An initial study into the potential of wind farm control to reduce fatigue loads and extend asset life

Matt Harrison, Ervin Bossanyi, Renzo Ruisi, Nick Skeen
DNV GL, One Linear Park, Avon Street, Temple Quay, Bristol, BS2 0PS, UK

matthew.harrison@dnvgl.com

Abstract. A quasi-static open loop wind farm control approach is considered, where optimisation is carried out offline in a simulation environment to create a lookup table of yaw setpoints implemented by a central wind farm controller. The objective of the optimisation is to reduce blade root bending moment for all turbines on the site, thereby increasing the asset life, and this is achieved by querying a fatigue loads database in DNV GL’s LongSim software for wind farm control design, optimisation and verification. The Lillgrund 48-turbine layout is used for this example. The optimisation results in a small increase in annual energy production of 0.13% which is combined with a 0.4% increase in blade life, which is translated to an increase in asset life to yield a 0.5% increase in energy production over the farm lifetime. In this case we make the simplistic assumption that blades have the minimum life of all turbine components, and limit fatigue life. The results are a step towards wind farm control techniques which maintain and extend wind farm life, whilst simultaneously increasing energy production.

1. Introduction

Optimisations using wind farm control techniques commonly focus on controlling individual turbine wakes to increase the total power generated by the farm, using changes in yaw angle (wake steering) or blade pitch angle and tip speed ratio (induction control). The change in wind conditions at each downwind rotor will also impact on turbine fatigue loading, due to changes in turbulence intensity and wind speed. This paper considers the possibility to reduce damage equivalent loads (DEL) across the farm, by using DEL as the objective of a merit function, building on a previous study for a row of 6 turbines [1].

A typical wind turbine life extension analysis makes use of the margin between the turbine site specific fatigue loads and design type class fatigue load, to calculate additional years of operation that may be permitted for a turbine component before the type class fatigue loads are exceeded. Wind farm control techniques, optimized to reduce fatigue loading, could change this margin and therefore modify the operational life of wind turbines.

Several papers have considered the impact of wind farm control on loads. This includes [2] which considers energy and load impacts of wind farm control on a 3x3 turbine grid, using engineering wake models and blade element momentum theory, and showed significant increases in energy and reduction in blade loading. In [3] a more advanced wake modelling approach is used to study the energy and loading, and in [4] the validity of a loads data-base interpolation approach is considered.
In this paper novel software tools developed by DNV GL for steady state and dynamic wind farm simulation, and wind farm control optimisation (called LongSim), are used to test a merit function which aims to reduce fatigue loads. The Lilgrund offshore wind farm in Sweden is used as an example, realistic, layout. The software tools are part of the DNV GL ENCORE framework for multidisciplinary design, analysis and optimisation.

2. Method

2.1. Software tool

DNV GL have developed software tools for steady-state and dynamic simulation of a wind farm [5], and setpoint optimisation for quasi-static open loop control, based on the steady state wake model of WindFarmer [6]. The tools are described below, and a more detailed description is found in [7].

Wind Field. A synthetic wind field is generated across the wind farm area based on a point time history of wind conditions from a met. mast. The wind field is divided into low and high frequency parts; low frequency variations are correlated across the farm using coherence functions and cause wake meandering and advection; high frequency variations are not correlated between turbines, and are superimposed at each turbine location with the local turbulence intensity increased according to the wake turbulence model. The Veers method [8] is used to generate correlated low wave number time histories at a grid of points covering the wind farm area at hub height.

Wake. In this case the Ainslie model [9] is used, which is based on an axisymmetric eddy-viscosity solution of the Navier-Stokes equations. The formulation is specific to WindFarmer [6] and has been validated against many wind farm measurements [10]. Wake turbulence is modelled using the empirical Quarton-Ainslie model [11]. Wake meandering is based on the model of Larsen et al [12]. Wakes are advected using a combination of the free wind speed and mean wake wind speed over the profile. Wake deflection is modelled using the model of Jimenez [13]. Wake superposition is modelled using the dominant wake model of WindFarmer [6].

Turbine. A 2D lookup table of power and thrust coefficients as a function of pitch angle and tip speed ratio was generated using blade element momentum theory in DNV GL’s Bladed software [14]. The effect of yaw misalignment was represented by running a set of steady Bladed calculations across the range of operational yaw angles. A timestep of 1 second is used, high-frequency structural dynamics are neglected, and blade, pitch and yaw degrees of freedom are modelled. PID based torque and collective pitch control are implemented with pitch gain scheduling. Supervisory control is modelled using a flexible syntax to define filters and alarms.

Loads. Fatigue loads are interpolated from a fatigue loads database which contains results of 10-minute turbulent power production simulations calculated using Bladed [14]. Wake effects are represented by rotor averaging the wake-modified wind speed and turbulence intensity and using these for the database lookups. This approach is simplistic since it ignores the position of the wake centreline, and the significant variations in wind conditions across the rotor plane caused by partial wake immersion. DNV GL are actively researching improved methods for wake representation in the fatigue loads database, which minimise the number of additional database dimensions, while giving a more accurate representation of the effects of varying wind speeds and turbulence across the rotor plane on fatigue loads.

Optimiser. A gradient based optimiser using the simplex method in MATLAB is used for optimisation. Optimisation proceeds by: evaluating the wake effects for a given set of wind conditions and turbine yaw angles; interpolating the loads at the calculated wind speed, turbulence intensity and wind direction at each turbine; evaluating the merit function at the current wind conditions (see 2.4.); calculating the gradient of the merit function; and then choosing new yaw angle setpoints for each turbine. This is continued until the change in merit function falls below a specified tolerance.
2.2. Site

The Lillgrund wind farm site is used as an example layout for the study. It is well suited to the type of flow modelling used, since it is offshore, with no terrain effects. The actual farm consists of 48 Siemens SWT-2.3-93 wind turbines. Inter-turbine spacings are small, at around 3-4 rotor diameters. In the current study a smaller 2MW 75m generic wind turbine model is used, which slightly increases relative turbine spacings to 4-5 diameters. The layout is shown in Figure 1.

Wind conditions for the site were derived from the Northern Europe Wind Energy Atlas (NEWA) [15] for the year 2018 and the data was binned to find the probability of each combined direction, wind speed, and turbulence intensity. This wind rose is shown in Figure 2.

Figure 1: Lillgrund site layout

Figure 2: Wind rose derived from NEWA data

2.3. Wind conditions for optimisation

Optimisations were made for the 1080 wind conditions shown in Table 1 which account for 54% of the wind conditions observed at the site over a year. The wind conditions for optimisation were limited to this range to reduce the amount of computation in this preliminary study. They were considered to have the greatest potential for gains with wind farm control (low turbulence, wind speed below rated).

Outside this range the turbines were simulated without wind farm control, but wake modelling was still used to account for changes in wind speed and turbulence across the site, and binned as shown in Table 2.

| Wind speed | 7, 9 and 12 m/s |
| Turbulence intensity | 3, 6, 9, 12, and 15% |
| Wind direction | 0 to 355 degrees in 5 degree bin sizes. |

Table 1: Wind conditions where wind farm control optimisation was applied

| Wind speed | 3, 5, 15, 18, 21, 24 m/s |
| Turbulence intensity | 3, 6, 9, 12, and 15% |
| Wind direction | 0 to 355 degrees in 5 degree bin sizes. |

Table 2: Wind conditions where wake effects were calculated but WFC was not applied

2.4. Merit function and optimisation

The merit function was formulated to minimise the maximum Blade 1 root bending moment (My) across all turbines on the site by changing the turbine yaw angle. Energy was not considered in merit.
function evaluations. Loads are interpolated from a loads database calculated using DNV GL’s *Bladed* software, as described in 2.1. For each wind condition a baseline load is established without any wind farm control optimisation. As the optimisation progresses for that wind condition, a new load is calculated at each turbine, and values are non-dimensionalised by the baseline load. The maximum non-dimensional load is found across all turbines on the site, and this is the objective of the minimisation. Each iteration of the optimiser seeks a new minimum of the maximum damage equivalent load of any turbine across the site. This optimisation process is repeated for all wind conditions shown in Table 1. The merit function is expressed in Equation 1.

\[
merit = W_P * F\left(\sum_i P_i\right) - W_L * F\left(\max L_i\right)
\]

Equation 1

Where \(L_i\) = load on turbine \(i\) (in this case, the blade root out of plane bending moment), \(P_i\) = power of turbine \(i\), \(W_L\) and \(W_P\) = the weightings, which sum to 1, and \(F(v) = (v - v_{Base})/v_{Ideal}\) is a normalising function defined as the difference of variable \(v\) from the base (uncontrolled) case, normalised by the value in the ideal (unwaked) case.

In this study \(W_L=1\) and \(W_P=0\), so the benefit function is focussed 100% on using yaw angle to reduce maximum blade root bending moment.

2.5. *Yaw direction*

Turbines were permitted to yaw to \(\pm\) 30 degrees, and the effect of this yaw misalignment on blade root and tower base loads is shown in Figure 3. The effect is non-symmetric due to the interaction between the blade rotation, yaw angle, angle of attack and wind shear.

An example is shown in Figure 4 for a snapshot of time where a clockwise rotating blade is pointing vertically upwards:

- At negative yaw angles, angle of attack is increased when the blade is pointing upwards in the highest wind speeds (least affected by shear), increasing loads.
- At positive yaw angles, angle of attack is reduced when the blade is pointing upwards, reducing loads.

Rotation through the wind shear causes loading to vary with the varying incident wind speed, with lower loads when the blade is pointing down (Figure 4).

This load reduction at positive yaw angles with clockwise rotation leads some wind farm control studies to only yaw angles greater than 0 degrees [16].

Yawing in either direction may have a benefit when controlling the wind field through the site and steering wakes specifically to control flow at specific turbines. In the current study the optimiser seeks the optimal positive or negative yaw angle for each turbine to minimise loads across the farm.

3. Results

3.1. *Energy generated in one year*

After optimisation to minimise blade root bending moment across the site, the energy generated by the wind farm was increased by 0.13%. This number is calculated by calculating the additional energy generated in each wind speed bin (the product of the increase in power in that bin, and the number of hours spent operating in the bin over a year), summing the additional energy across the bins, and then normalising by the total energy generated without wind farm control.
Since energy increase was not the objective of the optimisation, this result indicates that a carefully formulated merit function which also includes power, may yield greater increases in power whilst reducing loads.

Preliminary tests were also run to optimise power across the site, which resulted in an increase in annual energy production of 6.9%. Another merit function was tested which aimed to increase power and simultaneously minimise blade root bending moment (equally weighted), and this resulted in a 4.5% increase in annual energy production. In both cases the effect on loads was not satisfactory. The formulation of such a merit function will be site and turbine specific and is the subject of further research.

Figure 3: Effect of yaw angle on blade root bending moment and tower base overturning moment

Figure 4: Effect of yaw on blade angle of attack. $U_i$ = Incident wind vector, $U_o$ = Wind vector due to rotation, $U_{rel}$ = Apparent wind speed, $\beta$ = Blade pitch angle, $\alpha_x$ = Angle of attack at yaw angle $x$, $Y_x$ = Yaw angle at value $x$. Black lines show vectors with yaw angle at 0. Red lines with yaw at +30 degrees, and blue lines at -30 degrees.

3.2. Change in loads

Figure 5 shows the change in both tower base fore-aft moment and blade bending moment damage equivalent load, for each turbine across the site, accumulated across all the wind conditions considered, including the 1080 bins where optimisation was used to reduce loads. The variation in the change in loading between turbines is a result of the site layout, the time spent in each wind bin over a year, and the setpoints applied at each turbine in each wind bin.

The blade root bending moment is reduced at 28 turbines by up to 0.5%, and increased at the remaining 20 by up to 0.3%. Tower base fore-aft moment is reduced by up to 0.3% at 23 turbines, and increased at the remaining 25 by up to 0.1%. Changes in fatigue load on components will result in a change in operating life and this is the subject of Section 3.3.
The optimiser favoured positive yaw angles, which follows the trends shown in Figure 3. For all turbines, across all the wind conditions considered for optimisation, 16.9% of yaw setpoints were positive while 4.5% were negative, with the remaining turbines unchanged following optimisation.

3.3. Change in asset life and total energy

It has been assumed that the baseline damage equivalent loads (without wind farm control) corresponds to a fatigue life of 20 years for all turbine components including tower and blade. The effect of loading is only evaluated on the tower and blade, and other components e.g. gearbox are not considered in the current study. The assumed 20 year life for tower and blade is conservative, since these components will be designed to type class loads which are higher than the site-specific loads (assuming no planned blade replacements), and therefore operating life will be increased by the margin between type class and site-specific loading. For the current simplified study it allows the effect of wind farm control on life to be understood in context of a standard turbine lifetime.

In Table 3 the total life of all 48 turbines on the site is shown in the first two columns, based on the tower and blade fatigue loads. The first row shows the baseline data without wind farm control. Total life is calculated for 48 turbines at 20 years. For the optimised case the modified life is calculated by taking the ratio of the baseline load to the new load, raised to the Wohler exponent for the component material (4 for the steel tower, and 10 for the glass fibre blades), and multiplied by the baseline life of 20 years, shown in Equation 2.

\[
L_{opt} = L_{base} \left( \frac{D_{base}}{D_{opt}} \right)^m
\]

Equation 2

Where \(L_{opt}\)=optimised component life, \(L_{base}\)=baseline component life, \(D_{base}\)=baseline component damage, \(D_{opt}\)=optimised component damage, \(m\)=Wohler exponent.

The life of each turbine is calculated individually, based on the load calculated from its lifetime wind conditions and probability distribution of yaw angles, and then summed to give the total life. This assumes varying decommissioning dates for each turbine, which is unlikely to occur in practice, but allows the individual turbine lives to be used as a metric for the benefit of wind farm control.

The optimisation resulted in a small increase in total blade life of 0.4% and no change in tower life. Blade lives ranged from 19.4 to 21 years, and life was extended at 28 turbines. The energy generated by the farm is calculated multiplying the power generated by the farm in in wind condition, but the number of hours spent in that condition each year. This gives an annual energy yield which is then multiplied by the life of each turbine to get its total lifetime energy generation. This is obviously oversimplistic e.g. it ignores reduction in efficiency over the blade life, and uses varying decommissioning dates. Using this simple approach the energy increase reported in Section 3.1. is combined with the change in turbine lifetime, and indicating an increase in energy generation of 0.5% for the farm due to wind farm control optimisation.

The effect of discount rates on the value of the energy has not been considered here, but this will cause value to reduce over the life of the farm. Merit functions which increase energy may be more beneficial than those which extend life when the net present value of the energy is considered.

|               | Total tower life (yr) | Total blade life (yr) | Energy summed over tower life (TWh) | Energy summed over blade life (TWh) |
|---------------|-----------------------|-----------------------|-------------------------------------|-------------------------------------|
| Baseline      | 960.0                 | 960.0                 | 3.987                               | 3.987                               |
| Optimised     | 960.4                 | 963.7                 | 3.994                               | 4.007                               |
| \(\Delta\ %\) | 0.04%                 | 0.38%                 | 0.17%                               | 0.50%                               |

Table 3: Change in asset life and total energy generated over lifetime
Left: Change in tower base fore-aft moment  
Right: Change in blade root bending moment

**Figure 5:** Change in lifetime accumulated damage equivalent loads across all turbines on site.
3.4. Verification of results through dynamic simulation

To verify the load benefits seen in steady conditions, tests have also been made using dynamic simulation at a single wind condition. The wind conditions for the simulation were selected to demonstrate the effects of wake steering at a turbine at the centre of the farm, Turbine D-04. The change in steady-state loads at this turbine were analysed to find wind conditions where loads would be reduced, and a wind direction of 20 degrees was noted to see reductions in blade root bending moment.

Note that the analysis presented in Figure 5 is the change in loading across all wind conditions, which showed an overall increase in loading at turbine D-04. The analysis in this section only considers D-04 at a single wind condition, for which loading is reduced due to wind farm control.

Example met. mast data (not from the Lilgrund site, but an equivalent site) was interrogated to find a short time period where wind conditions included 20 degree wind direction, and were within the wind speeds and turbulence intensities where wind farm control setpoints had been calculated (7-12ms, 3-15% turbulence intensity). The wind conditions selected are shown in Figure 6. They were used to generate a synthetic wind field covering all wind turbine locations, as described in 2.1.

The example met. mast data was used to define the wind conditions for the setpoint lookups from the wind farm control lookup table, with a 5-minute averaging time. LongSim permits different approaches to estimate and average the wind conditions across the site for setpoint lookup, for example taking the average of wind conditions at un-waked turbines. It is important to test different calculation methods for the setpoint lookup input data, since it has a significant effect on the setpoints chosen during dynamic simulation and operation. The setpoints were updated every minute.

The time history of blade root bending moment damage equivalent load for both the baseline case (without wind farm control) and with optimisation, are shown in Figure 7. Note that this is a time history of damage equivalent loads calculated from 10-minute simulation which can be used as metric to represent the accumulation of fatigue damage. Over this period the blade root bending moment metric is reduced by 2.3% from a mean of 779kNm to 761kNm, confirming that wake steering is effective in reducing fatigue loading at this turbine in both steady state and dynamic wind conditions.

Figure 8 shows the yaw error at turbine D-04, and the two turbines that are directly upwind at a wind direction of 20 degrees. The trend of yaw error is fairly consistent between turbines, and it is hard to detect how much of the load reduction is driven by the yaw angle of D-04 or the altered wakes of turbines E-03 and D-03. Improved methods for analysing and presenting the results of dynamic wind farm control simulations across large wind farms are the subject of further work.

![Figure 6: Wind conditions over dynamic simulation period](image-url)
Figure 7: Example dynamic simulation results for Turbine D-04 at ~20 degrees, ~7m/s, ~10% ambient turbulence intensity.

Figure 8: Yaw error at turbines D-04, E-03 and D-03 under wind farm control

4. Conclusions

A merit function which aims to reduce blade root bending moment across a wind farm has been used to optimise quasi-static open loop wind farm control for the Lillgrund wind farm layout with an example 75m rotor. The optimisations were successful in increasing both component life and energy yield, increases were small, but promising at this early stage of development, and the total increase in energy over life was 0.5% calculated using steady state modelling.

DNV GL’s LongSim software toolset for wind farm control design and testing was used for the study and enables offline optimisation based on any user defined merit function of power and loads, based on a fatigue loads database calculated with Bladed. It was also used to verify the steady state optimisations in a dynamic simulation environment.

The results provide an example of the type of analysis that may be used to combine industry-standard life extension techniques with wind farm control to further extend wind farm life and increase energy yield. Future research will focus on improving the merit functions to achieve further reductions in load and increases in energy; using induction control together with wake steering in optimisations; and improving modelling of partial wake immersion in the loads database.
5. References

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