Wind Farm Yield and Lifetime Optimization by Smart Steering of Wakes

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Abstract. Wake steering has an impact on both the wind farm energy yield and turbine loads. We evaluate these effects based on yaw-corrected power and thrust curves and tabulated turbine load simulation results. In a first step, wind direction and wind speed dependent yaw angles were determined by maximization of the wind farm power for an example wind farm. Secondly, the optimizations were repeated for the objective of minimal flapwise blade fatigue loads. The results were then combined such that the power optimized yaw angles dominate the partial load region while the load optimized results were chosen for higher wind speeds. We find that this combination increases the annual energy production in an example wind rose while simultaneously reducing the lifetime damage equivalent loads. The analysis was repeated including wind direction uncertainty into the optimization. This significantly reduced the benefit of wake steering on AEP but caused only a mild decrease of the overall load reduction.

1. Introduction
One measure that summarizes the performance of a wind farm in a single number is the overall production of electrical energy over its lifetime. Many factors influence its value, and clearly the wind farm’s ability to harvest maximal power from the local wind potential contributes significantly to the outcome. Another obvious factor is the lifetime of the wind farm, being continuously diminished by turbulence and the resulting fatigue loads during the time of operation. In this work we combine the two objectives of maximal wind farm yield and minimal fatigue loads in the context of wake steering by controlled yaw misalignment.

The idea of controlling the wake effect and thereby reducing its impact on downstream turbines has been studied extensively in the recent years, cf. [1–11]. References [5, 7, 8] addressed the question of uncertainties in the wind measurement on the benefit of wake steering (also called active wake control). The authors of [8] find that an uncertainty in the wind direction measurement has the most significant influence on the results. In [5] it was shown that an optimal control that disregards this uncertainty would most likely rather lead to a decrease of AEP of the farm. Thus, the uncertainty of the wind direction measurement shall be explicitly considered in the design of the controller, and will also be investigated here. The effects of active wake control on energy yield and loads were studied by Kanev et al. in [6, 11], including the choice of lifetime energy production of the wind farm as objective function.

Our approach is based on the observation that in the full load region of the power curve any objective function that is purely based on turbine power is insensitive to variables that preserve the operation in that region. Concretely, wake steering has the potential to increase the wind
speed at downwind turbines. However, in situations where the latter operate in the full load region no power gain can be achieved by wake steering. On the other hand, turbine fatigue loads in general depend on the rotor effective wind speed (REWS), the yaw misalignment angle and turbulence intensity. Hence, wake steering can be expected to have an influence on damage equivalent loads (DEL) at any point of operation. This fact can be turned into an advantage by combining the maximization of the wind farm power in the partial load region with the minimization of DEL results at higher wind speeds. We investigate this idea with and without the consideration of an uncertainty of the wind direction in the optimization.

The paper is organized as follows. In the subsequent section details of the method are presented. This includes the introduction of a virtual example wind farm and an exemplary wind rose for quantitative evaluations. Also the load modelling is described, as well as the wake modelling approach and the optimization strategy. The results of the optimizations can be found in Section 3, followed by a discussion in Section 4. Section 5 concludes the work.

2. Method

2.1. Wind farm setup

In this work we study the regular $3 \times 3$ wind farm layout shown in Fig. 1 (left). The turbine spacing is 8 and 4 rotor diameters $D$ in x and y directions, respectively. All turbines are of the generic direct-drive IWT7.5 turbine model [12] with rotor diameter $D = 164$ m, hub height $H = 100$ m and 7.5 MW nominal power. For the sake of being able to carry out a concrete evaluation of our results, we also introduce an example wind time series that covers one year in half hour steps. The mean wind speed of the time series is 9.2 m/s and the mean wind direction is $294^\circ$. The corresponding wind rose is shown in Fig. 1 (right).

The effects of yaw misalignment on the turbine power $P$ and the thrust coefficient $c_t$ are modelled by the introduction of effective shifts in the REWS according to cosine exponents
Figure 2: The power and the thrust coefficient curves for three yaw misalignment angles.

\[ p = 1.88 \quad \text{and} \quad q = 1.0 \quad (\text{cf. [4]}), \text{respectively}, \]

\[ P(u, \theta) = P_{\text{curve}}(u_P(u, \theta)) \]

\[ c_t(u, \theta) = c_{t,\text{curve}}(u_{ct}(u, \theta)) \left( \frac{u_{ct}(u, \theta)}{u} \right)^2, \]

\[ u_P(u, \theta) = u \cos(\theta)^\frac{p}{3}, \quad u_{ct}(u, \theta) = u \cos(\theta)^\frac{q}{2}. \]

Here \( u \) denotes the REWS and \( \theta \) the yaw misalignment angle. \( P_{\text{curve}} \) and \( c_{t,\text{curve}} \) represent the power and thrust coefficient curves of the IWT7.5 turbine for \( \theta = 0 \), respectively. Note that the quadratic factor in \( c_t(u, \theta) \) translates the correction of the thrust by the reduced effective wind speed \( u_{ct}(u, \theta) \) into a corrected thrust coefficient for REWS \( u \). The resulting power and thrust coefficient curves for different \( \theta \) values are shown in Fig. 2. In this work we shall ignore all potential issues arising from low REWS values near the cut-in wind speed in the above model.

2.2. Load modelling

A database of fatigue loads is created by performing load simulations using The Modelica library for Wind Turbines (MoWiT). The software is developed at Fraunhofer IWES as a object-oriented library for fully-coupled aero-hydro-servo-elastic simulations of wind turbines on- and offshore, with bottom-fixed substructures and even floating wind turbines. The software is continuously verified to other load simulation software in various industrial projects using internal verification procedures [13]. Detailed information on the development of MoWiT, as well as on the structure and components of this library can be found in the literature [14, 15]. For this paper, parameter combinations of mean wind speed, turbulence intensity and the yaw angle are used. In detail, this includes

- 12 mean wind speeds (\( u \)): 4, 5, 6, \ldots, 24 m/s
- 9 turbulence intensities (TI): \( TI_i = (\sqrt{2})^{i+1}, i = 1, \ldots, 9 \)
- 13 yaw angles (\( \theta \)): \(-30^{\circ}, -25^{\circ}, \ldots, -5^{\circ}, 0^{\circ}, 5^{\circ}, \ldots, 25^{\circ}, 30^{\circ}\).  

The incoming wind fields are created using the Kaimal-model in Turbsim [16]. For each parameter combination 6 different stochastic wind seeds of 10 minutes are simulated. Short term DELs are computed for each combination of the input parameters using rainflow counting and Miner’s rule with a component specific Wöhler exponent \( m \). Combined tower bottom bending moment, i.e. the sum of moments in all three directions (side-side, fore-aft and torsional), as well as blade root bending moments are considered in this case. Here, flapwise bending moments, acting perpendicular to the rotor plane and edgewise bending moments, acting in direction of the rotor plane, are used. The coordinate system is thereby rotating with
the blade pitch angle. For the blade root bending moments, $m=10$ is chosen and for the tower root bending moments $m=3$. In order to obtain a smooth function for arbitrary combinations of values, a polynomials of degree 8 are fitted through the discrete data points. An advantage over linear interpolation of the simulated data points is that it suppresses the effect of outliers that may arise from specific turbulent seeds.

![Figure 3: Short term DELs of blades and tower for $y = 0^\circ$](image1.png)

![Figure 4: Short term DELs of blades and tower for TI = 5.56%](image2.png)

Fig. 3 shows the dependency of the DELs on wind speed and TI for a fixed yaw angle misalignment angle $\theta = 0^\circ$ for all three components. The flapwise bending moments (flapwise bm) are strongly increasing with both wind speed and TI (Fig. 3a) while the effect of TI on tower bottom bending moments (tower bm) is stronger than the influence of the wind speed (Fig. 3c). The edgewise bending moments (edgewise bm) decrease with increasing wind speeds once the turbine starts pitching. The influence of TI is comparably low (Fig. 3b).

Fig. 4 shows the dependency of the DELs on wind speed and yaw for a fixed TI value $TI = 5.66\%$. For all three components the influence of the yaw angle also depends on the wind speed and can have positive or negative influence on the loads. For the flapwise bm, yawing the turbine with a positive yaw angle results in reduced loads for wind speeds below 17 m/s. Above 17 m/s, yawing the turbine to $\theta = -30^\circ$ reduces DELs (Fig. 4a). The effect of yawing on edgewise bm and tower bm in the full load region is lower compared to the flapwise bm.
Contrary behaviour can be seen for negative yaw angles at high wind speeds. The influence of load results on the optimization results will be discussed further in Section 4.

2.3. Wind farm and wake modelling
All wind farm and wake calculations in this work were carried out using the IWES software\(^1\) Farm Layout Program in Python (flappy). The code follows the paradigm of parallelized gridless wake superposition, and its development is based on previous experience with wind farm and wake modelling [17–20]. Flappy has been optimized for cases with large amounts of inflow states, for example long-term wind time series evaluations during wind farm pre-construction studies, or site-specific wind statistics for annual energy production (AEP) calculations. Various engineering wake models are implemented in flappy, and additionally CFD-based lookup-type wake modelling has been included. Technical details and the general validation of the software are beyond the scope of this paper and will be discussed elsewhere [21]. Instead this section only provides a brief overview over the model choices that are relevant for the present work. The software architecture of flappy is highly modular, providing modelling interfaces all along the steps of the wind farm calculation algorithm:

- **Rotor model:** Extracts rotor equivalent wind speed (REWS) and other rotor equivalent quantities using background inflow fields and wakes. In the present work the background wind is homogeneous and evaluated at the rotor centre, while wakes are being integrated over the rotor area in order to include partial wake effects.

- **Wake models:** Compute wind deficit and/or turbulence intensity contributions due to the wake of a single turbine. Here we apply the yaw sensitive Gauss-type wake model by Bastankhah and Porté-Agel [22] for the wind deficit. The wake induced turbulence intensity is calculated using the top-hat wake model as described in IEC-64100 (2019).

- **Wake frame:** Represents the coordinate transformation from the global frame of reference to the wake model frame. Here a curved wake centreline path is realized in the case of wake steering, following Bastankhah and Porté-Agel [22].

- **Wake superposition model:** Calculates the resulting combined wake deficit at the points of interest. Here quadratic wake superposition was chosen for wind deficit and maximal wake for turbulence intensity.

- **Turbine models:** Calculate turbine variables from existing turbine variables. Here the power \(P\) and the thrust coefficient \(c_t\) are obtained from linear interpolation of the un-yawed power and thrust curves. Yaw effects are then imposed as described by Eqs. (1) and (2). The DEL calculations for loads (see Sec. 2.2) are also included as turbine models.

These model choices apply to all turbines of the wind farm from Figure 1.

2.4. Optimization
In the following we apply the Simple Genetic Algorithm (SGA) from the pygmo library [23, 24] to the problem of yaw misalignment optimization. All single-objective optimizations were carried out using 200 generations, population size 40 and uniform mutation with crossover rate 90%.

Two different objectives were investigated in this study. One is maximal wind farm power, calculated as the sum of the individual turbine power results. The latter were obtained as the mean with respect to the considered inflow states. The second objective is the minimization of mean DEL of the flapwise bm over all turbines of the farm.

For each of these two objectives we ran independent SGA optimizations with the stated parameters for all bins of a wind rose with \(2^\circ\) spacing in wind direction and 1 m/s in wind

\(^1\) flappy v0.4.3.3
speed. We first studied single-state inflow conditions, where each bin represents uniform inflow of fixed wind speed and wind direction. Additionally we repeated the optimizations including wind direction uncertainty, with assumed standard deviation of $\sigma_{wd} = 3.5^\circ$. This was realized by discretizing a Gaussian function by 50 states in the range of $3\sigma_{wd}$ around the central wind direction bin value. For given yaw settings of all turbines, the objective function result for the bin in question was then calculated as the weighted sum over these 50 states, each representing a different wind direction. The background turbulence intensity was set to 5% for all cases, and the air density was fixed to 1.225 kg/m$^3$.

The four calculated optimization cases are called P1, P2, L1, L2 and summarized in Table 1.

| Case | Objective | Uncertainty | Description                  |
|------|-----------|-------------|-------------------------------|
| P1   | Power     | no          | SGA power maximization        |
| P2   | Power     | yes         | SGA power maximization        |
| L1   | DEL flap  | no          | SGA load minimization         |
| L2   | DEL flap  | yes         | SGA load minimization         |
| C1   | -         | no          | Combination of P1 and L1     |
| C2   | -         | yes         | Combination of P2 and L2     |

Table 1: The studied optimization cases and their combinations.

2.5. Combined cases

Since the power curve has a plateau in the full load region, cf. Fig. 2, the power optimization from cases P1 and P2 cannot lead to a sensible result when using the genetic algorithm. Instead, the latter is bound to yield random values whenever the objective function has no sensitivity on the design variables. Hence we can replace the results in this region by those from load minimization cases, i.e., cases L1 and L2, respectively, without expecting a substantial loss in the overall wind farm power. In this work invoke a sharp transition from the power to the load optimization results for inflow wind speeds equal or greater than 14 m/s. The resulting combined cases C1 and C2 exclude and include wind direction uncertainty, respectively, cf. Table 1.

3. Results

Fig. 5 shows the results of the yaw misalignment angle $\theta$ for the combined case C1 for all turbines in the wind farm layout from Fig. 1. Each polar plot represents the value of this variable for the corresponding turbine as a function of wind direction (azimuthal axis) and wind speed (radial axis, in m/s). Note that in the layout the turbine spacing in x-direction is double the spacing in y-direction, and this is not reflected in the placement of the polar plots. In the partial load region, the wake steering solution from P1 is clearly visible. High yaw angles are only obtained in certain wind directions where the wake is deflected to increase wind speed of the downstream turbine. The full load region is dominated by large yaw misalignment angles.

The corresponding changes of relative power and flapwise DEL in comparison to the case without wake steering (the so-called 'greedy' case) are shown in Figs. 6 and 7. In the partial load region the solution shows a relative power increase, partially in combination with higher flapwise bm DEL values. In the full load region we find a substantial decrease of the latter without power losses due to the yawing.

The results of the quantitative evaluation based on the wind rose in Fig. 1 for all optimization cases from Table 1 are listed in Table 2. We find that the introduction of wind direction uncertainty into the power optimization reduces the AEP benefits due to wake steering from 1.26% in case P1 to 0.44% in case P2. The effect of uncertainty on the load optimization cases L1 and L2 is not as significant. In both cases we find a reduction of the flapwise bm lifetime...
Figure 5: The results for the turbine yaw misalignment angle $\theta$ in the case C1. Each polar plot represents results for the corresponding turbine in the wind farm layout from Fig. 1.

Figure 6: The relative power changes of the yawed compared to the greedy case, for C1. Each polar plot represents results for the corresponding turbine in the wind farm layout from Fig. 1.
Figure 7: The relative DEL\_flap (DEL of flapwise bm) changes of the yawed compared to the greedy case, for C1. Each polar plot represents results for the corresponding turbine in the wind farm layout from Fig. 1.

| Case | Delta AEP [%] | Delta LDEL\_flap [%] | Delta LDEL\_edge [%] | Delta LDEL\_tower [%] |
|------|---------------|----------------------|----------------------|----------------------|
| P1   | 1.26          | 6.65                 | 0.31                 | -1.59                |
| P2   | 0.44          | 5.75                 | 0.28                 | -1.08                |
| L1   | -7.42         | -18.61               | -1.49                | -4.44                |
| L2   | -7.26         | -19.49               | -1.48                | -2.52                |
| C1   | 1.18          | -15.87               | 0.09                 | -0.68                |
| C2   | 0.36          | -16.89               | 0.04                 | -0.34                |

Table 2: The relative changes of AEP and lifetime DEL results in the optimized scenarios compared to greedy settings (optimized minus greedy), evaluated for the wind rose from Fig. 1. Here LDEL is an abbreviation for lifetime DEL.

DEL (LDEL\_flap) by roughly 19%, and a unfavorable reduction of the AEP by about 7% when introducing yaw misalignment. The cases C1 and C2 combine the AEP benefits from the partial load region with the lifetime DEL reductions at high wind speeds.

4. Discussion

The power maximization in cases P1 and P2 is accompanied by an increase in the lifetime DELs of the flapwise bm compared to greedy settings. The latter is mainly caused by increasing wind speeds in partial load (cf. Table 2). On the other hand, tower loads are slightly reduced in that region due to wake induced turbulence contributions, and the influence of wakes on the edgewise DELs is negligible. Minimizing flapwise bm DELs (cases L1 and L2) does not only significantly reduce the latter but also slightly reduces tower and edgewise bm DELs (LDEL\_tower and LDEL\_edge). The load reduction of these components is mainly generated in the partial load region and therefore the load reduction effect is diminished in the combined cases. In fact,
Reducing flapwise bending moments (DELs) by yawing at high wind speeds can have negative effects on other components. Compromises could be found by using multi-objective optimization and computing the Pareto-fronts.

In the combined cases C1 and C2, the significant reduction of LDEL* flap is mainly due to the strong decrease of loads with yaw in full load. At high wind speeds above 17 m/s, the reduction is achieved with yaw angles approaching $\theta = -20^\circ$ to $\theta = -30^\circ$. For wind speeds in the range 14-17 m/s on the other hand, the yaw angle with minimal value is near $\theta \sim 30^\circ$, hence the ring-like structures in Fig. 5 in the full load region. Those values correspond to the minimum flapwise bending moment DELs of a single turbine in yaw, as it was mentioned in section 2.2. In the full load region, a wake steering effect on the optimization results cannot be determined since there is no variation of the results with wind direction. Therefore, the significant reduction of its individual loads is only caused by the yawing of each turbine. Similar effects using yaw misalignment for the alleviation of blade loads were examined for a single turbine in [25].

The results in Fig. 5 for the yaw misalignment angle clearly indicate the transition from the power to the load optimal solution at the selected inflow wind speed value of 14 m/s. This value was applied globally to all turbines and for all wind directions. This choice is mainly based on the observation that from that value onward the turbine operates in the full load region according to the power curve (cf. Fig. 2). However, due to the wake effect this conclusion is not exactly true for all turbines and all wind directions. The rigorous approach would be to solve the multi-objective optimization problem for both power and load objectives in the transition region, and then analyse and utilize the corresponding Pareto-fronts.

In agreement with earlier studies, we find a significant reduction of the benefits of wake steering on AEP results when introducing wind direction uncertainty [5, 7, 8]. However, our findings indicate that the load reduction by yawing turbines at high wind speeds is not sensitive to wind direction uncertainty. This may be related to the robustness of the above-mentioned minimum in that region which is not a wake-induced phenomenon but a consequence of the behaviour of the individual wind turbine operation. Contrarily, the hard switch of the yaw angle e.g. between 17 and 18 m/s from negative to positive does not consider uncertainties in the wind speed yet. For increasing wind speeds above 20 m/s, operating the turbine at $\theta = 30^\circ$ even induces the highest flapwise bending moment loads (cf. Fig. 4a). Considering uncertainties in wind speed could account for that and hence reduce the load reduction effect.

In general, the presented optimization results represent independent yaw values for each wind direction and wind speed bin. This implies the possibility of sudden changes of the yaw misalignment angle or even a change of sign between neighbouring bins. For practical applications in wind farm control such abrupt changes have to be overcome, for example by involving neighbour bin values into the definition of the objective function in order to guarantee smooth solutions. Alternatively, time-series-based local optimizations can prevent undesired frequent alternations of the yaw angle.

For most wind directions the turbines are exposed to partial or multiple wake effects. While this is addressed in the wake modelling by calculating the REWS based on the integration of Gaussian wake shapes over the rotor disk, the underlying load simulations do not include such effects. A partial wake overlap can increase loads significantly [26], hence covering those effects should be addressed in the future. This may reduce a potential overestimation of the observed DEL reducing effects due to wake deflection.

5. Conclusion
Wake steering in the full load region of the wind turbine power curve has no influence on the wind farm yield. Based on this observation and detailed fatigue load simulations we investigated the combination of wind farm yield optimization in the partial load region with fatigue load optimization at higher wind speeds. According to our results, this combination preserves the
The benefits of active wake control on the AEP results while significantly reducing the flapwise blade lifetime DEL compared to scenarios with zero yaw misalignment. Furthermore, the load reduction is robust in the sense that it is not sensitive to wind direction uncertainty. This is in contrast to the known reduction of the gain in AEP due to wake steering under uncertain wind direction conditions. The reason is that AEP results are intimately related to wake losses which are intrinsically sensitive to wind direction changes, while the load reduction under yaw is mainly linked to operational properties of the wind turbine in the full load region. The robustness of the load reduction to wind speed uncertainty needs to be investigated further.

The presented combination of optimization results involves a harsh transition at inflow wind speed 14 m/s, irrespective of the turbine’s position in the farm and its currents wake situation. The detailed modelling of a more refined transition method from the partial to the full load region by the analysis and exploration of wind-condition-dependent Pareto fronts is left for future work. Also, the adoption of the approach to time series based real-time control which prevents sudden changes of the yaw angle at all turbines was beyond the scope of this work and needs to be addressed elsewhere.

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