

LES of wind farm response to transient scenarios using a high fidelity actuator disk model

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Abstract. Large eddy simulations coupled to Actuator Disks are used to investigate wake effects in wind farms. An effort is made on the wind turbine model: it uses the prevailing velocities at each point of the disk to estimate the aerodynamic loads and is improved using a tip-loss correction and realistic control schemes. This accurate and efficient tool is used to study the wind farm response in terms of flow and power production during an unsteady scenario: this work focuses on an emergency shutdown of one rotor inside a wind farm.

1. Introduction

Numerical simulations offer a convenient framework to investigate transient events occurring in a wind farm and the resulting response in terms of wake dynamics, loads and power variation. This last feature is important for grid integration, in particular, the management of intermittency and the quality of electricity service (frequency). It will be useful for the elaboration of wind farm control schemes allowing to regulate the global power production. In order to make such a study possible, the simulations need to be sufficiently accurate, with a realistic response of wind turbines, while remaining affordable at the scale of a wind farm.

We propose to achieve this compromise through an approach based on classical structured mesh CFD. It consists in Large Eddy Simulation (LES) on relatively coarse meshes and the use of an Actuator Disk (AD) model for the wind turbines. An effort is made here to increase the accuracy of the tool by improving the rotor model: the disk accounts for torque effects, non-uniform forces repartition based on local disk velocities and realistic controller schemes. The ground effect is taken into account by adding wall models, allowing a representation of the wind shear and turbulence structures for an Atmospheric Boundary Layer (ABL) under neutral conditions.

This developed tool is used to study wind farm responses to transient scenarios: we consider here a wind farm with 15 machines where an emergency shutdown occurs. Different studies exist about the consequences of such a stop on the structural loads of the rotor itself [1, 2, 3], but there is currently no investigation of the effect on other wind turbines. This paper aims at studying the impacts of such a stop on the defective machine but also on the wakes and power production at wind farm scale. It is organised as follows: the wind turbine model and the LES framework are described in Section 2; Section 3 presents the wind farm arrangement, the inflow characteristics and the results. Finally, our conclusions are drawn in Section 4.



2. Methodology

2.1. Flow solver

We consider the LES of incompressible turbulent flows. It is performed using a fourth order finite differences code developed at UCL [4], formulated in primitive variables (i.e. in velocity and pressure) and using a structured staggered mesh arrangement. The Navier-Stokes equations, supplemented by a subgrid scale (SGS) model, are solved using a fractional-step method with the delta form for the pressure [5] and are discretized in space using a fourth order finite difference scheme [6, 7]. The Poisson equation for the pressure is solved using a multigrid solver with Gauss-Seidel smoother. The time integration is carried out using an explicit second-order Adams-Bashforth scheme. We use a standard Smagorinsky model for the SGS model [8]. The wind turbine effect is added through external body forces (per volume) acting on the flow (discussed in Section 2.2).

x is the streamwise direction, y , the vertical direction and z the spanwise direction. Instantaneous velocities are imposed at the inlet boundary (see Section 2.3) and a convective boundary condition is applied at the outflow. Periodic boundary conditions are imposed in the z direction and no-through flow is enforced at the top. At the bottom, wall effects are included using a wall model [9], which is required for simulations at high Reynolds number, as in ABL simulations. A wall stress model for a rough wall is here applied, to compute the surface shear stress as a function of the LES velocity field at the third vertical grid point.

2.2. Wind turbine model

The wind turbine is accounted for through an AD: with this model, the actual geometry of the rotor blades is replaced by body force terms acting over the surface swept by the rotor. Thrust and torque effects are taken into account, and the relations for aerodynamic loads computation are based on the prevailing velocities at each point of the disk: the wind turbine thus reacts in synchronization with the incoming structures of wind turbulence or wakes. The local disk velocities are modified using a tip-loss factor in order to account for the finite number of blades; the computation of this correction is here improved thanks to a local estimation of the effective upstream velocity at every point of the AD. This model, coupled to LES, has been verified through a comparison with higher fidelity results, produced using a Vortex Particle-Mesh method with immersed lifting lines [10].

The chosen wind turbine is the “NREL offshore 5 MW baseline wind turbine” [11]. This wind turbine model is characterized by a rotor diameter, D , equal to 126 m and a hub height of 90 m. It is here equipped with generator-torque and blade-pitch controllers [11] and a yaw controller [12]. An emergency shutdown procedure has also been added, based on the aerodynamic braking principle only: this is a method typically used for variable blade-pitch wind turbines [13]. This is done by turning off the generator torque and pitching the blades to feather (90°) at the maximum pitch rate ($8^\circ/s$ for the NREL 5MW [11]). The wind turbine behavior during such a shutdown is studied in Section 3.2.

2.3. Turbulence generation

The code can handle turbulent inflow conditions in two fashions: using precursor LES results or using turbulent fluctuations pre-generated with the Mann algorithm [14] and overimposed to a chosen velocity profile at the inlet. For wind farm simulations, the first approach is the most appropriate: it involves running a prior simulation of a turbulent boundary layer flow without wind turbines and, once the flow reaches a statistically-steady state, yz -planes of instantaneous velocities are saved for a certain number of time steps and later used as inflow for simulations with wind turbines. For this pre-simulation, periodic boundary conditions are applied in both x and z directions, while the conditions for the vertical direction remain the same. The flow is driven by a constant pressure gradient, proportional to the friction velocity, u_τ and the height

of the boundary layer, $H : \frac{1}{\rho} \frac{\partial p}{\partial x} = \frac{u_\tau^2}{H}$. The wall stress model, used at the bottom plane, also depends on the roughness length, y_0 ; this value and u_τ are imposed according to the desired resulting velocity profile and turbulence intensity. The precursor simulation can be performed on coarser meshes, which allows faster simulation times.

3. Results

3.1. Set-up and precursor simulation

The LES coupled to AD are used to investigate transient scenarios occurring at a wind farm level and the impacts in terms of resulting power and wake dynamics. The chosen scenario is an emergency stop of a wind turbine within a wind farm of 15 machines; the rotor for which a shutdown procedure is required (Fig. 1) is located in the middle of the farm, in the second row and on the center line (WT2 in Fig. 2). There are 7D between the wind turbines, in both horizontal directions and the first wind turbines are located at 14D from the inlet. The global domain size is $52D \times 8D \times 28D$ with a resolution of 16 points per D in each direction, leading to a cell size h of about 7.88 m. With such a resolution, the forces distribution of the lower points of the disk can directly affect a sample location of the wall model, thus leading to a lower local acceleration below the rotor. One solution would consist in refining the resolution in the vertical direction: it is currently investigated.

The inflow condition is obtained from a prior simulation without wind turbines: it is performed on a domain of the same size as the main simulation but with a coarser resolution, 12 points per D in the vertical direction and 6 points per D in x and z directions. y_0 and u_τ are 0.1 mm and 0.25 m/s respectively, typical values for offshore conditions. Once the flow reaches a statistically-steady state, yz -planes of velocities are saved to finally obtain about 3000 s of wind, that are interpolated on the inlet grid of the wind farm simulation.

We obtain a time-averaged hub height wind speed, $\bar{u}_{hub}$, of about 8.8 m/s and a TI, normalized by $\bar{u}_{hub}$, of about 6 %. The wind turbines then operate in the region II of their controllers [11], in which the maximum energy is extracted from the wind. In this region, only the torque-controller is active and the pitch angle of the blades is set to 0° . The shutdown occurs at $t = 1500s (= T_{SD})$.

We have also performed a simulation without rotor stop: the results will provide us reference for power productions and allow to clearly identify the emergency stop effects on power through the wind farm.

3.2. Wind farm simulation and emergency shut down

We first study the transient behavior of the faulty wind turbine: Fig. 1 shows the blade pitch angle, the rotational speed, the aerodynamic and generator torques as functions of time (graphs are only displayed for a short time interval). When the emergency stop occurs, the blades are pitched to their feather position (Fig. 1(a)), and the generator torque is turned off (Fig. 1(c)). This results in the rotor speed decreasing (Fig. 1(b)) and in the aerodynamic torque becoming negative (Fig. 1(c)), which successfully brings the rotor to a stop within 20 seconds. Before decreasing, the rotor speed presents a positive spike, which is due to the disconnection of the generator and the sudden removal of resistive torque. Afterwards, the negative aerodynamic torque builds up and slows the rotor down. These transient states are similar to results of other studies [1]. Such a shutdown has consequences on structural loads (tower top and flapwise blade tip displacements, bending moments,...); those are not investigated in this work.

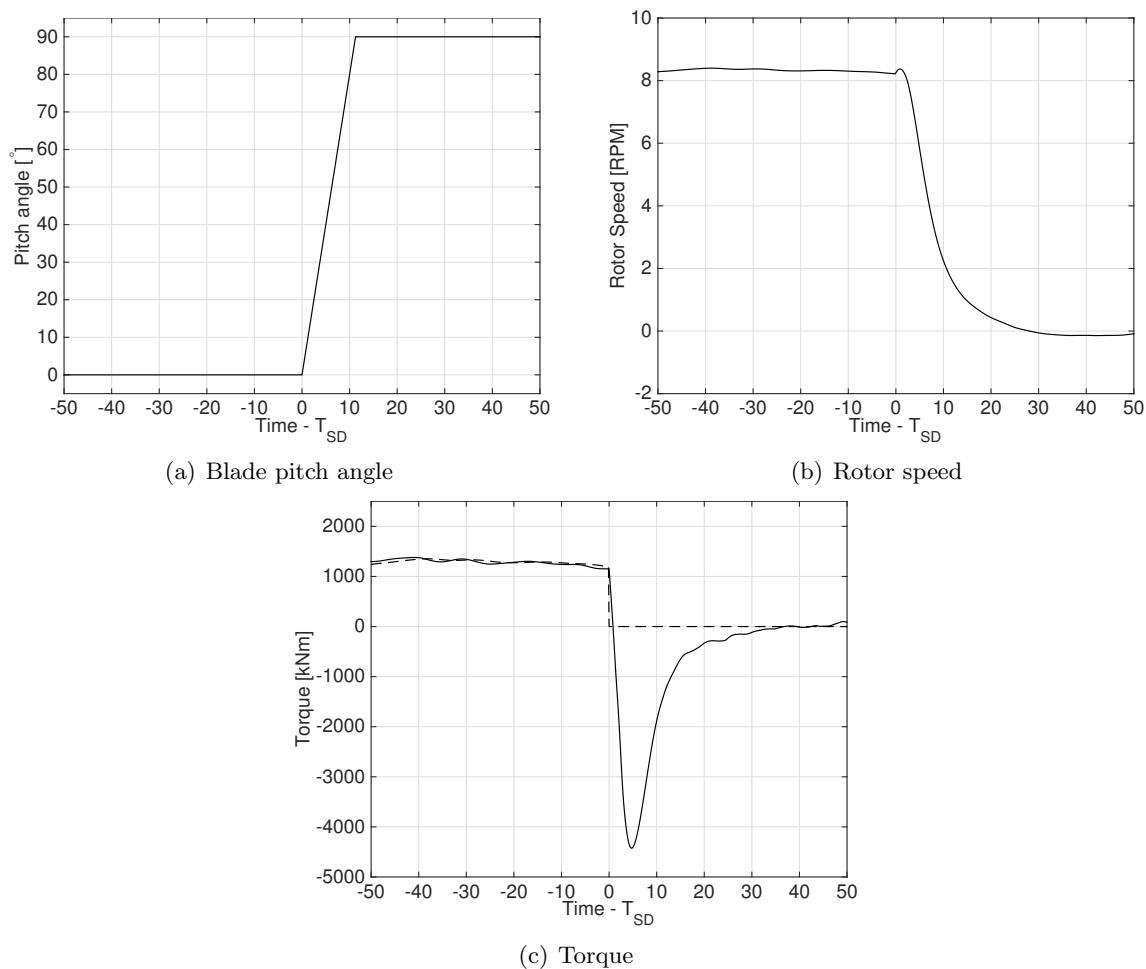


Figure 1. Faulty wind turbine data : blade pitch angle, rotor speed, generator and aerodynamic torques (dashed line and solid line) as functions of time, with T_{SD} the time of the shutdown.

The shutdown of the wind turbine impacts the productions of the downstream wind turbines. These data can be linked to the evolution of the flow and wakes, presented in Figs. 2 and 3: Fig. 2 shows horizontal slices of axial velocities at hub height, and Fig. 3, xy -planes taken at the middle of the farm, at $z/D=14$. These slices present instantaneous data at various relevant times. Figures 4 and 5 present the rotor speed and power of the machines of the second line.

When the second wind turbine stops producing power at $t = T_{SD}$, its wake still impacts the wind turbine located downstream, WT3. Therefore, a certain delay after the failure is necessary before observing a rise of rotor speed (Fig. 4), from about $t = T_{SD} + 150$ s. This delay is equal to the time for the wake of WT2 to cross the distance between WT2 and WT3. Figures 2(b) and 3(b) highlight this: 100 s after the emergency stop, we still see some remnants of the WT2 wake just before WT3. From 150-200 s after the WT2 shutdown, WT3 produces more power (Fig. 5) but does not reach the production of the first wind turbine WT1: indeed, the WT1 wake effect is still felt 14D downstream, at the WT3 location (Figs. 2(c) and 3(c)). We also notice larger oscillations for the WT3 production (Figs. 4 and 5) after the emergency stop: it can be due to the large distance between WT1 and WT3, which allows higher amplitudes of oscillation of WT1 wake when it impacts WT3. The change in WT3 operating conditions does not affect a lot the fourth (WT4) and fifth (WT5) wind turbines of the line: it will be better highlighted when time-averaged power productions will be studied.

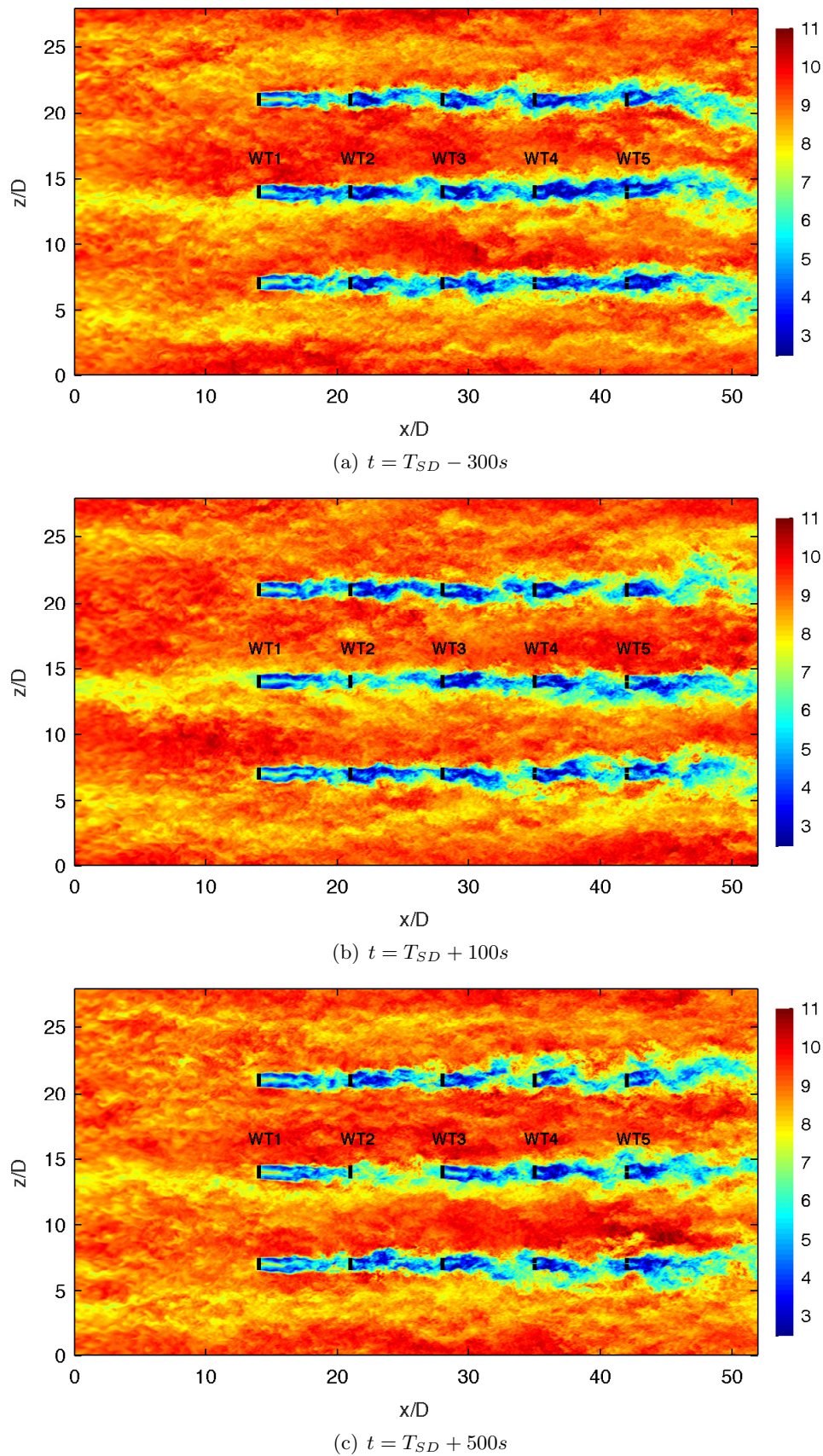


Figure 2. Horizontal slices of axial velocities taken at the hub height for three times: long before the shutdown ($T_{SD} - 300s$), during the transient behavior ($T_{SD} + 100s$) and long after the shutdown ($T_{SD} + 500s$). The data are in m^5/s .

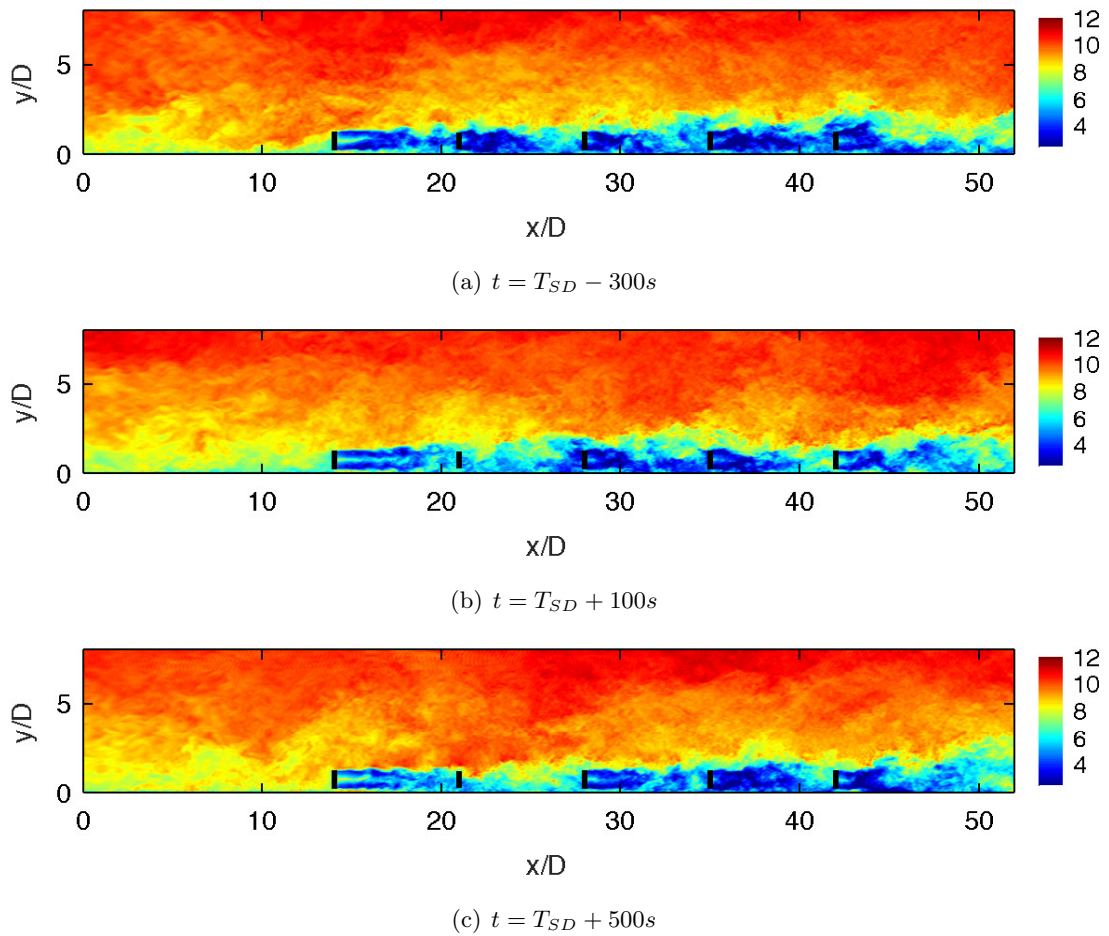


Figure 3. Vertical slices of axial velocities taken at $z/D=14$ (center of the second line) for three times: long before the shutdown ($T_{SD} - 300s$), during the transient behavior ($T_{SD} + 100s$) and long after the shutdown ($T_{SD} + 500s$). The data are in m/s.

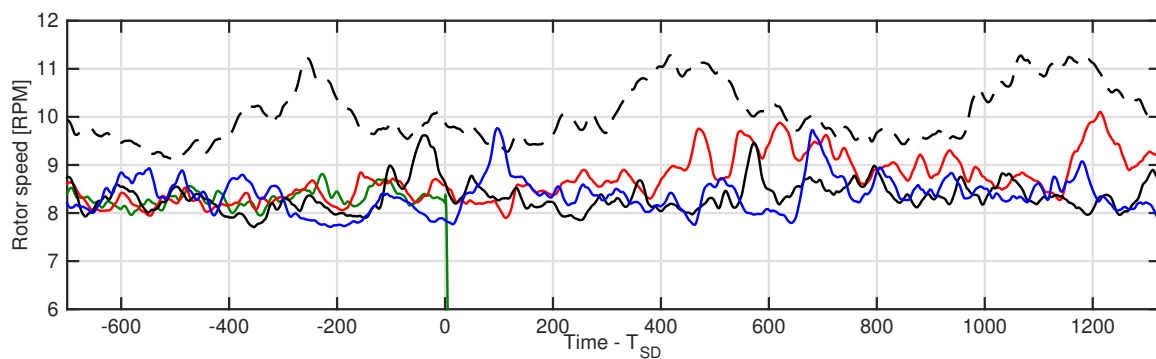


Figure 4. Rotor speeds as functions of time for the wind turbines of the second line: WT1 (---), WT2 (—), WT3 (—), WT4 (—) and WT5 (—).

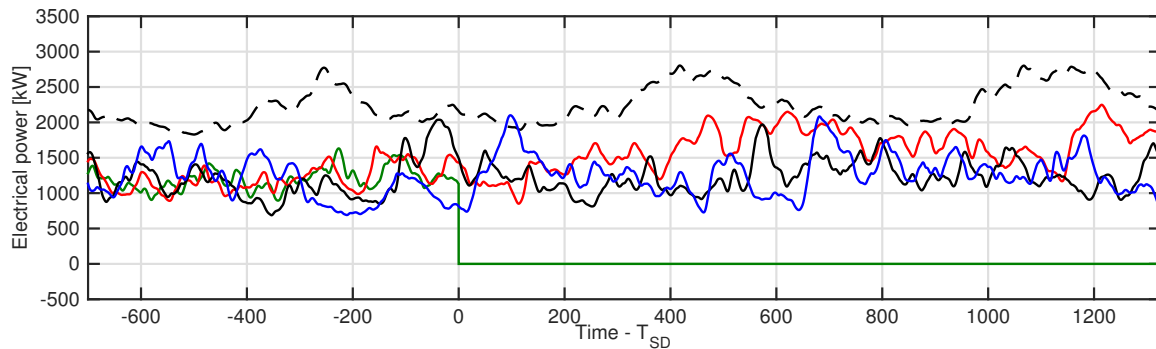


Figure 5. Powers as functions of time for the wind turbines of the second line: WT1 (---), WT2 (—), WT3 (—), WT4 (—) and WT5 (—).

Fig. 6 shows the time-averaged power production of the second line for the two main simulations (with and without the emergency shutdown), normalized by the power production of WT1. These values are averaged over a period of about 745 s (corresponding to $52 D/\bar{u}_{hub}$), from a time of 600 s after T_{SD} . When all the wind turbines are active, we see that the WT2 power is about 55 % of the first one, while the power production of the downstream machines stabilizes and is close the WT2 power production. In the case with the emergency shutdown, the WT2 power is null and WT3 produces more power. WT4 then adopts the behavior of the second wind turbine in a line, with an important power reduction. However, the WT3 wake is more turbulent, less structured than the WT1 wake, the power loss between WT3 and WT4 is thus less important than that observed between WT1 and WT2 before the shutdown: we obtain $\bar{P}_{WT4}/\bar{P}_{WT3} = 0.74$ while $\bar{P}_{WT2}/\bar{P}_{WT1} = 0.55$. As already noticed, $\bar{P}_{WT4}$ and $\bar{P}_{WT5}$ do not differ sensibly: to really validate this, powers should be averaged on longer times.

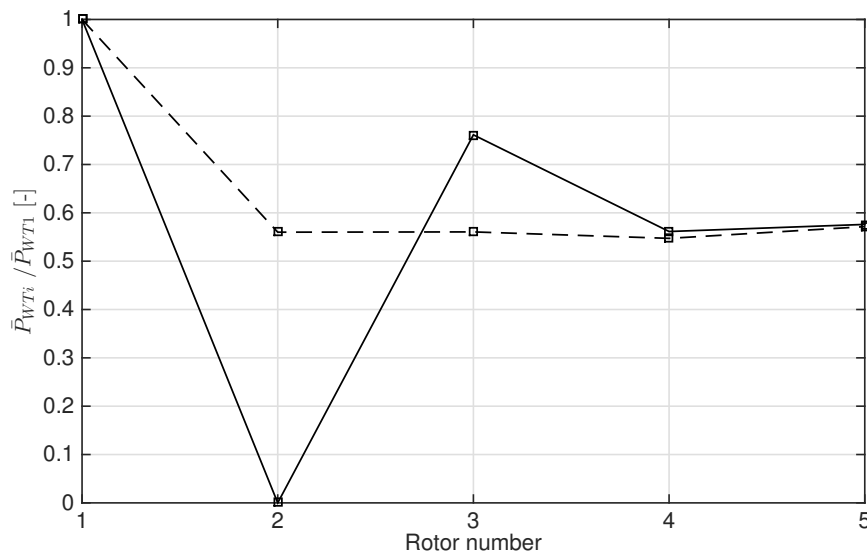


Figure 6. Second line powers: time-averaged power produced by each wind turbine, $\bar{P}_{WTi}$, for the simulation without (---) and with (—) the shutdown, normalized by the time-averaged power of the first rotor in the line, $\bar{P}_{WT1}$.

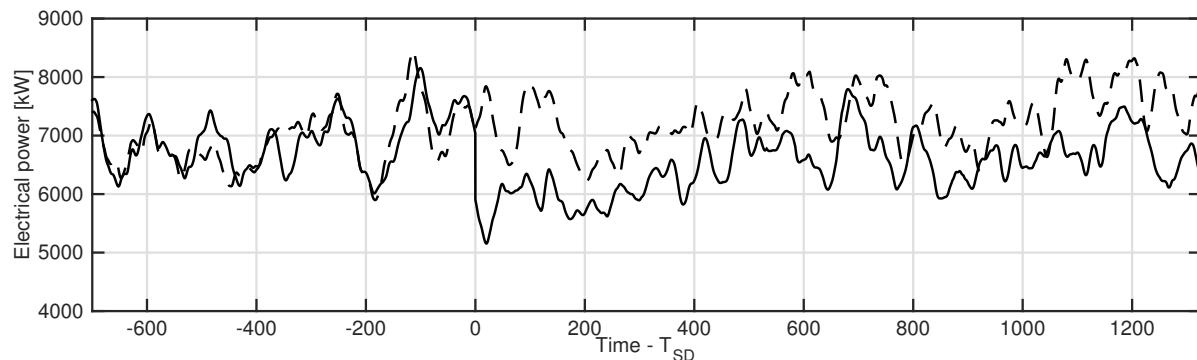


Figure 7. Global power as function of time for the second line, for the simulation without (---) and with (—) the shutdown.

Figure. 7 shows the power history of the second line; it is compared to that produced by the second line of the wind farm without an emergency shutdown. The small discrepancies observed between the two curves before T_{SD} are due to different initial conditions of the wind turbines: this does not however impact the global behavior and the averaged values. We see the sudden decrease in power at the shutdown time T_{SD} . The global power then progressively increases, when WT3 begins to produce more power, but still remains below the power production without the shutdown. Globally, this event leads to a power loss lower than $\bar{P}_{WT2}$ computed without shutdown: the increase of the WT3 production attenuates the stop of WT2, leading to a global deficit of about 60 % of $\bar{P}_{WT2}$.

4. Conclusions and perspectives

We use LES coupled to Actuator Disks to perform accurate, yet still affordable, unsteady wind farm simulations. Higher fidelity is injected into the rotor representation by including torque effects, non-uniform forces repartition, tip-loss corrections and realistic controllers. The code is used to study unsteady phenomena while keeping a reasonable CPU cost, to allow fast-time and near real-time studies. A transient event has been investigated: the failure of a wind turbine inside a wind farm, with a required emergency shutdown. The impact of such an event has been studied in terms of wake dynamics and resulting rotor speed and power variations. Other transient events are also envisaged, such as gust propagation through the wind farm, with a variation in intensity and direction.

Such studies allow a better understanding of the operating condition variations during complex scenarios, and are useful for the elaboration of future global control schemes. Indeed, it is envisaged to leverage this tool for a full-chain simulation in order to improve the management of wind and grid events through farm-scale control.

Before coupling the CFD code to a grid side model, this tool needs further improvements and verifications, mainly for the ABL simulation. Indeed, currently, instantaneous velocity planes are saved to be used later in wind farm simulations, implying large storage requirements. It is planned to implement a concurrent precursor method [15], allowing inflow conditions to be directly transferred to the inlet of the wind farm domain. Recycling methods [16] can also be an alternative, where only one simulation is needed. However, this requires a larger domain and this does not allow the ABL simulation to be performed on coarser meshes. The concurrent method appears to be the most appropriate, although the impact of changing the mesh between the ABL and the wind farm domains must still be analysed. A validation step is finally required for the wind farm tool, based on existing set-up and productions.

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