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A REVIEW OF WIND TURBINE WAKE MODELS FOR WIND PARK OPTIMIZATION

Antonio Carlos de Barros Neiva
Vanessa Gonçalves Guedes
Caio Leandro Suzano Massa
Daniel Davy Bello de Freitas
Centro de Pesquisas de Energia Elétrica – CEPEL – Av. Horácio Macedo 354, Cidade Universitária – Rio de Janeiro, RJ.
neiva@cepel.br, vanessag@cepel.br, caiomassa@poli.ufrj.br, danieldavy@poli.ufrj.br

Abstract. *The energy production of a wind park is strongly affected by the turbine wakes, which may reduce up to 20% of the power output due to velocity deficit and turbulence. Two problems on physics dynamics, atmospheric turbulence and airfoil flow, must be handled by the wake model so the energy production forecast has enough precision as required by financial institutions. The computational cost and the precision of the available models are inversely related, many choices are available and there is a vast opportunity for improvement in ongoing research. In this paper we review seven wake models, three commercial software available on the market that use the turbine wake models, and two open source tools developed in NREL (National Renewable Energy Laboratory (NREL): FLORIS (FLOw Redirection and Induction in Steady state) and SOWFA (Simulator fOr Wind Farm Applications), with different physical approaches that can be used to better understand the complex flow around the turbine and in a wind park. Floris uses kinetic based models to predict wind flow and it can quickly calculate and simulate a great range of parameters, while SOWFA uses complex CFD (Computer Fluid Dynamics) schemes.*

Keywords: *wind power, wake effect, mathematical models, CFD*

1. INTRODUCTION

The growth of economic activities and of the earth population leads to an increasing energy demand. Environmental issues connected to the global warming due to greenhouse gas emission in the atmosphere place restriction on the use of the fossil fuels, so renewable energy sources have experienced considerable and consistent growth. In Brazil, wind energy has a special appeal, as the higher capacity factor achieved due to our wind quality leads to expressive financial advantages, and as a result the installed capacity increased from under 1 GW in 2010 to over 14 GW in 2018 (ABEEolica, 2019).

In the wind farms, wind turbines are placed relatively close to each other. It is well-known that the region downstream of any obstacle suffers with increased turbulence and wind velocity reduction, which reduces the amount of energy available to the downstream turbines. This aerodynamic interference is known as wake effect. To achieve better production in a competitive market, a better knowledge of the energy loss due to the wake is necessary.

Modelling wind turbine wake is especially important for offshore applications. The reduction of the energy production due to the presence of upstream wind turbines can reach 20% (Gaumont *et al*. 2012). Nowadays, besides optimisation of the wind plant layout to maximise energy production, the use of wake models have applications for daily operation, known as wind sector management, which may include individual yaw control (Gebraad *et al*., 2014).

2. ENGINEERING WAKE MODELS

In a general form, wake models apply aerodynamic simulations considering mass and momentum conservation principles. These models assume the wake is homogeneous, axisymmetric and consider wake expansion.

2.1 Park / Modified Park / Jensen

The Park wake model was originally developed by Jensen (1983). It is an empirical model, based on the linear expansion of the wake considering balance of momentum and the wind speed deficit evaluated by a single parameter, related with the thrust coefficient of the turbine. This model was enhanced, thus being known as the Modified Park Model (Katic *et al.*, 1986), by considering specific wind turbine characteristics, and the calculated wake loss is proportional to the sum of the squares of velocity deficits.

The wind velocity deficit in the wake region is calculated as:

$$D_u = \frac{1 - \sqrt{1 - C_T}}{(1 + \frac{2\alpha x}{D})^2} \tag{1}$$

$$D_u = \Delta U / U_0 \tag{2}$$

Where U_0 is free stream wind speed, C_T is the thrust coefficient, D is the rotor diameter, x is the distance in the downstream direction, D_u is the velocity deficit on the wake and α is the wake radius increase rate (or wake decay constant) which default value is 0.075. It was shown by Peña and Rathmann (2014) that the wake decay constant is dependent of roughness, turbulence separation and atmospheric stability, and the authors recommend a function that has good agreement with data from a wind farm. Figure 1 shows the wind velocity deficit propagation applying the Jensen model generated within the Floris framework.

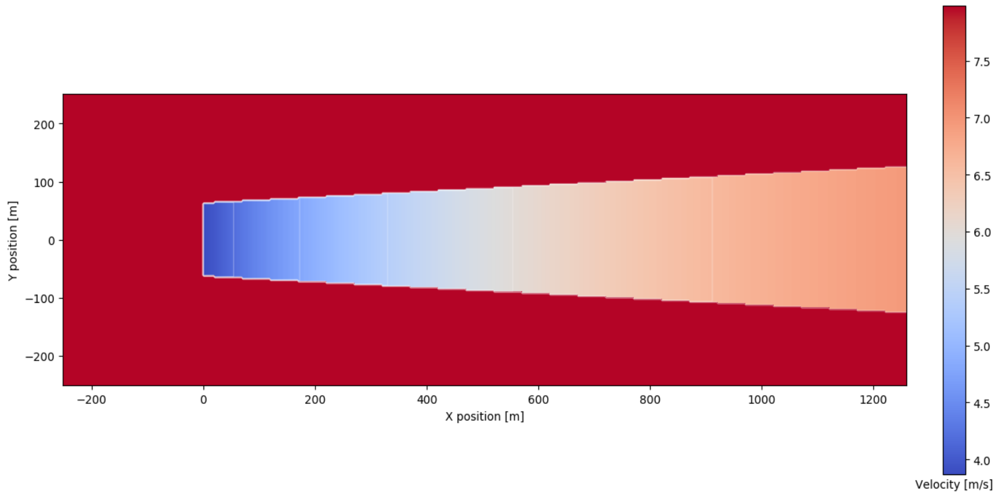

Figure 1 - Jensen model wake propagation - Generated within Floris framework (see section 5.1.2)

This model predicts the wake well under normal operation conditions and is computationally very efficient (Churchfield and Sirnivas, 2018), but due to the simplicity of implementation and the physical considerations, it does not conserve momentum, is not very accurate under specific atmospheric inflow conditions and may overpredict the energy production of the last turbines (Gaumont *et al.*, 2012). The model has been improved by Choi and Shan (2013) to include partial wake interaction, yaw misalignment and adjustment for unsteady wind.

2.2 Larsen

The Reynolds-Averaged Navier-Stokes equations (RANS) decompose the flow properties as an expected averaged value plus a fluctuation term, which results in the existence of a non-linear Reynolds stress term.

Larsen (1988) uses first and second order approximations of RANS, the Reynolds stress is modelled using mixing length theory and the pressure term is not considered. The problem is assumed to be steady, axisymmetric and self-similar along the perpendicular direction to the flow. The first order wake model is expressed as

$$U_0 \frac{\partial u_x}{\partial x} = \frac{1}{r} \frac{\partial}{\partial r} \left[{l_m}^2 r \left(\frac{\partial u_x}{\partial r} \right)^2 \right] \tag{3}$$

$$u_x(x,r) = \frac{U_0 (C_T A x^{-2})^{1/3}}{9} \left[r^{\frac{3}{2}} (3{c_1}^2 C_T A x)^{-1/2} - \left(\frac{35}{2\pi} \right)^{\frac{3}{10}} (3{c_1}^2)^{-1/5} \right]^2 \tag{4}$$

Where $l_m$is the mixing length, u_x is the wake perturbation along the axial direction, u_r is the wake perturbation along the radial direction, r is radial direction, and c_1 is a calculated parameter.

He improved the model in 2009, with empirically determined boundary conditions and developed a procedure to adapt to wind farm applications, due to earlier version considering the single wake case only and providing no solution for multiple wake situations. The later version of the model defines two methods to calculate the inflow speed at each turbine, the geometric averaging and the momentum balance. The total velocity deficit for a given location is calculated as the linear sum of the velocity deficits induced by all upstream turbines. The velocity recovery and wake expansion are controlled by the thrust coefficient and the ambient turbulence intensity.

2.3 Frandsen

The Frandsen model has the objective to cover all the scales of flow and contains three regimes of wake. The first is a multiple wake-flow exposed to turbines, the second is when the wakes from neighboring rows meet and merge and the third is the effect of the wind farm on planetary boundary layer.

The wind speed in the wake *U(x)* varies in the stream-wise distance (*x*) but is assumed as constant in the wake area (Frandsen *et al*., 2006), determined as:

$$\frac{U(x)}{U_0} = \frac{1}{2} \pm \frac{1}{2}\sqrt{1 - 2\,\frac{A_0}{A(x)}C_T} \tag{5}$$

Where A_0 is the rotor area and A(x) the wake area; (A(x =0) = A_0). The '+' signal must be used when the induction factor $a \leq 0,5$, and the '-'applies for $a > 0,5$; assuming $a = 1 - \sqrt{1 - C_T}$.

The authors suggest the following expression for the expansion of the wake diameter of a single wake.

$$D(x) = \left(\beta^{k/2} + 2\alpha S\right)^{1/k} D_0 \quad ; \quad \beta = \frac{1+\sqrt{1-C_T}}{2(\sqrt{1-C_T})} \tag{6}$$

Where $D(x)$ is the wake diameter, D_0 is the rotor diameter, $= \frac{x}{D_0}$, k = 2, and α is the expansion constant, that should be determined experimentally An initial estimate of the expansion constant combining different models was presented by the authors,

$$\alpha = \beta^{k/2}[(1 + 0{,}1S)^k - 1]s^{-1} \tag{7}$$

2.4 Bastankhah and Porté-Agel Wake Model

The model proposed in 2014 by Bastankhah and Porté-Agel (2014), also known as BP wake model, is an analytical model based on a Gaussian distribution for the velocity deficit in the wake, applying conservation of mass and momentum, ignoring the viscous and pressure terms in the momentum equation. The velocity deficit assumed in the model is as follows:

$$\frac{\Delta U}{U_0} = C(x)e^{-\frac{r^2}{2\sigma^2}} \tag{8}$$

Where σ is the standard deviation of the velocity deficit profiles, and $C(x)$ is the maximum normalized velocity deficit at the wake centre. Using this expression in the simplified momentum and considering a linear expansion for the wake region we have the following expression:

$$\frac{\Delta U}{U_0} = \left(1 - \sqrt{1 - \frac{C_T}{8\left(\varepsilon + \frac{\alpha x}{d_0}\right)^2}}\right) exp\left(\frac{-1}{2\left(\varepsilon + \frac{\alpha x}{d_0}\right)^2}\left[\left(\frac{z - z_h}{d_0}\right)^2 + \left(\frac{y}{d_0}\right)^2\right]\right) \tag{9}$$

Where $\varepsilon = \frac{\sqrt{\beta}}{4}$

And β was defined above (Frandsen *et al*., 2006), x, y and z are streamwise, spanwise and vertical coordinates, respectively, d_0 is the diameter of the wind turbine and z_h is the hub height. Figure 2 shows the wind velocity deficit propagation using the BP model and has been generated within the Floris framework. It is noticeable the gauss like behavior of the wake decay.

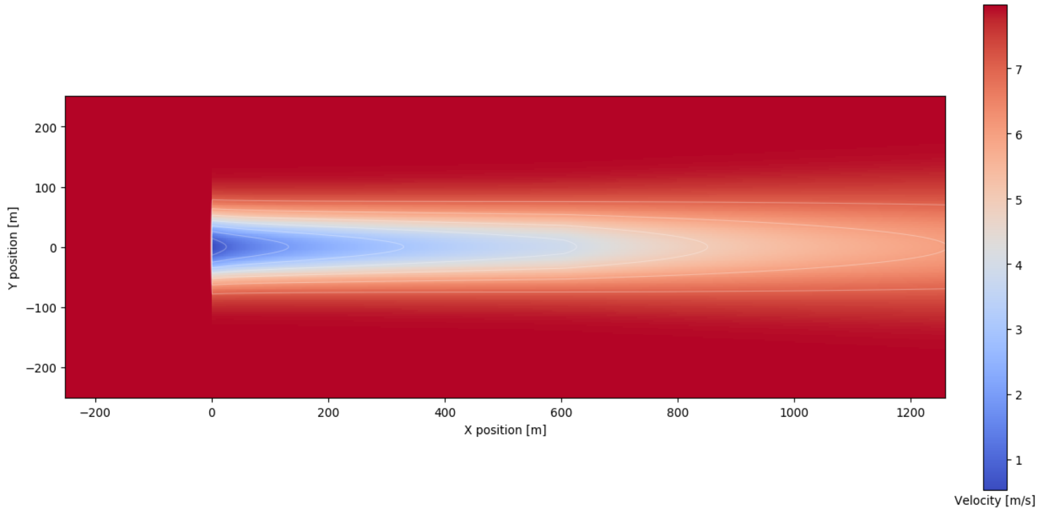

Figure 2 - BP model wake propagation -Generated within Floris framework (see section 5.1.2)

The authors found that the comparison with high-resolution wind-tunnel measurements and high-quality Large Eddy Simulation (LES) data shows that the velocity profiles obtained with the proposed model are in acceptable agreement with these experimental and LES data for different case studies.

3. MODIFIED RANS WAKE MODELS

The following models incorporate either the interaction of one of the previous models with a Planetary Boundary Layer model or a CFD (Computational Fluid Dynamics) algorithm based on RANS. The challenge of the advanced wake models is to achieve realistic results at a computational cost that is acceptable for the desired application.

These models also consider turbulence intensity, added turbulence generated by upstream turbines and include atmospheric stability, while some of them consider asymmetric effects such as the lateral displacement of the wake from the rotor axis and the Coriolis acceleration.

3.1 Ainslie or Eddy-Viscosity (EV)

Based on Ainslie (1988), this model was derived by simplification of the RANS equation, with thin shear layer approximation and the eddy-viscosity closure term for the Reynolds stress. It is assumed that the wake is axisymmetric, stationary, turbulent, without tangential velocities.

$$U\ \frac{\partial U}{\partial x} + V\ \frac{\partial U}{\partial r} = -\frac{1}{r}\ \left(\frac{\partial (r\overline{u'v'})}{\partial r}\right) \tag{10}$$

U and V are the axial and radial velocities, respectively.

A few diameters downstream, the wind profile is considered a Gaussian curve in the near wake, calibrated using wind tunnel data, and turbulent mixing with free-stream wind is used to describe the shear stresses. The Reynolds stress is modeled as:

$$-\overline{u'v'} = \varepsilon\ \frac{\partial U}{\partial r} \tag{11}$$

$$\varepsilon = l_w(x)u_w(x) + \varepsilon_a\ = F[k_1 b(U_0 - U_w\ ) +\ K_M] \tag{12}$$

Where ε is the dissipation of turbulent energy, l_w is a suitable length scale, u_w is a suitable velocity scale, ε_a is the ambient turbulence contribution. The length and velocity scales are proportional to the wake width and the velocity difference across the wake shear layer. k_1 is the dimensionless constant proposed by Ainslie, that equals this value to 0.015, and K_M is the eddy viscosity of momentum. In the near wake (up to 5D), a filter function (F) is applied to correct for the lack of equilibrium between the mean velocity field and the turbulence field. The flow field can then be solved with a finite difference scheme.

$$F = \begin{cases} 0.65 + \left[\dfrac{x - 4.5}{23.32}\right]^{1/3}, & x < 5.5 \\ 1, & x \geq 5.5 \end{cases} \tag{13}$$

3.2 Fuga

Based on the RANS equations with simple turbulence closure, the Fuga model (Ott and Nielsen, 2014) is an improved model that account for atmospheric stability. Simple turbulence closure with atmospheric stability is expressed as:

$$\upsilon_t = u_* \kappa z \tag{14}$$

Where κ is Kármán constant and $u*$ is the friction velocity. This model uses a simplified and linearized RANS equation with Taylor expansion, ignoring the terms with orders higher than one for the velocity, pressure, forcing term, turbulent kinetic energy and the dissipation of turbulence energy.

$$u_j \frac{\partial u_i}{\partial x_i} = \frac{\partial}{\partial x_j} \frac{u_* \kappa z}{\phi_m(z/L)} \left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right] - \frac{\partial p}{\partial x_i} + \xi f_i$$
$$u_i = u_i{}^0 + u_i{}^1 \xi + u_i{}^2 \xi^2 + \cdots \tag{15}$$

The zero order is the case without perturbation to the flow, i.e. the case without turbines. The resulting equation is simplified again using the Fourier transformation. The turbine is modelled using an actuator disk technique, and for the multiple wake case it uses a system of look-up tables and linear summation to construct the velocity field of the array.

The latest version includes detailed atmospheric stability and wake meandering effects, but it still assumes a horizontally homogeneous atmospheric boundary layer, Therefore, it is best suited for flat terrain with a relatively constant roughness length, so it is mainly used for offshore wind farms. Due to its simplicity in wake modelling, Fuga has shown to perform as well as full CFD at 10^{-5} to 10^{-8} the cost (Churchfield, 2013). Measurements at two offshore wind farms were compared to three model results (Gaumond *et al*. 2012 and Beaucage *et al*. 2012), where Fuga achieved better fit to data than Park or Larsen models.

4. MICROSCALE COMMERCIAL TOOLS FOR WAKE MODELLING

Commercial tools that creates a Wind Resource Grid (WRG) on the area where the wind farm is (or will be) installed are microscale models. The WRG is a wind map that is used for optimization of the positioning of the wind turbines at the site and to calculate the energy production of the wind farm. In the following sections, the main features concerning wake turbine of three products commercially available are commented.

4.1 WAsP

WAsP is developed by the DTU Wind Energy, uses a linearized RANS wind flow model and the Modified Park model is available for modelling wake energy losses. The combined effect of the turbine wakes is based on the model described in Katic *et al.*, 1986. The model considers the incident wind, the wind turbine characteristics (thrust coefficient and the rotor diameter), the wind farm layout and the wake decay constant. The wake decay can be specified according to the wind direction sector. DTU offers the Fuga wake model as a stand-alone application for offshore wind farms. It does not run on WAsP itself, but it takes most of its input from it.

4.2 Openwind

Openwind is a UL product (former AWS Truepower and DEWI) for creating and optimizing turbine layouts. It runs a mass-consistent based wind flow model, being an increasingly popular tool due to the friendly graphic user interface, low computational cost and good agreement with experimental results. It includes the following wake models: Jensen, Modified Park, EV, Deep Array Park Variant and Deep Array EV, the latter being the default option for energy production estimates. Both Jensen and Modified Park models have similar settings, but for multiple turbines the Modified Park uses the maximum deficit, whereas Jensen combines their effects.

The Deep Array Wake Model (DAWM) theory states that a large wind farm interacts with the Planetary Boundary Layer (PBL) by creating an Internal Boundary Layer (IBL) of slower flow due to increased surface roughness (Churchfield, 2013). Two components are used on DAWM; one is the IBL approach based on Frandsen model, and the other uses a standard model, such as EV or Park. The main parameters for the DAWM are the wind park equivalent roughness length and the wake width angle. Their default values are respectively 1.65 m for onshore or 1.16 m for offshore, and 7.5° for both onshore and offshore wind farms, according to validation performed by the developer (Brower and Robinson, 2012). A similar approach has been taken on the "Large Array Wind Farm model" in WindFarmer (Beaucage *et al*. 2012), the wind resource assessment software by DNV-GL.

4.3 WindSim

The wind flow model in WindSim is a CFD based on RANS. The available wake models used for energy production estimates are analytical. However, instead of this post-processing treatment, 3D models of the turbines can also be included in the wind flow model using the actuator disk theory. Jensen and Larsen are the basic models available. Additionally, WindSim includes a third wake model with the rate of wake expansion depending on turbulence (Ishihara *et al*., 2004). The user must then select how to combine the effects from multiple wakes—either by linear summation or by the root sum of squares.

5. FULL CFD WAKE MODELS

Turbine modelling may use either the Actuator Disk Model (ADM) or the Actuator Line Model (ALM). The ADM describes the turbine blades as a disk which is divided into many elements, while the ALM represents the turbine blades as they actually are discretized into spanwise sections (Sørensen and Shen, 2002). Drag and lift are calculated at each section based on physical and operational parameters. The ALM is able to capture vortical structures due to the presence of individual blades while the ADM considers a symmetric wake. All previous models reported are ADM, because ALM and BEM simulations are only possible within CFD models.

As commercial wind modeling tools have greater commitment with computational cost and user friendly interface, strong simplification of fluid flow are assumed. By the other hand, full CFD models consider full Reynolds-Averaged Navier Stokes (RANS) or Large Eddy Simulation(LES), with advances being made to use Detached Eddy Simulation (DES). Due to extremely expensive computational cost, Direct Numerical Simulations (DNS) is no used for wind turbine simulations yet.

Full fluid motion modelling retains all the terms of the Navier-Stokes equations. Réthoré (2009) argued that the Boussinesq hypothesis, which has shown to dominate RANS wind turbine wake simulations, is violated in the vicinity of a wind turbine. LES achieves better agreement with field measurements but needs a finer mesh and long simulation time to resolve the wake, requiring three orders of magnitude more computational resource than RANS.

5.1 DEVELOPMENT TOOLS

The National Renewable Energy Laboratory (NREL) is a leading developer in the renewable engineering field, which has created a family of open source computational models, such as SOWFA (Simulator fOr Wind Farm Applications), FAST (Fatigue, Aerodynamics, Structures and Turbulence), and FLORIS (FLOw Redirection and Induction in Steady state). These applications are used for wind farm control design and optimisation (Jonkman *et al*., 2017).

Important details can be implemented in CFD turbine wake models, such as asymmetric effects and detailed atmospheric stability effect on the PBL. The lateral displacement of the wake from the rotor axis may be caused by the so-called wake meandering (Trabucchi *et al*., 2015) or by the Coriolis force. It deflects the turbine wake clockwise, when observed from above in the northern hemisphere (Abkar *et al*., 2018 and Laan and Sorensen, 2017).

5.1.1 Floris

FLORIS (FLOw Redirection and Induction in Steady state) is wind plant performance optimization software framework that uses an open source set of control and optimization tools, designed to provide a computationally inexpensive, controls-oriented modelling of the steady-state wake. It is recommended to use Python virtual environment for FLORIS implementation. The package includes different wake models, turbine models and LIDAR (Light Detection and Ranging) measured wind data handling. The wake models in FLORIS provide simulation tools for velocity deficit and wake deflection. It is structured for simple implementation of different analytical wake models, with improvements to account for the partial wake overlap and rotor rotation, in order to increase the accuracy in controls to account for multiple wake zones, wake interaction and wake deflection in yawed flow.

It is also used for wind farm performance estimation, and to predict the effective flow velocities and energy production per turbine as a function of the yaw angle and axial induction of the rotors. Figure 3 shows FLORIS simulations for some wind speeds and directions, using the BP model.

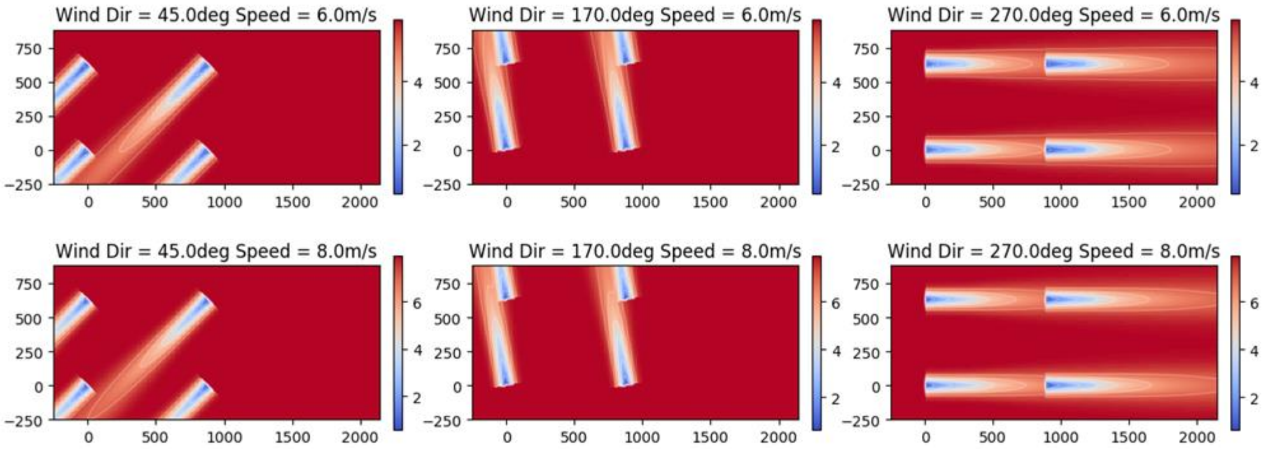

Figure 3-Example of FLORIS implementation - BP model

5.1.2 SOWFA

SOWFA is a CFD toolbox based on OpenFOAM (Open-source Field Operation And Manipulation"), which is the leading free open source software for computational fluid dynamics (CFD), and allows users to investigate the performance of wind turbine and wind plant using LES applying the actuator line turbine wake model. The mechanical effects at the turbine are modelled with FAST (Fatigue, Aerodynamics, Structures, and Turbulence) which is an aeroelastic simulator that predicts fatigue and extreme loads in wind turbines.

SOWFA can incorporate the effects of yaw alignment control in redirecting the wake, pitch control, generator torque control, and atmospheric stability on wakes. All these issues can be combined on the wind sector management facility. In fact, it has been used to demonstrate that the plant power output can be increased by slightly misaligning the first turbine in a row in relation to the wind, thus laterally displacing its wake (Ciri *et al*., 2018)

Being a LES based system, it is mostly used to generate high quality data and to calibrate and evaluate simpler models, because the computational resource needs are relatively high, so not viable for broader use. Figure 4 compares the differences between engineering wake models implemented in FLORIS and the full CFD wake model in SOWFA, for the same input parameters. The inflow angle not perpendicular to the turbine plane is a better opportunity to enhance the difference among the simulations, both close and far from the turbine. The full CFD model also shows an upwind influence on the velocity field.

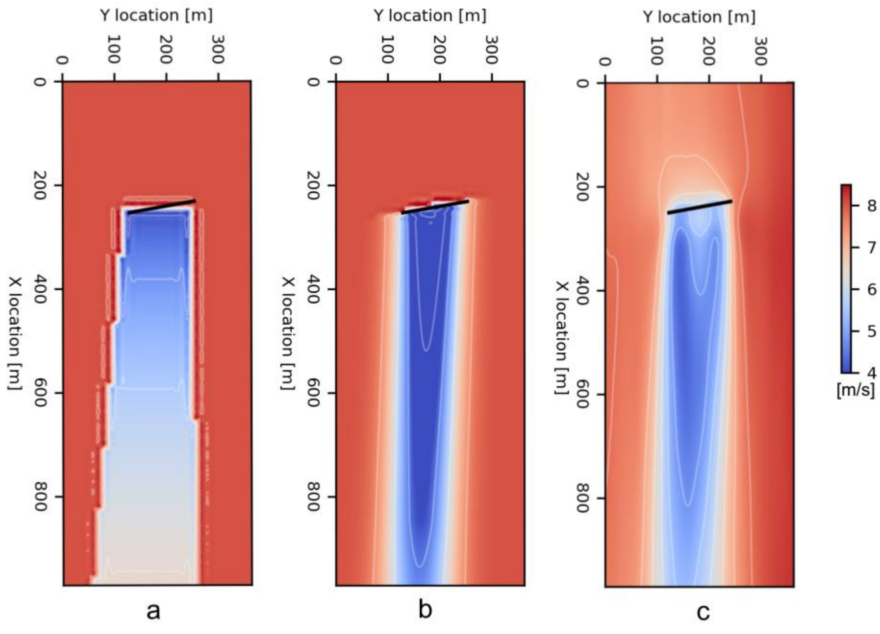

Figure 4 - Comparison of wake models applications:
a) FLORIS – Jensen, b) FLORIS – BP, c) SOWFA – Full CFD actuator line wake model.

6. FINAL REMARKS

The IEC 61400-1 standard requires mechanical loads due to wake turbulence to be determined by the Frandsen wake model, taking into account the effective turbulence intensity I_{eff} at hub height (IEC, 2014). However, pre-construction energy production calculation is not yet covered by IEC standards, but it is expected to feature on the unreleased IEC 61400-15 standard. Meanwhile, the MEASNET guideline lists Park, EV and Larsen for the estimate of wake losses, but states that wake modelling could also be treated as a part of the wind flow model instead (MEASNET, 2016). It also mentions that the uncertainty of the wake losses can be very significant, since most of the wake models are adjusted to small wind farms and near-neutral stratification conditions (MEASNET, 2016), but some of the more advanced models seen in this paper are already capable of handling more complex situations.

The different approaches of wake modelling lead to a variety of choices available for the wind plant designer. The low-level models are fast, require low computing cost, but are not so precise. On the other hand, the expensive and accurate high-level CFD models have their share due to great agreement with experimental data. They are used on research and more recently as a reference for adjusting lower level wake models, eventually using Neural Networks, as developed by Chi Yan (2018).

Future research shall also focus on the asymmetry in the wake propagation, including the effect of the rotational direction of the wind turbine blades, understanding of the strengthens and limitations of the different methodologies and the integration of different techniques to better predict the complex field of wake propagation and wind farm optimisation.

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