Numerical Validation of Wind Plant Control Strategies

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Abstract. Research work carried out with the support of the CL-Windcon EU project where flow control strategies (flow redirection or yaw misalignment, and flow induction control or de-rating) are validated. These strategies were divided in optimizing a wind farm (WF) in terms of wind farm Annual Energy Production (AEP), and in optimizing the wind farm to reduce the worst Damage Equivalent Load (DEL) in blade root flap-wise moment that sees a wind turbine (WT) while keeping the WF AEP as high as possible. Two numerical methods were employed. A modified FLORIS that takes into account the DEL was used in the optimization process and the simulations, the baselines and the optimized configurations, were replicated with a higher fidelity method, SOWFA, to verify the lower fidelity tool results prior to implementation in a real system. From the studied cases, it has been found that the wake steering approaches maximized the total power by 6 to 15%, and the flow induction strategies, despite having a poor performance increasing of the overall power productions, showed their validity for reducing the flap-wise moment DEL of the WT blade. Numerically, SOWFA and FLORIS simulations showed significant discrepancies in partial wake conditions, which suggested a need of a new tuning of the FLORIS parameters for partial wake conditions. Finally, mention that now, thanks to EU CL-Windcon project there are publicly available experimental data, wind tunnel data, and SOWFA data that could be used for validation purpose.

1. Introduction and objectives
The wind turbines are not operated anymore as isolated wind power systems. The current trend brings them to work as a team, moving from a greedy WT control concept, in which turbines are operated to achieve individual optimal performance, to more general wind farm control (WFC) strategies that optimizes the overall wind farm Annual Energy Production (AEP) or that maximizes the wind turbines’ lifetime while minimizing the AEP losses [1,2]. Among different WFC methods, some recent works [1-4] suggest that the strategies based on axial induction or wake redirection are some of the most prominent methods to maximize the total power output or to decrease the turbine structural loads, or both. Therefore, framed by the CL-Windcon project [5], this work presents the results of a novel WFC strategy that uses the methods of wake redirection and the axial flow induction, and also a combination of them, so that 1) it maximizes the AEP and 2) reduces the DEL on the blade root flap-wise bending moment of the most affected WT within a WF while keeps the AEP as high as possible.

In order to develop this (and any other) WFC algorithm that considers the coordinated operation of wind turbines, it is necessary to study the wake and wake interaction of each turbine with its neighbors under different operating conditions. While some of these interactions have been recently studied
experimentally through wind tunnel tests (e.g. [6, 7]) and field campaigns [8], reliable numerical wake models are still required for the design, optimization and verification of any WFC strategy prior any implementation in a real device.

This work makes use of a CENER modified version [9] of the FLOw Redirection and Induction in Steady-state (FLORIS) framework [10-11] to account for the damage equivalent loads to generate the optimal control strategies of two different wind farm configurations on flat/offshore conditions. Afterwards, following the work of [12], different high-fidelity simulations of the selected wind farm scenarios under the WFC strategies were carried out with the Simulator for On/Offshore Wind Farm Applications (SOWFA) tool [13] in order to verify the consistency of the control strategies under two models of very different fidelity level.

2. Methodology

Two scenarios were configured, based on the wind turbine locations, with typical offshore climate and surface conditions, that is, average wind speed of 11.4m/s at hub height (HH), 119m, of the 10MW machines [14], low turbulence intensity level of around 5.8%, and the aerodynamic roughness length ($z_0$) of 0.001m. These scenarios were used to verify power and damage equivalent load predictions from modified FLORIS tool. The first scenario can be seen in Figure 1, where the three wind turbines are located at 5 diameters (D) from each other in the flow direction, being the third one also displaced 0.5D perpendicular to the inflow direction to analyse the partial wake effect on the WT. In Figure 2, the 9 wind turbine wind farm was sub-divided in three single column wind farms. This was done for using the computational time efficiently (instead calculating each row independently) taking into account that at this flow direction the wakes of each column did not reach or influence the other columns. Therefore, the three isolated wind farms were composed by 3 wind turbines located at 7D from each other.

![Figure 1](image1.jpg)

**Three wind turbine cases**

Wind from:
South ($x$) - West ($y$) [225°]

INNWIND 10MW WT
Diameter: 178.3m

WT base location (HH=119.0m):
WT1 = (954.5, 954.5, 0.0)
WT2 = (1584.9, 1584.9, 0.0)
WT3 = (2152.3, 2278.4, 0.0)

Wind direction

Figure 1: The employed 3 WT wind farm scenario.
These scenarios were simulated with both numerical tools: the modified FLORIS version as low-fidelity model, and SOWFA as high-fidelity model. First, the turbines were operated facing the wind as they will do it in a traditional greedy control strategy, to generate the baseline cases. Then the modified version of FLORIS was used to generate the optimal operational points in depowering and/or yawing in each wind turbine in order to maximizing AEP and in terms of the combined objective to improving AEP while reducing DEL of the blade root bending moment for these scenarios. These operational modes optimized results in each wind turbine were implemented and simulated in SOWFA. SOWFA is considered a higher fidelity tool, and the cases were resolved under a more realistic inflow conditions generated by the same SOWFA after simulating the precursor state. In total, 8 strategies were verified. In the Modified FLORIS subsection, the main parameters of the modified FLORIS and SOWFA can be seen, and in the result section the most relevant cases of these eight strategies, 4 maximizing AEP and other 4 maximizing AEP while reducing the DEL of the blade root bending moment at the worst WT of each WF.

2.1. Modified FLORIS

FLORIS is a tool composed by a set of low-fidelity steady-state wind farm models developed by the Delft University of Technology and the US National Renewable Energy Laboratory (NREL) [9], and for this work the python version has been used. Among its several options, the selected wake model for these studies was Bastankhah and Porté-Agel, and the turbulence model Crespo and Hernandez [15].

The model parameters were set to their default values as maintained in NREL repository at the time of making predictions and are provided in [16]. This model has been chosen because it was found to be the most accurate model for predicting the wake velocity deficits and wake widths for the neutral and stable atmospheric conditions in single wake model benchmark with field data [18].

Developments have been done by CENER in FLORIS to add the functionality that considers loads at each wind turbine blade inside the simulated wind farm. This implementation is based on look-up tables created by pre-calculating DEL of an unaffected wind turbine by OpenFAST [17] for a range of wind speeds (4m/s to 24m/s with deltas of 1m/s), turbulence intensities (5%, 8%, and 20%), yaw
misalignments ($\pm 30^\circ$, $\pm 25^\circ$, $\pm 20^\circ$, $\pm 15^\circ$, $\pm 10^\circ$, $\pm 7.5^\circ$, $\pm 5^\circ$, $\pm 2.5^\circ$, $0^\circ$), and wind turbine de-ratings (rated power reduced from 100% to 50% of its nominal value). These wind conditions values were chosen because they could be present in a normal range of WT operation. Also, values of possible yaw misalignment and power reduction are under plausible operational points without taking risk in structural components. Regarding DEL estimations for cases without wind turbines in partial wake, the interpolation from pre-calculated databases is straightforward and it is already a validated approach [13]. However, the cases where the wind turbine is in partial wake condition, there is a significant effect of the reduction of the velocity and increase of turbulent intensity on the load calculations in certain regions of the azimuth, depending on the wake impingement. Using the mean velocities obtained for several radial positions at blade azimuth angles of $0^\circ$, $90^\circ$, $180^\circ$, and $270^\circ$, it is possible to translate from these velocities to cyclic loads with an addition of an extra signal that causes turbulent variations to the undisturbed wind signal. In particular, at these studies the targeted DEL was the blade flap-wise bending moment, but other loads could also be computed in a similar way. More details about this methodology can be found in [13].  

It is needed to couple wind turbine dynamics with atmospheric flow conditions in the immediate vicinity of the rotor. For that, parameterised power and thrust curves (Cp-Ct curves) are added to dataset to the modified FLORIS version. In order to generate the curves representing different operating conditions, various simulations were run with OpenFAST [16], at several wind speeds, turbulence intensities (TI), yaw misalignments, and de-ratings. The control strategy to get these de-rating settings in the reference InnWind 10MW [13] wind turbine was to minimise the thrust coefficient minCT, while keeping desired power reference signal demand from optimisation algorithm, which is based on genetic algorithm written in Python.

2.2. SOWFA

SOWFA [12] has been used during this study as the baseline tool since it is considered a high-fidelity method. This computationally expensive tool has been therefore used to check the optimised solutions found by FLORIS for the two wind farm scenarios and the two strategies: Maximisation of power and reduction of damage equivalent load (DEL) of the blades. For these, it has varied the wind turbine yaw, their power extraction (de-rating) or the combination of both of them.

Regarding the employed method, the flow and the turbines, with actuator lines, were computed through windPlantSolver.ALMAdvanced solver from SOWFA [18] on these simulations (the latest version that was available the 12/12/2018 in the Master branch of the SOWFA repository). The precursors were generated with the ABlSolver also from SOWFA (the latest version that was available the 26/07/2018 in the Master branch of the SOWFA repository) [18], and the details about the precursors, employed meshes or the wind turbine, can be found in the CL-Windcon EU project deliverable 3.5 [14].

3. Results

From the eight cases that were analysed, three cases in operational modes are shown here (the other five were excluded due to their similarity). From these, the first two are related to the wake redirection technique, or yaw misalignment, the next one is based on induction variation through de-rating technique while the wind turbines have a fixed yaw misalignment. Next subsections are divided depending on objectives in cost function during optimization process.

3.1. Maximizing AEP when the WT are located at 5D distance from each other (C1 case)

This case was done for the 3 WT configuration (Figure 1), where the WT are spread with a distance of 5D. Its schematics are shown on the Figure 3 (where a 600 second averaged solution is compared without and with flow misalignment optimization, B1 vs C1).

For that purpose, FLORIS model was optimised forcing the genetic algorithm to find a solution based on the yaw misalignment technique (no option for de-rated wind turbines at this case). The optimization brings yaw misalignment angles from first to third WT of $-19.0^\circ$, $-14.4^\circ$, and $+0.4^\circ$ (at this configuration,
negative values indicate that turbine faces more towards south, and the positive values that faces towards west). The predicted gain in power, when compared the optimised solution of FLORIS (C1) with the baseline case (B1) was of 15.8%.

The next step was to validate this static gain prediction in a more realistic scenario. For that SOWFA (C1) vs. SOWFA (B1) was compared and it can be seen graphically in the Figure 4. This comparison reduces the predicted gain but still reaches a positive gain of wind farm generated power of 5.9%. The explanation for this increment in power is related to the increase in average wind speed in the second and third wind turbines, which is show on the top of Figure 4. WT1 remains constant because the applied yawing angle of -19° was not enough to bring the WT in SOWFA simulation outside of the maximum power at the considered dynamic wind speed.

Furthermore, damage equivalent load of the flap-wise moment is also reduced at this case, despite it was not considered at the optimisation function. Due to the yawing of the upstream wind turbines, wake is redirected away from the downstream turbine. Moreover, in SOWFA simulations the wind speed increment is seen only for WT3 while in FLORIS there's an increment also for WT2 due to wake recovery model. The flow in the downstream wind turbines also have less turbulence intensity (see Table 1) in FLORIS simulations, dealing in minor DEL. In SOWFA this reduction is smaller than for FLORIS but still provides a gain in the direction that was desired.

Figure 3: Flow field computed with SOWFA of the B1 and C1 cases, where the AEP maximising strategy was adopted through flow redirection. Contours of averaged (600s) wind speed are shown.
3.2. Maximizing AEP when the WT are located at 7D distance from each other (C2 case)

This case was simulated using a 3 WT column of the 9WT configuration, where the WT are spread but aligned with a distance of 7D. Its schematics are shown on the Figure 5 (where a 600 second averaged solution is compared without and with flow misalignment optimization). As a baseline, B2 or B6 identical cases should be considered, the column at the bottom of the Figure 5.

Figure 4: Wind speed, turbulence intensity, generated power, and DEL values for FLORIS & SOWFA computations on AEP maximizing strategy (C1 vs. Baseline).
The optimization in this case brings yaw misalignments angles from first to third WT of -18.4°, -10.1°, and +0.1°. In this case, the optimum yaw angles that have found the optimiser are a bit smaller than for the C1 case (see at subsection 3.1), since at this WF the wind turbines are more spaced (7D vs. 5D), and therefore the yaw misalignment could be more relaxed to redirect effectively the flow, if compared to the C1 case. On the other hand, it can be seen in Figure 6 that the second wind turbine has a larger energy production at C2, when compared with C1 due to a 2 diameter larger recovery of the flow. The predicted gain in power, when compared the optimised solution of FLORIS (C2) with the baseline case (B2) is of 10.4%.

Analysing SOWFA predictions, the gain has similar order of magnitude, being of 13.4% which is highly influenced by the third turbine generated power behaviour, since FLORIS and SOWFA have opposite trend at this case, which is also in the direction of a larger decrease of wind speed for FLORIS prediction than the SOWFA one at the last wind turbine. The turbulence intensities have increased similarly at last wind turbines for FLORIS and SOWFA, and in connection with them, both show a larger DEL than the baseline cases for this power optimisation strategy. However, the increase of the DEL in SOWFA in much larger than the one observed with FLORIS, keeping however the trend between the both simulation tools.
3.3. Reducing the worst DEL while keeping AEP as high as possible, when the WT are yawed -5° and located at 7D distance from each other (C7 case)

This case was also simulated using a 3 WT column of the 9WT configuration, where the WT are spread with a distance of 7D and all 3 wind turbines were with a fixed yaw of -5° (simulating a yaw error or a mismatch on a flow direction prediction).

Its schematics are shown on Figure 7. The optimization here was carried out based on inflow induction (or de-rating), from 1st to 3rd WT – 95%, 85%, & 95.

Figure 6: Wind speed, turbulence intensity, generated power, and DEL values for FLORIS & SOWFA computations on AEP maximizing strategy (C2 vs Baseline).
Figure 7: Flow field computed with SOWFA of the B7 and C7 cases, where DEL minimizing strategy while keeping the AEP as high as possible was adopted through derating. Contours of averaged (600s) wind speed are shown.

Figure 8: Wind speed, turbulence intensity, generated power, and DEL values for FLORIS computations on DEL minimizing strategy while keeping AEP high (C7 vs Baseline).
The optimization for this case was to minimize maximum DEL of the flap-wise bending moment while keeping total generated power in the wind farm (as high as possible). Since there are two variations for this configuration, the yaw angle and the de-rating of the wind turbines, due to its much more affordable computing time, FLORIS was computed as a baseline case shown previously (with no yaw misalignment and neither de-rating, \textit{B7\_FLORIS}) and also with -5\(^\circ\) of yaw misalignment but without de-rating to decouple the differences, \textit{B7\_FLORIS\_yaws5deg}. FLORIS optimised predictions show a decrease on DEL with respect to the B7\_yaw5 of 26.2\% and the baseline case of 22.6\%. This shows that the -5\(^\circ\) of yaw misalignment applied for these cases increases the DEL by 5\%, as can be seen in Figure 8. Regarding the total generated power, there is an increase of 1.6\% of the optimised case with respect to the baseline case (B7), while keeps the value similar to the B7\_yaw5, which highlights the larger influence of wake steering respect to the inflow induction technique regarding the WF power output.

Figure 9: Wind speed, turbulence intensity, generated power, and DEL values for FLORIS & SOWFA computations on DEL minimizing strategy while keeping AEP high (C7 vs Baseline).
In Figure 9 is shown the dynamic solutions comparisons provided by SOWFA, where the DEL gain is reduced from 22.6% to 13.7% which still is significant, with a penalty in generated power of 4.0% loss for SOWFA, while as mentioned before, FLORIS sees a gain of 1.6%. The trend between SOWFA and FLORIS shows a better agreement, locally and globally, than at previous cases probably caused by a smaller yaw misalignment.

4. Conclusions
From the overall results, the wake steering approach (yaw misalignment) is promising in terms of maximising the total power. The studied cases show an improvement of around 6 to 15%. Furthermore, in full wake situation, even the loads could be reduced with this strategy. But this must be taken with care since for one of the cases a reduction of 6-11% was observed while for the other had increments of 5 to 50% on DEL.

On the other hand, significant discrepancies were aroused between SOWFA and FLORIS simulations in partial wake conditions. Further investigation is needed to include a numerical or experimental based FLORIS parameters tuning for partial wake conditions, which affect directly position where wake centre impingement in downstream turbines. Similarly, FLORIS flow prediction at 7D differs more than at 5D with respect to SOWFA, as it also occurs when the yaw misalignment is larger. Despite at the time of carrying out this work was not available, experimental data, wind tunnel data or SOWFA data generated within the CL-Windcon project, it is now publicly available if requested to clwindconftp (at) cener.com that could be used for the improvement or calibration of the modified FLORIS model.

The flow induction strategy (de-rating) reduces the damage equivalent load (DEL) for the flap-wise moment of the blade, but it showed low capability to increase the overall power production. It could be however a very useful technique but also further analysis is needed in terms of how it could affect in the LCoE model in order to balance the reduction in loads and power, when this strategy is applied.

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References

[1] A. C. Kheirabadi and R. 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, 2019.

[2] S. Boersma, et al. 2017 American Control Conference Seattle 24-26 May (IEEE/IFAC (IEEE)) A tutorial on control-oriented modeling and control of wind farms

[3] E. Bossanyi. Combining induction control and wake steering for wind farm energy and fatigue loads optimisation. In: Journal of Physics: Conference Series. Vol. 1037. 3. 2018, p. 032011.

[4] D. A. Juangarcia, I. Eguinoa, and T. Knudsen. Derating a single wind farm turbine for reducing its wake and fatigue. In: Journal of Physics: Conference Series. Vol.1037. 3. IOP Publishing. 2018, p.032039

[5] CL-Windcon, -Closed Loop WIND farm CONtrol-. H2020 CL-Windcon project website, www.clwindcon.eu, 2019.

[6] F. Campagnolo, et al.: Wind Tunnel Testing of Wake Control Strategies, in: Proceedings of the American Control Conference, Boston, MA, USA, 513–518, 2016

[7] J. Bartl, et al.: Wind tunnel study on power output and yaw moments for two yaw-controlled model wind turbines, Wind Energ. Sci., 3, 489–502, https://doi.org/10.5194/wes-3-489-2018, 2018.

[8] P. Fleming, et al.: Initial results from a field campaign of wake steering applied at a commercial wind farm – Part 1, Wind Energ. Sci., 4, 273–285, https://doi.org/10.5194/wes-4-273-2019, 2019.

[9] M. Aparicio-Sanchez, I. Eguinoa and D. Astrain-Juangarcia. Estimation of partial wake loads for wind farm control design”. In: Wind Energy Science Conference (WESC), Cork, Ireland, 17-20 June 2019. DOI: 10.5281/zenodo.3365913.

[10] FLORIS - FLOW Redirection and Induction in Steady-state, 2019 Available at: https://github.com/NREL/floris

[11] J. Annoni, et al. (2018). Analysis of Control-Oriented Wake Modeling Tools Using Lidar Field Results. Wind Energ. Sci. Discuss., 2018, 1-17. doi:10.5194/wes-2018-6

[12] P. Fleming, et al. Evaluating techniques for redirecting turbine wakes using SOWFA. Renew Energy, vol: 70 pp: 211-218, 2014

[13] M. Churchfield, and S. Lee. NWTC design codes (SOWFA). Available at: http://wind.nrel.gov/designcodes/simulators/SOWFA; 2013.

[14] INNWIND. D1.21: Definition of the reference Wind Turbine-Analysis of Rotor Design Parameters. 2013. URL: http://www.clwindcon.eu/public-deliverables/

[15] M. Bastankhahand, and F. Porté-Agel. Experimental and theoretical study of wind turbine wakes in yawed conditions. In: Journal of Fluid Mechanics 806(2016), pp. 506–541.

[16] CL-Windcon. D3.5: Demonstration of combined turbine/farm level controls by simulations. Technical Report. CL-Windcon, 2019. URL: http://www.clwindcon.eu/public-deliverables/.

[17] J. Jonkmanand, and M. Sprague. FAST v8 and the transition to OpenFAST. Tech. rep. Golden, CO: NREL, 2017. URL:https://nwtc.nrel.gov/OpenFAST.

[18] NREL. SOWFA repository from NREL, Master branch, 12th December 2018. URL:https://github.com/NREL/SOWFA.