Dynamic Analysis and Measurement of a Hydrostatic Transmission for Wind Turbines

Dipl.-Ing. Dipl.-Wirt.Ing. Johannes Schmitz

Dipl.-Ing. Nils Vatheuer

Professor Dr.-Ing. Hubertus Murrenhoff

RWTH Aachen University, Institute for Fluid Power Drives and Controls (IFAS), Steinbachstrasse 53, D-52074 Aachen, E-Mail: johannes.schmitz@ifas.rwth-aachen.de

Abstract

Within the scope of a current research project a hydrostatic transmission for wind turbines is being developed at IFAS. In this paper, two different strategies to control a hydrostatic transmission in wind turbines are presented and discussed. Main criteria are the optimal adaption of the system to the current wind situation and at the same time the reduction of loads on the system. In the second part of the paper the two strategies are analysed on a test bench. Therefore three different types of loads are applied considering the behaviour of the controller and the drive train. It can be proven that a torque based controller has the ability to adjust the rotation speed and at the same time reduce peak loads on the drive train. In an outlook, the next steps on the way into a pilot plant are described.

KEYWORDS: hydrostatic transmission, wind turbine, hardware-in-the-loop, dynamic measurement

1. Introduction

The high demand for renewable energy sources being driven by the target to replace all fossil and nuclear power plants has lead to a rapidly growing market for new energy technologies. One major sector here is wind energy. In the past 20 years a huge number of new turbines has been installed and within this process technology to generate electrical power from wind has been improved significantly.

Today the market is dominated by two different types of turbines, both using a three bladed rotor with a horizontal axle of rotation. The first type uses a mechanical transmission to transfer the slow turning shaft of the rotor into a higher rotation speed and drive a generator. With the second one no mechanical transmission is required since a huge generator is installed that can utilize the high torque directly and convert it

to electrical energy. In both cases the rotation of the generator and therefore the frequency of the produced electricity is coupled with the turbine. Due to a variable rotation speed of the turbine a frequency converter is needed to connect each turbine to the grid. Furthermore reliability problems with mechanical gear boxes have occurred and the high weight of the directly driven concept is becoming a problem when increasing turbine sizes. The usage of rare earths could reduce this disadvantage but their rapidly increasing costs due to the high demand are a big element of uncertainty when making the decision on a drive train concept /1/. The most important value to compare the effectiveness of a turbine is the cost of energy since all resulting costs for production and operation are opposed to the produced energy.

A new concept, transferring the power via a hydrostatic drive train is supposed to combine good efficiency and grid stability with high reliability and low costs. In the scope of a research project funded by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety of Germany, IFAS has developed a prototype of a hydrostatic transmission for wind energy plants of the 1-MW power class which is intended to replace the commonly used gearbox and the frequency converter. The idea is to use a slow turning pump that is directly connected to the turbine shaft to transfer the power into a high pressure oil flow and to use a hydrostatic motor that can convert this oil flow back into mechanical power to drive the generator. The high transmission ratio of pump and motor. By using a variable displacement motor the transmission ratio can be varied so that the generator can run at constant speed directly connected to the grid.



Figure 1: Power and torque of a three bladed wind turbine

One of the main requirements when dimensioning a transmission is a good efficiency at rated power as well as in partial load, where the turbine is operating most of the time. At the same time the rotor also influences the total power output, since the energy captured from the wind can be optimised by adjusting the rotation speed of the turbine to the actual wind situation. **Figure 1** shows a power and a torque plot of a three bladed rotor over wind speed and over rotation speed. It can be seen that to each wind speed a specific rotation speed maximises the captured power. At the same time these points of operation are not at maximum torque.

Optimal power production of a wind turbine is achieved by optimizing the drive train to the important points of operation and simultaneously use a control strategy leading to an operation in these points. Therefore a compromise between steady state operation and controllability has to be found. The following chapter 2 describes previous presented work of optimization the hydrostatic drive train. The main properties of the control strategy are described in chapter 3 and 4.

2. Previous work

2.1. Design of the transmission

Initial point for the dimensioning of the hydrostatic transmission was the selection of a wind turbine providing a torque curve over wind speed and rotation speed. Furthermore, previous simulations had proven that by switching of single pumps and motors of a hydrostatic transmission the overall efficiency in partial load can be increased. Subsequently, different combinations of pumps and motors were analysed leading to the transmission shown in **figure 2**.



Figure 2: Hydraulic diagram of the hydrostatic transmission

Two radial piston pumps with a total displacement of 66 l/rev drive three variable and one constant displacement hydraulic motor. The four motors are mounted to two generators. In partial load the pump with 80 % of the total displacement can be switched off by opening a valve to low pressure. Due to the reduced flow rate to the motors three of these are switched off in this point of operation /2/.

2.2. Test bench to validate simulation results

Since not all component data for the simulation were available in this project a test bench to measure single components as well as the entire transmission was designed and built up in the IFAS laboratory. This test bench can be used to validate static and dynamic measurements. In order to operate the test bench efficiently and to avoid a 1.2 MW electric motor and a 1 MW generator, a hydrostatic power feedback was installed. It allows using the output power of the transmission to drive the slow turning input shaft. Figure 3 shows a picture as well as the layout of the hydrostatic transmission and the test bench drive. Two electric motors, powering two axial piston pumps (A1 & A2), feed in losses of the transmission and the drive. A radial piston motor (A3) is used to represent the wind turbine and drives the slow turning shaft. The output power of the transmission is fed back to the electric motors. In this way, the installed electric power is only 2 x 200 kW whereas 1 MW can be applied on the turbine shaft. At all transitions of power across the system boundaries of the transmission, rotation speed and torque is measured to evaluate the overall efficiency. In steady state measurements the rotation speed is controlled by the hydraulic motors of the transmission, while the test bench drive applies a specific torque controlled by altering the two axial piston pumps.



Figure 3: 1 MW test bench for the hydrostatic transmission

2.3. Measurement results of overall efficiency

In the first series of measurements the overall efficiency of the transmission was measured in the point of operation of the turbine marked with the line in figure 1 /3/. Due to the possibility of adapting the transmission to the power to be transferred also the measurements were performed in different configuration. The overall efficiency

from the slow turning shaft to the output of the hydraulic motors is plotted in **figure 4** versus turbine rotation speed. In case both pumps and all motors are activated the overall efficiency at maximum rotation speed is 85 %. With a decreasing rotation speed also the transferred power is decreased and due to constant losses in the system overall efficiency is reduced. The diagram shows, that below a rotation speed of 16 rpm it becomes beneficial to switch off one of the generators and use only two motors. At even lower speed and much lower torque one pump can be set to idle mode leading to an increased system pressure and improved component efficiency.



Figure 4: Measurement result of overall efficiency

In figure 4 there is also one measurement in which the smallest motor is in operation, but another one is still connected to the generator shaft and therefore causes a constant amount of drag losses. In this case the overall efficiency is worse compared to activating the motor and using two motors at a much lower displacement. For the dimensioning of the components this means that the rated power of the generators should be adjusted to the size of the pumps. Thus a pump and a generator can be activated at the same time avoiding drag losses of motors in idle mode. Altogether the simulation result predicting advantages by deactivating single units could be proven in these measurements.

3. Controller strategies to optimize the power production

Besides the overall efficiency of the drive train itself the effectiveness of capturing the power from the wind has a big influence on the total power production. In order to achieve this, the optimal rotation speed of the blades has to be adjusted by the drive train to the actual wind speed as shown in figure 1.

3.1. Control of the turbine's rotation speed

It is obvious that the rotation speed of the turbine can be adjusted by varying the displacement of the hydraulic motors. Since the generators operate at grid frequency their rotation speed is constant and the swash plate motors can define the flow rate in the system by changing the angle of displacement. In addition the used pumps have a constant displacement leading to a proportional correlation of flow rate and rotation speed. In case this strategy was selected the controller would have to use the actual wind speed and specify the optimal rotation speed according to the characteristics of the blades. The desired rotation speed could then be adjusted by the motors.

However, there are two major challenges with this strategy. First of all the actual wind speed is hard to measure on a real wind turbine. Because of the large area covered by the blades the wind varies within this area in speed and direction. A single wind speed sensor mounted on top of the nacelle can hardly detect all these effects and deliver only approximate values. Furthermore the big inertia of the turbine makes it difficult to change the rotation speed synchronously to the fast fluctuating wind. Each short gust of wind would lead to a short acceleration of the turbine initiated by the controller. In this phase all the incoming power would be stored in the rotor's inertia leading to interrupted power production. After the gust the controller would decelerate the rotor again having an increased power output for a short time. These described fast load changes are possible with the hydrostatic transmission but make the adaption of the system to the actual load more complicated. When using the switching strategy presented in figure 4 each harsh change of the braking torque involves the switching of several components. Due to a high priority on reliability such an operation of the system has to be avoided.

3.2. Control of the transmission's load torque

In contrast to the control strategy presented before the rotation speed of the wind turbine can also be adjusted by controlling the braking torque of the transmission. In case the rotation speed is too high a defined amount of additional braking torque could be added to decelerate the turbine. However the controller needs information about the actual wind speed to define the optimal rotation speed.

One solution avoiding wind speed measurement is to conclude the wind situation according to the acceleration of the turbine. This method is used in the following control strategy: The controller of the hydrostatic transmission applies a braking torque on the turbine according to the actual rotation speed assuming an optimal point of operation.

Figure 5 shows the torque equilibrium on the inertia of the rotor. The braking torque applied by the transmission shown on the right is independent from wind speed.



Figure 5: Equilibrium of torque on the turbine

In case wind speed is higher than assumed, more torque than discharged by the transmission will be captured leading to an acceleration of the turbine. To illustrate the operation of the turbine a diagram with the maximum of both plots in figure 5 was generated in **Figure 6** on the left. It can be seen that a groove between the two surfaces occurs in which the turbine will operate in steady state. The marked arrows in the plot show the reaction on a gust of wind. Whenever a fast gust occurs the captured torque will increase accelerating the turbine. With the increasing rotation speed the transmission will also increase the braking torque of the drive train. Once the gust is going down, the braking torque is too high decelerating the turbine to the groove again.



Figure 6: Controller strategy of the hydrostatic transmission

By varying the parameter of the torque curve deposited in the controller this groove can be adjusted to the optimal point of operation in which the overall efficiency of turbine and drive train is optimal. The two plots on the right in figure 6 show a simulation result of the controller. The upper curve describes the applied wind speeds on the simulated turbine leading to the points of operation marked below. It can be seen how all points accumulate around a straight line defined by the groove shown on the left.

In contrast to the control strategy described in chapter 3.1 the torque based control strategy leads to a smoothened power production since the turbine's inertia is used as flywheel to store peak power from the wind. This effect will be shown in measurement results in the following chapter. The switching between different transmission-configurations is without any problems since the braking torque can only change as fast as the rotation speed does. Most importantly, the strategy is based on the rotation speed of the turbine which can be measured precisely and cost-effective.

4. Validation of the dynamic behaviour on the test bench

4.1. Measurement setup

To get the possibility of verifying simulation results of the controller on the test bench, the inertia of the turbine has to be included into the tests too. Since it is not possible to install such a huge flywheel directly on the test bench it has to be considered virtually in a real-time simulation. **Figure 7** demonstrates the coupling of the simulated inertia to the test bench and which signals are being transferred in the following test.



Figure 7: Integration of the rotor's inertia to the test bench

Initial point is a torque signal applied on the model of a flywheel in the real-time simulation. The rotation speed of the inertia is sent to the test bench drive where a rotation speed controller sets the same rotation speed on the test bench. The braking torque of the hydrostatic transmission is measured at the slow turning shaft and transmitted into the simulation to be applied on the inertia as load torque. In the following measurements all units of the hydrostatic transmission will be in operation but

two different setups will be used. In the first one all motors are set to a constant displacement whereas in the second one a controller for the braking torque as shown in chapter 3.2 is activated.

4.2. Consulted loads cases

The effects of the control strategy will be demonstrated using three different load cases shown in **figure 8**. Load Case A is a simple torque step from 100 kNm to 150 kNm. The considered case B is the torque curve of a gust of wind also called a 'Mexican Hat' and case C is a 50 seconds section of real operation. The data for the two last files was generated in the certificated software bladed by TU Delft. The software considers all relevant aerodynamic effects of the blades and is widely used in wind energy branch.



Figure 8: Three different load cases used to test the hydrostatic transmission

4.3. Measurement results

4.3.1. Torque step

The measurement result with an applied torque step is shown in **figure 9**. The two upper diagrams present the behaviour of the hydrostatic transmission with constant motor displacement. On the left side the applied torque step and the resulting load torque measured for three different inertias of the turbine are plotted. It can be seen that after the torque step occurs the measured torque on the test bench also rises and oscillates to the new value. With an increased inertia of the turbine the resonant frequency of the drive train is decreasing /4/. The diagram on the right presents the effect on the rotation speed of the turbine. Due to a rising pressure in the transmission

the leakage is increased leading to a slightly increasing rotation speed of the turbine. The higher the turbine's inertia is set, the more energy is stored in the flywheel with the slight change of speed.



Figure 9: Measurement result of an applied torque step

The plots in the second half of the diagram display the same measurement as before but with a torque controlled transmission. In this case the torque step leads to higher applied torque than braked by the transmission and consequently a rising rotation speed. The load torque on the test bench rises proportional to the rotation speed until the equilibrium of torque is set again.

4.3.2. Gust of wind

For the load case 'Mexican Hat' the same two different measurements were performed. **Figure 10** shows the results. With a constant motor displacement there is only a short delay between applied and measured torque. The rotation speed can only rise slightly and therefore the peak power delivered by the wind has to be transferred by the transmission. Due to the elasticity of the hydraulic drive train the measured torque on the test bench is even higher than the one applied on the inertia. Again the second half of figure 10 presents the result with a torque controlled transmission. In this case the turbine can speed up about 2 rpm and thereby store most of the peak energy of the gust. The maximum torque measured on the test bench is 120 kNm lower than the applied load. When this torque is going down again, rotation speed decreases also extracting stored energy in the flywheel and going back to constant operation.



Figure 10: Measurement result of an applied Mexican Hat

4.3.3. Real wind conditions

In the last measurement all usual effects like the tower shadow effect, short gusts of wind and a changing wind speed in the long term were considered. **Figure 11** shows the measured torque and the behaviour of the rotation speed with the two different control strategies.



Figure 11: Measurement result of a real wind load

In case the motor displacement is set constant the measured torque follows the applied torque only smoothening torque peaks with a short delay. In case the torque controller is activated the power smoothening is much better due to a changing rotation speed. The short oscillations of this torque signal show that the controller of the transmission has to be optimised.

5. Conclusion and Outlook

In this paper two different ways to control a wind turbine using a hydrostatic transmission have been discussed and validated on a test bench. It has been shown, that a torque based control strategy can deliver a good compromise of adjusting an optimal rotation speed and guarantee a continuous power production. This behaviour gives the possibility to adapt the transmission to the point of operation by switching off single components of the drive train.

In a next phase of the project funded by the Fluid Power Research Fund the different controller modules switching the components and controlling the rotation speed will be brought together with all required safety functions. In parallel all needed peripheral system like cooler and supply pumps will be installed at the test bench. An improved aerodynamic model that can run in the real-time simulation at the test bench will make it possible to apply direct data from wind measurements on the test bench. Thus the transmission will be acting if being installed in a turbine. At the end of this project the transmission will be ready to be installed in a pilot plant.

6. References

- /1/ Vath, A.; Schmidt, S.: Design of efficient and reliable drive trains for large offshore wind turbines, EWEA Offshore 2011, November 29-30, 2011, Amsterdam, The Netherlands.
- /2/ Schmitz, J.; Vatheuer, N.; Murrenhoff, H.: Hydrostatic drive train in Wind Energy Plants, EWEA 2011, Brussels, March 14-17, 2011, Brussels, Belgium, pp. 20-23.
- /3/ ISO 4409:2007(E), Hydraulic fluid power Positive-displacement pumps, motors and integral transmissions – Methods of testing and presenting basic steady state performance, Second edition 2007-04-01.
- /4/ Murrenhoff, H.: "Servohydraulik Geregelte hydraulische Antriebe," 3rd ed., RWTH Aachen, Aachen, Germany, 2008.