

# Wind Farm

NIELS VAN DUIJN, JURRIAAN GOVERS, LUUK VAN HAGEN  
JOCHEM HOORNEMAN, MAX VAN LEEUWEN

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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 ipsum.*

## I. INTRODUCTION

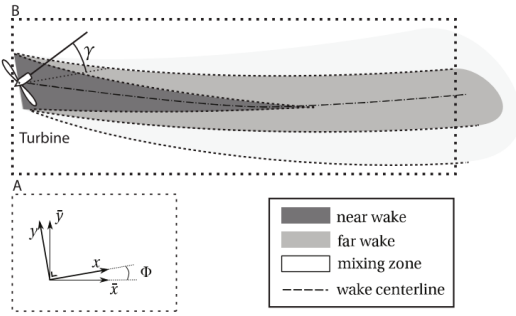
**T**O minimize cost of wind energy and to efficiently use resource rich locations, wind farms are constructed, characterized by a large concentration of wind turbines. An inherent side effect of wind turbine however is a wake. When wind turbines are placed in close proximity of each other in a wind 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 representation 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 Figure 1). The size of the wake diameter  $D_{w,q,i}$  increases proportionally to the downwind distance ( $x$ ). Let  $D_i$  denote the diameter of the  $i$ th 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,

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

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

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

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

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

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

$$U_{w,i}(x, y) = U_i (1 - 2a_i c_{i,q}(x, y)) \quad (4)$$

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

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

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

$$C_p(a_i, \gamma_i) = 4a_i(1 - a_i)^2 \eta \cos(\gamma_i)^{pP} \quad (6)$$

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

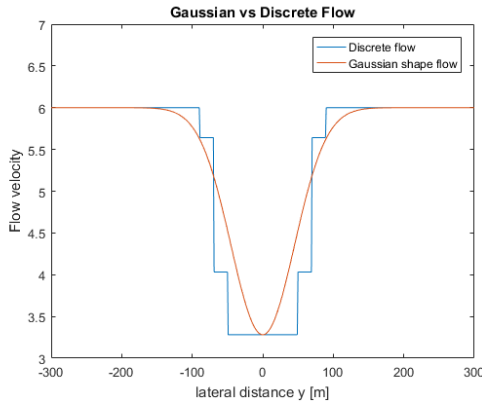
Although less accurate than SOFWA high fidelity CFD simulation, computation time is much faster for FLORIS. As a result, FLORIS can be used for on-site optimization.

*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
$m_{e,1}$	-0.5
$m_{e,2}$	0.22
$m_{e,3}$	1
	$a_U$
	$b_U$

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,

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

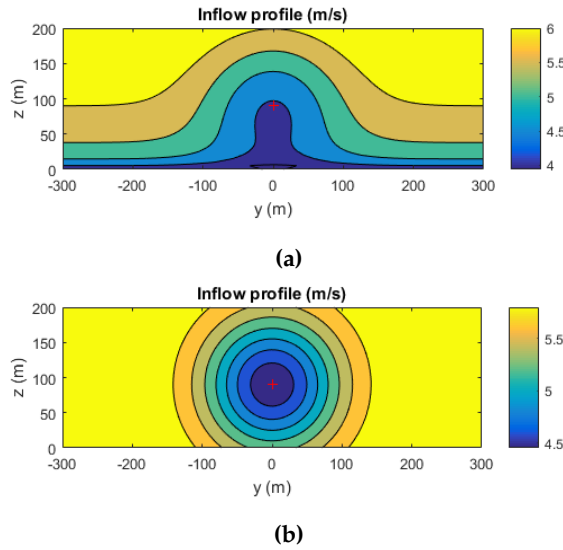
where the amplitude of the Gaussian,  $A$ , is equal to the velocity loss of the inner wake zone which is calculated with equation 1. Values  $\sigma_y$  and  $\sigma_z$ , in equation 7, reflect the Gaussian standard deviation in horizontal and vertical direction, respectively. Both these standard deviations 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,  $\sigma_y$  and  $\sigma_z$  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,

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

where  $v$  and  $v_{ref}$  are the velocity at heights  $h$ , and  $h_{ref}$  respectively. Value  $\alpha$  is the wind shear coefficient which depends on different factors. Coefficient  $\alpha$  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



**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 ( $D_{wake}$ ), 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.

*verandwoording van de parameters:*

de parameters waarmee de LUT is opgebouwd zijn zo gekozen dat ze gezamenlijk een representatief beeld kunnen geven van elke mogelijke flow profiellen wanneer er tussen de data punten lineair word geïnterpoleerd. de

**Table 2:** Overview of the minimum value, maximum value, and step size of the parameters, diameter of outer wake zone ( $D_{wake}$ ), 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
$D_{wake}$	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].

ranges en stepsizes die hiervoor zijn gekozen verschillen per parameter.

de  $y_{wake}$ , representing the center to center distance of the wake and the downwind turbine, is performed between the ranges of -250 and 250 meter. hiermee kan de wake van kant naar kant over de hele turbine worden getrokken en aan beide kanten zonder overlap eindigen. de stepsize voor de  $y_{wake}$  is vrij klein gekozen, dit omdat de DELs als gevolg van c2c zich alles behalve linear gedragen (zoals weergegeven in fig...) waardoor linear fitten geen goede resultaten zou boeken.

de  $D_{wake}$  is op zo'n manier gekozen dat ,bij normale omstandigheden, alle turbines binnen ... en ... meter kunnen worden gefit, de DEL relatie met de  $D_{wake}$  loopt mim of meer lineair, vandaar kon een relatief grote stepsize worden gekozen.

de  $U$  is zo gekozen dat we in het geval van een constante inflow van 8m/s en het windfarm setup van de 9 turbines altijd kunnen werken, hierbinnen word ook lineair geïnterpoleerd. bij grotere windparken, dan wel andere windsnelheden zal hiervoor een grotere data range nodig kunnen zijn.

de  $yaw$  parameter wordt niet gebruikt voor de generatie van het flow profiel op de downwind turbine. This parameter is used to in-

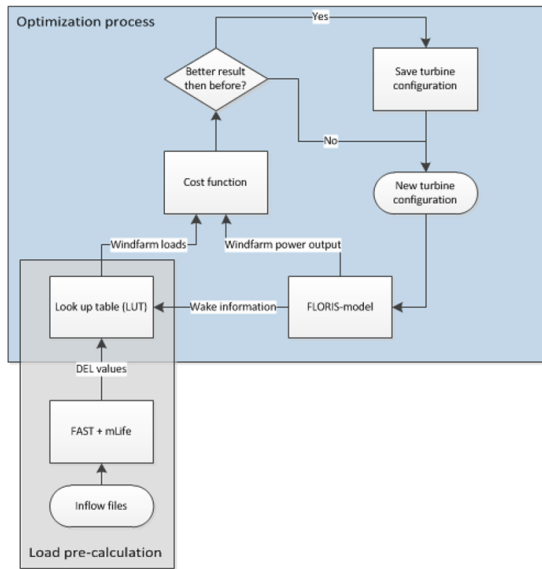


Figure 4: Overview of the optimization procedure.

corporate the damage in the upwind turbines themselves as a result of yawing. these ranges are chosen between -30 and 30 degree, (waarom??) and the has a step size of 10deg, with an additional measurement point at +- 5 deg, to improve the accuracy of the fit in the lower regions.

Optimization: Game Theory

### III. RESULTS

Figures, tables with results and explanation.

— show the effect of

— The aimed outputs are the optimal variable settings of yaw and axial induction, at which the DELs are minimised for a given power output??(de enige outputs??). As discussed in the previous chapter, is the optimisation characterised by input settings. Altering these settings in a specific way can lead to a entirely different type of optimisation. This chapter will show some of the more significant cases.

as previously stated, is the cost function dependent of a optimisation factor, this factor

influences how high the DELs and power way in the optimailisation. by setting this factor at 0??, shall only loads be a concern for optimailisation, as such would the power then be ignored. this would be the other way around with an optimailisation factor of 1?? ...more?

this optimailisation method (onderscheid zichzelf) by beeing able to guarantee a certine constant power output. however, set the reference power above the maximum and now this method can be used to maximize the power much in the same way as in previous research.

the other extreme case is when a reference power of 0MW is required. ... shows that is stops te turbines, validates the methode??

the number of iterations that GT uses has a direct influence on the (prestatie). however, it also drastically increases the computation time, see here the effect of .. times more iteraton, the DELs continiu to drop. however, an (afweging zal moeten worden gedaan) whether this improvement is worth the increse in computation time

————— - a realistic run ( 4MW ?)

- one with a ref power above the max, making it also optimize for power

-one extreme(0 power), validation the optimailisation methode for the extremes, relating it to the axial induction?

-one with more/less iterations, evaluating accuracy and computation time.

— bandwidth -jurriaan? experimenting with relevance — optimailisation factor -only loads? -only power? —————

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### IV. DISCUSSION

What have we done and how to interpret the results

Recommendations for further studies

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