Wind Farm

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Abstract

This will be the abstract of our paper. We will show how cool our research is and how important we are. Blabla Lorem impsum.

I. Introduction

To minimize cost of wind energy and to efficiently use resource rich locations, wind farms are constructed, characterized by a large concentration of wind turbines. An inherent side effect of wind turbine however is a wake. When wind turbines are placed in close proximity of each other in a wind farm, a wake can have negative effects. A wake forms behind an upwind wind turbine and can have severe effects on the power production and loads of the downwind turbine.

With an increasing role of wind energy in Europe's energy production [1], it is important for wind farms to be able to meet the demands of the power system [2]. Controlling the power output of a wind farm is essential because an overload of energy can decrease the stability of the power system [2]. Currently, most wind farms operate based on 'greedy control', meaning that the individual turbines always try to deliver maximum power. This causes a problem when the power demand is low and the dependency on the wind energy is high, resulting in an overload of the power system. Active power control can solve this problem, by regulating the power output of a wind farm.

There are several methods of active power control in a wind farm, two of which will be discussed in this paper, that is, 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 (verwijzing). A disadvantage of yawing is an increase of the load on individual turbines, and thus reducing its lifespan [3, 4]. 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 would reduce the loads and increase power output of the downwind turbine(verwijzing). 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 [5, 6](nog meer verwijzingen). Therefore, it is necessary to understand the effects of yawing a turbine with respect to wake propagation. Axial induction can control the power output by varying the axial induction factor during the optimization. Loads that are introduced by axial induction 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 of must be made between active power control and loads minimization.

Previous studies have mainly focused on optimizing the power output, rather than con-

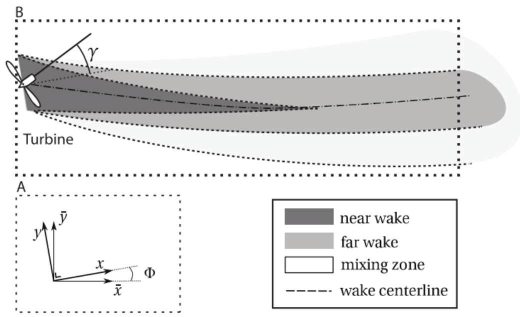


Figure 1: *Simplified repesentation of a wake by FLORIS.*

trolling the power output (verwijzingen naar studies die dit hebben gedaan). Other studies focus on power optimization, while also taking the loads into account, so that an optimum is found between the two (verwijzing naar wie dit heft gedaan). The use of axial induction in optimizing power control has been marginally studied(heb hier nog geen goede bron voor kunnen vinden). Active power control through a combination of yaw control and axial induction control while minimizing loads is still novel.

This paper will focus on the optimization of active power control and loads, by means of yaw control and axial induction control. In addition, a method is developed so that on-site power control can be realized.

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

II. Method

Short introduction on method

FLORIS: The FLOw Redirection and Induction in Steady state (FLORIS) model gives a two-dimensional approximation of the steady-state effect of yaw misalignment and axial induction. It creates a wake model with equation (1 to 4). The wake is divided into three zones, q_1 to q_3, where q_1 refers to the near wake, q_2 to the far wake, and q_3 to the mixing zone (see Figure1). The size of the wake diameter $D_{w,q,i}$ increases proportionally to the the downwind distance (x). Let D_i denote the diameter of the ith turbine, k_e a coefficient that describes expansion of the zones [8], $m_{e,q}$ expansion factor. The diameter of the wake diameter is computed by,

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

The value $m_{U,q}$ is calculated with model parameters a_U, b_u, $M_{U,q}$, and computed as,

$$m_{U,q}(\gamma_i) = \frac{M_{U,q}}{cos(a_U + b_U\gamma_i)} \tag{2}$$

The value $c_{i,q}$ is the wake decay coefficient, which is calculated with,

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

The axial induction factor is denoted by a and the velocity deficit of the wake is calculated with,

$$U_{w,i}(x,y) = U_i\left(1 - 2a_i c_i(x,y)\right) \tag{4}$$

FLORIS gives a power output for each turbine, which for turbine i is give by,

$$P_i = \frac{1}{2}\rho A_i C_p(a_i,\gamma_i)U_i^3 \tag{5}$$

where, ρ is the air density, A the rotor area, U the wind velocity, and C_p is equal to,

$$C_p(a_i,\gamma_i) = 4a_i(1-a_i)^2\eta cos(\gamma_i)^p P \tag{6}$$

Where η and pP are power modeling parameters. The values of the different parametric parameters are found in Table 1

Although less accurate than SOFWA high fidelity CFD simulation, computation time is much faster for FLORIS. As a result, FLORIS can be used for on-site optimization.

FAST & MLife: FAST (Fatigue, Aerodynamics, Structures and Turbulence) is a programming tool for the simulation of dynamic (load)

Table 1: *Overview of parametric parameters, with, the wake expansion factor for zone i $m_{e,i}$, wake decay factor for zone i $m_{U,i}$, wake decay parameters a_U and b_U.*

Expansion		Velocity	
k_d	0.15	$M_{U,1}$	0.5
$m_{e,1}$	− 0.5	$M_{U,2}$	1
$m_{e,2}$	0.22	$M_{U,3}$	5.5
$m_{e,3}$	1	a_U	5
		b_U	1.66

Note: Table adjusted from Gebraad [8](nog correcte verwijzing toevoegen)

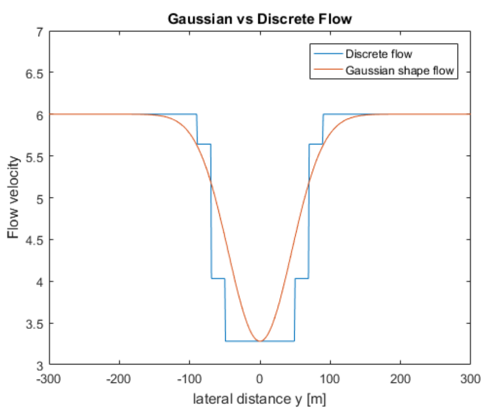


Figure 2: *Discrete wake versus Gaussian wake*

responses of wind turbines (by NREL) [9]. It uses wind turbine specifications as well as wind flow situations. By evaluating a flow field, FAST computes the bending moment of a blade. MLife is an application to process the bending moment to compute the damage equivalent loads (DELs).

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 4)). The wake is divided into three zones as described is in in the section on FLORIS. A real wake will not have discrete zones, but a more fluent transition between the wake zones (see Figure 2 Plaatje van de gaussian vs discrete wake). To create a more fluent transition between the different wake-zones a Gaussian distribution of the flow field is preferred [7]. The Gaussian distribution is calculated as followed,

$$G(x, y) = Ae^{-\frac{y^2}{2\sigma_y}+\frac{z^2}{2\sigma_z}} \tag{7}$$

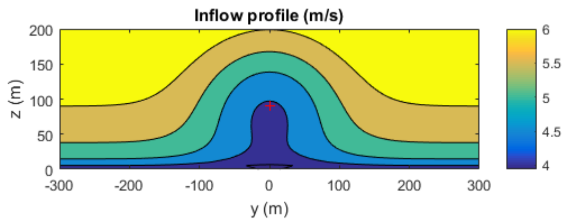
where the amplitude of the Gaussian, A, is equal to the velocity loss of the inner wake zone which is calculated with equation 1. Values σ_y and σ_z, in equation 7, reflect the Gaussian standard deviation in horizontal and vertical direction, respectively. Both these standard deviations are linked to the spread of the Gaussian function. The standard deviations are linked to the outer wake zones, which are calculated by equations (numbers). In the model, σ_y and σ_z are a function of the diameter of the outer wake zone, $D_{w,i,q=3}$, which is divided by a constant. This constant is equal to 4, which results in a standard deviation of two. As a result, the central 95.45% of the values in the Gaussian distribution are taken.

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 [10] (see Figure 3). This velocity distribution is calculated with,

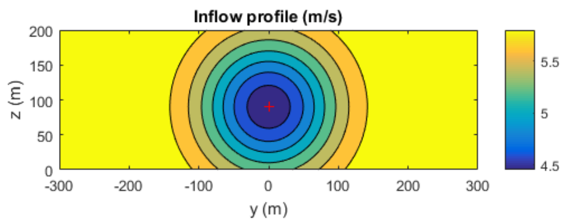
$$v = v_{ref} \left[\frac{h}{h_{ref}} \right]^{\alpha} \tag{8}$$

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 [10]. The wind shear is implemented in the flow field.

LUT: To reduce computational time during optimization a look-up table (LUT) is created. The LUT is created using FAST and MLife, and it encompasses a wide variety of wind field



(a)



(b)

Figure 3: *(a) Gaussian flow field with windshear. (b) Gaussian flow field without windshear.*

conditions. These different conditions are described by the ranges of the parameters (see Table 2). The parameters are wake characteristics and can be extracted from FLORIS. The parameters chosen for the LUT are diameter of outer wake zone (Dwake), freestream 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). The output of the LUT are the DELs. The LUT generation is time consuming, as such, it cannot account for all integer values of the parameters. The step-size of these parameters is chosen such that interpolation will give a representative result. For each parameters step-sizes are selected, as shown in Table (see Table 2). With the use of the pre-calculated LUT, the optimization can run more swiftly, and is able to be used on-site.

Optimization: Game Theory

III. Results

Figures, tables with results and explanation.

Table 2: *Overview of the minimum value, maximum value, and step size of the parameters, diameter of outer wake zone (Dwake), freestream 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	vary
y wake	-250	250	10

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

IV. Discussion

What have we done and how to interpret the results

Recommendations for further studies

References

[1] Energieonderzoek Centrum Nederland. "Nationale Energieverkenning 2016"

[2] J. O. G. Tande. "Grid integration of wind farms," in Wind Energy, 2003

[3] D. S. Zalkind and L. Y. Pao. "The fatigue loading effects of yaw control for wind plants," in American Control Conference (ACC), 2016

[4] S. K. Kanev and F. J. Savenije. "Active wake control: loads trends," in Wind Energy, 2017

[5] B. Wilson. "Wind Farm Control: Robust Multi-Objective Optimization of a Wind Farm for Different Control Strategies," Unpublished Master's Thesis, 2017

[6] M. T. van Dijk, J. W. van Wingerden, T. Ashuri, Y. Li, and M. A. Rotea. "Yaw-Misalignment and its Impact on Wind Turbine Loads and Wind Farm Power Out-

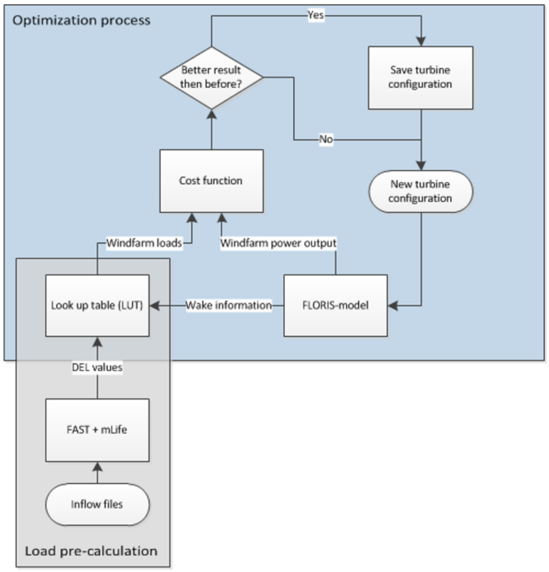


Figure 4: *Overview of the optimalization procedure.*

put," in Journal of Physics: Conference Series, 2016

[7] M. Bastankhah and F. Porte-Agel. "Experimental and theoretical study of wind turbine wakes in yawed conditions," in Journal of Fluid Mechanics, 2016

[8] P. M. O. Gebraad, F. W. Teeuwisse, J. W. Wingerden, P. A. Fleming, S. D. Ruben, J. R. Marden and L. Y. Pao. "Wind plant power optimization through yaw control using a parametric model for wake effects- a CFD simulation study," in Wind Energy, 2016

[9] J. M. Jonkman and M. L. Buhl Jr. "FAST User's Guide," National Renewable Energy Laboratory, Golden, CO, Technical Report No. NREL/EL-500-38230, 2005

[10] E. Firtin, O. Guler, and S. A. Akdag. "Investigation of wind shear coefficients and their effect on electrical energy generation," in Applied Energy, 2011