DOI: 10.15199/17.2023.6.3

The Finite Elements Method application to assesment the impact of turbulence generated by wind turbines on their location in close proximity of overhead high voltage power transmission lines

Zastosowanie metody elementów skończonych do oceny wpływu turbulencji generowanych przez turbiny wiatrowe zlokalizowane w pobliżu napowietrznych linii elektroenergetycznych wysokiego napięcia

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Keywords: *Electric power engineering, Finite element method application, Technical standard, Turbulent vortex, Wind turbines, Wind farm location*

Abstract
The paper presents selected aspects of network construction related to the location of wind turbines due to their aerodynamic impact on power lines of high and highest voltage. The technical context has been described on the applicable formal and legal conditions. Based on the source data concerning the aerodynamic impact of a wind farm consisting of eight turbines on a 400 kV transmission power line, an analysis of the possibility of wind farm locating in the immediate vicinity of the line was carried out. There are serious problems with locating higher capacity wind farms in the context of their connection to the transmission grid. One of the most important issues in the design/construction of wind farms is the rationalization of the typology of distribution of individual generating units due to the turbulence they generate . An example of a report on the assessment of the aerodynamic impact of wind turbines on a high-voltage power transmission line in the case of planning their location in the vicinity of the line is presented. Ways of solving the wind farm location problems have been proposed, which allow the wind farm to be located in the vicinity of an overhead high-voltage power transmission line.

Słowa kluczowe: *Elektroenergetyka, Zastosowanie metody elementów skończonych, Norma techniczna, Wir turbulentny, Turbiny wiatrowe, Lokalizacja farm wiatrowych*

Streszczenie
The paper presents selected aspects of network construction related to the location of wind turbines due to their aerodynamic impact on power lines of high and highest voltage. The technical context has been described on the applicable formal and legal conditions. Based on the source data concerning the aerodynamic impact of a wind farm consisting of eight turbines on a 400 kV transmission power line, an analysis of the possibility of wind farm locating in the immediate vicinity of the line was carried out. There are serious problems with locating higher capacity wind farms in the context of their connection to the transmission grid. One of the most important issues in the design/construction of wind farms is the rationalization of the typology of distribution of individual generating units due to the turbulence they generate . An example of a report on the assessment of the aerodynamic impact of wind turbines on a high-voltage power transmission line in the case of planning their location in the vicinity of the line is presented. Ways of solving the wind farm location problems have been proposed, which allow the wind farm to be located in the vicinity of an overhead high-voltage power transmission line.

1.Introduction

The advantages of onshore wind energy are obvious. Onshore wind energy is a relatively cheap technology for generating electricity. Currently, the latest generation wind farms installed onshore in Germany, Sweden, Finland, and Ukraine, with rotors from 150 m, tower heights from 160 m, and generator power from 4 MW, show a sustainable efficiency factor regardless of the location of the wind turbine in a given country. Important problems that hinder the development of wind energy, which undoubtedly have a negative impact, i.e. the stochastic nature of energy generation, e.g. are an increase in demand for flexible power in the system, potential social problems, and the impact on network problems (greater susceptibility to failures, the need for grid development, the aerodynamic impact of wind turbines on high and highest voltage power lines caused by the generation of turbulent vortices by them. There are very serious problems with locating higher capacity wind farms in the context of

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their connection to the transmission grid. One of the most important issues in the design/construction of wind farms is the rationalization of the typology of distribution of individual generating units due to the turbulence they generate [2].

There are many models (physical and mathematical methods) and the methods used to calculate the impact of turbulence on the efficiency of a wind farm. Their excellent characteristics are included in the work [3], where the currently used models and programs for numerical calculations are described. Reference [3] shows frequently used computational programs include: WAsP, WindPro, WindFarmer, WindFarm, WindSim, where respectively Jensen models [6] and the linearized CFD model are used, a module with WAsP; while the WindFarmer program uses the following models: Ainslie, RANS and CFD. On the other hand, the following models were used in the WindFarm software: Jensen, Ainslie, and Larsen, and the models: Larsen [6],[1] and Ishikara [5] in the WindSim program, which gives a relatively short computation time. Finite element methods are also used for modeling/calculating turbulence [9],[16],[10].

It should be noted that turbulence/disturbance of the even flow of air streams can reach considerable values, even up to 20%. The main source of turbulence is the terrain, the influence of electromagnetic radiation of the sun, and obstacles, e.g. trees, neighboring wind turbines, weather masts, and other obstacles in the field. In the case of wind farms (both off-shore and on-shore), the value of wind velocity turbulence is considered to be the main cause of a decrease in generated power, which in turn affects the stability of the electricity network. This is of paramount importance when planning the location of a wind farm near power lines, understood as distances up to 5 diameters (5d) of the turbine rotor. Assuming a kind of "obstacle" in the form of a power line occurring on the path of airflow from the turbine to the line (in the most unfavorable case perpendicular to the axis of the section/span route), it is necessary to take into account the aerodynamic impact of the turbine on the line, which practically means – when testing wind turbine location – analysis of the distance between its foundation and the power line. These issues are the subject of this article, in which the author shows a case study set in a real decision-making situation.

2. General formal and legal conditions

The public debate on the development of renewable energy sources often generalizes the issue of the adequacy of the transmission/distribution infrastructure, ignoring or trivializing the limitations resulting from it. As a result, from the point of view of network development planning and the concept of managing it, it creates a permanent state in which there is a very large surplus of projects, ideas, and concepts, most of which will naturally not be implemented.

Wind power plants require the existence of sources that will balance them in the period of the lack of primary energy. Currently, the "firm capacity" level for onshore wind farms is ca.10-15%, and offshore – ca. 20%.

This creates challenges for the centralization organization in the electricity wholesale market, as it should create a business space for balancing sources. At present, it seems that the market is not correctly evaluating the balancing value. It is indirectly done by the capacity market, but it is not treated as an opportunity to solve the problem – only as support for coal-based energy.

The intensive introduction of renewable energy sources (with their specific grid operation characteristics) causes an increasing number of grid operations different problems (failure frequency, source disconnection, a necessity to modernize and change grid automation). In summary, it is impossible to introduce all sources into the current networks in any way and the process of connecting (and obtaining permits) will become more and more complicated. This may be a factor that significantly limits, and certainly slows down, the possibility of introducing zero-emission energy – a factor that is not currently included in optimistic development plans.

Additionally, developing renewable energy, in particular wind farms, creates, inter alia, essential requirements for the location of wind turbines with a horizontal axis of rotation. One of the main obstacles in the development of renewable energy is the principle that determines the distance at which wind farms can be located and built. The permissible distance of the wind turbine from the residential buildings is to be equal to or greater than ten times the height of the wind turbine measured from the ground level to the highest point of the windmill, including the rotor with blades (10 h rule). The 10h rule, according to many experts, slowed down / expired construction of new wind farms and hindered spatial planning processes in the field of residential construction in communes where farms were previously located [4]. The rigidly defined distance from buildings does not reflect the conditions of an individual location, as it may turn out to be too large or too small for a specific place. Since the often used onshore turbines have a total height of no more than approx. 220 m, it is difficult/impossible to develop further projects, because the existing wind farm sites will not be able to be used for more modern and more efficient machines due to the lack of areas for their development. Changing the 10h rule seems to be necessary to avoid an investment gap in wind farms. There is a risk of such stagnation in investments in a few years, after the completion of investments in the recently concluded auctions. The change would unblock the development of wind energy and planning difficulties in land development. Besides, it is advisable to introduce the principle of reliable forecasting of noise emissions, in particular, the impact of a turbine as a source of turbulence, at the stage of investment preparation and preparation of planning documents, and then appropriate measurements after the completion [4]. One can then check whether the assumed acoustic standards are met and whether any problems can be remedied, which in practice happens occasionally due to the technical conditions of the devices. In the opinion of the author of this paper, the existing rules for the location of wind turbines should be clarified, while maintaining the safety requirements for the construction of the wind turbine foundation in the event of resignation from the rigid 10 h distance criterion, as the postulates to introduce transitional regulations or attempts to ease the distance criterion do not solve the location problems.

3.Technical context

In general, the assumption of a rational reduction in air velocity as it passes through the turbine, where the air velocity behind the rotor is 1/3 of the velocity in front of the rotor, leads to Betz's law (the power of the wind varies proportionally to the third power of its speed), by which the theoretical maximum useful power is taken from the flowing air stream is calculated according to the formula [15]:

$$P_{u,max} = \frac{8}{27} pA_1V_0^3 \tag{1}$$

$P_{u,max}$ – theoretical maximum useful power taken from the air stream,
V_0 – wind speed in front of the wind turbine set rotor,
ρ – air density,
A_1 – surface "swept" with the rotor of the wind turbine set.

Betz's law determines the maximum theoretical efficiency of converting the power of the wind flowing to the wind turbine set into mechanical power used by this turbine set (this efficiency is approximately 59.3%). The occurrence of wind is stochastic. The wind speed, on the other hand, depends largely on the topography (roughness) and the height above the ground. There are various definitions of ground roughness depending on its topography. According to the study [15], three types of terrain roughness are most often distinguished:

- open (with few obstacles of low height),
- rural (with low buildings or wooded area),
- urban (with high buildings).

Table 1. Terrain roughness classes

Tabela 1. Klasy chropowatości terenu

Roughness class	Gradient wind height HG [m]	Roughness factor K	Exponent α	Description of the area
0	300	0,005	0,150	Flat open area where the height of unevenness is less than 0.5 m
1	330	0,007	0,165	Flat, open, or slightly undulating terrain. There may be individual buildings or trees at large distances from each other
2	360	0,010	0,190	Flat or undulating terrain with large open spaces. There may be groups of trees or low buildings at a considerable distance from each other
3	400	0,015	0,220	Areas with obstacles, wooded areas, suburbs of larger cities and small towns, industrial areas with built-up areas
4	440	0,025	0,270	Areas with numerous obstacles in close proximity to each other, i.e. clusters of trees, buildings, at a minimum distance of 300 m from the observation site
5	500	0,035	0,035	Areas with numerous large obstacles located close to each other, forest areas, centres of large cities

A four-level scale of terrain roughness dominates in Europe, taking into account the height of obstacles, their cross-sections, and areas of horizontal projections. For the development of domestic wind energy, a more detailed, i.e. a six-level roughness scale [15] has been proposed, presented (while retaining the original markings) in Table 1.

The current standard technical specification of the transmission system operator (PSE) specifies the requirements for the distance between wind turbines and overhead high voltage power lines as a minimum of 3d, counting from the tip of the turbine blade to the axis of the line route, and the condition for using active anti-vibration protection in the case of locations less than 5d [12]. This is basically in line with the previously applicable PSE standard, where the distance is 3.5d, but from the axis of the turbine foundation to the axis of the line route. Interesting considerations are presented in [3], where, based on the standards [13], [14]; in addition to a brief description of the models and methods used to calculate the impact of turbulence on the farm efficiency, examples of sectors/areas in which the operation of the turbine are significantly influenced by various obstacles are given (creating an aerodynamic footprint) in the air/wind path (see Figure 1).

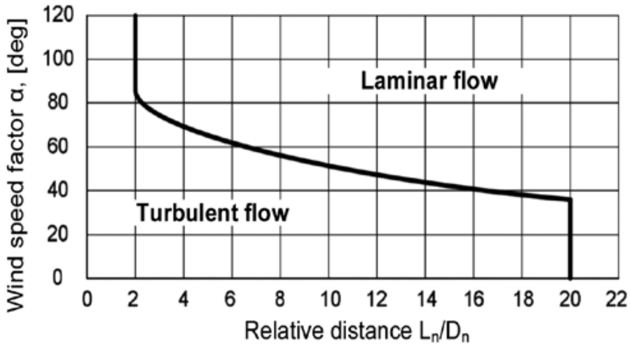

Fig.1. Air flows dependency on the relative distance L_n / D_n

Rys.1. Zależność przepływów powietrza od względnej odległości L_n / D_n

The study of the impact of obstacles on the efficiency of wind farms, and more specifically the impact of an obstacle on the value of wind speed, is illustrated by the coefficient α, which determines the rate of changes in wind speed as a function of distance and is calculated from the formula:

$$\alpha = \frac{0{,}5}{\ln \frac{z}{z_0}} \qquad (2)$$

where: z – the distance between the ground surface level and the turbine hub generating the disturbances,

z_0 – roughness coefficient of the terrain between the turbines (a kind of equivalent of the K coefficient from Table 1).

As is known, the value of α depends on the intensity of turbulence. Table 2 presents the relative values of wind velocity turbulence and the corresponding values of the change factor.

Table 2. The relationship between the value of turbulence and the coefficient of changes in wind speed

Tabela 2. Zależność wartości turbulencji w funkcji współczynnika zmian prędkości wiatru

No.	Turbulence intensity [%]	Change factor α
1	8	0,040
2	10	0,052
3	13	0,063
4	15	0,075
5	16	0,083
6	18	0,092
7	20	0,099
8	21	0,100
9	24	0,108
10	29	0,117

As the power of individual generating units increases, the rotor diameter grows. Therefore, the influence of turbines as a source of wind flow turbulence increases. According to the authors of the work [3], optimization of wind farm topology can be performed, based on TOPFARM programming, where one can model various

structures of wind farms use various models of wind speed distribution, considering turbulence components, analyze technical and economic aspects and carry out multi-criteria optimization.

Assuming the shape of a turbulent vortex as a truncated cone (with a slightly irregular shape) lying on its side, with a smaller circular base with a diameter equal to the diameter of the turbine rotor, and a larger one with a diameter equal to (d + 2ltgα, where for small values of the angle up to approx. 15 degrees – its tangent is equal to the angle of the arc measure), where l is the distance between the turbine and the line element (column, line segment, span, etc.), i.e. the height of our cone, and α – the cone/vortex forming angle with the base (in the longitudinal section of a trapezium[12] – for example, see Fig. 2, using the formulas of analytical geometry and planimetric relationships and having source data, it is possible to analyze and study possible cases of penetration of a turbulent vortex body with a line chain curve for each case of foundation of a specific turbine in the planned location.

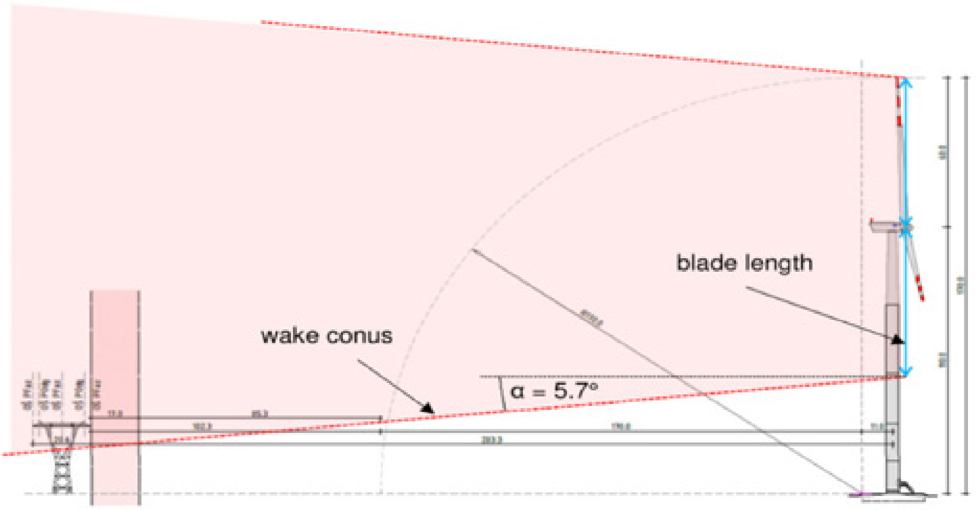

Fig.2. An example of a longitudinal section of a turbulent vortex for a specifically designed wind farm (original designations have been retained – adopted from [7])

Rys.2. Przykład przekroju podłużnego wiru turbulentnego dla zaprojektowanej farmy wiatrowej (zachowano oryginalne oznaczenia zastosowane w pracy [15])

The results of the calculations should be confirmed by numerical tests of the turbulent vortex in order to obtain a certainty bordering on the guarantee that the generated vortex will not harm the power line [7]. Despite the time-consuming numerical calculations of the turbulent vortex [7], the author of this paper considers carrying them out and developing an Assessment Report as necessary to make a decision on the location, close to the power grid.

4.Report for the assessment of the impact of turbulence generated by wind turbines on the highest voltage power line – case study

4.1 General remarks

In an exemplary preliminary evaluation report, the results of the author's rough formal analysis are presented and the author's calculations and an illustration of a trial application of the numerical analysis of turbulent eddies generated by the considered turbines in the planned places of their foundation are presented. The location of the planned wind farm is shown in Fig. 3.

4. 2. Presentation of the preliminary results of the analysis

Lightning protection wires (Pog) are the highest situated elements of the power transmission line excluding from the height of their suspension on a specific pole in relation to the ground surface. Using the equation of the chaining curve for their, at the point of intersection of the perpendicular line as the shortest distance to the longitudinal profile of power transmission line, the suspension heights Hpog for each turbine were calculated. The value of the "vortex spread angle" specified in the study by Aero Dynamic Consult [9] for a specifically planned turbine at 5.7 degrees was positively verified by two existing models of turbulent vortex propagation, as the author of this paper calculated it 5 to 6 degrees, depending on the model used [7]. It should be noted that the calculation of the height of the "excess" includes the tangent of the angle, which with these slightly different values is within the error resulting from rounding. Thanks to this, it can be assessed whether the phase conductors, as suspended lower than the lightning protection, may be located below the lower ribbon of turbulent eddies, which will flow above the line at the appropriate Hwir elevation (calculated from the ground surface). It is shown in Table 3, which presents a preliminary analysis of the phenomenon of "overshoot" of turbulent eddies while maintaining the original numbering of the power plant (EW-X) according to the order of location along the route of the transmission power line [12].

The results presented in Table 3 are rough calculation results. The author of this paper recommends detailed calculations and numerical analysis by the finite element method (in the past and currently used by many experts) of turbulent vortex propagation for 8 turbines (for 3 wind speeds: 10.8; 20.0; 25.0 [m / s]) and for the following four variants (W-1, W-2, W-3, W-4):

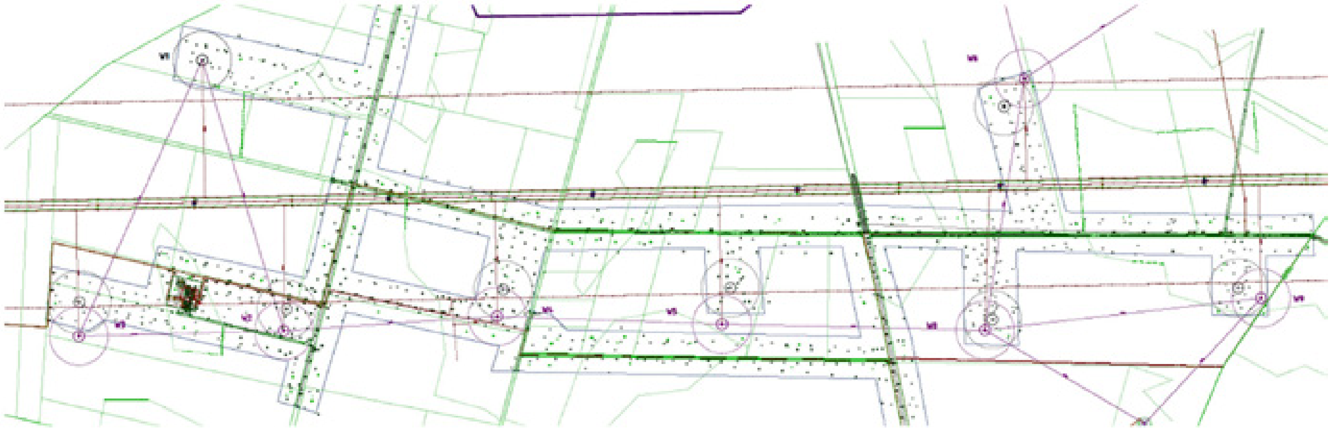

Fig.3.Wind turbines location

Rys.3. Lokalizacja turbin wiatrowych

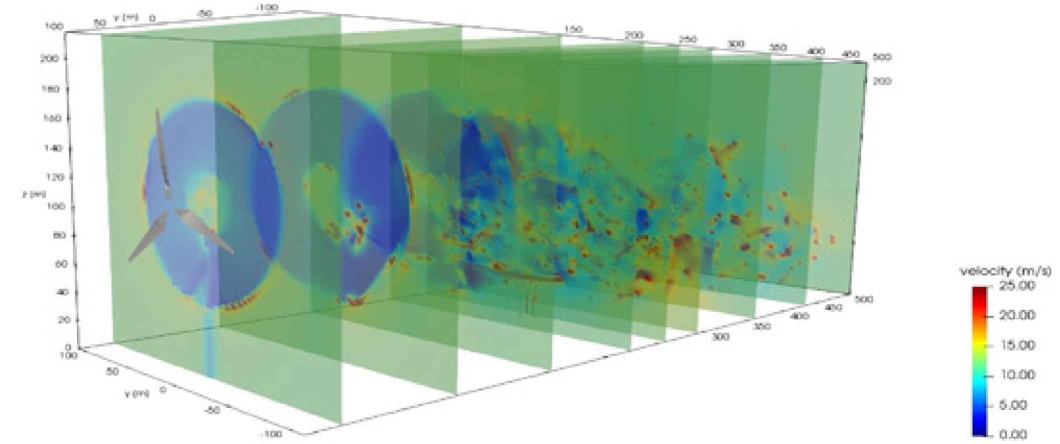

Fig. 4. View of a turbulent whirl (adopted from[8])

Ryc. 4. Widok wiru turbulentnego (zaczerpnięto z pracy[16])

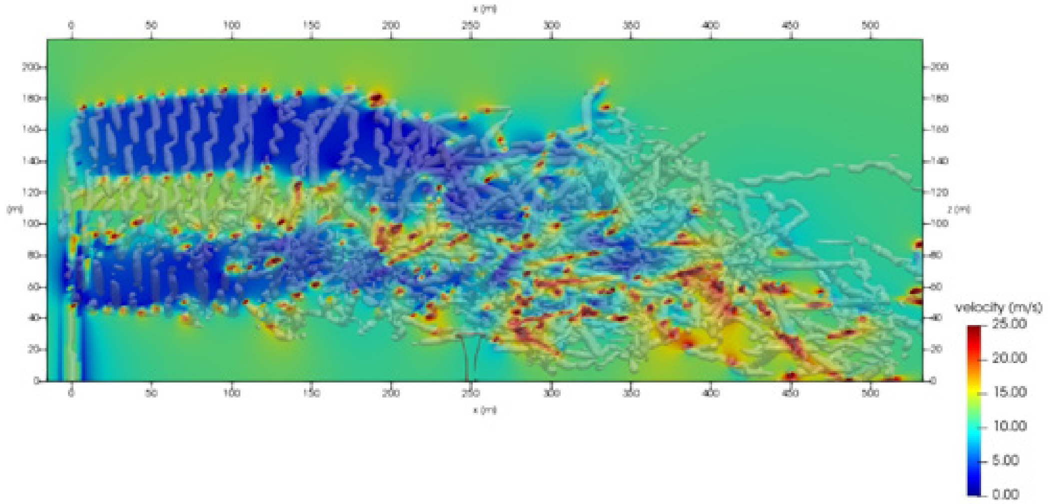

Fig. 5. Longitudinal section of a turbulent vortex (adopted from [8])

Rys. 5. Przekrój podłużny wiru turbulentnego (zaczerpnięto z pracy [16])

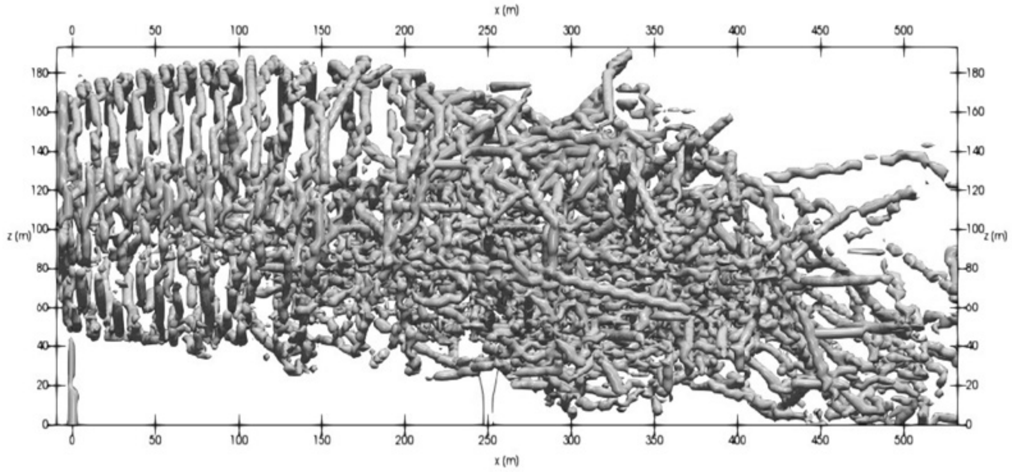

Fig. 6. Projection of the turbulent vortex (adopted from [8])

Rys. 6. Rzut wiru turbulentnego (zaczerpnięto z pracy [16])

Table 3. Results summary of the phenomenon of "surpassing" turbulent eddies analysis

Tabela 3. Podsumowanie wyników analizy zjawiska „przekraczania” wirów turbulentnych

No. wind power plant	Distance L from the line [m]	Suspension HPog [m]	Elevation Hwir [m]	Reserve[m]	Remarks
EW-3	260,2	22,17	24,14	+1,97	the vortex will not "catch" on the line
EW-1	283,3	29,79	21,84	-7,95	the vortex will "catch" the line
EW-2	258,2	23,25	24,34	+1,09	the vortex will not "catch" on the line
EW-4	237,9	22,73	26,35	+3,62	the vortex will not "catch" on the line
EW-5	263,7	18,46	23,79	+5,33	the vortex will not "catch" on the line
EW-8	287,2	28,65	21,45	-7,20	the vortex will "catch" the line
EW-6	209,9	26,25	29,14	+2,89	the vortex will not "catch" on the line
EW-9	233,1	22,45	23,78	+1,33	the vortex will not "catch" on the line

- **W-1 Basic**: turbine type 2.75 / 120, hub height 110 m and location – no changes;
- **W-2 Corrected A** – turbine type 2.75 / 120, for EW-1, EW-8 hub height change from 110 m, for example 139 m, without changing the location of all eight power plants;
- **W-3 Corrected B** – turbine type 2.50 / 120, for EW-1, EW-8 hub height change from 110m, for example 120m, without changing the location of all eight power plants;
- **W-4 Corrected C** – turbine type 2.75 / 120, hub height unchanged, and for EW-1, EW-8 change of location (approaching the line at a distance allowing to obtain the effect of "surpassing" the turbulent vortex, which will not catch on the line.

This will require, after detailed calculations and in-depth numerical analysis of turbulent vortices using the above-mentioned methods and models, the presentation of turbulent vortices originating from individual eight turbines on 96 drawings, and calculations and illustrations of "summary" vortices – resulting from the interaction of "adjacent" turbines together. To illustrate the scope of research and analysis, for illustrative purposes, below – examples of illustrations of a turbulent vortex (see Fig. 4-6) are attached below made at the Gdansk University of Technology [7], which were obtained for the object with the assumption that the wind blows from the left side to the right, the turbine stands on the X-axis in position 0, and the 400 kV transmission power line pole on the X-axis at 250 meters (it is hardly visible because it is low compared to the turbine itself).

As can be seen from the above illustrations, the lower ribbon of the turbulent vortex has a chance to flow above the power transmission line, if it is possible to bring the turbine closer to the line to a distance of Lmin. In this case maintain 10% buffer zone of construction safety related to the risk of the structure falling towards the line, which gives an obvious condition distances $L_{min} = z + d / 2 + 0.1 (z + d / 2)$, where z – the distance between the ground surface level and the noise generating turbine hub, d – turbine rotor diameter.

4.3. Final conclusions of the preliminary analysis

With the use of source materials [12], original calculations were made and a trial application of numerical analysis of turbulent eddies was made. On this basis, it can be concluded that out of the eight considered – six turbines can probably be located in the planned places of foundation. Turbines: EW-1, EW-8, located respectively at real distances: 283.3 m; 287.2 m from the 400 kV transmission power line will probably require additional procedures in order to be installed, which should be documented in the planned study based on in-depth research and numerical analyzes. This analyzes should include several calculations and tests to convince the owner/operator of the transmission power line to the advisability of changing the standards for locating wind farms due to the possibility of turbulent vortices that could threaten the safety of the power line structure.

5. Conclusions

Until 2030, with the gradual departure from carbon fuels caused by environmental pressure, renewable technologies will play a significant role in energy power development. They can partially replace the shrinking coal fuel base. Also, they can find employment/use of the constructed electricity transmission and distribution system infrastructure. Current development constraints for RES is among others lack of an adequate transmission/distribution network.

The place in the network is generally reserved at the stage of connection conditions establishment. This creates the famous case/possibility of "sitting" on the grid at an early stage of projects, blocking the development of others. Transmission operators call for actions in this area:

- introduction of master plans (Energy Policy, Climate Policy, etc.) – at least partially, specifically setting priorities in terms of the number, pace, and location of connected sources,
- in the case of sources benefiting from support – the introduction of a promising system, which would become connection conditions only after the received support,
- in the case of sources not benefiting from support – introducing a declaration of investment implementation without support along with a system of security and guarantees enabling "reservation" of a place in the network,
- unification of the law so that at the stage of applying for conditions, energy banks, like other sources, pay an advance on the connection fee.

The power grid should be planned and implemented sustainably, meeting the goals and directions for the development of the energy sector indicated in the country's energy policy, including e.g. diversification of electricity generation technology. In particular, the development of the transmission system must ensure the creation of technical conditions to cover the growing demand for power and electricity in individual areas of the country, power evacuation from the planned new generation sources, and improvement of conditions for the integration of the Pan-European energy market. In view of the rather irreversible direction of the transformation of the power sector (Green Deal), it will be necessary to invest in RES, which in real conditions will result in investing mainly in wind farms and photovoltaic farms. The current formal and legal conditions are rather not accommodating to such investments. Therefore, it seems necessary to change the law to avoid an investment gap in wind farms. Changes in the law could unblock the development of wind energy and planning difficulties on the part of municipalities. It is advisable to introduce the principles of reliably conducted noise emission forecasts, in particular, the impact of the turbine as a source of turbulence already at the stage of investment preparation and preparation of planning documents, and then taking appropriate measurements after the construction is completed. For example, it will require detailed calculations and in-depth numerical analyzes of turbulent eddies with the use of effective methods and models, studying the processes of generating turbulent vortices from turbines included in the wind farm, and calculations and illustrations of "summary" eddies – originating from the interaction with each other of "adjacent" turbines in the form of a compact report on the assessment of the aerodynamic impact of wind turbines on high and extra-voltage power lines. In the opinion of the author of this study, the existing rules for the location of wind turbines should be clarified, while maintaining the safety requirements for the construction of wind turbine foundation, in particular in the event of abandoning/resigning from the existing rigid distance criterion, which would allow for the acquisition of rational locations for the wind turbine foundation. ■

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of Interest: The author declares no conflict of interest.

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