# Verification of the Digital Twin of the Atmospheric Boundary Layer in the Area of the Wind Farm Based on Telemetry Data and Meteorological Measurements

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**Abstract**

The rapid development of wind energy, like any other alternative energy industry, is primarily aimed at reducing the carbon footprint. In recent years, the total capacity of wind power systems has increased dramatically. Thanks to improvements in wind energy technologies, wind farms can operate all year round in a wide temperature range, becoming more and more available as an alternative source of energy. To date, the actual problem of the practical use of wind energy is the study of complex turbulent flows in the wind farm area. In this paper, a numerical study of the turbulent wake of a single wind turbine was carried out in Simcenter STAR-CCM+ CFD software. The features of a turbulent wake are considered, for further study the mutual influence of wind turbines on each other. The LES-method (Large Eddy simulation) was used for the numerical study and modeling. The paper presents an approach for studying and verifying a digital twin of the atmospheric boundary layer in the region of a single wind turbine using telemetry data and meteorological measurements. The actuator-disk model (ADM) was used as a tool for modeling, the one-dimensional impulse method (1D - Momentum) was implemented, specially designed for modeling wind turbines.

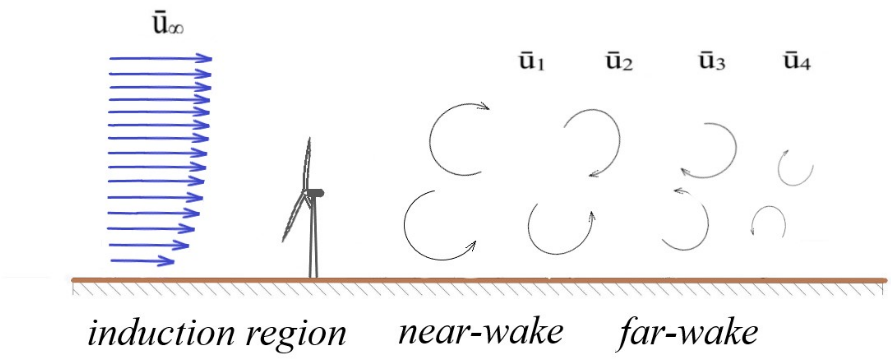
**Keywords: Atmospheric Boundary Layer, Mathematical Modeling, Wind Farm, Wind Turbine, Telemetry, Meteorological Data, 1D-Momentum, CFD**

## 1. Introduction

Against the backdrop of such global problems as climate change, humanity increasingly needs environmentally friendly renewable energy sources. The wind energy industry has become one of the most popular types of renewable energy. The number of wind farms around the world is increasing every year, occupying large areas for efficient operation. The most efficient and common types of wind turbines for high-power wind farms are horizontal-axis wind turbines [1]. The efficiency of wind farms depends on many factors, the main one being the shading effect, which raises the urgent question of studying this effect and the influence of wind farms on the atmospheric boundary layer and the environment. For a reliable approach to studying the movement of air masses in the area of a wind farm, a series of experimental meteorological measurements of the turbulent wake behind a wind turbine were carried out using telemetry data.

As air flows around wind turbines, significant turbulence occurs, leading to a speed deficit on the leeward side. Figure 1 schematically shows the areas of movement of air masses and highlights the areas of greatest speed deficit [2-4].

**Figure 1: Zones of Air Mass Flow in the Vicinity of a Single Turbine**




To carry out CFD modeling, the commercial product Simcenter STAR-CCM+ CFD software was used. The numerical simulation is based on the finite volume method (FVM), and the Navier-Stokes equation is used as the governing equation. Iterative calculations are performed for the velocity and pressure fields using an algebraic multigrid (AMG) linear solver. The work used a large-eddy simulation (LES) turbulence model with built-in software functions STAR-CCM+. Knowing the specific geometric characteristics of wind turbines, thrust coefficient and the dependence of the number of revolutions on wind speed, the use of Actuator Disk Model (ADM) becomes the best tool for research work. To optimize the calculation processes, the work proposes an approach based on (ADM) [5] of a representative Vestas V126-3.45 MW wind turbine using the one-dimensional momentum method (1D-Momentum), including data on the power curve and force coefficients of the simulated wind turbines [6]. 1D-Momentum method are applicable for a wind turbine simulation. The one-dimensional momentum method was developed specifically for modeling the horizontal wind turbines. Method takes into account axial and tangential effects wind turbines in flow. The main advantage of this method in that it specially intended for modeling wind turbines and wakes behind them. The modeling results by this method are pretty accurate.

The paper presents approaches to verifying and studying the movement of air masses in the area of a wind farm using CFD modeling, as well as the results of experimental meteorological measurements of the turbulent wake behind a wind turbine using telemetry data.

## 2. Meteorological Measurements

During the research work, meteorological data was collected behind a single turbine of the Ulyanovsk wind farm in the summer and winter seasons. To collect meteorological data, «Davis Vantage Pro 2» digital mobile weather stations were used. The weather stations were installed simultaneously at a height of 10 meters above ground level, at a distance of 200, 400, 600, 800, 1000, 1500, 2000 meters behind the wind turbine under study, Figure 2.

Based on the conditions of intensive operation of the wind farm, wind speeds averaged over one minute were used in the work. The «Davis Vantage Pro 2» measurement error for wind speed does not exceed 5%, and for wind direction does not exceed 3%. Based on the operating conditions of weather stations, data was recorded at a frequency of once every 2.5 seconds for wind speed and direction, and once every 10 seconds for air temperature. To conduct meteorological observations and collect data, days with the most stable weather conditions (minimum wind gusts, stable wind direction and speed) were identified. Speed telemetry data was obtained directly from the wind turbine at the time the meteorological data was taken. Table 1 presents the results of meteorological measurements and telemetry data.

**Table 1: Results of Telemetry and Meteorological Measurements**

| Season | Wind Speed at Hub Level (Telemetry Data), m/s | Wind Speed at an Altitude of 10 Meters (from Meteorological Station 0 in Front of the Wind Turbine), m/s | Temperature, °C | Wind Direction |
|---|---|---|---|---|
| **Winter** | 6.51<br>8.7<br>11.42 | 3.29<br>5.4<br>8.14 | -5.4<br>-11.9<br>-16.6 | SW |
| **Summer** | 6.5<br>8.68<br>11.36 | 3.22<br>5.39<br>7.95 | +24,3<br>+28,1<br>+19,0 | SW |

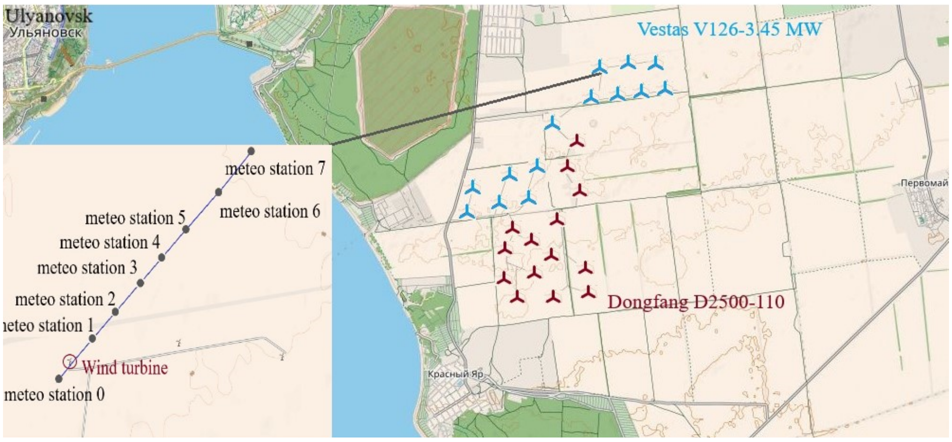
Table 2 presents the results obtained from digital weather stations located on the leeward side of the wind turbine at an altitude of 10 meters above ground level, at a distance of 200, 400, 600, 800, 1000, 1500, 2000 meters.

**Table 2: Results of Meteorological Measurements of the Near and Far Wake of a Wind Turbine**

| Season | Wind Speed at Point 1, 200 m | Wind Speed at Point 2, 400 m | Wind Speed at Point 3, 600 m | Wind Speed at Point 4, 800 m | Wind Speed at Point 5, 1000 m | Wind Speed at Point 6 1500 m | Wind Speed at Point 7, 2000 m |
|---|---|---|---|---|---|---|---|
| **Winter** | 2.01<br>4.09<br>6.21 | 2.30<br>4.35<br>6.56 | 2.64<br>4.69<br>7.05 | 2.88<br>4.91<br>7.28 | 3.01<br>5.06<br>7.52 | 3.15<br>5.21<br>7.75 | 3.28<br>5.35<br>7.99 |
| **Summer** | 1.98<br>4.02<br>6.18 | 2.29<br>4.28<br>6.48 | 2.62<br>4.68<br>7.04 | 2.86<br>4.89<br>7.21 | 3.01<br>5.06<br>7.39 | 3.13<br>5.16<br>7.51 | 3.21<br>5.28<br>7.71 |

Figure 2 shows a diagram of the location of the weather station in the wind farm area at a height of 10 meters above ground level and at a distance of 200, 400, 600, 800, 1000, 1500, 2000 meters behind the wind turbine.

**Figure 2: Layout of the Ulyanovsk Wind Farm and Meteorological Stations [7]**




## 3. Numerical Simulation and Verification

This paper describes the processes occurring in the atmospheric boundary layer behind Vestas V126-3.45 MW wind turbine [8], based on mathematical modeling and computational experiments in STAR-CCM+ Academic Pack software.

Knowing the characteristics of the wind turbine, it is possible to project its impact on the boundary layer. The LES method was chosen for the numerical study. The LES-method allows accurately modeling the complex turbulent air masses movement behind a wind turbine. Large eddy structures of a turbulent flow, as well as eddies of intermediate inertial scales, are explicitly calculated in the LES-method. Small-scale eddies structures must be parameterized using subgrid models. Similar subgrid models take into account the dissipation of turbulent energy by small eddies and its back dissipation from small to large eddies. The LES-method makes it possible to perform more accurate numerical calculations in the problems of analyzing atmospheric boundary layer in the wind farm area in comparison with RANS models [9,10] in view of the decomposition of the turbulent flow structure.

The turbine for this simulation had three blades with an outer radius of 63 m, and an inner radius of 0.65 m (the inner radius is the radius of the rotor hub). In the study, a blade 61.7 m long rotated at a speed of 6 rpm, the flow velocity was set from 1.0 m/s to 12.1 m. At the height of the rotor hub, the flow velocity was 6.5 m/s. The geometry of the virtual tunnel is made on a scale of 1:1. An automated mesh was generated in which a surface repeater of a polyhedral mesh with a base size of 25 m was used, an actuator virtual disk was created with a base cell size of 0.5 m. The number of cells was about 3 million (Figure 3). The physical calculation time was 350 seconds. The time step was set to 0.01 s for better accuracy. Three boundary conditions were specified for the velocity input, pressure output, and slip wall for the virtual tunnel. The calculation also took into account the surface roughness of the bottom wall, assumed to be Cf = 0.008 [11].

**Figure 3: Plane Section of the Virtual Tunnel with Mesh**

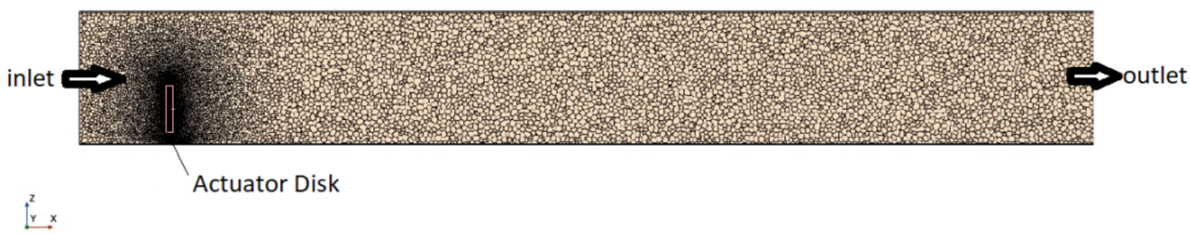
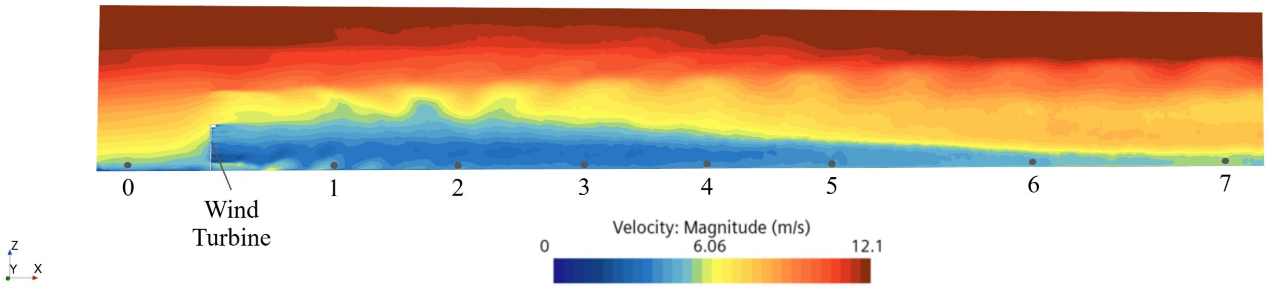


**Figure 4: Results of Numerical Study for the Velocity Magnitude Fields for Summer Season**

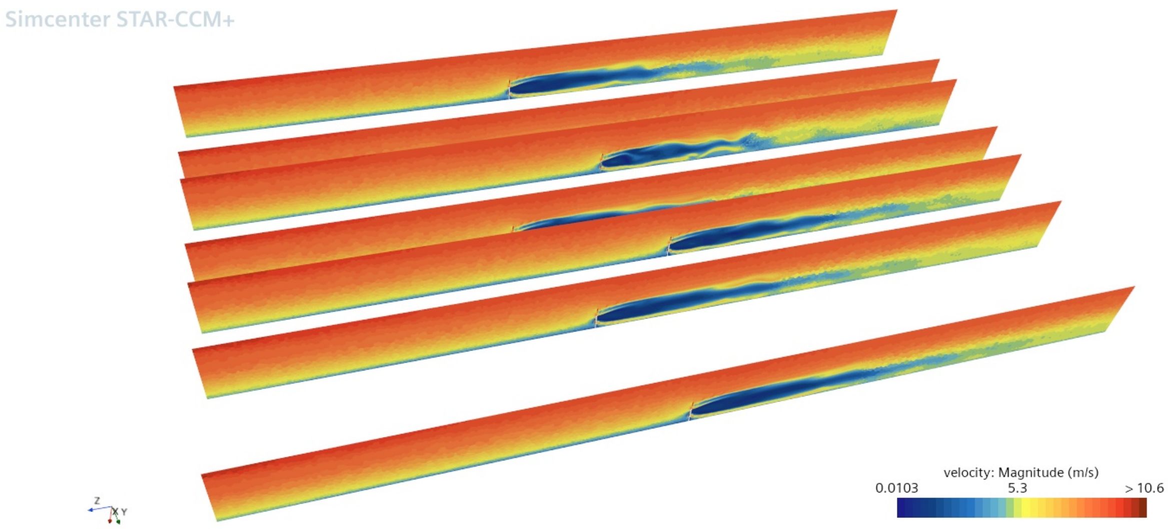



As can be seen from figure 4, the free flow significantly slow down behind the wind turbine as turbines extracts part of the kinetic energy. Points 0-7 show the location of installed meteorological stations «Davis Vantage Pro 2». The areas with reduced velocity and high level of turbulence are formed behind the wind turbine. The speed regime of the air masses is completely restored through 11 rotor diameters behind the wind turbine for the summer regime. For winter, the pattern of results does not change significantly. However, due to the higher air density in the cold season, the recovery of wake turbulence is reduced by approximately 5%.

As the speed of air mass flow increases, the number of rpm of the turbine rotor also increases. At a velocity at the hub level of 8.7 m/s, the turbulent wake is fully restored at a distance of 12.5 diameters; for a speed of 11.4 m/s, attenuation occurs only after 14 diameters of the turbine rotor.

The obtained results of modeling a single wind turbine were verified with experimental data from a full-geometric model of part of the Ulyanovsk wind farm, Figure 5. The verification error of a single turbine experiment using telemetry and meteorological data was 6.8%.

**Figure 5. Results of a Digital Twin Simulation at a Hub Height Velocity of 6.5 m/s**




## 4. Conclusions

The paper presents approaches to verifying and studying the movement of air masses in the area of a wind farm using CFD modeling, as well as the results of experimental meteorological measurements of the turbulent wake behind a wind turbine using wind turbine telemetry data.

To carry out CFD modeling, we used the commercial product Simcenter STAR-CCM+ CFD software using large-eddy simulation (LES) turbulence model with built-in STAR-CCM+ software functions. Knowing the specific geometric characteristics of wind turbines, the thrust coefficient and the inlet velocity profiles, the Actuator Disk Model (ADM) was configured for the selected type of wind turbine. For meteorological research behind a single turbine of the Ulyanovsk wind farm in summer and winter. Davis Vantage Pro 2 digital mobile weather stations were used to collect meteorological data.

The results obtained allowed us to verify the digital twin of a horizontal-axis wind turbine for two seasons and speeds at the hub level from 6.5 to 11.42. The average error for the summer period was 6.8%. The average value for the winter period was 7.6%.

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