POLITECNICO MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

Executive Summary of the Thesis

# Analysis of control system strategies for wind farm performance optimization

Laurea Magistrale in Energy Engineering - Ingegneria Energetica

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## 1. Introduction

As climate change becomes an increasingly critical issue, the urgency to adopt clean energy sources intensifies. To align with the Paris Agreement's objective of limiting global warming to 2 degrees Celsius, carbon emissions worldwide need to reach net zero by 2050. Wind power has significantly risen as a key player in the renewable energy sector, notably achieving for instance 54.0% of Denmark's electricity consumption in 2022, and seeing a global increase in installed capacity to over 900 GW by the end of the same year. This growth highlights wind power's role in expanding renewable capacity, with it accounting for up to a third of the world's energy production by 2050 according to forecasts [3]. Despite historical successes in technological advancements and cost reductions, the wind industry faces financial difficulties, as shown in Fig. 1, with major Western manufacturers experiencing losses and a slowdown in project development outside China. Challenges such as lengthy permitting processes and increased costs are affecting onshore wind deployment in the European Union. Addressing these issues requires enhancing operational efficiency and reducing the cost of wind energy production per megawatt and this can be achieved also with the fundamental contribution of wind farm flow control. Henceforth, the aim of this thesis is to provide a structured framework in which different wind farm control strategies are analyzed with respect to the objective of power production maximization, and ultimately assess their viability and limitations.

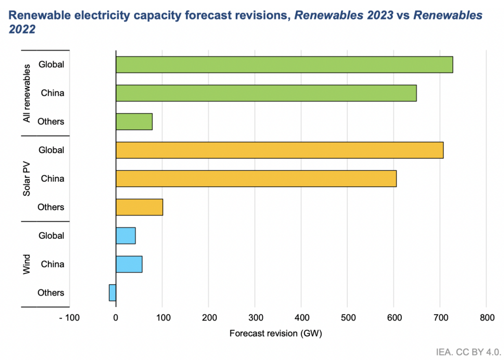


Figure 1: The wind forecast is less optimistic outside of China. Figure from [3].

## 2. Wake modelling and wind farm control strategies

Significant progress has been made in wind turbine aerodynamics since Betz and Joukowsky, notably with Glauert's development of the blade element momentum (BEM) theory in 1935, paving the way for modern rotor design. Despite these advancements allowing wind turbines to approach the Betz–Joukowsky efficiency limit, performance prediction remains challenging due to complex interactions with the turbulent atmospheric boundary layer (ABL). The problem of flow dynamics is made more complex when evaluating the wakes produced by upstream turbines and the effects they have on the operation of downstream ones. Therefore, the research field of wake models aims at simulating as realistically as possible such aerodynamic interactions [1]. Among the most commonly used wake models in literature, the Jensen model and the Gaussian model stand out, the former for its simplicity and the latter for its accuracy [2], which are represented by a top-hat shaped wake profile and by a gaussian-shaped one, respectively. Wakes behind wind turbines lead to slower wind speeds and increased turbulence downstream, as shown in Fig. 2, negatively affecting both the energy production and the structural health of the turbines.

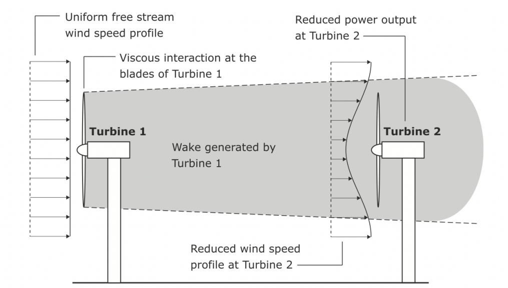


Figure 2: The phenomenon of aerodynamic coupling between two wind turbines aligned with the free stream wind. Figure from [4].

Although wind farm layouts are designed to minimize these wake effects, they cannot be entirely eliminated. Recently, the wind energy community has been exploring innovative approaches to mitigate turbine wake impacts, notably through wind farm flow control techniques. These methods involve adjusting turbine operations to either lessen or alter the direction of the wakes as they move across the wind farm. For instance, derating (or curtailing) a turbine reduces its thrust force, thereby diminishing the wake's strength. Similarly, wake steering involves deliberately misaligning a turbine from the prevailing wind direction to shift the wake sideways, reducing its impact on subsequent turbines. While these strategies entail a trade-off of reduced power output from the upstream turbines, they offer the potential for improved conditions for turbines downstream, resulting in faster and smoother wind flow, as depicted in Fig. 3.

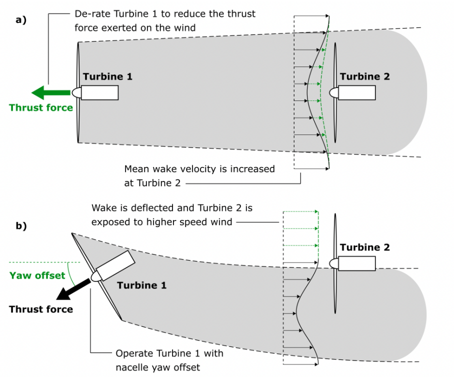


Figure 3: Graphical representation of derating and wake redirection. Green elements highlight changes in turbine operation and wake conditions. Figure adapted from [4].

## 3. Methodology

For this thesis, a wind farm model with two IEA 10 MW turbines was analyzed using the `HAWCStab2` tool for aeroservoelastic stability across wind speeds of 4 to 25 m/s, rotor speeds of 6 to 8.68 rpm, and pitch angles of 0 to 50 degrees. Initially, a power maximization algorithm was applied to recreate the turbine's regulation trajectory, which matched the operational data and plots (Fig. 4) from the technical report of the reference turbine.

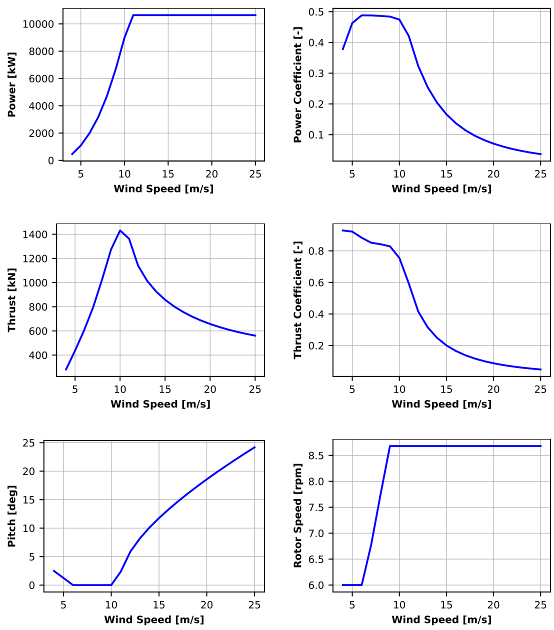


Figure 4: Steady-state performance and operation of the 10-MW rotor.

A thrust coefficient ($C_T$) minimization was then selected as the derating strategy for its effectiveness in reducing turbine loads [5]. However, challenges arose due to the collinearity of $C_T$ and $C_P$ isolines, necessitating an additional constraint. To address this issue, the rotor speed $\omega$ was fixed to the optimal value $\omega_{\mathrm{P,max}}$ provided by the regulations trajectory and the blade pitch angle $\beta$ was kept as the only design variable. The resulting algorithm, for each wind speed from cut-in to cut-out, is:

$$\beta_d = \arg\min_{\beta} C_T(\beta)$$

$$\text{Subject to:} \begin{cases} C_{P,d}(\beta_d) = \Delta P C_{P,\max} \\ \omega_d = \omega_{\mathrm{P,max}} \\ \beta_{\min} \leq \beta_d \leq \beta_{\max} \end{cases}$$

Ultimately, it was essential to integrate the deratable turbine within the `PyWake` environment to create a `WindTurbines` class capable of derating, along with selecting and adapting a site and wind farm configuration from `PyWake`'s built-ins for the project's specific requirements.

# 4. Simulations and results

The findings from the methodology section are now applied in an optimization framework designed to increase wind farm power generation. It examines the impact of derating and yaw-based wake control strategies using an open-loop method, supported by `OpenMDAO`, a NASA-developed optimization framework for complex, multidisciplinary engineering challenges. `OpenMDAO`'s highlights include its modular structure, gradient-based optimization, component-based design, and Python compatibility, facilitating easy tool integration and model reuse. The approach starts with a simple two-turbine layout to test control strategies, setting a foundation for more complex future research. For each control strategy, the optimization process involves the testing of the wind farm performance by varying:

- the wind speed in [8, 9, 10, 11] m/s;
- the wind direction in [0, 90, 180, 270] degrees;
- the spacing in [3, 4, 5, 6] rotor's diameter.

For the briefness of this summary, only the simulations' outcomes at 10 m/s are presented.

## 4.1. Baseline case

Without any control strategies in place, the wake effect significantly reduces power output, whose values are indicated in Table 1. This is illustrated by comparing power output values for wind directions at 90 and 270 degrees, as will be later shown. These directions, due to the specific farm layout, are the only ones that initiate aerodynamic interactions worth comparing for this study, while directions at 0 and 180 degrees do not contribute to the comparative analysis of control strategies.

| wind speed = 10 m/s | |
|---|---|
| Spacing | Power [kW] |
| 3D | 10743.14 |
| 4D | 11493.45 |
| 5D | 12308.76 |
| 6D | 12977.60 |

Table 1: Baseline case of power output for various spacings at 10 m/s.

## 4.2. Derating only

The simulation results highlight the following important observations:

- Altering turbine spacing impacts power output due to wake effects, with wider spacing reducing the need for derating.

- Increasing wind speeds makes down-regulation less beneficial, as the gain in downwind turbine power doesn't compensate for the reduction in the upstream turbine.

These findings, consistent across wind directions of 90 and 270 degrees (which mirror each other in aerodynamic effects), are summarized in Table 2.

| Wind speed = 10 m/s | | |
|---|---|---|
| Spacing | Turbine derating[1] [%] | Power [kW] |
| 3D | 12.50 | 11092.87 |
| 4D | 7.81 | 11797.34 |
| 5D | 5.47 | 12465.72 |
| 6D | 5.47 | 13103.50 |

Table 2: Derating and power values for 90-270 degrees of wind direction as spacing varies at 10 m/s.

## 4.3. Wake redirection only

As noticeable from the obtained results (Table 3), this strategy, that required the `OpenMDAO` problem to be integrated with two more inputs for both the turbines' yaw angles, shows that:

- The yaw angle doesn't follow a monotonous, growing trend as the spacing decreases. Nonetheless, the values are reasonable given that 3D is almost near-wake region and 6D is really conservative for the analysis. What is very relevant is that the yaw angle does diminish by 2 degrees between 4D and 5D, which are the commonly used spacings.
- As for derating, the increase of wind speeds causes the wake redirection to be less and less useful to prevent wake losses, as the balance between gain in the downstream machine and loss in the upstream one is not positive.

| Wind speed = 10 m/s | | |
|---|---|---|
| Spacing | Turbine yaw [°] | Power [kW] |
| 3D | 9.87 | 10783.83 |
| 4D | 13.97 | 11654.31 |
| 5D | 12.12 | 12428.28 |
| 6D | 13.16 | 13120.53 |

Table 3: Yaw misalignment and power values for 90-270 degrees of wind direction as spacing varies at 10 m/s.

## 4.4. Combination of wake redirection and derating

The implementation of wake steering and derating strategies with the sole aim of enhancing power output has been found to lead to numerical instability issues. During the evaluation process, simulation outcomes for wind directions at 90° and 270° exhibited varying yaw and derating setups, unexpectedly, given the anticipations of identical results owing to the scenarios' mirror symmetry. This discrepancy has highlighted the challenges in pinpointing a global optimum, attributed to the local minima issue and `OpenMDAO`'s dependency on gradient-based optimization techniques, underscoring the approach's inherent weakness. To address this situation, a multi-start method and a parametric analysis were carried out, which ultimately led to the same results.

For 10 m/s, the combination of yaw and derating that ensured the highest power output among the five cases of the multi-start method is:

| Wind speed = 10 m/s | | | |
|---|---|---|---|
| Spacing | Derating [%] | Yaw [°] | Power [kW] |
| 3D | 11.4 | 6.2 | 11084.4 |
| 4D | 7.1 | 7.7 | 11806.5 |
| 5D | 5.4 | 11.5 | 12496.3 |
| 6D | 2.5 | 10.7 | 13151.2 |

Table 4: Derating, yaw misalignment and power values for 90-270 degrees of wind direction as spacing varies at 10 m/s.

The parametric analysis was led at 10 m/s and a spacing of 4 rotor diameters, and produced the contour plot in Fig. 5.

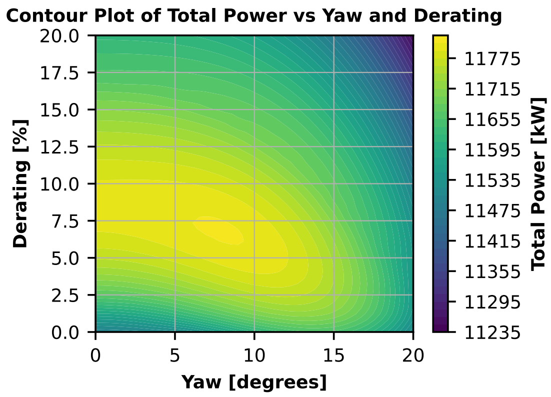


Figure 5: Contour plot from the parametric analysis.

The multi-start method's optimal yaw and derating configuration at a spacing of 4 rotor diameters (4D) was identified as 7.1% derating and 7.7 degrees of yaw misalignment, aligning with the specified yellow area in the contour map. This finding suggests that incorporating an additional goal, like load reduction, into the optimization problem could potentially prevent local minima issues or enhance robustness. Moreover, using a gradient-based optimization approach like Sequential Least Squares Programming (SLSQP), instead of COBYLA, especially when combined with analytical gradient calculations, might facilitate the identification of the global optimum more effectively.

## 5. Conclusions

The current study has underscored the potential advantages of integrating yaw and derating strategies for enhancing power production. According to the data presented in Table 5, at a wind speed of 7 m/s, the synergistic approach yields a maximum 10% increase in power output compared to the baseline scenario. This significant improvement underscores the efficacy of the combined strategy. However, it also indicates that the benefits derived from implementing derating and wake steering may vary depending on wind speed conditions. Specifically, at a wind speed of 10 m/s, the combined strategy's effect is nearly equivalent to that achieved through derating alone, suggesting a nuanced approach to optimization based on specific environmental conditions.

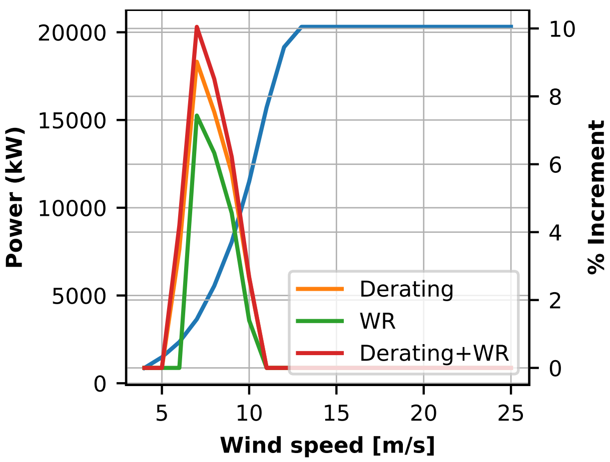


Figure 6: Baseline power curve and percentage increments for each control strategy.

| Wind speed = 7 m/s | | |
|---|---|---|
| | Power output [kW] | % Increase |
| Baseline | 3648.8 | - |
| Derating only | 3977.9 | 9.0 |
| WR only | 3920.1 | 7.4 |
| Derating+WR | 4015.4 | 10.0 |
| **Wind speed = 8 m/s** | | |
| | Power output [kW] | % Increase |
| Baseline | 5547.6 | - |
| Derating only | 5965.8 | 7.5 |
| WR only | 5898.9 | 6.3 |
| Derating+WR | 6019.8 | 8.5 |
| **Wind speed = 9 m/s** | | |
| | Power output [kW] | % Increase |
| Baseline | 8045.1 | - |
| Derating only | 8506.7 | 5.7 |
| WR only | 8412.1 | 4.6 |
| Derating+WR | 8545.2 | 6.2 |
| **Wind speed = 10 m/s** | | |
| | Power output [kW] | % Increase |
| Baseline | 11493.5 | - |
| Derating only | 11797.3 | 2.6 |
| WR only | 11654.3 | 1.4 |
| Derating+WR | 11806.5 | 2.7 |

Table 5: Comparison of power outputs across strategies at 4D.

Additionally, the values reported in Tables 2, 3, 4 highlight that the combined approach is safer in terms of mechanical loading on the turbines as lower and thus less impacting levels of misalignment are combined with milder derating, which is in general beneficial for the structural integrity of the upstream turbine.

### 5.1. Future developments

The subsequent phase of this research should encompass the incorporation of load minimization objectives into the analysis, which is expected to yield more compelling outcomes and provide a comprehensive understanding of the advantages and limitations of the control strategies in question. Moreover, enhancing the complexity of the layout, despite its challenges, is expected to offer more profound insights into the dynamics of actual wind farms. Additionally, conducting an economic analysis to evaluate the financial benefits of wind farm control strategies would be a valuable addition, offering a perspective on their cost-effectiveness.

## References

[1] S. Boersma, B.M. Doekemeijer, P.M.O. Gebraad, P.A. Fleming, J. Annoni, A.K. Scholbrock, J.A. Frederik, and J-W. van Wingerden. A tutorial on control-oriented modeling and control of wind farms. In *2017 American Control Conference (ACC)*, pages 1–18, May 2017. ISSN: 2378-5861.

[2] Filippo Gori, Sylvain Laizet, and Andrew Wynn. Sensitivity analysis of wake steering optimisation for wind farm power maximisation. *Wind Energy Science*, 8(9):1425–1451, September 2023. Publisher: Copernicus GmbH.

[3] IEA.

[4] Ali C. Kheirabadi and Ryozo Nagamune. A quantitative review of wind farm control with the objective of wind farm power maximization. *Journal of Wind Engineering and Industrial Aerodynamics*, 192:45–73, September 2019.

[5] Fanzhong Meng, Alan Wai Hou Lio, and Jaime Liew. The effect of minimum thrust coefficient control strategy on power output and loads of a wind farm. *Journal of Physics: Conference Series*, 1452(1):012009, jan 2020.