
8-15	1-2

For every turbine for which the generated power is approximately linear with the wind speed the design speed of the turbine is one and a half times the cut in wind speed of the turbine. Looking at fig 2.4 can best be seen what is meant by a linear power system. This picture shows the power output for different wind speeds (calculated with simulation, chapter 6). With a linear model it is assumed that the power for wind speed 5 to 15 m/s is linear. After 15 m/s it is assumed to be constant.

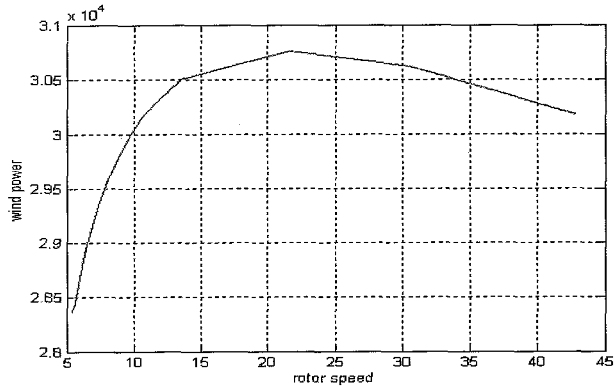


Figure 2.4: Power output for different wind speeds. Originated from simulation Chapter 6. Measured output for different wind speeds and constant load.

For such a linear turbine (simplified case) the power coefficient can be calculated with:

$$C_p = C_{p,\max} * 6.75 \frac{V_{in}^3}{V^3} \left(\frac{V}{V_{in}} - 1\right), \qquad \text{(eq. 2.15)}$$

With V_{in} the cut in wind speed of the turbine.

With $C_{p,\max}$ is 0.47 and a cut in wind speed of 3 m/s Cp as a function of the wind speed looks like:

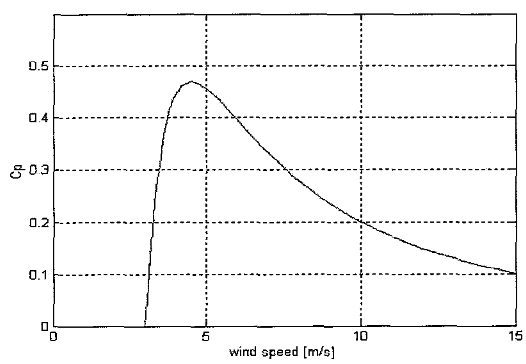


Figure 2.5: Cp as a function of the wind speed.

3 Motors/ Generators

The generator of the wind turbine converts mechanical energy to electrical energy. The shaft that is directly coupled with the turbine rotor delivers the mechanical energy. Wind turbines can be build with synchronous or with asynchronous generators and can differ in way of electrical grid connection.

§ 3.1 The synchronous generator

A 3-phase synchronous motor uses a rotating magnetic field. In the figure below there are three magnets, which are each bounded with there own phase of the three phase electrical grid. The rotor will follow the magnetic field generated by the stator exactly. That is why this generator is called synchronous. The rotor makes one revolution per cycle. When the rotor is attached to a 50 Hz electrical grid the rotor will make 50x60 =3000 rounds per minute (rpm). When the 2-pole permanent magnet synchronous motor from figure 3.1 is enlarged to a 4-pole motor the rotor will make a half revolution per cycles. The result is that the motor speed is decreased to 1/2x50x60=1500 rpm.

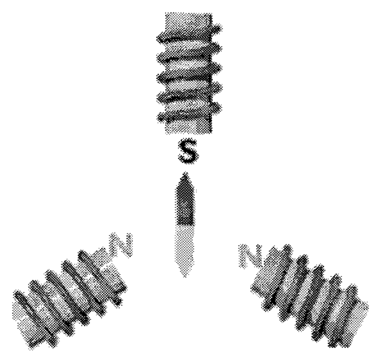


figure 3.1: synchronous machine

In the next table there is a view of motor speeds at different number of poles and by 2 different numbers of frequencies of the electrical grid.

Table 3.1:rpm generator, dependent of frequency and number of poles

Number of poles	50 Hz	60 Hz
2	3000	3600
4	1500	1800
6	1000	1200
8	750	900
10	600	720
12	500	600

The reason why the motor from figure 1 is called a 2-pole motor is that it has one North and one South Pole. It looks like there are three poles, but the compass needle feels the pull from the sum of the magnetic field around its own magnetic field. So, if the magnet at the top is a strong South Pole, the two magnets at the bottom will ad up to a strong North Pole. It is also possible to change the permanent magnet with an electromagnet, which maintains its magnetism through a coil, which is fed with direct current. The electromagnet is powered by using brushes and slip rings on the shaft of the rotor. This is preferred because permanent magnets will lose their force in a strong magnetic field. Another reason is that the permanent magnet motors are expensive in buying.

When the rotor is rotated from the outside and not by the electrical field generated by the stator, the synchronous motor will work like a synchronous generator. Via the rotor and stator there is send back a current into the electrical grid. When the rotor is rotating with a constant speed, the synchronous generator produces a voltage with a constant frequency. The more force is applied to the generator the more electricity is generated, but the generator will still rotated with the speed which is defined by the electrical grid frequency.

§ 3.2 The asynchronous generator

For generating an alternating current an asynchronous generator is mostly used. The choice to use an asynchronous generator for wind turbine application is that they are really reliable and comparatively inexpensive. Other advantages of the asynchronous generator are the slip and a certain overload capacity.

The difference between the synchronous and asynchronous generator is the rotor. The rotor consists of a number of aluminium or copper bars which are electrically connected with the electrical grid by aluminium end rings.

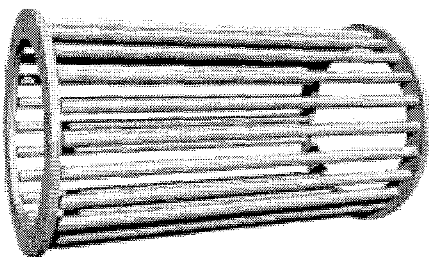


Figure 3.2: rotor of the asynchronous machine

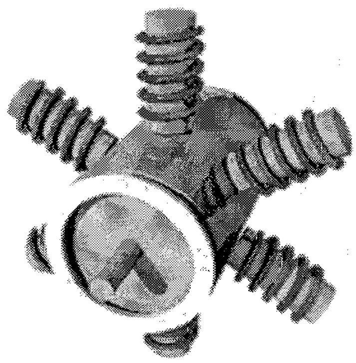


Figure 3.3: stator of the asynchronous machine

In figure 3.3 you can see the outside of the asynchronous generator. It also consists like a synchronous generator of a number of poles that can produce a magnetic field for the rotor. When the current is fed to the stator the generator will act like a motor and turns with a speed lower than the synchronous speed.

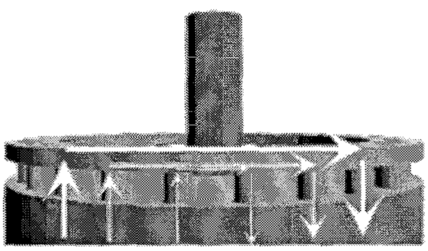


Figure 3.4: magnetic field in the rotor

In picture 3.4 the rotor is shown with the magnetic field coming from the stator, which arouses a current in the rotor bars. These bars will offer very little resistance, since they are dragged along by the electromagnet force from the rotating magnetic field in the stator.

When the rotor rotates with a speed equal to the speed of the asynchronous generator, forced by the frequency from the electrical grid and the number of poles, the generator will not have power output. This is because there is no induction between the rotor and stator. For generating a current the rotor will have to rotate at a higher level as the magnetic field. The harder you crank the rotor, the more power will be transferred as an electromagnetic force to the stator, and in turn converted to electricity which is fed into the electrical grid.

So the speed of the asynchronous generator varies with the torsion acting on the incoming shaft. The difference between the speed on peak power and on ideal power is in order of a number of percents. The difference in percents of the synchronous speed is called the generators slip. A 4-pole generator will rotate ideal with 1500 rpm when attached to the 50 Hz electrical grid. When the generator produces its peak power, the generator rotates about 1605 rpm. This will follow from figure 3.5 and equation (3.1).

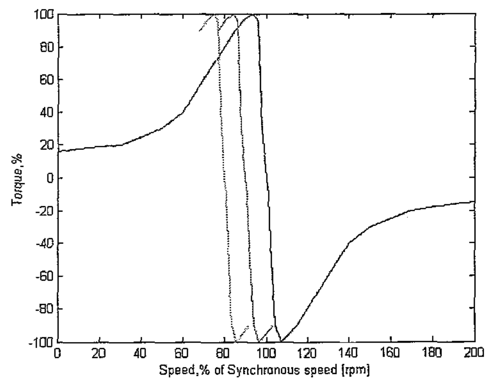


Figure 3.5: electromagnetic torque as function of the speed

$$s = \frac{\omega_s - \omega_r}{\omega_s} = \frac{1500 - \omega_r}{1500} = -0.07 \Rightarrow \omega_r = 1605 \qquad \text{(eq. 3.1)}$$

The slip is a function of the direct current resistance in rotor windings of the generator. An increase in resistance will induce an increase in slip. By enlarging the resistance, the slip may increase to 10 percent.

A very useful mechanical property of the asynchronous generator is that it will not decrease of increase its speed much when the torsion varies. This means there is less wear and tear to the gearbox, caused by lower peak forces. This is one of the main reasons why people choose an asynchronous generator rather than a synchronous one. Another advantage is that the rotor adapts by itself the number of poles in the stator. This is why the rotor can be used for a large variation of number of poles.

§ 3.3 Choice for kind of grid connection

There are two possible forms for connection to the electrical grid: direct and indirect grid connection of the generator. Direct connection means that the generator will be directly connected with a 3-phase alternating current grid. By indirect grid connection the current passes trough a number of electrical components in which the current is matched to the grid. In case of an asynchronous generator this is done automatically.

In the past wind turbines ran at almost constant speed with direct grid connection, but nowadays more and more wind turbines run at variable speed. With variable speed it is not possible to connect direct to the electricity grid. These wind turbines act on their own separated grids. An inverter controls this grid so the frequency of the alternating current can be varied. In this way its possible to rotate the turbine with varying speeds. The generator generates an alternating current with the same frequency, which is applied to the stator.

Alternating current (AC) with a varying frequency can not be connected directly to the grid. That is why the alternating current is converged into a direct current (DC). For the conversion of AC to DC you can use a thyristor or large power transistors. The fluctuating DC will be converged to an AC with the same frequency as the grid. This can be done with an inverter. The inverter has a low efficiency because there is not a smooth sinus coming out of it. By filtering the signal you can make the sinus smooth, but it will not happen beautiful.

§ 3.3.1 Advantage and disadvantages of indirect grid connection

The main advantage of indirect grid connection is that you can rotate the wind turbine with varying speeds. In case of a gust in wind the rotor can turn faster, thus storing part of the excess energy as rotational energy until the gust is over. For this case the system needs an intelligent controller, since there must be made a difference between gusts and higher wind speeds. By storing the energy of a gust it is possible to reduce the peak torque, and so reducing the wear and tear on the gearbox and generator.
The second advantage is that the electronics can control the reactive power. With the reactive power is mended the phase shifting of current relative to voltage in the AC grid. These should be equal to the power quality in the electrical grid. This may be useful, particularly if a turbine is running on a weak electrical grid.

The last advantage is that it is possible to let the generator work in its optimal point.

The most basic disadvantage of indirect grid connection is the costs. As mentioned before there should be used a couple of electrical components to match the current from the generator to the grid. The costs for these components are nowadays high and not attractive. Another disadvantage are the energy losses in de AC-DC-AC conversion. Also the power electronics may introduce harmonic distortion of the alternating current in the electrical grid, thus reducing power quality. The problem of this harmonic distortion arises because the filtering process mentioned above is not perfect.

§ 3.4 Two speed, pole changing generators

It's possible to equip your wind turbine with two generators: A small generator for periods with low wind speeds and a large generator for periods with high wind speeds. The disadvantage of this construction with two generators is the costs. A more common design on newer machines is pole-changing generators. Depending on how the stator magnets are connected you may run the generator with a different number of poles, and thus with a different rotational speed.

Before you choose to use two generators or a higher number of poles for low wind speed, you should look what the profit on this will be. If the costs for such an application are higher then the incomes, it's not recommend to build such a system. The energy content for low wind speeds is very small and so thus the electricity. An advantage to use a two-generator system is that you can run your turbine at lower speeds and this means less noise from the rotor blades.

§ 3.5 Starting and stopping the generator

When the generator is fed with a current the generator acts like a motor. At low speeds the generator has no output. This is not efficient because you want a current sent back into the electrical grid. Once the wind becomes powerful enough to turn the rotor and generator at their rated speed its important that the generator becomes connected to the electrical grid at the right moment. When the moment is wrong there will be mechanical resistance in the gearbox and generator. The consequence of this is that the rotor cannot accelerate or it will over speed. To prevent this there are two safety devices:

Aerodynamic braking system: tip brakes

The primary braking system for most modern wind turbines is the aerodynamic braking system, which essentially consists in turning the rotor blades about 90 degrees along their longitudinal axis (in the case of a pitch controlled turbine or an active stall controlled turbine or in turning the rotor blade tips 90 degrees (in the case of a stall controlled turbine).

These systems are usually spring operated, in order to work even in case of electrical power failure, and they are automatically activated if the hydraulic system in the turbine loses pressure. The hydraulic system in the turbine is used turn the blades or blade tips back in place once the dangerous situation is over. The normal way of stopping a modern turbine (for any reason) is therefore to use the aerodynamic braking system.

Mechanical braking system

The mechanical brake is used as a backup system for the aerodynamic braking system, and as a parking brake, once the turbine is stopped in the case of a stall-controlled turbine.
Pitch controlled turbines rarely need to activate the mechanical brake (except for maintenance work), as the rotor cannot move very much once the rotor blades are pitched 90 degrees.

To protect for a brownout it's not possible to use a normal switch for switching the turbine to the electrical grid. It's necessary to use a soft starting device with a thyristor. This thyristor gradually connects and disconnects the generator with the grid. The losses of these are 1 to 2 per cent of the energy running through them. By using a bypass switch, which is activated after the turbine has been soft started, it is possible to minimize the amount of energy wasted.

By variations of the wind speed there is also a variation in the voltage applied to the grid. This is called flicker. When the wind turbine is connected to a weak grid you will notice this flicker. There are various ways of dealing with this issue in the design of the wind turbine. This can be done mechanically, electrically and by using power electronics.

In case that the wind turbine becomes disconnected from the grid, it's important that after the re-connection the current matches with the grid. Otherwise it may cause huge current surges in the grid and the wind turbine generator. Like spoken before this will cause a huge blow of energy in the mechanical drive train (shafts, gearbox and rotor). It's the task for the electronic controller to monitor constantly the voltage and frequency of the alternating current. In case the voltage or frequency of the local grid drifts outside certain limits, the turbine will automatically disconnect from the grid and stop itself immediately.

§ 3.6 Running a pitch controlled turbine at variable speed

As mentioned before it's possible to use pitch to slow down the speed of the turbine. The purpose of this is to control the torque and not to overload the gearbox and the generator. The advantage of variable speed is that you can rotate the generator on half its slip at his rated power. In case there is a gust in wind the speed of the generator can be increased. In the mean time it's possible to the pitch mechanism to pitch the blades more out of the wind. Once the pitch mechanism has done its work, the slip is decreased again. In case the wind suddenly drops, the process is applied in reverse order.

The main advantage of this control strategy is that the fluctuations in power output are liquidated by varying the generators slip and storing or releasing part of the energy as rotational energy in the wind turbine rotor. A disadvantage is that if you run the generator with a high slip it will produce more heat and thus runs less efficiently.

§ 3.7 Cooling system

During the operation of producing electricity the generators need to be cooled. It's possible to use a large fan for air-cooling, but also water-cooled generators are used. The main advantage for using a water-cooled system is that it can be built more compactly. This gives some electrical efficiency advantages. The disadvantage of this system is that they need a radiator to get rid of the heat. This radiator should be placed in the nacelle.

§ 3.8 Gearbox

When the wind activates the rotor of the wind turbine, it will also rotate the shaft in direction of the generator. The following parts of the power train will follow the rotation of the rotor: the slow-speed shaft, the gearbox and the high-speed shaft.

To transport the rotational energy from the rotor to the generator you can use a gearbox. The generator is fed by the electrical grid with 50 Hz and makes 1500 rpm if there has been chosen a 4-pole generator. The turbine rotates much less and so the speed should be increased. This can be done with the gearbox. The gear ratio is typically approximately 1 to 50. While using a gearbox you convert slow speed to high speed and high torque to low torque. In these situations the wind turbines does not change gears.

4 The continuous variable transmission

§ 4.1 The dry belt variator

By using a continuous variable transmission (CVT) it is possible to transform a wind speed varying turbine speed in an almost constant generator speed. This will result in a higher efficiency of the generator. The ratio of the CVT will compensate the fluctuations in the wind.

By using a dry belt variator the necessary pulley pressure is reduced. This is useful because it is now possible to actuate the pulley mechanically. The primary pulley is driven by a spindle mechanism in combination with an electromotor. The force on the secondary pulley is delivered by a spring. The efficiency of the CVT in a low ratio is higher than 95 per cent when the incoming torque is higher than 20 Nm.

§ 4.2 Modeling of the CVT

For the modeling of the CVT the next controller system can be used:

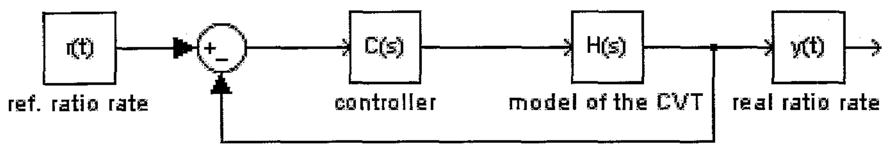


Figure 4.1: controller system for the CVT

The feedback controller consists of a controller C(s) and a model H(s) of the CVT. In the model r(t) and y(t) are respectively the wanted ratio rate and the true ratio rate of the CVT. The transfer function of the CVT describes the dynamic response of the ratio on a changing incoming torque and voltage of the electro motor. The transfer function for the CS-PTO system developed at the TU/e is by equation 4.1:

$$H(s) = \frac{14.7}{s^2 + 39.2s + 1.7} \qquad \text{(eq. 4.1)}$$

The CVT has a maximum commute speed of -0.3 - 0.3 1/s. This commute speed is implemented by using a rate limiter. For the CVT the low and high ratio (0.505 respectively 2.17) are implemented by using a saturation. The total ratio range will be 4.415. The Matlab/ Simulink model is shown below:

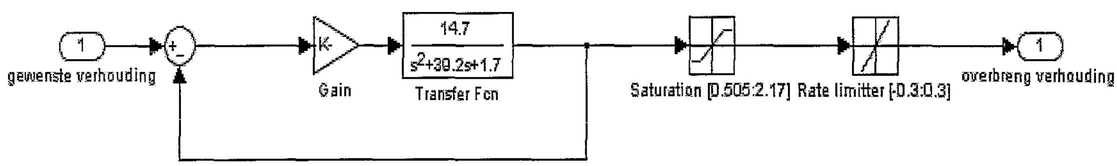


Figure 3.2 Matlab/ Simulink model of the CVT

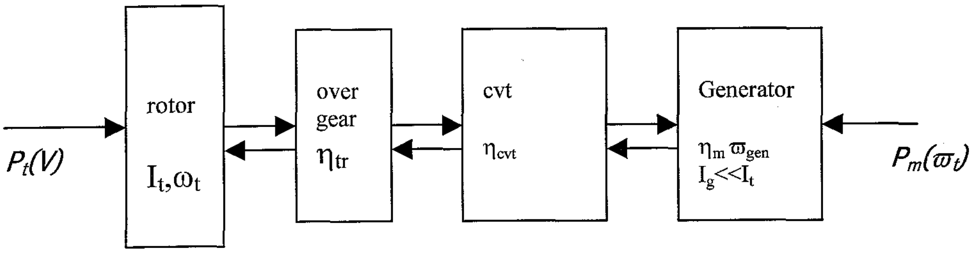
In this thesis the simulation will not be calculated with the dynamic response of the CVT. This because the calculation of the dynamic response will cost a lot of time and is not interesting for this case. The value of H(s) and the gain in this case will be chosen 1. So the desired ratio times the rate limiter and the saturation is equal to the true ratio.

5 Mathematical model of the turbine

The power in the wind that is consumed by the turbine is equal to:

$$P_t(V) = C_p 0.5 \rho V^3 \pi R^2 \ , \qquad \textit{(see §2.4)}$$

For a simplified situation under non-steady state conditions the simplified dynamic model for the turbine connected to an over gear, CVT and a asynchronous generator can now be derived:



$$P_t(V) - P_m(s) = I_t \dot{\omega}_t \omega_t \ , \qquad \textit{(eq 5.1)}$$

$$P_m(s) = \frac{P_{m,gen}(s)}{\eta_{tr}\eta_{cvt}\eta_m} \ , \qquad \textit{(eq. 5.2)}$$

$$\Rightarrow \dot{\omega}_t = \frac{P_t(V) - P_m(s)}{I_t \omega_t} \ , \qquad \textit{(eq. 5.3)}$$

Herein I_t is the inertia of the turbine rotor, ω_t is the rotor speed $P_{m,gen}(s)$ is the electro mechanical power of the generator dependent on its rotor speed (slip S). Furthermore η_{tr}, η_{cvt} and η_m are the efficiencies of the over gear and the CVT and the mechanical efficiency of the generator. By integrating equation 5.3 the turbine rotor speed can be calculated. The difference between the power that is consumed from the wind and the electro mechanical power generated in the generator is used as kinetic energy for the turbine rotor. When these two powers are equal the rotor speed will be constant. The inertia of the turbine axel, the over gear, the CVT and the generator are neglected in this simplified situation. This is possible because they are very small compared to the rotor turbine inertia. Thinking of a turbine which consists of a over gear, a CVT and a generator the Torque and the speed on the in going axel of the CVT can be calculated by:

$$T_{cvt,in} = \frac{[P_t(V) - I_t \dot{\omega}_t \omega_t]\eta_{tr}}{i_{tr1}\omega_t} \ , \ \omega_{cvt,in} = i_{tr}\omega_t \ , \qquad \textit{(eq. 5.4)}$$

With i_{tr} the gear ratio of the over gear. The use of this gear is necessary to drive up the speed of the CVT to bring down its torque. The ingoing torque $T_{gen,in}$ and speed $\omega_{gen,in}$ of the generator can then be calculated by respectively dividing and multiplying $T_{cvt,in}$ and

$\omega_{cvt,in}$ with the time varying gear ratio of the CVT. Furthermore the power has the be multiplied by the efficiency of the CVT.

$$T_{gen,in} = \frac{\left[P_t(V) - I_t\dot{\omega}_t\omega_t\right]\eta_{tr}\eta_{cvt}}{i_{tr}i_{cvt}(t)\omega_t}, \omega_{gen,in} = i_{tr}i_{cvt}(t)\omega_t, \qquad \textit{(eq. 5.5)}$$

6 Simulation

§ 6.1 Simulation purpose

The purpose of the simulation is to see whether a CVT in combination with a controller can be used to let the rotor speed follow the wind speed profile and thus keeping the tip speed ratio constant and optimising the maximum power coefficient (see eq. 2.13).
To test the CVT to its limits a turbulent wind field and an extreme wind gust will be used as inputs. The CVT will thus take over the role of the inverter, but in comparison to an inverter it will be a simple and cheaper solution. In this simulation the system with CVT will be compared to a constant speed system. This to make it clear why tip speed control is a must. For a constant speed system the electric generator must either rotate at constant speed (synchronous generator) or at slightly varying speed (asynchronous generator). The CVT on the other hand will control the turbine rotor speed to follow the wind speed exactly and keep the generator speed within its small allowable range (asynchronous generator).
Thus for a turbulent wind field the efficiency of a CVT equipped system will be compared with an conventional system at constant speed.
Furthermore for a turbulent wind field the efficiency of a CVT equipped system will be compared with a conventional constant speed system.

§ 6.2 Simulation modelling

For the modelling of the wind turbine the programme Matlab/ Simulink has been used. To get a wind turbine with an average output of 10 KW a rotor radius of 5 m is used. With an average wind speed of 10 m/s 10KW of power is produced. For the calculation of the power coefficient a drag to lift ratio (D/L) of 0.01 is assumed (see eq. 2.13). Furthermore a turbine rotor design with three blades and an approximated inertia of 1000 kgm^2 has been used in the simulation.
For the Simulink models that where used see the appendix.

To generate the set point for the CVT a very simple controller has been used. It is not within the purpose of this scope to develop a reliable and efficient controller.
The set point controller that has been used only looks at the difference between the turbine rotor speed and the ideal rotor speed for optimal tip speed ratio that is dependent of the wind speed. This difference is then fed into a relay, which only looks at the sign of this difference. The output of the relay is high speed if the difference is negative and low speed if it is positive. The point at which the relay changes output sort of operates as the controller gain. The generator thus generates either a low or a high mechanical torque, which allows the turbine rotor speed to increase or decrease.
The set point controller can be seen in the appendix.

§ 6.3 Simulation results

First the dynamic response of the turbine with CVT will be investigated. As ingoing wind profile a wind gust that stays constant at peak speed will be used. The wind speed changes rapidly from 10 m/s to 17 m/s in approximately 2.5 seconds [see fig 6.1]. This can be compared to a step change in wind speed. As can be seen from figure 6.2 the rotor speed changes from 8 to 13.6 rad/s in 4.2 seconds this is due to the large inertia of the turbine rotor. In figure 6.3 can be seen that the CVT changes its ratio slowly in 4.2

seconds from 0.95 to 0.56. Thus even in this very extreme wind profile the CVT manages to control the rotor speed all due to the large inertia of the turbine rotor. The dynamics that can be seen at constant ratio are due to the lack of a good controller.
Furthermore the maximum torque and speed of the CVT are 60 Nm and 620 rad/s this is within the allowable range of a dry belt CVT (max 74 Nm and 838 rad/s).

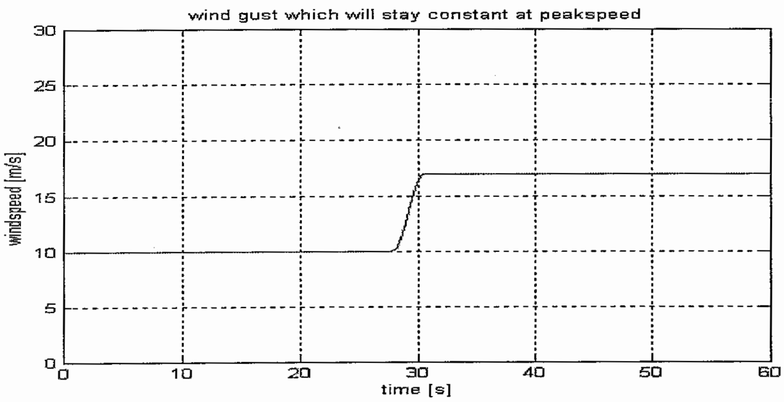


Figure 6.1: Wind gust which will be constant at peak speed.

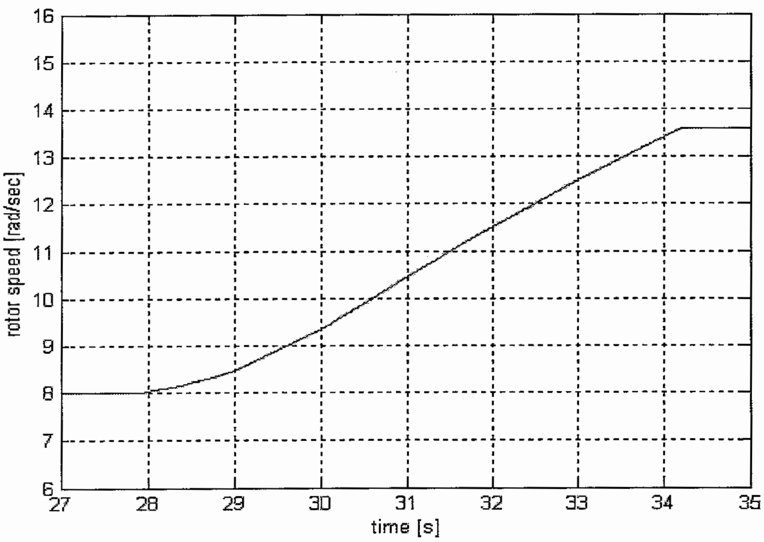


Figure 6.2: Rotor speed after a gust in wind speed.

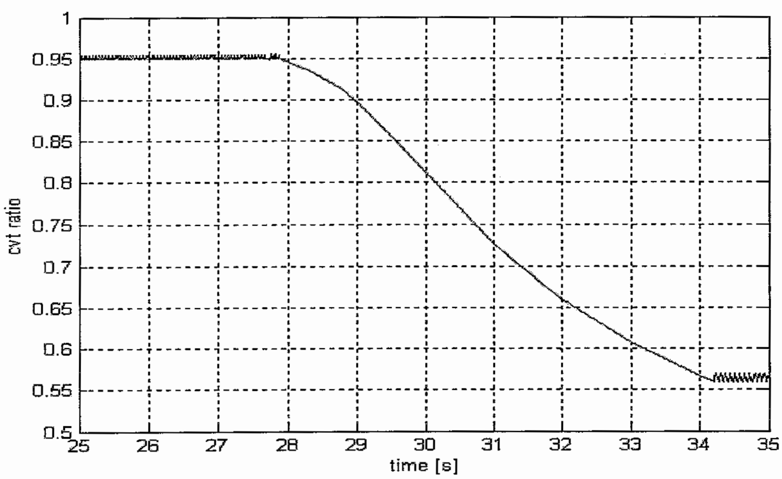


Figure 6.3: CVT ratio after a gust in wind speed.

Now the behaviour of the system with CVT will be investigated with a turbulent wind profile. The profile used can be seen in figure 6.4 and is generated with equation 1.5. As can be seen in figure 6.5 the rotor speed follows the wind speed very closely even with the use of a very simple set point controller.

That the machine runs at optimum efficiency can be seen in figure 6.6. The tip speed ratio is almost constant at its optimum value. Deviations of this value are caused by the absence of a good controller.
As can be seen in figure 6.7 the generator speed stays within its allowable asynchronous range so the electric output of the generator has a constant frequency. The CVT is thus usable as a replacement for an inverter.
The maximum torque and speed on the CVT is 60 Nm and 600 rad/s, this allowable for a dry belt CVT.

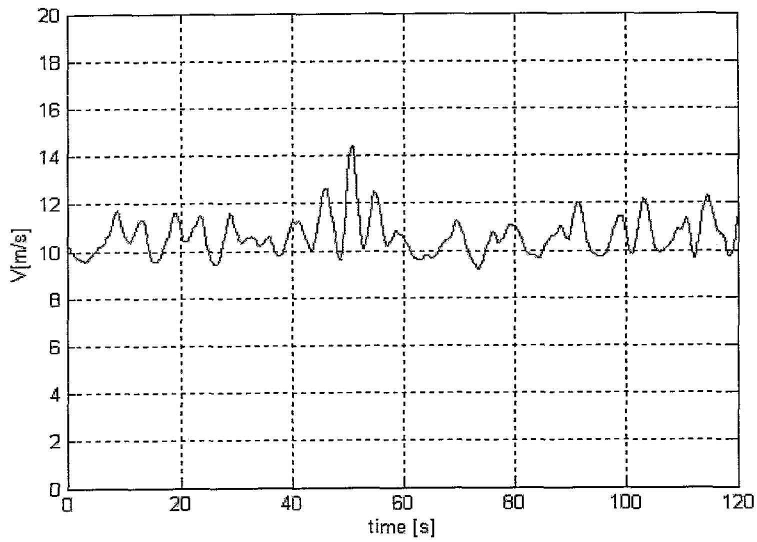


Figure 6.4: Turbulent wind profile.

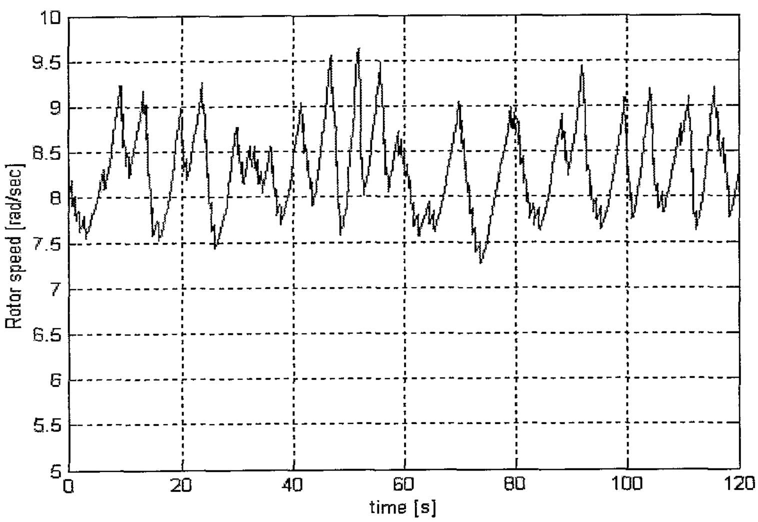


Figure 6.5: Turbine rotor speed due to turbulent wind profile.

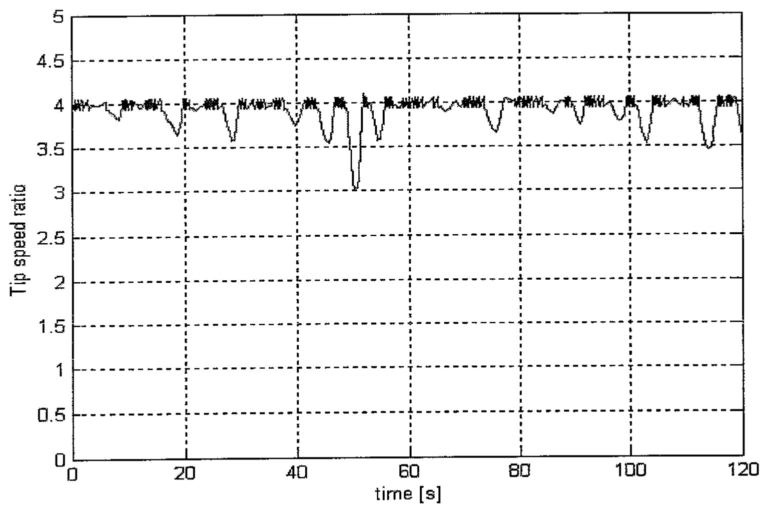


Figure 6.6: Tip speed ratio due to turbulent wind profile.

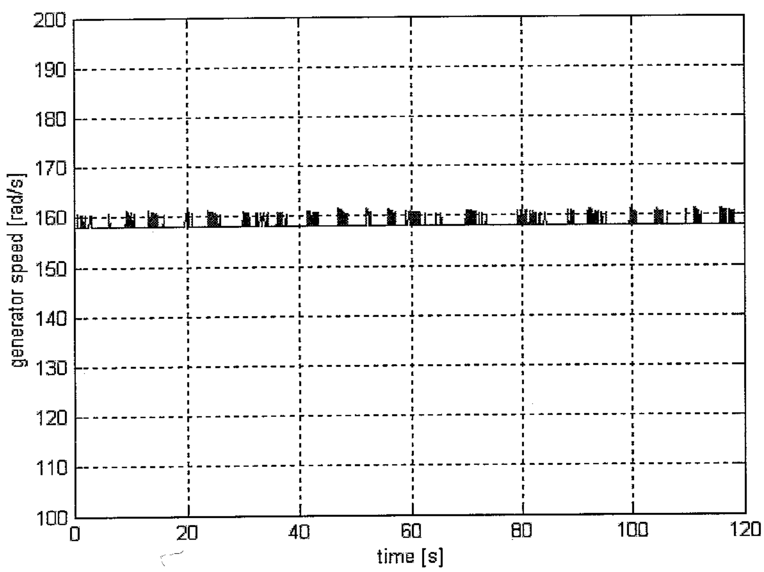


Figure 6.7: Generator speed.

Finally the response of the CVT equipped system is compared to a constant speed system with the same turbulent wind profile. In figure 6.8 the turbine rotor speed of both systems is shown.
Furthermore figure 6.9 shows the difference in tip speed ratio, as can be seen the tip speed ratio is much more constant for the system with CVT. The system with CVT runs more efficient then the constant speed system.

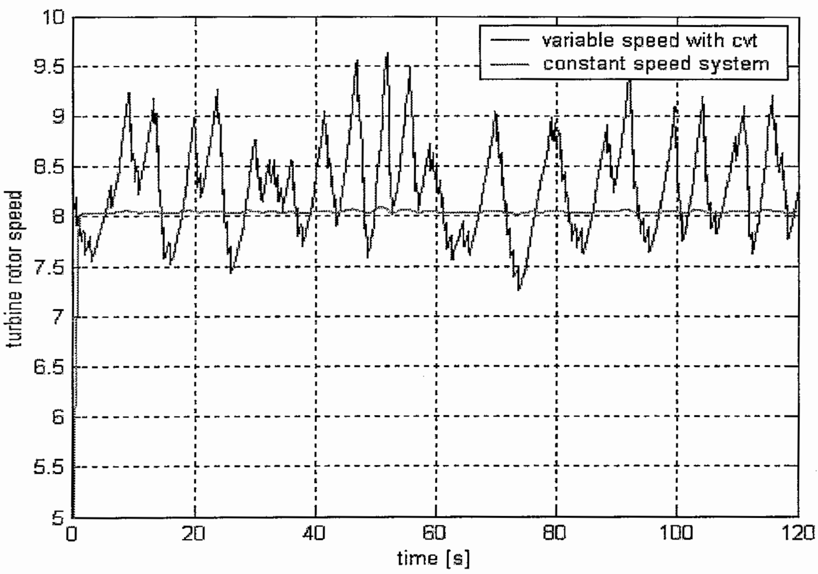


Figure 6.8: Turbine rotor speed with and without CVT.

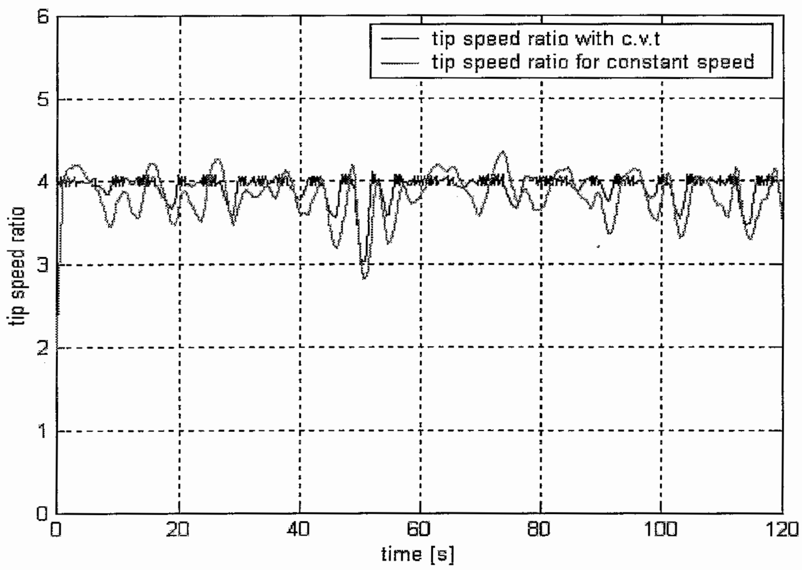


Figure 6.9: Tip speed ratio for the CVT system and constant speed system.

The power delivered to the generator of the system with CVT and the constant speed system is almost the same (about 1.5% more for the system with CVT). This is because the constant speed system is operated at its ideal design wind speed of 10 m/s , Its tip speed ratio is then optimal around 4. But if we now use a turbulent wind profile with another mean wind speed you will see that the power output for the CVT system is not the same, the tip speed ratio of the CVT system will stay at its optimum of 4, but the constant speed systems tip speed ratio will drop or rise with the wind speed and thus influence the power output. We will now use a different turbulent wind profile with a different mean wind speed; lets choose it to be 12 m/s [fig 6.10].

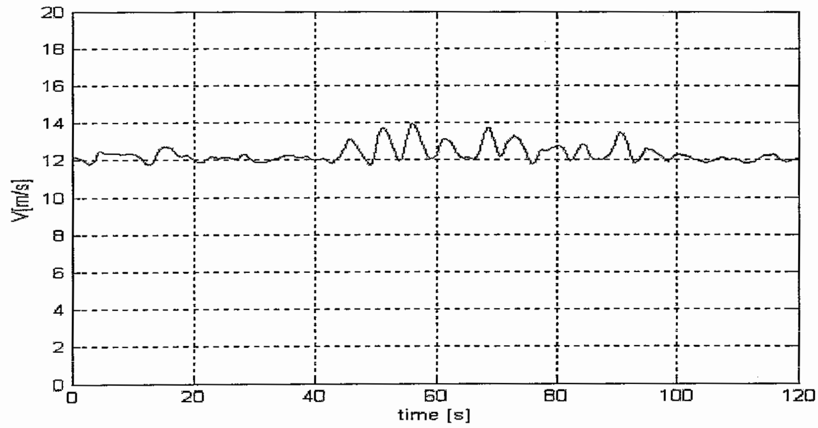


Figure 6.10: Turbulent wind profile with mean wind speed of 12 m/s.

Now the tip speed ratio of both systems is compared (fig 6.11). The tip speed ratio for the constant speed system drops to around 3.2. Thus the power output also significantly drops. In figure 6.12 the average power output for both systems is compared. The power of the variable speed CVT system is about 42% higher than the constant speed system. This outlines the reason why variable speed control is a must.

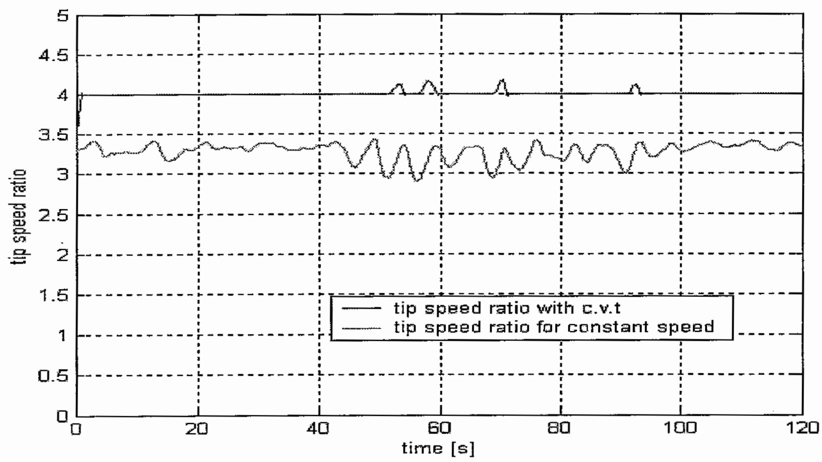


Figure 6.11: Tip speed ratio with CVT and for the constant speed system.

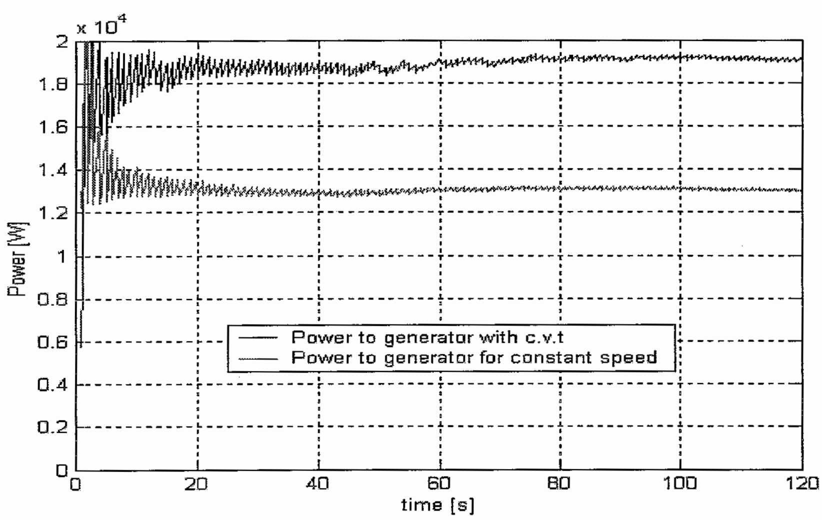


Figure 6.12: Time average power output for the CVT system and the constant speed system.

7 Conversation at Windwall

One of the goals of this internship is to examine the interest of the wind turbine manufacturers for the CVT. The biggest problem for the CVT is still the low torque it can handle on the incoming shaft, namely 74 Nm. After a couple of calculations a value for the maximum power of a wind turbine has been found, namely 30 kW. However, most of the wind turbine manufacturers built wind turbines over 100 kW. After a search on the Internet there has been found a company who produces a new design of wind turbines. They built a H-type Darrieus turbine for placing inside the build surrounding on sloping and flat roofs. Even placing the turbine in vertical position is possible. This design is also convenient for turbulent wind conditions around buildings. The power of this H-type Darrieus is 10 kW. Big advantages of this design are the low noise because it is rotating at low speed and the small radius of the Darrieus rotor.

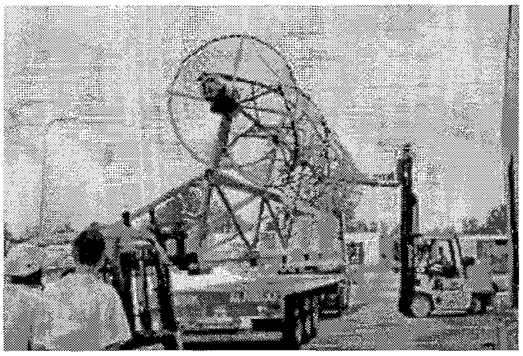


Figure 7.1:H-type Darrieus wind turbine, used for the Windwall

After a visit to and conversation with one of the people at Windwall there can be made some conclusions:

- The CVT has a great advantage with respect to the generator costs. In the current application the generator is oversized, because the H-type Darrieus rotor speed is low and so the torque is low. To get some power out of the generator it is chosen to be bigger than needed.
- The CVT will also give advantages with respect to the costs of the inverter. If you use a CVT to hold the speed of the generator on a certain speed level, it is possible for the CVT to takes over some properties of the inverter. The inverter can be replaced by a soft starter, which is needed to protect the grid for a brownout.
- The biggest problem for the manufacturer of Windwall was the use of a fixed gear in the design. A development in the world of wind turbines is direct drive, in this application no gears are used and thus no wear and tear of transmissions occurs. This with respect to the great variations in torque that occur in a wind turbine. Windwall also doesn't want to use fixed gears because of wear and tear. Without fixed gears the torque on the incoming shaft of the CVT is too high.
- To fix this problem there should be investigated which other possibilities there are for transmission application between turbine and CVT.

If the CVT is implemented in the design of the Windwall there should first be taken care of the following points:

- What will be the lifecycle of the CVT?
- In which time intervals should maintenance be conducted to the CVT?
- What is the profit in efficiency of the CVT in comparison with the inverter?

Conclusion

The goal of this internship is to investigate the possibility of using a CVT in a wind turbine application. After investigating the incoming side, the profile of the wind, and the out going side of the wind turbine, the generator with its properties, it was possible to make a simulation. Because this is a first step in this particular research for the use of a CVT in wind turbine application, there are better results possible for the simulation, such as a better set point control for the CVT.

After the simulations it was possible to look at the (dis) advantages of the CVT application. One great advantage is the removal of a great part of the inverter and the profits of a more efficient power output. With the use of a CVT the tip speed ratio will be kept constant at varying speeds. A disadvantage is the need of fixed gears, which are nowadays more and more replaced by direct drive systems.

After a conversation with Windwall, a manufacturer of H-type Darrieus wind turbines, the general manager was interested, but he doesn't want to use fixed gears because of the wear and tear.

Recommendations

When the CVT is used for wind turbine design it is recommended to develop an easy and quick maintenance procedure. Further more, it's easier to built a complete CVT unit with built in gearbox, which generates low noise and little wear and tear. For better controlling the CVT and get better dynamic response it is recommended to design a better controller.

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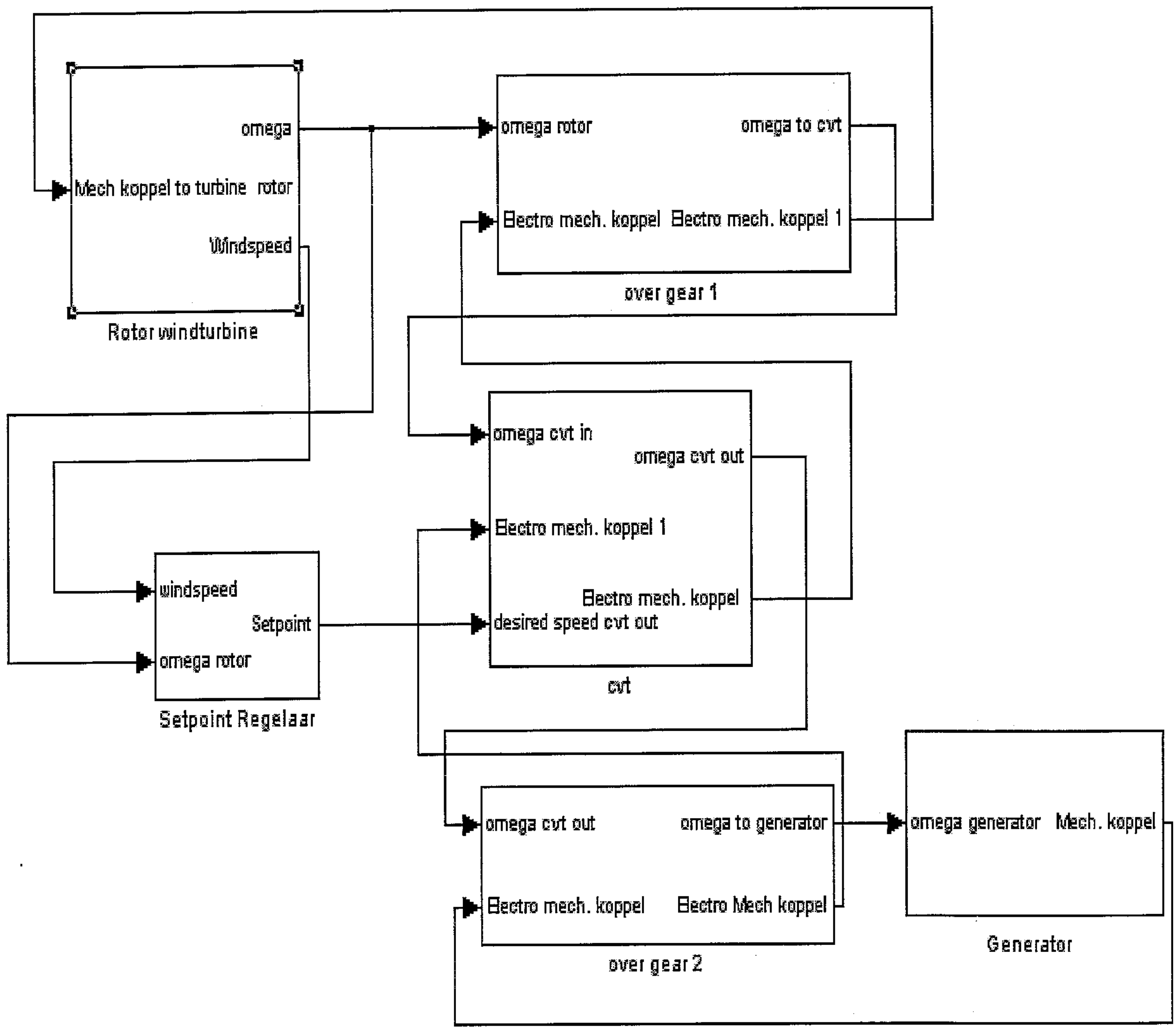
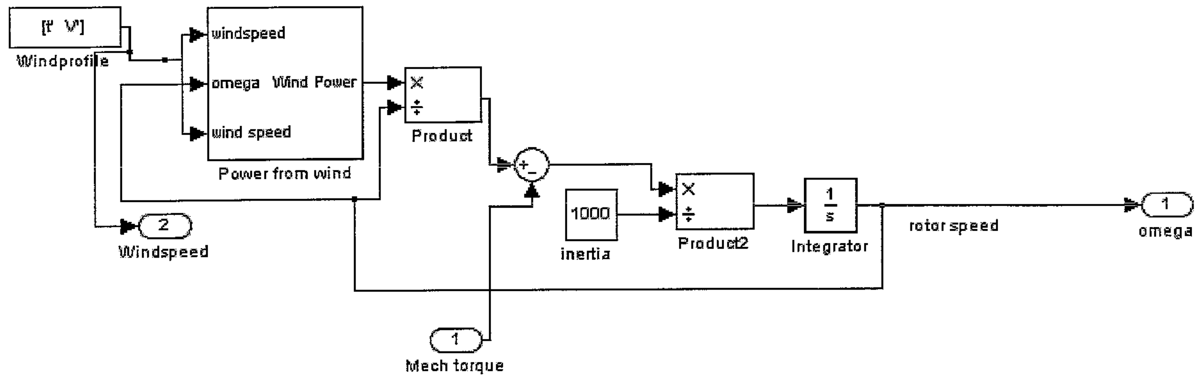
Appendix

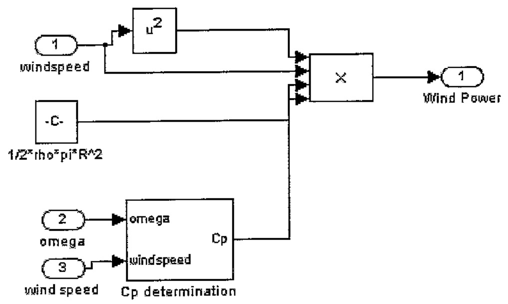
Simulink model of the wind turbine equipped with a CVT



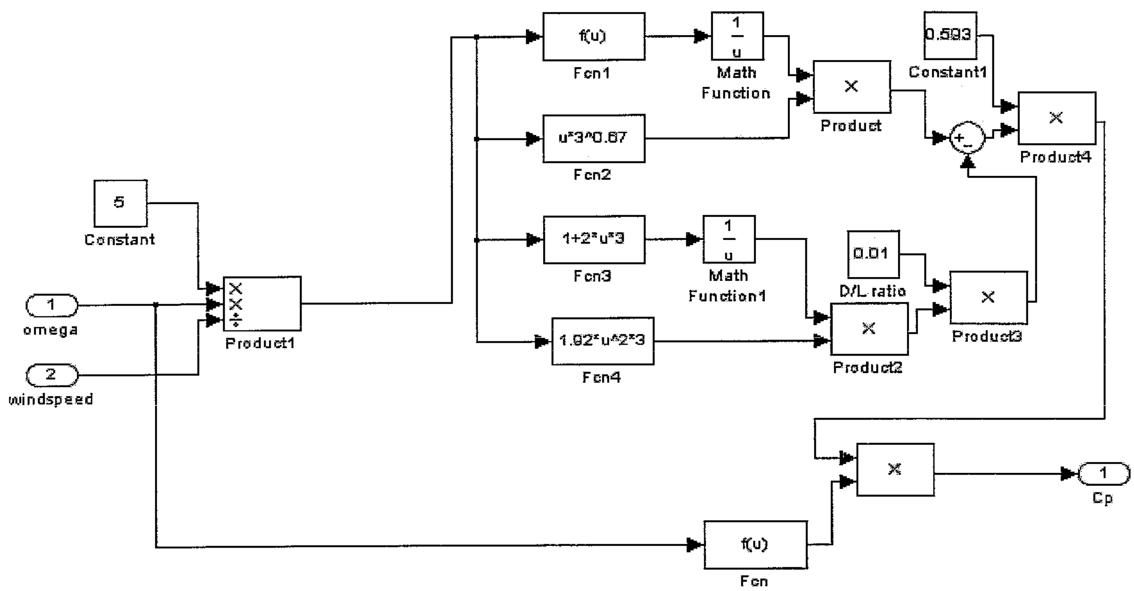
Rotor wind turbine



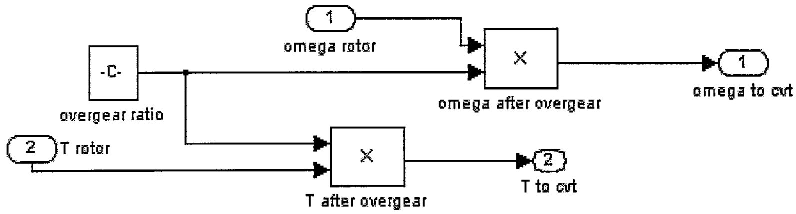
Power from wind



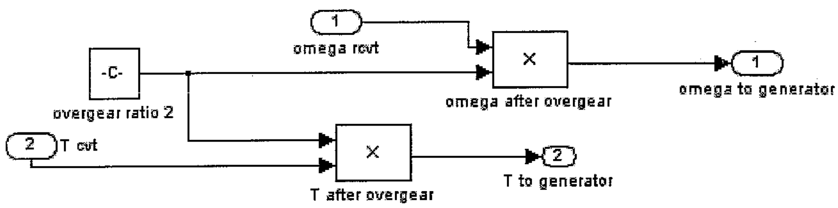
Cp determination



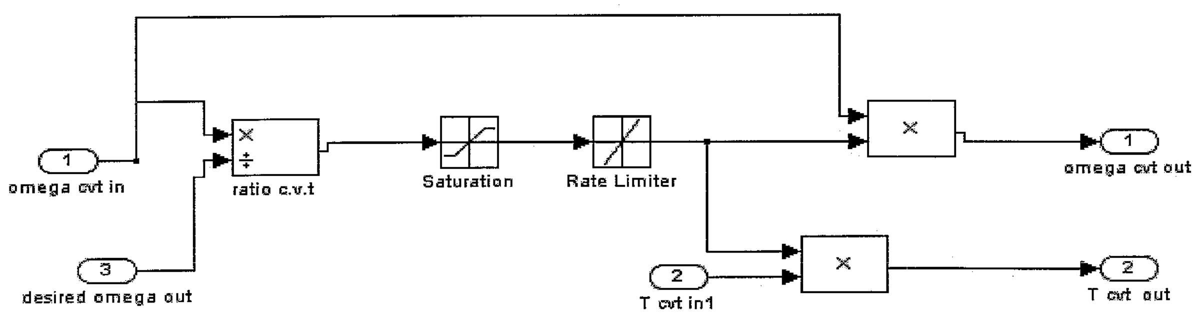
Over gear 1



Over gear 2



CVT



Set point controller