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Possible Improvements for Present Wind Farm Models Used in Optimal Wind Farm Controllers

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***Abstract* — The use of optimal wind farm control can potentially mitigate adverse wake effects that cause up to 40% power loss in wind farms. The aim of this work is to benchmark a typical optimal wind farm control approach using wind farm measurements and numerical simulations. The aerodynamic model of the controller is based on the Jensen wake model, which is the most widely used model in wind farm control. The controller is tested on a typical offshore wind farm, which is related to the Horns Rev I farm. The comparison of the model with wind farm measurements shows that power losses are overestimated by the model. When estimating wind farm power using the model of the optimal controller, the use of optimal wind farm control results in an up to 14% increase in total farm power in particular wind directions. In the same direction, simulations of the farm using the numerical simulation tool SimWindFarm however show a gain of 1.6%. The effects of wake meandering and turbine dynamics, which are only modelled in SimWindFarm, result in this smaller gain in SimWindFarm. Overall, the results show that there is a need for improved, validated models in optimal wind farm control.**

Keywords – Wind farm control, power maximisation, wakes, model improvement,

I. INTRODUCTION

In wind farms the interaction of wind turbine wakes with downstream turbines results in loss of total power of up to 30-40% [1]. The objective of optimal wind farm control is to mitigate these wake effects by coordinating the operating point of wind turbines in the wind farm given the aerodynamic interaction of the turbines. In the present work control approaches are investigated that change the turbine operating point using the blade pitch angle. The objective of optimal wind farm control in this work is to maximize the total wind farm power output.

For this objective the operational strategy is based on the hypothesis that a reduction in the power extraction of upstream turbines by pitching the blades towards a feathering position would increase the total power output. The reduced extraction of power at the upstream turbine weakens its wake and as a result to higher wind speeds are experienced by downstream turbines. An increase in total power output is reported in various numerical [2]–[6] and experimental [2], [7]–[10] studies. The use of models in these studies is however expected to result in a deviation of the observed behaviour of the model farm from the real wind farm performance. For instance, the use of downscaled models of wind turbines in wind tunnel experiments results in a lower Reynolds number compared to the full-scale, and as a result in differences of the turbine performance [11]. There is however also a full-scale experimental study on two 2.5MW wind turbines [8] that reports a gain in total power in certain wind conditions.

An important success factor of model-based optimal wind farm controllers is the quality of the used wind farm operation model. Most studies on optimal wind farm control with the objective of total power maximisation use the original Jensen model or a modified version for the prediction of turbine interaction through wakes [12]–[15]. None of these studies is however comparing the wind farm modelling approach against the real wind farm performance. Neither are the modifications of the Jensen model validated with measurements.

The present work examines the impact of a typical optimal wind farm control approach on the total power of a typical offshore wind farm for the full range of wind directions. The results are used to discuss areas of improvement of wind farm models used in present optimal wind farm control approaches. First the controller's wind farm model, which is based on the Jensen model, is compared with the performance of a real wind farm. The wind farm layout and wind conditions are closely related to the Horns Rev I wind farm in western Denmark. The comparison results show that there is a clear need for the improvement of present wind farm operation models for optimal wind farm control. Thereafter the study discusses the increase in total power of the wind farm under operation with the optimal wind farm controller. The whole range of wind directions is covered by the analysis. Finally, the optimal wind farm controller is tested using the dynamic simulation tool SimWindFarm in order to investigate the impact of dynamic operational effects on the performance of the controller.

II. METHODOLOGY

A. *Optimal Wind Farm Control Approach*

This section presents the optimal wind farm control approach of the present work. The controller uses wind farm measurements as input to the wind farm model of the controller. The distribution of the optimum turbine pitch angles is derived using a numerical optimisation of the model-based estimate of total wind farm power. The optimized turbine operation set-points are then introduced to the turbines. In the following the problem formulation of the optimisation and the wind farm operation model used by the controller are presented. More details on the controller framework can be found in [16].

1) Problem Formulation

The objective of the optimal wind farm controller is the maximisation of the stationary total power output of the wind farm. Hence the following objective function $J(\underline{\beta})$ is maximised

$$J(\underline{\beta}) = \sum_{i=1}^{N} P_i(\beta_i) \tag{1}$$

$P_i(\beta_i)$ is the stationary turbine power of turbine *i*, which is operating at blade pitch angle β_i . $\underline{\beta}$ is the vector containing the blade pitch angles of all turbines. *N* is the number of turbines of the wind farm. The optimisation problem is solved using a non-linear, iterative optimisation algorithm.

2) Wind Farm Operation Model Used in Optimisation

The stationary power output of turbine *i* is calculated as

$$P_i(\beta_i) = \frac{1}{2}\rho A_i u_{inl,i}^3 c_p(\lambda_{opt}, \beta_i) \tag{2}$$

ρ is the density of air, A_i the turbine rotor area, $u_{inl,i}$ the turbine‘s inlet wind speed and $c_p(\lambda_{opt}, \beta_i)$ the turbine power coefficient as a function of blade pitch angle. λ_{opt} is the tip-speed ratio that maximises the turbine power coefficient. It is assumed that air density is constant throughout the wind farm and turbine inlet wind speed is constant over the rotor area.

The turbine‘s inlet wind speed depends on the aerodynamic influence from upstream turbines. In case of no influence, the inlet wind speed is set to the freestream wind speed. Otherwise it is given by the wind speed in the upstream turbine's wake at the position of the downstream turbine. A wake is set to affect a downstream turbine up to a separation distance of 20D from the upstream turbine to the downstream turbine. No partial wake situation is considered. In case of multiple turbine wakes affecting a downstream turbine, the wake of the closest upstream turbine is considered according to the suggestions in [17]. As such a turbine's inlet wind speed is determined by the array of upstream turbines that have the closest separation distance and interact through their wakes. In [18] such a multiple wake effect model yielded the best fit with experimental data.

The wake wind speed is estimated using a modified version of the Jensen wake model [19], which is the same as used in the simulation tool for the testing of control strategies. The wake wind speed u_{wake} is estimated as

$$u_{wake}(\beta) = u_{inl}\left(1 - \frac{1}{2}c_T(\lambda_{opt}, \beta)\left(1 + \frac{d}{4R}\right)^{-1}\right) \tag{3}$$

u_{inl} is inlet wind speed of the wake generating turbine, $c_T(\lambda_{opt}, \beta)$ is this turbine's thrust coefficient and R its rotor diameter. d is the downstream distance in the wake measured from the wake generating turbine.

The radius of the wake R_{wake} is modelled using Jensen's model of wake expansion [20]

$$R_{wake} = \sqrt{4R^2 + Rd} \tag{4}$$

B. Numerical Simulation Approach - SimWindFarm

The SimWindFarm simulation tool [21] is used for the testing of the above presented optimal wind farm control approach. SimWindFarm was developed aiming "at providing a fast wind farm simulation environment for the development of wind farm control algorithms" [21]. The SimWindFarm tool allows for the simultaneous, dynamic simulation of the wind flow in a wind farm, the turbine operation, the actions of the wind farm controller, the transmission system operator and the electric transmission system. The simulations in the present work do not consider the effects of the system operator and transmission system.

Wind flow aerodynamic modelling is divided into an ambient field model and a turbine wake model part. The ambient wind field is modelled as the hub height, turbulent wind flow advected with the mean wind speed under the assumption of Taylor's frozen turbulence. The turbulent wind field is generated according to the norm IEC 61400-3 concerning offshore turbines. The model neglects lateral and vertical wind velocity components. Wake flow modelling includes wind speed deficit, wake width expansion, wake meandering and wake merging. The wind turbine operation model is based on a simplified version of the NREL5MW virtual turbine model [22]. Wind turbine aeroelastics are modelled using turbine power coefficient and thrust coefficient. Further, the drive train, generator and pitch actuator are simulated using up to 3rd order dynamic models. The turbine controller is modified as such that it takes the blade pitch angle as input instead of a turbine power reference. A torque controller is used to keep the turbine operating at the optimal tip-speed ratio λ_{opt} , which is introduced in the section above. More information on the simulation tool – including also detailed information on the modelling of wind field and wind turbines – can be found in [23].

C. Wind farm

The controller is tested on a typical offshore wind farm. The wind farm layout and wind conditions are closely related to the Horns Rev I wind farm in western Denmark. The wind farm is built up of a total of 80 wind turbines. Figure 1 shows the wind farm's layout, which is a regular rhomboidal structure of eight times ten turbines. The numbering of the turbines is used later in the discussion of simulation results.

The real Horns Rev I wind farm is built up of VESTAS V80-2.0 MW wind turbines. At the time of the study there was however no model of this wind turbine type available in SimWindFarm. The simulations are thus performed using the NREL5MW wind turbine model discussed above. The rotor diameter of the NREL5MW turbine is 126m and hence 1.575 times larger than the 80m rotor of the VESTAS V80.

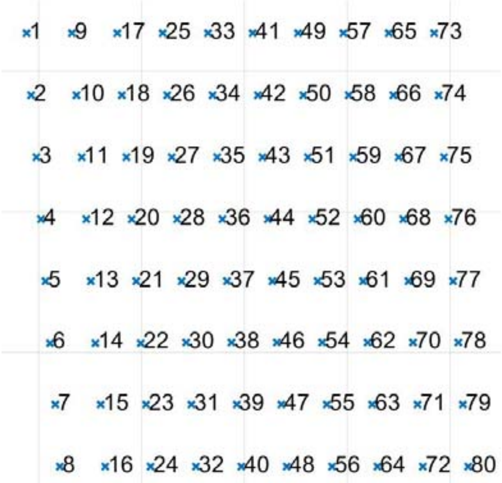

Figure 1: Layout of simulated wind farm. Blue crosses and numbers indicate the position and number of turbines, respectively.

In order to account for this difference with regard to the interaction of turbines through wake flow, the wind farm layout is stretched by this factor (1.575). Thereby the distance between the turbines normalised by the turbine diameter is the same in the simulated and the real wind farm. A summary of the technical data of the turbines used in the simulations is shown in Table 1 unterhalb.

TABLE 1: SUMMARY TECHNICAL DATA OF SIMULATED WIND TURBINES

Type	Quantity	Rated Power (MW)	Rotor diameter (m)	Cut-in / Rated / Cut-out wind speeds (m/s)
NREL 5MW	80	5	126	4 / 12 / 25

Figure 2 shows a wind rose based on 31 month-long met-mast measurements at Horns Rev I wind farm. The wind rose is binned into directional bins of 5 deg range and wind speed bins of 4m/s range. It can be observed that there is two dominant wind direction sectors: the south-to-northwest sector and the east-eastwest sector. Since the objective is to estimate the impact of optimal wind farm control on the annual energy yield, the full range of wind directions is covered. Dominant wind speed ranges are 4 m/s to 8 m/s and 8 m/s to 12 m/s, with the most likely wind speed of 8m/s. The simulations are thus carried out for an average freestream wind speed of 8 m/s. Barthelmie et al. [24] reported that turbulence intensity at turbine hub height in Horns Rev I wind farm ranges from 2.5% to 10% at a wind speed of 8m/s. The turbulence intensity in the SimWindFarm simulations is set to 8%. Future studies shall also investigate the effect of turbulence intensity levels on the benefit of optimal wind farm control strategies.

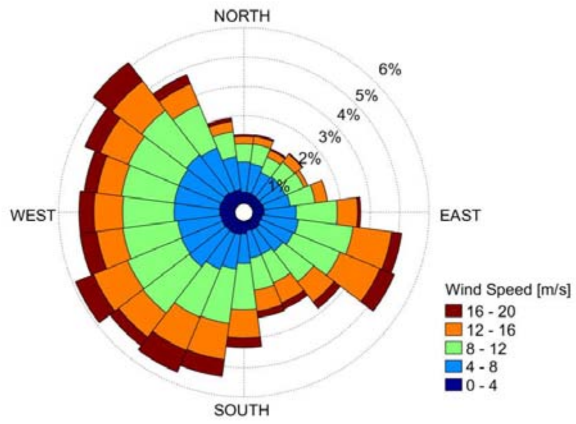

Figure 2: Wind rose based on 31 month-long met-mast measurements at wind farm site.

III. RESULTS & DISCUSSION

The objective of the present work is to examine the impact of a typical optimal wind farm control approach on the total power of a typical offshore wind farm. The results are used to discuss areas of improvement of wind farm models used in the wind farm control approach of this work and of other studies. In the following first the effect of wake shadow on the total power of Horns Rev I wind farm is examined with regard to wind direction. Second, the impact of the use of the optimal wind farm controller is discussed for the wind direction with the largest loss in total power. Third, the gain in power resulting from the use of the optimal controller is discussed with regard to the whole range of wind directions. Finally the impact of the optimal controller on the wind farm's annual energy yield is presented.

Figure 3 shows the effect of wake shadow on the normalised Horns Rev I total power output with regard to wind direction. The total wind farm power is obtained from SCADA data and the wind farm operation model used by the optimal wind farm controller. SCADA data is obtained from the freestream wind speed range of 8m/s +/-0.5m/s. The simulations are performed for the mean freestream wind speed of 8m/s. The total power is normalised by the output power of wind turbines in undisturbed flow.

In most directions the loss in total power is between 15% to 25%. SCADA and model estimates show a good agreement for these directions. Four distinct sectors around 90deg, 170deg, 270deg, and 355deg show above average loss in total power. The SCADA data results show up to 33% total power loss and the model estimates up 65% loss. A smaller, but distinct drop in power is also observed around the directions of 40deg, 130deg, 220deg and 310deg in the model-based results. The drop in power is less clear in the SCADA data. In these eight directional sectors the average loss in power results due to the small spacing between wind turbines in these directions. According to the wind farm model, up to 88% of turbines are, on average, fully immersed in upstream turbine wakes in these directions.

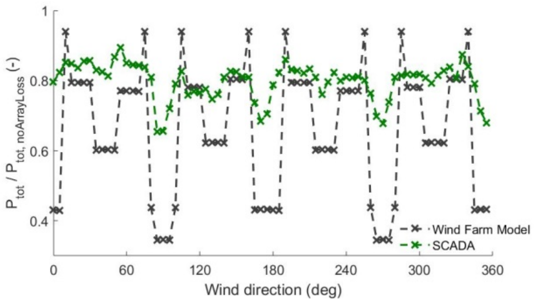

Figure 3: Effect of wake shadow on normalised Horns Rev I total power output for entire range of wind directions. Power is normalised by the output power of wind turbines in undisturbed flow. Shown are the data from SCADA [25] and estimates by the wind farm model.

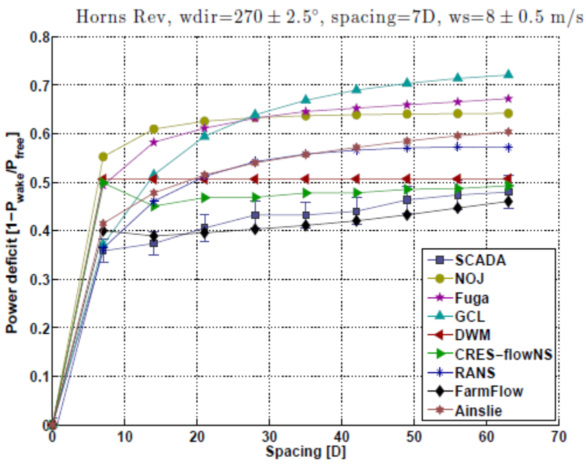

Figure 4: Effect of wake modelling approach on power deficit of wind turbines of a 10 turbine array aligned with wind direction [25].

The results show that there is a large difference between SCADA data and model estimates in the directions with closely spaced turbines and many wake interactions. Similar results are reported by the EERA-DTOC wake modelling benchmark study [25]. Figure 4 shows the individual turbine power deficit along a row of 10 turbines aligned with wind direction in Horns Rev I wind farm. The power deficit is estimated using the most common wake modelling approaches. That study shows that engineering wake models overpredict the power loss by up to 60%. Future work thus aims on using the more advanced PossPOW algorithm [26] for the estimation of the total wind farm power. The algorithm's aerodynamic model is based on a recalibrated version of the Gunnar Larsen model. The algorithm is validated both under normal and downregulated operation of wind farms.

Next the benefit of the use of the optimal wind farm controller is examined in 72 wind directions that cover the full range of wind directions. The simulations are performed using the wind farm model of the optimal wind farm controller.

Figure 5 shows the effect of the optimal wind farm controller on the total wind farm power compared to the normal wind farm controller.

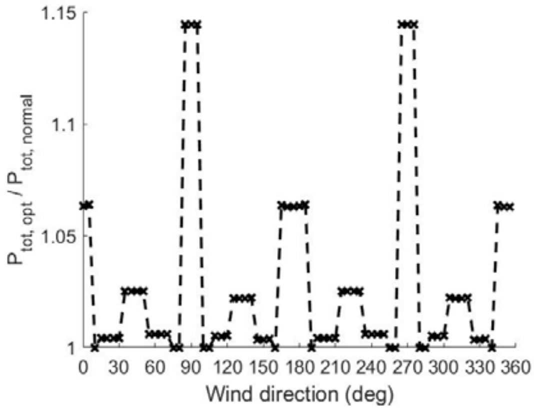

Figure 5: Effect of optimal wind farm controller on total wind farm power compared to normal wind farm operation. Wind farm power is estimated using wind farm model of optimal wind farm controller.

Generally the results show that in directions with larger loss in total power compared to the undisturbed situation, optimal wind farm control is more beneficial. It can be observed that the farm power is increased by up to 14% by the optimal wind farm controller around the wind direction of 90deg and 270deg. In these directions the largest loss in total power is observed in the real wind farm, as discussed with Figure 3. For a wind direction of 90 deg, for example, the loss in total wind farm power of 33% would be reduced to 23%.

The impact of the observed increase in total farm power on the annual energy yield is discussed in the following. The yield increase is calculated as

$$\Delta\%E_{annual} = \left(\frac{8760h * P_{opt,weighted}}{8760h * P_{normal,weighted}} - 1\right) P_{fract,below\ rated} \quad (5)$$

where $P_{opt,weighted}$ and $P_{normal,weighted}$ are the directionally weighted total power output of the wind farm under optimal control and normal control respectively. $P_{fract,below\ rated}$ is the fraction of power generated by a turbine between cut-in wind speed and rated wind speed weighted by the probability of wind speed. Hence the calculation is based on the assumption that the benefit of the optimal control is uniform in this wind speed range. $P_{opt,weighted}$ is calculated as

$$P_{opt,weighted} = \sum_{i=1}^{N} p_{dir,i} P_{rel,i} \Delta\%P_{opt,i} \quad (6)$$

where $p_{dir,i}$ is the probability of wind direction i and N the number of wind directions. $P_{rel,i}$ is the wind farm efficiency observed in SCADA data, as discussed with Figure 3. $\Delta\%P_{opt,i}$ is the percentagewise increase in total farm power when the comparing optimal wind farm controller to the normal controller. $P_{normal,weighted}$ is calculated as

$$P_{normal,weighted} = \sum_{i=1}^{N} p_{dir,i} P_{rel,i} \quad (7)$$

Based on the probabilities shown in the wind rose in Figure 2, the use of the optimal wind farm controller would result in an increase of the annual energy yield by 1.0%.

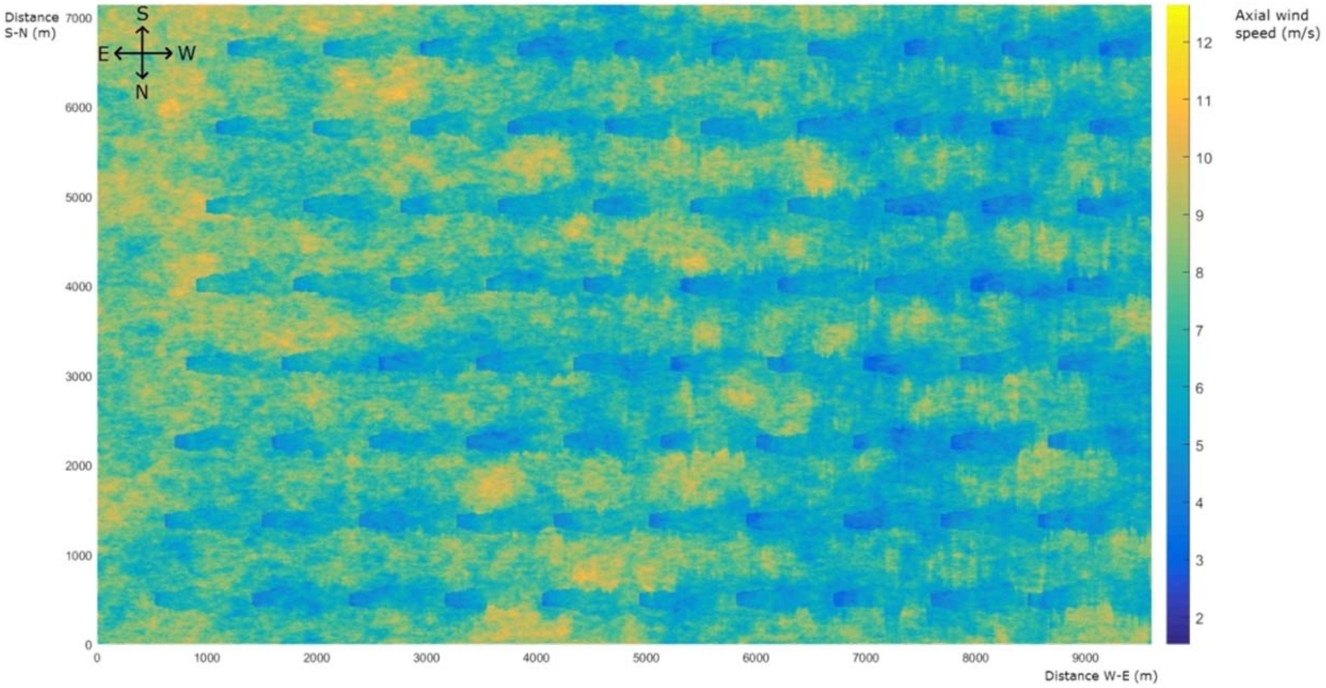

Figure 6: Contour plot of axial hub height wind speed of Horns Rev I wind farm operating in wind direction of 90deg and in mean wind speed of 8 m/s. Wind field and wind farm operation simulated using SimWindFarm.

In order to test the performance of the wind farm controller in the dynamic conditions of wind farm operation, simulations are performed using the dynamic wind farm simulation tool SimWindFarm. In the following the performance of the optimal wind farm controller is first discussed for the wind direction of 90 deg. This is the direction that shows one of the largest losses in total power. Figure 6 shows a contour plot of the simulated axial hub height wind speed in the wind farm operating in wind from this direction. In this SimWindFarm simulation, the wind farm is controlled using a normal wind farm controller. In a normal wind farm controller each turbine maximises its individual power output. Dark blue areas with lower wind speed show the evolution of the wind speed deficit behind the turbines. It can be observed that the strength of the deficit increases with further downstream distance. This is due to the interaction of downstream turbines with upstream turbine wakes. This interaction results in the large loss in power of the farm in this direction.

Next the performance of the wind farm under control of the normal wind farm controller is compared to the optimal wind farm controller. A SimWindFarm simulation of the wind farm is carried out for each of the controllers. In order to allow for a comparison of the controllers the same wind field is used in both simulations. In Figure 7 the average individual turbine power of a turbine row aligned with the wind direction is compared between the two wind farm controllers. Turbine No. 80 is the most upstream turbine and the smaller the turbine number the more downstream the turbine. It can be observed that for both controllers the turbine power is monotonically decreasing with each downstream turbine. While the first three turbines perform worse under optimal control, the seven more downstream turbines show an increase in power compared to normal operation. In total the wind farm produces 1.5% more power under optimal control.

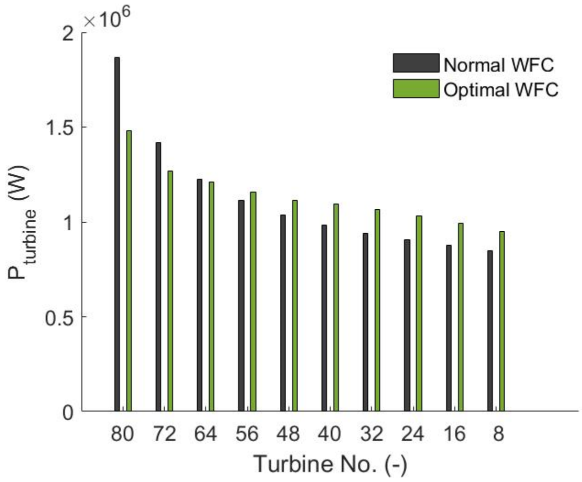

Figure 7: Effect of optimal wind farm controller (WFC) on time-averaged turbine power output of turbine row aligned with wind direction of 90deg. Turbine operation is simulated using SimWindFarm.

Next the wind farm is simulated in the directions of 170deg, 270deg and 355deg. As discussed with

Figure 5, the largest relative gain in power is predicted by the controller's wind farm model for these directions. Figure 8 shows the gain in power of the wind farm when controlled by the optimal controller. The gain ranges from 0.8% to 1.6%. The observed gains are comparable to the study by Heer et al. [12], which reports an increase of 1.4%. The study investigates the operation of Horns Rev I wind farm in the direction of 270deg using SimWindFarm. Thus both the simulation environment and the simulated wind farm are the same in that study and the present work.

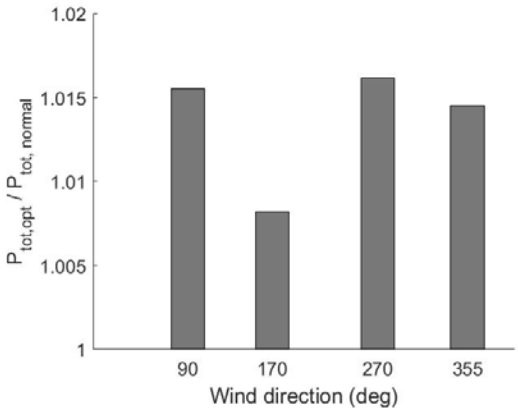

Figure 8: Effect of optimal wind farm controller on total farm power compared to normal wind farm control estimated using SimWindFarm simulation tool. In normal wind farm control the power of each individual turbine is maximised.

It can be observed that the gain in power is up to 88% less in SimWindFarm as compared to the estimates by the model of the optimal controller. The main difference between the model of the optimal controller and SimWindFarm is that effects of wake meandering and turbine dynamics are only considered in SimWindFarm. Since these effects are neither considered in other studies on optimal control [12]–[14], [27], [28], future research should also focus on the modelling of these effects for the use in wind farm control. As regards this study, future work plans to implement the PossPOW algorithm in order to use more advanced wind farm models. This algorithm also considers the effects of wake meandering.

IV. CONCLUSIONS

The present work examines the impact of a typical optimal wind farm control approach on the total power of a typical offshore wind farm for the full range of wind directions. The results are used to discuss areas of improvement of wind farm models used in present optimal wind farm control approaches. When estimating wind farm power using the model of the optimal controller, the use of optimal wind farm control results in an up to 14% increase in total farm power. Based on these results, it is estimated that the use of the optimal controller would result in an increase of the farm's annual energy yield by 1.0%. However, the simulation of the most beneficial wind directions using the dynamic simulation tool SimWindFarm shows a smaller gain in total power ranging between 0.8% and 1.6%. Thus, the effects of wake meandering and turbine dynamics, which are only modelled in SimWindFarm, result in a smaller gain of the optimal controller. Considering these effects in the optimisation model could improve the performance of the controller. In general, it is concluded that there is a need for improved models for optimal wind farm control. It is imperative that these models are validated against real wind farm performance. Future work shall focus on the design of more advanced wind farm models based on the existing modelling infrastructure and data of DTU Wind Energy.

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