

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.

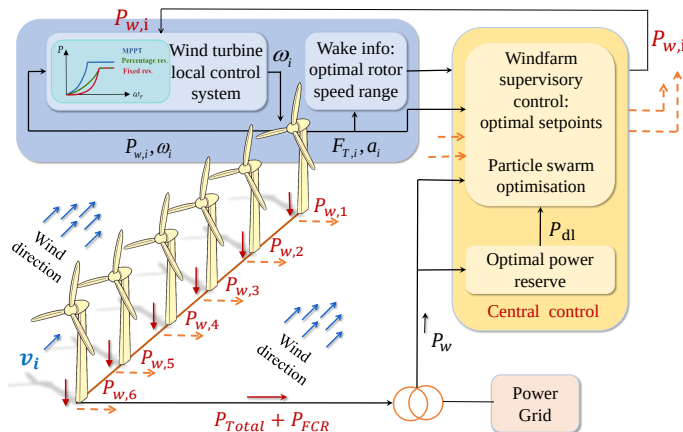
Many studies have been carried out focusing on the technical capability of wind energy conversion systems considering grid

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.

2 An optimal operational strategy



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 sub-optimal 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:

$$\max_{\omega_i^{dl}} \sum_{i=1}^N P_{W,i} \quad (7)$$

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

$$\underline{\omega}_i \leq \omega_i^{dl} \leq \overline{\omega}_i \quad (8)$$

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

$$\sum_{i=1}^N P_{w,i} = P_{dl} \quad (10)$$

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-deloeading (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 farm 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

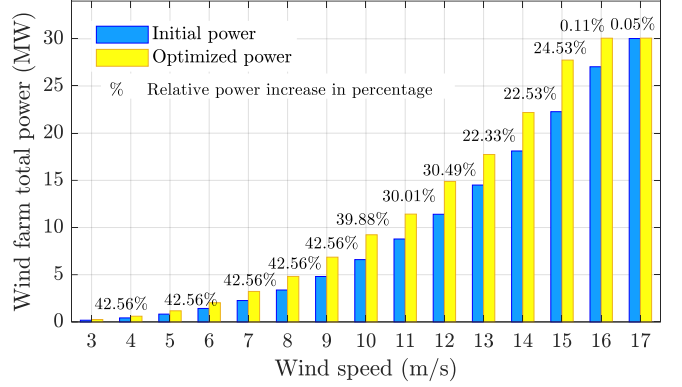


Fig. 2 Wind farm relative power increase in normal and axial induction optimiser mode.

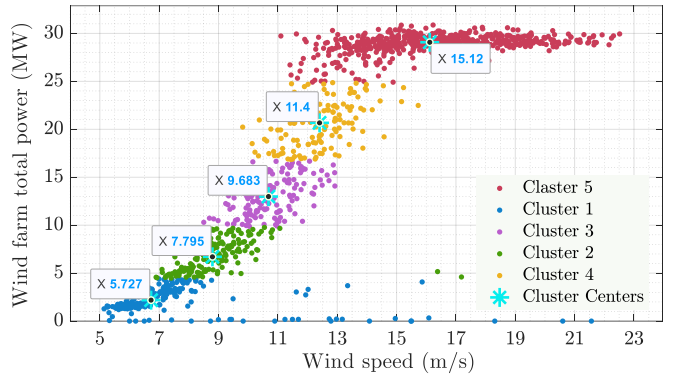


Fig. 3. Wind farm operation using Axial induction optimiser.

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

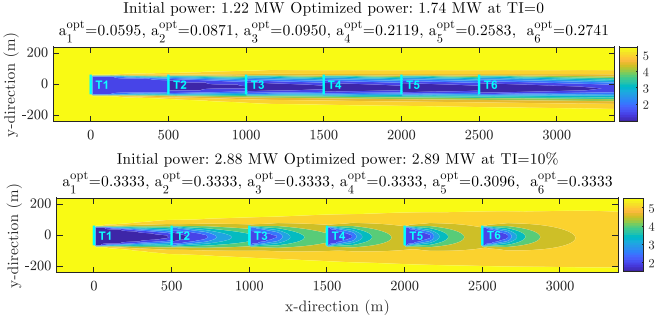


Fig. 4 Wind farm operation under axial induction optimiser and at mean wind speed of first cluster center (5.7 m/s).

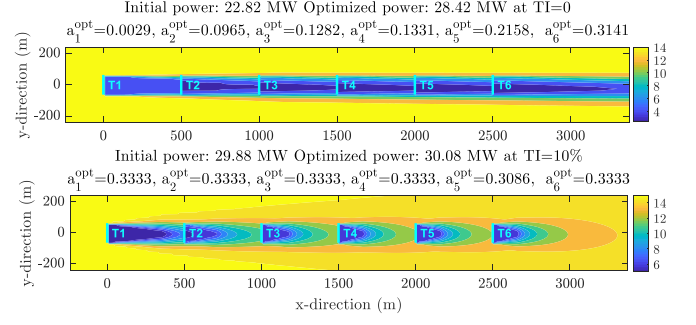


Fig. 8 Wind farm operation under axial induction optimiser and at mean wind speed of third cluster center (15.12 m/s).

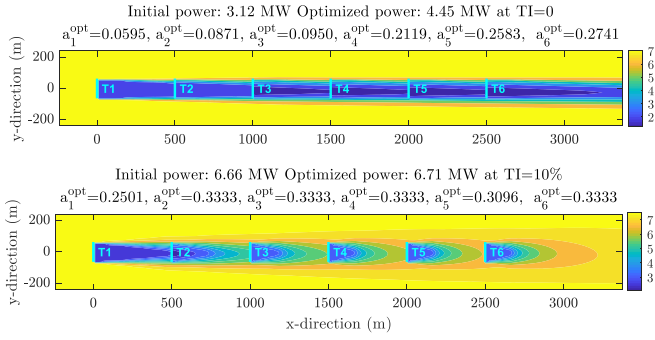


Fig. 5 Wind farm operation under axial induction optimiser and at mean wind speed of second cluster center (7.79 m/s).

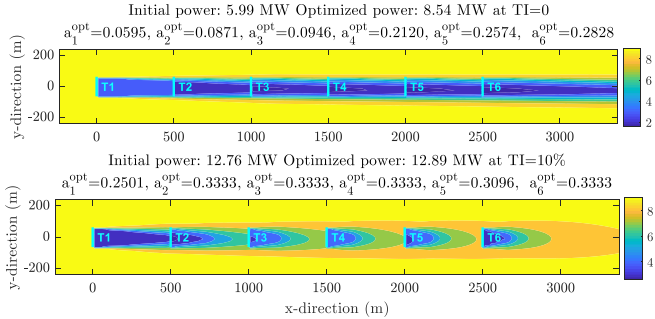


Fig. 6 Wind farm operation under axial induction optimiser and at mean wind speed of third cluster center (9.68 m/s).

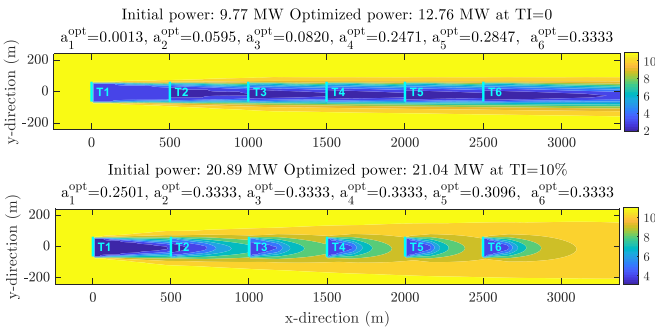


Fig. 7 Wind farm operation under axial induction optimiser and at mean wind speed of third cluster center (11.4 m/s).

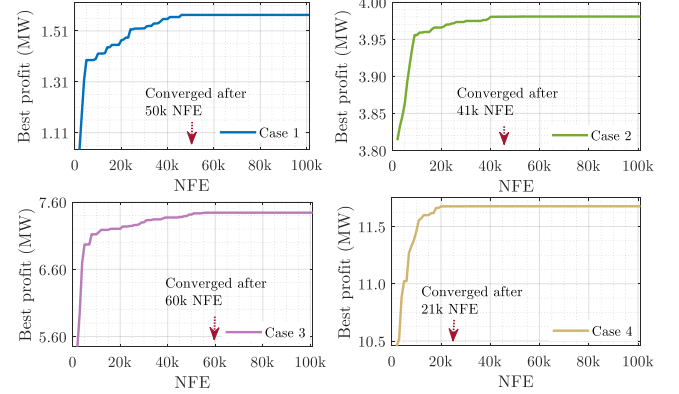


Fig. 9 The convergence curves of number of function evaluation and maximised total power production.

speed and the share of each wind turbine are given in Table 1. 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			Case 2			Case 3			Case 4			Case 5		
	$P_{res} = 122 \text{ kW}$			$P_{res} = 312 \text{ kW}$			$P_{res} = 599 \text{ kW}$			$P_{res} = 997 \text{ MW}$			$P_{res} = 2.282 \text{ MW}$		
	ω_{opt}^{nom}	ω_{opt}^{dl}	WT	ω_{opt}^{nom}	ω_{opt}^{dl}	WT	ω_{opt}^{nom}	ω_{opt}^{dl}	WT	ω_{opt}^{nom}	ω_{opt}^{dl}	WT	ω_{opt}^{nom}	ω_{opt}^{dl}	WT
	rad/s	rad/s	share	rad/s	rad/s	share	rad/s	rad/s	share	rad/s	rad/s	share	rad/s	rad/s	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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