Modeling and Control of wind turbines using a Continuously Variable Transmission

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Abstract

Conventional variable speed wind turbines obtain their variable speed operation by controlling the generator torque. This control uses the power electronics that connect the generator to the electrical grid. The range of variable speed in these systems is limited and the power electronics are one of the main sources of failure in wind turbines. Therefore, the possibility of using a continuously variable transmission for the control of a wind turbine is investigated. From this study it is expected that a CVT controlled wind turbine will be able to operate over a wider speed range than the conventional systems controlled by the generator torque. The speed range is expanded mainly to lower speeds, making it possible to track the optimal rotor speed starting from a lower wind speed. This will result in a higher energy capture. Simultaneously the dynamic loads acting on the mechanical components are limited to prevent extra maintenance costs and early failures. For this purpose a wind energy conversion system is modeled in Matlab/Simulink®. The entire model consists of five main parts; the wind model, rotor model, drivetrain model, generator model and the model of the electrical grid. During the modeling of the drivetrain, an assumption is made for the ratio of the fixed gearbox and the range of the CVT. These assumptions are based on the speed range of existing wind turbines in the MW-range and the capabilities of the GCI chain-CVT.

The two control objectives for this study, maximizing energy capture and limiting dynamic loads, are met in two steps. First an algorithm is developed that uses a filtered version of the actual wind speed, the optimal tip speed ratio and the rotor diameter to create a setpoint for the CVT ratio. This setpoint takes into account both control objectives. The trade-off that is made between the two objectives can be shifted to either side by changing the frequency at which the measured wind speed is filtered.

Secondly, a control system is developed for the CVT. Therefore, first the nonlinear model of the CVT is linearized and analyzed using the 'Control and Estimation Tools Manager' within the Matlab/Simulink® environment. Based on different operating points of the linearized system, a control system for the CVT is designed. This control system consists of two control loops, one loop for the ratio control and one for the slip control. The design of the controllers is performed using sequential loop closing. The setpoint for the slip control is assumed to be constant at 1% slip. The bandwidth of the control system is 0.2 Hz, resulting in an accuracy of 0.003 in the ratio control and a slip in the range of 0.8 – 1.2%. Looking at the design specifications, these accuracies are sufficient.

Implementing the setpoints and the ratio and slip controllers, results in a system that is able to capture more energy from the wind during periods of low wind speeds, compared to the conventional wind turbines that control the rotor speed using the generator torque. During high wind speeds, but below the rated wind speed, the energy capture is equivalent to that of the conventional systems. The dynamic loads, which should be limited mainly in high wind speeds, are comparable to those in conventional systems.
Samenvatting

Conventionele wind turbines kunnen op variabele snelheid draaien dankzij een regelsysteem dat het koppel van de generator regelt. Deze regeling maakt gebruik van vermogenselektronica die de generator met het elekriciteitsnet verbindt. Het snelheidsbereik van dergelijke systemen is beperkt en de vermogenselektronica is één van de voornaamste oorzaken van uitval in wind turbines. Om deze redenen wordt er onderzoek gedaan naar de mogelijkheden om een continu variabele transmissie (CVT) te gebruiken voor het regelen van een wind turbine. Er wordt verwacht dat men met een CVT geregelde wind turbine het snelheidsbereik van de rotor kan vergroten ten opzichte van huidige systemen die gebruik maken van het generatorkoppel. Het bereik wordt voornamelijk naar beneden uitgebreid waardoor de optimale snelheid van de rotor vanaf een lagere windsnelheid al gevolgd kan worden. Dit zal resulteren in een grotere energieopbrengst voor lage windsnelheden. Tegelijkertijd worden de dynamische belastingen op de mechanische componenten beperkt om extra onderhoudskosten en vroege uitval te voorkomen.

Om deze verwachtingen aan te kunnen tonen, is er een wind energie conversie systeem (WECS) gemodelleerd in Matlab/Simulink®. Dit model bestaat uit vijf hoofdcomponenten: het wind model, rotor model, de aandrijflijn, de generator en een model van het elekriciteitsnet. Tijdens het modelleren van de aandrijflijn zijn er aannames gedaan omtrent de overbrenging van de vaste tandwielkasten en het bereik van de CVT. Deze aannames zijn gebaseerd op het snelheidsbereik van huidige systemen in de MW-range en de mogelijkheden van de GCI-ketting CVT. De regeldoelen voor dit project, het maximaliseren van de energieopbrengst en het beperken van de dynamische belasting, worden behaald in twee stappen. Allereerst wordt er een algoritme ontwikkeld dat gebruikt maakt van een gefilterde versie van de windsnelheid, de optimale tipsnelheid-ratio en de rotor diameter om een referentie signaal te creëren voor de ratio van de CVT. Dit referentie signaal houdt rekening met beide regeldoelen. De afweging welk doel het belangrijkste wordt geacht, kan vastgelegd worden door de filter frequentie, waarmee de gemeten windsnelheid wordt gefilterd, aan te passen.

Vervolgens wordt er een regelsysteem ontworpen voor de CVT. Hiervoor wordt het niet-lineaire model van de CVT eerst gelineariseerd rondom een stabiel werk punt waarna het systeem geanalyseerd kan worden met behulp van de ‘Control and Estimation Tools Manager’ binnen de Matlab/Simulink® omgeving. Een regelsysteem voor de CVT wordt ontworpen gebaseerd op het gedrag in verschillende werkpunten. Het regelsysteem bestaat uit twee regelringen, een lus voor het regelen van de ratio en een lus voor het regelen van de slip in de CVT. Het ontwerpen van de regelaars is uitgevoerd met behulp van Sequential Loop Closing. Het referentie signaal voor de slip wordt vastgesteld op een constante waarde van 1%. De bandbreedte van het geregelde systeem is 0.2 Hz, wat resultert in een nauwkeurigheid van 0.003 in de ratio regeling en een slip binnen een bereik van 0.8 – 1.2%. Met deze nauwkeurigheden voldoet het systeem aan de gespecificeerde regelparameters.

Implementatie van de referentie signaal en de ratio en slip regelaars, resulteert in een systeem dat tijdens perioden van lage windsnelheden meer energie uit de wind kan halen dan de huidige systemen. Tijdens perioden van hoge windsnelheden, maar onder de windsnelheid waarop de turbine op vol vermogen draait, is de energieopbrengst van een CVT geregelde wind turbine equivalent aan die van de huidige turbines. De dynamische belasting, die vooral bij hoge windsnelheden een rol speelt, is vergelijkbaar met de belastingen in conventioneel geregelde turbines.
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Chapter 1

Introduction

Global warming, the increase in the average temperature of the Earth’s near-surface air and oceans, is a major issue all over the world. According to the Intergovernmental Panel on Climate Change (IPCC) the majority of the temperature increase is caused by the greenhouse effect [1]. The greenhouse effect refers to the change in steady state temperature of a planet by the presence of an atmosphere containing gas that absorbs and emits infrared radiation. Over three-quarters of the greenhouse gas emissions on earth are caused by the combustion of fossil fuels. Renewable energy technologies, such as wind power, solar power, hydropower and biomass, can reduce the emission of greenhouse gases significantly and at the same time reduce the dependency on the oil industry. These two arguments combined make renewable energy a hot item all over the world. The fastest growing renewable energy source is wind power. Wind power is currently responsible for about 1.5% of the world’s electricity use [2]. Because of this high interest in wind energy, it becomes more and more important to increase the efficiency of wind energy conversion systems (WECS), also called wind turbines.

A wind turbine extracts kinetic energy from the wind and converts this into mechanical energy. This mechanical energy is then converted to electrical energy by means of a generator. A wind turbine extracts the maximum amount of energy from the wind when operating at an optimal rotor speed, which depends on the wind speed. Because the wind speed is variable by nature, the optimal rotor speed also varies. Earlier research has shown that variable speed operation of the rotor results in a higher energy production compared to a system operating at one constant speed. Next to an increase in energy production, variable speed operation enables a reduction in dynamic loads acting on the mechanical components [3, 4, 5, 6]. However, a problem arises when the speed of the rotor varies while the wind turbine must deliver AC power with a fixed phase and frequency to the electrical grid. To match the grid requirements, current variable speed wind turbines incorporate expensive power electronics to convert the variable frequency power to a constant frequency. The power electronics have a limited efficiency and they can introduce harmonic distortion of the AC current in the electrical grid, reducing the quality of the produced power [7]. Next to these disadvantages, power electronics are one of the main sources of failure in wind turbines. They account for about 25% of turbine failures and, unlike mechanical failures, they are not predictable and therefore increase maintenance costs. Additionally, when looking at the North American market, GE owns a patent on variable speed wind turbines incorporating power electronics [8]. This increases the interest for variable speed systems using a different technology.
At the moment, a number of wind turbines using a different technology to obtain the variable speed are available on the market. These technologies incorporate some kind of variable transmission in the drivetrain to control the rotor speed. For example, Wikov Wind in cooperation with ORBITAL2 Ltd. has launched a 2 MW wind turbine equipped with a variable transmission \[9\]. Another concept on the market is the 2 MW turbine by DeWind, incorporating a different technology \[10\]. Finally, there is the NuVinci continuously variable transmission (CVT) by Fallbrook Technologies. Together with the National Renewable Energy Laboratory (NREL) located in Colorado, an assessment has been performed on the potential of the NuVinci CVT in wind turbines \[4\].

In this thesis, a different technology to obtain variable speed operation is investigated. This technology replaces one fixed gear set with a continuously variable transmission. More specific, a chain-CVT developed by Gear Chain Industrial B.V. (GCI) in Nuenen, the Netherlands. The chain-CVT will be responsible for the variable speed operation. This thesis comprises of the modeling of a wind energy conversion system, followed by the development of a control system for the CVT. The goal of the thesis is to show that variable speed operation by means of a CVT can achieve equivalent, or even better, results compared to conventional control systems using power electronics. The results are compared in terms of energy capture and dynamic loading. All of the existing CVT technologies implemented in wind turbines are different from that of the chain-CVT developed by GCI.

The outline of this thesis is as follows. First, the physics behind extracting power from the wind is discussed. This discussion includes a comparison between constant speed and variable speed systems, with efficiency and dynamic loading as the main interests. After that, several variable speed operation techniques that are different from the conventional technology using power electronics. Next, Chapter 3 explains the working principle of the electrical generator, which is used to convert the mechanical power to electrical power. The influence of the choice of generator on the total system is also discussed. Another important part of the WECS is the CVT itself. Chapter 4 elaborates on the chain-CVT developed by GCI. Besides an assessment on the potential of a CVT for wind turbines in the MW-range, the characteristics of a chain-CVT in combination with a gearbox are discussed. These characteristics include the desired ratio of the fixed gearbox and the range of the CVT. With the knowledge of these characteristics, the behavior of the wind on the rotor and the generator operating principle, a model is developed in Matlab/Simulink$^\text{®}$ consisting of the main components in a WECS; the wind, rotor, gearbox, generator and electrical grid. Chapter 5 describes the modeling of each of these components. The model is then used to design a control system for the CVT which takes two main objectives into account; 1) maximizing energy capture and 2) reduction of dynamic loads. The ratio setpoint for the CVT is an important feature for the system performance according to these two objectives. Chapter 6 discusses the design of the ratio setpoint, as well as the design of the control system for the CVT. For this control, first the CVT system is analyzed after which a control system is designed, implemented and tested. The performance of the CVT is compared to the conventional control using power electronics. Finally, conclusions and recommendations are presented in Chapter 7.
Chapter 2

Wind Turbines

The technology of extracting energy from the wind is an old technology. The first wind mills date back more than 2000 years and were for example used as a water pump. Over the years, especially around the 17th century, more applications have been developed and wind mills became an important feature in the industrialization.

Nowadays, wind mills are better known as wind turbines and they are not used for milling grain, sawing wood or pumping water, but they are used to generate electricity. This so-called ‘green’ electricity has evolved enormously over the past few decades. The high prices and coming shortage of oil, together with the global warming caused by the emission of carbon dioxide, are the main reasons for the interest in sustainable energy. Since wind is a natural resource, the technology is sustainable and at the same time the emissions during operation are close to zero. These are all characteristics that make the wind energy industry so interesting. The energy payback time of a wind turbine is about 3 – 6 months, depending on the availability of wind at the turbine location. This number is based on a 1.8 MW wind turbine [11].

In this chapter, first the general working principle of a wind energy conversion system is explained. Next, the relation between the amount of power in the wind and the potential energy production is described. Then the concepts of constant speed and variable speed wind turbines are explained and compared. Finally, a number of existing drivetrain techniques used in wind turbines are discussed.

2.1 Wind energy conversion system

The complete system required to convert the energy in the wind to electricity is called a wind energy conversion system (WECS). Such a system consists of a rotor to capture the energy in the wind, a gearbox configuration to speed up the rotational speed of the shaft and a generator to convert the mechanical energy into electrical energy. A schematic view of a WECS is shown in Figure 2.1. The efficiency of the total system is not only determined by the efficiencies of the gearbox and generator, but also by the amount of energy that can be extracted from the wind.
2.2 Energy in the wind

A wind energy conversion system consists of a number of components to transform the energy in the wind to electrical energy. One of these components is the rotor, which is the component that extracts energy from the wind. The theory behind this method of converting wind energy to mechanical energy is mainly set by Albert Betz in 1926 \[12\]. Betz showed that the mechanical energy extractable from an air stream passing through a given cross-sectional area is restricted to a certain fixed proportion of the energy or power contained in the air stream, the so-called power coefficient \(C_p\). The maximum power coefficient according to Betz is given by:

\[
C_{p_{\text{max-th}}} = \frac{16}{27} = 0.593 \quad (2.1)
\]

Important to know is that this ‘ideal’ power coefficient is derived for an ideal, frictionless flow, which obviously is never the case. Also, this \(C_{p_{\text{max-th}}}\) is the theoretical maximum. The power coefficient \(C_p\) is mainly dependent on the ratio of the rotating speed of the tip of the blades and the speed of the wind. This so-called tip speed ratio \(\lambda\) is defined as:

\[
\lambda = \frac{u}{v_w} = \frac{\omega R}{v_w} \quad (2.2)
\]

- \(u\): tangential velocity of the rotor blade tip [m/s]
- \(v_w\): velocity of the wind [m/s]
- \(\omega\): rotational speed [rad/s]
- \(R\): radius of the rotor [m]

Now the maximum power that can be extracted from the wind exists at the optimal tip speed ratio. The optimal tip speed ratio is different for each turbine design and is a system parameter of the entire WECS. For a three-bladed rotor, a general curve of the tip speed ratio versus power coefficient is shown in Figure 2.2. From this figure it can be concluded that an optimal tip speed ratio of around 7.5 is most common in three-bladed wind turbines \[12\]. The amount of power extracted from the wind by the rotor is determined by:

\[
P_r = \frac{1}{2} \rho A C_p v_w^3 \quad (2.3)
\]
2.2. ENERGY IN THE WIND

The power coefficient can be seen as a measure for the efficiency with which the turbine extracts power from the wind and is a function of the tip speed ratio $\lambda$ and the blade pitch angle $\beta$. Information about blade pitch control and its influence on the power coefficient is presented in Section 2.3.1. Next to the $C_p$-$\lambda$ curve, the power curve is characteristic for the operation of each wind turbine. It shows the power output in relation to the wind speed. An example of a power curve for a 2MW, three-bladed turbine is depicted in Figure 2.3 [13]. The operating regime of a wind turbine is divided into three regions. Region 1 is the low wind speed region for which the turbine does not produce any power, the rotor is standing still and the turbine is disconnected from the grid. When the turbine would be connected to the grid at these low wind speeds, the generator would start working as a motor, driving the turbine. The turbine would then actually be working as a huge fan, consuming energy instead of producing. The second region, region 2, is the region between the wind speed at which the turbine starts to operate ($v_{w,cut-in}$) and the wind speed at which maximum power is produced ($v_{w,rated}$). This is the region for which maximizing energy capture is very important, but limitation of dynamic loads also becomes more important. In a typical wind turbine, region 2 operation accounts for more than 50% of the annual energy capture. This indicates the importance of efficient operation in this regime. Finally there is region 3, which is the region from the rated wind speed to the wind speed at which the turbine is stopped to prevent damage ($v_{w,cut-out}$). In this region, energy capture is limited such that the turbine and generator are not overloaded and dynamic loads do not result in mechanical failure. The limitation in energy capture is generally controlled by pitching the rotor blades, this control principle will be explained more elaborately in Section 2.3.1.
A final important parameter in wind turbines is the behavior of the torque transmitted to the rotor axis. The rotor performance is dictated by the torque coefficient $C_Q$, which is related to the power coefficient $C_p$ and the tip speed ratio $\lambda$.

\[ T_r = \frac{1}{2} \rho ARC Q v_w^2 \]  

$T_r$ = mechanical torque on the rotor shaft [Nm]  
$C_Q = \frac{C_p}{\lambda}$ = torque coefficient [-]

With the equations above, it is possible to determine the amount of mechanical torque produced by a specific wind turbine.

### 2.3 Constant versus variable speed turbines

Wind turbines that operate at constant speed obtain the highest aerodynamic efficiency only at one specific wind speed, the design wind speed. At this wind speed the optimal tip speed ratio is obtained. In variable speed systems, it is possible to run the turbine at optimal $\lambda$ for variable wind speeds. This is for example possible by controlling the torque generated by the generator. This torque is counteracting the torque created in the rotor shaft and can therefore increase or decrease the angular speed of the rotor. This type of control will be explained in detail in Section 6.2.1.

Figure 2.4 is an example to show the difference in constant and variable speed operation and the influence of the tip speed ratio on the power output. The difference is mainly applicable to the region 2 operating range in Figure 2.3, because in that range it is possible to obtain optimal $\lambda$.

As an example a wind profile is considered starting at 7 m/s and gradually increasing to 12 m/s. The constant speed turbine is assumed to operate at 10 rpm. At 7 m/s both constant and variable speed operation produce around 20% of the nominal power. Just above 7 m/s, the variable speed
2.3. CONSTANT VERSUS VARIABLE SPEED TURBINES

turbine starts to produce 40% while the constant speed does not reach this percentage until 7.5 m/s. At higher wind speeds, the constant speed turbine will never produce more than 60% of the nominal power. In the same wind profile, the variable speed turbine will be able to produce up to 100% of the nominal power.

Next to the advantage of variable speed, this figure also shows the importance of maintaining optimal $\lambda$. To illustrate, the line of power produced when operating at a tip speed ratio of 13 is drawn. In that case, the produced power never exceeds 20%. This can be explained by looking at Figure 2.2, the power coefficient at $\lambda = 13$ is only 0.25 instead of the maximum of 0.48. The profile in Figure 2.4 is constructed for a particular turbine, but curves for other turbines are similar.

![Figure 2.4: Influence of $\lambda$ and variable speed on the output power](image)

Combining figures 2.2, 2.3 and 2.4 results in a graph of the wind speed versus the power coefficient, shown in Figure 2.5. This figure obviously shows the advantage in efficiency of variable speed operation. Next to an improvement in efficiency, variable speed systems are less sensitive, in terms of dynamic loads, to fluctuations in the wind profile. Part of the energy from a wind gust can be captured by the inertia of the rotor by allowing an increase in rotor speed. This results in a decrease of the fatigue loads acting on the drivetrain components.

Variable speed systems that are currently in operation throughout the world produce current with a variable frequency, due to the variable speed of the generator shaft. The electrical grid to which the turbines are connected, requires a constant frequency of 50 Hz (60 Hz in the United
States). Therefore, additional power electronics are required to change variable AC power to a constant voltage and frequency. These power electronics increase the overall costs of the turbine and decrease the efficiency and reliability of the total system. More information on these power electronics can be found in Section 2.3.2.

Figure 2.5: Efficiency of constant speed and variable speed systems [14]

The advantages and disadvantages of variable speed systems over constant speed systems have been thoroughly investigated by [3, 4, 5, 6]. A wind energy conversion system can be improved in different ways. In this report, optimization by means of implementing a continuously variable transmission will be discussed. Information about other optimization possibilities can be found in [12, 15].

2.3.1 Blade pitch control

Blade pitch control is used to control the aerodynamic power captured from the wind. By pitching the rotor blades along their longitudinal axis, the aerodynamic efficiency of the rotor is changed. This change is caused by a modification in the aerodynamic angle of attack. The aerodynamic angle of attack is defined as the angle between the chord line of the rotor blade and the direction of the approaching wind, as seen by the rotor blade. Figure 2.6 illustrates a rotor blade in an air stream \( V_w \) and how this air stream is seen by the blade \( V_r \). The chord line of the blade is drawn and the angle \( \alpha \) defines the angle of attack [12]. When decreasing the angle of attack, called feathering, the lift capacity of the blades is reduced and therefore the power captured by the rotor decreases. Conversely, an increase in the angle of attack, with respect to the operational position in Figure 2.6a, will lead to a higher power capture due to a reduction in drag. When the critical aerodynamic angle of attack is reached, the airflow separates at the surface of the rotor blades, limiting the power. This effect is called stall.

Below rated wind speed, the pitch angle can be controlled to change the tip speed ratio. However, application of blade pitch control to follow the desired tip speed ratio is limited by the rate at which the blades can be pitched and the reaction time of the rotor speed to change. A disadvantage of
2.3. CONSTANT VERSUS VARIABLE SPEED TURBINES

using blade pitching below rated speed is that less energy is extracted from the wind, decreasing the efficiency. This effect is shown in Figure 2.7, where the shifting of the $C_p$-$\lambda$ curve is shown for different pitch angles. For this reason, blade pitch control is generally not used below the rated wind speed.

Above rated wind speed, blade pitch control is used to limit the angular speed of the rotor by capturing less power from the wind than available and to protect the system from excessive forces. By pitching the blades, the operating range of the turbine in terms of wind speed is increased. Without blade pitch control, the maximum operating speed would be rated wind speed. Above rated, the dynamic loads on the mechanical components would become too high and the angular speed of the rotor would exceed its maximum. With blade pitch control, the operating range is typically increased up to 25 m/s [12, 16].

2.3.2 Power Electronics

Variable speed operation of the generator results in the production of current with a variable frequency. The frequency of the produced current is determined by the electrical angular speed of the generator. For the electrical grid to remain stable, the frequency and phase of all power generating units must remain synchronous within narrow limits. When the frequency of the generator varies too much, in the order of 2 Hz, circuit breakers cause the generator to disconnect from the system, preventing damage to the grid. However, small deviations in the generator frequency can indicate instability in the grid. The grid frequency is not exactly 50 Hz at all times, variations in this frequency directly influence the generator frequency [17].

Figure 2.6: a) operational, b) feathered and c) stall position of the rotor
The quality of the power supplied to the grid has to meet certain requirements. The Dutch requirements for non-utilities on a grid in normal operating mode are listed in Table 2.1, also mentioned in the norm NEN-EN 50160:1995 named “Current-characteristics in public utility-grids” [18].

<table>
<thead>
<tr>
<th>Quality aspect</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>frequency</td>
<td>50 Hz $+1%$ during 99.5% of the time</td>
</tr>
<tr>
<td></td>
<td>50 Hz $+4%/-6%$ during 100% of the time</td>
</tr>
</tbody>
</table>

Table 2.1: Frequency requirements for the Dutch electrical grid

As mentioned earlier, to meet these requirements it is necessary to implement power electronics between the generator and the grid. These power electronics usually consist of a rectifier and an inverter. The rectifier converts the variable frequency AC current to a DC current. After which the inverter converts the DC current to a constant frequency AC current that can be supplied to the grid (Figure 2.8). An inverter is in fact the inversion of a rectifier. Inverters and rectifiers are operated in a switching mode to reduce power loss. A disadvantage of using a switching mode is the generation of harmonic distortion. The switching frequency depends on the type of switching device that is used. Commonly used switches in the wind turbine industry are MOSFET’s (metal-oxide-semiconductor field effect transistor) and IGBT’s (insulated-gate bipolar transistor). MOSFET’s have a high switching frequency but their power ratings are low (600 V, 50 A, 1000 kHz). The power rating refers to the maximum power that can run through the device. On the other hand, IGBT’s tend to have a lower switching frequency but high power ratings (1500 V, 1000 A, 30 kHz) [19, 20].

Power electronics is a technology that is developing rapidly. Higher current and voltage ratings are available, efficiency increases and costs decrease. Therefore, power converters are widely used in the wind turbine industry to improve the performance of wind turbines. However, there are also a number of disadvantages of using power electronics.
2.4. DRIVETRAIN TECHNIQUES

The biggest disadvantage of power electronics is the reliability. Mechanical components show wear and tear and therefore any failures in these components can be monitored and predicted, maintenance can be scheduled before failure occurs. Unfortunately power electronics do not show signs of degrading, therefore failures cannot be predicted and these sudden failures are very expensive to repair. Together with high failure costs, power electronics tend to fail quite rapidly because they are very sensitive to voltage spikes [19]. In the wind energy industry about 25% of all failures is due to the power electronics.

2.4 Drivetrain techniques

Most generators used in wind energy conversion systems require an input speed of around 1500
rpm. Since the rotor shaft rotates at only a fraction of this speed, a step-up gear is required to obtain the desired speed at the generator shaft. In a 2 MW turbine, this step-up gear typically has a ratio of around 1 : 100. This ratio can be obtained by implementing 2 or 3 gear sets, mostly a combination of planetary and parallel gears. The efficiency of the complete drivetrain depends on the number of sets and the efficiency of each set. In general, spur (or parallel) gears have an efficiency of around 98% while planetary gears even reach 99% efficiency [12]. Advantages of using a spur gear are its wide availability and low cost. On the other hand, planetary gears are slightly more efficient and it is possible to obtain higher gear ratios in a smaller package. A Spur gear set can have a gear ratio up to 1 : 5, while planetary sets are built with ratios up to 1 : 12. Next to a higher possible ratio, the design of planetary gears is more compact. Furthermore, the loads are better distributed through the multiple contact points. This also gives planetary gears a higher torque capability. Finally, the bearing forces in planetary gears are lower than in spur gears. Both configurations are depicted in Figure 2.9 [12].

<table>
<thead>
<tr>
<th>Spur gears</th>
<th>Planetary gears</th>
</tr>
</thead>
<tbody>
<tr>
<td>wide availability</td>
<td>high efficiency</td>
</tr>
<tr>
<td>low cost</td>
<td>high torque capability</td>
</tr>
<tr>
<td></td>
<td>high gear ratio</td>
</tr>
<tr>
<td></td>
<td>good load distribution</td>
</tr>
<tr>
<td></td>
<td>compact</td>
</tr>
</tbody>
</table>

Table 2.2: Advantages of spur and planetary gears

The design of the drivetrain does not only depend on the efficiency of each set, but also on the rated power of the turbine. In the megawatt range, the relative costs of the gearbox are reduced significantly when using planetary gears. This is mainly because of the lower mass and smaller size. Planetary gears are preferable in megawatt turbines.
Next to the conventional drivetrains using spur and planetary gears, a number of different technologies are used within the wind turbine industry. Although these technologies are not yet implemented on a large scale, they have a high potential.

First of all, the Vestas 2.0 MW V80 turbine is equipped with a combined spur and planetary gear, consisting of 3 sets. This results in a total gear ratio of $1 : 100.5$. Vestas has developed a control system to be able to control the slip in the asynchronous generator. This system, called OptiSpeed®, allows the angular speed of the rotor to vary up to 60% from nominal speed, 30% above and below synchronous speed. In case of the V80 turbine the variable ratio equals $1 : 167 - 1 : 79$, resulting in a speed range of the rotor of $9 - 19$ rpm. The range of variable ratio is 2.1. Because of this variation, wind gusts are exploited better in terms of energy capture, increasing the annual energy production by around 5%, and it reduces the wear and tear on the drivetrain. OptiSpeed® is not available in the US and Canada. This is the result of a patent on variable speed wind turbines, owned by GE Wind energy [8, 21].

A different drivetrain configuration is used in the 2.0 MW Wikov Wind W2000 turbine. In this turbine Wikov Wind uses a Superposition Gear (SPG) system, consisting of 2 step-up planetary gear sets, followed by a parallel shaft connected to a patented epicyclic differential. The parallel shaft is connected to the input carrier of the differential, while the generator is connected to the annulus and a hydrostatic shunt transmission to the reaction sun wheel. When a wind gust increases the torque on the parallel shaft, the variable stroke hydrostatic transmission is adjusted such that the torque on the generator shaft is constant. This enables variable rotor speed while maintaining constant speed of the generator shaft. The SPG gearbox is designed by ORBITAL2 Ltd. The variable transmission ratio in this case equals $1 : 125 - 1 : 79$, resulting in a variable rotor speed of $11.5 - 19$ rpm and a ratio range of 1.65. Next to the advantage of variable speed, a synchronous generator directly connected to the grid can be used and power electronics are no longer required [9, 22].
Another concept available on the market is the 2.0 MW DeWind D8.2. The drivetrain of this turbine consists of a combined planetary/spurwheel gear (2 sets) followed by the Voith WinDrive Hydrodynamic gearbox. The WinDrive® combines a superimposing gear unit with a torque converter. Figure 2.10 shows the working principle of the WinDrive. From the left, the variable speed input of the rotor is connected to the step-up gear sets. The output shaft of these sets is connected to a hydrodynamic torque converter, of which the output is connected to the generator. The hydrodynamic torque converter used in the WinDrive decouples the rotor from the generator, therefore it dampens vibrations and shocks in the driveline. The transmission ratio is controlled by adjusting the angle of the vanes in the torque converter, therefore changing the amount of transmitted torque. The variable transmission creates an operating range for a 2.0 MW turbine of 11.1 – 20.7 rpm. The variable ratio then equals 1 : 135 – 1 : 72 with a ratio range of 1.86. Because of this wide ratio range, a synchronous generator connected directly to the grid can be used and power electronics are not required. [10, 23, 24].

![Figure 2.10: WinDrive](image)

The last concept to be discussed is the NuVinci® continuously variable transmission developed by Fallbrook Technologies Inc. This so-called Continuously Variable Planetary (CVP) technology uses rotating spheres to transmit power from an input disc to an output disc using elastohydrodynamic lubrication. The transmission ratio between input and output disc is varied by changing the angle of the spheres’ rotational axes. The contact diameters of the spheres change and therefore the speed ratio changes. The NuVinci® CVT is equipped with 3 to 20 spheres, depending on the required torque capacity. Increasing the number of spheres within a fixed diameter, increases the torque capacity [4].
Chapter 3

Generators

One of the most important and prominent parts of a wind turbine is the generator. The generator is used to convert the mechanical energy of the rotor to electrical energy. The output of the generator is connected to the electrical grid, which operates with a 3-phase alternating current at a frequency of 50 Hz (Europe) or 60 Hz (US).

To begin with, the general working principle of a generator is explained, together with the physics that is used in electrical machines, electromagnetism. After that the losses that exist in a generator are described. Then a more specific overview of the working principle of a synchronous generator is provided, after which the same is done for an induction generator. Finally these two types are compared to determine which type of generator is preferred when implementing a CVT in a wind turbine.

3.1 Working principle

The working principle of generators is based on electromagnetism; a change in a magnetic field induces an electric current and similarly, a change in an electric current generates a magnetic field. The strength of this magnetic field is determined by Ampere’s Law [25]:

\[ \mu_0 I_f = \oint B \cdot dl \]  

(3.1)

- \( \mu_0 \) = absolute permeability of free space [\( \text{[m]} \)]
- \( I_f \) = electric field current [\( \text{[A]} \)]
- \( B \) = magnetic field [\( \text{[T]} \)]

Generators consist of a stator and a rotor. A rotating magnetic field is created in the air gap between the stator and rotor. The windings in which the voltages are induced (armature windings) are located on the stator, which indicates that they stay at a fixed position. Now the rotating magnetic field continuously changes the flux linkage in these static armature windings. This change in flux linkage induces a voltage in the stator coils according to Faraday’s Law:

\[ \epsilon = -N \frac{d\phi}{dt} \]  

(3.2)
Important concepts in this system are the armature and field windings, either located on the stator, rotor or both. The field winding is defined as the winding through which a current flows to produce a magnetic field, the primary source of flux. The armature windings are always located on the stator, while the field windings can either be located on the stator (induction generator) or on the rotor (synchronous generator). The basic structure of a synchronous generator is shown in Figure 3.1, including the armature and field windings. Both types of generators will be discussed in Sections 3.3 and 3.4.

The most common generators are 3-phase generators. In that case, the voltages are phase-shifted $360^\circ / 3 = 120^\circ$. The angular speed of the rotor together with the number of poles in the generator determine the frequency of the induced voltage:

$$ f = \frac{np}{120} \tag{3.3} $$

- $f$ = frequency of induced voltage [Hz]
- $n$ = rotor speed [rpm]
- $p$ = number of pole pairs

For synchronization to the grid, the frequency of the induced voltage should be 50 Hz (in Europe). Increasing the number of poles will lead to a lower required rotor speed but it will increase the size and costs of the generator [7]. For example, the angular speed of a 4-pole generator should be 1500 rpm when directly connected to the European grid [7, 19, 26].

When mechanical power is added to the generator, the rotor is turned forward by a load angle $\delta$. The load angle is defined as the relative angle between the $abc$-axis of the stator, rotating at
synchronous speed, and the $dq$-axis of the rotor. The definition of both axes is given in Figure 3.1. The relation between the load angle and the output power is shown in Figure 3.2. As can be seen, the electrical power output increases as the load angle increases. The size of the load angle is a measure for the level of loading, being positive in generator mode. Maximum power is produced when the load angle is 90°. When the load angle exceeds 90°, the generator will lose its synchronism. When a synchronous generator loses its synchronism, instability in the power system occurs [20, 27]. According to the Association of German Electrical Engineers, the nominal operating point of a generator should be at a load angle of 30° [12].

The load angle can be controlled by the excitation voltage $v_F$. When the system is over-excited, the load angle becomes small, leading to a very stable system. On the other hand, under-excitation leads to a high load angle. In that case, the load angle can increase until the system loses its synchronism, therefore under-excitation results in less stability. The influence of the excitation voltage on the load angle directly links the load angle to the power factor, which will be explained in the next section [28].

For a 3-phase generator, the power transfer is given by:

$$P = 3V_I I_a \cos(\theta) \quad (3.4)$$

- $P$ = power output [W]
- $V_I$ = terminal voltage [V]
- $I_a$ = armature current [A]
- $\cos(\theta)$ = power factor [-]

The terminal voltage is constant, while the armature current and power factor vary with the level of loading [19].
3.1.1 Power factor

An important parameter when discussing generators is the power factor, which has a value between 0 and 1. When determining the power factor it is important to consider three parameters; real power $P$, reactive power $Q$ and apparent power $S$. The real power is defined as the actual power delivered to the grid. Reactive power is the power required by magnetic equipment to produce a magnetizing flux. Apparent power is a vectorial summation of the real and reactive power (Figure 3.3). The power factor of a process is then defined as the ratio between real power and apparent power:

$$\text{Power factor} = \frac{\text{real power}}{\text{apparent power}} = \cos(\theta) \quad (3.5)$$

In generators, the reactive power is determined by the amount of phase shift between the armature current and the terminal voltage. If the current and voltage are in phase, the reactive power is zero and therefore the power factor is 1. The more current and voltage are out of phase, which is defined by $\theta$, the lower the power factor will be according to (3.5) [20, 27, 29].

The power factor can either be leading or lagging, meaning that the phase current lags or leads the phase voltage by some angle. A leading power factor exists when the system is under-excited and indicates that the generator takes reactive power from the grid. A lagging power factor is present when the system is over-excited and indicates that the generator produces reactive power for the system. This said, the power factor in a system can be controlled by controlling the excitation voltage. In practice, most generators are operated with a lagging power factor. This may not seem the most efficient operation, but it is preferable in maintaining synchronism and increases the stability during disturbances [28].

A low power factor requires an increase in the generation of electricity to handle the reactive power component. A higher current is required to produce the same real power. A higher current will lead to an increase in copper and iron losses in the equipment. This decreases the efficiency of the system. Next to a decrease in efficiency, a low power factor is less cost effective. Utilities often charge additional fees to customers with power factors less than 0.95 [30, 31].
3.2 Generator losses

The efficiency of each generator is determined by its losses. Figure 3.4 illustrates the power flow within a generator, with $P_{ag}$ the power across the air gap. The three basic types of losses in a generator are: core, copper and stray losses. In this section each of these types will be discussed.

![Power flow in a generator](image)

**Figure 3.4: Power flow in a generator**

### 3.2.1 Core losses

Core losses are magnetic losses that appear due to hysteresis and eddy currents flowing through the core. Hysteresis occurs in the core during magnetization and can be explained as the flux density lagging the magnetic intensity during a cycle of variation in the current $i$. Meaning that $B$ lags $H$ (Figure 3.5). The hysteresis loss $P_h$ is defined as the loss of power in the core due to the hysteresis effect:

$$P_h = K_h B_{max}^n f$$  \hfill (3.6)

- $K_h$ = constant depending on material and volume of the core
- $n$ = varies between 1.5 and 2.5
- $f$ = frequency of variation in $i$

![Hysteresis loop](image)

**Figure 3.5: Hysteresis loop**
Eddy currents occur when the flux density in the core changes rapidly. Because of the time-dependent flux, a voltage will be induced in the core. With this voltage a current will also flow, known as an eddy current. Because of the resistance of the core, this eddy current will lead to a power loss $P_e$ of:

$$P_e = K_e B_{\text{max}}^2 f^2$$  \hspace{1cm} (3.7)

$K_e$ = constant depending on material and lamination thickness

This eddy current loss will heat up the magnetic core. Reduction of the eddy current loss can be affected by the choice of magnetic material and by using a laminated core [19].

3.2.2 Copper losses

Copper losses occur in the form of heat in both armature and field windings. The power loss over the windings can be expressed as:

$$P_a = 3I_a^2 R_a$$

$$P_f = 3I_f^2 R_f$$  \hspace{1cm} (3.8)

Here the subscript $a$ is for armature winding and $f$ for field winding. Copper losses can be minimized by using windings with a low resistance, for example by enlarging the diameter of the wire. In case of permanent magnets, copper losses are limited because of the absence of field windings but not eliminated due to the windings on the stator [19].

3.2.3 Stray losses

Stray losses are energy losses that not directly relate to any of the above and are related to the construction of the generator. The stray losses are load-dependent and can be divided into magnetic and mechanical losses. An example of a magnetic stray loss is the interaction between magnetic fields in the generator (so-called armature reaction). Mechanical losses are losses due to the motion of moving components, for example friction and vibration [32].

3.3 Synchronous generator

As mentioned earlier, the field winding of a synchronous generator is located on the rotor. This field winding is an electromagnet which is fed with a current from the grid, $I_f$. This excitation current generates the magnetic field in the air gap. Figure 3.1 already showed the basic structure of a 3-phase synchronous generator. In synchronous generators the angular speed of the rotor and that of the magnetic field in the air gap are equal, i.e. no relative movement exists. This means that there is no so-called slip present in the system. Therefore, when connected directly to the grid any perturbation in the rotor speed will be transferred directly to the mechanical components, resulting in high dynamic loads. These loads can lead to early failure of the components. However, the rotor does slightly turn forward or back compared to its idle position when mechanical power is added or taken, respectively. The angle of displacement between the actual rotor position and idle is the load angle [12].
Synchronous generators can be divided into two types, the cylindrical-rotor and salient-pole generator. The first type is mainly used in high-speed applications, while the salient-pole is mostly used in low-speed generators. The main difference between these generators is that the cylindrical-rotor has one distributed winding and a uniform air gap, while the salient-pole generator has concentrated windings and a nonuniform air gap. A detailed description of both types can be found in Appendix B.1.

### 3.4 Induction generator

In induction generators, both armature and field windings are located on the stator (Figure 3.6). This in contrast to the synchronous generator configuration, where the field windings are located on the rotor. The rotor of an induction generator consists of a number of aluminum or copper bars which are electrically connected by aluminum end rings, also called a squirrel-cage. Both windings are supplied with a magnetizing current to generate and maintain magnetic flux in the air gap. This magnetizing current can be taken from the grid and since the grid has a constant frequency, the magnetic stator field rotates at a fixed speed, the synchronous speed.

![Figure 3.6: Basic structure of an induction generator](image)

Now, when the rotor rotates slightly above the synchronous speed, the rotating magnetic stator field moves relative to the rotor. This relative movement causes the magnetic flux to change in time and thus inducing an electromotive force (3.2). The induced emf reaches its maximum when the magnetic fields are 90° out of phase, meaning that the load angle equals 90°. Since the emf varies sinusoidally, the current resulting in the circuit is an alternating current. The amplitude of the emf can be increased by increasing the rotational speed, the strength of the magnetic field, the loop area or by increasing the number of loops [7, 25, 33].
The difference between the angular speed of the magnetic stator field and that of the rotor is defined as the slip. In generator mode the mechanical speed is higher than the synchronous speed, resulting in a negative value for the slip:

$$s = \frac{n_{\text{syn}} - n_{\text{mech}}}{n_{\text{syn}}} \quad (3.9)$$

The electrical efficiency of induction generators is a function of this slip. A higher percentage of absolute slip will decrease the efficiency, but at the same time lead to better damping of dynamic loads. Generators in the megawatt range have a slip percentage around $-1\%$ [12].

As an example, a 4-pole generator has a synchronous speed of 1500 rpm, for a slip of $-1\%$ peak power is produced at 1515 rpm (3.9). Because of this $-1\%$ slip, the generator is able to absorb some of the loads that act on the rotor during wind gusts. Unfortunately, the energy in such a wind gust is lost when absorbed by slip. However, slip does reduce the wear on the gearbox, making the generator slip one of the advantages of the use of an induction generator.

A disadvantage of the induction generator is the required reactive power. A higher reactive power will lead to a lower power factor (see Section 3.5), which has direct consequences to the power output as seen in (3.4).

### 3.5 Synchronous versus induction generators

Different generator systems are advantageous for different applications. Therefore, it is useful to determine a number of assessment criteria which can be used to choose the generator system that is best suited to be used in wind turbines [12].

**Reactive power**  
As mentioned in Section 3.4, reactive power costs energy and money. Therefore it is best to keep this reactive power as low as possible. In the case of synchronous generators, the reactive power can be controlled by increasing or decreasing the excitation voltage. In induction generators, reactive power from the grid is required to establish the magnetic stator field. This reactive power can be compensated for by adding capacitors [34].

**Synchronization to the grid**  
Synchronization of the generator to the grid is highly important concerning the quality of the power output and to prevent damage to the grid due to fluctuations in the output. In synchronous generators, the terminal voltage is controlled by the excitation voltage, while the frequency is determined by the speed of rotation. Though when the generator rating is small compared to the electric system to which it is connected, which is the case here, the terminal voltages will not change significantly when changing the excitation voltage. Because of these relations, synchronous generators would need some damping or speed elasticity in the driveline to obtain a high quality power output. In the case of induction generators, voltage and frequency are dictated by the utility grid. Additionally, generator slip improves the compatibility with the grid.

**Load absorption**  
The speed of the wind is an unpredictable parameter, causing variations in the rotor speed. When the generator is connected directly to the grid, the variations in the generator speed should be
minimized to prevent damage to the grid. Since the generator speed is prescribed by the electrical grid, any perturbations in the wind speed are collected in the rotor, resulting in high dynamic loads acting on the mechanical components. This problem exists in both synchronous and induction generators. However, in induction generators, part of these dynamic loads are eliminated due to the existing slip, resulting in better damping characteristics. The slip also makes induction generators more robust against disturbances. The entire problem can be solved by adding power electronics between the generator and the grid, which allows the generator to work at different input speeds and still deliver 50 Hz to the grid.

### Speed range

To obtain the highest efficiency in a wind energy conversion system, the turbine should operate completely wind-oriented. This means that the system runs with optimal efficiency at any wind speed. Though the generator slip in induction generators creates some speed elasticity, the maximum speed range that can be achieved is not sufficient for wind-oriented operation. Complete wind-oriented operation is generally achieved by adding power electronics. However, other possibilities are available as discussed in Section 2.4.

### Efficiency

Synchronous generators are slightly more efficient than induction generators. This difference is generally about 1%.

### Costs

Synchronous generators are generally cheaper than induction generators. However, additional requirements like control systems increase the application costs for synchronous generators. On the other hand, induction generators can deliver power back to the grid. Additional features like these make it hard to determine which application is more expensive. Another option is to use a low-speed generator, in that case the costs for a gearbox can be eliminated, but the costs for the generator itself increase significantly.

A summary of the advantages and disadvantages of the synchronous and induction generator can be found in Table 3.1 and 3.2, respectively [35, 36, 37].

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>power factor control</td>
<td>high dynamic loads</td>
<td>better synchronization</td>
<td>low power factor</td>
</tr>
<tr>
<td>efficiency costs</td>
<td></td>
<td>more robust</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1: Synchronous generator

Table 3.2: Induction generator

The choice between using a synchronous or induction generator when obtaining variable-speed operation through a continuously variable transmission is made based on the information above. The main interests when looking at wind turbines are the efficiency and load absorption. In terms of efficiency, synchronous generator have an advantage. In a CVT controlled wind turbine, load absorption is performed by the CVT which is located in front of the generator, not by power electronics after the generator. Therefore, load absorption in the generator is not important for this application. The same is true for synchronization and robustness. Now looking at Tables 3.1
and 3.2, the advantages relevant for wind turbines equipped with a CVT are efficiency and costs. These aspects are in favor of the synchronous generator, making this the best choice for the CVT controlled wind turbine.

In current wind energy conversion systems induction generators are used more often than synchronous generators. The reason for this is that an induction generator allows a certain percentage of slip on the input shaft. This slip is used to allow both the rotor and input shaft of the generator to rotate at a variable speed, creating the energetic and load absorbing advantages of variable speed operation. However, power electronics are required to obtain a constant frequency current. In the wind turbines discussed in Section 2.4, synchronous generators are used because a constant input speed can be provided, eliminating the need for power electronics, and still dynamic loads can be limited.
Chapter 4

Continuously Variable Transmission

A continuously variable transmission (CVT) is a transmission that is able to shift between an infinite number of ratios between the upper and lower ratio. CVT’s are mainly used in passenger cars, providing a better fuel economy and a more comfortable driving experience. However, many other applications for CVT’s exist. This chapter will elaborate on the working principle of the GCI chain-CVT, the control system and the potential use of a CVT in a wind turbine.

4.1 GCI chain-CVT

The continuously variable transmission developed by Gear Chain Industrial B.V. basically consists of two pulleys and a chain. Each pulley consists of two conical discs, one of these is fixed to a shaft while the other one can move in axial direction. The movable discs are located crosswise of each other. The chain is running between the two pulleys. This configuration is shown in Figure 4.1.

The movable discs are connected to hydraulic cylinders, which supply the required clamping force to control the ratio and prevent the chain from slipping too much. By increasing the pressure of the primary hydraulic cylinder $P_p$, the clamping force on the primary movable disc $F_p$ is increased, causing the disc to move in axial direction towards the opposite disc. By shifting these discs closer to each other, the running radius of the chain at the primary side is increased, resulting in a higher ratio. The geometric ratio of the CVT is defined as:

$$ r_g = \frac{R_p}{R_s} $$  \hspace{1cm} (4.1)

$R_p$ = primary running radius [m]  
$R_s$ = secondary running radius [m]

The chain is running between the two pulleys based on friction and since both the chain and pulleys are made of metal, metal-to-metal contacts exist. Because of these contacts the chain must be lubricated at all times to function properly. The lubrication oil has two functions; lubricate the contact points and act as a coolant.
The ratio range of a CVT is defined as the range between the maximum possible ratio and the minimum:

\[
\text{range} = \frac{r_{g_{\text{max}}}}{r_{g_{\text{min}}}}
\]  

(4.2)

The ratio range of the GCI chain-CVT can be as high as 8. The ratio range and desired load capacity are the main parameters to determine the required size of the CVT. Table 4.1 shows the dimensions of a GCI chain-CVT for different maximum levels of loading at a secondary pulley speed of 1500 rpm.

<table>
<thead>
<tr>
<th>(T_{\text{cvt, max}} ) [Nm]</th>
<th>Power [kW]</th>
<th>Range</th>
<th>Width [mm]</th>
<th>Length [mm]</th>
<th>(R_{\text{min}} ) [mm]</th>
<th>(R_{\text{max}} ) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000</td>
<td>1600</td>
<td>4</td>
<td>103</td>
<td>2282</td>
<td>128</td>
<td>257</td>
</tr>
<tr>
<td>10000</td>
<td>2500</td>
<td>2.5</td>
<td>130</td>
<td>2362</td>
<td>162</td>
<td>256</td>
</tr>
<tr>
<td>20000</td>
<td>3900</td>
<td>1.5</td>
<td>163</td>
<td>2422</td>
<td>204</td>
<td>249</td>
</tr>
</tbody>
</table>

Table 4.1: Typical dimensions of a CGI chain-CVT for different maximum loads

An important feature of the GCI chain is the possibility to scale the load significantly. This is because of minimal internal heat generation, which is a result of the open structure of the chain. Therefore, CVT’s up to 5+ MW can be build. Other advantages of the GCI chain-CVT are [38, 39, 40]:

- High load capacity (5+ MW)
- High load density (high specific power per unit of mass and per unit of volume)
4.1. GCI CHAIN-CVT

- High mechanical efficiency (96%)
- Low specific mass, allowing high chain speeds (max 40 m/s)
- Sturdiness against overload, mistreatment and pulley misalignment

4.1.1 Dimensions of a CVT for MW wind turbines

The dimensions of a CVT for wind turbines in the MW range are dependent on a number of parameters. These parameters are; the range and output speed $\omega_g$ of the CVT, the maximum rotor torque $T_{in,max}$ and the ratio of the fixed gearbox $i_{total}$ located in front of the CVT. From these parameters, the maximum input torque $T_{cvt,max}$ and nominal input power $P_{cvt,nom}$ for the CVT are determined according to:

$$T_{cvt,max} = S_f \left(\frac{T_{in,max}}{i_{total}}\right)$$
$$P_{cvt,nom} = \omega_{rs,\text{max}} \left(\frac{T_{in,max}}{i_{total}}\right)$$

Where $S_f$ is a safety factor of 2.5 and

$$\omega_{rs,\text{max}} = \omega_g \sqrt{\text{range}}$$

From a reference chain and $T_{cvt,max}$ and $P_{cvt,nom}$, a scaling factor is determined. This scaling factor determines the required dimensions of the CVT according to a reference chain. The relations used for scaling the CVT can be found in Appendix C.1.

Table 4.2 shows the influence of the fixed gearbox ratio on the speed range of the wind turbine and the wind speed at which maximum power can be produced. The range of the CVT is assumed to be 3 to create a maximum speed range of the rotor. This table clearly shows the influence of the fixed ratio on the speed range of the turbine. Increasing the fixed ratio shifts the range of wind speeds for which optimal $\lambda$ can be followed to a higher level. Assume for example that the rated wind speed is 13 m/s. When choosing the fixed ratio at 132, the turbine will not be able to follow the optimal operating line for wind speeds from 10.6 m/s up to the rated 13 m/s. Since the energy in the wind scales with the third power of the wind speed, this will lead to a large energy loss in this region. By decreasing the fixed ratio to 110, the turbine can operate at optimal rotor speed up to 12.8 m/s. It is true that the turbine will not start operating optimally until a wind speed of 4.3 m/s is reached instead of the 3.6 m/s in the previous example, but the amount of energy present in low wind speeds is much lower than in high wind speeds. However, decreasing the fixed ratio to 100 will not result in a significantly higher energy capture because there is no use for the turbine to operate at optimal $\lambda$ for wind speeds above rated. Above rated the energy capture should be limited instead of optimized.

Another issue in increasing the fixed ratio is that the maximum rotor speed increases. However, the maximum allowed rotor speed is limited by the amount of noise that is produced by the rotating rotor blades. Aerodynamic noise emission increases at higher tip speed ratios. Because the tip speed ratio depends on the rotor speed according to (2.2), a smaller fixed ratio results in an higher tip speed ratio and therefore a higher Sound Pressure Level, which is the most important parameter describing the overall acoustic noise intensity at a specific location [12]. Taking into account noise production, maximization of energy capture and assuming a rated wind speed of
about 12 m/s, a fixed ratio of 1 : 121 is chosen for a 2 MW wind turbine. Extensive research on
the combination of fixed gear ratio and CVT ratio is recommended to obtain the optimal config-
uration.

Next, the effect of changing the fixed ratio and range of the CVT on the parameters of the CVT
is investigated. As can be seen in Table 4.3, the maximum input torque for the CVT $T_{cvt,max}$ is
restricted by the fixed ratio and the range. Another limitation is the maximum chain speed of 40
m/s. The torque capacity of the CVT can be increased by decreasing the range. A smaller range
of the CVT will lead to a smaller speed range of the wind turbine, which may not be desired. It
also increases the scaling factor and the dimensions of the CVT. The relations to determine the
dimensions of the CVT can be found in Appendix C.2.

<table>
<thead>
<tr>
<th>$i_1 \times i_2$</th>
<th>$i_{total}$</th>
<th>$v_{w,\text{rated}}$ [m/s]</th>
<th>rotor speed [rpm]</th>
<th>$\lambda_{opt}$ range [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 × 12</td>
<td>132</td>
<td>12.9</td>
<td>6.6 – 19.7</td>
<td>3.6 – 10.6</td>
</tr>
<tr>
<td>11 × 11</td>
<td>121</td>
<td>12.4</td>
<td>7.2 – 21.5</td>
<td>3.9 – 11.6</td>
</tr>
<tr>
<td>11 × 10</td>
<td>110</td>
<td>11.8</td>
<td>7.9 – 23.6</td>
<td>4.3 – 12.8</td>
</tr>
<tr>
<td>10 × 10</td>
<td>100</td>
<td>11.3</td>
<td>8.7 – 26.0</td>
<td>4.7 – 14.0</td>
</tr>
</tbody>
</table>

Table 4.2: Influence of the fixed gear ratio on wind turbine performance

Keeping in mind the desired torque capacity and speed range of the wind turbine, the gearbox
will consist of two gear sets each with a fixed ratio of 1 : 11, resulting in a total ratio of 1 : 121. The
range of the CVT is assumed to be 3. These design choices result in the following dimensions
and characteristics of the GCI chain-CVT:

- chain width = 117 mm
- min. running radius = 146 mm
- max. running radius = 254 mm
- center distance of the pulleys = 509 mm
- max. chain speed = 39.8 m/s
- Length of the chain = 2298 mm
- max. input torque = 18595 Nm

Table 4.3: Influence of scaling on the chain width and maximum torque

The scaling rules that have been applied here are based on the scaling rules used in the automo-
tive industry. However, the maximum torque and maximum chain speed situation is different for
wind turbines. In the automotive industry, maximum torque occurs when driving in first gear,
which is equivalent to an underdrive situation. The maximum chain speed is reached when the
car is driving at maximum speed, in this situation the CVT is in overdrive. Both situations are de-
4.2 Potential of a CVT in Wind Turbines

The goal of this project is to investigate the feasibility of implementing a CVT in a wind turbine, more specific the GCI chain-CVT. Previous research on the potential of a CVT in wind turbines can be found in [4, 5, 41]. The main advantage of implementing a CVT in a wind turbine is that it eliminates the use of power electronics. As mentioned in Chapter 2.3, current variable speed systems produce power with a variable frequency. This power needs to be converted to power with a constant frequency to be able to deliver the power to the electrical grid. The required frequency is dependent on the location of the wind turbine (Europe 50 Hz, US 60 Hz). The efficiency of a converter is estimated at 96% at rated power and dropping drastically at wind speeds below rated. Appendix D shows some examples of the efficiency of power converters used in wind turbines. With a CVT in the driveline, the angular speed of the input shaft of the generator can be kept constant while the wind speed is fluctuating, due to the possibility to continuously change the ratio of the CVT. This eliminates the need for power electronics.

Another advantage is that the range of variable speed can be increased, meaning that variable speed operation can start at a lower wind speed. The system can than operate at optimal tip speed ratio over a wider range of wind speeds, increasing the total energy capture. The gain in energy production is dependent on the chosen range of the CVT. There is not too much energy to win at these low speeds, but it can increase the annual energy yield by approximately 0.5% [4]. Table 4.4 shows some parameters of a number of existing multi-megawatt turbines. The cut-in wind speed and speed range are responsible for the tip speed ratio at the cut-in wind speed \( \lambda_{cut-in} \) and the wind speed from which the optimal lambda can be followed, \( v_w \) for \( \lambda_{opt} \). In the determination of \( \lambda_{cut-in} \) and \( v_w \) for \( \lambda_{opt} \) the assumption is made that all turbines have an optimal \( \lambda \) of 7.75. In
reality this optimal $\lambda$ is a result of the rotor design and therefore differs per wind turbine but stays around 7.5. Furthermore, the turbines DeWind D8.2, Wikov W2000 and Vestas V80 have been discussed earlier in Section 2.4. The first two incorporate some kind of variable transmission while Vestas uses its OptiSpeed® system.

As an example, the Vestas turbine has an operating speed range of $9 - 19$ rpm and a cut-in speed of $4 \text{ m/s}$. The tip speed ratio of this turbine at cut-in speed can be calculated by equation (2.2), resulting in a tip speed ratio of approximately 9.4. By increasing the range of the gear ratio, the operating speed range is expanded and $\lambda$ at cut-in speed can be lowered. For example, when the operating range is expanded to $8 - 19$ rpm with the same cut-in speed of $4 \text{ m/s}$, the tip speed ratio at cut-in speed is lowered to 8.4. The minimum wind speed for which it is possible to obtain the optimal tip speed ratio is lowered when expanding the speed range downwards, so decreasing the minimum rotor speed. In the case mentioned above, this wind speed decreases from $4.9 \text{ m/s}$ to $4.3 \text{ m/s}$. For this example, the effect of changing the operating range on the power output is shown in Figure 4.3.

<table>
<thead>
<tr>
<th>Turbine type</th>
<th>$P_{\text{rated}}$ [MW]</th>
<th>DxH [m]</th>
<th>$v_w$ cut-in [m/s]</th>
<th>Speed range [rpm]</th>
<th>$\lambda_{\text{cut-in}}$ [-]</th>
<th>$v_w$ for $\lambda_{\text{opt}}$ [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DeWind D8.2</td>
<td>2.0</td>
<td>80 x 80</td>
<td>3</td>
<td>11.1 - 20.7</td>
<td>15.5</td>
<td>6.0</td>
</tr>
<tr>
<td>Wikov W2000</td>
<td>2.0</td>
<td>80 x 78</td>
<td>3.5</td>
<td>12 - 19</td>
<td>14.4</td>
<td>6.5</td>
</tr>
<tr>
<td>Vestas V80</td>
<td>2.0</td>
<td>80 x 78</td>
<td>4</td>
<td>9 - 19</td>
<td>9.4</td>
<td>4.9</td>
</tr>
<tr>
<td>Gamesa G80</td>
<td>2.0</td>
<td>80 x 78</td>
<td>4</td>
<td>9 - 19</td>
<td>9.4</td>
<td>4.9</td>
</tr>
<tr>
<td>Suzlon S88</td>
<td>2.1</td>
<td>88 x 80</td>
<td>4</td>
<td>15.3 - 18.3</td>
<td>17.6</td>
<td>9.1</td>
</tr>
<tr>
<td>Nordex N80</td>
<td>2.5</td>
<td>80 x 80</td>
<td>3</td>
<td>10.9 - 19.1</td>
<td>15.2</td>
<td>5.9</td>
</tr>
<tr>
<td>GE energy</td>
<td>3.6</td>
<td>104 x ..</td>
<td>3.5</td>
<td>8.5 - 15.3</td>
<td>13.2</td>
<td>6.0</td>
</tr>
<tr>
<td>Acciona AW-3000</td>
<td>3.0</td>
<td>100 x 98.2</td>
<td>4</td>
<td>10 - 17.1</td>
<td>13.1</td>
<td>6.8</td>
</tr>
<tr>
<td>REpower 5M</td>
<td>5.0</td>
<td>126 x 100</td>
<td>3.5</td>
<td>6.9 - 12.1</td>
<td>13</td>
<td>5.9</td>
</tr>
<tr>
<td>GCI chain-CVT</td>
<td>2.0</td>
<td>80 x ..</td>
<td>3.6</td>
<td>7.2 - 21.5</td>
<td>7.9</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Table 4.4: Technical data for various wind turbines

Figure 4.3: a) rotational speed and b) power curve versus wind speed
Finally, variable speed operation can be obtained with efficient synchronous generators. Without a CVT, slip in the generator is of vital importance to be able to obtain variable speed operation. Therefore, induction generators are used which are about 0.5% less efficient than synchronous generators, when operating at −1% slip. Increasing the absolute slip to obtain a wider range of operating speeds, decreases the efficiency of the generator even more [12].

An additional advantage of variable speed operation by using a CVT is that this technology can also be used in the United States without paying license fees. At the moment, variable speed operation by means of power electronics is patented in the US. The patent is owned by GE Wind Energy [8].

4.3 Conclusion

To summarize, a CVT controlled system has the following advantages compared to existing variable speed wind turbines with power electronics:

- wider speed range (increased energy capture)
- elimination of power electronics
- use of synchronous generator (higher efficiency)
- variable speed concept that can be used in the United States, without paying license fees
Chapter 5

Modeling

A wind energy conversion system can be divided into five main blocks. First of all the velocity of the wind should be modeled, taking into account turbulence, tower interference, wind gusts, etc. Secondly, this wind speed is converted to a mechanical torque acting on the rotor of the wind turbine. The third block consists of the drivetrain components, this is where a planetary gearbox and continuously variable transmission are modeled. The fourth block represents the synchronous generator, which is responsible for the conversion from mechanical to electrical energy. Finally, the generator is connected to the electrical grid, to which the power is delivered and transported to customers [42, 43]. In this chapter the structure of each component in the model of the wind energy conversion system will be discussed.

5.1 Wind model

The velocity of the wind is modeled using the model ‘Wind Model SB-1’ from the Wind Turbine Blockset in Matlab/Simulink®, which has been developed at RISØ National Laboratory [44]. The wind speed is calculated as an average value of the fixed-point wind speed over the whole rotor, taking into account the tower shadow and rotational turbulences. The chosen model is based on the Kaimal spectrum, for which three spatial wind components are created; longitudinal, vertical and lateral wind speed. The Kaimal spectrum implies a relatively low terrain roughness. It only applies for neutral conditions (strong winds) because convection is not accounted for. However, these conditions are met in a large number of applications. The Kaimal spectrum is widely used due to its simple expression [45, 46].

In the model a normally distributed white noise generator, the Kaimal spectrum and harmonic filtering are responsible for the variation in one spatial component of the wind speed. The block diagram of the model can be found in Appendix E.1. In the wind model it is possible to adjust several parameters. These parameters are: rotor diameter, average wind speed, turbulence length scale, turbulence intensity and sample time. The rotor diameter is a given parameter. The average wind speed can be set to investigate the behavior at different levels of loading. The turbulence length scale depends on the surface roughness and the tower height and is typically set at 600 m. The turbulence intensity can be varied to create larger wind gusts. This parameter is used to set the amplitude of the wind gusts. The time interval in which the wind speed changes can be set with the sample time. A short sample time will result in a higher frequency of the fluctuations in the wind speed. The sample rate is generally at least 1 Hz [15].
5.2 Rotor model

The rotor model is based on the theory explained in Section 2.2. The rotor extracts power from the wind and this power is converted to a torque acting on the rotor shaft according to (2.4). The rotor power coefficient $C_p$ in this equation is a function of the tip speed ratio $\lambda$, while $\lambda$ depends on the rotor speed and wind speed $\lambda(\omega_r, v_w)$. The $C_p-\lambda$ curve used in this model can be found in Figure 2.2. The flow dynamics in the wind are assumed to be negligible [12]. The mechanical torque resulting from this model is used as an input for the drivetrain model. The block diagram of the rotor model can be found in Appendix E.2.

5.3 Drivetrain model

The drivetrain model consists of three main parts; the first gear set, the second gear set and the CVT. The fixed gear sets are simply modeled as a fixed ratio, $i_1$ and $i_2$ respectively. Both gear sets are modeled with a constant efficiency ($\eta_1$, $\eta_2$) of 99%, assuming that planetary gears are used. Damping and dependency of the efficiency on the level of loading are neglected. This is done because the main objective of the project is to determine the feasibility of controlling the wind turbine using a CVT, the exact behavior of the fixed gear sets is therefore not required. However, for further research it is desired to model the gear sets more accurately to be able to assess the dynamic loading in these gear sets. The ratio of the fixed gear sets is determined by the desired operating speed range and the available range for the CVT. Both the ratio for the fixed gear sets and the range of the CVT have already been discussed in Section 4.1.1. The fixed ratio is set at 1 : 121 and the range of the CVT is 3.

Figure 5.1: Schematic setup of a CVT

In the model of the CVT, the rotating shafts are assumed to be rigid, as well as the chain itself. A schematic setup of the CVT is shown in Figure 5.1. The primary side of the CVT is connected via the fixed gearbox to the rotor. Because of the assumption that the rotating shafts and chain are rigid, the inertia felt by the primary side of the CVT is equal to $J_{rs} = J_r/(i_1^2 i_2^2)$, where $J_r$ is defined as the inertia of the rotor. The rotor torque is also directed through the fixed gearbox, resulting in a converted rotor torque $T_{rs}$ acting on the CVT of $T_{rs} = T_r/(i_1 i_2) (\eta_1 \eta_2)$, where the subscript $rs$ stands for 'rotor secondary'. The same is true for the angular speed of the input shaft of the CVT, $\omega_{rs} = \omega_r i_1 i_2$. Correspondingly, the inertia at the secondary side of the CVT is equal
5.3. DRIVETRAIN MODEL

to the inertia of the generator \( J_g \) and the torque \( T_g \) is the resulting torque of the generator. The primary and secondary shaft have one rotational degree of freedom, together with the variable transmission ratio, this results in a third order system. The dynamics of the CVT are shown in the free body diagrams in Figure 5.2. The equations of motion of this system are given by:

\[
\begin{align*}
J_{rs} \dot{\omega}_{rs} &= T_{rs} - T_p \\
J_g \dot{\omega}_g &= T_s - T_g \\
r_g &= \kappa_{cmm}(r_g, [F_s]) \dot{\omega}_p (\ln \frac{F_p}{F_s} - \ln \Psi)
\end{align*}
\]

(5.1)

\( J_{rs} \) = converted rotor inertia \([\text{kgm}^2]\)  \( r_g \) = geometric ratio [-]
\( J_g \) = generator inertia \([\text{kgm}^2]\)  \( \kappa_{cmm} \) = function of \( r_g \) and \( F_s \) [-]
\( T_{rs} \) = converted rotor torque \([\text{Nm}]\)  \( \omega_{rs} \) = angular speed of the primary pulley \([\text{rad/s}]\)
\( T_p \) = primary torque \([\text{Nm}]\)  \( F_p \) = primary clamping force \([\text{N}]\)
\( T_s \) = secondary torque \([\text{Nm}]\)  \( F_s \) = secondary clamping force \([\text{N}]\)
\( T_g \) = generator torque \([\text{Nm}]\)  \( \Psi \) = clamping force ratio at \( \dot{r} = 0 \) [-]

\( \dot{\omega}_p \) = angular speed of the primary pulley \([\text{rad/s}]\)
\( \ln \) = natural logarithm

Figure 5.2: Free body diagram of the CVT

The third differential equation represents the rate of change of the geometric ratio. In this case, the Carbone Mangialardi Mantriota (CMM) model is used to describe the shifting speed of the variator. This model assumes that the shifting speed of the variator should be approximately linear with the logarithm of the clamping force quotient \( F_p/F_s \). As can be seen from (5.1), the primary and secondary clamping forces determine the shifting speed of the CVT. Therefore, these are the input variables for the ratio control of the CVT. The clamping force ratios for which the variator does not shift are assumed to be independent of the scaling factor. The outputs of the CMM model are the primary pulley radius \( R_p \) and the geometric ratio \( r_g \). To simplify the model, the parameter \( \kappa_{cmm} \) is assumed to be constant, \( \kappa_{cmm} = 0.001 \) [47, 48].
From the first equation of motion in (5.1) it can be seen that the primary pulley speed $\omega_{rs}$, and therefore the rotor speed $\omega_r$, can be adjusted by controlling the difference between the input torque of the rotor $T_{rs}$ and the primary torque in the CVT $T_p$. For the wind turbine application, a hydraulically actuated CVT is used. In that case, the primary torque in the CVT is a function of the secondary clamping force, the primary radius and the traction coefficient:

$$T_p = 2\mu(\nu) \min(F_p, F_s) R_p(r_g)$$

(5.2)

\[\begin{array}{ll}
\mu & \text{traction coefficient [-]} \\
R_p & \text{primary pulley radius [m]}
\end{array}\]

The traction coefficient $\mu$ is a function of the percentage of slip present in the CVT. The relation between traction $\mu$ and slip $\nu$ is given in a traction curve (Figure 5.3). This curve is dependent on the ratio of the CVT $r_g$ and the amount of slip $\nu$. In the model, these traction curves can be found in a lookup-table. The assumption is made that the traction curves will not be influenced by scaling. The ratio is given by the CMM model and the slip is calculated according to:

$$\nu = 1 - \frac{r_s}{r_g}$$

(5.3)

\[\begin{array}{ll}
r_s & \text{speed ratio [-]} \\
r_g & \text{geometric ratio [-]}
\end{array}\]

This expression of slip describes the relative motion between the pulleys and the belt and is therefore called relative slip. The traction curve in Figure 5.3 shows that the traction increases to a maximum value when slip increases. Also, traction is zero when there is no slip. Equation (5.2) shows that the primary torque is zero when the traction coefficient is zero, therefore it can be concluded that slip must be present to transmit torque [48].
Knowing the primary torque and the opposing rotor torque, the acceleration or deceleration of the primary pulley is determined by:

$$\omega_{rs} = \frac{1}{J_{rs}} \int (T_{rs} - T_p) dt \quad (5.4)$$

The angular speed of the primary pulley is transmitted through the 2-step gearbox, resulting in a rotor speed $$\omega_r = \omega_{rs}/(i_1 i_2)$$. Neglecting all inertia effects of the chain, the torque transmitted to the generator is defined by:

$$T_s = \left(\frac{T_p}{r_g}\eta_{cvt}\right) \quad (5.5)$$

$$\eta_{cvt} = \text{efficiency of the CVT} \ [\%]$$

An assumption is made about the efficiency of the CVT related to the level of loading and the ratio in which the CVT is running. This assumption is based on measurements that are done on a small GCI-chain (chain width 30 mm). Appendix F elaborates on how the efficiency is estimated. Finally, the second equation in (5.1) will be used during the modeling of the generator. The block diagrams used in the modeling of the drivetrain can be found in Appendix E.3.

### 5.4 Generator model

The heart of the wind energy conversion system is the generator. The model of the generator is based on the knowledge from Chapter 3. Basically, the generator model consists of two main parts, the mechanical part and the electrical part (Figure 5.4). Both parts will be discussed in detail.

![Block diagram of the generator model](image)

**Figure 5.4:** Block diagram of the generator model

The model of the mechanical part of the generator has two inputs and one output. The inputs are the mechanical torque from the CVT $$T_s$$ and the electromagnetic torque created by the generator $$T_g$$. The output is the angular speed of the input shaft of the generator $$\omega_g$$. This output is obtained from the second equation of motion of the CVT:

$$\omega_g = \frac{1}{J_g} \int (T_s - T_g) dt \quad (5.6)$$
\( \omega_g \) = angular speed of the generator shaft [rad/s]
\( J_g \) = generator inertia [kgm^2]
\( T_s \) = mechanical torque from the drivetrain [Nm]
\( T_g \) = generator torque [Nm]

The model of the electrical part of the generator has three inputs and three outputs. The inputs are the angular speed of the generator shaft \( \omega_g \), the field voltage \( v_F \) and the three-phase net voltage \( v_a, v_b, v_c \). The outputs are defined as the electromagnetic torque \( T_g \), the load angle \( \delta \) and the electrical power output \( P_e \). The voltages on the stator of the generator are called the terminal voltages. These voltages are defined in matrix form as:

\[
\begin{bmatrix}
v_a \\
v_b \\
v_c \\
-v_F \\
0
\end{bmatrix} = \begin{bmatrix}
r_a & 0 & 0 & 0 & 0 \\
0 & r_b & 0 & 0 & 0 \\
0 & 0 & r_c & 0 & 0 \\
0 & 0 & 0 & r_F & 0 \\
0 & 0 & 0 & 0 & r_D
\end{bmatrix} \begin{bmatrix}
i_a \\
i_b \\
i_c \\
i_F \\
i_D
\end{bmatrix} + \begin{bmatrix}
\dot{\lambda}_a \\
\dot{\lambda}_b \\
\dot{\lambda}_c \\
\dot{\lambda}_F \\
\dot{\lambda}_D \\
\end{bmatrix} + \begin{bmatrix}
v_n \\
0
\end{bmatrix} \tag{5.7}
\]

\( r_i \) = resistance in winding \( i \) [\( \Omega \)]
\( \dot{\lambda}_i \) = flux linkage in winding \( i \) [Wb-turns]

Note that the stator currents are assumed to have a positive direction flowing out of the machine since the machine is a generator. As can be seen from this equation, the voltage equations are complicated by the presence of time-varying flux-linkage terms, \( \dot{\lambda}_i \). Flux-linkage is a measure of the linkage of one inductor to another expressed in Wb-turns [27]. These time-varying terms can be eliminated by transforming the rotating stator frame to a rotating reference frame located on the rotor. Therefore the stator variables are projected on three axes; one along the direct axis of the field winding (direct axis, \( d \)), one along the neutral axis of the field winding (quadrature axis, \( q \)) and one on a stationary axis (\( 0 \)). Meaning that the \( abc \)-frame of the stator is transformed to the \( dq0 \)-frame of the rotor (Figure 5.5). This so-called Park transformation is explained in Appendix G [27, 49, 50].

![Figure 5.5: abc and dq frame in a synchronous generator](image-url)
The transformation results in a nonlinear state-space system:

\[ L \dot{i} = -R(\omega_g)i - Bu \]  

\( L \) = inductance matrix  
\( R \) = resistance matrix  
\( B \) = input matrix  
\( i \) = state vector  
\( u \) = input vector  

This state-space system is nonlinear because the resistance matrix is depending on the generator frequency \( \omega_g \). The state-space system is implemented in the model, resulting in currents that are delivered by the generator to the electrical grid. The Matlab m-file that is used to determine these equations is presented in Appendix H. The parameters relevant to model the generator are given in Appendix F. The outputs of the model are the electromechanical torque \( T_g \) and the generated electrical power \( P_e \) given by:

\[ T_g = \frac{p}{2} \left[ (L_d - L_q)i_d i_q + L_m (i_{fd} + i_{fD})i_q - L_m q i_d i_Q \right] \]  
\( P_e = i_d v_d + i_q v_q \)

In the modeling of the generator, the losses that are induced by the excitation voltage \( v_F \) are not included. The block diagram of the electrical part of the generator can be found in Appendix E.4.

5.5 Electrical grid

The electrical grid is modeled as an infinite inertia which prescribes the required frequency of the current delivered by the generator. As mentioned earlier, the electrical grid in Europe requires a constant frequency of 50 Hz, while in the United States a frequency of 60 Hz is required. The terminal voltage of a generator connected to the grid is a 3-phase voltage. In this case, the three phase voltages \( (v_a, v_b, v_c) \) have a frequency of 50 Hz with an amplitude of 4 kV (Figure 5.6).

![3-phase terminal voltage](image)

Figure 5.6: 3-phase terminal voltage at 4 kV

At first the grid frequency is assumed to be constant at all times. However, in real life the net frequency fluctuates slightly. It is recommended to investigate the effect of such voltage spikes on the stability of the system.
Chapter 6

Control

6.1 Control objectives

When designing a control strategy for a wind turbine, it is important to keep in mind the goals that should be achieved by the control system. These goals are called the control objectives. In general, the control objectives for wind turbine control strategies are [15, 51]:

1. maximizing energy production
2. minimizing operation and maintenance costs by limiting aerodynamic loads
3. ensuring safe turbine operation

The latter objective is mainly applicable to wind speeds above rated, region 3 in Figure 2.3. Safe turbine operation is then ensured by limiting the angular speed of the rotor shaft and by constraining the operating range of the turbine to a maximum wind speed of 25 m/s. This maximum is determined by the noise level produced by the rotating blades, which is related to the ratio between $\lambda$ and $v_w$, and the forces acting on the blades, tower, etc [52]. In this case only the region 2 speed range is of interest and therefore this objective is not applicable to the control strategy. Maximizing energy production can be achieved by obtaining the optimal tip speed ratio for each wind speed. Operation and maintenance costs can be minimized by limiting the dynamic loads acting on the mechanical components. This can be done by, for example, capturing wind gusts in the inertia of the rotor.

The importance of each objective depends on the operating point of the wind turbine. From the cut-in speed to the rated wind speed, region 2, energy production should be maximized while also monitoring the dynamic loads on the mechanical components. This is the region where CVT control comes in and for which a control scheme is designed. In most of today’s wind turbines, the objectives for region 2 wind speeds are reached by controlling the generator torque. The performance of the CVT control will be measured against the performance of this conventional generator torque control. The goal is to show that with a CVT the same, or even better, results can be achieved as with the conventional control, in terms of energy capture and limiting dynamic loads. Note that this project focuses on the feasibility of a CVT controlled wind turbine and not yet on the optimal control strategy for the CVT. For this reason the control system that will be discussed in this chapter is not necessarily the optimal control.
CHAPTER 6. CONTROL

The actual control of the CVT is affected by a servo hydraulic actuation system. This system consists of two pumps, one pressure pump and one ratio pump, and two servomotors. The pressure pump pressurizes oil in the secondary pulley cylinder, providing clamping force and preventing chain slip. The ratio pump is responsible for the ratio change of the variator. Therefore, oil is displaced from the secondary cylinder to the primary, or vice versa. The modeling of this servo hydraulic control system is left out in this thesis. As a result, the inputs for the ratio control in the model are the required clamping forces to obtain the desired ratio or ratio change [39, 40].

6.2 Setpoint strategy

The setpoint for the CVT ratio determines for a large part whether the control objectives will be fulfilled. The ratio setpoint is designed in a such a way that the resulting energy capture and dynamic loading are at least equivalent but preferably better than that obtained with conventional generator torque control. Therefore, first the conventional generator torque control is explained, after which a control system for the CVT is developed. Both control strategies are valid for the region 2 operating mode.

6.2.1 Generator torque control

In conventional variable speed wind turbines, the variable speed operation in region 2 is obtained by controlling the generator torque. A conventional way to control the generator torque is by using the power electronics that connect the generator to the grid. With these power electronics it is possible to rapidly set the generator torque at almost any desired value, because the power electronics determine the frequency and phase of the current flowing from the generator [15]. The conventional region 2 generator torque control law for variable speed turbines is given by:

\[
T_c = k \omega_r^2 \frac{C_p \lambda^3}{\lambda_{opt}^3}
\]

\[
k = \frac{1}{2} \rho AR^3 \frac{C_{p_{max}}}{\lambda_{opt}^3}
\]

(6.1)

This control law is designed to keep the turbine operating near the optimal tip speed ratio \(\lambda\), to maximize the energy capture. However, during wind gusts the optimal \(\lambda\) will not be followed exactly but the rotor will decelerate or accelerate according to the strength of the wind gust. Implementing (6.1) in the mechanical relation between torque and angular acceleration of a simple rigid body model of a wind turbine

\[
\dot{\omega}_r = \frac{1}{J_r} (T_r - T_c)
\]

(6.2)

results in the following expression:

\[
\dot{\omega}_r = \frac{1}{2J_r} \rho AR^3 \omega_r^2 \left( \frac{C_p}{\lambda^3} - \frac{C_{p_{max}}}{\lambda_{opt}^3} \right)
\]

(6.3)

Because all terms outside the brackets are nonnegative, the sign of \(\dot{\omega}_r\) depends on the sign of the difference within the brackets. Since by definition \(C_p \leq C_{p_{max}}\), the rotor will decelerate when the actual \(\lambda > \lambda_{opt}\). On the contrary, the rotor will accelerate when \(\lambda \leq \lambda_{opt}\) and \(C_p \geq \frac{C_{p_{max}}}{\lambda_{opt}^3} \lambda^3\).
From (6.2) it can be seen that by controlling the generator torque $T_c$, the angular speed of the rotor can be controlled. By controlling $\omega_r$, the optimal tip speed ratio can be obtained, while at the same time wind gusts are partially captured in the inertia of the rotor to limit the dynamic loads in the drivetrain [53].

A model of the generator torque control is developed in Matlab/Simulink®. This model is based on the parameters from the 'Gamesa G80-2.0MW' wind turbine. This turbine is chosen because of its wide speed range, 3 – 19 rpm, obtained by controlling the generator torque. The Gamesa G80-2.0MW is equipped with a gearbox consisting of one planetary stage and 2 parallel stages, together responsible for a ratio of 1 : 100.5. Additional information on this specific turbine can be found in [13]. A simulation is performed with the generator torque control implemented in this model. The wind profile used in this simulation consists of primarily low wind speeds. This profile is chosen because this is the region where it is expected that the CVT control will capture more energy due to its wider speed range. The turbulence in the wind block is set to 10%, resulting in high wind gusts. The wind profile is shown in Figure 6.1. For this profile, the conventional torque control leads to a torque level acting on the rotor as presented in Figure 6.2a. The generated power is shown in Figure 6.2b. Finally, Figure 6.3 shows the rotor speed when following optimal $\lambda$ at all times and the actual rotor speed. From this figure the limitation of the minimum rotor speed becomes obvious.

![Wind profile](image)

**Figure 6.1: Simulated wind profile**

Besides the increased power capture and limitation of dynamic loads, the conventional torque control does have some shortcomings that will probably result in power loss. The main uncertainty is related to the gain $k$ in (6.1). First of all, this gain is difficult to determine accurately due to the complex aerodynamics that are involved, such as the $C_p$-$\lambda$ curve of the wind turbine. Secondly, the gain $k$ is optimal for steady wind conditions. The presence of turbulence in the wind forces the turbine to operate off its optimal point. The reason for this is that the high inertia of the rotor creates a delay in the tracking behavior. A higher turbulence will result in a less accurate tracking of the optimal operating point, which leads to less energy capture. There exist several controllers that take this transient behavior into account to prevent energy loss. One of these is the optimally tracking rotor (OTR) controller proposed in [54]. This controller reduces the amount of time required for the turbine to regain the optimal tip speed ratio when high wind...
6.2.2 CVT ratio control

In the CVT controlled variable speed wind turbine, the variable speed operation in region 2 is obtained by controlling the angular speed of the rotor through the continuously variable transmission. The input speed of the generator is kept constant within the margins given in Table 2.1 while the rotor speed is adjusted. This means that the CVT, together with a gearbox with a fixed ratio, is responsible for the difference in angular speed between the generator input shaft and the gusts occur. This is done by using the generator torque to assist in the deceleration or acceleration of the rotor. Other proposed control schemes to optimize the gain \( k \) are presented in [53]. The importance of tracking the optimal \( \lambda \) has been illustrated in an earlier study, showing that an error of 5\% in the optimal tip speed ratio can cause an energy loss, just in region 2 operation, of \( 1 - 3\% \) [53, 54].
6.2. SETPOINT STRATEGY

The fixed gearbox comprises of a double gear set. The ratio of each of these sets has been determined in Section 4.1.1, both sets have a ratio of 1 : 11. This results in a total ratio of the fixed gearbox of 1 : 121.

As the secondary speed of the CVT $\omega_g$ is prescribed at $\approx 50\pi$ rad/s (net frequency of 50Hz, 4-pole generator), the ratio of the CVT $r_g$ together with the slip $\nu$ determine the primary speed of the CVT $\omega_{rs}$. Finally, the gearbox ratio $i_{total}$ determines the rotor speed $\omega_r$. Therefore, by designing a setpoint for the rotor speed, this setpoint can be transformed to a ratio setpoint $r_{g,ref}$ according to the relations:

$$r_{g,ref} = \frac{\omega_g/\omega_{rs,ref}}{1-\nu_{ref}}$$

$$\omega_{rs,ref} = \omega_{rs,ref}i_{11/2}$$

(6.4)

The setpoint for $\omega_r$, when only the objective of tracking the optimal tip speed ratio is kept in mind, thus not taking dynamic loads into account, is given by:

$$\omega_{rs,ref} = \lambda_{opt}R/v_w$$

(6.5)

However, strictly following this setpoint at all times will result in high dynamic loads in the shafts and the drivetrain, especially the loads on the CVT become high because the shifting speed and frequency is relatively high. A simulation is performed for the wind profile shown earlier, a constant slip setpoint of 1% and a ratio setpoint that follows $\lambda_{opt}$ at all times. Before performing this simulation, a basic control system is designed such that the CVT will adjust its ratio to the new operating point, which depends on the wind speed. The control system consists of two PI controllers, one for the ratio control and one for the slip control. The controllers are presented in Table 6.1 and are used in every simulation performed in this section.

<table>
<thead>
<tr>
<th></th>
<th>ratio controller</th>
<th>slip controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>P (proportional)</td>
<td>10</td>
<td>-1e4</td>
</tr>
<tr>
<td>I (integral)</td>
<td>0.1 Hz</td>
<td>1.0 Hz</td>
</tr>
</tbody>
</table>

Table 6.1: Ratio and slip controller

The required clamping forces on the primary and secondary pulley are shown in Figure 6.4a. The variation in these clamping forces is large and this variation is transferred through the CVT to the generator and finally appears in high variations in the generated energy. The high fluctuations in the required clamping forces will lead to a lower efficiency of the actuation system and also to a higher loading of the actuation system. Higher loading will lead to more required maintenance, early failures, etc. The generator torque is shown in Figure 6.4b, a time interval of 60 seconds is shown to emphasize the negative generator torques that occur at some points. This indicates that the system would be operating as a motor at that point, taking torque from the generator instead of delivering. To change the direction of transmitted torque, also the sign of the slip reference should change, which is not done here. The negative clamping forces in Figure 6.4a are an artefact in the model.
Now the challenge is to follow $\lambda_{opt}$ at variable wind speeds, but at the same time limit the dynamic loading on the drivetrain. Strictly following $\lambda_{opt}$ results in high dynamic loads, on the other hand, just reducing the dynamic loads will result in a $\lambda$ far off the optimal line, which will reduce the energy capture. Therefore, a trade-off is required between following the optimal $\lambda$ and limiting the dynamic loads. One way to obtain such a trade-off is to filter the turbulent wind speed and use this filtered signal as the input for the calculation of the optimal rotor speed ($6.5$). In fact, this is what the conventional torque control does. The conventional control law is non-linear, by linearizing this control at a specific operating point, it is possible to determine the transfer function of the linear model at this point. From the transfer function, the gain $K$ and time constant $\tau$ that are used in the conventional control can be determined and used in the design of a low-pass filter for the wind speed. The filtered wind speed can then be used to design the setpoint for the CVT ratio control. The non-linear model of the conventional torque control is given by:

$$\dot{\omega}_r = \frac{1}{J_r} \left( T_r(v_w, \omega_r) - T_g(\omega_r) \right) = \frac{1}{J_r} \left( \frac{1}{2} \rho \pi R^3 \frac{C_p(\lambda)}{\lambda(\omega_r, v_w)} v_w^2 - \frac{1}{2} \rho \pi R^5 \frac{C_{p_{max}}}{\lambda_{opt}} \omega_r^2 \right)$$

For linearization, a state-space description of the system is used. Since this system has only one differential equation, the general equation of the state-space system is given by:

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

$\dot{x}$ = small perturbation around state variable $\omega_{r0}$

$u$ = small perturbation around input signal $v_{w0}$

The non-linear model is linearized around a steady-state operating point. The linearization with respect to the steady-state point is only valid for small perturbations around this point. Taking into consideration the dependency of $\lambda$ and $C_p$ on the rotor speed and wind speed ($\omega_r, v_w$), the matrices $A$ and $B$ of the linearized model are given by:
6.2. SETPOINT STRATEGY

\[ A = \left[ \frac{1}{2Jr} \rho \pi R^2 \left( \frac{\delta C_p v_w^3}{\omega_r} - C_p(\omega_r, v_w) \frac{v_w^3}{\omega_r^2} - 2R^3 \omega_r \frac{C_{p_{max}}}{\lambda_{opt}^3} \right) \right]_{\omega_{r0}, v_{w0}} \]  

(6.8)

\[ B = \left[ \frac{1}{2Jr} \rho \pi R^2 \left( 3C_p(\omega_r, v_w) \frac{v_w^2}{\omega_r} + \frac{\delta C_p v_w^3}{\delta v_w \omega_r} \right) \right]_{\omega_{r0}, v_{w0}} \]  

(6.9)

The linearized model is evaluated at different operating points. Appendix I contains a more elaborate explanation of the linearization and its stability at different operating points. The transfer function of the linearized model is determined from

\[ H(s) = C(s - A)^{-1}B + D \]  

(6.10)

With \( D = 0 \) and \( C = 1 \). This transfer function is written as a first order low-pass filter

\[ H(s) = \frac{1}{2\pi f} \frac{s}{s + \frac{CB}{-A}} = \frac{CB}{-A} \frac{1}{s + \frac{1}{\tau}} \]  

(6.11)

With \( \frac{CB}{A} \) defined as the gain \( K \) and \( \frac{1}{\tau} \) as the time constant \( \tau \). The \( A \) and \( B \) values are determined for different wind speeds and from there the gain \( K \) and time constant \( \tau \) are determined. The value of \( A \) depends on the existing wind speed, resulting in a variable cut-off frequency of the low-pass filter:

\[ f = \frac{1}{2\pi \tau} \]  

(6.12)

The filter parameters for different wind speeds in combination with a constant optimal \( \lambda \) are presented in Table 6.2. Evaluating the system at a constant \( \lambda \), results in a constant gain \( K = \frac{C_{p_{max}}}{\lambda_{opt}^3} \). The table also shows that the filter frequency in the conventional control law increases with increasing wind speed (and constant \( \lambda_{opt} \)).

<table>
<thead>
<tr>
<th>( v_w ) [m/s]</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K ) [-]</td>
<td>0.1938</td>
<td>0.1938</td>
<td>0.1938</td>
<td>0.1938</td>
<td>0.1938</td>
<td>0.1938</td>
<td>0.1938</td>
<td>0.1938</td>
<td>0.1938</td>
</tr>
<tr>
<td>( f ) [Hz]</td>
<td>0.0144</td>
<td>0.0192</td>
<td>0.0240</td>
<td>0.0288</td>
<td>0.0337</td>
<td>0.0385</td>
<td>0.0433</td>
<td>0.0481</td>
<td>0.0529</td>
</tr>
</tbody>
</table>

Table 6.2: Parameters for variable cut-off frequency of the low-pass filter

For the design of the ratio setpoint, a low-pass filter with a variable cut-off frequency is designed based on the parameters obtained from the linearization of the conventional control law at different operating points. This low-pass filter is designed in a C-function. The inputs for this function are the actual wind speed and a lookup-table that contains data relating wind speed and filter frequency, according to Table 6.2. The output is the wind speed filtered at a variable frequency. From this filtered wind speed, a setpoint for the ratio of the CVT is calculated according to (6.4). Applying this setpoint results in the rotor torque level presented in Figure 6.5a, the torque levels for conventional control are also shown. The torque levels for the CVT control are shifted to a
higher level, meaning that more energy is captured from the wind. It can also be seen that the number of times each torque level appears does not change much, from this it can be concluded that the dynamic loading is comparable to the conventional control. Figure 6.5b shows the power that is produced over this specific wind profile. The total amount of energy generated over this wind profile has increased around 5% compared to the conventional torque control applied to the Gamesa G80-2.0MW wind turbine:

conventional control: \( E_{\text{total}} = 42.4 \text{ GJ} \)

CVT control: \( E_{\text{total}} = 44.5 \text{ GJ} \)

These figures show that it is possible to achieve a higher energy capture while maintaining an equivalent dynamic loading by implementing a CVT. Only part of this increase in energy production is due to the wider speed range, the other part is due to the efficiency of the total system. The efficiency mainly depends on the number of gear sets, the efficiency of the generator and
the efficiency of the power electronics/CVT. The speed range is responsible for the wind speed region in which it is possible to track the optimal tip speed ratio. The actual energy profit because of the wider speed range is determined by looking at the time interval during which the CVT controlled wind turbine is able to run at optimal $\lambda$ while the conventional torque controlled turbine maintains its minimal rotor speed of 9 rpm. From Figure 6.3 this time interval is determined at $140 - 240$ seconds. During this period, the amount of energy generated by both systems is:

- conventional control: $E_{\text{total}} = 6.6 \text{ GJ}$
- CVT control : $E_{\text{total}} = 6.7 \text{ GJ}$

The CVT controlled turbine does generate more energy, but the profit is only a fraction of the total energy generated over the period of 300 seconds. This is due to the limited amount of energy present in the wind during low wind speeds. Nevertheless, the CVT controlled turbine captures more energy from the wind.

### 6.3 System analysis

Before being able to design a control system for the CVT, an analysis of the system is performed. Therefore, the Control Design™ toolbox in Matlab/Simulink® is used. First a set of steady-state operating points is obtained after which the linear analysis is performed on three different operating points. The input signals for the linear analysis are the absolute clamping force level to maintain the desired slip $F_{\text{slip}}$ and the required ratio between primary and secondary clamping force to obtain the desired ratio change $F_p/F_s$. The output signals are the actual ratio $r_g$ and the slip $\nu$. The control layout and location of these signals are shown in Figure 6.6.

In the 'Control and Estimation Tools Manager' within Matlab/Simulink® it is possible to choose the desired linearization points. The inputs and outputs are assigned to the signals mentioned above. First the plant of the CVT is analyzed at a constant wind speed of 7 m/s while maintaining optimal $\lambda$. The measured bode diagram is shown in Figure 6.7. The open-loop poles and zeros
of the CVT system are given in Table 6.3. All poles are located in the left half plane, thus it can be concluded that the system is stable.

![Figure 6.7: Bode diagram of the CVT at \( v_w = 7 \) m/s](image)

<table>
<thead>
<tr>
<th>poles</th>
<th>zeros</th>
<th>( F_p F_s ) to ( r_g )</th>
<th>( F_p F_s ) to ( \nu )</th>
<th>( F_{\text{slip}} ) to ( r_g )</th>
<th>( F_{\text{slip}} ) to ( \nu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>all</td>
<td>(-3.46 + 314.15i)</td>
<td>(-3.46 + 314.15i)</td>
<td>(-3.46 + 314.15i)</td>
<td>(-3.45 + 314.15i)</td>
<td>(-3.45 + 314.15i)</td>
</tr>
<tr>
<td></td>
<td>(-3.46 - 314.15i)</td>
<td>(-3.46 - 314.15i)</td>
<td>(-3.45 - 314.15i)</td>
<td>(-3.45 - 314.15i)</td>
<td>(-3.45 - 314.15i)</td>
</tr>
<tr>
<td></td>
<td>(-6.92 + 49.69i)</td>
<td>(-6.98 + 50.12i)</td>
<td>(-0.35 + 50.80i)</td>
<td>(-0.31 + 18.28i)</td>
<td>(-0.31 + 18.28i)</td>
</tr>
<tr>
<td></td>
<td>(-6.92 - 49.69i)</td>
<td>(-6.98 - 50.12i)</td>
<td>(-0.35 - 50.80i)</td>
<td>(-0.31 - 18.28i)</td>
<td>(-0.31 - 18.28i)</td>
</tr>
<tr>
<td></td>
<td>(-1.40)</td>
<td>(-1.40)</td>
<td>(-1.40)</td>
<td>(-1.40)</td>
<td>(-1.40)</td>
</tr>
<tr>
<td></td>
<td>(-0.79)</td>
<td>(-0.79)</td>
<td>(-0.79)</td>
<td>(-0.79)</td>
<td>(-0.79)</td>
</tr>
<tr>
<td></td>
<td>(-0.24)</td>
<td>(-0.23)</td>
<td>(-0.23)</td>
<td>(-0.23)</td>
<td>(-0.23)</td>
</tr>
<tr>
<td></td>
<td>(-0.03)</td>
<td>(-2.09)</td>
<td>(-0.03)</td>
<td>(-1.4e11)</td>
<td>(-0.03)</td>
</tr>
<tr>
<td></td>
<td>(-5.46)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.3: Open-loop poles and zeros of the CVT plant at \( v_w = 7 \) m/s
6.3. SYSTEM ANALYSIS

The resonances and anti-resonances in the system are induced by the generator. Figure 6.7 shows both the CVT plant with the generator connected and without. Apart from the influence of the generator, the CVT acts as a first order system. In the transfers from $F_{\text{slip}}$ to the ratio $r_g$ and slip $\nu$, decoupling of the generator occurs around 3 Hz. Looking at the transfer function of the generator, this is the location of its resonance peak. The generator acts as a second order system. A more extensive explanation of this behavior can be found in Appendix J.

When looking at the location of the poles of the CVT plant for different levels of loading, the poles are located further in the left half plane when the level of loading increases (operating point related to the wind speed). Figure 6.8 shows the bode diagrams for three different operating points $v_w = [4 \text{ m/s}, 7 \text{ m/s}, 10 \text{ m/s}]$. The location of the poles influence the location of the decoupling. This can be seen in Figure 6.8 where the decoupling shifts to a lower frequency for increased loading. The difference in the bode diagram for different operating points is an effect of the nonlinearities in the model, the initial conditions change when the operating point is changed.

![Figure 6.8: Bode diagram of the CVT at different operating points](image-url)
The phase of the transfer from $F_{\text{slip}}$ to the slip $\nu$ starts at $180^\circ$, this is due to a minus sign in the system. The phase at low frequencies for the operating point of 4 m/s is located at $360^\circ$ instead of $180^\circ$ like the higher operating points. This can be explained by looking at the zeros of this transfer function. At 4 m/s the transfer function of $F_{\text{slip}}$ to $\nu$ contains one RHP (Right-Half-Plane) zero around $10^{-3}$ Hz. This RHP zero imposes a $180^\circ$ phase lag.

6.4 Controller design

As mentioned in Section 5.3, a hydraulically actuated CVT is considered. The modeling of the hydraulic system is left out in this thesis, therefore the control is based on controlling the primary and secondary clamping forces. The control for the CVT consists of two control loops, one for the ratio control and one for the slip control. Most production CVT systems control the level of the clamping forces only with the secondary clamping force, which is the basis for the slip control. The primary clamping force is then used to control the ratio of the CVT [48]. This type of control is also used in the CVT ratio control for wind turbines.

The speed ratio of the CVT is controlled by changing the ratio between the primary and secondary clamping forces. For each desired ratio $r_g$ there exists a clamping force ratio for which $r_g$ is constant. This ratio between the primary and secondary clamping force for which the variator is in equilibrium is given by:

$$
\Psi = \frac{F_p}{F_s \mid r_g=0} \tag{6.13}
$$

The ratio of the CVT can be changed by changing the ratio between the two clamping forces $F_p/F_s$ with respect to the equilibrium point of the current ratio. This transient behavior is introduced in Section 5.3 as the CMM model (5.1). The setpoint for the CVT ratio is determined by an algorithm that depends on the wind speed. This has been discussed in the previous section.

The percentage of slip in the variator is controlled by prescribing the absolute level of clamping force required to maintain the desired slip. The required clamping force is determined by:

$$
F_{\text{slip}} = T \frac{R_p \cos \beta}{2\mu_{\text{max}}} \tag{6.14}
$$

This clamping force level and the desired ratio between the primary and secondary clamping forces are used to determine the actual required primary and secondary clamping forces:

$$
\begin{align*}
F_p &= \max(F_{\text{slip}}, F_p,F_s) \\
F_s &= \max(F_{\text{slip}}, \frac{1}{T} F_p,F_s)
\end{align*} \tag{6.15}
$$

The setpoint for the slip control is determined by looking at the traction curve of the CVT, Figure 5.3. The maximum amount of torque that can be transmitted is reached when the traction coefficient is at its maximum. The torque capacity of the CVT increases with increasing slip. The maximum is reached at a slip percentage of about 2%. At higher values of slip, the torque capacity
6.4. CONTROLLER DESIGN

decreases. The slip could then increase indefinitely at a constant torque level or even when the torque is decreased. Because of this unstable slip behavior, the slip percentage should always stay on the increasing part of the traction curve [55]. To obtain some margin in the stable region, the setpoint for the slip control is set at 1%.

The control system for the CVT will be designed using the CVT dynamics that are derived in Section 5.3. The modeling of these dynamics introduces two kinds of errors compared to the reality; unmodeled dynamics and parameter errors. In this thesis, unmodeled dynamics are for example caused by leaving nonlinear parts out of the model by linearizing the model. Other examples of unmodeled dynamics are the assumption that the rotating shafts and chain are rigid, and the hydraulic actuation system. Parameter errors are caused by uncertainties in parameters, such as the CMM constant \( \kappa_{cm} \), the assumed nondependence of the gearbox efficiency on the level of loading, the estimated CVT efficiency, etc. The control design should be robust for these model uncertainties and parameter errors. This is achieved by specifying the desired robustness margins. The maximum sensitivity of the closed-loop system is set at 6 dB, the phase margin should be at least 35° and the gain margin should be greater than 6 dB. These requirements are also shown in Table 6.4.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>phase margin</td>
<td>&gt; 35°</td>
</tr>
<tr>
<td>modulus margin</td>
<td>&lt; 6 dB</td>
</tr>
<tr>
<td>gain margin</td>
<td>&gt; 6 dB</td>
</tr>
</tbody>
</table>

Table 6.4: Required robustness margins

The bandwidth of the control system is limited by the bandwidth of the clamping force actuation system, which is assumed around 8 Hz [48]. The maximum error allowed in the slip control is determined by looking at the traction curve (Figure 5.3). As mentioned before, unstable slip behavior can occur when the slip becomes too high. The slip is required to stay within the range of 0.6 – 1.4%, this includes a margin for robustness of the system. For the ratio control a maximum error of ±0.01 is allowed.

6.4.1 Sequential Loop Closing

The control problem for the CVT control is a 2 × 2 multi input - multi output (MIMO) problem, as can be seen in Figure 6.6. A MIMO system can either be controlled by a centralized MIMO controller or by a decentralized MIMO controller which consists of a set of SISO controllers. In general, the design of a MIMO controller is more difficult than that of a SISO controller. However, the presence of interaction in a MIMO system can make it very difficult, or even impossible, to design a set of stable SISO controllers. Figure 6.7 shows that the MIMO system in this thesis is not diagonal dominant, this might complicate the design of SISO controllers. Nevertheless, a decentralized control method is used for this problem, more specific the Sequential Loop Closing (SLC) method. The concept of SLC is to design a controller for the MIMO system by sequentially designing SISO controllers. These controllers are designed by identifying the transfer function between one paired input and output, in this case the diagonal entries, at each step [56, 57].
The starting point in the Sequential Loop Closing method is the measured CVT plant from Figure 6.7. Two sequential loop closing procedures are performed to investigate the influence of the chosen bandwidth for the control system. First a control system with a high bandwidth of 2 Hz is designed. The first diagonal entry, \( F_p F_s \) to \( r_g \), is isolated and controller \( C_1 \) is designed for this transfer function using SISO loop shaping techniques. The result is a PI-controller \( C_1 \) with parameters and robustness margins shown in Table 6.5. Now the first loop is closed while keeping the second loop open, as is the situation in Figure 6.9. With this configuration, the transfer function of the second diagonal entry becomes:

\[
\hat{g}_{22} = g_{22} - \frac{g_{21}c_1 g_{12}}{1 + g_{11}c_1} \tag{6.16}
\]

For this transfer function a controller \( C_2 \) is designed, again using SISO loop shaping techniques. This results in the PI-controller \( C_2 \) and robustness margins shown in Table 6.5.

<table>
<thead>
<tr>
<th></th>
<th>step 1</th>
<th>step 2</th>
<th>step 3</th>
<th>step 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_1 )</td>
<td>80</td>
<td>-3e5</td>
<td>120</td>
<td>-8e5</td>
</tr>
<tr>
<td>( C_2 )</td>
<td>2 Hz</td>
<td>2 Hz</td>
<td>2 Hz</td>
<td>2 Hz</td>
</tr>
<tr>
<td>proportional gain</td>
<td>2.14 Hz</td>
<td>2.23 Hz</td>
<td>3.20 Hz</td>
<td>2.61 Hz</td>
</tr>
<tr>
<td>integral pole</td>
<td>60.2°</td>
<td>83.8°</td>
<td>65.6°</td>
<td>63.7°</td>
</tr>
<tr>
<td>bandwidth</td>
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<td>0.8 dB</td>
<td>0.3 dB</td>
<td>0.2 dB</td>
</tr>
<tr>
<td>phase margin</td>
<td>( \infty ) dB</td>
<td>( \infty ) dB</td>
<td>( \infty ) dB</td>
<td>( \infty ) dB</td>
</tr>
<tr>
<td>modulus margin</td>
<td>( \infty ) dB</td>
<td>( \infty ) dB</td>
<td>( \infty ) dB</td>
<td>( \infty ) dB</td>
</tr>
<tr>
<td>gain margin</td>
<td>( \infty ) dB</td>
<td>( \infty ) dB</td>
<td>( \infty ) dB</td>
<td>( \infty ) dB</td>
</tr>
</tbody>
</table>

Table 6.5: SISO controllers with a high bandwidth, including the robustness margins

Although the performance specifications are already met after step 2, an iteration of the tuning sequence is executed to investigate whether the performance can be improved. Therefore, the next step is to close the secondary loop and open the primary loop. The transfer function of the primary diagonal entry then becomes:

\[
\hat{g}_{11} = g_{11} - \frac{g_{12}c_2 g_{21}}{1 + g_{22}c_2} \tag{6.17}
\]
Controller $C_1$ is redesigned for this transfer function. The resulting controller and margins are shown under 'step 3' in Table 6.5. After step 4 the system performance has not increased significantly and therefore no more iterations are performed. The resulting robustness margins and the open-loop bode and nyquist diagrams of both diagonal entries are shown in Figure 6.10.

![Open-loop bode of the ratio control](image1)

![Nyquist diagram of the ratio control](image2)

![Open-loop bode of the slip control](image3)

![Nyquist diagram of the slip control](image4)

Figure 6.10: Stability of ratio and slip control loop for low and high bandwidth

The same procedure is repeated to design a control system with a low bandwidth of 0.2 Hz. The specifications are again met after only 2 steps, because of the previous experience of repeating the sequence no additional steps are taken. This results in the controllers and robustness margins presented in Table 6.6 and the open-loop bode and nyquist diagrams in Figure 6.10.

As mentioned earlier, Figure 6.7 shows that the CVT plant is not diagonal dominant and therefore interaction in the system is definitely present. One way to analyze the existing interaction is by looking at the closed-loop step responses of the MIMO system. These step responses are presented in Figure 6.11 for both the low and high bandwidth control system. From this figure it can be concluded that a high interaction is present between the ratio setpoint and the actual slip. Because of this high interaction and the low interaction between the slip setpoint and the ratio, better results might be achieved by designing the slip control loop with a high bandwidth.
while keeping the ratio control loop at a low bandwidth. In that case, some of the high interaction between $r_{g,ref}$ and $\nu$ can be transferred to the low interaction between $\nu_{ref}$ to $r_g$. Other options to take the interaction into account is to design a MIMO controller or to use a decoupling matrix to decouple the system.

<table>
<thead>
<tr>
<th></th>
<th>step 1 $C_1$</th>
<th>step 2 $C_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>proportional gain</td>
<td>20</td>
<td>$-1e4$</td>
</tr>
<tr>
<td>integral pole</td>
<td>0.1 Hz</td>
<td>1 Hz</td>
</tr>
<tr>
<td>bandwidth</td>
<td>0.22 Hz</td>
<td>0.22 Hz</td>
</tr>
<tr>
<td>phase margin</td>
<td>86.2°</td>
<td>48.5°</td>
</tr>
<tr>
<td>modulus margin</td>
<td>0.0 dB</td>
<td>2.2 dB</td>
</tr>
<tr>
<td>gain margin</td>
<td>$\infty$ dB</td>
<td>$\infty$ dB</td>
</tr>
</tbody>
</table>

Table 6.6: SISO controllers with a low bandwidth, including the robustness margins

Figure 6.11: Step responses of the linearized closed-loop MIMO system
6.4. CONTROLLER DESIGN

6.4.2 Controller choice

The choice between a high or low bandwidth controller is made based on the tracking behavior of both control loops, the required clamping forces provided by the hydraulic actuation system and the total amount of energy produced over the wind profile of Figure 6.1.

First the tracking behavior of both control systems is examined, resulting in the tracking errors as presented in Figure 6.12. The error in the ratio control for a high bandwidth controller is in the order of $10^{-5}$, while for the slip control the error lies around $10^{-3}$. For both control systems, the tracking behavior is acceptable when looking at the specifications. At higher wind speeds, the tracking behavior of slip control tuned with a low bandwidth becomes less accurate but still the specifications are easily met. The behavior for high wind speeds is shown in Appendix K.

![Graph of Error in ratio setpoint](image)

![Graph of Error in slip setpoint](image)

Figure 6.12: Error in tracking for low and high bandwidth

Secondly, the hydraulic clamping force actuation system requires a higher bandwidth when increasing the bandwidth of the CVT control. This is shown in Figure 6.13, where the secondary clamping force required for the slip control is oscillating at a higher frequency in the high bandwidth control. These oscillations in the clamping force might influence the efficiency of the actuation system.
Secondary clamping forces

The oscillating behavior of the clamping force is transferred to the output torque of the CVT and therefore also to the generated energy. The total energy produced over this wind profile with a low bandwidth is $< 0.1\%$ less than with the high bandwidth control. In the high wind speed regime this difference is even less (Appendix K).

Taking into account the advantages and disadvantages of a high bandwidth control compared to a low bandwidth control, for this application a low bandwidth control is chosen. Allowing the slip to increase or decrease slightly will limit the dynamic loading on the CVT and decrease the required clamping forces. The loss of energy due to the existing slip is negligible. Another reason for choosing the lower bandwidth is that the setpoint that should be followed is already a filtered signal. The filter frequency of the ratio setpoint does not exceed 0.12 Hz. For the ratio control it is therefore not interesting to have a bandwidth of 2 Hz. As for the slip control, the requirements in tracking the slip setpoint are easily met with a bandwidth of 0.2 Hz.

6.5 Conclusions

From the simulations that have been performed, it can be concluded that controlling a wind turbine using a continuously variable transmission is very well possible. A CVT controlled wind turbine is able to capture more energy from low wind speeds, because of a wider range in operating speeds of the rotor. At higher wind speeds, the CVT controlled wind turbine achieves the same energy capture as the conventional generator torque control systems do. In terms of dynamic loading, the CVT is able to limit the loads just as much as the conventional control can. It is possible to give a preference to more energy capture or to limit the dynamic loading more by changing the frequency at which the wind speed is filtered. Finally, the control system designed using Sequential Loop Closing is sufficient for this application. However, other control systems might be able to reduce the existing interaction and lead to better performance.
Chapter 7

Conclusion and Recommendations

7.1 Conclusion

A study on implementing a continuously variable transmission in a wind turbine has lead to several expectations. The energy that is captured from the wind will increase in the low wind speed regime because a wider speed range of the rotor is available when a CVT is used. Therefore, the optimal operating line can be followed starting from a lower wind speed. The dynamic loads acting on the drivetrain can be limited to a level equivalent to those in conventional control. An advantage is that the power electronics that are currently used to obtain a constant frequency output of the generator are no longer required.

This thesis has shown that it is possible to achieve each of these expectations. The configuration of the drivetrain is based on the possibilities of the CVT and the desire for a wide speed range. By modeling the main components of a wind turbine and developing a ratio setpoint algorithm, a control system is developed that can accurately track the setpoint for the ratio as well as maintain a certain percentage of slip in the variator. The ratio setpoint algorithm, drivetrain configuration and control system are responsible for the positive results achieved in this thesis. In low wind speeds, the energy capture is increased by approximately 5% while keeping dynamic loads under control. For high wind speeds, the energy capture is equivalent to the existing control techniques that use power electronics to control the generator torque. The dynamic loads are also limited to the same level as in conventional control systems.

7.2 Recommendations

Although this study is an interesting beginning for the implementation of a GCI chain-CVT in wind turbines, a number of recommendations are in place.

Drivetrain configuration: The drivetrain configuration assumed in this thesis is not yet the optimal solution. A study should be performed on the optimal ratio for the fixed gearbox in combination with the range of the CVT. In this study the effect of increasing or decreasing the range of the CVT on the speed range of the rotor and the efficiency of the CVT should be investigated, as well as the location of the CVT with respect to the fixed gearbox. The location should be reconsidered while taking into account the scaling rules applicable for wind turbines and by looking at the dimensioning and the adjoining change in weight, size,
cost and efficiency. Another approach is to look at the influence of changing the number of poles in the generator. By increasing this number, the required input speed for the generator decreases and the total step-up ratio of the drivetrain can be lowered.

**Model uncertainties:** During the modeling of the wind turbine, a number of assumptions have been made that influence the quality of the model. First of all, the planetary gear sets in the drivetrain have unmodeled dynamics and the efficiency is assumed to be independent of the level of loading, which is not the case in reality. Next, the rotating shafts and the GCI chain are assumed to be rigid, again resulting in unmodeled dynamics. The stationary clamping force ratio in the shifting model and the traction curve of the CVT are assumed not to be influenced by scaling. The CMM parameter in the shifting model is assumed to be constant. The efficiency of the CVT is deducted from measurements on a small-scale CVT, which leads to a large uncertainty. Due to all these uncertainties it is difficult to assess the actual profit in energy production. Therefore, these uncertainties should be examined and if possible eliminated.

**Control system:** The step responses in the closed-loop MIMO system show high interaction in the system. It is recommended to investigate different control strategies to minimize this effect, such as the design of a MIMO controller. At the same time, the reaction of the system on external disturbances should be examined. For example, how the system reacts to voltage spikes in the electrical grid.

**Cost of Energy:** The costs for a CVT controlled wind turbine should be estimated. Together with the expected annual energy yield, maintenance costs and investment costs, a cost of energy (expressed in €/kWh) can be determined. This number will show whether wind turbine manufacturers will actually be interested in CVT controlled wind turbines.
Bibliography


[23] Voith Turbo - WinDrive®, Voith Turbo GmbH & Co.KG, technical brochure.


Appendix A

Nomenclature

Acronyms

WECS Wind Energy Conversion System
CVT Continuously Variable Transmission
GCI Gear Chain Industrial B.V.
CMM Carbone Mangialardi Mantriota
OTR Optimally Tracking Rotor
MIMO Multi Input - Multi Output
SISO Single Input - Single Output
SLC Sequential Loop Closing

Symbols

\( \Psi \) [-] stationary clamping force ratio
\( \beta \) \([\degree]\) blade pitch angle
\( \alpha \) \([\degree]\) angle of attack
\( \delta \) \([\degree]\) load angle
\( \epsilon \) \([\text{V}]\) electromotive force
\( \theta \) \([\degree]\) power factor angle
\( \kappa_{cmm} \) [-] CMM parameter
\( \lambda \) [-] tip speed ratio
\( \lambda_{opt} \) [-] optimal tip speed ratio
\( \lambda_i \) \([\text{Wb-turns}]\) flux linkage
\( \mu_0 \) [-] absolute permeability of free space
\( \mu \) [-] traction coefficient
\( \mu_{max} \) [-] maximum traction coefficient
\( \nu \) [-] variator slip
\( \rho \) \([\text{kg/m}^3]\) density
\( \tau \) \([\text{s}]\) time constant
\( \phi \) \([\text{Wb}]\) magnetic flux
\( \omega_i \) \([\text{rad/s}]\) angular speed
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
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<tr>
<td>A</td>
<td>m²</td>
<td>area</td>
</tr>
<tr>
<td>B</td>
<td>T</td>
<td>magnetic field</td>
</tr>
<tr>
<td>C_p</td>
<td>-</td>
<td>power coefficient</td>
</tr>
<tr>
<td>C_p,max</td>
<td>-</td>
<td>maximum power coefficient</td>
</tr>
<tr>
<td>C_Q</td>
<td>-</td>
<td>rotor torque coefficient</td>
</tr>
<tr>
<td>F_p</td>
<td>N</td>
<td>primary clamping force</td>
</tr>
<tr>
<td>F_s</td>
<td>N</td>
<td>secondary clamping force</td>
</tr>
<tr>
<td>F_{slip}</td>
<td>N</td>
<td>slip force</td>
</tr>
<tr>
<td>I_a</td>
<td>A</td>
<td>armature current</td>
</tr>
<tr>
<td>I_f</td>
<td>A</td>
<td>field current</td>
</tr>
<tr>
<td>J_i</td>
<td>kg m²</td>
<td>mass moment of inertia</td>
</tr>
<tr>
<td>K</td>
<td>-</td>
<td>low-pass gain</td>
</tr>
<tr>
<td>L</td>
<td>H</td>
<td>inductance matrix</td>
</tr>
<tr>
<td>L_d</td>
<td>H</td>
<td>d-axis inductance</td>
</tr>
<tr>
<td>L_q</td>
<td>H</td>
<td>q-axis inductance</td>
</tr>
<tr>
<td>L_f</td>
<td>H</td>
<td>field inductance</td>
</tr>
<tr>
<td>N</td>
<td>-</td>
<td>number of coil turns</td>
</tr>
<tr>
<td>P_i</td>
<td>W</td>
<td>power</td>
</tr>
<tr>
<td>R</td>
<td>Ω</td>
<td>resistance matrix</td>
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<td>R</td>
<td>m</td>
<td>rotor diameter</td>
</tr>
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<td>R_p</td>
<td>m</td>
<td>primary pulley radius</td>
</tr>
<tr>
<td>R_s</td>
<td>m</td>
<td>secondary pulley radius</td>
</tr>
<tr>
<td>R_i</td>
<td>Ω</td>
<td>resistance</td>
</tr>
<tr>
<td>S_f</td>
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<td>safety factor</td>
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<td>T_i</td>
<td>N m</td>
<td>torque</td>
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<tr>
<td>V_t</td>
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<tr>
<td>f</td>
<td>Hz</td>
<td>frequency</td>
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</tr>
<tr>
<td>i_2</td>
<td>-</td>
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</tr>
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<td>i_d</td>
<td>A</td>
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</tr>
<tr>
<td>i_q</td>
<td>A</td>
<td>q-axis current</td>
</tr>
<tr>
<td>n</td>
<td>rpm</td>
<td>angular speed</td>
</tr>
<tr>
<td>p</td>
<td>-</td>
<td>number of poles</td>
</tr>
<tr>
<td>r_g</td>
<td>-</td>
<td>geometric ratio of CVT</td>
</tr>
<tr>
<td>r_s</td>
<td>-</td>
<td>speed ratio of CVT</td>
</tr>
<tr>
<td>s</td>
<td>-</td>
<td>generator slip</td>
</tr>
<tr>
<td>u</td>
<td>m/s</td>
<td>tangential velocity of blade tip</td>
</tr>
<tr>
<td>v_d</td>
<td>V</td>
<td>d-axis voltage</td>
</tr>
<tr>
<td>v_q</td>
<td>V</td>
<td>q-axis voltage</td>
</tr>
<tr>
<td>v_F</td>
<td>V</td>
<td>field/excitation voltage</td>
</tr>
<tr>
<td>v_w</td>
<td>m/s</td>
<td>wind speed</td>
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Appendix B

Generator information

In this appendix, the working principle of both cylindrical-rotor and salient-pole synchronous generators are explained in more detail. Furthermore, a comparison is made between the excitation system of generators, namely electromagnets and permanent magnets.

B.1 Generator configuration

Synchronous generators can be divided into two categories based on the type of rotor, namely cylindrical and salient-pole rotors. The basic structure of both rotor-types can be found in Figure B.1. In the following sections both of these types will be discussed.

![Different types of rotors](image)

**Cylindrical-rotor synchronous generator**

Figure (B.2b) shows the phasor diagram of a cylindrical-rotor synchronous generator. A phasor diagram shows the relationship between voltages and currents and is based on the per-phase equivalent circuit (B.2a). The terminal voltage $V_t$ is dictated by the electrical grid. The armature current $I_a$ is induced by the rotating magnetic fields. The excitation voltage $v_F$ can be controlled when using electromagnets. The load angle $\delta$ is defined by the angle between the excitation voltage $v_F$ and the terminal voltage $V_t$. The power factor angle $\theta$ is defined by the angle between
the terminal voltage $V_t$ and the armature current $I_a$. Now, the actual power factor of the generator is defined as $\cos(\theta)$ and a higher power factor will result in a higher power output. Therefore, $V_t$ and $I_a$ should be in phase as close as possible (small $\theta$). One way to decrease $\theta$ is to increase the load angle $\delta$. This can be done by controlling the excitation voltage $v_F$. The internal power angle $\psi$ will remain constant while $\delta$ increases, resulting in a decrease of $\theta$. The influence of $\theta$ and $\delta$ on the generated power is visible in the expression for the power:

$$P_{out} = 3V_tI_a \cos(\theta) = 3 \frac{V_t v_F}{X_s} \sin(\delta) \quad (B.1)$$

where:

$V_t$ = terminal voltage [V]  
$I_a$ = armature current [A]  
$v_F$ = excitation voltage [V]  
$X_s$ = synchronous reactance [$\Omega$]

![Figure B.2: Cylindrical-rotor synchronous generator](image)

**Salient-pole synchronous generator**

In case of salient-pole synchronous generators, the armature current can be resolved into two components, the d-axis current $I_d$ and q-axis current $I_q$. The d-axis is located along the poles, where the magnetic reluctance $X_d$ is low and the q-axis is located between the poles, where the magnetic reluctance $X_q$ is high (Figure B.1). In cylindrical-rotor synchronous generators, the same flux is produced regardless the rotor position due to the uniform air gap. This is not the case in salient-pole generators, which have a non-uniform air gap. The equivalent circuit and phasor diagram of the salient-pole synchronous generator are shown in Figure B.3 [19].

![Figure B.3: Salient-pole synchronous generator](image)

The terminal voltage $V_t$ is equal to that in the cylindrical-rotor case. Assuming the magnetic field is created using electromagnets, the excitation voltage $v_F$ can be controlled and the armature current $I_a$ is determined by $I_d$ and $I_q$. Again, the power factor angle $\theta$ should be as small as
B.2 ELECTROMAGNETS VERSUS PERMANENT MAGNETS

possible, while the load angle $\delta$ should be as high as possible. The generated power in a salient-pole synchronous generator is equal to that of a cylindrical-rotor plus a power term due to the saliency ($X_d \neq X_q$):

$$P_{out} = 3 \frac{V_t V_F}{X_d} \sin(\delta) + 3 \frac{V_t^2 (X_d - X_q)}{2X_d X_q} \sin(2\delta)$$

(B.2)

B.2 Electromagnets versus permanent magnets

The magnets that produce the magnetic field in the air gap can be of different types. Two types of magnets used in generators are electromagnets and permanent magnets. The advantages and disadvantages of both types are now explained.

**Electromagnets**

The magnetic field created by electromagnets is actually produced by the flow of an electric current, the excitation current. This current can be taken from the electrical grid. However, the grid supplies alternating current while the magnets need direct current. Therefore the AC current is converted to DC current before it is sent to the coil windings around the electromagnets.

The main advantage of electromagnets is that the strength of the magnetic field, and therefore the induced voltage, can be controlled by changing the amount of current applied to the electromagnets. In this way it is possible to control the power factor in synchronous generators [12].

**Permanent magnets**

Another possibility is to use permanent magnets (PM) in synchronous generators. One of the major advantages of using permanent magnets is the fact that there is no need for direct current to excite the magnetic field, i.e. no reactive power is required. This results in a higher efficiency and therefore a higher annual energy production. The higher efficiency is also a result of the small core losses, due to the small resistance, and small iron losses due to the laminated stator core and absence of armature reaction. Next to the improved efficiency, permanent magnets have better thermal characteristics due to the absence of field losses and a higher reliability due to the absence of mechanical components like slip-rings. A disadvantage is that permanent magnets can become demagnetized by working in high temperatures (above the curie-point) and the cost of permanent magnet material is high, increasing the total generator costs [58, 59, 60].

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
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<tbody>
<tr>
<td>high efficiency</td>
<td>no power factor control</td>
</tr>
<tr>
<td>no external excitation</td>
<td>possible demagnetization</td>
</tr>
<tr>
<td>reliability</td>
<td>material costs</td>
</tr>
<tr>
<td>thermal characteristics</td>
<td></td>
</tr>
</tbody>
</table>

Table B.1: Permanent magnets in relation to electromagnets
Appendix C

Dimensions of a GCI chain-CVT

C.1 Scaling factor

From a reference chain and $T_{cvt,max}$ and $P_{cvt,nom}$, a scaling factor is determined. The dimensions for a GCI chain-CVT can be determined when this scaling factor compared to a reference chain is known. The parameters of the reference chain are:

- chain width $= w_{chain} = 24$ mm
- nominal torque $= T_{ref} = 160$ Nm
- nominal power $= P_{ref} = 85$ kW
- min. running radius $= R_{min} = 30$ mm

The torque scales with the third power while the power scales quadratically. The scaling factors are then determined by:

$$f_{torque} = \left(\frac{T_{cvt,max}}{T_{ref}}\right)^{1/3}$$
$$f_{power} = \left(\frac{P_{cvt,nom}}{P_{ref}}\right)^{1/2}$$

(C.1)

C.2 Dimensional relations

The relations that determine the required dimensions of the CVT are given by:

$$w_{chain} = fw_{chain,ref}$$
$$R_{min} = fR_{min,ref}$$
$$R_{max} = \sqrt{\text{range}}R_{min}$$
$$a = 2R_{max} + 2$$
$$v_{max,OD} = \omega_{p,min}R_{max}/1000$$
$$v_{max,LD} = \omega_{p,max}R_{min}/1000$$

(C.2)

$f$ = scaling factor [-]

$w_{chain}$ = chain width [mm]

$R_{min,max}$ = min/max running radius [mm]

$a$ = center distance [mm]

$v_{max,OD,LD}$ = maximum chain speed in low and over drive [m/s]
Where the +2 in center distance is an extra margin and $v_{\text{max},LD}$ is the maximum speed that the chain can reach. This chain speed is limited at 40 m/s.

The efficiency of the CVT at different levels of loading and in different working points (different ratios) is assumed from the measured data in Figure C.1. The assumed efficiency deducted from this figure is shown in Figure C.2.

![Measured efficiency data](image1)

**Figure C.1:** Measured efficiency data of a 30 mm GCI chain-CVT

![Efficiency of power converter and CVT](image2)

**Figure C.2:** Estimated efficiency of a 120 mm GCI chain-CVT
Appendix D

General converter efficiency

Figure D.1: Efficiency of different converters at variable wind speeds
<table>
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<th>wind speed [m/s]</th>
<th>baseline 3 kHz</th>
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<th>MOSFET 9 kHz</th>
<th>MOSFET 50 kHz</th>
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<td>3</td>
<td>39.2%</td>
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<td>73.9%</td>
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<tr>
<td>3.5</td>
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<tr>
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<td>73.9%</td>
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</tr>
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<td>97.3%</td>
<td>96.9%</td>
<td>94.4%</td>
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<td>8.5</td>
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<td>97.4%</td>
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<tr>
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<td>97.8%</td>
<td>97.4%</td>
<td>95.3%</td>
</tr>
<tr>
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<td>97.7%</td>
<td>97.4%</td>
<td>95.3%</td>
</tr>
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<td>10.0</td>
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<td>97.4%</td>
<td>95.3%</td>
</tr>
<tr>
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</tr>
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<td>96.2%</td>
<td>97.3%</td>
<td>97.0%</td>
<td>95.0%</td>
</tr>
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</table>

Table D.1: Efficiency of 4 types of power converters used in wind turbines [61]
Appendix E

Model in Matlab/Simulink

The block diagrams of the complete model of the wind energy conversion system can be found here.

E.1 Wind model

Figure E.1: Block diagram of the wind model
E.2 Rotor model

Figure E.2: Block diagram of the rotor

Figure E.3: Block diagram of the rotor aerodynamics

E.3 Drivetrain model

Figure E.4: Block diagram of the drivetrain
Figure E.5: Block diagram of the fixed gears

Figure E.6: Block diagram of the CVT

Figure E.7: Block diagram of the CMM model
APPENDIX E. MODEL IN MATLAB/SIMULINK

Figure E.8: Block diagram of the traction

Figure E.9: Block diagram of the primary torque

Figure E.10: Block diagram of the primary pulley speed
E.4 Generator model

Figure E.11: Block diagram of the mechanical part of the generator

Figure E.12: Block diagram of the electrical part of the generator

Figure E.13: Block diagram of the Park transformation (abc->dq0)
Appendix F

Generator parameters

The parameters that are used to model the generator are given in Table F.1. These parameters are obtained from ECN and are valid for a 2.75 MW synchronous generator.

<table>
<thead>
<tr>
<th>number of poles</th>
<th>( p )</th>
<th>4</th>
<th>[-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>d-axis inductance</td>
<td>( L_d )</td>
<td>0.007627</td>
<td>[H]</td>
</tr>
<tr>
<td>q-axis inductance</td>
<td>( L_q )</td>
<td>0.00518</td>
<td>[H]</td>
</tr>
<tr>
<td>d-axis mutual inductance</td>
<td>( L_{md} )</td>
<td>0.007373</td>
<td>[H]</td>
</tr>
<tr>
<td>q-axis mutual inductance</td>
<td>( L_{mq} )</td>
<td>( L_{md} )</td>
<td>[H]</td>
</tr>
<tr>
<td>field winding inductance</td>
<td>( L_F )</td>
<td>0.0085659</td>
<td>[H]</td>
</tr>
<tr>
<td>stator resistance</td>
<td>( R_s )</td>
<td>0.006635</td>
<td>[( \Omega )]</td>
</tr>
<tr>
<td>d-axis resistance</td>
<td>( R_d )</td>
<td>( R_s )</td>
<td>[( \Omega )]</td>
</tr>
<tr>
<td>q-axis resistance</td>
<td>( R_q )</td>
<td>( R_s )</td>
<td>[( \Omega )]</td>
</tr>
<tr>
<td>field winding resistance</td>
<td>( R_F )</td>
<td>3.91e-4</td>
<td>[( \Omega )]</td>
</tr>
<tr>
<td>damper inductance</td>
<td>( L_D )</td>
<td>0.043</td>
<td>[H]</td>
</tr>
<tr>
<td>damper inductance</td>
<td>( L_Q )</td>
<td>0.052</td>
<td>[H]</td>
</tr>
<tr>
<td>damper resistance</td>
<td>( R_D )</td>
<td>0.05</td>
<td>[( \Omega )]</td>
</tr>
<tr>
<td>damper resistance</td>
<td>( R_Q )</td>
<td>0.055</td>
<td>[( \Omega )]</td>
</tr>
<tr>
<td>generator inertia</td>
<td>( J_g )</td>
<td>44</td>
<td>[kgm^2]</td>
</tr>
<tr>
<td>friction factor</td>
<td>( F )</td>
<td>0</td>
<td>[-]</td>
</tr>
</tbody>
</table>

Table F.1: Synchronous generator parameters
The efficiency of the modeled synchronous generator at different wind speeds is computed and given in Figure F.1.

Figure F.1: Efficiency of the modeled synchronous generator
Appendix G

Park transformation

Park’s transformation greatly simplifies the mathematical description of the synchronous generator. This transformation defines a new set of stator variables such as currents, voltages and flux linkages in terms of the rotor variables. The actual variables are projected onto three axes: one along the direct axis of the field winding on the rotor, one along the neutral axis of the field winding, called the quadrature axis, and one on a stationary axis. Park’s transformation is defined as [27, 49, 19]:

$$\mathbf{P}(\theta) = \sqrt{2/3} \begin{bmatrix} \cos \theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ \sin \theta & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \quad (G.1)$$

Where $\theta$ is defined as the angle between the $a$-axis on the stator and the $d$-axis on the rotor (Figure 5.5). This transformation is power invariant, because $\mathbf{P}(\theta)$ is orthogonal, and therefore the expression for the power is equal whether the $abc$ or $dq0$ reference frame is used:

$$p = v_a i_a + v_b i_b + v_c i_c$$
$$= v_{0d} + v_{d} i_d + v_{q} i_q \quad (G.2)$$

Applying this transformation to the net voltages ($\mathbf{v}_{abc} = [v_a \, v_b \, v_c]^T$)

$$\mathbf{v}_{dq0} = \mathbf{P} \mathbf{v}_{abc} \quad (G.3)$$

results in the following expressions for $v_d$, $v_q$ and $v_0$:

$$v_d = \sqrt{2/3}[v_a \cos \theta + v_b \cos(\theta - 2\pi/3) + v_c \cos(\theta + 2\pi/3)]$$
$$v_q = \sqrt{2/3}[v_a \sin \theta + v_b \sin(\theta - 2\pi/3) + v_c \sin(\theta + 2\pi/3)]$$
$$v_0 = 1/\sqrt{3}[v_a + v_b + v_c] \quad (G.4)$$

Applying Park’s transformation to the voltage equations (5.7) and substituting $\lambda$ by $L \dot{i}$ (this can be done because the inductance matrix in this case is constant) results in the transformed matrix form of the terminal voltages:

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = - \begin{bmatrix} r & \omega L_q & 0 \\ -\omega L_d & r & 0 \\ 0 & 0 & r + 3r_n \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} - \begin{bmatrix} \omega k M_F & 0 & 0 \\ 0 & -\omega k M_D & 0 \\ 0 & 0 & r_F \end{bmatrix} \begin{bmatrix} i_F \\ i_D \\ i_Q \end{bmatrix}$$

83
\[
\begin{bmatrix}
L_d & 0 & 0 & kM_F & kM_D & 0 \\
0 & L_q & 0 & 0 & 0 & kM_Q \\
kM_F & 0 & 0 & L_F & M_R & 0 \\
kM_D & 0 & 0 & M_R & L_D & 0 \\
0 & kM_Q & 0 & 0 & 0 & L_Q
\end{bmatrix}
\begin{bmatrix}
i_d \\
i_q \\
i_F \\
i_D \\
i_Q
\end{bmatrix}
= \begin{bmatrix}
\dot{i}_d \\
\dot{i}_q \\
\dot{i}_F \\
\dot{i}_D \\
\dot{i}_Q
\end{bmatrix}
\] (G.5)

\[L_d = \text{d-axis self-inductance}\]
\[L_q = \text{q-axis self-inductance}\]
\[kM_F = kM_D = \text{d-axis mutual inductance}\]
\[kM_Q = \text{q-axis mutual inductance}\]

All equations are coupled, except for the voltage on the stationary axis \(v_0\) which depends only upon \(i_0\) and \(i_0\). Therefore, this equation can be solved separately and the remaining five equations are rewritten as

\[L\dot{i} = -R(\omega)i - Bu\] (G.6)

With state vector \(i = [i_d, i_q, i_F, i_D, i_Q]^T\) and input vector \(u = [v_d, v_q, v_F]^T\). Where \(i_d, i_q, v_d\) and \(v_q\) are projections of the terminal currents and voltages on the rotor axes \(d\) and \(q\) (Park transformation), \(i_F\) and \(v_F\) are the field current and voltage and the states \(i_D\) and \(i_Q\) are currents in the two damper windings. Now the transformed inductance matrix \(L\), resistance matrix \(R\) and input matrix \(B\) are represented by:

\[
L = \begin{bmatrix}
L_d & 0 & L_{md} & L_{md} & 0 \\
0 & L_q & 0 & 0 & L_{mq} \\
L_{md} & 0 & L_F & L_{md} & 0 \\
L_{md} & 0 & L_{md} & L_D & 0 \\
0 & L_{mq} & 0 & 0 & L_Q
\end{bmatrix}
\] (G.7)

\[
R = \begin{bmatrix}
R_d & \omega L_q & 0 & 0 & \omega L_{mq} \\
-\omega L_d & R_q & -\omega L_{md} & -\omega L_{md} & 0 \\
0 & 0 & R_F & 0 & 0 \\
0 & 0 & 0 & R_D & 0 \\
0 & 0 & 0 & 0 & R_Q
\end{bmatrix}
\] (G.8)

\[
B = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & -1 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\] (G.9)
Appendix H
Matlab m-file for solving state-space equation

% calculation of 5th order model for the generator

syms ud uq uf Ld Lq Lf LD LQ Lmd Lmq Rd Rq Rf RD RQ w
syms id iq ifd iD iQ

%% L matrix %%
Ls = [Ld 0;0 Lq];
M = [Lmd -Lmd 0;0 0 Lmq];
Lr = [Lf Lmd 0;Lmd LD 0;0 0 LQ];
L = [Ls M;transpose(M) Lr];

%% R matrix %%
Lsr = [0 -Lq;Ld 0];
Mr = [0 0 Lmq;-Lmd -Lmd 0];
Rs = [Rd 0;0 Rq];
Rr = [Rf 0 0;RD 0;0 0 RQ];
R = [Rs+w*Lsr w*Mr;zeros(3,2) Rr];

%% B matrix %%
B = [1 0 0;0 1 0;0 0 1;0 0 0;0 0 0];

%% current and voltage vectors %%
i = [id; iq; ifd; iD; iQ];
u = [ud; uq; uf];

%% calculate di(punt)/dt %%
didt1 = inv(L)*(-R*i-B*u);

eigenvaluesL = eig(L);
eigenvalues \( R = \text{eig}(R); \)

%%% constants for calculation of \( \frac{\text{d}i_d}{\text{d}t} \):
\[
\begin{align*}
% & a11*id+a12*iq+a13*iff+a14*iD+a15*iQ+a16*ud+a17*uq+a18*uf \\
% & a11 = (Lmd^2-Lf*LD)/(2*Lmd^3+Lmd^2*Ld+Lf*Lmd^2+Lmd^2*LD-Ld*Lf*LD)*-Rd; \\
% & a12 = (Lmd^2-Lf*LD)/(2*Lmd^3+Lmd^2*Ld+Lf*Lmd^2+Lmd^2*LD-Ld*Lf*LD)*Lq*w; \\
% & a13 = (Lmd+LD)*Lmd/(2*Lmd^3+Lmd^2*Ld+Lf*Lmd^2+Lmd^2*LD-Ld*Lf*LD)*-Rf; \\
% & a14 = (Lmd+Lf)*Lmd/(2*Lmd^3+Lmd^2*Ld+Lf*Lmd^2+Lmd^2*LD-Ld*Lf*LD)*RD; \\
% & a15 = (Lmd^2-Lf*LD)/(2*Lmd^3+Lmd^2*Ld+Lf*Lmd^2+Lmd^2*LD-Ld*Lf*LD)*Lmq*w; \\
% & a16 = (Lmd^2-Lf*LD)/(2*Lmd^3+Lmd^2*Ld+Lf*Lmd^2+Lmd^2*LD-Ld*Lf*LD); \\
% & a18 = (Lmd+LD)*Lmd/(2*Lmd^3+Lmd^2*Ld+Lf*Lmd^2+Lmd^2*LD-Ld*Lf*LD); \\
\end{align*}
\]

%%% constants for calculation of \( \frac{\text{d}iq}{\text{d}t} \):
\[
\begin{align*}
% & a21 = -LQ/(-Lq*LQ+Lmq^2)*-Ld*w; \\
% & a22 = -LQ/(-Lq*LQ+Lmq^2)*-Rq; \\
% & a23 = -LQ/(-Lq*LQ+Lmq^2)*Lmd*w; \\
% & a24 = -LQ/(-Lq*LQ+Lmq^2)*Lmd*w; \\
% & a25 = -Lmq/(-Lq*LQ+Lmq^2)*RQ; \\
% & a27 = -LQ/(-Lq*LQ+Lmq^2)*-1; \\
\end{align*}
\]

%%% constants for calculation of \( \frac{\text{d}iff}{\text{d}t} \):
\[
\begin{align*}
% & a31 = (Lmd+LD)*Lmd/(2*Lmd^3+Lmd^2*Ld+Lf*Lmd^2+Lmd^2*LD-Ld*Lf*LD)*-Rd; \\
% & a32 = (Lmd+LD)*Lmd/(2*Lmd^3+Lmd^2*Ld+Lf*Lmd^2+Lmd^2*LD-Ld*Lf*LD)*Lq*w; \\
% & a33 = -(Lmd^2-Ld*LD)/(2*Lmd^3+Lmd^2*Ld+Lf*Lmd^2+Lmd^2*LD-Ld*Lf*LD)*-Rf; \\
% & a34 = -(Lmd+LD)*Lmd/(2*Lmd^3+Lmd^2*Ld+Lf*Lmd^2+Lmd^2*LD-Ld*Lf*LD)*RD; \\
% & a35 = -(Lmd+LD)*Lmd/(2*Lmd^3+Lmd^2*Ld+Lf*Lmd^2+Lmd^2*LD-Ld*Lf*LD)*-Lmq*w; \\
% & a36 = -(Lmd+LD)*Lmd/(2*Lmd^3+Lmd^2*Ld+Lf*Lmd^2+Lmd^2*LD-Ld*Lf*LD); \\
% & a38 = -(Lmd^2-Ld*LD)/(2*Lmd^3+Lmd^2*Ld+Lf*Lmd^2+Lmd^2*LD-Ld*Lf*LD); \\
\end{align*}
\]

%%% constants for calculation of \( \frac{\text{d}iD}{\text{d}t} \):
\[
\begin{align*}
% & a41 = -(Lmd+Lf)*Lmd/(2*Lmd^3+Lmd^2*Ld+Lf*Lmd^2+Lmd^2*LD-Ld*Lf*LD)*-Rd; \\
% & a42 = -(Lmd^2-Ld*LD)/(2*Lmd^3+Lmd^2*Ld+Lf*Lmd^2+Lmd^2*LD-Ld*Lf*LD)*Lq*w; \\
% & a43 = -(Lmd+LD)*Lmd/(2*Lmd^3+Lmd^2*Ld+Lf*Lmd^2+Lmd^2*LD-Ld*Lf*LD)*RD; \\
% & a44 = -(Lmd^2-Ld*LD)/(2*Lmd^3+Lmd^2*Ld+Lf*Lmd^2+Lmd^2*LD-Ld*Lf*LD)*RD; \\
% & a45 = -(Lmd+Lf)*Lmd/(2*Lmd^3+Lmd^2*Ld+Lf*Lmd^2+Lmd^2*LD-Ld*Lf*LD)*-Lmq*w; \\
% & a46 = -(Lmd+Lf)*Lmd/(2*Lmd^3+Lmd^2*Ld+Lf*Lmd^2+Lmd^2*LD-Ld*Lf*LD); \\
% & a48 = -(Lmd+Ld)*Lmd/(2*Lmd^3+Lmd^2*Ld+Lf*Lmd^2+Lmd^2*LD-Ld*Lf*LD); \\
\end{align*}
\]

%%% constants for calculation of \( \frac{\text{d}iQ}{\text{d}t} \):
\[
\begin{align*}
% & a51 = Lmq/(-Lq*LQ+Lmq^2)*-Ld*w; \\
% & a52 = Lmq/(-Lq*LQ+Lmq^2)*-Rq; \\
% & a53 = Lmq/(-Lq*LQ+Lmq^2)*Lmd*w; \\
% & a54 = Lmq/(-Lq*LQ+Lmq^2)*Lmd*w; \\
% & a55 = Lq/(-Lq*LQ+Lmq^2)*RQ; \\
% & a57 = Lmq/(-Lq*LQ+Lmq^2)*-1; \\
\end{align*}
\]
Appendix I

Linearization

For linearization, a state-space description of the system is used. Since this system has only one differential equation, the general equation of the state-space system is given by:

\[
\dot{\tilde{\omega}}_r = A\tilde{\omega}_r + B\tilde{v}_w
\]  
(I.1)

\(\tilde{\omega}_r\) = small perturbation around state variable \(\omega_r\)

\(\tilde{v}_w\) = small perturbation around input signal \(v_w\)

Where the matrices \(A\) and \(B\) are defined as partial derivatives of (6.6) with respect to \(\omega_r, v_w\) and have the dimension \(1 \times 1\):

\[A = \frac{\delta f}{\delta \omega_r} \bigg|_{\omega_r, v_w}\]

\[B = \frac{\delta f}{\delta v_w} \bigg|_{\omega_r, v_w}\]  
(I.2)

The linearized model is given by:

\[A = \left[ \frac{1}{2 J_r} \rho \pi R^2 \left( \frac{\delta C_p}{\delta \omega_r} \frac{v_w^3}{\omega_r} - C_p(\omega_r, v_w) \frac{v_w^3}{\omega_r^2} - 2R^3 \omega_r \frac{C_{p_{max}}}{\lambda^{3 \text{opt}}} \right) \right]_{\omega_r, v_w, 0}\]  
(I.3)

\[B = \left[ \frac{1}{2 J_r} \rho \pi R^2 \left( 3C_p(\omega_r, v_w) \frac{v_w^2}{\omega_r} + \frac{\delta C_p}{\delta v_w} \frac{v_w^3}{\omega_r} \right) \right]_{\omega_r, v_w, 0}\]  
(I.4)

Evaluation of the linearized model is performed at different operating points. An operating point is called stable when the poles of the system are located in the left half plane. The poles are determined by the eigenvalues of the matrix \(A\). Table I.1 shows the values for \(A\) and \(B\) at three constant wind speeds but variable rotor speed. Figure I.1 is a graphical representation of this table. An operating point is called stable when the poles of the system are located in the left half plane. The poles are determined by the eigenvalues of the matrix \(A\). From the course of the value for \(A\), as shown in Figure I.1a, the rotor speed for which the system becomes stable increases for increasing wind speed. At 4 m/s the system is stable for all rotor speeds above 0.52 rad/s, while at 10 m/s stability does not occur until the rotor speed reaches 1.32 rad/s.
Figure I.1: Course of $A$ and $B$ at $v_{w0} = [4 \ 7 \ 10]$ m/s

Table I.1: $A$ and $B$ values at different operating points

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>$A$</th>
<th>$A$</th>
<th>$A$</th>
<th>$B$</th>
<th>$B$</th>
<th>$B$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4 m/s</td>
<td>8 m/s</td>
<td>12 m/s</td>
<td>4 m/s</td>
<td>8 m/s</td>
<td>12 m/s</td>
</tr>
<tr>
<td>2</td>
<td>0.0125</td>
<td>0.0250</td>
<td>0.0375</td>
<td>0.0006</td>
<td>0.0012</td>
<td>0.0017</td>
</tr>
<tr>
<td>3</td>
<td>0.0619</td>
<td>0.1239</td>
<td>0.1858</td>
<td>0.0003</td>
<td>0.0007</td>
<td>0.0010</td>
</tr>
<tr>
<td>4</td>
<td>0.0390</td>
<td>0.0780</td>
<td>0.1170</td>
<td>0.0041</td>
<td>0.0082</td>
<td>0.0124</td>
</tr>
<tr>
<td>5</td>
<td>0.0144</td>
<td>0.0288</td>
<td>0.0432</td>
<td>0.0079</td>
<td>0.0158</td>
<td>0.0236</td>
</tr>
<tr>
<td>6</td>
<td>-0.0369</td>
<td>-0.0737</td>
<td>-0.1106</td>
<td>0.0144</td>
<td>0.0289</td>
<td>0.0433</td>
</tr>
<tr>
<td>7</td>
<td>-0.1027</td>
<td>-0.2054</td>
<td>-0.3081</td>
<td>0.0223</td>
<td>0.0446</td>
<td>0.0669</td>
</tr>
<tr>
<td>7.75</td>
<td>-0.1208</td>
<td>-0.2417</td>
<td>-0.3625</td>
<td>0.0234</td>
<td>0.0468</td>
<td>0.0702</td>
</tr>
<tr>
<td>8</td>
<td>-0.1256</td>
<td>-0.2513</td>
<td>-0.3769</td>
<td>0.0235</td>
<td>0.0470</td>
<td>0.0705</td>
</tr>
<tr>
<td>9</td>
<td>-0.1390</td>
<td>-0.2781</td>
<td>-0.4171</td>
<td>0.0228</td>
<td>0.0455</td>
<td>0.0683</td>
</tr>
<tr>
<td>10</td>
<td>-0.1463</td>
<td>-0.2926</td>
<td>-0.4390</td>
<td>0.0209</td>
<td>0.0418</td>
<td>0.0627</td>
</tr>
<tr>
<td>11</td>
<td>-0.1550</td>
<td>-0.3099</td>
<td>-0.4649</td>
<td>0.0193</td>
<td>0.0387</td>
<td>0.0580</td>
</tr>
<tr>
<td>12</td>
<td>-0.1615</td>
<td>-0.3229</td>
<td>-0.4844</td>
<td>0.0172</td>
<td>0.0345</td>
<td>0.0517</td>
</tr>
<tr>
<td>13</td>
<td>-0.1706</td>
<td>-0.3412</td>
<td>-0.5118</td>
<td>0.0159</td>
<td>0.0318</td>
<td>0.0476</td>
</tr>
<tr>
<td>14</td>
<td>-0.1791</td>
<td>-0.3581</td>
<td>-0.5372</td>
<td>0.0143</td>
<td>0.0287</td>
<td>0.0430</td>
</tr>
<tr>
<td>15</td>
<td>-0.1876</td>
<td>-0.3752</td>
<td>-0.5628</td>
<td>0.0128</td>
<td>0.0256</td>
<td>0.0385</td>
</tr>
</tbody>
</table>
Appendix J

Bode diagram of the generator

A linear analysis of the generator model is performed at three different operating points, resulting in the bode diagram shown in Figure J.1. As can be seen here, the operating point of the system does influence its behavior. A higher level of loading results in more damping between the generator and the electrical grid. The shifting of the resonance peak can be explained by the fact that the inertia of the rotor changes relative to the inertia of the generator. The rotor inertia changes because the ratio of the CVT changes, affecting the way in which the generator ‘feels’ the rotor inertia. This can be seen in the definition of the rotor inertia:

\[ J_{r,eq} = \frac{J_r}{\frac{2}{2} + \frac{2}{2} g} \]  

Figure J.1: Bode diagram of the Generator
Appendix K

Behavior in high wind speeds

Figure K.1 shows the wind profile that is used in the evaluation of the system behavior in the high wind speed regime.

First the influence of the wind speed regime on the performance of the ratio setpoint is investigated. The rotor torques for the ratio setpoint with a variable frequency control are compared to the conventional generator torque control. These results are shown in Figure K.2. The total amount of power produced during the high speed wind profile are:

- conventional control: \( E_{\text{total}} = 429.1 \text{ GJ} \)
- CVT control: \( E_{\text{total}} = 431.8 \text{ GJ} \)
Figure K.2: Conventional versus CVT control in high wind speeds

The secondary clamping force required for the slip control is shown in Figure K.3. From the frequency of the oscillations in the clamping force, it can be concluded that the bandwidth for the clamping force actuation should be higher for a CVT control system with a high bandwidth.

Figure K.3: Secondary clamping force for low and high bandwidth control

Figure K.4 shows the tracking behavior of the low and high bandwidth control system when operating in the high wind speed regime. As can be seen when comparing these errors to the errors in the low wind speed regime, mainly the tracking error in the slip control tuned with a low bandwidth is less accurate. But the specification of a maximum tracking error of 0.4 is easily met.
Finally, the influence of the control bandwidth on the generated power is investigated. First of all, the oscillating behavior of the clamping forces is transferred through the CVT into the generator, resulting in faster fluctuations in the generated output power when choosing a high bandwidth. This effect is shown in Figure K.5. The difference in the total amount of energy produced over the wind profile in Figure K.1 is less than 0.01% and therefore not significant in the choice between a low and high bandwidth.
Figure K.5: Oscillating behavior of the generated power in low and high wind speeds, resp.