Actuator Line Model simulations to study active power control at wind turbine level

Andrés Guggeri, Martín Draper, Bruno López and Gabriel Usera
Universidad de la República, Facultad de Ingeniería, Instituto de Mecánica de los Fluidos e Ingeniería Ambiental, Julio Herrera y Resissig 565, Montevideo, Uruguay
E-mail: aguggeri@fing.edu.uy

Abstract. Wind energy is expanding rapidly worldwide, being horizontal axis wind turbines the technology of larger installed capacity. Modern multi-MW wind turbines have a torque controller and a collective pitch controller to control their power output, particularly when the wind speed is greater than the rated one, or when it is required to down-regulate the turbines’ production. In this work we show results of a validated numerical method [1], based on a Large Eddy Simulation-Actuator Line Model framework, applied to evaluate active power control on a real 7.7MW [2][3] onshore wind farm of Uruguay. We describe the implementation of these controllers in the caffa3d solver [4] and present the methodology we applied to obtain the controller parameters, such as the gain scheduling of the closed loop Proportional-Integral pitch controller. For validation, the simulation results are compared with 1Hz data obtained from the Supervisory Control and Data Acquisition System of the wind farm, focusing on the temporal evolution of the following variables: wind velocity, rotor angular speed, pitch, aerodynamic and electric torque and power. We analyze the Active Power Control response under different de-rate signals, both constant and time-varying, and subject to two wind profiles and two different wind directions, one of them with significant influence of wakes on one wind turbine. The dependence of the wake on the de-rate value is also evaluated, assessing the streamwise velocity component and the turbulence intensity in the wake.

1. Introduction
There has been a significant development of methods and tools for performing high fidelity simulations of wind flow through wind turbines applied to real wind farms, providing useful data for the stages of design or operation of wind farms, within the Large Eddy Simulation (LES) alongside with Actuator Models, such as the Actuator Disk (ADM) or the Actuator Line for representing the wind turbines rotors Model (ALM) [5] [6] [7] [8] [9] [10] [11][12][13]. Recently, the authors presented an application of the LES-ALM methodology, simulating a real wind farm under various wind conditions [2], validating the results with Supervisory Control and Data Acquisition System of the wind farm, focusing on the temporal evolution of the following variables: wind velocity, rotor angular speed, pitch, aerodynamic and electric torque and power. We analyze the Active Power Control response under different de-rate signals, both constant and time-varying, and subject to two wind profiles and two different wind directions, one of them with significant influence of wakes on one wind turbine. The dependence of the wake on the de-rate value is also evaluated, assessing the streamwise velocity component and the turbulence intensity in the wake.

As in many parts of the world, in Uruguay there has been a significant increase in the penetration level of wind energy in the utility power grid, reaching an installed capacity of over 1500MW, representing 70% of the peak power demand [15] [16]. This fact, together with the uncertainty of the power output of a wind farm, caused among other factors by the variability of the wind flow within a wind farm, makes it more difficult for the transmission system operator (TSO) to regulate the power grid. These facts motivate research about wind farms’ ability to...
provide grid balancing services, as primary and secondary frequency regulation, as there will be an increasing need for this ancillary service. One method of providing this service is active power control (APC), in which the wind farm should track a power reference signal provided by the TSO, with the objective of helping to balance the total power generated with the power consumed on the grid [17][18].

The implementation of the wind turbine torque and pitch controllers in the CFD code caffa3d [4][19], with the aim of regulating active power, was presented in [20]. In that work, an arrangement of two semi-aligned wind turbine models, operating above-rated wind speed, was simulated, comparing the numerical results with data obtained from a state-of-the-art wind tunnel campaign. Continuing with this line of research, the aim of the present paper is to show numerical results of the operation of wind turbines under APC. Some results are compared with high frequency SCADA data considered at specific dates, in order to validate them. With this purpose the 7.7MW onshore wind farm 'Libertad', the same as used in [2][3], was simulated, considering two atmospheric boundary layers (ABL) as inflow condition as well as two different wind directions, one of them showing strong interactions between the turbines due to their wakes. The caffa3d solver is used to simulate the wind flow, while representing the wind turbines with the Actuator Line Model (ALM) [21].

The rest of this paper is organized as follows: the next Section presents the simulated wind farm Libertad; Section 3 gives details of the simulation setup, such as the computational domain, the grid characteristics and the inflow conditions considered at the inlet. Section 4 describes the implementation of APC control, including the methodology to estimate the pitch-controller gains, based on the one presented by NREL 5-MW reference wind turbine [22]. In Section 5 the numerical results are shown and discussed, ending with conclusions and future work in Section 6.

2. Libertad wind farm

The simulated wind farm is Libertad (Figure 1), the one described in [2][3], a 7.7MW onshore wind farm located in the south of Uruguay, which has been operated since August 2014 by the Uruguayan company Ventus (www.ventusenergia.com). It consists of four Vestas V100 wind turbine (WT) generators, with rated rotor speed ($\omega_0$) of 14.9RPM, two with rated power ($P_{\text{rated}}$) of 1.9MW (WT1 and WT2) and two of 1.95MW (WT3 and WT4), all four with a hub height of 95m and a rotor diameter of 100m. The farm has a meteorological mast with anemometers at 95m, 80m and 60m, and wind vanes at 93m and 58m height. The terrain surrounding the wind turbines is mostly flat, with no significant slopes according to annex B of IEC 61400-12-1 Standard.

Data acquired by the SCADA
system of the turbines is recorded on a 1Hz frequency basis, at selected periods of time and compared with the simulation’s results. For this work we consider the temporal evolution of the following 5 signals of each turbine: electric power, aerodynamic and electric torque, wind speed, rotor angular speed and blades pitch-angle. Also, ten-minutes mean and standard deviation of several signals are available for the whole period of operation of the wind farm. The mean free wind velocity and direction is computed from the ten-minutes averages measured at the meteorological mast at the same time periods. It is worth mentioning, that the electric and aerodynamic torque are not directly measured by the SCADA system, but we estimate them according to Eq. (1) and Eq. (3), considering the electric power and rotor speed as measured signals.

3. Numerical Setup
Caffa3d.MBRi [4][19] is an open source, finite volume (FV) code, second order accurate in space and time, parallelized with Message Passage Interface (MPI), in which the domain is divided in unstructured blocks of structured grids. The ALM has been implemented in the code [23] to represent wind turbines rotors in the simulations. For further information about the code and its application in wind energy, please see [2][3][24][25][26][27].

The size of the computational domain is 3km by 2km by 0.75km, in the stream-wise, span-wise and vertical direction, respectively. The domain is uniformly divided into 144 x 128 grid cells in the stream-wise and span-wise directions, respectively while a stretched grid with 80 grid cells is used in the vertical direction. This spatial resolution implies a cell size of 20.8m by 11.7m, while in the vertical direction, 19 grid cells cover the rotor diameter [3].

Two different ABL wind profiles, which are obtained from precursor simulations as described in [2][3], are considered at the inlet of the domain. The span-wise average of the mean stream-wise velocity component at hub height ($V_{HH}$) is 9m/s and 12.6m/s respectively, and the stream-wise turbulence intensity is 9.1% and 7.8%, respectively. The inlets are referred to as 9m/s and 12m/s in future sections of this work.

The Crank-Nicolson scheme is used to advance in time, with a temporal step set to 0.25s and the scale-dependent dynamic Smagorinsky model is used to compute the subgrid scale stress. To represent the wind turbine rotor, the ALM is used the same way as in [3]. The presence of the tower and nacelle are taken into account through drag coefficients, in a similar approach as presented in [6]. The chord and twist angles as well as the airfoil’s data, and the relationship between the rotational speed of the rotor and its torque are taken from [3]. At each time step of the simulation, the rotational speed is obtained from the rotor momentum balance equation (1), where $M_{gen}$ is the generator torque, $\omega$ is the angular speed of the rotor at the current time step, $I$ is the sum of the inertias of the rotor, shaft and generator, referring to the low-speed side. $\Delta t$ corresponds to the temporal step and $\omega_{t-1}$ accounts for the rotational speed of the previous time step.

$$I \frac{d\omega}{dt} = M_{aero} - M_{gen} \Rightarrow \omega_t = \frac{(M_{aero} - M_{gen})}{I} \Delta t + \omega_{t-1}$$

The inertia was estimated taking into account the rotor diameter, the material it is made of and the wind turbine rated power [28], obtaining a value of $I = 1.72 \times 10^7 kgm^2$. Finally, the aerodynamic and electric power are calculated as the rotational speed multiplied by the shaft aerodynamic torque and the generator torque, Eq. (2) and Eq. (3) respectively.

$$P_{aero} = M_{aero} \omega$$

$$P_{electric} = M_{gen} \omega$$
4. Power controllers
A power control system was implemented in the code, in the same manner as described in [20], which in turn is based on the NREL 5MW reference wind turbine [22]. It consists of two control systems which work independently, the generator torque \( M_{\text{gen}} \) and the blade-pitch \( \theta \) controllers.

4.1. Generator torque controller
At the below-rated rotor speed range, referred to as region 2, the objective is to maximize power capture [29]. When the rotor speed is below \( 0.9 \times \omega_0 \), being \( \omega_0 \) the rated speed, the equation that governs the generator torque controller is:

\[
M_{\text{gen}} = K \omega^2 \tag{4}
\]

\( \omega \) accounts for the instantaneous rotor angular speed and \( K \) is a constant that optimizes the power extraction from the wind and which depends on the aerodynamics and geometrical characteristics of the rotor, defined as in Eq. (5), where \( \rho \) is the air density, \( A \) is the area swept by the rotor, \( R \) is the rotor radius, \( CP_{\text{opt}} \) is the optimal power coefficient, computed with the Blade Element Momentum method, and \( \lambda_{\text{opt}} \) is the optimal tip speed ratio.

\[
K = \frac{1}{2} \rho AR^2 \frac{CP_{\text{opt}}}{\lambda_{\text{opt}}^3} \tag{5}
\]

This constant was estimated from the turbines ten-minutes SCADA data, by computing the mean angular speed and mean electric torque at wind speed bins, considering only the below-rated range of wind speed. The obtained value was \( 4.38 \times 10^5 \text{W}(\text{rad s})^2 \), which differs 25% from the theoretical value, obtained based on the BEM method. In the simulation, the SCADA-obtained value of \( K \) was used, as we think it was a better representation of the real operation of the turbine, based on real data.

At the above-rated wind-speed range, region 3, the goal is to ensure the power output is at the desired level, for example at rated power or a given fraction of it, regardless of the fluctuations that the rotor speed may have. The conditions to be at region 3 are either that A) \( \omega \) is greater than \( \omega_0 \), or B) the pitch angle is greater than a minimum value, which in our simulated V100 model is 1°. At region 3, \( M_{\text{gen}} \) is computed according to equation (6). \( M_{\text{gen}} \) has an upper bound of \( \text{SatFactor} \times M_{\text{rated}} \), being \( \text{SatFactor} = 1.1 \) a saturation factor and \( M_{\text{rated}} \) the rated torque (Eq. (7)) [22].

\[
M_{\text{gen}} = \frac{P_{\text{rated}}}{\omega} \tag{6}
\]

\[
M_{\text{rated}} = \frac{P_{\text{rated}}}{\omega_0} \tag{7}
\]

When none of the conditions defining region 3 are fulfilled, and \( \omega \) is between \( 0.9 \times \omega_0 \) and \( \omega_0 \), then \( M_{\text{gen}} \) is computed as a linear interpolation between \( M_{\text{rated}} \) and \( M_{\text{optimal}} \), according to equation (8), where \( M_{\text{optimal}} \) is computed as \( K \times (\omega_0 \times 0.9)^2 \). This region is called 2.5, and is a transition between regions 2 and 3.

\[
M_{\text{gen}} = M_{\text{rated}} + \frac{(M_{\text{rated}} - M_{\text{optimal}})}{(0.1 \times \omega_0)} \times (\omega - \omega_0) \tag{8}
\]
4.2. Blade-pitch controller
This controller operates only at region 3, and its objective is to regulate the generator speed, and thus the rotor angular speed, at the rated operation point. At region 2, the pitch-angle of the blades is fixed at its minimum value, $-2^\circ$ in order to optimize the power extraction from the wind. This minimum value was obtained from the 10-minute mean of the pitch signal, with data corresponding to the operation at region 2 only. At regions 2.5 and 3, the rotor-collective blade-pitch-angle values are computed using a proportional-integral (PI) gain-scheduled control on the speed error ($\Delta \omega$) between the current WT speed and the rated speed ($\omega_0$) [22], as shown in Eq. (9).

$$\theta = K_P \Delta \omega + K_I \int_0^t \Delta \omega dt$$

(9)

where \(\theta\) is the pitch angle and \(K_I\) and \(K_P\) account for the proportional and integral gains, respectively. The integral term accounts for the accumulated error over time, and in the simulations it is computed by simply adding \(\Delta \omega\) to its previous value, in each time step. By linearizing Eq. (9), the PID-controlled rotor-speed error respond as a second-order system with a natural frequency $\omega_{\phi n}$, and damping ratio, $\zeta_{\phi}$. Based on [22], $K_I$ and $K_P$ are computed as described in equation (10).

$$K_P = \frac{2 I.\omega_0 \zeta_{\phi} \omega_{\phi n}}{-\partial P/\partial \theta}; \quad K_I = \frac{I.\omega_0 (\omega_{\phi n})^2}{-\partial P/\partial \theta}$$

(10)

The blade-pitch sensitivity, $\partial P/\partial \theta$, is an aerodynamic property of the rotor that depends on the wind speed, rotor speed, and blade-pitch angle. We estimated it for the above-rated wind speed range, considering the rated rotational speed, and the optimal pitch angle, which implied rated power. With the BEM method, we computed the difference in aerodynamic power ($\delta P$) by considering small variations of the pitch angle ($\delta \theta$) around its optimal value, and then calculated the blade-pitch sensitivity as the ratio between $\delta P$ and $\delta \theta$. As suggested in [22] we invoke the frozen-wake assumption, in which the induced wake velocities are held constant while the blade-pitch angle is perturbed. To validate this methodology we also computed it for the 5MW reference wind turbine, taking into account the published data in [22]. Figure 2 displays these results, showing very good agreement with the NREL turbine.

As it can be observed, the pitch sensitivity varies nearly linearly with blade-pitch angle, so a linear fit was computed, obtaining:

$$\frac{\partial P}{\partial \theta} (\theta = 0) = -1.025 \times 10^7 \frac{W}{\text{rads}} \quad \text{and} \quad \theta_{KK} = 11.8$$

(11)
where $\theta_{KK}$ is the blade-pitch angle at which the pitch sensitivity has doubled from its value at ($\theta = 0$). The natural frequency value is the same as the one considered in [22], but we chose a lower damping value than what was recommended, aiming for the controller response to be similar to what we observed in the 1Hz SCADA data. We chose the values of $\omega_{\text{ref}} = 0.7$ and $\zeta_\phi = 0.1$. Considering these values, the obtained gains are: $K_P(\theta = 0) = 0.314$ s$^{-1}$; $K_I(\theta = 0) = 0.942$. The gain-correction factor, which multiplies each gain and depends on the blade-pitch angle, is computed as:

$$GK(\theta) = \frac{1}{1 + \frac{\theta}{\theta_{KK}}}$$

(12)

Based on SCADA data and [22], the pitch-angle is limited by saturation values, of [-2°, +90°], and its maximum rate of change is set to 8°/s. This PI controller ensures that $\omega$ fluctuates around its reference value, and thus the active power output fluctuates around the active power rated value, $P_{\text{rated}}$.

### 4.3. Active Power Control

If the wind speed is high enough, a way to track a power reference signal given by the TSO can be to de-rate the wind turbines from their rated power. To accomplish this, three de-rating modes are proposed in [17][18]: 1) capturing a fraction of the rated power; 2) maintaining a constant power reserve, as a fraction of the rated power; and 3) producing a fraction of the available power. In the present work only the first mode is considered. For the other two modes a estimation of the available power is required. For the selected mode, the generator torque controller is the same as presented in sub-section 4.1, but applying an upper bound to $M_{\text{gen}}$ of $Sat_{\text{Factor}} \times M_{DR}$, instead of $Sat_{\text{Factor}} \times M_{\text{rated}}$. $M_{DR}$ is computed considering the de-rating command ($DR$) required by the TSO (Equation 13).

$$M_{DR} = \frac{P_{\text{rated}}}{\omega_0} \times DR$$

(13)

This mode is simply an extension of the controllers presented in the previous sub-sections 4.1 and 4.2, where the wind turbine, when it is operating at region 3, limits its power production to the required value when the wind speed is high enough, regulating the aerodynamic torque with the blade-pitch controller. When there is not enough wind to generate the required power, the wind turbine operates at region 2, optimizing the power extraction from the wind by regulating the rotor speed with the generator torque controller.

In the simulations $DR$ can be a constant signal or vary over time, but it needs to be specified for each wind turbine individually, prior to the execution of the simulation. In the near future it is planned to implement a wind plant global controller, to coordinate the actions of the individual turbines, accounting for the interactions of wakes based, for example, on the available power of each turbine, as in [30] or [31].

### 5. Results and discussion

In this section the results of the simulations are presented, focusing on the temporal evolution of the controller signals: aerodynamic and electric torque, power, rotor speed, wind speed and pitch angle. In the first place, we performed simulations without considering any de-rate commands applied to the turbines. Numerical results of selected wind turbines are compared to 1Hz SCADA data on a specific period, in order to validate the controllers. Secondly, we present only numerical results, considering several de-rate signals, another wind speed profile, as described in Section 3, and different wind directions, to evaluate the effect of wake interaction in the power control. Also results of the total production of the wind farm are shown, comparing 3 constant de-rate signals.
Finally, a single wind turbine simulation was performed, without considering topography, to evaluate the effect of de-rating a wind turbine on its wake.

5.1. Controllers validation

Figure 3a depicts the temporal evolution of 1200 seconds simulation and SCADA data of WT3. The SCADA data corresponds to a period starting on the 23rd November 2017 at 12.30hs, when the average wind speed and wind direction were 12.5m/s and 264° respectively, according to the meteorological mast measurements. Figure 3b shows the histograms of occurrence of the same signals. The wind direction considered at the simulation was 250°. It is worth noting that in none of these directions (250° and 264°) the wind farm turbines are affected by the wake of another turbine, and as the wind speed was similar in both periods, no significant differences were noticed in the operation of the turbines.

Figure 3: Comparison between simulation results and high frequency SCADA data, of WT2 on 5th May 2018 16.00hs. a) Raw time series, the gray area indicates transients effects at the beginning of the simulations. b) Histograms of occurrence [%].

The shown signals are wind speed, rotor angular speed, pitch angle and aerodynamic and
electric power. The simulated wind speed signal corresponds to the value at the cell located at the inlet of the domain, at hub height and just upstream of the corresponding wind turbine position; the SCADA signal is the velocity measured at the wind turbine nacelle. For all the signals, we obtained good agreement between the mean values of the simulation and the SCADA data. For the velocity, pitch and torque histograms, a somewhat different shape can be observed, being narrower and with a higher peak in the simulation. This can be explained by the fact that, in the simulation, the turbulence intensity is lower than in the real event, and also because in the simulation we considered only a single wind direction, while the SCADA data accounts for a range of wind directions.

It can also be noticed that the oscillations in the aerodynamic torque are significantly larger than in the electric torque, both for the simulation and SCADA variables. By computing the signals spectrum (not shown here), peaks at a frequency of 0.75Hz can be observed in the simulation signal, which is equal to 3 times the frequency associated to $\omega_0$, and is due to the passage of the blades in front of the tower. The difference between the electric and aerodynamic torque is what causes the acceleration and deceleration of the rotor. Looking at the time series, the pitch signals take values above the minimum during the entire 1200s period, which shows that pitch-controller is operating to regulate the power output. Significant peaks can be observed in the electric power SCADA signals during a few seconds, but this paper does not focus on them. We assume they are caused by the operation of electric components (e.g. the inverter or the generator), which we do not consider in our simulation. The gray zone at the beginning of the time series represents the first 200 seconds, and indicates the period affected by transient effects, such as the development of the wakes, due to the sudden inclusion of the turbines in the simulations.

5.2. Active Power Control at wind turbine level

We performed simulations considering several de-rate values for each turbine, another wind direction and a different ABL velocity profile at the inlet. The figures in this Section depict numerical results of the temporal evolution of WT3 and WT4 signals. These turbines were chosen because WT3 performance was clearly affected by the WT4 wake in the 147° wind direction simulation (see Figure 1). Figure 4 compares results of WT3 operation at 250° and 147° with wind speed at the inlet and hub height equal to 12m/s. Two constant de-rate commands are considered: 100% (equivalent to rated power, Figure 4a) and 60% (Figure 4b). As there is enough wind to reach rated power for both wind directions, the required levels of electric power can be accomplished, as it can be seen in the bottom subplot of the figure, while the rotor speed oscillates around its rated value in all cases. Regarding the pitch angle, higher values are observed at wind direction 250° than at 147° because in the latter WT3 is in the wake of WT4 and, therefore, with less available power. Also higher pitch values are adopted for de-rate command 60% than for 100%, for the same wind direction (e.g. 250°), as it is expected.

Figure 5 shows the operation of WT3 and WT4, respectively, at 147° for the other wind profile described in Section 3, with a span-wise averaged velocity of 9m/s at hub height. 6 de-rate commands are considered for both wind turbines: 100%, 90%, 80%, 70%, 60% and 50%.

In the case of WT3, which for this wind direction is in the wake of WT4, it is clearly noticed that the turbine does not reach the required de-rated power, except for some moments with DR=50% and DR=60%, when there is enough available power in the wind flow. Also, it can be noticed that the power production of WT3 decreases with higher de-rate values of WT4, as there is less available power due to its wake. The angular speed is regulated, and the pitch angle is kept constant at its minimum value most of the time. In the case of WT4, the required power is reached in all de-rate levels, although for DR=100%, 90% and 80% there are periods where the angular speed does not reach rated value, and thus the generator torque controller operates at region 2, regulating rotor speed to optimize the power extraction from the wind.
Figure 4: WT3 operation at \( \text{Dir} = 147^\circ \) and \( \text{Dir} = 250^\circ \); \( V_{HH} = 12 \text{ m/s} \) at inlet and hub height.

Again, for lower de-rate commands, higher pitch angles are adopted. In these situations, the transient effects at the beginning of the simulation can be clearly observed in the angular speed, pitch and power signals, showing the downwind wake propagation from WT4.

Figure 6 depicts the total wind farm power output, comparing three de-rate levels, for case \( \text{Dir} = 147^\circ \) and \( V_{HH} = 9 \text{ m/s} \). The de-rate commands are uniformly distributed to each turbine, regardless of their capacity to reach the desired power. As it can be seen, only in the case of \( \text{DR}=60\% \) the required level is reached most of the time. In the other simulations, the required power is not reached, mainly because WT3 does not reach its required power as it is strongly affected by the WT4 wake. These results show the need to implement a global wind farm controller, with the purpose of assigning de-rate commands based on the available power of each individual wind turbine, especially when there are turbines operating in the wake of others. Different types of global controllers were studied in [30] and [31], where they evaluate the effect of considering an open-loop or a closed-loop global controller, on the total power.

The response of the controller under different time-varying de-rate signals was also evaluated: a step type signal, which changes its DR value every 300s, from 80%, 50%, 100%, to 70%; and a sinusoidal signal with frequency \( 4 \times 10^{-3} \text{ Hz} \), which oscillates between \( P_{\text{rated}} \) and \( 0.4 \times P_{\text{rated}} \), but those results are not shown here. Although the aerodynamic power presented significant oscillations, the electric power followed the required signal shape. It is worth mentioning that
Figure 5: WT3 and WT4 operation at $\text{Dir} = 147^\circ$; $V_{HH} = 9\text{ m/s}$ at inlet and hub height.

Figure 6: Power production of the wind farm operating at 3 different de-rate commands, at $\text{Dir} = 147^\circ$; $V_{HH} = 9\text{ m/s}$ at inlet and hub height.

the electric power presented minor oscillations, of around 5%, which can be observed in Figure 3a, with a zoomed scale. In future work it is planned to evaluate the response of a whole wind
farm subject to APC signals that are typically required by the TSO, in order to provide ancillary services, e.g. contributing to the system frequency regulation.

5.3. Wake characteristics of a down-regulated wind turbine
Finally, the dependence of the velocity deficit and turbulence intensity on the wake, with respect to the de-rate value, was evaluated. For this, we simulated the operation of a single wind turbine subject to the ABL profile with 9m/s at hub height on flat terrain. Figure 7 depicts profiles of the mean stream-wise velocity component \( (U) \) and turbulence intensity of the stream-wise velocity component \( (TI_U, \text{ see Eq. (14)}) \), in a horizontal plane at hub height.

\[
TI_U = \frac{\sigma_u}{\langle U \rangle}
\]

in which \( \sigma_u \) is the standard deviation and \( \langle U \rangle \) the mean value of the stream-wise velocity component, respectively. As expected, the wake velocity deficit increases with higher de-rate commands, as the turbine extracts more power from the wind flow, and causes higher turbulence intensity. The maximum turbulence intensity is obtained between 3D and 5D from the rotor plane, similar to the results presented in [1][25][6].

Figure 7: \( \langle U \rangle \) (left) and \( TI_U \) (right) horizontal planes at hub-height. Single wind turbine operating with 3 different de-rate commands. \( V_{HH} = 9m/s \) at inlet and hub height.

6. Conclusions and future work
A Large Eddy Simulation framework with the Actuator Line Model to represent wind turbine rotors has been used to simulate the operation of a 7.7MW onshore wind farm. The simulations
considered two different ABL wind profiles, with hub height velocities close to or higher than the rated one, and also considered two different wind directions, one of them with strong interaction between wakes and wind turbines. A closed-loop collective-pitch and a torque controller was implemented in the CFD code based on the one presented in [22]. The results of the simulations were compared to high frequency data (1Hz) from the SCADA system, obtaining good agreement, both regarding the mean values and the temporal evolution of the signals.

The response of the controller subject to different de-rate values, both constant and time-varying, was evaluated. We show that when there is enough wind power in the flow, the individual wind turbines can follow the required signal, but when it comes to the total wind farm power output, it fails to accomplish what is required because of the interaction between wakes and turbines. These results show the necessity of implementing a global controller, which takes into account the available power of each individual wind turbine. We plan to work on this in the near future. In this sense, a preliminary evaluation of the dependence of the wake shape on the de-rate signal, was performed, and further investigation on this subject will be useful to determine the available power of each individual turbine and of the whole wind farm.

Besides, the use of GPU computing platform as considered in [32] is now being expanded to the full flow solver, using a dual CUDA/OpenCL syntax on top of the coarse MPI parallelization. This approach achieving speedups of up to 30x with respect to the CPU only solver and will next be extended to the wind turbine module routines.

References

[1] M.Draper, A.Guggeri, M.Mendina, G.Usera, and F.Campagnolo. Journal of Wind Engineering & Industrial Aerodynamics A Large Eddy Simulation-Actuator Line Model framework to simulate a scaled wind energy facility and its application. 182(September):146–159, 2018.
[2] A.Guggeri, D.Slamovitz, M.Draper, and G.Usera. A High-Fidelity Numerical Framework For Wind Farm Simulations. In Tenth International Conference on Computational Fluid Dynamics (ICCFD10), 2018.
[3] A.Guggeri, M.Draper, and G.Usera. Simulation of a 7.7 MW onshore wind farm with the Actuator Line Model. Journal of Physics: Conference Series, 854(1), 2017.
[4] M.Mendina, M.Draper, A. P.Kelm Soares, G.Narancio, and G.Usera. A general purpose parallel block structured open source incompressible flow solver. Cluster Computing, 17(2):231–241, 2014.
[5] F.Porté-Agel, Y. T.Wu, H.Lu, and R. J.Conzemi. Large-eddy simulation of atmospheric boundary layer flow through wind turbines and wind farms. Journal of Wind Engineering and Industrial Aerodynamics, 99(4):154–168, 2011.
[6] Y.-T.Wu and F.Porté-Agel. Large-Eddy Simulation of Wind-Turbine Wakes: Evaluation of Turbine Parametrisations. Boundary-Layer Meteorology, 138(3):345–366, 2010.
[7] F.Porté Agel, Y.-t.Wu, and C.-h.Chen. A Numerical Study of the Effects of Wind Direction on Turbine Wakes and Power Losses in a Large Wind Farm. pages 5297–5313, 2013.
[8] R. K.Rai, H.Gopalan, J.Sitaraman, J. D.Mirocha, and W. O.Miller. Environmental Modelling & Software A code-independent generalized actuator line model for wind farm aerodynamics over simple and complex terrain. Environmental Modelling and Software, 94:172–185, 2017.
[9] M. J.Churchfield, S.Lee, P. J.Moriarty, L. A.Martinez, S.Leonardi, G.Vijayakumar, and J. G.Brasseur. A large-eddy simulation of wind-plant aerodynamics. AIAA paper, 537, 2012.
[10] X.Yang, M.Pakula, and F.Sotiropoulos. Large-eddy simulation of a utility-scale wind farm in complex terrain. Applied Energy, 229(May):767–777, 2018.
[11] P. K.Jha, M. J.Churchfield, P. J.Moriarty, and S.Schmitz. Accuracy of state-of-the-art actuator-line modeling for wind turbine wakes. AIAA Paper, (2013-0608), 2013.
[12] R. J. A. M.Stevens, L. A.Martinez-Tossas, and C.Meneveau. Comparison of wind farm large eddy simulations using actuator disk and actuator line models with wind tunnel experiments. Renewable Energy, 116:470–478, 2018.
[13] L. A.Martinez-Tossas, M. J.Churchfield, and S.Leonardi. Large eddy simulations of the flow past wind turbines: actuator line and disk modeling. Wind Energy, 18(6):1047–1060, 2014.
[14] M.Draper, A.Guggeri, B.López, A.Díaz, F.Campagnolo, and G.Usera. A Large Eddy Simulation framework to assess wind farm power maximization strategies: Validation of maximization by yawing. In Journal of Physics: Conference Series, volume 1037, 2018.
[15] Ministerio de Energía Industria y Minería. https://ben.miem.gub.uy/oferta5.html, 2019.
[16] El País. https://negocios.elpais.com.uy/noticias/eolica-principal-fuente-generacion-primeravez.html, 2018.
[17] J.Aho, A.Buckspan, L. Y.Pao, and P. A.Fleming. An Active Power Control System for Wind Turbines Capable of Primary and Secondary Frequency Control for Supporting Grid Reliability. AIAA/ASME Wind Symposium, (January):1–13, 2013.
[18] J.Aho, P.Fleming, and L. Y.Pao. Active power control of wind turbines for ancillary services: A comparison of pitch and torque control methodologies. 2016 American Control Conference (ACC), pages 1407–1412, 2016.
[19] G.Usera, A.Vernet, and J. A.Ferré. A Parallel Block-Structured Finite Volume Method for Flows in Complex Geometry with Sliding Interfaces. Flow, Turbulence and Combustion, 81(3):471, 2008.
[20] A.Guggeri, M.Draper, G.Usera, and F.Campagnolo. An Actuator Line Model Simulation of two semi-aligned wind turbine models, operating above-rated wind speed. In Tenth International Conference on Computational Fluid Dynamics (ICCFD10), 2018.
[21] J. N.Sorensen and W. Z.Shen. Numerical Modeling of Wind Turbine Wakes. Journal of Fluids Engineering, 124(2):393, 2002.
[22] J.Jonkman, S.Butterfield, W.Musial, and G.Scott. Definition of a 5-MW reference wind turbine for offshore system development. Technical report, National Renewable Energy Laboratory (NREL), Golden, CO., 2009.
[23] M.Draper. Simulación del campo de vientos y de la interacción entre aerogeneradores. PhD thesis, 2015.
[24] M.Draper and G.Usera. Evaluation of the Actuator Line Model with coarse resolutions. Journal of Physics: Conference Series, 625(1):12021, 2015.
[25] M.Draper, A.Guggeri, and G.Usera. Validation of the Actuator Line Model with coarse resolution in atmospheric sheared and turbulent inflow. Journal of Physics: Conference Series, 753:82007, sep 2016.
[26] M.Draper, A.Guggeri, and G.Usera. Modelling one row of Horns Rev wind farm with the Actuator Line Model with coarse resolution. Journal of Physics: Conference Series, 753:82028, sep 2016.
[27] M.Draper, A.Guggeri, M.Mendina, G.Usera, and F.Campagnolo. A Large Eddy Simulation model for the study of wind turbine interactions and its application. In Tenth International Conference on Computational Fluid Dynamics (ICCFD10), 2018.
[28] A. G.González Rodríguez, A.González Rodríguez, and M.Burgos Payán. Estimating Wind Turbines Mechanical Constants. volume 1, pages 9–11, 2007.
[29] M. O.Hansen. Aerodynamics of Wind Turbines. 2008.
[30] P.Fleming, J.Aho, P.Gebraad, L.Pao, and Y.Zhang. Computational Fluid Dynamics Simulation Study of Active Power Control in Wind Plants. American Control Conference, pages 1413–1420, 2016.
[31] J. W.van Wingerden, L.Pao, J.Aho, and P.Fleming. Active Power Control of Waked Wind Farms. IFAC-PapersOnLine, 50(1):4484–4491, 2017.
[32] P.Igounet, P.Alfaro, G.Usera, and P.Ezzatti. Towards a finite volume model on a many-core platform. International Journal of High Performance Systems Architecture 12, 4(2):78–88, 2012.