sgurr energy
Sustainable Engineering Worldwide

Windfarm Simulation: Flow and Wake Modelling

Aravind Ramachandran

Wind Series

1 Introduction – Wind Farm

Wind farms/Wind Power Plants are a group of wind turbines installed in a specific geographical which has very high wind potential. The turbines are placed in such a way that it maximizes the extraction of kinetic energy from the wind and minimizes wake losses. Wind farms are often located in areas such as coastal regions, plains, and elevated/Undulated landscapes where wind speeds are higher.

The main challenge faced during optimizing the design, operation, control, and grid- integration of these wind farms is the prediction of its performance due to its multi-scale flow interaction between the wind turbines and the turbulent atmospheric conditions prevailing on site.

Industry-standard software linearized fluid flow modelling techniques such as improved ***Jackson and Hunt*** (With RIX corrections) or Computationally Intensive Fluid dynamic solvers such as ***RANS*** (Reynolds-Averages Navier-Stoke techniques) and LES (Large Eddy simulations) to simulate the complex interactions between wind turbines and atmospheric conditions. Also, the wake interactions between these turbines are modelled using different wake modelling techniques such as ***Eddy Viscosity*** or ***N.O Jensen.*** By incorporating blockage deficit and turbulence models, these simulation models provide a reliable estimation of the actual wind flow conditions at the intended project site, enabling the approximate assessment of energy yields for the wind farm. Figure 1-1 depicts the diverse flow interactions observed within a wind farm, which are simulated through the utilization of various engineering models within simulation software.

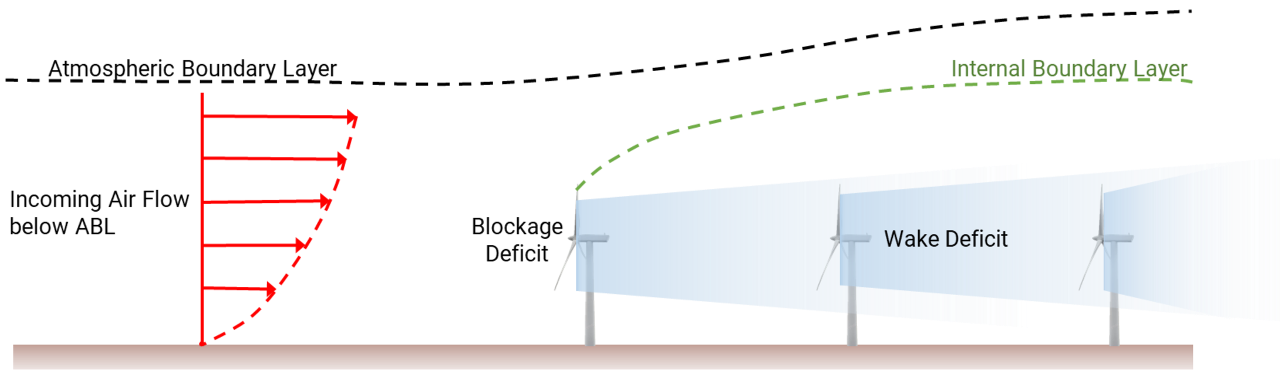

Figure 1-1: Atmospheric flows and their interaction with wind farms

In the following sections of this paper, we will provide a brief overview of different engineering models that form the foundation of various wind farm simulation softwares. These models can be classified into the following categories:

- Wind farm flow model/ Spatial Extrapolation models
- Wind farm/turbine Wake and Superposition model
- Wind farm/Turbine Induction/blockage effect models

Figure 1-2 illustrates the various wind farm flow, wake models and other models utilized by prominent wind farm modelling and energy prediction software's.

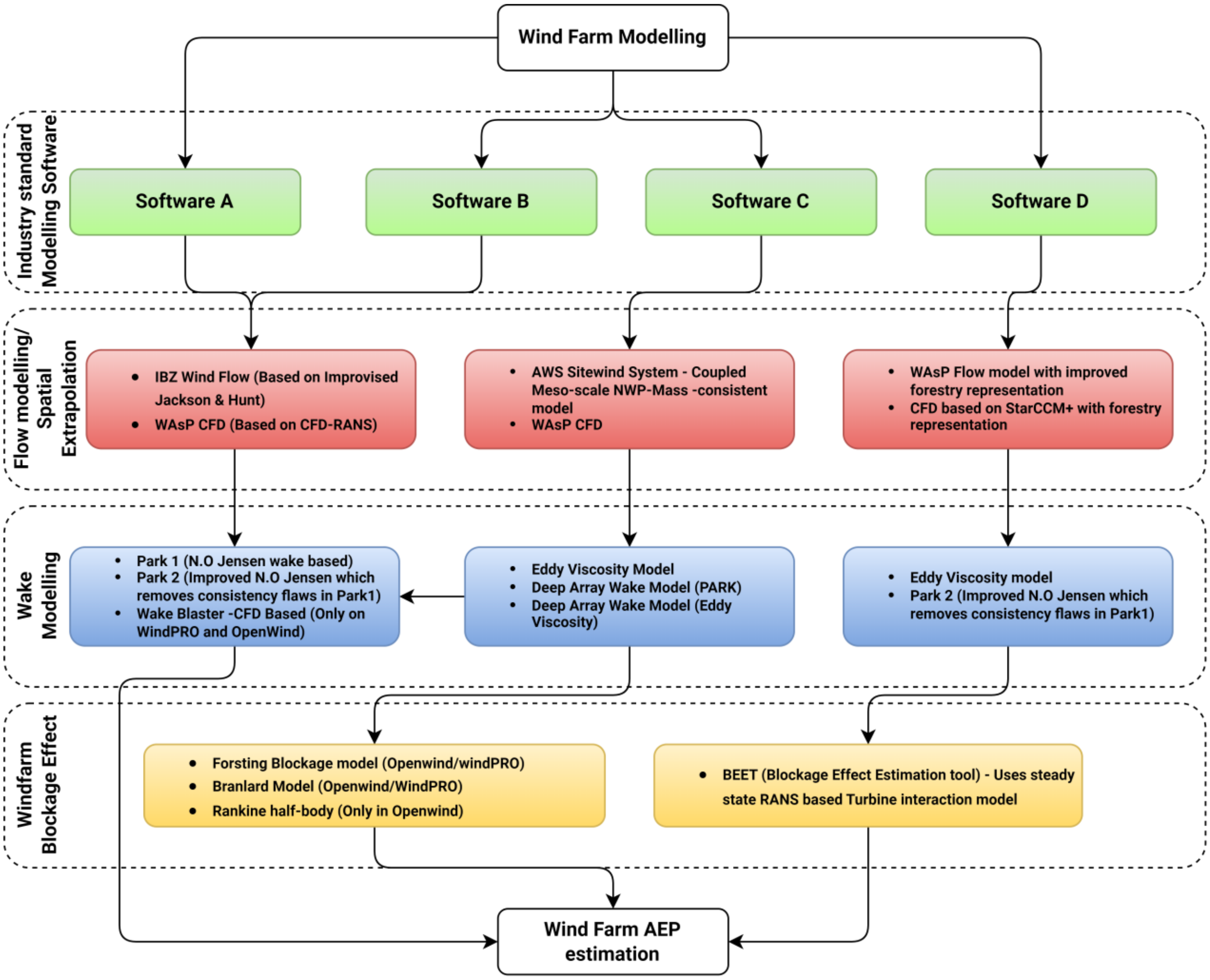

Figure 1-2: Industry standard wind energy software engineering models for wind farms.

In conclusion, wind farm simulations rely on a variety of models to create accurate and comprehensive representations of a wind farm's behaviour; these models should be selected based on relevant site conditions that may affect this behaviour. These encompass flow dynamics, resource grids, wake effects, blockage considerations, and turbulence analysis. By integrating these models, engineers can assess energy production, optimize turbine layout, and evaluate the overall performance of wind farms. The use of simulation models enhances our understanding of wind farm behaviour, aiding in the development of more efficient and productive wind energy systems.

2 Windfarm Flow Models

Wind is a global phenomenon caused due to the differential heating effect of the Earth due to the sun and the Earth's rotational effects. Air acting as fluid moves from the high-pressure region to the low-pressure region created due to this differential heating. From a fluid mechanics perspective, this moving air creates an Atmospheric Boundary Layer (ABL) which is largely affected by local conditions such as surface heating, Turbulent mixing, Advection, surface roughness, and stability. Wind prevailing beyond the ABL are called the geostrophic winds which are not affected by these local conditions. The wind flow models aim to establish a relationship between the complex interactions of air inside ABL and wind turbines. Prominent flow models used for the prediction of wind speeds across the wind farm boundary are mentioned below:

2.1 *IBZ flow model with orographic corrections*

The ***IBZ*** is based on the linearized flow model of ***Jackson & Hunt***[1] where the flow is considered neutral over the terrain. The flow model linearizes the equations of motion (Continuity and ***Navier-stokes*** equations) in Cartesian coordinates for neutral flow perturbations relative to a reference state with constant (height-independent) horizontal wind velocity. This model excludes the stress terms in the governing equations thereby resulting in a flow that is identical to inviscid flow.

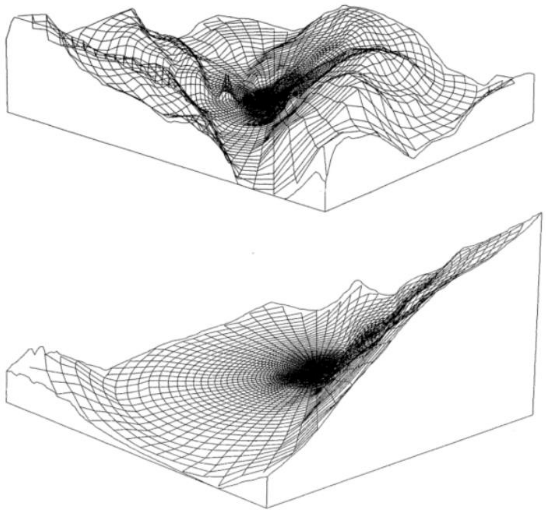

Figure 2-1: Polar Zooming grid theory by Troen

A similar orographic flow model is explained in detail by *Troen* (1989)[2], corrects for the impact of hilly terrain on wind flow by utilizing a polar coordinate system, *Bessel* functions, and *Fourier* series to

[1] Jackson and Hunt (1975) "*Turbulent flow over low hill",* Quarterly Journal of the Royal Meteorological Society Vol 101, Issue 430

[2] Troen (1989) "*A high resolution spectral model for flow in Complex terrain"* Denmark Technological University

calculate potential flow perturbations. The model incorporates the effects of surface friction through turbulent momentum transfer and applies corrections at specific heights. These calculations are performed on a grid, with the point of interest at the center (Polar Zooming Grid)[3]. In addition to these WAsP has introduced the RIX (Ruggedness Index) correction factor to limit the over-prediction of wind farms which is outside the performance index of this type of flow model. The wake interactions between the turbines are modelled separately since they don't capture unsteady and turbulent conditions and are explained in detail in subsequent chapters of this paper.

2.2 *Computational Fluid Dynamic Models*

RANS (***Reynolds-Averaged Navier-Stokes***) and ***LES*** (Large-Eddy Simulation) are two commonly used Computational Fluid Dynamics (CFD) models in wind farm simulations.

In wind farm simulations, ***RANS*** models are commonly used for initial assessments and cases where computational resources are limited. They provide a computationally efficient solution by time-averaging the flow equations (steady State-Incompressible) and using turbulence closure models (*k-epsilon, k-omega Turbulence models*). ***RANS*** models are suitable for analyzing mean flow characteristics and overall wind farm performance considering wind turbines as actuator disk models. However, they may not accurately capture unsteady flow phenomena and detailed turbulent structures such as wake interactions and turbulence fluctuations.

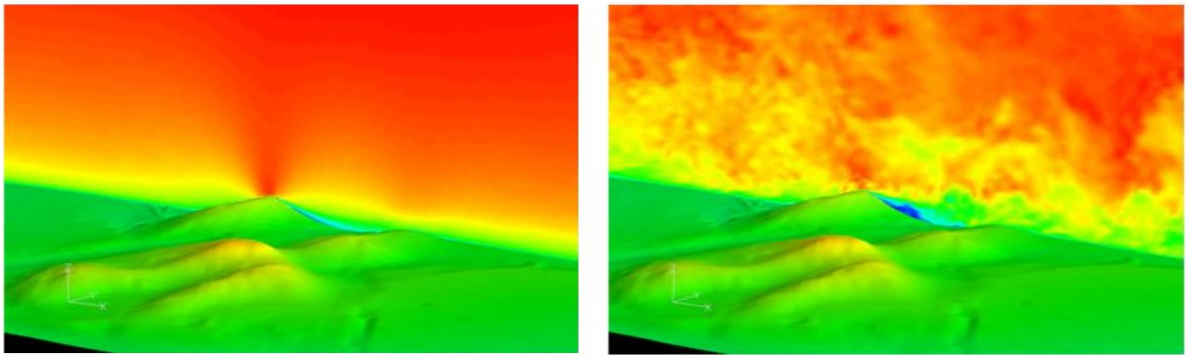

Figure 2-2: Askevian Hill Flow field (RANS vs LES CFD) Simulations[4]

On the other hand, ***LES*** models are preferred for more advanced wind farm simulations that require detailed analysis of turbulent flow and wake interactions. ***LES*** directly resolves a significant portion of the large-scale turbulent structures, providing more accurate predictions of the flow field. It captures the energetic eddies that play a crucial role in wind farm behaviour. This approach is particularly suitable for wind farm simulations as it captures the complex interactions between the atmospheric

[3] Haakon Jahr Sletsjøe (2020) "*Complex terrain: from ruggedness index (RIX), towards physical parameterization*" Master thesis report – Denmark Technological University.

[4] Bechmann & N N Sørenson (2007) *"Atmospheric Flow Over Terrain using Hybrid RANS/LES"* European wind Energy conference and Exhibition

boundary layer (ABL) and wind turbines. ***LES*** provides insights into the spatial and temporal variations of flow velocities, turbulence intensity, and wake dynamics, crucial for optimizing wind farm layout and turbine performance. By accounting for the unsteady and turbulent nature of wind flow, ***LES*** allows for a better understanding of wake effects, turbulence-induced loads on turbines, and the impact of turbine wakes on downstream turbines. However, ***LES*** simulations are computationally demanding due to the need to resolve a wide range of turbulent scales, making them suitable for cases with sufficient computational resources.

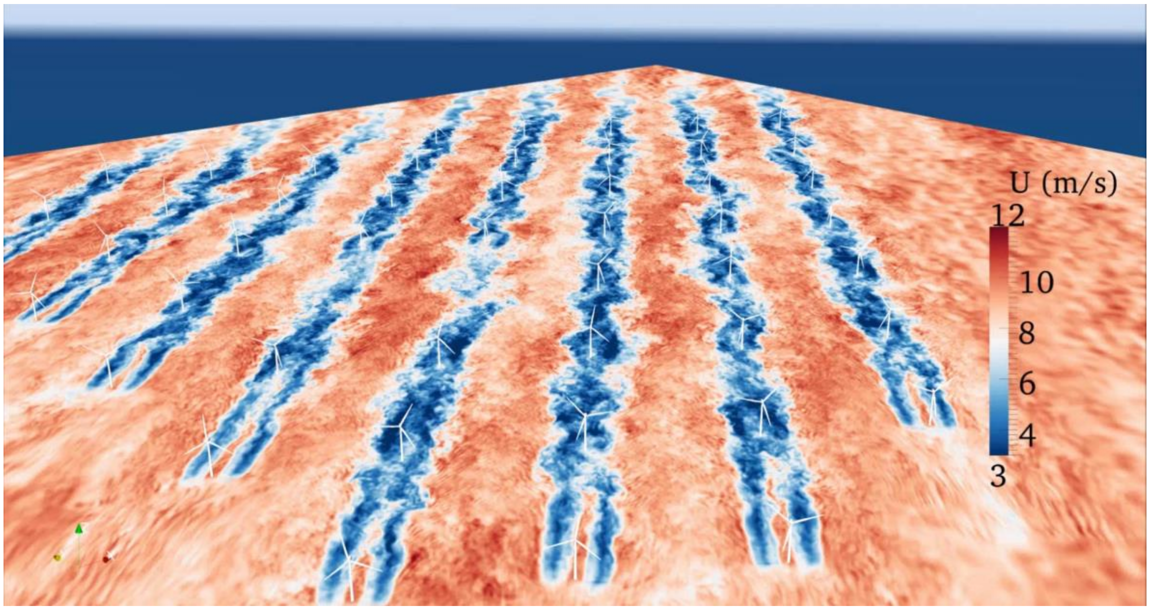

Figure 2-3: Large-Eddy simulations for wind farm applications[5]

The choice between ***RANS*** and ***LES*** depends on the specific objectives of the wind farm simulation. RANS models are often used for preliminary assessments and overall performance evaluations, while LES models are employed when capturing wake interactions and accurately predicting the effects of turbulence on wind turbine performance is crucial. The decision also takes into account the available computational resources and the desired level of accuracy in the wind farm analysis.

[5] Simulator for Wind Farm Applications (SOWFA - NREL) 2017, NAWEA 2017 Training Session

3 Windfarm Wake Models

Wake refers to the disturbed region of airflow that occurs downstream of a wind turbine. As the turbine blades extract energy from the wind, they create a pressure drop and alter the flow direction, leading to the formation of a wake characterized by reduced wind velocity and increased turbulence. This wake is created through the shedding of vortices and exhibits lower wind speeds and higher turbulence levels. Over the years, various wake models have been developed and incorporated into software applications for studying wind turbine wakes. These models vary in type and fidelity, offering different levels of accuracy and detail in capturing complex wake phenomena. Following are the prominent wake models used for modelling wake effects in wind farms:

- ✓ ***N. O. Jensen*** *(PARK2)*
- ✓ ***Bastankhah-Gaussian***
- ✓ ***Eddy Viscosity*** Model
- ✓ ***Frandsen*** Wake Model
- ✓ Large Windfarm Array Wake ***(Deep Array Wake effects)***

In addition to these wake models, this chapter also discusses about various superposition models which are used to define the interaction of multiple wakes between wind turbines due to downstream flow

3.1 *N. O Jensen Wake model (PARK2)*

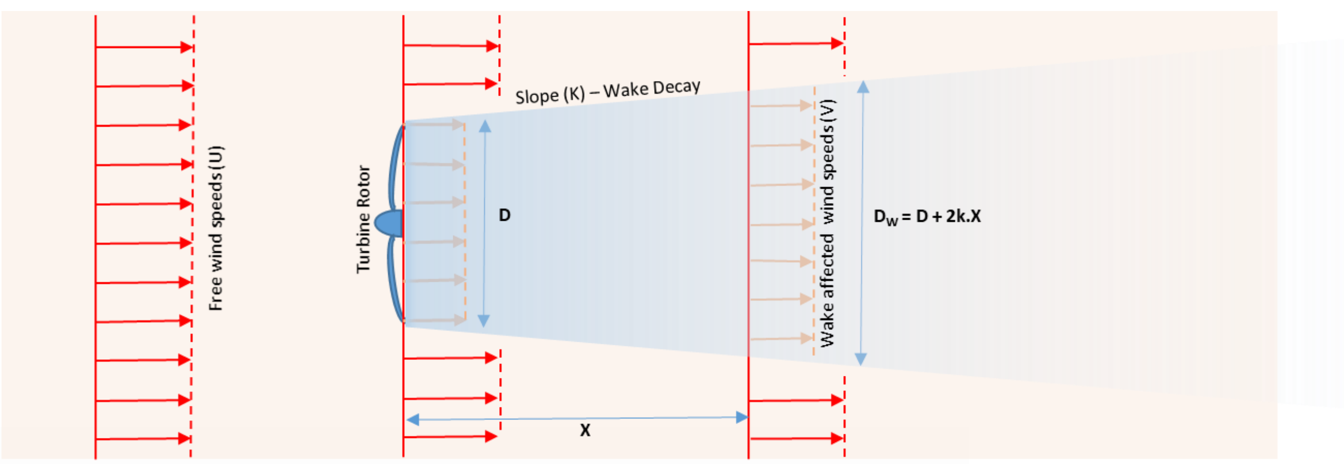

Figure 3-1: *N.O Jensen (PARK2)* top hat wake profile

The ***Park*** model is a commonly used simplified ***N.O Jensen*** wake model in wind farm control studies. This model (i.e. the top-hat wake profile shown in Figure 3-1) is deficient for the far wake but a good approximation in the near wake, e.g. at two rotor diameters downstream[6].

[6] Peña, Réthoré & Paul van der Laan (2015) "*On the application of the Jensen wake model using a turbulence-dependent wake decay coefficient: the Sexbierum case*" Wind Energy , Wiley Publications

It assumes that the turbine can be represented as an actuator disk in a uniform and steady flow. The model incorporates the principles of mass conservation and takes into account parameters such as the thrust coefficient, rotor radius, and wake decay coefficient (*k* - a non-dimensional wake parameter). It calculates the velocity deficit in the wake based on the distance downstream and radial position relative to the turbine rotor. The ***Park*** model assumes a constant radial speed within the wake, expanding radially at a rate determined by k^*x, as depicted in Figure 3-1. However, the model neglects the velocity components in directions other than the axial direction and does not consider turbulence effects or provide insights into structural loads on the turbines[7].

3.2 *Bastankhah-Gaussian Wake Model*

The model, known as the ***Gaussian Wake*** Model (GWM), incorporates the principles of mass conservation and momentum conservation[8]. The velocity deficit is calculated using a normalized equation that considers the maximum deficit, radial distance, and characteristic wake width. The characteristic wake width is assumed to follow a Gaussian distribution. The model also introduces the concept of wake expansion and includes parameters such as the thrust coefficient and rotor diameter. By solving the equations, the normalized velocity deficit in the wake region can be obtained. The model requires the determination of a single parameter, "k^*," which can be derived from experimental data of the velocity profile. The model offers improved accuracy and can be tailored to specific site parameters such as surface roughness and turbulence intensity.

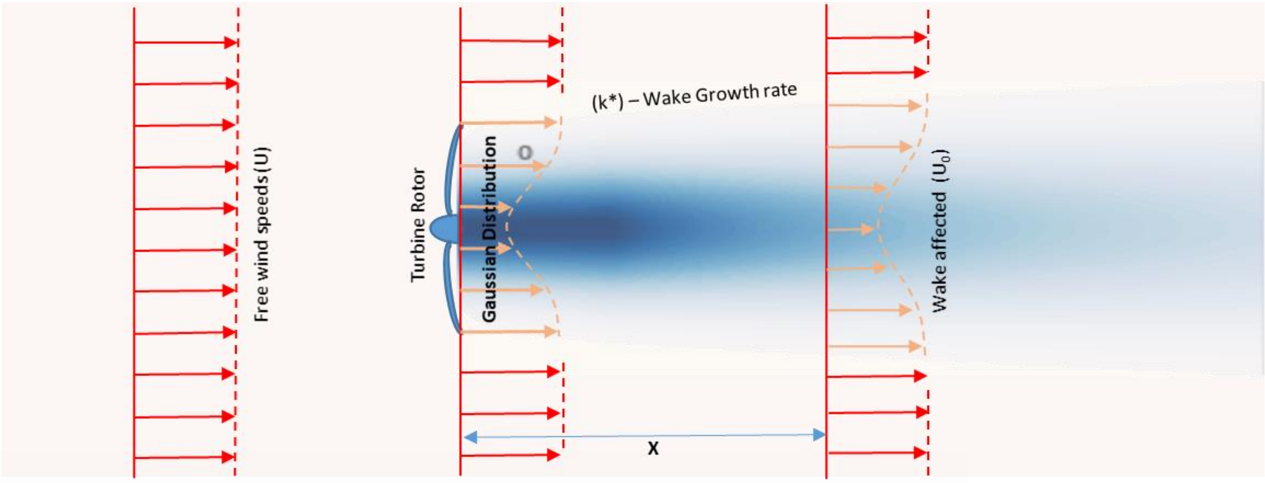

Figure 3-2: *Bastankhah- Gaussian* wake model[9]

[7] Annoni, Seiler, Johnson, Fleming & Gebrand (2014) *"Evaluating Wake Models for Wind Farm Control"* American Control Conference (ACC)

[8] Batankhah & Porté-Agel (2014) *"A new analytical model for wind-turbine wakes"* Renewable Energy an International Journal

[9] Qian & Ishihara (2018) *"A New Analytical Wake Model for Yawed Wind Turbines" Energies* 11(3):665

3.3 *Eddy Viscosity Wake Model*[10]

The ***Eddy Viscosity*** wake model is a computational fluid dynamics (CFD) calculation that represents the development of the velocity deficit field using a finite-difference solution of the thin shear layer equation of the Navier-Stokes equations in axisymmetric co-ordinates. The model takes into account the conservation of mass and momentum in the wake. An eddy viscosity averaged across each downstream wake section, is used to relate the shear stress to gradients of velocity deficit. The mean field can be obtained by a linear superposition of the wake deficit field and the incident wind flow. The model equations involve the Navier-Stokes equations with Reynolds stresses, which are simplified by dropping the viscous terms. The eddy viscosity parameter is introduced to describe the shear stresses in terms of velocity deficit gradients. The model also includes an ambient term to account for the turbulent nature of the ambient wind flow in wind farm conditions.

A center line velocity deficit and wake width are calculated based on empirical equations to initialize the model. The wake development is then calculated by applying a parabolic solution to the Reynolds-averaged Navier-Stokes equations. The incident wind speed for each downstream turbine within the wake is determined, and the velocity profile across the turbine rotor at hub height is integrated to obtain the mean wind speed incident across the rotor. Also, Turbulence intensity plays a crucial role in the model, and it is calculated based on an empirical characterization that considers the ambient turbulence level, turbine thrust coefficient, downstream distance from the rotor plane, and the length of the near wake

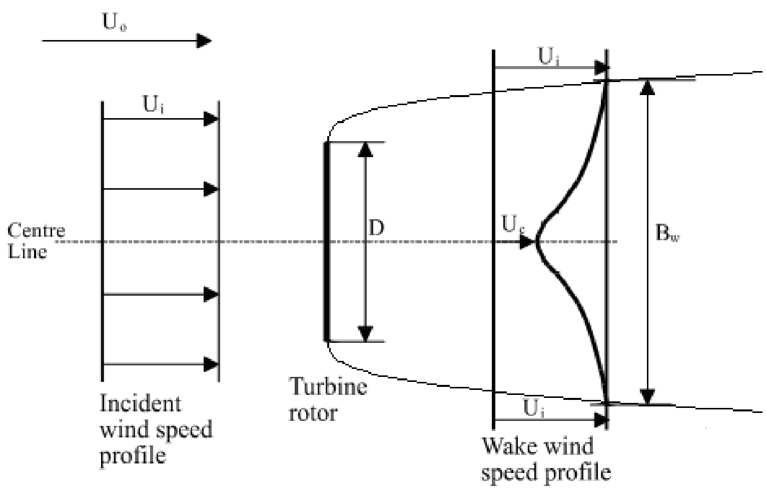

Figure 3-3: *Eddy viscosity* wake model as implemented in WindFarmer[11]

[10] Ainslie (1988) "*Calculating the flow-field in the wake of wind turbines"* Journal of Wind Engineering and Industrial Aerodynamics Vol 27, Issues 1-3, Pages 213-224

The adaptation of this model in software also takes into account the modification of the wake and turbulence by terrain effects[11]. The wind flow acceleration over terrain is considered to adjust the mean wind speed, and the standard deviation of turbulence is assumed to remain constant while modifying the turbulence intensity[12].

3.4 *Frandsen Wake Model*

Frandsen's model considers a cylindrical control volume representing the wake, with a constant cross-sectional area, aligned with the mean wind direction. The control volume approach is used to analyze the flow around the turbine. By applying the momentum equation within this control volume, neglecting certain terms such as acceleration and pressure gradients, and assuming equalized pressures upwind and downwind, the simplified form of the equation is obtained. This simplified equation relates the wake flow speed to the free flow speed and the wake area. Based on self-similarity assumptions, the wake flow speed profile can be represented by a minimum wake flow speed, distance from the center of the wake, and a characteristic width. The model then incorporates the expansion of the wake by proposing a relationship between the wake diameter and the distance downwind[13].

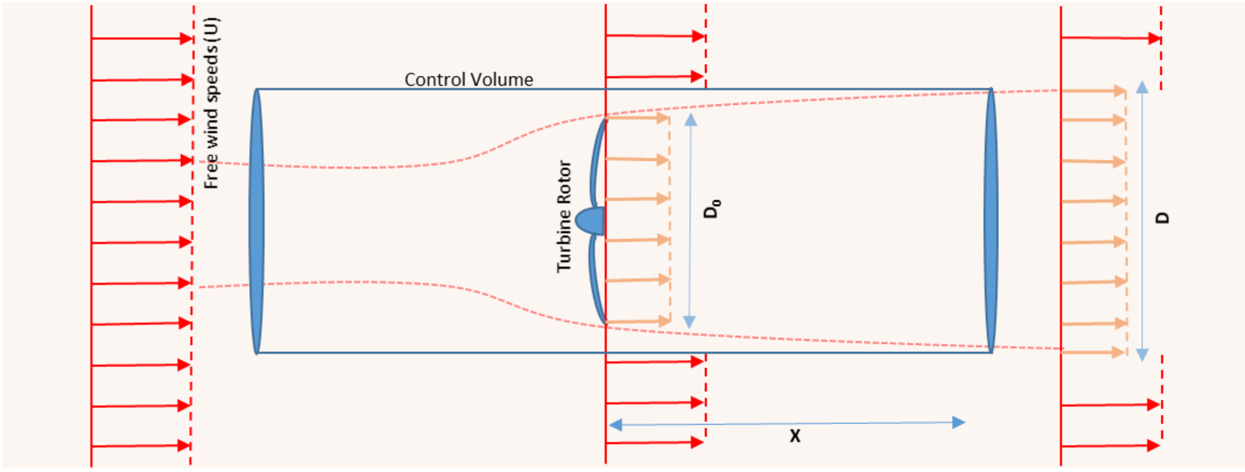

Figure 3-4: *Frandsen* wake model using control volume concept

A similar implementation of this model in Wind energy software's also accounts for the interaction between rows of wind turbines. It provides equations to calculate the wake velocity deficit and expansion in a row of turbines, considering the effect of the wake from the previous turbine on the subsequent turbines. This allows for an estimation of the impact of wake interactions within a row. By

[11] *Eddy Viscosity* Model – WindFarmer Documentation

[12] Ajao & Adegun *"Evaluation of The Rotor Aerodynamics Of A Wind Turbine Using Combined Blade Element And Momentum Theory"* Researcher

[13] Frandsen et.al., (2006) *"Analytical Modelling of Wind Speed Deficit in Large Offshore Wind farms"* Wind Energy – Wiley Publications 9:39-53

incorporating the wake expansion and velocity deficit calculations for each row, the model enables the assessment and optimization of wind farm layout and turbine spacing to minimize wake effects and maximize overall power production.

3.5 *Super positioning of wind turbine wakes*

Wake superposition in the context of two turbines refers to the combined effect of the wake generated by the upstream turbine on the downstream turbine. When the upstream turbine operates, it creates a wake of slower-moving air behind it. This wake, characterized by reduced wind speeds and altered wind directions, influences the performance of the downstream turbine. Wake superposition involves analyzing and modelling the interaction between these wakes to understand how they combine and impact the downstream turbine's operation.

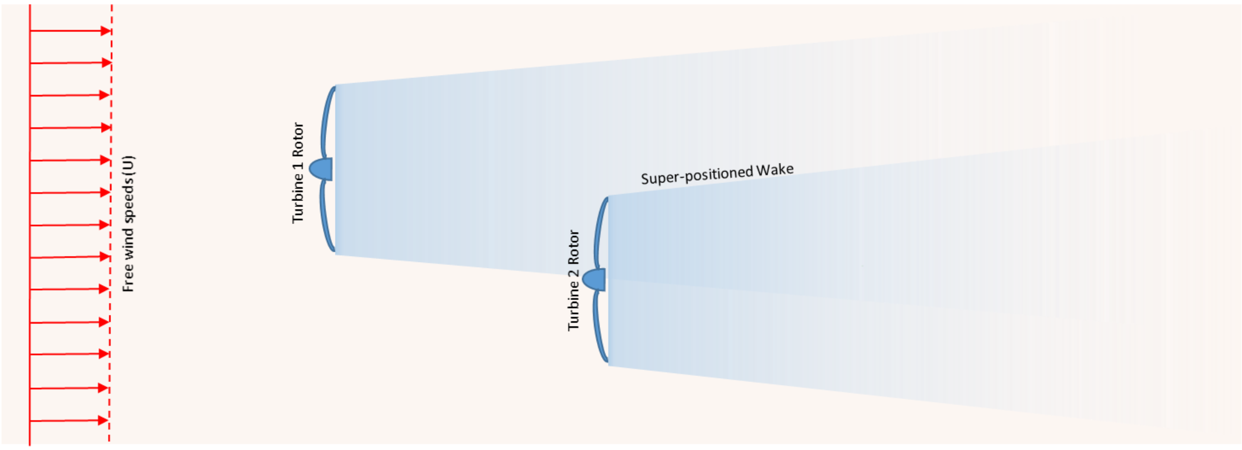

Figure 3-5: Super-positioned wake between turbines

Following are the major models used for modelling of super-positioned wake in leading wind farm simulation software's.

- ✓ **Linear Superposition:** The linear superposition of velocity deficits (LSVD)[14] is a modelling approach that assumes the velocity deficit experienced by a downstream turbine in a wind farm is the sum of the velocity deficits caused by all the turbines located upstream from it. In the LSVD model, each upstream turbine is considered to independently contribute to the overall reduction in wind speed at the downstream turbine, with the deficits simply accumulating as they propagate downstream. While this simplistic approach neglects the complex interactions and dynamics of wake flows, it provides a practical and easily implementable estimation of the wake impact.
- ✓ **Sum Square:** The Sum of Squares (SS)[14] method is an alternative wake superposition model used to evaluate the impact of upstream wakes on a downstream turbine within a wind farm.

[14] Kuo, Romero & Amon (2015) *"A mechanistic semi-emperical wake interaction model for wind farm layout Optimization"* Energy, Vol :93 ,Part: 2, Pages 2157-2165

In the SS approach, instead of directly summing the velocity deficits, it involves calculating the sum of the squares of the individual velocity deficits caused by each upstream turbine. Each wake's velocity deficit is squared and then summed to determine the cumulative effect on the downstream turbine. This method accounts for the magnitude and intensity of each wake disturbance, giving more weight to larger deficits. By squaring the velocity deficits, the SS model emphasizes the significance of high-impact wakes and captures the non-linear behaviour of wake interactions.

- ✓ **Maximum Sum:** The max deficit wake superposition method focuses on the maximum velocity or energy deficit caused by the closest upstream wind turbine when estimating the wake effect at a specific location. It assumes that the dominant wake influence is determined by the closest turbine, overlooking potential interactions with other wakes. By emphasizing the maximum deficit, this method simplifies the analysis of wake interactions and provides a straightforward representation of the downstream flow[15].

3.6 *Large Windfarm Array Wake (Deep Array Wake effects)*

Frandsen in his investigations revealed that standard wake models under-predict wake effects for very large wind farms. This is mainly due to the fact that, the wake effects of large wind farms on Atmospheric Boundary Layers (ABL) are not accounted. To incorporate these effects Frandsen suggested that the wake effect of a Very large wind farm resembles as that of a change in surface roughness, i.e. a change to an increased roughness length also termed "*Apparent*" roughness which represents additional shear stress in the wind flow caused by the wind farms[13].

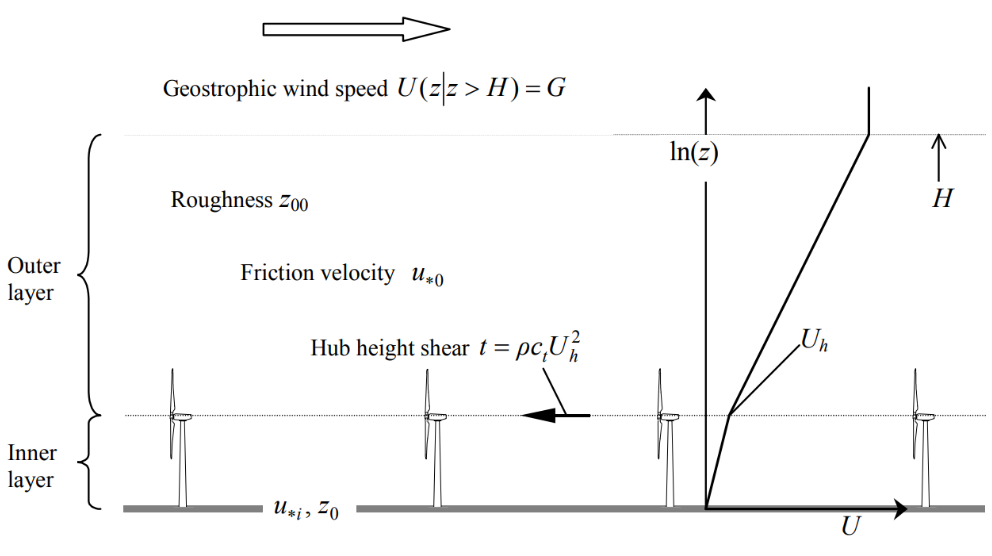

Figure 3-6: Speed deficit due to infinite array setup

[15] O.H.G Bossuyt (2018) *"Modelling and validation of wind turbine wake superposition Using wind farm data"* M.Sc Thesis, Delft University and Technical university of Denmark.

To arrive at the effective surface roughness of the wind farm, *Frandsen* made the following assumptions:

- ✓ The wind farm is sufficiently large for the horizontal average of the vertical wind profile to be horizontally uniform.
- ✓ The thrust on the wind turbine rotors is assumed to act primarily at the hub height.
- ✓ The horizontally averaged vertical wind profile follows a logarithmic pattern above and below the hub height, similar to the development of the internal boundary layer after a change in surface roughness.
- ✓ The vertical wind profile remains continuous at the hub height.
- ✓ Horizontally averaged turbulent wind speed fluctuations exhibit horizontal uniformity.
- ✓ The height of the Atmospheric boundary layer is significantly greater than the wind turbine hub height (H >> h). However, due to technological advancements, this assumption is now only partially satisfied, depending on the chosen boundary layer height.

Using these assumptions and an approximation of the geostrophic drag law (with a modified geostrophic law constant), one can derive **the Asymptotic wind speed and wind speed deficits at hub height of the very large wind farm**[16].

One significant limitation of this ***Frandsen*** theory is its failure to account for the wake effects of individual turbines. Instead, it treats the wind farm array as an infinite expanse of undifferentiated surface drag. Consequently, the predicted wind resource at a specific location remains unaffected by the presence or absence of turbines directly upwind, which is an unrealistic assumption. Additionally, the roughness in the theory depends on the array's density, necessitating recalculation whenever the layout is modified. To be more valuable for wind project design and optimization purposes, the ***Frandsen*** theory requires either modifications or integration with turbine wake models to address these shortcomings. Following are the major wake models that are integrated with the theory for accounting deep array effects in wind farms[17]:

3.6.1 Adjustment to PARK2 wake model for deep array effect

In order to improve the accuracy of the ***Park*** model in simulating infinite wind farms, a modification is proposed. The objective is to align the model with the boundary-layer-based asymptotic wind speed deficit observed in such wind farms. Specifically, when dealing with positions deep within the wind

[16] Frandsen & Nielsen (2010) "*Wake Decay Constant for the infinite wind turbine array*" EWEC 2010 Technical Track "Wake" paper ID 265

[17] Frandsen et.al., (2006) "Analytical Modelling of Wind Speed Deficit in Large Offshore Wind farms" Wind Energy – Wiley Publications 9:39-53

farm, adjustments are made to the wake expansion coefficient *'k'* in the ***Park Model***. The aim is to bring *'k'* closer to a corresponding value known as 'k_{inf},' which represents the asymptotic speed deficit predicted by the boundary-layer model.

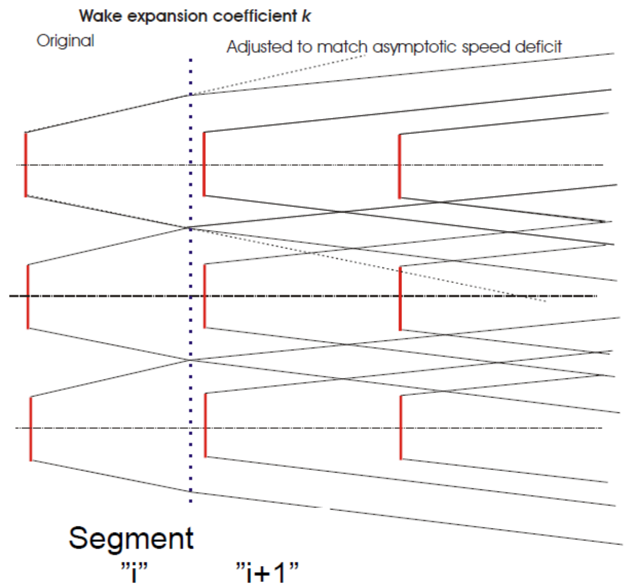

Figure 3-7: Adjustment of wake expansion rate at downward wind turbines[16]

Every time a wake overlaps with a downwind turbine rotor the wake expansion coefficient *k* is made to relax towards k_{inf} according to a relaxation expression, where the relaxation depends on the overlapping fraction and a relaxation constant F_{relax}, which is common to all wind turbines in the wind farm. By implementing these adjustments, the ***Park model*** can better capture the characteristics and behavior of infinite wind farms. The process of gradual adjustment of the wake expansion coefficient is illustrated in Figure 3-7

3.6.2 Adjustments to *Eddy Viscosity model* for Deep Array effect:

This modification of Frandsen theory is being entirely implemented in wind energy *Software D*. It relies on equations derived for accounting for downstream effects of roughness changes in wind speed. Each turbine in the wind farm is assumed to occupy a discrete area of increased surface roughness and as wind speeds arrive, an Internal Boundary layer (IBL) is developed for each and every turbine. Within this IBL the vertical wind shear is defined by the turbine's roughness than the ambient roughness, with the constraint that the speed at the top of the IBL should match the speed immediately above it. Once the wind has passed the turbine, a second IBL is formed, representing the transition back to the ambient surface conditions (Ambient surface roughness is considered for the second IBL).

The adjusted hub-height wind speeds of the turbines are then derived using the above conditions for each IBL pair. Also, Any IBL that has not attained hub height is assumed to have no impact on the hub-height speed and any IBL that exceeds the height of a previous IBL supersedes the previous IBL.

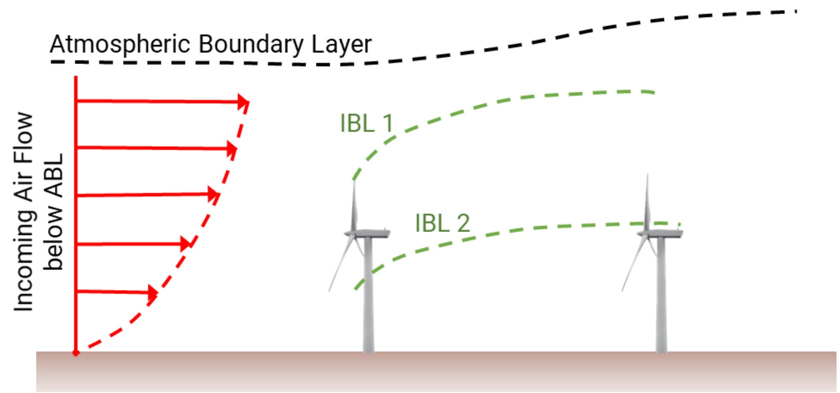

Figure 3-8: Internal Boundary layer developement

After conducting various experiments, it was determined that the initial height for the first Internal Boundary Layer (IBL) associated with each turbine would be set at the top of the turbine rotor. Similarly, the second IBL would be initialized at the bottom of the rotor. This decision is based on the physical understanding that turbines operate not at the surface but across the rotor plane. By giving the IBLs this initial positioning, it allows them to have a head start and facilitates the more rapid development of the large-array effect.Due to the gradual growth of the Internal Boundary Layer (IBL), the method mentioned underestimates the immediate downstream wake impact of individual turbines. To provide a comprehensive understanding of wake effects throughout the array, it becomes necessary to combine this method with the ***Eddy Viscosity model*** (EV) wake model.

Wind Energy Software's has implemented this by estimating the net output of each turbine in 2 separate methods,

- ✓ **Method 1:** In this approach, the wake model (EV model) is used alone with no roughness effect. It estimates the net output of each turbine without considering the roughness effects caused by the IBL.
- ✓ **Method 2:** In this approach, the roughness effect is considered separately with no EV model. The net output of each turbine is estimated by solely accounting for the roughness effect caused by the IBL.

To determine the appropriate wake deficit prediction, the results from both methods are compared. The approach selects the result that predicts the largest wake deficit, indicating the dominant wake effect. This methodology implicitly divides the wind project into two zones: a "shallow zone" where the conventional wake model applies, and a "deep zone" where the roughness effects become more pronounced. Through testing, it was observed that the dividing line between these zones typically occurs around three rows into the wind project[18].

[18] Brower & Robinson (2017) "*THE OPENWIND DEEP-ARRAY WAKE MODEL: Development and Validation*" UL solutions (Validation Report)

4 Induction and blockage effects modelling

From the perspective of wind turbines, the term induction refers to the slowdown of wind as it reaches the rotor of the turbines, whereas blockage refers to the slowdown in front of the wind farm. In most wind farm energy software's, the blockage effects are modelled based on superposition of induction effects of the wind turbines. Following are the major induction effect models prominent in wind energy software applications:

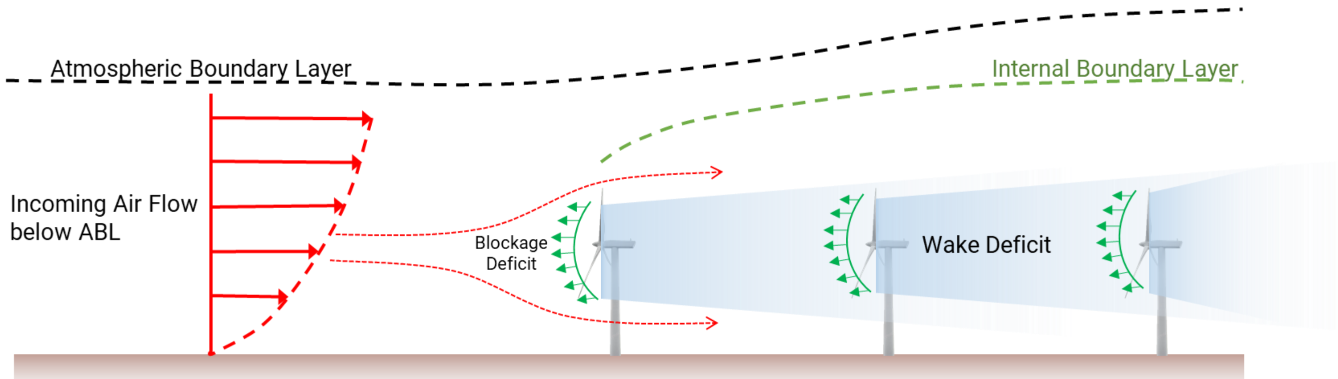

Figure 4-1: Induction + Wake effects on Wind farms

4.1 *Vortex Cylinder Model (Branlard Model)*

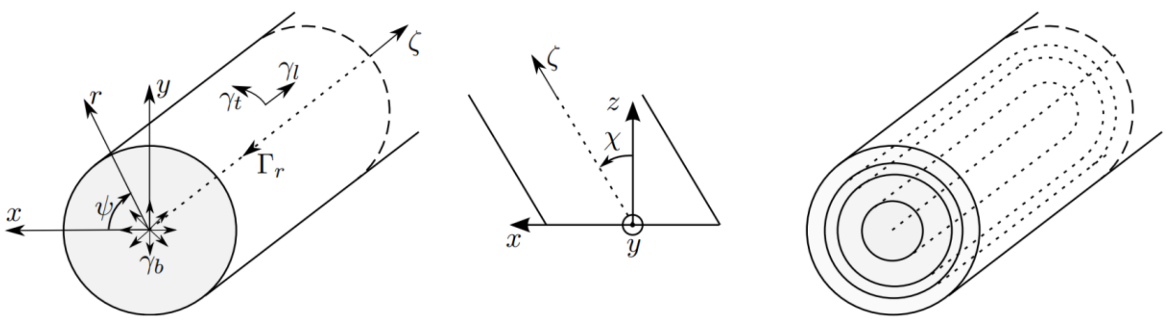

Figure 4-2: Vortex model used by Branlard[19]

The ***vortex cylinder (VC) model*** characterizes the wake geometry as a semi-infinite cylinder with constant tangential vorticity. This tangential vorticity is determined by the free-stream velocity and the wind turbine thrust coefficient[20]. The model incorporates the axial induction factor to account for the reduction in axial velocity caused by the turbine rotor. The velocity field within the wake is obtained by integrating the Biot-Savart law, incorporating the tangential vorticity and a circulation function. The

[19] Branlard, Forsting *"Using a cylindrical vortex model to assess the induction zone in front of aligned and yawed rotors" DTU, Wind Energy , Denmark,* Proceedings of EWEA Offshore 2015 Conference, 2015

[20] Forsting et.al, (2019) *"Verification of induction zone models for wind farm annual energy production estimation"* Wake Conference 2021, IOP publishing

model allows for the calculation of the axial velocity perturbation at different positions in the wake. On further simplification of the axial velocity equation, the velocity upstream of a turbine or assessing near-wake expansion using mass conservation can also be computed.

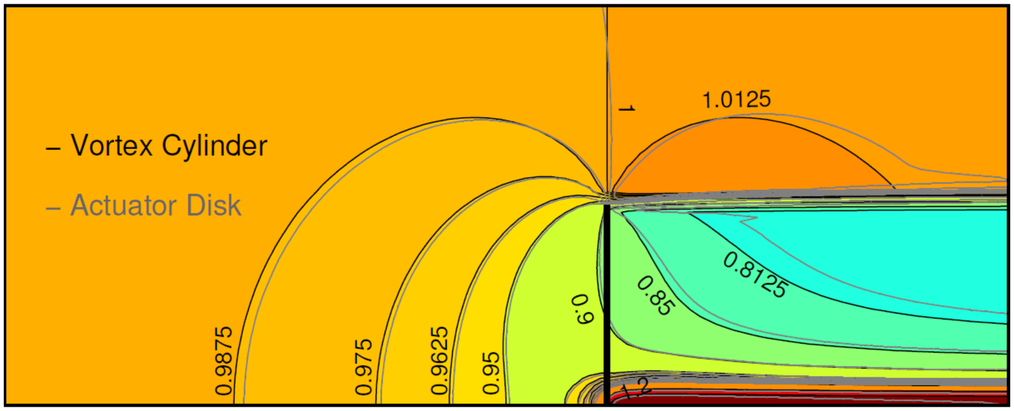

Figure 4-3: Vortex Cylinder induction effect on an Actuator disk model

4.2 *Vortex Dipole / Rankine-Half Body Model*

The ***Vortex Dipole (VD) model*** approximates the far-field behavior of the VC model by representing its vorticity as a point vortex doublet, resulting in an induced axial velocity that decreases with increasing downstream distance and radial distance. The *Rankine* half-body approach, on the other hand, models the rotor as a potential flow point source, yielding similar flow perturbations to the VD model but including an equation for the stagnation line. However, in the context of wind farm blockage, the calculation of the stagnation line is not necessary. Both models provide simplified representations of the flow around a wind turbine rotor, but the VD model focuses on the induced axial velocity, while the Rankine half-body model adds the concept of a stagnation line without impacting wind farm blockage considerations.

4.3 *Coupling of Blockage effects with Wake model*

The blockage model needs the thrust coefficient of every turbine as input. This information is provided by the wake model, as turbines operating in a wake experience a lower inflow wind speed, leading to a modified thrust coefficient. However, the blockage from the other turbines in the wind farm also changes the available wind speed at every turbine position. This means that the wake model and the blockage model need to be coupled together, so that the output from one model can be used as an input for the other. To solve this problem, it is iterated for each wind speed and wind direction combination. The steps are as follows:

- ✓ The wake model is solved in the upwind to downwind direction. This results in turbine-specific thrust coefficient values that reflect the pattern of the wake-induced wind speed variation.

- ✓ The wind farm blockage effect at each turbine position is calculated in the downwind to upwind direction using the thrust coefficient values from step 1 as inputs. This reduces the wind speed at each turbine position in the absence of wakes from U_0 to $U_{0i} = U_0(1 + \Delta U_i/U_o)$.
- ✓ The wake model is run again with U_{0i} replacing U_o.

Steps 2 and 3 should be repeated until the wind speeds at each turbine have converged. This iterative framework is independent of the specifics of both the wake and the blockage model implementations. The only requirement is that both models are based on the *superposition* of wind turbine interaction effects from individual turbines. This means that it is possible to replace the wake and/or the blockage model used here with any models[21].

[21] Branlard & Forsting (2019) "*Assessing the blockage effect of wind turbines and wind farms using an analytical vortex model*" Wind Energy, Wiley Publications

5 Conclusion

In this white paper, we have explored the essential engineering models that form the foundation of industry-standard wind energy software used for wind farm simulations. These models play a crucial role in predicting wind farm performance, optimizing turbine layout, and evaluating the overall behavior of wind farms. The accuracy and comprehensive understanding provided by these models are essential for the successful development of efficient and productive wind energy systems.

The wind farm flow models, such as the IBZ flow model with orographic corrections and Computational Fluid Dynamic models (RANS and LES), enable the simulation of wind flow conditions within the atmospheric boundary layer. These models account for the complex interactions of air inside the ABL and the turbulent atmospheric conditions prevailing at the wind farm site. They provide valuable insights into wind speeds, resource grids, and atmospheric stability, enabling the estimation of energy yields for the wind farm.

Wake models are critical for understanding the disturbed airflow downstream of wind turbines. Models such as ***N.O. Jensen (PARK2), Bastankhah-Gaussian model, Eddy Viscosity model,*** and ***Frandsen wake model***, offer different levels of accuracy and fidelity in capturing wake phenomena. Wake modeling is essential for assessing turbine spacing, optimizing wind farm layout, and mitigating wake effects to improve overall power production. Furthermore, the concept of superposition of wind turbine wakes allows for the combination of the impact of multiple wakes on downstream turbines. Linear superposition, Sum of Squares, and Maximum Sum methods are commonly used for modeling superposition. Understanding these wake interactions is crucial for optimizing wind farm design and minimizing power losses due to wake effects.

Moreover, the deep array wake models, like the ***Frandsen theory*** on IBL and its integration with existing wake models, address the impact of very large wind farms on the atmospheric boundary layer. By accounting for the additional roughness caused by the wind farm, these models provide a more accurate representation of wake effects in large-scale wind farms.

Finally, induction and blockage effects modelling, using ***Vortex cylinder models*** and ***Vortex Dipole/Rankine-Half Body models***, are crucial for understanding the slow-down of wind as it reaches the rotor of turbines and the slowdown in front of the wind farm. Coupling the blockage model with the wake model ensures accurate predictions of the available wind speed at each turbine position, considering the combined impact of wakes and blockage.

In practice, the appropriate choice of models should align with the specific objectives of the simulation, the scale of the wind farm, and the available computational resources. By leveraging the expertise of the wind engineer, the most suitable combination of models can be employed to achieve accurate and reliable predictions of wind farm behaviour, contributing to the successful and effective representation of windfarm energy systems.