Wind Farm Power Regulation Using Yaw Control and Axial Induction Control

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Abstract

With wind energy gaining importane on the energy marked, wordt optimaal gebruikmaken van de beschikbare resorces, zowel als betrouwbaarheid en stabielitijd van steeds groter belang. Nowadays, more and more of the wind energy is generated in windfarms. These farms have the advantages of beeing cheaper in instalation aswell as maintanance. However, the currend controll method(gready controll) is far from optimal, and only takes power into account. This paper combines the use of 2 other types of controll methods (yaw and axial induction controll) to find the optimal running procedure of a windfarm. Decresing the damaging loads on the turbines, while beter regulating the poweroutput. At the same time making wind energy cheaper aswell as increasing its stabillitie. Making windenergy ready for the future.

1. Introduction

To efficiently use wind resource rich locations and minimize the cost of wind energy, wind turbines are constructed in close proximity of each other, creating wind farms. A side effect of wind turbine operation is the development of wakes. When wind turbines are placed in close proximity of each other, wakes can have negative effects on downwind turbines. A wake is developed behind a wind turbine and can reduce the power production while increasing the loads of the downwind turbine. A wake can be described by several characteristics, such as a decreased wind velocity caused by the turbine's extraction of energy, an increased turbulent wind flow caused by the rotation of the turbine blades, and a wake deflection can occur which can lead to suboptimal power and load conditions [6, 8, 9, 4, 3].

With an increasing role of wind energy (quantify this) in Europe's energy production new challenges arise[1]. While the electrical power system becomes more dependent on wind energy, it is important for wind farms to be able to meet the demands of the power system by regulating its power output [2]. Traditionally, the need for power regulation of a wind farm was not necessary, because the wind farms energy production was only a small part of the total energy production. As a result, the wind farms could always perform at maximum capacity, without the risk of overloading the power system. However, because wind energy production has increased in the recent years, and will continue to increase, regulating rather than maximizing power output becomes more important.

Regulating the power output of a wind farm is essential because an under- or overload of energy can decrease the stability of the power system [2]. Instability can lead to suboptimal operation of the power system, such as an energy overload [2, **?**]. Currently, most wind farms operate based on 'greedy control', meaning that each individual turbine is set to run for maximum power production, without taking loads into account introduced by power maximization. This could lead to problems when, for example, the power demand is low while the power system depends largely on wind energy. With the risk of resulting in an overload of the power system. Power regulation of a wind farm can solve this problem.

There are several methods for power regulation of a wind farm, two of which will be discussed in this paper, those are, yaw control and axial induction control. Yaw control can be used as a method to reduce the power output of a single wind turbine and as a method to increase power output and reduce loads of a wind farm [9, 8, 4, 16]. A disadvantage of yawing is an increase of load on the yawed turbine, and thus reducing its lifespan [3, 7]. In addition, yawing a turbine can deflect a wake. This can be used as a method to redirect a wake from a downwind turbine. This reduces the loads and increases the power output of the downwind turbine(van dijk, wilson, fleming). However, under unfavorable conditions it can result in an asymmetrical overlap of the wake on the downwind turbine. This can significantly increase the loads of the downwind turbine [8, 9]. Therefore, it is necessary to understand the effects of yawing a turbine, what this does with its wake, and how this effects the downwind turbines.

Axial induction control influences the power output of a turbine by means of the blade pitch angle and generator torque. The axial induction factor is denoted by a, and reflects the relation between the decrease in wind velocity of the free stream wind and the wind velocity leaving the rotor. By varying the axial induction factor of a wind turbine, the power output can be controlled. Loads that are introduced by varying a turbine's axial induction factor will not be discussed in this paper. As yawing of the turbine and the deflection of a wake can cause additional loads on the turbines of a wind farm, a trade-off must be made between power regulation and loads minimization.

Previous studies have mainly focused on maximizing the power output while taking the loads into account, so that an optimum is found between the two [9, 16, 8]. However, increased loading effects on a turbine due to yaw misalignment were not considered. Furthermore, the objective of these studies is power maximization rather than power regulation. Power regulation through a combination of yaw control and axial induction control while minimizing loads is still novel. This paper will focus on the optimization of power regulation, by means of yaw control and axial induction control, while minimizing the loads. In addition, the loading effects on a turbine caused by yaw misalignment is studied.

Hier nog een overzicht van wat er in paper te vinden is. Moet later geschreven worden als de rest af is.

2. Method

To realize active power control and minimizing loads by yaw control and axial induction, it is necessary to know the effects of different flow conditions on the total power of the wind farm and the effect of different flow conditions on the loads for each of the turbine. Moreover, there need to be an optimizer which executes the optimization to approach a set value for the power and to minimize the loads.
The total power of the wind farm is calculated with the FLORIS-model. Besides, FLORIS is able to adjust the turbine configurations, the axial induction and yaw position. The effect

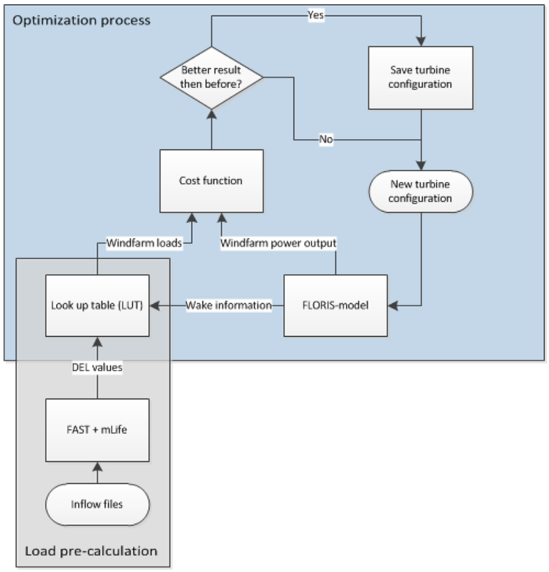


Figure 1: *Overview of the optimization procedure.*

of the wind flow on a turbine, regarding the loads, are given by the programs FAST and MLife. The output of these programs are Damage Equivalent Load values (DELs), which are a measure of equivalent load damage to the turbine concerning the material properties.[14] These DELs are calculated for a different set of wind and turbine conditions and are stored in a look-up table(LUT).

The optimizer takes the desired power production of the wind farm as an input. It used the configurations of the turbines from FLORIS to find the corresponding DEL values in the look-up table. If the configurations of the turbines are an improvement compared to the previous one, i.e. a improved power control or a reduce in the loads, FLORIS will save this turbine configurations. An overview of the optimization procedure is shown in Figure 1.

In the following sections, different models and model steps, used to perform the optimization, are explained:

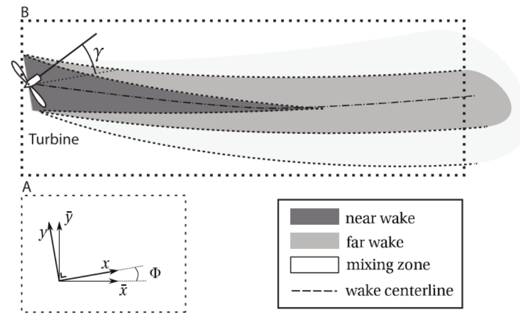


Figure 2: *Simplified top view representation of a wake of a turbine by FLORIS.[11]*

2.1. FLORIS

The FLOw Redirection and Induction in Steady state (FLORIS) model calculates the power of the wind farm as a function of the yaw misalignment and the axial induction. [11] FLORIS is a relative accurate[9] and a low computation model, due to the fact that it uses high-fidelity data from a computational fluid dynamics simulation.

2.1.1 Wake modelling

As can be seen in Figure 2, FLORIS contains a wake model which divides the wake in different zones: the near wake, the far wake, and the mixing zone, $q = 1$, $q = 2$, and $q = 3$ respectively. Each zone has its own diameter and wind speed, which are calculated by FLORIS.(1 to 2).
Let D_i denote the rotor diameter of the i^{th} turbine, k_e a coefficient that describes expansion of the zones , and $m_{e,q}$ the expansion factor which are calculated by Gebraad.[11]. The size of the wake diameter $D_{w,q,i}$ increases proportionally to the downwind distance (x). The diameter of the wake diameter is computed by,

$$D_{w,i,q}(x) = max(D_i + 2k_e m_{e,q}([x - X_i], 0) \quad (1)$$

Also the velocity depends on the downwind distance (x), which is an argument of the wake decay coefficient $c(x,y)$.2. This wake decay coefficient is multiplied by the axial induction factor and subtracted from the free stream velocity U_i. The axial induction factor is a value for the decrease in wind velocity behind a turbine relative to its own rotor speed. The wake decay coefficient describes the decay of velocity for each wake zone and is defined in 3. The model parameter $M_{U,q}$, which depends on the wake zone and the yaw angle, is calculated by Gebraad.[11]

$$U_{w,i}(x,y) = U_i\,(1 - 2a_i c_i(x,y)) \tag{2}$$

$$c_{i,q}(x) = \left[\frac{D_i}{D_i + 2k_e m_{U,q}(\gamma_i)[x - X_i]}\right]^2 \tag{3}$$

2.2. FAST & MLife

FAST is a programming tool for the simulation of dynamic (load) responses of wind turbines (by NREL) [12]. It uses wind turbine specifications as well as wind flow situations. By evaluating a flow field, FAST computes the bending moment of a blade. Since the bending moment of a blade does not give direct information about the effect on the life-cycle time of a turbine, the program MLife is used to convert the bending moment to damage equivalent loads (DELs).

2.3. Inflow files, Flow field

FLORIS describes a discrete flow field of a wake, with three zones. The flow field of the wake in FLORIS is calculated with equations ((1 to 2)). The wake is divided into three zones as described in paragraph 2.1.1. A real wake will not have discrete zones, but a more fluent transition between the wake zones. To create a more fluent transition between the different wake-zones a Gaussian distribution of the flow field is preferred [10].The difference of wake shape between a Gaussian and discrete shape can be seen in Figure 3. The Gaussian distribution is calculated as followed,

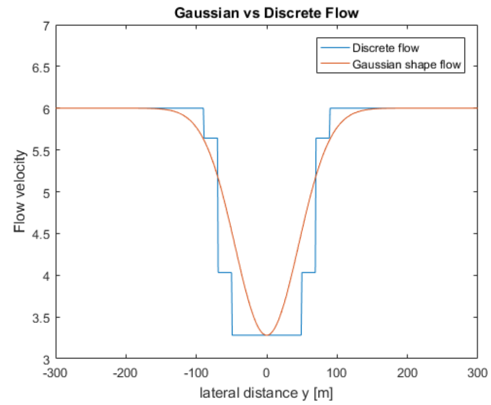


Figure 3: *Discrete wake versus Gaussian wake*

$$G(y,z) = A[e^{-(\frac{y^2}{2\sigma_y}+\frac{z^2}{2\sigma_z})}] \tag{4}$$

where the amplitude of the Gaussian, A, is equal to the velocity loss of the inner wake zone, $U_{w,1}$, which is calculated with equation 2. σ_y and σ_z reflect the Gaussian standard deviation in horizontal and vertical direction, respectively. The standard deviations are related to the outer wake zone $D_{w,i,q=3}$ which is given in 5,

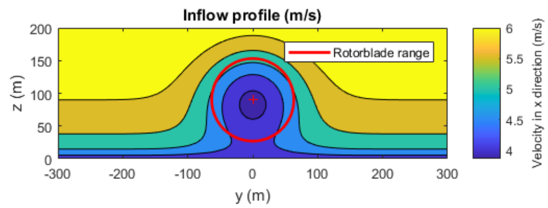
$$\sigma_y, \sigma_z = D_{w,i,q=3}/n \tag{5}$$

Where n can be modified to change the width of the Gaussian. Consequently, it is possible to fit the Gaussian to the wake zones of Gebraad. (Figure 3)

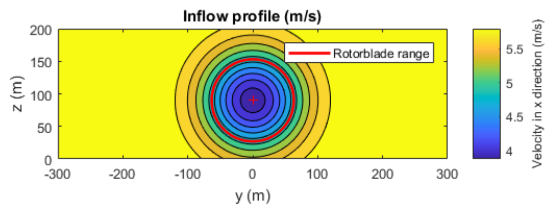
2.4. Wind shear

Wind shear can cause an important difference in velocity speeds between the rotor hub height, the end of the rotor blades at their highest points and the end of the rotor blades at their lowest point [13]. The velocity distribution is calculated with,

$$v = v_{ref}\left[\frac{h}{h_{ref}}\right]^{\alpha} \tag{6}$$



(a) *Flow field with wind shear.*



(b) *Flow field without wind shear*

Figure 4: *Gaussian wind fields with a free stream velocity of 6 m/s at a height of 90 m. The outer diameter of de wake is 220 m and the diameter of the rotor blades is 126.4 m.*

where v and v_{ref} are the velocity at heights h, and h_{ref} respectively. Value α is the wind shear coefficient which depends on different factors. Coefficient α is fixed at value 0.1, reflecting a terrain type close to ocean and smooth ground [13]. The wind shear is implemented in the flow field. The difference between a flow field with and without wind shear can be seen in Figure 4

Table 1: *Overview of the minimum value, maximum value, and step size of the parameters, diameter of outer wake zone (Dwake), free stream wind speed (U), yaw of the turbine (yaw), and the center to center distance between the center of the turbine and the center of the wake (y wake).*

	Minimum	Maximum	Step-size
Dwake	180	330	25
U	6	8	2
yaw	-30	30	*
y wake	-250	250	10

*Input values for yaw are [-30, -10, -5, 0, 5, 10, 30].

2.5. LUT

To reduce computational time during optimization a look-up table (LUT) is created. The LUT is created using FAST and MLife, and it contains a a large number of DEL values for a wide variety of wind field conditions on a wind turbine. These different conditions are described by the ranges of the parameters, which can be seen in Table 1. The parameters are wake characteristics which can be extracted from FLORIS. The parameters chosen for the LUT are:

- the free stream wind speed, U
- the outer diameter of the wake, Dwake
- the yaw of the turbine, yaw
- the center to center distance between the turbine and the wake, y wake

To save calculation time, the LUT parameters are discretized, given each parameter a certain step-size. This step-size is chosen such that interpolation will give a representative result. For each parameters step-sizes are selected, as shown in Table 1. With the use of the pre-calculated LUT, online optimization can be realized.

This paper uses the wake diameter as a parameter to characterise the wakes. However, as stated before are the diameter of the wake, the downwind distance and the windspeed reduction behind the turbine(Udef) related by fitting equations. This means that the distance and the Udef could have been used as parameter just as well. The choice for the diameter comes since Floris searches for the best fit of the shape of a wake in the LUT data. And the diameter gives a more direct interpretation of the shape of the wake than the others do, subsequently meaning that the diameter comes more intuitively.

2.6. Optimization

To optimize for power reference tracking and load minimization, a game-theoretic approach was used.[15] The optimization algorithm searches for the optimal yaw and axial induction settings of each individual turbine. These can influence the power and loads significantly, so both are combined in a cost function. [15][9]

2.6.1 Cost Function

The cost function depends on two variables: a normalized power and a normalized load variable. To achieve the optimal yaw and axial induction settings a mixed-objective cost function is defined as follows:

$$J(P, DEL) = c * ((P_{ref} - P(a_i, \gamma_i))/P_{bw})^2 + (1 - c) * DEL(a_i, \gamma_i)/DEL_{base} \quad (7)$$

Where c is the tuning parameter for the optimization between power and loads and P_{ref} is the desired power output of the wind farm. P_{bw} and DEL_{base} are the power and loads baselines respectively, to create normalized variables.
To execute the optimization, the cost function has to be minimized. To obtain power production close to the reference, the power part of the cost function is a quadratic difference. As a result values much larger than the reference are heavily penalized, whereas the power crosses P_{bw} the emphasis shifts to the loads.

2.6.2 Game Theory

The game-theoretic approach uses random perturbations for the yaw angles and the axial induction to optimize the cost function. When new values for yaw and axial induction settings give an improvement regarding the cost function, the settings are saved and the process will be repeated with the new settings. Because of the fact it uses random perturbations, the game theoretic approach is an adequate optimizer to find the global minimum of the cost function.[9]

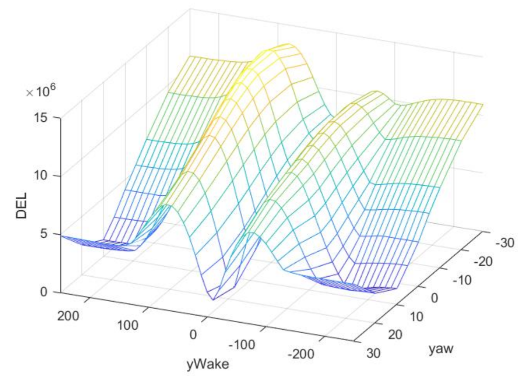


Figure 5: *Slice of the LUT with a D_{wake} of 230m and a U_{fs} of 8m/s*

3. Results

In this chapter different results are shown.

3.1. Look-up-table

As an example of the DEL values stored in the LUT a visualization of a slice with a D_{wake} of 230m and a U_{fs} of 8m/s is shown in figure 5. Slices for different D_{wake} and U_{fs} look similarly.

3.2. Optimization

The optimization script is run on a set of nine wind turbines which are place in a 3-by-3 grid. As a reference 'greedy control' is used. To determine the maximum power the nine wind turbines can deliver an optimization is executed taking only power into account. See table 2 for the power and DEL values for both these situations.
To show the optimization script in action five cases are evaluated. Each case has its reference power P_{ref} set as a percentage of the maximum power. In figure 7 power and DEL values during optimization with a reference power of 90% are shown. Figure 6 shows the final turbine configuration for this optimization run.
Figure 8 shows the DEL values for different reference powers.

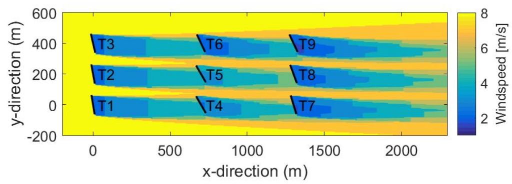


Figure 6: *Turbine configuration after optimization with P_{ref} at 90%*

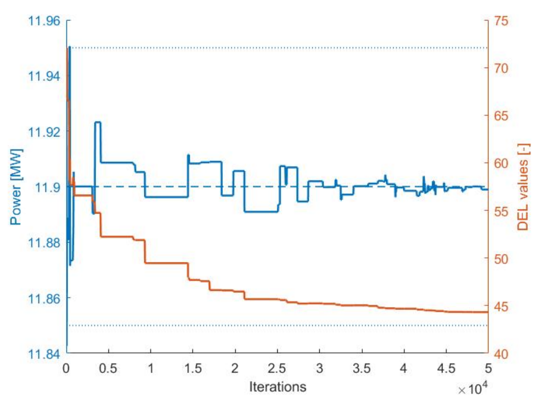


Figure 7: *Loads and power during optimization with P_{ref} at 90%*

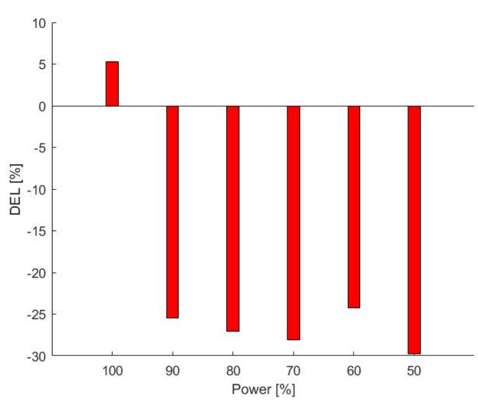


Figure 8: *DEL values for different P_{ref}*

Table 2: *Power and DEL values for greedy control and power-only optimization*

	Greedy control	Power-only
Power [MW]	12.42	13.22
DEL value [-]	5.94E7	-

4. Conclusion, Discussion and Recommendations

What have we done and how to interpret the results

4.1. Conclusion

Conclusion about the results, Power reduction by axial induction and yaw control will lead to a reduction in the loads on the wind farm.

4.2. Discussion & Recommendations

This article which presents the results of an multi-objective wind farm optimization through yaw control and axial induction is bound to a number of limitations:

The low fidelity steady state model FLORIS is used to calculate the flow in the wind farm. Turbulence and dynamic propagation of the wake as a consequence of turbine settings, and the effect of wakes influencing each other, are not implemented. Moreover, the turbine determines its loads only for the most overlapping wake on the turbine, for other overlapping wakes a mean value of the velocity is taken. Besides, axial induction of the turbine is not applied to the loads but only to the power production of the turbine. Furthermore, the results for reference power tracking and load minimizations are only obtained from a three by three setup of wind turbines. Another setup or number of wind turbines may lead to other results.

FAST calculates the loads on the turbine

based on a modeled inflow field which also does not take turbulence effects in the wake into account. The effect of dynamic propagation of the wake will lead to other load values. The shear effect on the wind speed of the inflow field is calculated for a reference height and speed. Also the shear constant was set for a flat ocean ground surface.
The continuous wake profile uses only the velocity in the inner wake zone and the diameter of the outer wake zone from Gebraad. [11] The partition of the wake in several wake zones with its own diameter and velocity is not longer implemented. For a sufficient model of the wake, a continuous function with more adjustable variables compared to one Gaussian function should be considered.

Linear interpolation out of the LUT is used to calculate the DEL values for intermediate parameter values. This can lead to a deviation in DEL values with respect to a direct calculation. For one range of calculations of the LUT some extreme values occur. These values have been smoothed. However, these values lay out of the scope of the optimization problem so it had not an effect on the optimization at all.

Individual Pitch Control is not implemented in the values of the LUT, but could be an interesting addition to reduce the loads.[8]

Although the possibility of minimizing loads by reducing power and the change of yaw and axial induction is demonstrated in this article, a global minimum in the optimization problem is not found. Several simulations with the same input settings lead to small differences in final power and load values. Moreover, the yaw and axial induction settings were complete different for every simulation.
The loads are only minimized for the complete wind farm, not for an individual turbine. A suggestion for further research is to set a constraint for the maximal DEL value for each of the turbine in the wind farm. This also could be a solution for more identical results regarding the turbine settings.

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