Investigation of Wind Farm Control Strategies

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Abstract

Wind turbines that are clustered in a wind farm have interactions with each other through the aerodynamics of wakes, which are the flow structures that form behind each turbine. The wake is characterized by a reduced velocity and an increased turbulence intensity compared to ambient conditions, caused by the extraction of energy from the air flow by the turbine. The velocity deficits cause a decrease of power production of turbines standing in the wake of another turbine, and the increased turbulence may increase the fatigue loads on those downstream turbines. Wind farm control strategies take into account wake interaction effects in the coordination of the control actions of the wind turbines, in order to improve the performance of the wind farm, in terms of total electrical energy production, and the loads on the individual wind turbines. Enhancing wind plant performance in this way contributes to the reduction of the cost of wind energy.

In this thesis a novel low fidelity modelling tool for the study of wind farm control is developed. The tool, named FASTnAT, simulates a row of turbines in a line facing a turbulent wind, aligned with its direction, combining the turbine modelling tool FAST with algebraic wake models to describe the interactions between turbines on a wind farm. The model is verified and validated. Reasonable agreement was found between FASTnAT and measurement data from the Horns Rev wind farm. FASTnAT displays similar modelling tendencies as model FLORIS.

FASTnAT is used with an optimisation framework to suggest blade pitch settings as a means of studying the axial-induction-based pitch control strategy. It is found that there can be energy production improvement of up to 14.71% through integrated pitch action, although the degree to which such improvements can be achieved depends highly on the ambient wind velocity, and on the topology of the considered wind farm.
Keywords: Wind plant control, Axial-induction-based pitch control, Wake loss reduction, Wind farm modelling

1. Introduction

Clustering a group of Wind Turbines (WTs) in a Wind Farm (WF) helps to reduce installation & maintenance costs. A disadvantage of doing so is that the turbines will aerodynamically interact with each other through their wakes, which may have negative effects on the total power production, and may increase the loads experienced by the turbines. The negative effects of this aerodynamic interaction may be mitigated by using Wind Farm Control (WFC) techniques during the operation of the WF, that aim at improving the performance of the wind plant as a whole through coordination of the control operations across the wind turbines.

The objective of the present thesis is to investigate WFC strategies, particularly the axial-induction-based control strategy, and aim to develop a WF model for WFC analysis. Appropriate existing wake models are used, coupled with the engineering WT model Fatigue, Aerodynamics, Structures and Turbulence turbine aeroelastics simulator (FAST), to make FAST n Aligned Turbines (FASTnAT), a novel WFC analysis tool that simulates a WF composed on a given number of turbines in a line facing turbulent incoming wind, aligned with its direction. Particularly, the thesis will aim to use the developed tool to study the effectiveness of the axial-induction-based control strategy.

Section 2 provides a theoretical background relevant for the work developed in the current thesis. Section 3 details the development and implementation of the novel model FASTnAT. Section 4 presents the verification and validation of the model. In section 5 FASTnAT is used in an optimisation framework to study axial-induction-based WFC. Section 6 states the most important conclusions drawn about the FASTnAT model development, and about the axial-induction-based pitch control optimisation study made with it.

2. Background

2.1. Wake Flow Definition

As a WT extracts energy from incoming wind, it perturbs the wind flow, forming behind it a wake characterised by reduced velocity and increased levels of turbulence. The reduction in velocity is directly related to the Thrust Coefficient (C_T) of the turbine. As the wake travels downstream, the velocity gradient between the wake and the free stream flow originates additional turbulence, which boosts the transfer of momentum into the wake from the surrounding flow. The velocity deficit in the wake is dissipated as it convects, until the flow has fully recovered far downstream in a proccess called wake recovery. The rate at which the wake flow recovers energy is faster the higher the ambient turbulence level.

The wake zone behind a WT is called the near wake, which typically extends to 2-5 diameters downstream of a turbine. The wake's pressure recovers to the atmospheric level along the near wake. As the tip vortices break down, the point in which the velocity reaches its minimum level marks the passage from near to far wake. From this point onwards, the velocity recovers, eventually reaching the free stream value. The characteristics of the far wake are mainly dictated by the WT diameter, and atmospheric and topographic effects [1]. Several physical phenomena characterise the flow of a WT's wake. The velocity deficit approaches a Gaussian profile in the far wake, which is axisymmetric and self similar. A wake expands in size as it travels downstream. Wake meandering is an unsteady large scale stochastic phenomenon in which the entire wake structure will show horizontal and vertical oscillations over time, instead of maintaining a fixed position and expanding shape.

2.2. Wind Farm Control Strategies

The scientific premise of the present work is that control *can* improve the performance of a WF by taking advantage of intelligent actuation on specific control Degrees of Freedom (DOFs) to influence wakes. Generally, the principle is that some of the energy production of an upstream turbine is sacrificed to influence its wake, which should be compensated by an increased energy production in downstream turbines. This scientific topic is relevant as WFs typically have around 10% losses due to wake interaction [2].

There are two main actuations methods for wake control: Axial-induction-based Pitch Control (AIBPC), and wake steering. Since FASTnAT is a tool for studying AIBPC, it is detailed next.

2.2.1. Axial-Induction-Based Wake Control

The principle behind the axial-induction-based control strategy, also called *derating*, is that the power extraction of WTs can be adjusted to influence the velocity deficits in their wakes, by adapting the control settings to influence the axial induction factor a. Control inputs such as the Turbine Collective Blade Pitch Setting (β) and the generator torque can be used to adjust a.

Below-rated wind conditions the axial-induction-based control concept relies on the fact that, at the maximum production operating point of a turbine, the power production sensitivity to β and Tip Speed Ratio (TSR) is small. This is a result of the surface $C_P = f(\beta, TSR)$ being flat around its optimal pitch angle and TSR, while C_T is more sensitive to these control variables around that operating point. This is illustrated in figure 1 for the National Renewable Energy Laboratory (NREL) 5 MW machine [4]. By deviating a small amount from the point of maximum Power Coefficient (C_P) on the upstream turbines, the power production of that turbine will be slightly reduced, whereas the C_T will reduce enough to significantly increase the velocity in the wake [3].

2.3. Wind Energy Modelling Tools

This section presents models and modelling tools relevant for the development of FASTnAT.

2.3.1. Wind Turbine Modelling Tool: FAST

FAST [5] is a multiphysics engineering tool capable of coupling the aero-hydro-servo-elastic dynamics of onshore, bottom-fixed offshore, or floating offshore WTs. FAST purpose is to aid in the design of WTs, and of linearising such systems, for use in developing state space models for control algorithms. It was developed by NREL under a modularization framework, with each module corresponding to a different physical domain of the coupled solution, coordinated by a driver code that passes variables between modules. FAST has been used extensively in reference work relevant for this thesis [3, 6, 7], and has been found suitable for the calculation of offshore WT loads for design and certification [8].

2.3.2. Jensen Wake Deficit Model

The Jensen model [9] is an established model that has been used extensively in the wind energy industry. The assumptions are a steady inflow acting on an actuator disk with uniform axial loading, and linear expansion of the wake. The slope of the wake is determined by the wake decay coefficient k. Typical k values are 0.04 for offshore wind installations, or 0.075 for onshore installations. The general form of the model, for N turbines aligned with the incoming wind direction, is presented in equation 1.

$$\frac{V_N}{U} = 1 - \left(1 - (1-2a)\frac{V_{N-1}}{U}\right)\left(\frac{r_o}{r_o + kX}\right)^2 \quad (1)$$

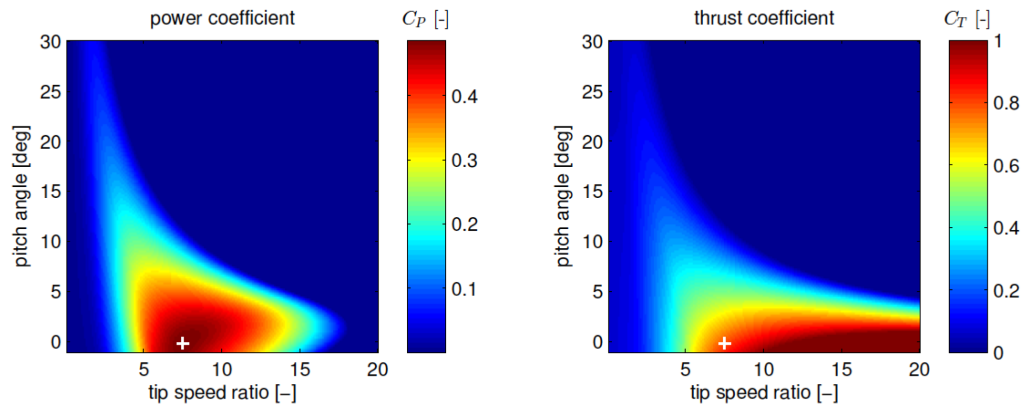


Figure 1: Power and thrust coefficient of the NREL 5-MW turbine as a function of β and TSR. The cross (+) indicates the operation point of maximum C_P. Taken from [3].

2.3.3. Crespo & Hernández Model

Crespo & Hernández [10] have made an analysis on the evolution of turbulence characteristics in WT wakes, with the goal of developing analytical models to predict turbulence characteristics of single wakes. These correlations are obtained from results of the UPMWAKE code [11]. Different formulations are fit for the near and far wake, and calculate the Turbulence Intensity (TI) added to the flow due to WT energy extraction as a function of T and the distance downstream of the WT.

For the near wake, Crespo & Hernández developed the following correlation for the maximum added turbulence intensity ΔI_m:

$$\Delta I_m = 0.725a = 0.362(1 - \sqrt{1 - C_T}) \qquad (2)$$

Equation 2 has good agreement with results of UPMWAKE.

For the far wake, expression 3 was fitted, giving the best least square fitting with UPMWAKE results. There is good agreement between equation 3 and UPMWAKE numerical results.

$$\Delta I_m = 0.73a^{0.8325} I_\infty^{0.0325} (\frac{x}{D})^{-0.32} \qquad (3)$$

3. Model Implementation

In the present work a WF model was developed, named FASTnAT, that simulates a WF composed by given Number of turbines (N) in a line facing a turbulent wind, aligned with its direction and a distance of $X * D$ between each other. FASTnAT takes as input the mean U_∞ and the TI_∞ of the atmospheric wind and assesses the impact of performing AIBPC on the WF. It provides detailed data on power and loads of all the considered WTs, by relying on NREL's FAST tool to simulate them, in conjunction with wake models to estimate the properties of the air flow that reaches WTs beyond the first. FAST is a reliable tool for simulating individual WTs, and so FASTnAT is valuable for performing loads and fatigue analysis on a WF in acceptable computing periods. The tool is considered of low fidelity because its current wake model is composed of simple equations.

3.1. Turbine Model

FAST was chosen for the present work because its capability for WT design and performance analysis is well demonstrated. FAST simulates one WT with a specific incoming wind field. The wind field for a simulation is generated using TurbSim, a stochastic inflow turbulence simulation tool developed by NREL. As used in this thesis inputs for the generation of one incoming wind profile are the mean freestream speed U_∞, and TI_∞ in percentage. In the scope of this thesis all FAST simulation instances will be of an NREL 5-MW baseline Horizontal Axis Wind Turbine (HAWT) [4].

3.2. Wake model

The wake model of FASTnAT is structured as follows: at each turbine in a FASTnAT simulation, the wake velocity deficit is calculated with the Jensen model, and the added turbulence intensity is calculated with the Crespo & Hernández parametric equation. This simple combined wake model keeps the total simulation time of FASTnAT limited by FAST.

The model uses equation 1 from the Jensen model. This equation returns the mean Wind Speed (WS) of the wake flow at a specified distance downwind of a particular WT of the simulated WF, based on its C_T. In [12] values for k between 0.04 and 0.075 were tested to determine which one fits measured data of the Horns Rev WF the best. The wake decay value that fits the data best is 0.06, so this value is used in the present thesis. FASTnAT's wake model considers equations 2 and 3 from the Crespo & Hernández model to estimate the TI of the wake flow at a specified distance downwind of a WT, for the near and far wake respectively. The axial induction factor a on equation 3 is obtained through actuator disk theory. The present implementation of these two models assumes full wake overlap between the wake of a turbine and the rotor area of the next turbine in a row of a simulated WF.

3.3. Code Architecture

The idea behind FASTnAT is that a WF can be replicated by instacing FAST in a serial manner, applying a wake model in between each simulation to calculate the wake's flow characteristics, and superimposing those characteristics on the incoming flow reaching a downstream turbine. In this way, this model can provide detailed analysis on the forces acting on WTs in a WF simulation, within acceptable computation periods. The model was constructed with MATLAB [13].

The physical inputs of the model are the number of turbines in the desired WF scenario N, the distance between each turbine Downstream Distance (X) (multiple of turbine diameter), the mean incoming free-stream velocity U_∞, and the ambient turbulence intensity TI_∞. The model begins by running TurbSim, to generate the appropriate file relating to a turbulent wind field with mean velocity $U_1 = U_\infty$ and turbulence intensity $TI_1 = TI_\infty$. Then, FAST is summoned to simulate the most upstream turbine, *i.e.* the "first" turbine in the WF's single row that faces undisturbed wind. When the simulations ends, the wake model is applied to compute the mean velocity and TI at the second turbine in the row, U_2 and TI_2, taking into account X. TurbSim is run to generate a turbulent wind field with these traits. Afterwards, FAST is summoned again to simulate the second turbine, and this process is repeated until all N turbines are simulated. FASTnAT is able to simulate a WF composed of N aligned turbines with a specific β on any turbine, so as to evaluate the potential of AIBPC to affect the wake interaction between turbines.

3.4. Additional Considerations

It is useful to define a measure of farm-wide energy production and fatigue loads, so as to assess how WFC might affect a WF performance.

The Farm-wide Energy Production (FWEP) is determined by calculating the sum of the time-averaged turbine power for all turbines simulated with FASTnAT, as shown in equation 4.

$$\mathrm{FWEP} = \sum_{\mathrm{i}=1}^{\mathrm{N}} \overline{\mathrm{P_i}} \tag{4}$$

The measure chosen to represent fatigue damage for the present work is the Standard Deviation (STD) of the Blade Root Bending Moment (BRBM) of one blade, σ_{BRBM}. Forces at the blade root are sensible to control parameters and ambient wind speed and turbulence profile, reflecting the changes in the optimiser input parameters. So Farm-wide Fatigue Loads (FWFL) are defined as the root-sum-square of the time-averaged STD of one blade's BRBM (σ_{BRBM}) for all turbines considered in a simulation, as shown in equation 5.

$$\mathrm{FMFL} = \sqrt{\sum_{\mathrm{i}=1}^{\mathrm{N}} \sigma^2_{\mathrm{BRBM_i}}} \tag{5}$$

4. Turbine and Farm Model Validation

Simulations were run for a wide range of wind conditions and pitch settings, with which the performance of the tool is assessed. First the impact of applying AIBPC on a single turbine is analysed. The modelling of a WFs is then verified.

4.1. Turbine Modelling Verification

The impact of applying AIBPC on a single turbine is assessed.

4.1.1. Impact of generator torque control on turbine behaviour

The baseline controller included in the NREL 5 MW model turbine imposes a generator torque control, below rated speed, which relies on airfoil aerodynamic coefficient's table for collective pitch blade setting $\beta = 0^\mathrm{o}$. Since FASTnAT will be used in an optimisation framework to study AIBPC, the generator torque controller must be overruled. In FASTnAT, the generator torque controller dynamics are switched off, and the rotor speed is constant, calculated through the turbine's control laws. The impact of switching off the generator torque controller dynamics on the behaviour of a WT was evaluated by comparing two different FAST simulations with the same wind field conditions, one with the baseline generator torque controller operating normally (termed traditional case), and the other with constant rotor speed (FASTnAT case). The simulation time was 10 minutes. It was found that the TSR in the FASTnAT case displays larger amplitude oscillations during operation than the traditional case. The control action by the generator to make its torque proportional to the WS translates into a more consistent TSR over time.

The TSR's STD in the FASTnAT case increased by 91% comparing to the traditional case, which is consistent with the observed increase of 29% in the STD of the C_T in the FASTnAT case. The mean of both C_P and C_T is largely unaffected. Despite the larger STD of the C_T, a comparison between both cases' time series of the BRBM reveals no clear difference.

Physical input domains	
Input	Range
N [–]	{2; 4; 6; 8; 10}
X [m]	{3; 5; 7; 9; 11}
U_∞ [m/s]	{4; 6; 8; 10; 12}
TI_∞ [%]	{4; 6; 8; 10; 12}

Table 1: Range of each parameter considered for the present verification.

It is hard to ascertain the impact of the decision to turn off the generator torque controller on a WT's operation. However the aforementioned analysis showed that it has a small impact on the observed power production (albeit only in a steady-state scenario as considered in FASTnAT) and on the variability of the loads experienced by a turbine.

4.1.2. Simulation output quantification

Several simulations were run to collect data on power and BRBM response, varying U_∞, TI_∞ and β. It was found that FASTnAT's capability to describe WT behaviour is satisfactory, as expected of the turbine modelling component FAST. It must be mentioned that, during this analysis, it became evident that FAST simulations do not converge for scenarios with low WS and large β. In such conditions, it could be that the Attack Angle (α) becomes negative, meaning that the lift force would reverse its direction. This event provokes a numerical error since Blade Element Momentum (BEM) theory, the underlying aerodynamic model of FAST, assumes that the main component of the lift force is aligned with the direction of the incoming wind. This will be addressed in chapter 5 by adding a constraint to the optimisation framework.

4.2. Wind Farm Modelling Verification

This section verifies FASTnAT's capability to model a WF, and the application of AIBPC.

4.2.1. FASTnAT Response to Varying Physical Inputs

The present verification was done in the following way: a set of WF topology & atmospheric conditions are defined as the baseline WF (N = 5; X = 7D; $U_\infty = 8$ m/s; $TI_\infty = 8\%$). The chosen topology & wind conditions are meant to represent a row of turbines of a typical modern offshore WF, producing energy in a day with reference conditions [14]. Then simulations are run varying each physical input in turn, testing 5 different values for each parameter. Table 1 presents the ranges for each input parameter considered in the present analysis. Each individual turbine simulation was run for 10 minutes. A summary of the verification conclusions is given here.

Regarding N, it was seen that the more turbines a WF has, the more power it is able to output, while the overall fatigue loads increase as well. Increasing the number of turbines on the considered farm does not change the wind conditions at which those turbines operate, since one given turbine is influenced only by the turbine upstream of it (if there is one) through the wake model. In reality the turbines in a WF have more complex interactions with each other through their wakes to be modelled.

Regarding X, it was observed that the FWEP increases as X increases. As a wake flow is convected downstream it regains energy from the surrounding atmospheric wind due to turbulent mixing, and naturally the amount of recuperated energy is larger the more the wake as travelled. FASTnAT is able to depict this behaviour fairly. The FWFL seem to be practically unaffected by varying X, this is because two effects happen when the distance between turbines is increased. On one hand the speed of a wake seen by a given turbine beyond the first gets larger, which would make that turbine act a larger thrust force on the incoming wind, and thus its overall loads would go up. On the other hand the TI seen by that same turbine is decreasing, which reduces the variability of forces experienced by the turbine, and thus the overall loads would decrease. These two effects seem to balance each other out in the considered system, as the FWFL seem to remain virtually the same.

Regarding U_∞, it was observed that a wind with larger velocity makes the farm output more power, as would be according to the power equation of a HAWT [1]. The FWFL decrease when U_∞ goes from 4 m/s to 8 m/s, and then increase as U_∞ increases to 12 m/s. The increased FWFL seen for the lower WS cases is related to the observed larger TI experienced in such circumstances. Since the FWFL are calculated through the STD of BRBM, a larger TI implies a higher variability of forces felt by a turbine, which then increases the loads.

Regarding TI_∞, it was observed that the FWEP is practically not affected by varying TI_∞. A wind with larger TI has larger turbulent velocity fluctuations which implies that that wind has a higher energy content, however it is not a type of energy that a turbine can extract. Also, a higher TI_∞ increases the FWFL, since a higher TI would increase the variability of forces felt by a turbine and therefore the STD of the BRBM, as detailed before. The results showed that the FWFL are more sensible to U_∞ than to TI_∞.

4.2.2. FASTnAT Response to Pitch Input

The beneficial effect of AIBPC for the optimisation of WF total power production was investigated in [6] using Simulator for On/Offshore Wind Farm Applications (SOWFA) [15]. In [6] a setup with

Setting	Value
N	2 turbines
U_∞	8 m/s
TI_∞	6 %
X	7

Table 2: FASTnAT simulation conditions for comparison with [6].

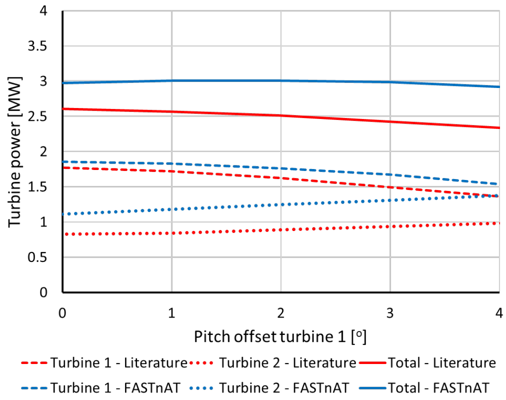


Figure 2: Effect of different pitch offsets on the front turbine, in a two turbine scenario. SOWFA data retrieved from [6].

two turbines aligned with the air flow direction is defined and simulated multiple times with different pitch offsets on the most upstream turbine. As a means of comparison a similar setup was simulated with FASTnAT, with conditions equal to [6] and stated in table 2. The considered HAWTs are the NREL 5 MW reference turbine for both cases. The results of applying different pitch offsets on the front turbine of the detailed two turbine setup of both SOWFA and FASTnAT are shown in figure 2.

FASTnAT predicts a higher total power output than SOWFA, in particular for the second turbine. FASTnAT estimates an increase by the pitch offset on the total power output of the two turbines up until pitch offset of $2,5^o$, while SOWFA estimates a decrease regardless of the pitch offset. The Jensen model simply outputs the average WS at a given distance in the wake of a WT, and may not be able to accurately depict what is happening to the energy added to the wake flow due to AIBPC action. Its usage with FASTnAT in the present thesis assumes full wake overlap between the wake of a turbine and the rotor of a downstream turbine at all times. In a real WF the wake of a turbine meanders as it travels downstream, which may cause that unperturbed atmospheric wind would hit a turbine's rotor along with the wake. These two effects may be accumulating, resulting in an overestimation of the positive effect of offsetting the pitch on the total

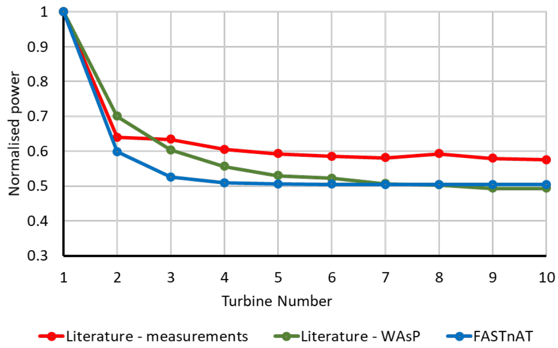


Figure 3: Comparison of power output between the Horns Rev case study, a simulation using the tool WAsP, and the FASTnAT simulation. Data of case study and CFD simulation retrieved from [14].

power output of the two turbines, when compared to SOWFA.

It can be observed that the FASTnAT tool predicts a higher individual power output for the first turbine, for all pitch settings. Besides the different modelling tool used in the simulation cases, the only other significant difference is the absence of generator torque control in FASTnAT case. In the mentioned SOWFA simulations the baseline torque controller is functioning normally. In FASTnAT, for a WS of 8 m/s, the turbine rotor speed is constant such that the tip-speed ratio is around its optimal value, which might not be so in the SOWFA simulations. Overall it can be observed that both models show similar trends in the response of the system.

4.3. Wind Farm Modelling Validation

This section validates FASTnAT's capability to model a WF by comparing it with relevant literature.

Detailed case studies of power losses due to wakes at the large WFs at Nysted and Horns Rev have been analysed in [14]. A FASTnAT scenario was simulated to match the setting of the Horns Rev case study, whose conditions are equal to those shown in table 2 except that $N = 10$ turbines.

Figure 3 shows a comparison of the observed power output in the Horns Rev case study with the FASTnAT simulation results. Also in this figure is a Computational Fluid Dynamics (CFD) simulation made with Wind Atlas Analysis and Application Program (WAsP) [16] to emulate the case study. The WAsP setup was meant to reproduce the case study results, as such it is included in figure 3 for comparison. There is good agreement between FASTnAT and WAsP on the last 5 turbines. The mismatch between the models on turbines 2 through 5 may come from that fact that the WAsP simulations are for a $\pm 5^o$ sector, relative to the wind direction aligned with the considered row of turbines.

Comparing the measurements to FASTnAT results, it is observed that FASTnAT overestimates the wake effects. The Jensen model does not take into account all the wake effects mentioned in section 2.1, particularly wake meandering. The present implementation of the Jensen model assumes full wake overlap, but even when a WT stands fully in the wake of another, the wake's oscillation as it advects downstream may allow undisturbed wind to reach its swept area, increasing the available energy in the incoming wind seen by the turbine.

5. Wind Farm Pitch Optimisation Study

This chapter describes an optimisation study that employs the FASTnAT model to evaluate the AIBPC strategy as a means to improve WF performance.

5.1. Optimisation Setup

The developed optimiser code utilises MATLAB's Optimisation toolbox to find the minimum of a constrained nonlinear cost function, through the solver *fmincon*. In order to have the optimisation running time within workable limits, it is useful to decouple the FAST software from the optimiser code. A total of 576 FAST simulations were run by varying wind conditions (U_∞ and TI_∞) and β, so as to accumulate sufficient turbine performance data to build accurate fit functions. Three fit functions were built that calculate the 10-minute time-averaged of the turbine power, σ_{BRBM} and the C_T, as a function of the ambient WS, ambient TI and β. The power & C_T functions represent a turbine accurately. The σ_{BRBM} function has an error of $\approx$ 5% relative to FAST. Nonetheless the fit functions are considered sufficiently precise to use in the optimisation study.

The present optimisation analysis will consider 3 different objectives: Maximise total WF energy production (**Objective 1**); Minimise fatigue loads across a WF (**Objective 2**); Maximise total energy production while minimising loads (**Objective 3**).

Regarding objective 1, the impact of AIBPC on the WF's total energy production will be estimated by calculating the sum of the time-averaged turbine power $\overline{P_i}(\beta_i)$ for all N turbines in the farm, relative to the baseline case (all $\beta_i^{opt} = 0$. Equation 6 presents the cost function defined for objective 1.

$$C_1(B_{opt}) = -\frac{\sum_{i=1}^{N} \overline{P_i}(\beta_i) - \sum_{i=1}^{N} \overline{P_i}(0)}{\sum_{i=1}^{N} \overline{P_i}(0)} \quad (6)$$

The cost function for objective 2 is defined in equation 7. The function represents the farm-wide change in fatigue loads by calculating the root-sum-square of the individual loads, relative to the baseline case.

$$C_2(B_{opt}) = \frac{\sqrt{\sum_{i=1}^{N} \sigma^2_{BM_i}(\beta_i)} - \sqrt{\sum_{i=1}^{N} \sigma^2_{BM_i}(0)}}{\sqrt{\sum_{i=1}^{N} \sigma^2_{BM_i}(0)}} \quad (7)$$

The cost function for objective 3 is simply the sum of cost functions 1 and 2. It is defined in equation 8.

$$C_3(B_{opt}) = \lambda C_1(B_{opt}) + (1-\lambda) * 10 * C_2(B_{opt}) \quad (8)$$

The term for function C_2 is multiplied by a factor of 10 to center the function C_3, that is so that both functions C_1 and C_2 have similar impact on the evaluation of function C_3. For the purposes of this study, all optimisations run with objective 3 have $\lambda = 0,5$, meaning that objectives 1 and 2 have an equal relative importance.

A constraint is added to the optimiser code in order to ensure convergence of the solution, shown in equation 9.

$$\beta < \frac{U}{2} + 1 \quad (9)$$

5.2. Results and Discussion

Three case studies are considered in the present optimisation study to evaluate the AIBPC strategy as a means of improving WF performance.

Axial-induction-based WFC is studied in [17], by evaluating blade pitch DOFs as means to improve WF performance. A scenario of five turbines in a row aligned with wind direction is investigated with both FLOw Redirection and Induction in Steady-state (FLORIS) [6] and SOWFA, to evaluate the overall impact of AIBPC on a WF's performance. An optimisation procedure is used to reproduce an application of AIBPC in steady state. Such work was replicated in the present thesis as case study 1, as a means of comparison. The FASTnAT physical inputs used for case study 1 will act as a reference WF, presented on table 3. Then case study 2 will focus on how varying both U_∞ and TI_∞ affects the AIBPC strategy effectiveness. Case study 3 will focus on how the AIBPC strategy may improve the performance of different WFs. This will be done by varying inputs N and X, for the wind conditions of the reference WF, and analysing the impact on the effectiveness of AIBPC.

5.2.1. Case Study I: Comparison with Higher Order Models

The optimiser was run with conditions equal to those shown in table 3, so as to mimic the literature

Farm Topology		Atmospheric conditions	
N	X	U_∞	TI_∞
5 turbines	5	8 m/s	6%

Table 3: FASTnAT input values that make up the reference WF for the optimisation study.

simulations' scenario. Three optimisations were made with each control objectives. The optimisation results run with objective 1 are the ones comparable to the literature, so constitute the FASTnAT *optimised case* in the present comparison.

The results for case study 1 are presented in figure 4. The baseline and optimised cases are shown for each model, where baseline results are simulations where no AIBPC was in place, *i.e.* traditional single turbine control algorithms are in effect. FASTnAT and FLORIS predict an increase of $14,17\%$ and $24,82\%$ in FWEP, respectively, on the optimised case, whereas SOWFA predicts a decrease of $9,84\%$. Both FASTnAT and FLORIS indicate that derating the upstream turbines will result in power increases at each downstream turbine. In FLORIS the modelling of the wake velocity deficit is similar to the Jensen model, so the results suggest that changes in axial induction through pitch action are not so well described by a Jensen-type model. Despite the differences in simulation results, one can observe than the general modelling tendencies of FLORIS and FASTnAT are similar.

The optimiser results indicate that there could be an energy production improvement of $\approx 14\%$ through AIBPC for the reference conditions. The results also indicate that AIBPC has a relatively small potential to reduce the overall fatigue-inducing loads, since that best reduction in FWFL achieved is of $0,44\%$, considering objective 2. As expected the results considering objective 3 are in between the other cases' results. There is no big difference between the amount of performance improvement across cases, and all cases demonstrate the general principle behind axial-induction-based active wake control: the control action worsens the performance of the first turbine, which is compensated by the betterment of the performance of downstream turbines. The optimiser solution tends to pitch values in the interval $2,5^{o} - 3^{o}$ for all turbines except for the last turbine where $\beta = 0,5^{o}$, when considering objective 1,. The objective 2 case displays a smaller β values for all turbines, except the last turbine where $\beta = 0^{o}$. The mixed objective case shows intermediate pitch values.

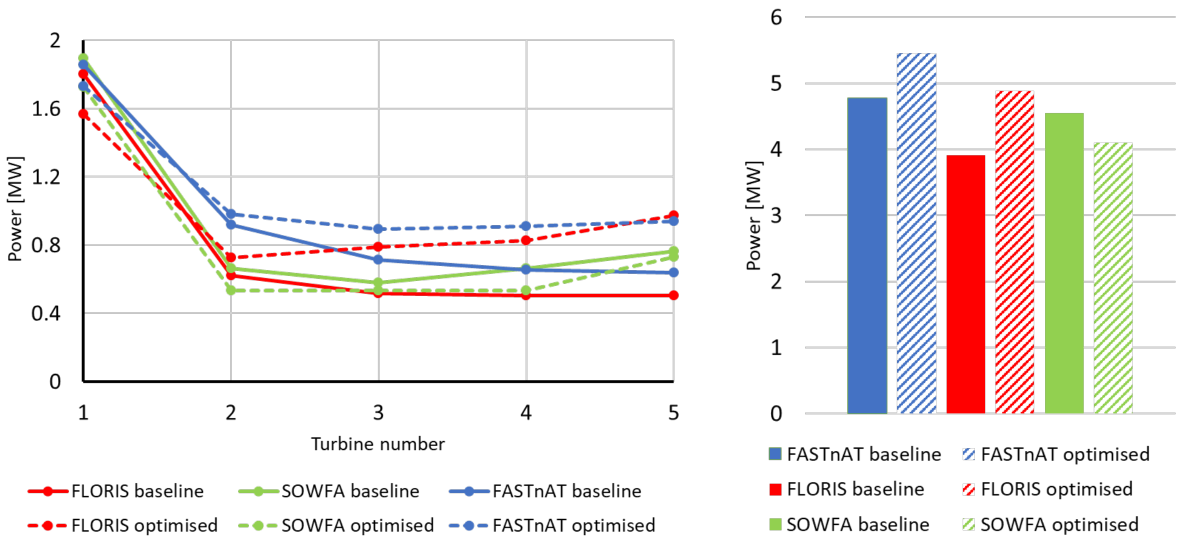
5.2.2. Case Study II: Changing Atmospheric Setting

This section focuses on investigating how the effectiveness of the AIBPC strategy is affected by varying atmospheric conditions. Several optimisations were run on the reference WF but using two different values of parameter U_∞ ($U_\infty = 6$ m/s and $U_\infty = 10$ m/s) and of parameter TI_∞ ($TI_\infty = 2\%$ and $TI_\infty = 10\%$) in turn spanning all three optimisation objectives per value, totalling 12 runs.

A general tendency for the effectiveness of pitch control action to improve overall energy production decreases as U_∞ increases is observed. Considering objective 1, an increase in FWEP of 50% is achieved for $U_\infty = 6$ m/s , then for $U_\infty = 8$ m/s the pitch action increases the farm's power production by up to $14,1\%$, and less than 10% for $U_\infty = 8$ m/s. The response may be related to the (β, TSR) operation point at which the turbines are located. Employing AIBPC increases the the averaged speed of the wake that turbines downstream of the first turbine face. For $U_\infty = 6$ m/s a decrease in C_P from turbine to turbine for the baseline case is observed, because all turbines are operating in the start-up control region. This means their operating points are shifted horizontally to the right in figure 1. It enables the action of increasing the pitch setting of the turbines to raise their C_P beyond the baseline values in general, which favours the improvement of FWEP. So for $U_\infty = 6$ m/s employing AIBPC action not only increases the averaged speed of wakes but also elevates the C_P to values higher than the baseline case, which results in a relative gain of power larger than what is seen in the results for $U_\infty = 8$ m/s and $U_\infty = 10$ m/s, in which cases the turbines are in control region 2, and so they operate at the optimal TSR.

The amount of FWFL reduction when objective 2 is considered decreases from $1,56\%$ to $0,44\%$ as the ambient WS goes from $U_\infty = 6$ m/s to $U_\infty = 8$ m/s, and then increases to $\approx 4,8\%$ when $U_\infty = 10$ m/s. Increasing the pitch of a turbine increases the velocity while reducing the turbulence of its wake, which has conflicting effects from the perspective of diminishing overall fatigue-inducing loads. When the optimiser is aiming at minimising the FWFL, its algorithm attempts to balance these effects. For $U_\infty = 8$ m/s the optimiser converges to a solution that balanced the two effects. The rise in wake velocity due to pitch action prevails over the decrease in wake turbulence level in dictating the loads of a downstream turbine for the considered lower WS, so a better load reduction is achieved for $U_\infty = 6$ m/s than for $U_\infty = 8$ m/s. The mixed objective case originates a solution that improves WF performance in terms of energy production compared to objective 2, with similar values of load reduction.

Varying TI_∞ as a relatively small impact on the AIBPC strategy's capability to improve the FWEP, while slightly worsening the ability to reduce fatigue



(a) Power of each turbine in the scenario.

(b) Total WF power.

Figure 4: Results for case study 1. FLORIS and SOWFA data taken from [17]. On the left the turbine time-averaged power P is shown. On the right the FWEP is shown.

inducing loads. A general rise in loads can be observed for all baselines cases as TI_∞ gets larger, due to the overall increase in turbulence on wakes. However for optimised cases, the performance of the WF is practically not affected by i ncreasingTI_∞, which makes the effectiveness of the control action decrease.

5.2.3. Case Study III: Changing Wind Farm Topology

This section states how the AIBPC strategy may improve WF performance in different WF topologies. Several optimisations were run on the reference WF but using two different values of parameter N ($N = 3$ and $N = 7$) and of parameter X ($X = 7$ and $= 9$) in turn spanning all three optimisation objectives per value, totalling 12 runs.

It is observed that the capability of AIBPC to make a WF output more energy is larger the more turbines there are on the farm. Naturally more machines on a farm means more agents through which integrated control may improve energy production. It became evident that adding more machines at the end of a row of WTs does not change the performance of preceding turbines, since one given turbine only has notion of the turbine upstream of it through the wake model. Additionally, the relative increase in power of a given turbine due to integrated control action is not uniform, and seems to get larger the more downstream that turbine is placed.

The observed effectiveness of the AIBPC to reduce FWFL is diminished as N increases. This is because in general the impact of AIBPC on the WF's loads is not as even on all turbines: the two most upstream turbines have their loads reduced the most by AIBPC, and in any additional turbines a relatively small load reduction is achieved. Therefore the positive effect that the integrated control action has on a given turbine becomes diluted as more turbines are added to the farm, justifying the observed response.

It is observed that the capability of the integrated control action to improve WF energy output is diminished as the distance between turbines increases. A greater distance between turbines permits a larger recovery by the their wakes to the ambient conditions, which increases the available energy in the wind and thus energy production. This however also causes that any increase in the amount of energy in a wake due to AIBPC is less impactful the more a wake is allowed to recover.

Conversely the capability of the AIBPC action to reduce FWFL is better the greater the distance between turbines in a farm. The wake added turbulence, as modelled by the Crespo & Hernández model, is inversely proportional to X. Since the wakes properties are closer to the ambient ones at greater downstream distances, turbines downstream of the first face smaller TIs. In spite of this the overall loads increase because the average velocity of the wakes is also larger at greater downstream distances. σ_{BRBM} is more sensible to U than to TI, so for this conditions increasing the distance between turbines causes a relatively small rise in the FWFL.

6. Conclusions

The objective of this thesis was to investigate WFC strategies, with a focus on axial-induction-based control. To that effect a new low fidelity model was developed and verified, named FASTnAT. The steady-state tool uses a combined wake model, composed of the Jensen model to estimate the WS and of the Crespo-Hernández model to estimate the wake's TI at a downstream distance. The FASTnAT tool was then utilised within an optimisation framework that varies the collective blade pitch setting β of each turbine in the WF so as to improve the farm's performance, in terms of energy production and fatigue damage reduction.

The conclusions from verifying FASTnAT's performance are:

- The NREL 5MW reference turbine included a generator torque control, which had to be overruled. The impact of switching to a constant rotor speed operation was assessed and found to have little effect on the turbine performance.
- The developed model overestimates the wake effects. The Jensen model is a simple representation of wake behaviour. Full wake overlap is assumed, and the model does not take into account the meandering of a wake. These two effects probably explain the overestimation.
- When compared to SOWFA, it was found that FASTnAT overestimates the positive effects of AIBPC, in terms of potential energy production, due to assuming full wake overlap, and the lower fidelity of the Jensen model. Nonetheless, overall FASTnAT is able to model the steady-state response of a system of a row of WTs, aligned with the incoming wind direction, when AIBPC is applied as a means to improve WF performance. Its capability to do so is within what is expected of a low fidelity tool.

The next set on conclusions are drawn from the optimisation study:

- Comparing the simulation results of FASTnAT, FLORIS and SOWFA, it was found that FASTnAT and FLORIS predict an increase in the FWEP, while SOWFA predicts a decrease. Changes in the axial induction of a turbine through pitch action on a turbine upstream of it are not so well described by a Jensen-type model. Despite FASTnAT's low fidelity the model is able to describe the general tendencies of applying AIBPC on a WF.
- The optimisation results of case study 1 indicate that there can be significant energy output improvement on a WF through AIBPC, at least for the reference conditions.
- The ambient WS has a pronounced effect on the AIBPC strategy's capability to influence the performance of a WF. As the velocity gets larger, improvements to the farm's energy output through pitch action are lessened, because the system's sensitivity to the pitch action is reduced. The impact U_∞ on the capacity of pitch action to affect farm's overall loads is not linear, because the magnitude of the ambient WS influences the load's sensitivity to the TI. Although loads can be reduced with AIBPC for all of the considered optimisation objectives, the ambient WS can either augment or diminish the potential of load reduction. The ambient TI has little impact on the AIBPC strategy's capability to influence the performance of a WF.
- The greater the distance between the turbines of a farm, the lesser the effect of AIBPC on the FWEP. The wakes in the farm recover more energy from the surrounding atmosphere, and as such the energy added to them through pitch control is less impactful. A greater distance between turbine in a WF increase the AIBPC strategy's capability to reduce loads. This is so because increasing the downstream distance has little impact on the evolution of loads on the considered optimised cases, but provokes a rise in turbine loads of the baseline case.

6.1. Future Work

Throughout the present work there were a few matters that came up as propositions to develop FASTnAT further. They are stated in this section.

- A turbine will most likely operate with the generator controller on. A way to run a FAST simulation with $\beta \neq 0^o$ and with a functioning generator torque controller would improve the accuracy of FASTnAT.
- FASTnAT's accuracy is dependent on the fidelity of its wake model. A next step in developing FASTnAT would be to improve the fidelity of its wake model.

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References

[1] Burton, T., Jenkins, N., Sharpe, D., and Bossanyi, E. *Wind Energy Handbook*. John Wiley and Sons, Ltd., 2nd edition, 2011. ISBN: 978-0-470-69975-1.

[2] Knudsen, T., Bak, T., and Svenstrup, M. Survey of wind farm control-power and fatigue

optimization. *Wind Energy*, 18(8):1333–1351, May 2014.

[3] Gebraad, P., Fleming, P., and van Wingerden, J. Comparison of actuation methods for wake control in wind plants. In *2015 American Control Conference (ACC)*. IEEE, July 2015.

[4] Jonkman, J., Butterfield, S., Musial, W., and Scott, G. Definition of a 5-MW reference wind turbine for offshore system development. Technical report, February 2009.

[5] NREL. NWTC information portal (fast v8). https://nwtc.nrel.gov/FAST8. Last modified 04-January-2018 ; Accessed: 12/06/2019.

[6] Gebraad, P. M. O. *DATA-DRIVEN WIND PLANT CONTROL*. PhD thesis, Delft University of Technology, 2014. Electronic version: http://repository.tudelft.nl/.

[7] Gebraad, P. M. O., Teeuwisse, F. W., van Wingerden, J. W., Fleming, P. A., Ruben, S. D., Marden, J. R., and Pao, L. Y. Wind plant power optimization through yaw control using a parametric model for wake effects-a CFD simulation study. *Wind Energy*, 19(1):95–114, December 2014.

[8] Manjock, A. Design code FAST and ADAMS for load calculations of onshore wind turbines. Technical Report 72042, Germanischer Lloyd WindEnergie GmbH, Germanischer Lloyd WindEnergie GmbH Steinhoeft 9 20459 Hamburg Germany, May 2005. https://nwtc.nrel.gov/system/files/GL_Report.pdf Acessed: 21/08/2019.

[9] Jensen, N. O. A note on wind generator interaction. *Roskilde: Risø National Laboratory*, (2411), 1983.

[10] Crespo, A. and Hernández, J. Turbulence characteristics in wind-turbine wakes. *Journal of Wind Engineering and Industrial Aerodynamics*, 61(1):71–85, June 1996.

[11] Crespo, A., Hernandez, J., Fraga, E., and Andreu, C. Experimental validation of the UPM computer code to calculate wind turbine wakes and comparison with other models. *Journal of Wind Engineering and Industrial Aerodynamics*, 27(1-3):77–88, January 1988.

[12] Wade, B. M. Investigation of offshore wind farm layout optimization regarding wake effects and cable topology. Master's thesis, Instituto Superior Técnico, 2018.

[13] Inc., T. M. MATLAB 9.5 (r2018b) and simulink toolbox, control systems toolbox, symbolic toolbox, optimisation toolbox, curve fitting toolbox. https://www.mathworks.com/. Natick, Massachusetts, USA.

[14] Barthelmie, R., Hansen, K., Rados, K., Schlez, W., Jensen, L., and Neckelmann, S. Modelling the impact of wakes on power output at nysted and horns rev. *European Wind Energy Conference and Exhibition 2009, EWEC 2009*, 2, January 2009.

[15] NREL. NWTC information portal (sowfa). https://nwtc.nrel.gov/SOWFA. Last modified 31-March-2015 ; Accessed: 02/03/2019.

[16] of Denmark (DTU), T. U. Wind Atlas Analysis and Application Program: WAsP. https://www.wasp.dk/. Accessed: 11/08/2019.

[17] Annoni, J., Gebraad, P. M. O., Scholbrock, A. K., Fleming, P. A., and van Wingerden, J.-W. Analysis of axial-induction-based wind plant control using an engineering and a high-order wind plant model. *Wind Energy*, 19(6):1135–1150, August 2015.