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A Gaussian Wake Model and OpenFAST Based Wind Farm Simulation

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Abstract

Wake interaction is a key issue in wind farms as it is the main cause of power loss and dynamically varying loads for the downstream turbines. To develop optimal control, It is necessary to properly model the rotor wake and to understand the effects and the interaction of wakes based on models tuned against experiments and numerical data. In this paper, a Gaussian Wake Model (GWM) is proposed and coupled with OpenFAST, improving the accuracy compared with other models. A GWM based platform, Floris, is used to simulate the wake and partial wake conditions and is coupled with OpenFAST. The OpenFAST aerodynamic module is adopted to calculate the rotor aerodynamics on the actual rotor flow field, in which the action of wake is revealed. With the designed layout, wake interaction changes with wind direction. The simulations show how the wake causes a significant decrease on torque and power generation. The relationship between these losses and the particular configuration provides fundamental information on how to use yaw control for a wake redirection strategy which maximizes the power.

Keywords: Wind Farm Control, Wind Turbine, Wake Model, Floris, OpenFAST, Gaussian Wake Model

1 Introduction

Wind energy is a relatively new research field. For many years it has had a marginal place in the global energy production scenario and because of the limited resources invested it slowly advanced by taking ideas from the aerospace world. The fossil fuels crisis and the growing awareness of climate and sustainability issues drastically changed the situation. Now wind energy is an exciting, flowery multidisciplinary field employing experts in aerodynamics, materials, monitoring and diagnostics, electric and control systems.

One of the main issues when dealing with wind turbines is their positioning. There is a lot to things to take into account such as the vicinity to human settlements, the nature of the ground, the wind uniformity and intensity, the feasibility of efficient energy storage and transmission. It turns out that there is actually a very limited amount of onshore sites meeting all of these requirements and this constraint is actively dictating the new research trends in the field. If we want to exploit favourable sites we can think of building bigger turbines and or clustering them. We can also think of going offshore. Each one of this ideas introduces new, big challenges. Bigger rotors means longer, more flexible blades with structural and fatigue issues, clustering means having to deal with optimizing the layout, to begin with, going offshore means to consider new loads and new sources of instability.

If all of this challenges have been extensively tackled in the last couple decades what could really be a game changer and break down the LCOE for this technology is control. At the turbine level the control system guarantees a smooth power output and may optimize it at lower wind speeds. At the wind farm level though, the power production can be increased of the order of 10 % (taking greedy control as a baseline) even with the simplest static techniques.

The key instrument for developing and testing such techniques is the modeling of wake interaction. Currently, a lot of study is dedicated to the development of wind plant models having different levels of complexity and fidelity, based on the purposes for which they are used. Wind plant models have very different levels of complexity and fidelity and may have different purposes. Among these models, there are on one side high fidelity wake models which are particularly suited for model validation since they are able to grasp the physics behind the phenomenon represented and on the other side engineering and analytical models, that give a more rough estimation of the flow field or turbine performance, but are still valuable for the evaluation of turbine performances. Control oriented model are necessarily low fidelity since they have to be very quick to run in real-time if needed and dynamically optimize power extraction and loads.

An example of open-source control-oriented software is Floris, developed by NREL. It relies on the Bastankhah and Porté-Agel [1, 2] GWM and is able to fully characterize the flow field developed in a wind farm, considering steady-state environmental conditions. To work, this tool requires only four parameters determined experimentally and some inputs from the user related mainly to the farm geometry and the free stream wind. What we tried to do with this work was to position ourselves a bit further from the basic Floris on the spectrum that goes from very low fidelity models to CFD.

We will present a low-fidelity model based on the GWM and Floris. What makes it more advanced is that the GWM will be embedded and working in the OpenFAST framework coupled to the BEMT aerodynamic model of the turbine. The main difference with Floris is the capability of this new tool to model the wake generated by the machines keeping into account for the C_T and AIF developed on the whole plane of the rotor and calculated at runtime from the aero-elastic solver OpenFAST, and not only in a single point (at hub-height by means of pre-tabulated values like the $C_P - TSR$ or the $C_T - TSR$ table (like Floris does). This allows for a more accurate description of the wake. The proposed tool allows also for a characterization of the loads acting on the machines when they work in complete or partial wake condition under the assumption of steady-state environmental conditions. In addition to this, the model can be used to develop and test new control logics at wind farm level in order to maximize the power extraction under the hypothesis of steady-state flow condition but retaining the dynamics of the turbines (thanks to OpenFAST). It is also possible to investigate both the loads and the power extraction when the turbines are working in a yawed condition. Indeed, this new tool is particularly suited for research on wind farm control logics using wake steering methods, like the one proposed by van Dijk et al. [3] and Martinez et al. [4], Axial-Induction based methods, like the one presented by van Wingerden et al. [5], or a combination between them like in the work of Bossanyi et al. [6].

The paper is organized as follows. At first, there is an overview on the GWM and the analytical changes that have been made to it. Then there's a chapter dedicated to the implementation of the new GMW in the OpenFAST framework. Lastly, there is a presentation of a simulation carried out with the new developed tool and a discussion about the results and the future work.

2 Gaussian Wake Model

2.1 GWM Overview

One of the analytical models that can be used to characterize the wakes developing in a wind farm is the Gaussian Wake Model (or GWM) firstly proposed by Basthankhah and Porté-Agel [1, 2] and successfully implemented in the NREL's software FLORIS. The authors derived the wake model by performing a budgeting analysis on Reynolds Averaged Navier-Stokes equations (RANS). In this way, they were able to identify and to retain in the RANS equations the terms having the biggest impact on the wake's behaviour and to discard the other negligible terms. At the end of this process, the authors obtained two conditions that are used to obtain an expression for two fundamental terms of the model that are the wake deficit and the wake deflection as function of downstream position (with respect to the hub center point of the considered turbine).

For the wake deficit profile in wind speed (with respect to undisturbed wind), as it can be easily inferred from the title of the model, Basthankhah and Porté-Agel chose a gaussian shape; this choice was validated by further studies carried out by the authors, with the only limitation of having a relative angle between the free wind direction and the rotor plane of the turbines comprised in the range of [-30, +30] degrees. Out of this range, the gaussian shape is no more representing adequately the phenomenon. Another fundamental point described by the GWM is the wake deflection generated when the turbines are operating misaligned with respect to the undisturbed wind direction.

An important feature of the model is the separation of the wake in two main zones depending on the downstream distance from the turbine's rotor hub. The former is the near-wake region, while the latter is the far-wake region. It is in this region that the authors assumed valid the hypothesis of gaussian shape for both the wake deficit in wind speed and the wake deflection. Their expression is reported in Eqn. (1) and Eqn. (2).

$$\frac{\bar{u}(x,y,z)}{u_\infty} = 1 - C(x) e^{\frac{-(y-\delta)^2}{2\sigma_y^2}} e^{\frac{-(z-z_h)^2}{2\sigma_z^2}} \tag{1}$$

$$\frac{\theta(x,y,z)}{\theta_m} = e^{\frac{-(y-\delta+\sigma_y)^2}{2\sigma_y^2}} e^{\frac{-(z-z_h)^2}{2\sigma_z^2}} \quad \text{and} \quad \theta_m = \frac{\theta_c}{e^{-0.5}} \tag{2}$$

where $\bar{u}$ represents a time averaged velocity in a downstream location with respect to the considered turbine, $C(x)$ represents the normalized velocity deficit at the wake center in various downstream positions, δ represents the wake center deflection, z_h represents the hub height of the considered wind turbine, σ_y and σ_z represent the wake width in y and z direction, u_∞ represents the undisturbed fluid velocity and θ_c represents the wake skew angle of the wake center as function of the downstream distance.

For what regards the wake width, σ_y and σ_z, a linear formulation dependent on the downstream distance is proposed:

$$\frac{\sigma_z}{d} = k_z \frac{x - x_0}{d} + \frac{\sigma_{z0}}{d} \tag{3}$$

$$\frac{\sigma_y}{d} = k_y \frac{x - x_0}{d} + \frac{\sigma_{y0}}{d} \quad \text{and} \quad \frac{\sigma_{y0}}{d} = \frac{\sigma_{z0}}{d} \cos\gamma \tag{4}$$

$$k_y = k_z = k_a I + k_b \quad \text{and} \quad k_a = 0.38371, k_b = 0.003678 \tag{5}$$

where d represents the turbine's diameter, x_0 the downstream distance at which there is the onset of the far wake zone,σ_{y0} and σ_{z0} represent the wake width at the onset of the far wake zone, k_z and k_y are two constants hypothesized as linearly dependent from the wind turbulence intensity I, k_z and k_y are two constants determined experimentally and γ is the yaw angle of the turbine relative to the free-stream wind direction.

It is at this stage that the authors used the two conditions coming from the budgeted RANS equations (both in stream-wise and span-wise direction) to retrieve an expression for the wake center deflection δ and for the normalized velocity deficit at the wake center $C(x)$ as function of downstream position. The analytical expression for this functions can be found in Basthankhah and Porté-Agel's papers [1, 2].

To close the model, since all the functions obtained are strongly dependent on the onset of the far wake region, it is necessary to characterize it.

2.2 Determining the parameters in the far wake region

A relationship between the C_T and the a (AIF) of the turbine is needed; Basthankhah and Porté-Agel proposed a simplified, analytical formulation:

$$C_T \simeq 4a(1 - a\cos\gamma) \quad \text{and} \quad a \simeq \frac{1}{2\cos\gamma}\left(1 - \sqrt{1 - C_T\cos\gamma}\right) \tag{6}$$

This analytical formulation, as will be seen in Sect. 2.4, is fundamental in the formulation of the GWM since all the principal model parameters are depending on it. In the Floris software, to run the model, a $C_T - TSR$ and a $C_P - TSR$ table are required as input parameters. Thanks to them, the AIFs of the simulated turbines are derived by means of Eqn. (6), using the input Wind Speed to define the TSRs at which the machines are operating ($TSR \rightarrow C_T \rightarrow$ AIF).

Continuing with the GWM, by applying the definition of AIF and by applying the Bernoulli equation between an upstream (undisturbed wind) section and the rotor section of the turbine and between the rotor section and a downstream section, it is obtained:

$$\frac{u_R}{u_\infty} = \frac{C_T\cos\gamma}{2\left(1 - \sqrt{1 - C_T\cos\gamma}\right)} \quad \text{and} \quad \frac{u_0}{u_\infty} = \sqrt{1 - C_T} \tag{7}$$

where u_R is the wind speed at the turbine's rotor plane.

From this considerations, the theoretical value of the deficit at the rotor plane section C_0, a parameter on which $C(x)$ is relying (please make reference to Basthankhah and Porté-Agel [1, 2] for the complete dissertation), can be expressed as:

$$C_0 = 1 - \frac{u_0}{u_\infty} = 1 - \sqrt{1 - C_T} \tag{8}$$

Furthermore, assuming a constant velocity equal to u_0 in the the near wake zone, or "potential core" of the wake, and applying the budgeted RANS conditions at section $x = x_0$ and using Eqns. (7) it is possible to conclude that:

$$\frac{\sigma_{z0}}{d} = \sqrt{\frac{1 + \sqrt{1 - C_T \cos\gamma}}{8(1 + \sqrt{1 - C_T})}} \simeq \sqrt{\frac{1}{8}} \tag{9}$$

Passing to the wake deflection and using the Burton's approximation [7] to describe the flow skew angle with respect to the rotor's axis χ and by substituting the AIF with Eqn. (6) it is obtained that the θ angle (useful for estimating the flow angle at rotor disk) is:

$$\theta \simeq \frac{0.3\gamma}{\cos\gamma}(1 - \sqrt{1 - C_T \cos\gamma}) \tag{10}$$

Eqn. (10) is used to define the parameter θ_{c0} (the flow skew angle at the onset of the far wake region, where $x = x_0$). From this consideration, it is easy to see how the wake deflection δ_0 at $x = x_0$ can be expressed as:

$$\delta_0 = x_0 \tan\theta_{c0} \simeq x_0 \theta_{c0} \tag{11}$$

The last expression to be determined is x_0, the downstream distance at which there is the onset of the far wake region. To determine this unknown, the authors adopt a model from Lee & Chu [8] suggesting a proportionality between the change in width of the shear layer σ_{y0} to the velocity difference between the potential core of the wake and the unperturbed surroundings. They also recognized a proportionality of σ_{y0} with the incoming turbulence I that enhances flow entrainment and the growth of the shear layer. So, by carrying out further analysis and manipulation on the model's equations, they were able to define x_0 as:

$$\frac{x_0}{d} = \frac{\cos\gamma(1 + \sqrt{1 - C_T})}{\sqrt{2}[4\alpha I + 2\beta(1 - \sqrt{1 - C_T})]} \tag{12}$$

2.3 Additional Considerations

The GWM model described above is used to reproduce the wake generated by a single turbine. In general, when considering wind farms, interaction between wakes may happen and we must able to correctly reproduce them in the model. Just think of the case where more turbine are aligned to the wind direction; it is clear that, if the rotors are not extremely far one from the other, the waked flow field acting on a generic downstream rotor is the result of a composition of the wakes generated by some of the upstream turbines as it is possible to see in Fig. 1 obtained using NREL's Floris [9].

In this subsection, the methods used to keep into account for this phenomenon are exactly the ones proposed in the open-source NREL's Floris software. The correction used for the wind velocity was developed by Katic et al. [10] and proposes a superimposition of the local wakes to estimate the wake deficit on the $n + 1$ downstream turbine while Crespo et al. [11] propose a correction for the added turbulence due to the wake generation and mixing with the free-stream velocity:

$$\Delta u_{n+1} = \sqrt{\sum_{i=1}^{n} \Delta u_i^2} \quad \text{and} \quad I_+ = C_I A_{ol,\%} a_i^{e_1} I_0^{e_2} (\frac{x}{D_i})^{e_3} \tag{13}$$

where I_0 is the ambient turbulence intensity referred to the free stream condition, C_I, e_1, e_2 and e_3 are parameters to be determined experimentally, $A_{ol,\%}$ represents the ratio of overlapping area between the rotor diameter of a turbine and the wake area generated by upstream machines, D_i, a_i and I_0 represent respectively the rotor diameter, the Axial Induction Factor AIF and the incoming turbulence intensity

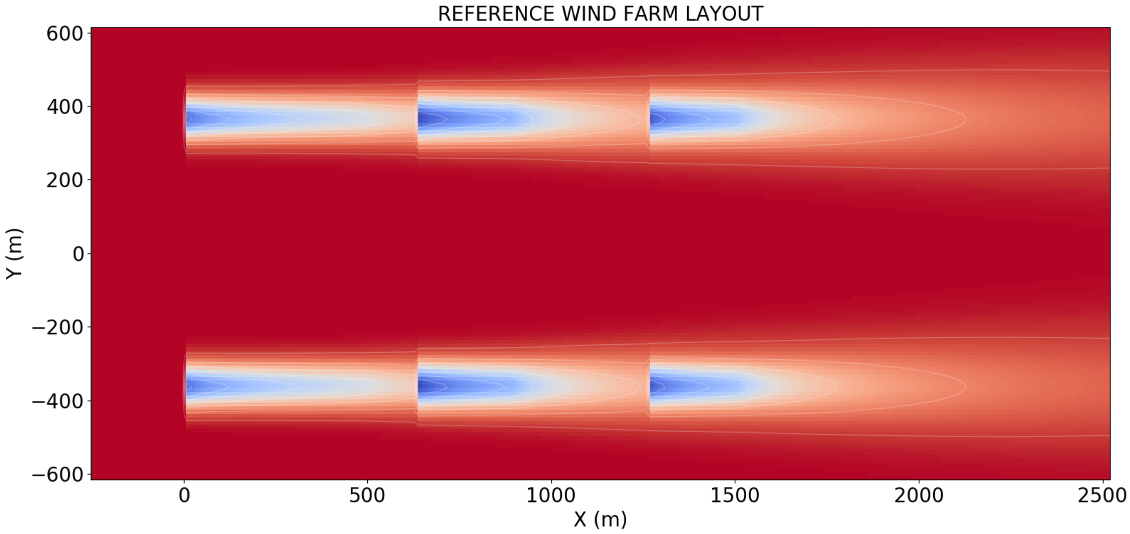

Figure 1: Wakes' superimposition in the layout used for this study, considering wind blowing from west direction (Image taken from NREL's Floris)

on the i-th considered machine. Also for the turbulence intensity I, due to the wake's superposition, a correction by Niayifar et al. [12] was implemented:

$$I = \sqrt{\sum_{i=1}^{n} I_{+,i}^2 + I_0^2} \tag{14}$$

2.4 Changes to the GWM and OpenFAST implementation

The GWM as presented makes reference to the original formulation of Basthankhah and Porté-Agel [1, 2]. Instead, the GWM used in this study has been changed to be implemented in OpenFAST (actually it is the C++ API of OpenFAST since it allows to run more turbine instances at the same time) [13] as an user-defined wind module written in Fortran in the file `IfW_UserWind.f90`.

The major change in this version is that both the C_T and AIF can be retrieved directly from OpenFAST as outputs of the AeroDyn module (performing the BEMT calculations on the aerodynamics of the turbine) of each simulated turbine composing the farm. We can treat OpenFAST as a black box that, given certain inputs is capable of output certain quantities like C_T and AIF, that are needed to run the GWM model. So, the analytical formulation in Eqn. (6) and all the mathematical steps deriving from it should be discarded when using OpenFAST; this means that Eqn. (7) has to be changed into:

$$\frac{u_R}{u_\infty} = 1 - a \quad \text{and} \quad \frac{\sigma_{z0}}{d} = \frac{1}{2}\sqrt{\frac{1-a}{1+\sqrt{1-C_T}}} \tag{15}$$

while Eqn. (10) is changed into:

$$\theta = 0.6a\gamma \tag{16}$$

and finally Eqn. (12) is written as:

$$\frac{x_0}{d} = \frac{\cos\gamma\sqrt{(1-a)(1+\sqrt{1-C_T})}}{4\alpha I + 2\beta(1-\sqrt{1-C_T})} \tag{17}$$

After applying these corrections to the GWM, the model is finally ready to be embedded in the OpenFAST framework.

The implemented function in `IfW_UserWind.f90` basically executes this task: given as input an array of positions near the rotor of each turbine (needed to solve the aerodynamics (BEMT) of the machine), the routine returns as output a matrix of values containing the wind speed in the three directions x, y and z for the selected positions.

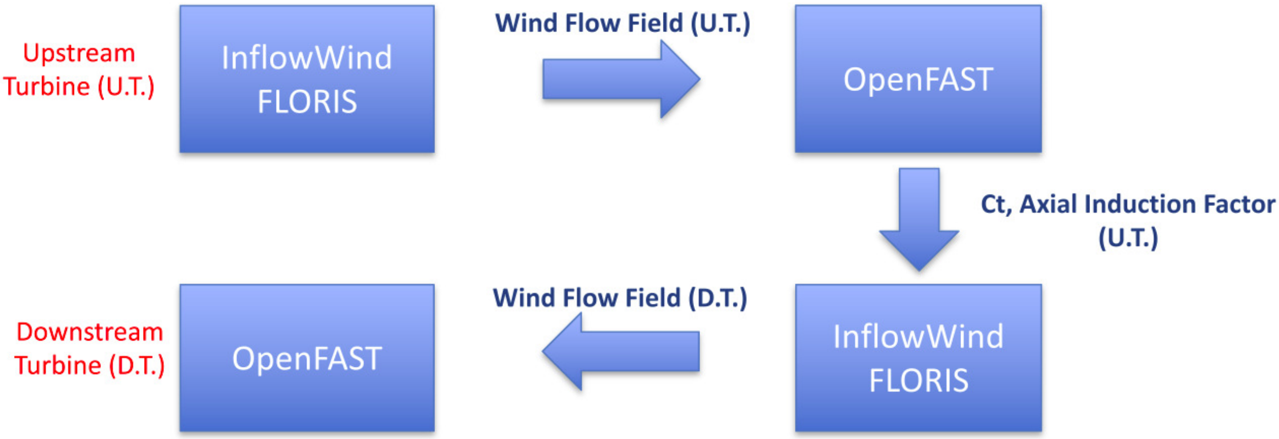

Figure 2: A schematic representation of how the GWM model is intended to work in the OpenFAST framework

In the main function, in addition to the GWM implementation, it was necessary to describe the free-stream wind acting on the first upstream turbine; to do so, the model chosen was the logarithmic profile of wind described in the EUROCODE [14].

In Fig. 2 a schematic representation of how the main routine is intended to work, when coupled with the OpenFAST framework, is presented.

For a generic time step, starting from the most upstream turbine, the wind routine evaluates the free-stream wind speed acting on it; then, the wind velocities are passed to the AeroDyn Module to solve the aerodynamics of the machine (using the BEMT model). After this passage, AeroDyn produces as output the $C_{T,i}$ value for the current turbine together with the AIF values at specific blades' section $a_{local,i}(r)$.

Then, once all the remaining calculations for the current OpenFAST instance (the current turbine) are over ,the next instance of OpenFAST, simulating the first downstream turbine (or another upstream turbine depending on wind farm layout and wind direction) is called to perform all its tasks. Once again, the user-specified InflowWind routine evaluates the wind speed acting on the positions required by OpenFAST that, this time, are affected by a certain wake deficit defined accordingly to the model. To perform such task, the $C_{T,i-1}$ and AIF a_{i-1} averaged on the rotor plane of the upstream turbines are needed. As before, the obtained values will be passed to the AeroDyn Module of the current OpenFAST instance to obtain the $C_{T,i}$ and $a_{local,i}(r)$.

This procedure is carried out for every turbine in the farm at every time step of the simulation. The routine as written gives also the possibility to linearly interpolate the wind input parameters of the simulated wind farm (like the wind speed, direction, surface roughness, etc.).

3 Numerical Setup of GWM and OpenFAST

OpenFAST is a widely used open-source software for wind turbine simulation which was developed by the National Renewable Energy Laboratory (NREL). There are many modules that can be combined depending on what kind of simulation we want to perform. We can include the effects of aerodynamics, servo-dynamics, and elasto-dynamics. In this paper, the proposed Gaussian Wake Model is applied as inflow wind to improve the wind turbine control. Thus, two primary modules are utilised: inflow wind and wind farm layout.

For this study, the reference turbine model is the NREL 5MW. It is not an actual turbine but its characteristics make it suitable to support concept studies and model assessments. It has a diameter of $D = 126.0\ m$ and a hub height $z_h = 90.0\ m$.

3.1 Inflow Wind

In the inflow wind module, the user-defined input file is coded in Fortran language. The main reason for using this language is its quickness. Floris is another NREL developed open-source platform. It is applied to realise the GWM and pass the result to the OpenFAST.

Given a certain height z, the turbulence intensity and the wind speed are calculated with the following equations:

$$u_\infty(z) = V_b k_r \ln(\frac{z}{z_0}), \quad z_{min} \leq z \leq 200m/300m \tag{18}$$

$$u_\infty(z) = u_\infty(z_{min}), \quad z < z_{min} \tag{19}$$

$$k_r = 0.19(\frac{z_0}{0.05})^{0.07} \tag{20}$$

$$I_0 = \frac{1}{\ln(\frac{z}{z_0})} \tag{21}$$

where z_0 is the surface roughness, V_b is the basic wind velocity, $z_{min} \in [1-10] \quad m$ is the minimum height at which the hypothesis of logarithmic profile is verified and k_r is the terrain factor.

Firstly, the free-stream wind is combined with GWM at the upstream wind turbine. There is an appropriate model for free-stream wind provided by the the EUROCODE [14].The input parameters of the free-stream logarithmic profile are shown in Tab. 1:

Wind Magnitude Parameters		
V_b	[m/s]	5.85
z_0	[m]	0.005
z_{min}	[m]	10.0
k_r	-	0.1617
$u_\infty(z = z_h)$	[m/s]	9.2694
$u_\infty(z = z_{min})$	[m/s]	7.1900
$I_0(z = z_h)$	-	0.1020

Table 1: Wind Magnitude Input for the OpenFAST simulation

With the inflow kept constant we set the different wind directions to analyze the performance of the waked turbines. The initial parameters are shown in Tab. 2:

Wind Direction Parameters		
t_{end} **[s]**	$\theta_{w,start}$ **[deg]**	$\theta_{w,end}$ **[deg]**
50.0	270.0	270.0
100.0	300.0	300.0

Table 2: Wind Direction Input for the OpenFAST simulation

Finally, as previously explained, the Bastankhah and Porté-Agel [1, 2] GWM takes the parameters shown in Tab. 3:

3.2 Wind Farm Layout

The considered wind farm as a 3x2 layout. The initial wind direction is 270 degree, i.e. the wind comes from west. The positions of the 6 NREL 5MW turbines are shown in the Tab. 4, where the diameter of blades is $D = 126.0\ m$, and the hub height is $z_h = 90.0\ m$, as previously specified.

In this layout, when the wind direction is blowing from west, turbines in the second row are affected by the wake generated by the first row ones and the ones on the third row by a superposition of the wakes coming from first and second.

BPA-GWM Parameters	
k_a	0.200
k_b	0.003
α	0.48
β	0.077
C_I	0.8
e_1	0.73
e_2	0.1
e_3	-0.275

Table 3: Bastankhah and Porté-Agel [1, 2] GWM Parameters for the OpenFAST simulation

Wind Farm Layout			
	x [m]	**y** [m]	**z** [m]
T1	0	363.51	90
T2	630	363.51	90
T3	1260	363.51	90
T4	0	-363.51	90
T5	630	-363.51	90
T6	1260	-363.51	90

Table 4: Reference 3x2 Wind Farm geometric configuration

3.3 General Modules Setup

After setting the inflow and the layout we should set the modules accounting for the turbines dynamic response. The input file ElastoDyn contains the model for the structural behaviour of the machine. The rated angular speed of the turbine is set to $\dot{\theta}_r = 12.1\,rpm$. The wind speed considered in the simulations is lower than the rated one, $u_{\infty,rated} = 11.4\,m/s$. It takes a certain time, about 50.0 s, for a steady state model to get the equilibrium point.

ElastoDyn is also used to simulate the aerodynamics nearby the turbine. If we turn on the Yaw DOF, the wake steering can improve the performance of power generation. We have to take into account the fact that changing the yaw angle causes different the wind magnitude on the $x - axis$ direction.

The input file AeroDyn v15 is responsible for controlling the simulation. A classical BEMT model and the relative parameters are applied in this module. The maximum number iterations, $n_{it} = 10000$, actives convergence of the AIF and TIF in the simulation. In this input file, Glauert tip loss and hub loss correction are implemented. The unsteady Beddoes-Leishman model with the Minnema-Pierce variant is also used for blade aerodynamics.

4 Simulation and Result

4.1 Simulation With 270 Degree Wind Direction

Fig.3 shows the wind velocity at different rows. First, second and third row of turbines are represented by red line, yellow line, and blue line respectively. The first row sees the uniform free-stream wind at 9.4 m/s. On the second row, the yellow line, we see a sharp decrease (about 17%) as effect of the wake from the upstream row. A slight additional decrease (about 7%) is experienced by the third row, as shown by the blue line.

Torque and power of the turbines are shown in Fig.4 and Fig.5. Between the first row and last two rows, there is a obvious decrease on torque and power, consequence of the less energetic flow investing them. Specifically, torque and power generator have about 30% and 31% reduction respectively. Analogously to what happened for the wind speed in Fig.3, machines at second and third rows have closer outputs, about 5% decrease for both torque and power generation. This means that the wake from the closest upstream turbine takes primary effect in this wind farm layout.

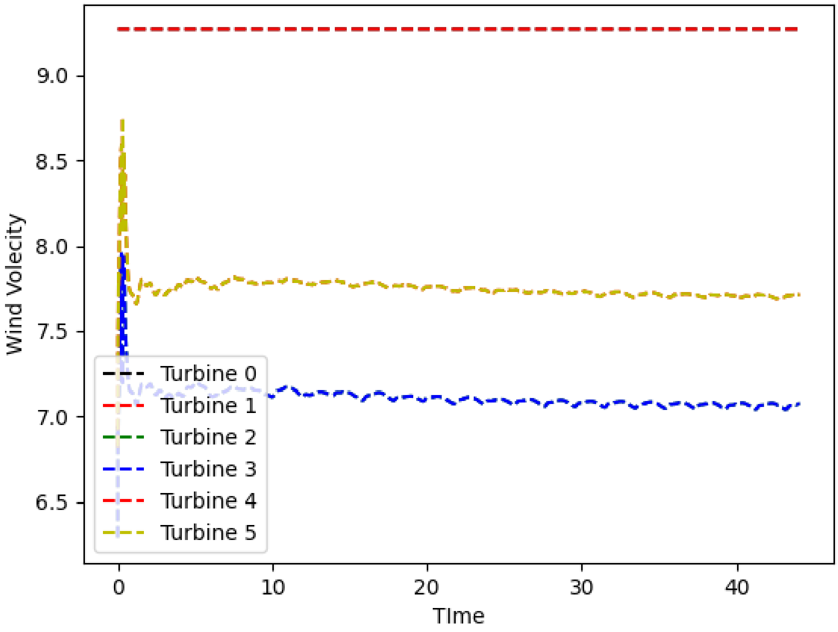

Figure 3: Wind velocity at different turbines against 270 degree wind direction

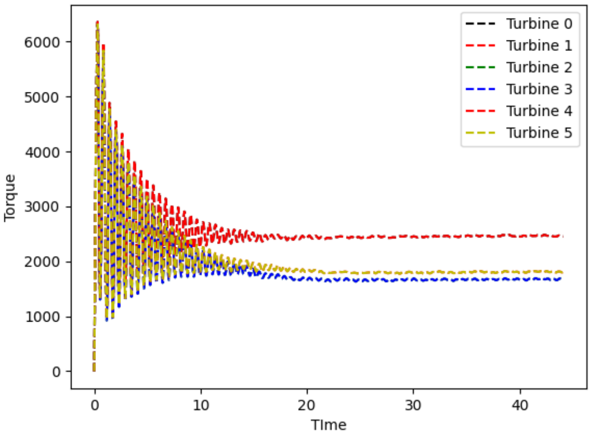

Figure 4: Toque of different turbines against 270 degree wind direction

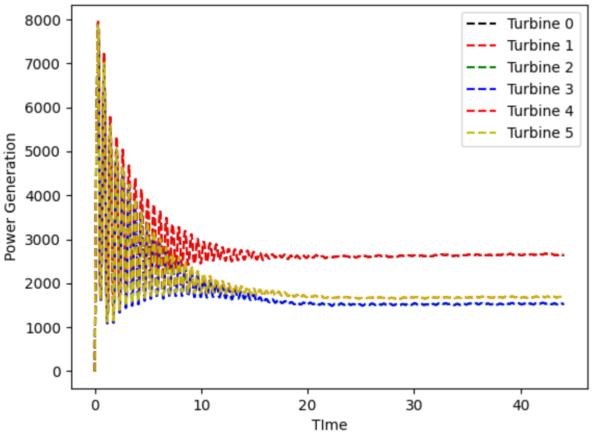

Figure 5: Power generation of different turbines against 270 degree wind direction

4.2 Simulation With 300 Degree Wind Direction

In this second simulation, the wind direction changes from 270 degrees to 300 degrees, i.e. there is a 30 degrees shift for each wind turbine. In this case, turbine 1 and turbine 6 align. With the proposed GWM, the diameter of the wake is too small to act on downstream turbines that do not align on the wind direction. Thus, only turbine 6 is affected by the wake from the turbine 1, other turbines are impacted by free-stream wind and their performances are not affected by waked conditions.

The incoming wind velocity on the different turbines is shown in Fig.6. Turbines 1 to 5 have same constant wind speed with the first row in Fig.3. Turbine 6 sees a lower velocity because of the influence of the wake. Because the high distance between the upstream turbine (1) and the downstream one (6),

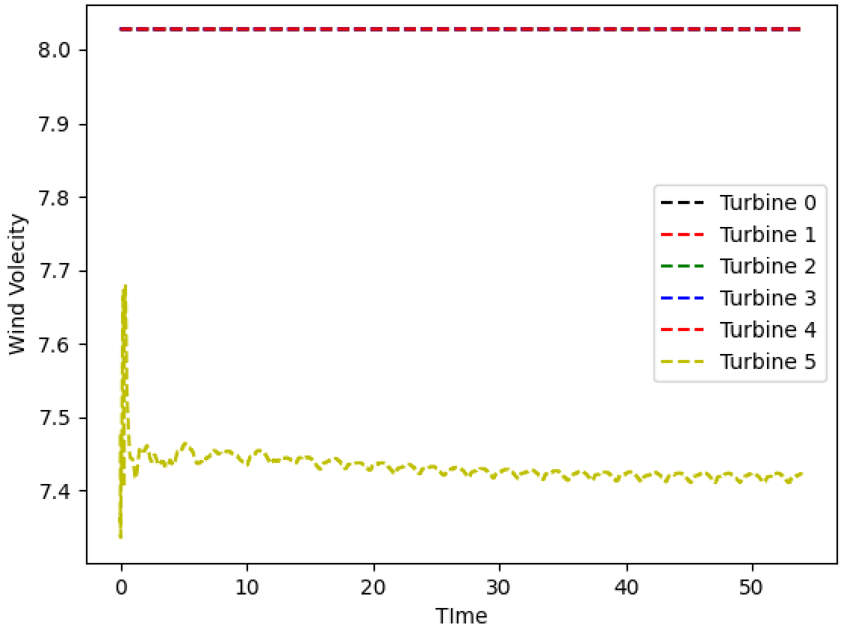

Figure 6: Wind velocity at different turbines against 300 degree wind direction

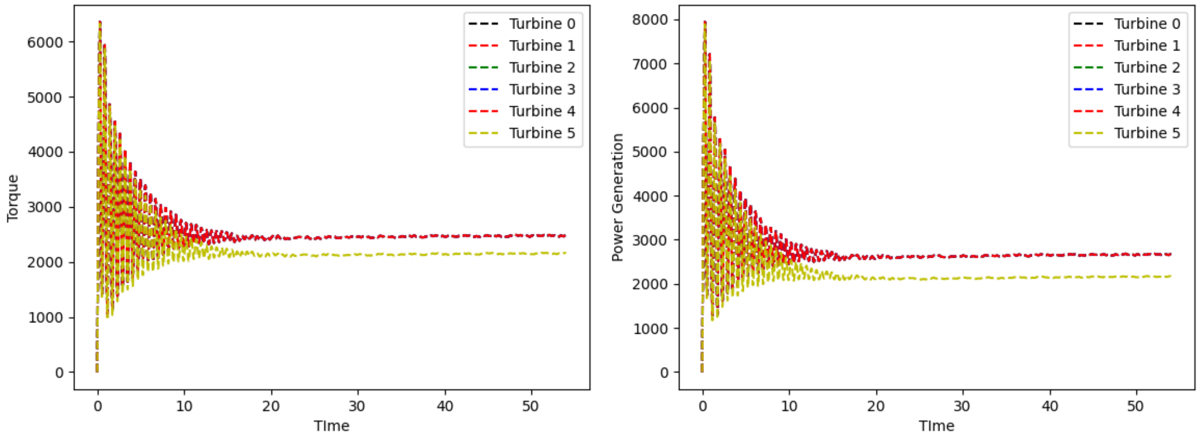

Figure 7: Toque of different turbines against 300 degree wind direction

Figure 8: Power generation of different turbines against 300 degree wind direction

the influence of wake becomes smaller with respect to the previous simulation and wind speed decreases of 7% only.

Fig.7 and Fig.8 show the torque and power generation for this case. As expected, the outputs of downstream turbine are larger than those of the last two rows in the previous simulation. Turbine 6 has a 16% reduction on torque and a 17% reduction on power generation. Comparing the result in these two simulation, again, the distance between upstream turbine and downstream turbine appears to play a critical role.

5 Conclusion and Future Work

In this paper, the GWM originally proposed by Bastankhah and Porté-Agel [1, 2] has been changed in order to be coupled to OpenFAST. To accomplish this task, a user defined InfloWind routine has been written in Fortran language. To test the new wind model, a simulation was performed using a 3x2 layout in two different wind configurations. The first, with the wind blowing from 270° and the second with the wind blowing from 300°. From these simulations, it is possible to see that the model is working as expected (lower wind speed on downstream turbines and, when the wind is rotated of 30° from the west direction, the wake generated by the Turbine 1 is covering the rotor of Turbine 6).

The newly proposed tool (OpenFAST coupled to the GWM) is a refinement of NREL's FLORIS, since now the AIF and C_T of the various turbines are obtained form an aero-elastic code (able to evaluate AIF and C_T on the whole rotor) and no more from a $C_T - TSR$ table. However, further improvements can be made to this software; among them, the most important are a wake transport model (that could be implemented to have a more realistic simulation) and a more detailed turbulence model. Adding these two model to the tool, would lead to the creation of a more complete software that could be used for real-time control (or for estimation purposes) of wind farms.

For what regards future work, the coupling between the GWM and OpenFAST offers many new research opportunities.

Of course, since the tool is new, much more simulations with different wind farm layouts and wind input parameters can and will be performed. Moreover, it could be possible to use the tool to investigate different layout configurations for new wind farm sites in order to reduce the rental cost for the owner while maximizing the power extraction from the machines. Another possibility, instead, could be to use it on already existing wind farms to perform studies on power maximization (i.e.: finding the optimal yaw angle set-points of the farm using the wake steering method), load minimization or multi-objective optimization in general (i.e.: combining load minimization and power maximization).

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