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# The impact of topology of wind farms on the production of electric energy

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Optimisation of the method of arrangement of the generating units in the wind farm significantly affects an increase in electric energy production. The paper defines the limitations and the impact of various factors on the energy efficiency of wind farms. The paper also presents the overview of methods applied in calculating the impact of turbulence on the efficiency of the wind farm. The use of the kinematic models is described based on an example and the presently applied mathematical models are characterised.

KEYWORDS: wind farm, offshore turbines, onshore turbines, wind turbulences

## 1. Introduction

Wind is a phenomenon which of stochastic nature. Wind speed depends, to a great extent, on the terrain as well as natural and artificial obstacles. Power generated by a wind turbine is, in accordance with the Betz's Law, dependent on, among others, the wind speed in the third power. The method of determination of the speed value raises a number of doubts. Turbulence, i.e. disturbance of the uniform flow of air streams may reach significant values, even up to 20%. The sources of turbulence include, above all, the terrain, the effect of electromagnetic radiation of the sun and obstacles, e.g. trees, neighbouring wind turbines, meteorological masts, etc.

In the case of both offshore and onshore wind farms, the value of wind speed turbulences is considered the basic cause of a decrease in the generated power, which, in turn, affects the stability of the electrical network. Research on the impact of obstacles on the performance of wind farms is conducted using physical and mathematical models.

## 2. Selection of the wind farm topology

The arrangement of generating units significantly affects the value of electric energy production, which, as a result, increases the effectiveness of the investment [1]. Assumptions presented below are often made in the process of optimisation of the wind farm topology.

- Assumption 1

The number of wind turbines is known and constant already at the design stage. Economic and environmental aspects as well as the availability of generating units are taken into account.

- Assumption 2

The maximum area for the construction of the farm is known. In the case of onshore wind farms, the value of the coefficient of aerodynamic terrain roughness will affect the use of the wind power.

- Assumption 3

It is assumed that all the generating units are homogenous. The homogeneity condition means that all the turbines have the same power curve in the wind speed function and are assembled at the same height.

- Assumption 4

It is assumed that the wind speed distribution at a specific height is compliant with the Weibull distribution. In general, this assumption does not raise any objections. However, for the purposes of calculations, it is assumed that the Weibull distribution parameters have the same values for different wind directions. This is a necessary assumption, though not compliant with the results of wind speed distribution tests.

- Assumption 5

Turbines are assembled at such a distance from each other that there is no reciprocal impact. In the U.S., the rule of thumb is often applied. The distance between the rows of turbines in the dominant wind direction should amount to (6÷8)D, where D is the rotor diameter. The distance between the turbines within one row should be at least (3÷5)D. Figure 1 presents the topology of the wind farm, using the rule of thumb.

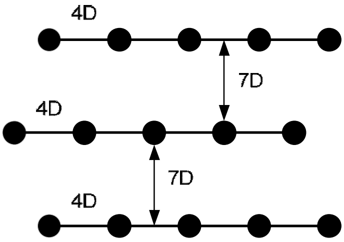

Fig. 1. Wind farm topology determined by the rule of thumb

It can be found that the distances between turbines in rows amount to ≈ 3D, and even less. While determining the minimum distance between the turbines in a given row, the assumption for the calculations in the U.S. is that the turbine power will be equal to at least 85% of the power generated by the preceding turbine.

Figure 2 presents the frequently used wind farm topologies.

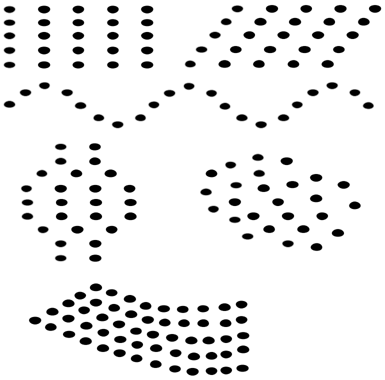

Fig. 2. Wind farm topology

The following commercial software is most frequently used to optimise the arrangement of generating units in wind farms: GL Garrad Hassan WindFarmer, AWS Truepower openWind, EMD WindPro and ReSoft WindFarm. At present, the Danish software – EMD WindPro – is considered the best tool available on the market for optimisation of the wind farm topologies.

Figure 3 presents the optimised arrangement of the wind turbines in wind farms, taking into account their unit powers, their number and the rotor diameters. In some cases, the wind farm topologies are compliant with the basic models which are presented in Fig. 2.

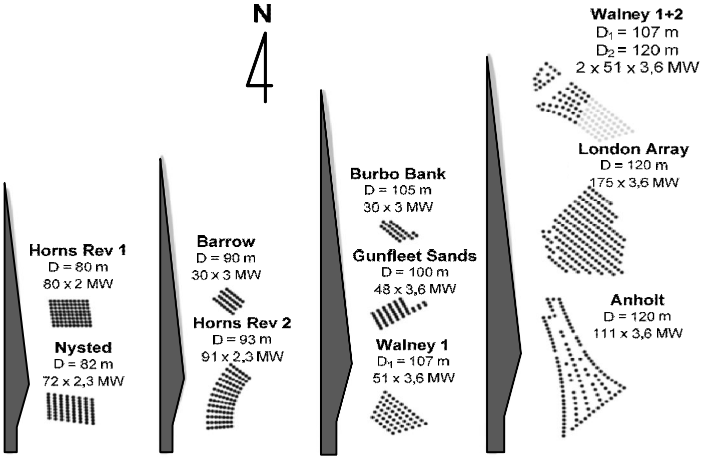

Fig. 3. Arrangement of wind turbines in wind farms, taking into account the rotor power and the diameter

## 3. Methods of testing of the impact of interaction between wind turbines and the power generated by the farm

Calculations of the AEP *(Annual Energy Production)* in the case of a single turbine are carried out on the basis of [2]. The AEP value can be calculated in two ways: one way is the measuring AEP and the other is the extrapolated AEP. Variation in the wind speed is described by the Rayleigh distribution. In the case of wind farms with n–turbines, the AEP value is never n–times higher than the energy efficiency value of a single turbine. Fig. 4 presents examples of sectors, in the case of which the wind turbine performance is greatly affected by obstacles.

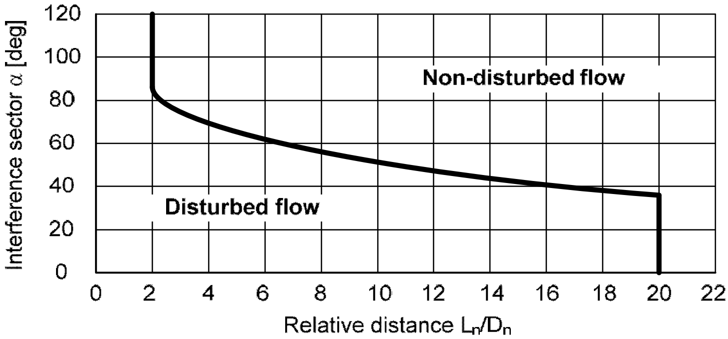

Fig. 4. Sectors excluded because of the aerodynamic wake of obstacles [2]

The method of calculation of the turbulence value and the impact of obstacles on the wind farm performance is described in [2]. In the model numerical tests of the impact of interferences on the performance of wind turbines, the CFD method is used most frequently. The method is based on the Navier–Stokes stream flow equations. Different methods of simulation are applied. In the DNS (*Direct Numerical Simulation*) method, the Navier–Stokes equation is solved directly. In view of the significant degree of complexity of the calculations, this method is not used in model tests of wind farms. The most frequently used method in model tests is RANS (*Reynolds Averaged Navier Stokes*) and LES (*Large Eddy Simulation*). In view of the elliptical nature of the pressure changes, the RAVS method in the Poisson equation is still time–consuming. Therefore, much faster methods based on the assumptions of the parabolic and linear pressure change are applied. The linear approximation is commonly applied, though it is accurate to the least extent. The most important advantage of using this approximation is the very short time of calculations – counted in hours. The LES method is an alternative to using the RANS method. In the LES method, vibrations of insignificant value are not considered in the calculations, and this has an impact on the considerable shortening of the time of calculations.

The RANS and LES methods are used in scientific research. As a tool that is used for design of wind firms, it is rarely used because of the long time of calculations which is counted in days.

The Frandsen's model or the SAM (*Storpark Analytical Model*) was used for the first time in the year 2006. In this model, the area covered by the wind farm is divided into three regions. The assumption for this model is that the distances between the turbines, between the rows, are so big that they do not constitute sources of turbulence. The sources of turbulence are turbines standing in columns. In region one, that is, the first couple of rows, the impact on all subsequent turbines changes n–times. In the second region, the value of turbulence is constant. The third region is located at a distance that is sufficiently far away from the turbines and the wind flow disturbances caused by obstacles are not present. Ratham adapted the Frandsen's model to conduct numerical calculations.

The most frequently used types of software that allow the speed deficit value caused by obstacles to be determined include WAsP, WindPro, WindFarmer, WindFarm and WindSim. The WAsP software uses the Jensen's models [4] and the linearised CFD. The WindPro software uses the Model module from WAsP. The WindFarma software uses the Ainslie, RANS and CFD models. The Ainslie model was presented in the year 1988. This model is based on the assumption of the normal distribution of the wind profile nearby the source of turbulence. Another popular name is also the EV (*Eddy Viscosity*) model. The term "near the turbulence source" is understood as the distance covering up to five rotor diameters. The WindFarm software uses the Jensen, Ainslie and Larsen's models [5]. The kinematic Jensen, Larsen and Ishikara's models [6] are used in the WindSim software. They are considered simple tools with the short calculation time. Therefore, they are commonly used in practice. Net prices of the software (excluding VAT) range between EUR 3 000 and 5 000, including the licence for one user. In scientific research, mathematical models are used more often.

## 4. Mathematical models for the turbulent wind flow

At wind farms, the turbines which neighbour each other are the source of the laminar wind flow disturbance. The variation in wind speed may also be the result of the terrain. The impact of the terrain can be determined by providing the value of the roughness coefficient. In many cases, both sources of the disturbance of the wind flow by the turbine rotor are present. The obstacles change both the wind speed value and its nature. There are local vibrations which cause turbulences, which in turn changes the nature of the air stream flow from laminar to turbulent.

Figure 5 presents the typical method of arrangement of wind turbines in farms.

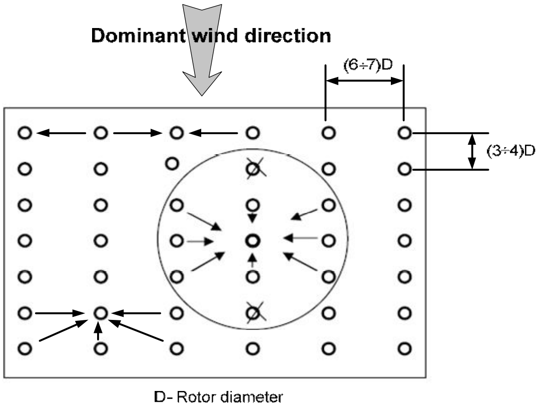

Fig. 5. Arrangement of wind turbines at a wind farm

If there is only one row of wind turbines, it is necessary to take into account the impact of the two neighbouring turbines, excluding those located at extreme ends. If there are two rows, this number is increased to five turbines. In the case of wind farms with many rows, the source of turbulence comprises eight neighbouring turbines.

Figure 6 presents the impact of an obstacle on the wind speed value in a simplified manner.

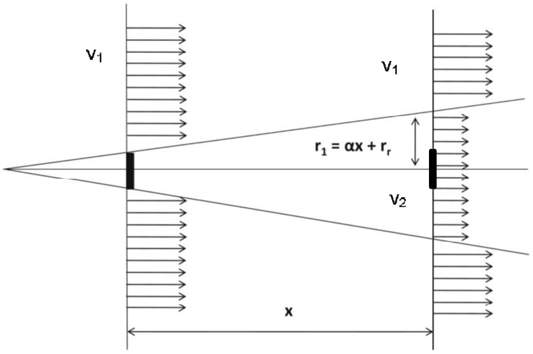

Fig. 6. Impact of an obstacle on the wind speed value

Coefficient $\alpha$ determines the wind speed variation rate vs. distance and is calculated from formula (1):

$$\alpha = \frac{0.5}{ln\frac{z}{z_0}} \tag{1}$$

where: $z$ – distance between the ground level and the turbine hub that generates disturbances, $z_0$ – coefficient of terrain roughness between the turbines.

According to the latest research results [7] value $\alpha$ depends on the turbulence intensity. Table 1 presents the relative wind speed turbulence values and the corresponding values of the coefficient of variation.

Table 1. Relationship between the turbulence value and the coefficient of wind speed variation rate [7]

| Turbulence intensity [%] | Coefficient of variation $\alpha$ |
|---|---|
| 8 | 0.040 |
| 10 | 0.052 |
| 13 | 0.063 |
| 15 | 0.075 |
| 16 | 0.083 |
| 18 | 0.092 |
| 21 | 0.100 |
| 24 | 0.108 |
| 29 | 0.117 |

Variation in speed $\delta v$, often called speed deficit, is calculated according to formula (2):

$$\delta v = \frac{v_1 - v_2}{v_1} \tag{2}$$

Figure 7 presents the impact of two turbines A and B on the value of wind speed reaching turbine C.

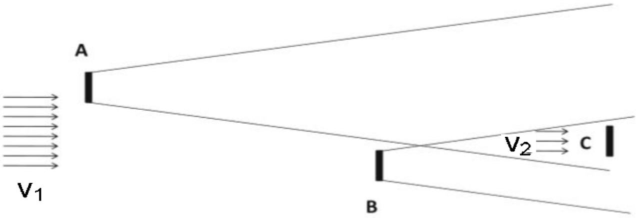

Fig. 7. Impact of several obstacles on the wind speed value

Wind speed $v_2$ acting on wind turbine $c$ is lower than wind speed $v_1$. This is the result of impact of the obstacles, that is, turbines A and B.

As the wind speed changes its value in the function of the distance from the ground level or sea level, the assumption of the constant wind speed reaching the turbine rotor is a simplified assumption. Fig. 8 shows the average value of wind speed variation in the function of the distance from the ground level.

In meteorology, the wind rose is usually presented in eight directions, i.e. four basic ones and for intermediate ones. In wind energy, the wind rose plot is more accurate and is determined in 12 directions. In navigation, the 32–rumbo scale of cardinal directions is used. The plot presented in Fig. 8 constitutes the average of twelve different cardinal directions. Fig. 9 presents changes in the wind speed value for three cardinal directions, i.e. north, north–northeast and east–northeast.

The difference in the speed of wind reaching the respective propellers of the rotor may exceed even 30%. The most frequently used analytical methods of testing of the impact of obstacles on the generated power by wind farms include the Jensen, Larsen and Isihara's models [4, 5, 8, 9, 10].

In the Jansen's model, the value of wind speed variation $\delta v$, resulting from the configuration of the wind farm is calculated according to formula (3):

$$\delta v = \frac{1-\sqrt{1-G}}{1+K(\frac{x}{r})^2} \tag{3}$$

where: $C_T$ – thrust coefficient, $D$ – rotor diameter, $x$ – distance between turbines, $K$ – experimentally determined value.

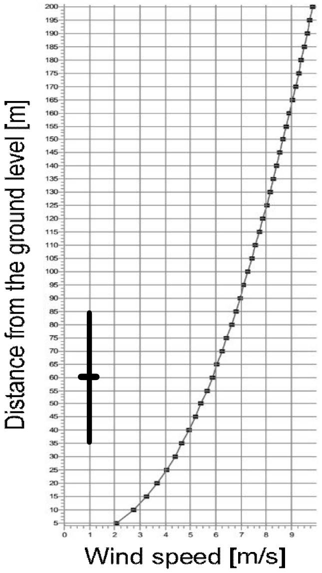

Fig. 8. The averaged course of wind speed variations in the function of the distance from the ground level [7]

Value $K$ typically ranges between 0.04 and 0.075. It can be precisely calculated from the following formula (4):

$$K = \frac{A}{\ln \frac{h}{z_0}} \tag{4}$$

where: $A = 0.5$, $h$ – height up to the hub, $z_0$ – terrain roughness.

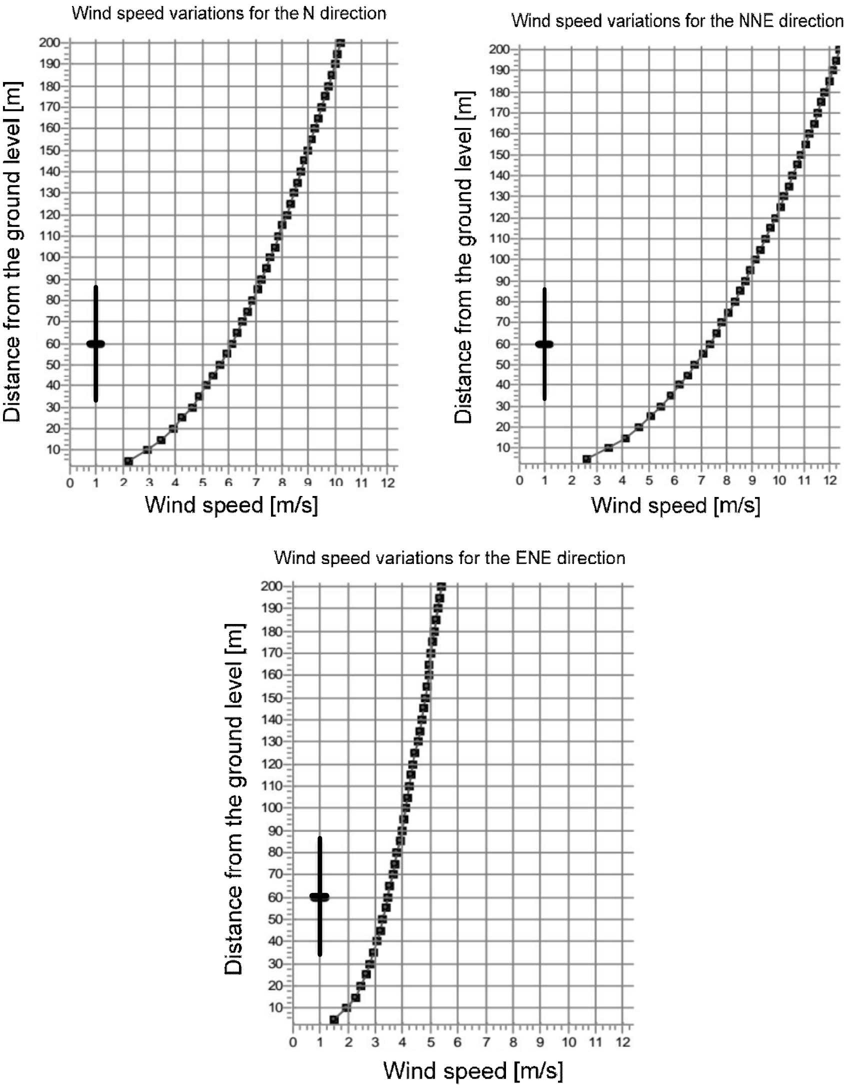

Fig. 9. Changes in the wind speed value in the north direction (N),north–northeast(NNE) and east–northeast (ENE) [7]

The value of the coefficient can be calculated from empirical formula (5), within the following wind speed variation range: 5 m/s < $v$ < 17.5 m/s.

$$C_T = -44.95\frac{1}{v^2} + 15.64\frac{1}{v} - 0.333 \tag{5}$$

where: $v$ – wind speed.

In the Larsen's model, the Prandtl equation is used. The value of the speed deficit is calculated according to formula (6):

$$\delta v = \frac{(C_1 A x^{-2})^{\frac{1}{3}}}{9}[r^{\frac{3}{2}}(3C_1^2 C_T A x)^{-\frac{1}{2}} - (\frac{35}{2\pi})^{\frac{3}{10}}(3C_1^2)^{-\frac{1}{5}}]^2 \tag{6}$$

where: $A$ – the area swept by the propeller, $C_1$ – Prandtl distance, $r$ – distance between neighbouring turbines, $D$ – rotor diameter.

Value of coefficient $c_1$ is calculated according to formula (7):

$$C_1 = (\frac{D}{2})^{\frac{5}{2}}(C_T A x_0)^{-\frac{5}{6}} \tag{7}$$

where: $x_0$ is calculated according to formula (8)

$$x_0 = \frac{9.5D}{(2\frac{R_{9.5}}{D})^3 - 1} \tag{8}$$

Value $R_{9.5}$ is calculated according to formula (9):

$$R_{95} = 0.5(R_{nb} + min(h, R_{nb})) \tag{9}$$

Value $R_{nb}$ is calculated according to formula (10):

$$R_{nb} = max[1.09D, 1.08D + 21.7D(I_a - 0.05)] \tag{10}$$

where: $I_a$ – value of turbulence at the height of a hub.

Jansen and his collaborators developed the model in the year 1983. Larsen and his collaborators developed the model in the year 1988. The Isihara model was presented only in the year 2004. In this model two components of turbulence are taken into account, i.e. the natural one and the forced one. The natural turbulence or the real turbulence $I_a$, results from the impact of terrain, i.e. the roughness value. The forced component of the turbulence is caused by the surrounding turbines.

Changes in wind speed are calculated according to formula (11):

$$\delta v = \frac{\sqrt{C_T}}{32}(\frac{1.666}{k_1})^2(\frac{x}{D})^{-p} exp(-\frac{r^2}{b^2}) \tag{11}$$

where: $k_1$ = 0.27, $b$ – turbulence breadth, $p$ – turbulence intensity calculated according to formula (12).

$$p = 6.0(I_a + I_w) \tag{12}$$

In the cases when the turbine operation is disturbed by more than one obstacle, the resultant impact can be calculated using two methods. The first one consists in the assumption of the linear impact of the respective obstacles, hence it takes advantage of the principle of superposition. This is the method which is used more rarely. More frequently, however, the disturbance is treated as something independent and the resultant disturbances are calculated from formula (13):

$$\delta v = \sqrt{\sum_{i=1}^{n} \delta v_i^2} \tag{13}$$

where: $\delta v$ – resultant wind speed variation, $\delta v_i$ – variation in speed caused by i–th turbine, $n$ – number of turbines affecting the variation in speed.

Formula (13) is recommended in [2] to determine the value of total uncertainty. The results of calculations of the speed deficit in the case of the distances between turbines $x = 200$ m, terrain roughness coefficient $z_0 = 0.3$ m, mast's height $h = 60$ m, rotor diameter $D = 40$ m, wind speed $v_1 = 12$ m/s.

The speed deficit is amounts to:

$\delta v_J = 5.51\%$ $\delta v_L = 6.41\%$ and $\delta v_I = 8.54\%$ respectively

Calculations made using the Jansen's method are the simplest and are considered the least accurate. Calculations using the Larsen's method are the most time–consuming. The values of speed deficits are at the same level. The average value of the speed deficit is 7%. Distance between the turbines was 5D, therefore it is higher than the recommended value – (3–4)D. In the case of wind farms, the turbines located in the middle rows are affected by as many as 8 disturbances caused by obstacles.

## 4. Summary

The optimisation of topology of generating units in the wind farm is, by definition, of multi–criterial nature. At present, genetic algorithms are used frequently. One of the most important criteria is the design of such a farm configuration that a reduction in the amount of the produced electric energy, caused by the neighbouring turbines, would not exceed the assumed level.

In order to describe the turbulent flow, the most frequently used equation is the Reynolds' equation. If the true value of the Reynolds number – Re – is lower than the theoretical one, the air stream flow is laminar. If the calculated value is higher than Re, the flow is metastable or turbulent. In real media, there are two critical Reynolds numbers which are determined – the lower one and the upper one . Below the global value, the flow is laminar, and above the upper one, it is always turbulent.

Turbulence reduces the amount of the electric energy generated by the turbine and affects the fatigue strength of external parts of the wind power plant. In order to determine the vertical wind profile, Lidars and Sodars are used. It is expected that wind farms will soon reach the power of 1–2 GW, at the unit turbine power of 10 MW. As the power of the respective generating units increases, the rotor diameter also becomes larger. Therefore, the impact of turbines as the source of wind flow turbulence is also increased. It seems that the calculation of turbulence by means of kinematic methods will be replaced by mathematical models in view of the wind speeds used more frequently in measurements, and the vertical wind distribution with Lidars and Sodars.

Determination of the impact of the neighbouring wind farms on the generated electric power is a separate issue which is not subject to analysis in this paper. This is a particularly important issue in the case of offshore wind farms.

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