eawe european academy of wind energy
U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

16th EAWE PhD Seminar on Wind Energy
14-16 December 2020
Online Event

An Optimal Control Strategy to Maximize Power in an Offshore Wind Farm by Reducing Wake Interaction

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Abstract

Large-scale offshore wind farms are growing considerably fast in Europe. Optimal operational strategies are needed to improve the economic and reliability conditions of these sources. Maximising the total energy production, minimising the operating costs, and providing grid balancing services to transmission system operators are potential objectives of the optimal problem. This paper deals with an optimal operation strategy, which intends to optimise the operation of the whole wind farm by operating some wind turbines at sub-optimum points instead of optimising the power extraction of each wind turbine individually without considering the wake effect inside the wind farm. The wake formation can be minimised by reducing the wind turbine thrust force. Therefore, the axial induction based wake control can be achieved by adjusting the pitch angle and rotor speed, which results in an optimal tip speed ratio. In this work, we use the FLORIS model, which predicts the time-averaged three-dimensional flow field and turbine power capture of a wind farm as a function of the turbine control settings and the incoming wind field. The proposed approach is performed to analyse the axial induction control results in increased energy production. The analysis of the simulations of the C-Power phase one offshore wind farms in the North Sea indicates that the wake controlled strategy using axial induction control results in increased energy production.

Keywords: Wind farm, Wake control, Power maximisation

1 Introduction

The global energy consumption has been growing since the industrial revolution. In Europe, crude oil and petroleum products with their inevitable consequences on the environment are still quantifying the most significant energy sources. Fortunately, the European Union's (EU) goal is to make Europe climate neutral by 2050. The EU has been creating an inclusive and sustainable growth of renewable energy technologies over the past decade and has become a global leader in tracking the record of decarbonising power systems [1]. Wind energy offers the most extensive contribution to the EU renewable energy and is expected to be responsible for supplying up to 759 TWh by 2030, which will be 23% of electricity demand [2]. Deployment of offshore wind, in particular, and finance in its underlying technologies are fully supported by the European parliament and its established policies. There are now 110 offshore wind farms in 12 European countries with a total capacity of 22,072 MW [3]. The Belgian government is targeting to extend the installed capacity of wind farms in the North Sea up to 5.4 GW by the end of 2028.

For moving towards a truly green vision, two key elements need to be considered, i.e., the efficient integration of wind energy into the power grid by involving wind farms in the electricity market, which increases the grid resilience, and to enhance the energy production capability of wind farms by using optimal operation strategies. The stochastic nature of wind flow is the primary cause of the uncertainties, which have been introduced to the grid. A solution to this problem is that offshore wind farms actively contribute to grid balancing [4], which is quite challenging. Nevertheless, enhanced knowledge of fluid dynamics and improved forecasting algorithms, along with optimal control strategies, enable the offshore wind farms to maximise their total power generation by reducing the wake interaction among wind turbines, and might also enhance the capability of wind farms in positive contributions to grid balancing [5, 6, 7].

The conventional wind farm control approach relies on greedy control, in which the operation of wind turbines is optimised individually in order to maximise its power extraction and to minimise structural loading. However, advanced control strategy aims to optimise the wind farm total production by operating some turbines at suboptimal points to reduce wake interactions [8, 9, 10]. In particular, the Belgian offshore is recognised as a high-density production zone, the proposed approach might lead to a low variability of the wind farm power, especially in case of a severe turbulent condition [11]. Moreover, to enable offshore wind farms to comply with the grid codes requested by transmission system operators, the power reserve dispatching should be conducted such that the aerodynamic coupling is less affected by the wake [12, 13].

In literature, among wind farm operation and active wake control strategies, two major control approaches can be characterised, i.e., Axial Induction Control (AIC) and Wake Redirection Control (WRC) through yawing or tilting wind turbines [14]. Steering the wakes away from downstream wind turbines by operating the wind turbines with a yaw misalignment is widely discussed in the literature [15, 16, 17].

The concept of axial induction control, which is the focus of this paper, is to reduce upstream wind turbines' thrust force and weaken wake formations by adjusting their axial induction factor through the pitch angle or tip speed ratio. This enables downstream wind turbines to extract more power and experience fewer wake turbulences [14]. A control design is proposed in [8] based on a coordinated control between a wind farm centralised and wind turbine local controllers. The central controller optimises the operation of each wind turbine to maximise the farm total power production, and the local controllers are responsible for regulating wind turbine speed at a predetermined setpoint. Furthermore, advanced control approaches with the target of lowering the Levelised Cost Of Energy (LCOF), including the reduction of fatigue load and enhancement of grid support measures, gained much attention in recent years [18, 19, 20].

This paper investigates the optimal operational strategy of the C-Power phase one offshore wind farm in the North Sea, which consists of six 5MW turbines in a single row, based on axial induction control. Section 2 discusses the axial induction control method and its fundamentals. Section 3 introduces the control Strategy and Wind Farm Modeling. Results of the wind farm simulation are given in section 4. The paper concludes with a summary in section 5.

2 Axial induction nontrol

To achieve axial induction based control, which aims to reduce the wake deficit downstream by reducing the axial induction factor of upstream wind turbines, the free-streamed wind turbines need to be operated outside their aerodynamic maximum by increasing the blade pitch angle or reducing the tip-speed ratio (operating at a suboptimal) [21]. This reduces the mechanical power P_m and the magnitude of the rotor's thrust force F_T given by (1) and (2).

$$P_m = \frac{1}{2}\rho A C_P(\beta, \lambda) v^3 \tag{1}$$

$$F_T = \frac{1}{2}\rho A C_T(\beta, \lambda) v^2 \tag{2}$$

where ρ is the air density, A is the rotor radius, C_p is the power coefficient, which is a function of the pitch angle β and tip speed ratio λ, and v is the wind speed. The tip speed ratio is defined as the ratio

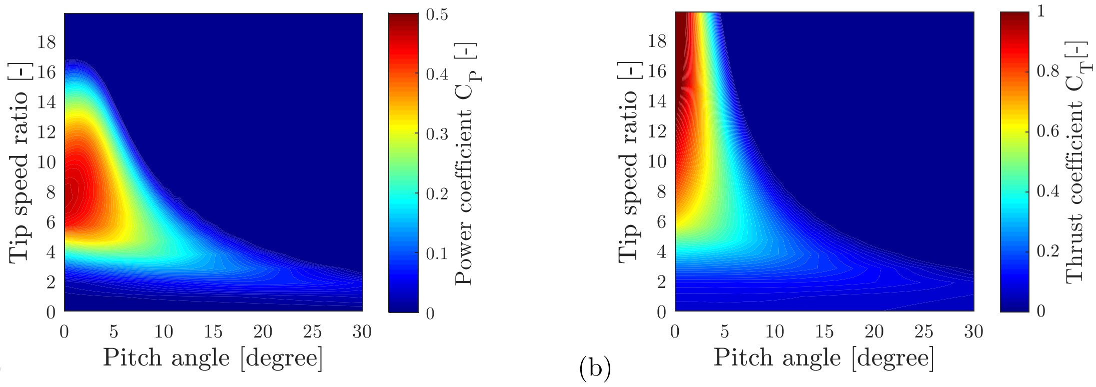

Figure 1: (a) Power coefficient and (b) Thrust coefficient in terms of the pitch angle and tip speed ratio distribution in the downstream direction.

of the blade tip speed over the speed of the incoming wind is given by (3).

$$\lambda = \frac{\omega R}{v} \tag{3}$$

The power coefficient and thrust coefficient of the 5 MW offshore turbine in terms of the pitch angle and tip speed ratio is shown in Figure 1. The power coefficient is 0.46 obtained at the pitch angle of 0° and the tip speed ratio of 7.56, whereas the maximum thrust coefficient of the wind turbine can be obtained at the pitch angle of 0° and the tip speed ratio of 18.6. Classically, the average wind velocity at the turbine can be given by the axial induction factor a. As shown in Figure 2, the extraction of energy by the turbine blades causes a reduction in the wind velocity at the turbine disk, and also in the wake of the turbine. Based on the continuity equation in the steady-state, the flow area will increase at the turbine, and even more at the wake, which results in flow reduction [22].

In this paper, the wake model available in FLORIS is employed, which incorporates Jensen's model incorporated with the wind farm model and its control tools [7, 23, 24]. It is necessary to have a sufficient understanding of the coupling between C_P and C_T to achieve the controllability of the wind farm. To provide a realistic description of turbine interactions in a wind farm, the 5 MW turbine model is simulated in FAST, which consists of a C_P/C_T table based on wind speed and blade pitch angle [7]. Moreover, C_P and C_T, correspond to the local conditions that each turbine is operating at, and can be defined as a function of the axial induction factor (a) as follows

$$C_P = 4a(1-a)^2 \tag{4}$$

$$C_T = 4a(1-a) \tag{5}$$

The wake model is also able to compute the turbulence that is generated by turbine operation and ambient turbulence conditions based on the number of turbines affecting the downstream turbines, the ambient turbulence intensity, and the added turbulence due to each turbine operation, which can be calculated in terms of C_T as a function of the axial induction factor.

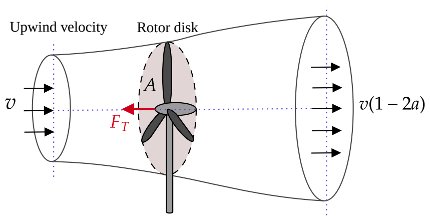

Figure 2: Stream-tube of a wind turbine.

3 Wind farm modeling and proposed control strategy

The simulation of the axial induction control strategy is implemented to the C-Power first phase offshore wind farm, which is the first operational wind farm located in the Belgian North Sea. The wind farm is neighbored by the second and third phases of the C-Power project consisting of 48 of 6M Senvion turbines with a total capacity of 295.5 MW. The first phase has been positioned in one row consisting of 6 5MW turbines with 500-meter distances between the turbines, which assumed are not influenced by the wakes of the C-Power second and third phases. The simulated wind farm layout and the flow estimation, by using FLORIS, is illustrated in Figure 3.

The purpose of axial induction control is to adjust the power production of upwind turbines away from their optimal settings to control the axial induction so that downwind turbines can produce more. This strategy is beneficial if the reduced power generation of the upwind turbine can be compensated by the downwind turbines and/or when the upstream turbine significantly affects the performance of the downstream turbines by its wake. In this work, the wind direction is aligned with a row of 6 turbines. For a given wind direction, maximum wake conflicts, less wake recovery, and fairly wake-rotor overlap can occur subsequently.

The wind farm total power generation is given by [25] can be maximized by solving the following optimization problem

$$Max \sum_{i=1}^{6} \frac{1}{2} \rho A C_P(a_i) v_i^3 \tag{6}$$

Varying an axial induction factor a_i not only influences the power production of the turbine i but also changes the speed of the wind traveling downstream of the turbine i due to the wake interaction. The control parameters a_i can be iteratively updated to search for an optimized solution. The optimisation process for the below-rated wind conditions with 10% turbulent intensity performs a reference calculation using the modified C_P/C_T map based on the pitch setting. The wake parameters are computed at each turbine location to adjust the axial-induction factor of the individual turbine. It is worth mentioning that the power coefficient C_P is less sensitive to the control settings at the maximum operating point, whereas the thrust coefficient C_T is more sensitive to the pitch action. Therefore, only the pitch of the most upstream turbines is optimised in this process. Earlier studies have indicated that increasing the pitch angle of downstream turbines does not improve the energy yield [21].

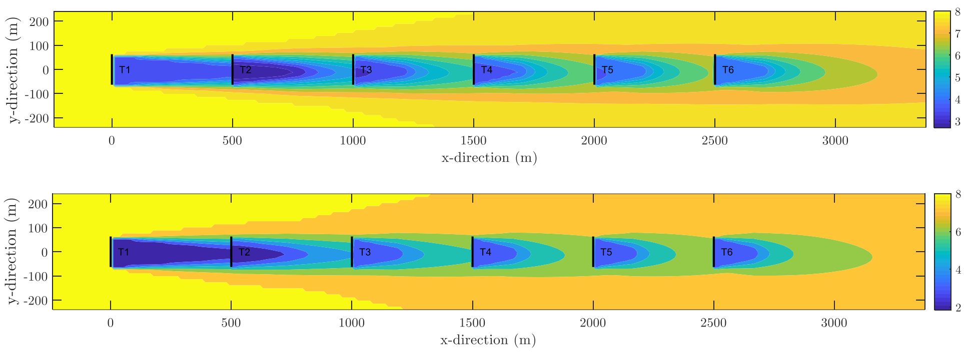

Figure 3: The layout of the simulated wind farm and flow estimation using FLORIS. Top: wake controlled. Bottom: nominal operation.

4 Simulation results

The results of the simulation at different wind speeds below the rated shows that using the axial induction control method can be beneficial in energy production since the overall power production is increased. The reduced turbulence intensity and the wake deflection of the upstream turbine can be observed in Figure 3. Due to the semi-uniform reduction in the axial induction factor, the wake shape remains similar for downstream turbines, and a small part of the kinetic energy of the wake can be diffused into the downstream turbine rotor diameter.

As shown in Figure 4, the power of the upstream turbine decreases when the wake controlled approach is activated through axial induction control. This is due to the pitch angle offset, which reduces the aerodynamic effectiveness of the blades. For most of the remaining turbines of the row, an increase in power can be observed, resulting in an overall power gain. The numerical results are given in Table 1.

Table 1: Numerical results

Wind speed m/s	5	6	7	8	9	10	11	12
Total power (MW) Nominal operation	1.39	3.31	4.00	6.03	8.50	14.44	18.35	22.09
Total power (MW) Wake controlled	1.43	3.43	4.17	6.31	8.90	14.76	18.83	22.44
Power gain %	2.59	3.68	4.25	4.60	4.70	2.21	2.60	1.58

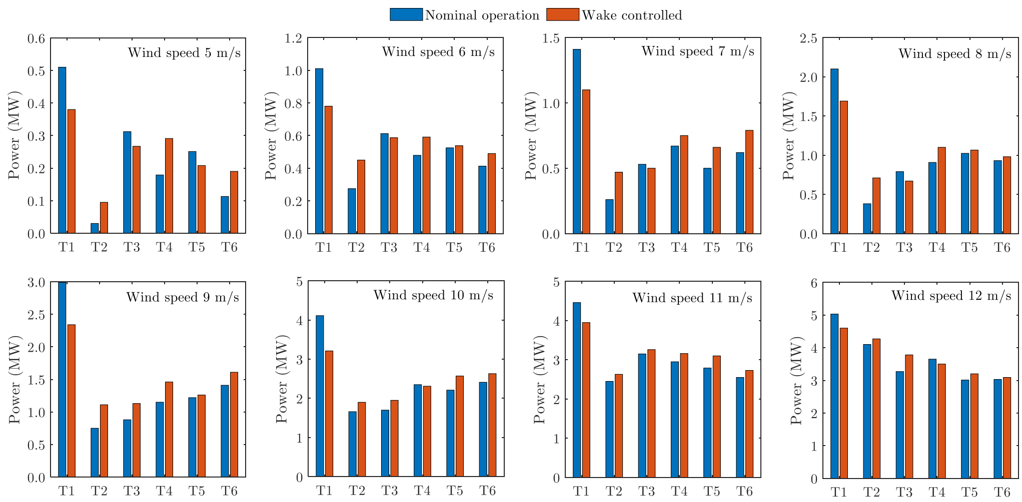

Figure 4: Power of turbines in row T1-T6 for wind speed of 5 m/s to 12 m/s in case of nominal operation and wake controlled.

5 Conclusion

In this paper, the performance of the wake controlled strategy using the axial induction control method is compared with the wind farm nominal operation. The first phase of the C-Power offshore wind farm layout is simulated using FLORIS. The axial induction control approach tries to optimise the total power production of a wind farm by minimising the overall wake deficit through adjusting control inputs. The results show that there is an advantage in using the proposed control method, particularly when the wind direction is aligned with the row of wind turbines. It has been conducted that this strategy can significantly improve the efficiency of the wind farm.

Further investigation can be made to analyse the impact of the wind turbines' structural load in case of applying this strategy. In this paper, it has been assumed that the wind turbines in the first phase are not affected by the wakes of the C-Power second and third phases. However, future studies can explore additional effects to see if the optimal wake adjustment can be reasonably used for the entire C-Power farm.

Acknowledgements

This work was performed in the framework of the Energy Transition Fund project BEOWIND of the Belgian federal government, and the FWO research project G.0D93.16N, funded by the Research Foundation Flanders.

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