An Optimal Wind Farm Control Strategy for Grid Frequency Support using Particle Swarm Optimization

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Abstract

Offshore wind farms are constantly growing in many countries around the globe and are becoming responsible for a significant part of electricity generation. Transmission system operators require these sustainable sources to contribute to ancillary services such as frequency containment reserve. Consequently, offshore wind farms are needed to temporarily increase and decrease the active power delivered into the power system to compensate for grid imbalances caused by electricity production and consumption unbalance. This paper studies a wind farm's optimal coordinated operation strategy, aiming to maximise the overall power production while providing active power control services to the power grid by minimising the wake interactions inside the wind farm. The particle swarm optimisation algorithm is used to decide each wind turbine's desired control setpoints for the optimal distribution of power reserve among the wind turbines. This strategy reduces the negative effect of wakes caused by the upstream turbines and thus maximises the power reserve and total power production. The first phase of the C-Power Belgian offshore wind farm in the North Sea with six wind turbines is considered to evaluate the performance of the proposed approach. Results demonstrate the effectiveness of the proposed control strategy in different operational conditions.

1 Introduction

The accelerating environmental crisis and cost-effectiveness of renewable energy sources (RES) have led to an enormously increased penetration level of these sources into the electrical power system. Wind energy is one of the fastest-growing, most qualified, economic, and well-developed RES. According to the Global Wind Energy Council, its capacity is expected to reach 234 GW by the end of 2030 [1]. The European Union (EU) is committed to evolving into the global leader in renewables, envisioned that wind power will be a vital key element in achieving the target to make the EU carbon-neutral by 2050 [2].

However, the increased integration of wind power has raised grid stability and reliability concerns. These circumstances are mainly due to the variability of wind power generation and the reduction of the total system inertia, which stem from the stochastic nature of wind and electrical decoupling between the rotor mechanical speed and the grid frequency [3, 4]. The mentioned issue poses significant challenges to Transmission System Operators (TSOs), who used to provide frequency regulation and maintain the balance of power supply-demand through conventional power plants [5]. Thus, TSOs are now demanding wind farms to actively contribute to the provision of ancillary services, which so far have been relying on conventional sources.

Many studies have been carried out focusing on the technical capability of wind energy conversion systems considering grid balancing services with either an individual wind turbine system or an aggregated wind farm [6]. The aerodynamic coupling between wind turbines in a wind farm creates a wind energy deficit between the wind leaving turbine (upstream wind turbine) and the wind arriving turbine (downstream wind turbine). This phenomenon, known as the wake effect, makes it challenging to estimate the exact wind farm total energy and its optimal contribution to reserve markets [7]. Wind farms must use operational control strategies to participate in active grid balancing services, such as deloading methods that maintain an adequate power reserve for providing an automatic and fast response to the TSO's demands and grid frequency changes [8]. The provision of power reserve adds complexity to such correlated aerodynamic systems. Some studies have focused on determining the effectiveness of including inertial response and frequency control techniques in wind power plants, considering the apparent limitations of wind farms compared to traditional power plants [9, 10].

Applying these techniques often reduces wind energy production by a certain level of energy or efficiency loss. [11] addressed the maximum harvesting kinetic energy during deloading control strategy using a game theory-based optimal control framework, which distributedly adjusts rotor speeds of individual wind turbines in a wind farm layout. Other studies propose coordinated control approaches for wind farms providing frequency control considering wake interactions inside the farm. In [12], a coordinated wind farm operation strategy is proposed that, instead of seeking to maximise the power generation of wind turbines individually, ensures the maximisation of the rotational kinetic energy while maintaining the optimal wind farm's overall performance. A control algorithm is suggested in [13] to distribute the power contribution of each turbine, aiming to minimise the wake effects and maximise the power reserve.

This study proposes an optimisation algorithm, which optimally distributes each turbine's power reserve contribution to minimise the wake effects and maximise the power production. First, the wind farm performance in fixed and turbulent wind conditions under the axial induction optimiser method is studied to understand the wake behavior and obtain each wind turbine's optimal axial induction factor. Then, the Particle Swarm Optimisation (PSO) tool is used to search for optimal rotational speed in deloading control strategies while satisfying the limitations that are initiated in axial induction optimiser operation mode. The paper is structured as follows: Section II introduces an optimal operational strategy for offering an optimal Frequency Containment Reserve (FCR) provision considering the deloading and wake controlled strategies. Section III formulates the optimal operation strategy for the wind farm case study. Section IV provides an overview of the outcomes and results, while Section V summarises and concludes the paper.

2 An optimal operational strategy

The general overview of the proposed wind farm's optimal operational strategy is shown in Fig. 1. Depending on the available power and the scheduled power reserve offered in the day ahead reserve market, the wind farm supervisory controller searches for each turbine's control setpoints to maximise the total power generation and minimise wake interactions. The axial induction optimiser suggested by [14] is considered for updating the wake information, which is needed for adjusting the constraints of the problem. The worst-case scenario of the wind speed being in the same direction as the wind turbines row is considered to address the challenges of wind farms' in high-density zones with the most increased wake interactions.

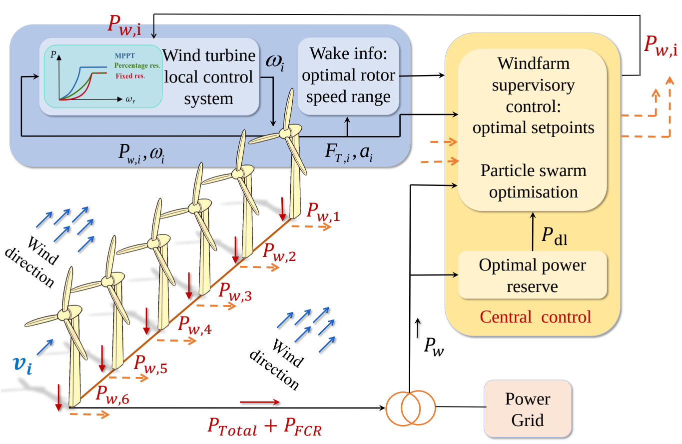

Fig. 1. A general framework for optimal operational strategy.

2.1 Control scheme

With total available power P_{av}^{t} higher than the scheduled power reserve P_{res}, the wind farm is able to deliver FCR in response to the grid frequency variations. The power that should be arranged among N wind turbines can be referred to as deloaded power:

$$P_{\text{dl}} = P_{\text{av}}^{t} - P_{\text{res}} \tag{1}$$

where

$$P_{\text{av}}^{t} = \sum_{i=1}^{N} P_{\text{av}}^{t}, i(v_i) \tag{2}$$

and v_i is the wind speed experienced by each turbine. At above-rated wind speeds, wind farms are able to satisfy the scheduled power reserve and provide FCR. However, at below-rate wind speeds, it is required to deload some wind turbines by increasing the rotational speed from optimal operation in normal mode $\omega_{\text{nom}}^{\text{opt}}$ to suboptimal operation in deloading mode $\omega_{\text{dl}}^{\text{opt}}$ so that the wind farm can meet the promised FCR provision in case the grid frequency drops and extra power needs to be injected proportionally to the grid. The electrical power of each wind turbine can be expressed as:

$$P_{W,i} = \frac{1}{2}\pi R^2 \rho v_i^3 C_p(\lambda, \beta) \tag{3}$$

where ρ is the air density, R is the blade length, and $C_p(\lambda, \beta)$ is the power coefficient, which varies with the tip speed ratio $\lambda = R\omega_i/v_i$ and the blade pitch angle β. An empirical $C_p(\lambda, \beta)$ equation can be found in literature [15], with an exponential form as follows:

$$C_P(\lambda, \beta) = c_1 \left(\frac{c_2}{\lambda_i} - c_3\beta - c_4 \right) e^{\frac{-c_5}{\lambda_i}} \tag{4}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + c_6} - \frac{c_7}{\beta^3 + 1} \tag{5}$$

where for different wind turbines coefficients $c_1, \ldots, c_6$ are different and for MW size wind turbines are 0.22, 116, 0.4, 5, 12.5, 0.088 and 0.035 respectively [16]. Moreover, C_p can be also written as a function of the axial induction factor a_i:

$$C_{p,i} = 4a_i(1 - a_i)^2 \tag{6}$$

The induction factor a_i can take values between 0 and 1/3, and the maximum value of C_p is obtained at a=0.33. The deloading operation strategy can be achieved by acting individually on pitch and torque control, ensuring suboptimal operation for a given v_i with optimal unique a_i under the axial induction optimiser control method. In this study, to fully explore the potential capacities of variable speed wind turbines in participating grid balancing services, the deloaded power generation is considered to be realised by accelerating the wind turbine's rotor speed into various but optimal values. However, the pitch control system can only be activated to adjust the limitations of the axial induction factor. The kinetic energy that can be stored in rotating masses of wind turbines can be released for further system support, e.g. in inertial response.

2.2 *Optimisation framework*

The scheduled reserve capacity should be optimally distributed depending on the location of each turbine within a farm and the airflow deficits caused by the wake effects induced by upstream turbines. Therefore, optimal rotor speed estimation can be achieved by considering the conflict between maximum generated power, complex interactions among wind turbines, and the amount of power reserve needed for the FCR provision. The main objective of the optimisation problem is to maximise the total output power of the wind farm $\sum P_{W,i}$. This can be achieved by operating some wind turbines in a suboptimal operation mode. It is possible to manage the minimum wake deflection by giving the upstream wind turbines less share in FCR contribution. Consequently, the optimisation problem for the optimal deloading control of wind turbines is given as follows:

$$\max_{\omega_i^{\text{dl}}} \sum_{i=1}^{N} P_{W,i} \tag{7}$$

where $P_{W,i}$ is given in (4) and (5). The objective function is subject to the following constraints:

$$\underline{\omega_i} \leqslant \omega_i^{\text{dl}} \leqslant \overline{\omega_i} \tag{8}$$

$$P_{W,i} \leqslant \frac{1}{2}\pi R^2 \rho v_i^3 C_p(a_i^{\text{opt}}) \tag{9}$$

$$\sum_{i=1}^{N} P_{w,i}, = P_{\text{dl}} \tag{10}$$

where the optimal rotor speed is limited to the minimum $\underline{\omega_i}$ and maximum $\overline{\omega_i}$ rotational speed allowable range. The maximum rotor speed is rated by the maximum speed of the turbine drivetrain. The minimum rotor speed ensures the optimal tip speed ratio in non-deloading (normal) operational condition. The constraint (9) ensures the output power of each wind turbine is limited by the power setpoint that is achieved under the axial induction optimiser method considering the wake minimisation approach. The constraint (10) also ensures maintaining the scheduled power reserve that has been foreseen for the wind farm to provide in the day-ahead reserve market, which is given in (1).

3 Case study and simulation results

3.1 *Wake modelling*

The suggested optimisation problem is used for the first phase of the C-power offshore wind firm in the North Sea, with six 5 MW wind turbines in a single line. In this section, the wind farm performance and the wake interactions are studied at different wind speeds in steady and turbulent wind conditions using the FLORIS' axial induction optimisers module [14]. The axial induction optimiser aims to increase overall wind plant performance by coordinating the operation of the turbines, in which the power extraction of the upstream turbines is adjusted to influence the velocity deficits in the wakes. Fig. 2 shows the wind farm's relative power increase in normal and axial induction optimiser mode. The simulations at different

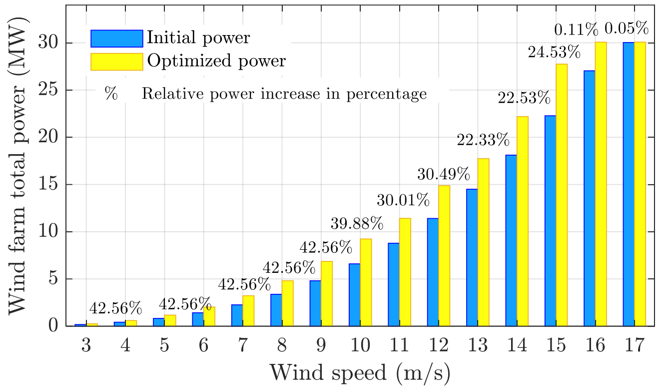

Fig. 2 Wind farm relative power increase in normal and axial induction optimiser mode.

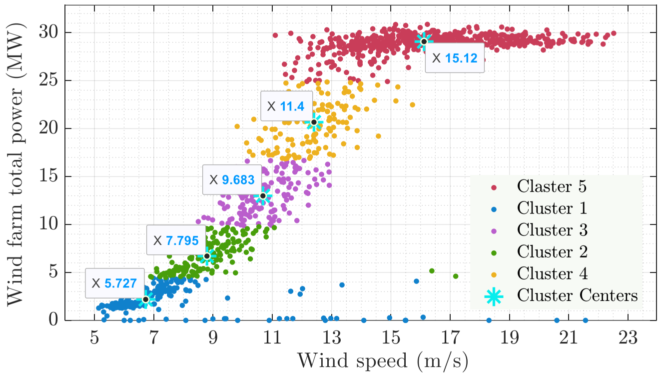

Fig. 3. Wind farm operation using Axial induction optimiser.

wind speeds illustrate that the effectiveness of the suggested approach increases by decreasing wind speed. Therefore, this strategy is more effective in below-rated wind conditions. To evaluate the performance of the proposed operational strategies, the K-means algorithm finds the potential dominant clusters in the wind farm power curve, which shows the total power production at the different wind speeds, directions, and turbulence intensities. Fig. 3 offers the five mean wind speeds, which can represent the wind farm behavior in all operating regions. Figs. 4 to 8 show the performance of the optimiser and optimal axial induction factors of the wind turbines in a steady wind (top) and a wind with 10% turbulence intensity (bottom). The obtained a_i^{opt} are used to formulate constraint (9) and limit the contribution of upstream wind turbines in FCR provision, which results in more wake formation. The simulation results show severe wake in steady winds and the necessity of applying the offered optimal coordination strategy in low wind speed and less turbulent wind conditions. However, it seems in turbulent wind conditions and higher wind speed availability, WT5 is more subjected to axial induction control limitation, and the rest of the wind turbines are allowed to operate greedily and maximise their respective output power.

3.2 *Optimal Rotor speed control*

This section gives the obtained results of the studied operational strategy utilising PSO for cases one to five (based on five clusters) in steady wind conditions. The optimal rotational

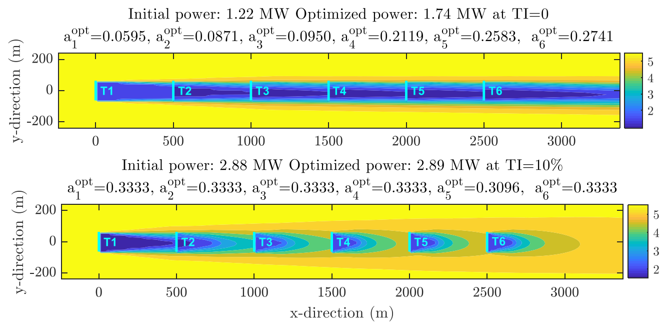

Fig. 4 Wind farm operation under axial induction optimiser and at mean wind speed of first cluster center (5.7 m/s).

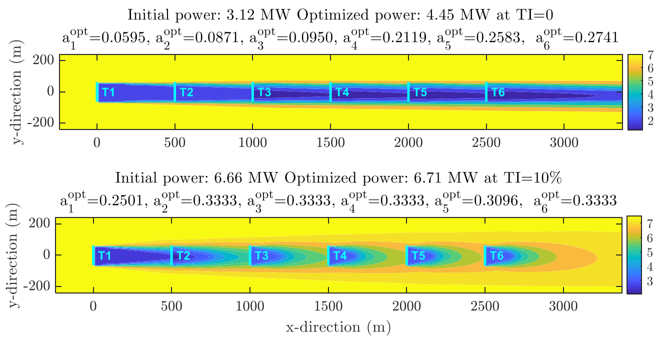

Fig. 5 Wind farm operation under axial induction optimiser and at mean wind speed of second cluster center (7.79 m/s).

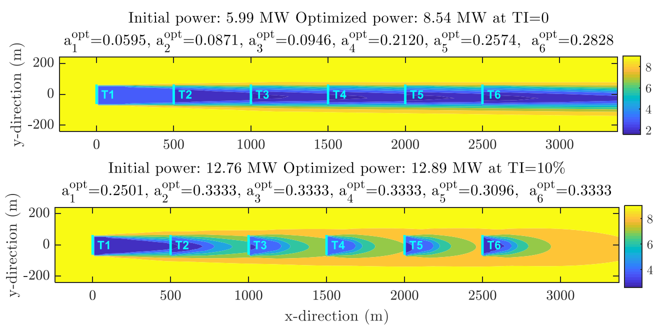

Fig. 6 Wind farm operation under axial induction optimiser and at mean wind speed of third cluster center (9.68 m/s).

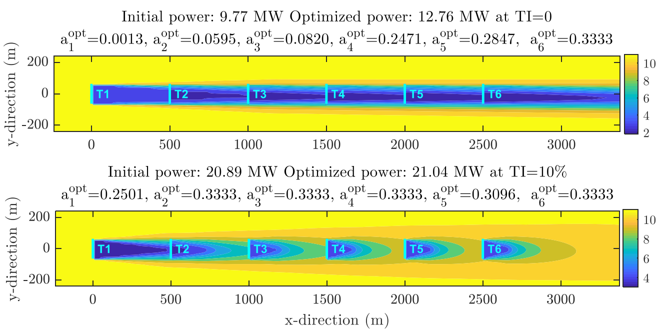

Fig. 7 Wind farm operation under axial induction optimiser and at mean wind speed of third cluster center (11.4 m/s).

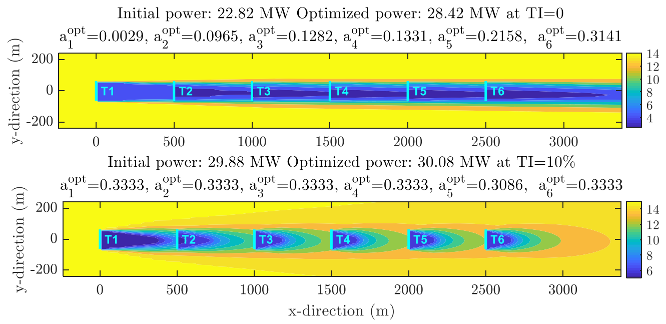

Fig. 8 Wind farm operation under axial induction optimiser and at mean wind speed of third cluster center (15.12 m/s).

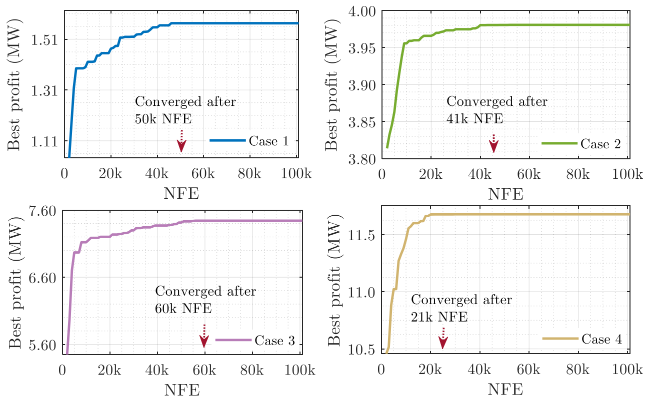

Fig. 9 The convergence curves of number of function evaluation and maximised total power production.

speed and the share of each wind turbine are given in Table1. The table of results shows the minimum contribution of the first three upstream wind turbines (less than 15%) and the maximum contribution of the last three downstream wind turbines (more than 85%). It can be concluded that the upstream wind turbines are not good candidates for providing FCR since the excessive rotor speed, which is required for power reserve, will result in massive wind speed deficiencies for the downstream ones. WT1 in case 5 should not be considered an FCR provider based on the founded optimal solutions since the wind speed goes above nominal and the optimal rotational speed reaches its rated value. However, WT6 in case 5 can be considered as the main FCR provider since it experiences wind speed at relatively high wind speed, and a_6^{opt} is not limited at all by the proposed axial induction optimiser. The studied optimal strategy suggests more diverse solutions in less turbulent wind conditions. However, the optimal solutions are less creative and offer an equal contribution of 17.1% for WT1, WT2, WT3, WT4 and WT6 and 14.5% for WT5 for all the studied cases at 10% turbulent intensity.

Moreover, Fig. 9 shows the performance of the PSO by giving the iterative best solution in maximising total power base on Number of Function Evaluations (NFE) for the first 4 cases. Case 5 with 10k NFE has the fastest convergence speed. For many tries the convergence of the proposed algorithm is less than 60k NFE.

Table 1 The optimal rotational speed and the share of each wind turbine in FCR provision.

	Case 1 $P_{res} = 122$ kW			Case 2 $P_{res} = 312$ kW			Case 3 $P_{res} = 599$ kW			Case 4 $P_{res} = 997$ MW			Case 5 $P_{res} = 2.282$ MW		
	$\omega_{\text{opt}}^{\text{nom}}$ rad/s	$\omega_{\text{opt}}^{\text{dl}}$ rad/s	WT share	$\omega_{\text{opt}}^{\text{nom}}$ rad/s	$\omega_{\text{opt}}^{\text{dl}}$ rad/s	WT share	$\omega_{\text{opt}}^{\text{nom}}$ rad/s	$\omega_{\text{opt}}^{\text{dl}}$ rad/s	WT share	$\omega_{\text{opt}}^{\text{nom}}$ rad/s	$\omega_{\text{opt}}^{\text{dl}}$ rad/s	WT share	$\omega_{\text{opt}}^{\text{nom}}$ rad/s	$\omega_{\text{opt}}^{\text{dl}}$ rad/s	WT share
WT1	0.686	0.671	6.6 %	0.934	0.929	1.84 %	1.160	1.105	13.1 %	1.267	1.271	0.86 %	1.267	1.299	5.60 %
WT2	0.325	0.318	3.1 %	0.443	0.433	3.19 %	0.550	0.538	2.84 %	0.648	0.634	3.25 %	0.860	0.840	3.25 %
WT3	0.345	0.338	3.5 %	0.470	0.460	3.39 %	0.584	0.571	2.96 %	0.688	0.672	3.43 %	0.912	0.892	3.43 %
WT4	0.345	0.406	26.5 %	0.470	0.553	27.0 %	0.583	0.687	24.3 %	0.687	0.809	27.7 %	0.911	1.073	27.9 %
WT5	0.345	0.402	25.0 %	0.465	0.547	27.0 %	0.578	0.680	24.1 %	0.680	0.800	27.4 %	0.902	1.062	27.6 %
WT6	0.339	0.421	37.5 %	0.461	0.574	37.0 %	0.573	0.713	32.7 %	0.675	0.839	37.3 %	0.928	1.113	47.3 %

4 Conclusions

This study proposes an optimal wind farm control strategy that provides FCR using an axial induction control method. The main objective is to maximise wind farm total power production while offering power reserve with a deloading control approach. Wind turbines' rotational speeds should be increased by setting tip speed ratios (TSR) at suboptimal values. This contradicts the axial induction optimiser goal, which aims to adjust the axial induction factor to reduce the wake effect. The solution to this study's main optimisation problem suggests higher power reserve and FCR contribution for the most downstream wind turbines. It also offers minimum power reserve for the most upstream wind turbines in the row, especially when the dominant wind speed is not very high and turbulent.

5 Acknowledgment

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6 References

[1] GWEC. "An offshore wind report 2020", , (2020).

[2] T. Muneer, E. Jadraque Gago, S. Etxebarria Berrizbeitia. "Wind energy and solar pv developments in the eu", *The Coming of Age of Solar and Wind Power*, pp. 139–177, (Springer, 2022).

[3] H. Bevrani, A. Ghosh, G. Ledwich. "Renewable energy sources and frequency regulation: survey and new perspectives", *IET Renewable Power Generation*, **4(5)**, pp. 438–457, (2010).

[4] X. Wang, A. Palazoglu, N. H. El-Farra. "Operational optimization and demand response of hybrid renewable energy systems", *Applied Energy*, **143**, pp. 324–335, (2015).

[5] D. Y. Li, P. Li, W.-C. Cai, Y.-D. Song, H.-J. Chen. "Adaptive fault-tolerant control of wind turbines with guaranteed transient performance considering active power control of wind farms", *IEEE Transactions on Industrial Electronics*, **65(4)**, pp. 3275–3285, (2017).

[6] A. Žertek, G. Verbič, M. Pantoš. "Optimised control approach for frequency-control contribution of variable speed wind turbines", *IET Renewable power generation*, **6(1)**, pp. 17–23, (2012).

[7] M. De-PradaGil, C. G. Alías, O. Gomis-Bellmunt, A. Sumper. "Maximum wind power plant generation by reducing the wake effect", *Energy conversion and management*, **101**, pp. 73–84, (2015).

[8] S. Boersma, B. Doekemeijer, S. Siniscalchi-Minna, J. van Wingerden. "A constrained wind farm controller providing secondary frequency regulation: An les study", *Renewable energy*, **134**, pp. 639–652, (2019).

[9] M. Dreidy, H. Mokhlis, S. Mekhilef. "Inertia response and frequency control techniques for renewable energy sources: A review", *Renewable and Sustainable Energy Reviews*, **69**, pp. 144–155, (2017).

[10] A. Fernández-Guillamón, E. Gómez-Lázaro, E. Muljadi, Ángel Molina-García. "Power systems with high renewable energy sources: A review of inertia and frequency control strategies over time", *Renewable and Sustainable Energy Reviews*, **115**, p. 109369, (2019).

[11] J. Zhang, Y. Li, Z. Xu, D. Qi, C. Li. "Game theory-based optimal deloading control of wind turbines under scalable structures of wind farm", *IET Cyber-Physical Systems: Theory & Applications*, **3(4)**, pp. 224–231, (2018).

[12] A. S. Ahmadyar, G. Verbič. "Coordinated operation strategy of wind farms for frequency control by exploring wake interaction", *IEEE Transactions on Sustainable Energy*, **8(1)**, pp. 230–238, (2016).

[13] S. Siniscalchi Minna, F. D. Bianchi, M. De Prada Gil, C. Ocampo Martinez. "A wind farm control strategy for power reserve maximization", *Renewable energy*, **131**, pp. 37–44, (2019).

[14] B. Doekemeijer, R. Storm, J. Schreiber, D. V. der Hoek. "TUDelft-DataDrivenControl/FLORISSE_M: Stable version from 2018-2019", , (January 2021).

[15] J. D. M. De Kooning, L. Gevaert, J. Van de Vyver, T. L. Vandoorn, L. Vandevelde. "Online estimation of the power coefficient versus tip-speed ratio curve of wind turbines", *IECON 2013-39th Annual Conference of the IEEE Industrial Electronics Society*, pp. 1792–1797, (IEEE, 2013).

[16] M. Carpintero-Renteria, D. Santos-Martin, A. Lent, C. Ramos. "Wind turbine power coefficient models based on neural networks and polynomial fitting", *IET Renewable Power Generation*, **14(11)**, pp. 1841–1849, (2020).