The Influence of Control Strategies on the Energy Capture of Wind Turbines

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Abstract

The energy capture of wind turbines depends not only on the wind conditions, but also on the control strategy used. This influence is difficult to measure experimentally, as differences in the site conditions are likely to enter the results. Therefore, a simulational approach is presented to compare the energy capture of different control concepts under different conditions. The results are therefore valid for a broad range of sites. They show that the very different figures found in the literature for such comparisons can be mainly explained by different parameters.

1 Introduction

In recent years, many different control strategies for wind turbines have been developed, which creates the problem of finding the best suited. One criterion is the annual energy capture of the respective concepts, but there are stll very different opinions on this. For example, the energy gain of variable speed over constant speed operation is said to be between 2% and 7% in [1], while [2] claims that it is up to 20% and [3] says that it is 38%.

As the energy capture of a wind turbine and its control strategy depends on the annual mean wind speed, on the turbulence, the aerodynamic profiles used for the rotor and the design tip speed ratio (and probably many other factors), it is clear that there will be different results. This paper shows the general influence of some parameters on the relative performance of different control strategies to show which conditions will favour which control strategy.

A comparison of different control strategies by measurements will always be problematic because of the influence of different site conditions. Furthermore, it is prohibitively expensive to use an adequate number of sites for measurements under many different conditions. Therefore, it is clear that simulation must be used here.

2 The simulation model

For the comparison of control strategies, a dynamic model of a $600kW$ wind turbine is used, which includes the aerodynamics, the inertia of the rotating masses and the controllers for torque and pitch angle. One time-domain simulation is done for each average windspeed and each turbulence level. After each simulation the average power for the time interval is calculated and after all simulations the energy capture is found by using a Rayleigh-distribution on the average power values.

The dynamic model consists of a windspeed generator which produces the actual windspeed according to the wanted mean windspeed and turbulence, which is then fed to the aerodynamical part of the model, consisting of a two-dimensional characteristic dependent on pitch angle and tip speed ratio delivering the power coefficient c_p. The characteristic is calculated from a blade element model in [4]. The turbine power P is then found from $P = 0.5\rho F v^3 c_p$, where ρ is the air density, F is the rotor area and v is the actual windspeed.

From the dynamics of the wind turbine only the rotor inertia of $500kNms^2$ is included, as it is the only property that influences the basic control strategy.

From the shaft power the losses of the system between the rotor axis and the grid connection point are subtracted. They are calculated from the following formulas, which are condensed from [5]. For a one- or two-speed turbine with gearbox and asynchronous generator:

$$P_l = 0.03P_r + 0.017P + 0.015\frac{P^2}{P_r}$$

For a variable speed turbine with direct driven synchronous generator:

$$P_l = 0.001P_r + 0.022P_r\frac{n}{n_r} + 0.029P\frac{n_r}{n} + 0.04\frac{P^2}{P_r}\frac{n_r^2}{n^2}$$

Here, P is shaft power, n is rotor speed, and the indices are l for losses and r for rated conditions. All concepts were calibrated so that the maximum average output power for 10% turbulence is $600kW$. The following control concepts were used in this comparison (numbers refer to numbers in figures):

Single-speed stall controlled wind turbine with asynchronous generator (1), two-speed stall controlled wind turbine with asynchronous pole-changing generator (2), single speed active-stall (pitchable rotor blades to make the stall controllable) controlled wind turbine with asynchronous generator (3), two-speed active stall controlled wind turbine with asynchronous pole-changing generator (4), single-speed pitch controlled wind turbine with asynchronous generator (5), two-speed pitch controlled wind turbine with asynchronous pole-changing generator (6), variable-speed stall controlled gearless wind turbine with converter fed synchronous generator (7) and variable-speed pitch controlled gearless wind turbine with converter fed synchronous generator (8).

3 Results

It is important to notice that in the following figures all energy captures are normalized to the energy capture of concept (1). Although this does not show the absolute energy capture, it makes the differences between the concepts much more visible.

3.1 The influence of site conditions

As shown in figure 1, the constant-speed concepts which can turn their rotor blades (3,5) increase their energy gain at low average windspeeds because of their ability to pitch the blades to an angle which optimizes the power coefficient. They also show an increased gain at high average windspeeds which is due to their ability to keep the output power constant at windspeeds above rated windspeed, while the output power of stall controlled concepts decreases here.

The two-speed, stall controlled concept (2) gives an increasing gain at low windspeeds, as the time

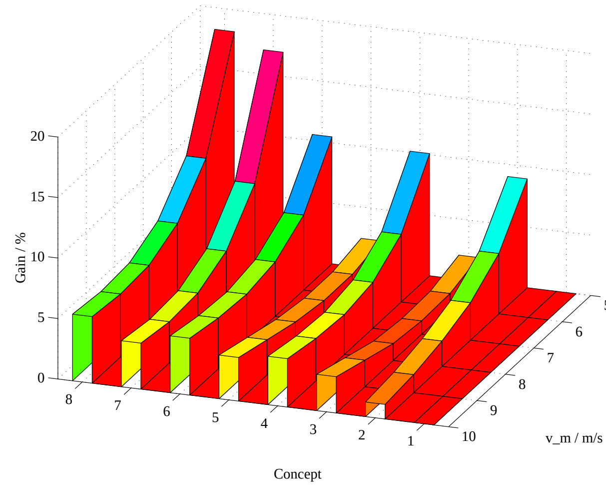

Figure 1: Energy Gain as a function of annual average windspeed. Turbulence 10%, design tip speed ratio 6, profile Goe 758

where the lower rotor speed is used increases here. The two-speed concepts with pitchable blades (4,6) combine the gains of the concepts (3,5) with the two-speed gain of concept (2).

The variable speed concepts (7,8) have the highest gains at low windspeeds as their ability to use the rotor with optimum efficiency pays off most here. The pitch controlled concept (8) keeps a slight advantage over concept (6) even at high windspeeds while the stall controlled concept (7) gives lower energy output at high average windspeeds which indicates that this concept might not be optimum for offshore use with high average windspeeds, although it was proposed for this recently.

Figure 2 shows the influence of turbulence on the energy capture for one annual average windspeed.

The gain values at zero turbulence show what would have been computed from steady state power curves. It can be clearly seen that the turbulence at the actual site is of great importance when judging different concepts.

The energy capture of the single-speed, active stall controlled concept (3) is almost independent of tur-

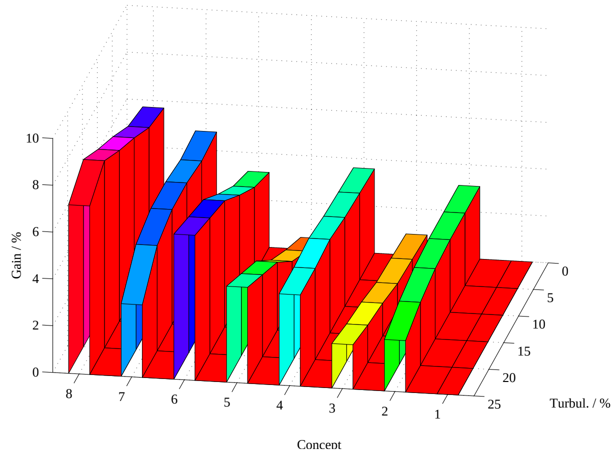

Figure 2: Energy Gain as a function of turbulence. Annual average windspeed $7m/s$, design tip speed ratio 6, profile Goe 758

bulence, as the active stall control allows the power to be controlled very fast, as the passive stall does in concept (1). The pitch control in concept (5) gives an increasing energy gain with increasing turbulence, because the power control is rather slow here due to the large turn angles needed. For high turbulence this slow control leads to average output power values which are much above rated power around rated windspeed, and this overpower leads to an increase in energy capture.

The energy capture of the two-speed, stall and active stall controlled concepts (2,4) falls with increasing turbulence, because at high turbulence levels the rotor will unwantedly stall during strong wind gusts while it is in low-speed mode. For the two-speed, pitch controlled concept (6) the effects mentioned for the concepts (4) and (5) add and it can be seen that the energy gain mentioned for (5) overcompensates the loss at low speed of (2,4).

The gain of the variable-speed, stall controlled concept (7) is almost constant at low turbulence, while it shows a strong decrease above 15% turbulence. This is caused by strong wind gusts stalling the rotor while the rotor speed is still low in partial load operation. The high rotor inertia prohibits the rotor from following the changes of the windspeed, an effect which will increase with increasing turbine size.

The energy gain of the variable-speed, pitch controlled turbine (8) increases with increasing turbulence at low turbulence levels because near rated windspeed some energy will be stored in an increase in rotor speed during wind gusts before the pitch controller is able to counteract. This energy can be used when the windspeed falls again. For high turbulence levels (above 20%), the loss described for concept (7) overcompensates this so that the energy gain decreases.

As the advantage of a variable-speed pitch controlled wind turbine (8) over a two-speed pitch controlled one (6) decreases both with increasing mean windspeed and with increasing tubulence, there must be a point where the two strategies give the same energy capture. This point is in the simulation at $9m/s$ average windspeed and 20% turbulence. For higher mean windspeeds and turbulence levels concept (6) will provide a higher energy capture. As the advantages of sophisticated control strategies as concept (8) are most likely overestimated in simulation, this crossover point will probably be at somewhat lower turbulence and mean windspeed in reality.

3.2 Influence of design tip speed ratio

Figure 3 shows the energy gain as a function of average wind speed again, but this time for a design tip speed ratio of 12, as high design tip speed ratios were recently proposed for offshore wind turbines. When comparing it to figure 1 it can be seen that the gains of all control strategies at low windspeeds are much higher for the high design tip speed ra-

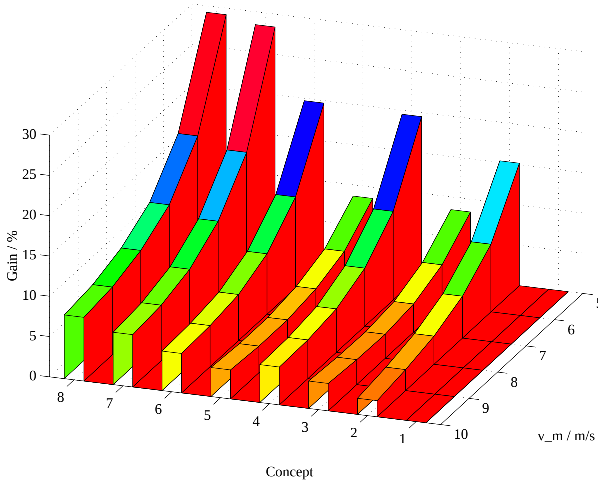

Figure 3: Energy Gain as a function of annual average windspeed. Turbulence 10%, design tip speed ratio 12, profile Goe 758

tio. The cause for this is that a rotor with a high design tip speed ratio has a “sharper” rotor characteristic, i.e. a steeper decrease in power if the rotor is operated off the design point. Especially the two-speed (2,4,6) and variable-speed (7,8) concepts benefit from this. Even at high windspeeds, the gains of the more advanced control concepts are higher than with a low design tip speed ratio. This means that a higher design tip speed ratio calls for variable-speed or at least two-speed operation.

3.3 Influence of rotor profile

The final paper will also contain a similar figure for a rotor profile with a much broader stall characteristic, which shows that for such a profile the energy gains are almost independent of turbulence, as the unwanted stall effects in partial load operation are mostly gone. Only the effects of stalling the rotor unwanted in low speed operation for the two-speed, stall controlled concept (2) and the energy storage in the rotor inertia for the variable-speed, pitch controlled concept (8) at high turbulence levels remain.

4 Conclusion and Outlook

This study has shown that the advantages in terms of annual energy capture of different control concepts are to a large extent dependent on site and turbine parameters. An overview of the dependence on some of these parameters is given, which shows that the different figures in different publications are mainly explainable by this.

If a similar study on the cost differences of the different concepts would become available, it would also be possible to select the control concept which delivers the lowest cost per energy depending on the intended site and project parameters from a similar comparison using the specific project data.

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