

Modeling of electricity production by wind power stations of Ukraine

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Abstract. Based on the results of actual multi-year measurements of wind speeds, numerical calculations have been made of the forecast energy productions of 43 megawatt-high power stations of the leading world producers in the wind conditions of the North Black Sea region of Ukraine. The established correlation between the annual energy production of wind power station (WPS) and its basic parameters (nameplate capacity, diameter of the rotor and hub height) allowed to develop a mathematical model of the forecast annual energy production of WPS. The calculations for the mathematical model are well in line with the operational parameters of the generation. The mathematical model makes it possible to quickly and reliably select (or design) the optimal wind turbine for industrial wind power in the North Black Sea, thus taking a significant step in reducing the energy dependency, environmental protection and the transition to energy-efficient and environmentally friendly technologies enabling Ukraine to reach the level of advanced states in the development of wind energy.

1 Introduction

1.1 Problem statement

Wind energy (WE) is considered to be one of the promising sources of renewable energy at the present stage of energy development in economically developed countries. This fact guarantees the harmonious development of the planet. The Paris Agreements (Paris, December 2015) have identified renewable energy as the leading instrument in the fight against climate change on the planet. This is becoming one of the main areas of technology development in the world. Along with information and nanotechnology, renewable energy is becoming an important component of the new post-industrial technological structure. Ukraine urgently needs to switch to energy-efficient and environmentally friendly technologies, including WE.

Ukraine is a country with a long tradition of using wind. In the first two stages of the global development of renewable energy, it was a significant success. In the third stage, which began in the early 80s of the last century, Ukraine, which has a high wind potential, began the industrial use of wind with almost 40 years behind world leaders [1].

The wide-scale building of wind power stations (WPS) in Ukraine will make it possible to take a significant step in reducing energy dependence, protecting the environment and creating conditions for the country to join the European community.

By building efficient industrial WPS, the WE of Ukraine can and should be brought to the level of the advanced countries of the world with generation of 25–35% of the total energy consumption, which is of great social and economic importance. Some countries have already done so. Their share of electricity generated by WPS has reached: in Denmark – about 50 %, in Uruguay and in Ireland – more than 25 %, in Portugal – 23 %, in Germany – 20 %, in Spain – 18 % [2]. In the European Union WE since 2016 became the second (after natural gas) source in electricity generation [3]. However, this can be done only after solving the most important scientific and applied problem of the rational choice of multi-megawatt-class wind turbines (WT) for the wind conditions of Ukrainian wind parks.

1.2 The relevance and purpose of the work

Problematic issues of mathematical and computer modeling the parameters of large WT are far from being resolved. The choice of effective WT in Ukrainian wind conditions, which should generate as much commercial energy as possible and satisfy the price/quality ratio, remains open. This significantly limits the reliable selection of WT for a specific construction site of industrial WPS and does not contribute to closing Ukraine's lag behind world leaders. Therefore, the development and implementation of industrial wind energy in the strategic plan for the modernization of the electric power industry is super relevant, the most promising and priority.

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The purpose of the work is the development of methods and computer tools for optimizing the operational parameters of industrial WT in the wind conditions of Ukraine.

2 Materials and methods

2.1 The analysis of factors affecting the performance of WT

An analysis of literature on systematic studies of wind use with the main task to identifying factors that influence the efficiency of WT and the current state of research on the scientific and applied problems of mathematical and computer modeling of large WT has been carried out.

In the works of P.F. Vas'ko et al. [4–6 et al.] proposed a method for determining the performance indexes of WT in relation to the wind conditions of Ukraine. The method is based on the approximation of the empirical dependences of the wind speed repeatability using the three-parameter Weibull-Gnedenko distribution (WGD).

The most important influence factor in this method is the repeatability of wind speeds at the WT installation areas, which is one of the main components of the wind energy cadastre. It shows how much of the time during the working year winds at a certain speed are observed. It is the repeatability of wind speeds that largely determines WT performance.

Offered in the works of P.F. Vas'ko recommending for determination the repeatability by either conducting wind measurements followed by correlation according to the nearest weather stations (WS) over the past 12 to 15 years, or their approximate receipt by extrapolating data from the nearest WS, it is absolutely unacceptable for large WT. Indeed, these WS's data characterize the wind potential very approximately and cannot be used in assessing the performance of WT (WPS). The author himself agrees that the direct use of the WS's initial data causes significant errors in determining the annual generation of electricity. And confirms this with examples: for the Ochakov WS's data the results are reduced by 36 %, and for the Odessa WS – by 180 % in comparison with the open area [5].

The problem of finding the repeatability of wind speeds in the world is solved in different ways. In Japan, for example, this problem first solved it in two stages: at the first stage, the wind speed and direction were recorded for several years; on the second, a landscape model in an aerodynamic tube was purged. Based on the data obtained, the wind energy cadastre was determined for any point of the simulated landscape [7].

Much later, evaluating the sea prospect of wind around Japan for offshore WPS, measurements were organized in two places: offshore - on a platform for natural gas extraction in the Pacific Ocean at the height of 94 m, in 37 km from the coast and directly on the coast. Average annual and monthly wind speeds were calibrated for a height of 80 m above sea level to provide a comparison between offshore and land measurements. Simultaneous three-year measurements showed that the average annual sea wind speed is 70% higher than on land [8].

The atlas of winds has been developed in Denmark, in which this task is solved on the basis of models that take into account various factors of the orography of the area and data of the WS [9].

The creation of such an atlas for the wind conditions of Ukraine, as well as the use of Japanese experience, are associated with high material costs and unacceptable for Ukrainian conditions.

The problem of finding promising areas for WT installation has not yet been completely solved and remains relevant for many regions [10-12]. It requires a directed study of the wind regime of territories not only near the earth's surface, but also at different heights of the atmospheric layers near the earth.

The disadvantage in the proposed by P.F. Vas'ko method is to use the coefficient $m = 1/7 = 0.143$, taking into account the change of wind speed with height in the surface layer of atmosphere. In modern large WT, the heights of the hub vary widely and the problem of restoring the wind regime at the same height where the hub located is extremely important. A number of works are devoted to its solution.

Hellmann [13] recommended up to a height of 16 m to take the value of this coefficient equal to $m = 1/4$, and for larger heights $m = 1/5$. In studies of 50-60 years of the last century, this coefficient was assumed to be constant and equal to 0.2 [14]. Researchers from the USA recommend values of the coefficient $m = 0.23 \pm 0.03$, and when averaging wind energy, they use $m = 1/7$. Recently, experts from the USA suggest using a logarithmic dependence, which, in contrast to the power law, gives almost average values between the extreme values of wind speed at low and large heights [15].

Actual values of the power index m for different regions vary significantly from 0.1 to 0.4 and even exceed the values of 0.6 and 0.7. Various engineering methods continue to be developed [16], but as a result, none of the m values gives a good approximation of the data for different WT locations, and therefore the problem of restoring the wind regime at a given height has not yet been solved.

It is not surprising that the recommendations of P.F. Vas'ko, repeatedly cited by various authors [17, 18 et al.], who proposed a scheme of zoning of the territory of Ukraine according to average annual wind speeds, which today has become the basis for the building of industrial WPS in Ukraine, cannot be fully used for WT of multi-megawatt power. After all, the work was carried out at the end of the 50s of the last century, more than 60 years ago, and was studied on WT of low and medium power using the database of the State Committee for Hydrometeorology, when there were not enough experimental and operational data, which inevitably led to significant errors. Therefore, the work contains dubious and erroneous conclusions and recommendations. For example: “An intensive change in the technically achievable wind potential is observed up to a height of 60 m, and then the intensity decreases significantly.” Or: “To ensure the capacity factor of wind turbines in Crimea at the level of 0.3, the rational value of the diameter of the rotor and the rated power of the installation are 48 m and 600 kW, respectively” [19].

As follows from the publications (and it has already become a global tendency), the efficiency of WT increases due to the growth of their rated power. Our studies show that focusing only on the rated power parameter leads to significant losses in electricity production.

On the process of choosing a WT is influenced by many factors: rated power, diameter and height of the rotor axis, operating time in certain zones of the power characteristic, capacity factor (CF). Therefore, a necessary condition for competent synthesis is only a differential approach to assessing each of the influence factors.

2.2 Electricity production of large WT in wind conditions of the Northern Black Sea region

For predictive calculations of the volume of electricity generated by any WT, it is necessary to have data about the wind potential on the area where the WPS equipped with these WTs is located, and a characteristic of the WT itself, i.e., the dependence of the electric power of the WT on the wind speed at the hub height.

The building of an industrial WPS in the Northern Black Sea region is planned in areas adjacent to the Adzhigol pilot WPS (AWPS), for which the distribution of probabilities of wind speed gradations for a period of 18 years measurements at a representative military aerodrome's WS, as well as measurements of wind speed and direction at the AWPS area by a Logger # 9200 device for 26 months at heights of 27 and 31.5 m and simultaneous measurements at heights of 31.5 and 10 m has been done.

The average wind speed over many years' studies, received from measurements data of a representative WS, reduced to the measurement conditions at the AWPS area (the windvane height 31.5 m), is 6.0 m/s. This speed is assumed to be the smallest in the calculations by different methods, which provides the most reliable forecast for a long period of WPS operation [20, 21].

For carry out the calculations of the volumes of electricity production by various WTs, the gradations of wind speeds at the height of the windvane to the hub heights of the studied WTs has been recounted. For recalculations of wind speeds from one height to another, the Hellman's power law has been used [12, 13]:

$$V_H / V_V = (h_H / h_V)^m. \quad (1)$$

Were:

V_V – wind speed at the windvane height $h_V = 31.5$ m;

V_H – the desired wind speed at a hub height h_H of the studied WT;

m – the coefficient of the vertical profile of the wind speed. As special tests have shown, on average for wind in AWPS area $m = 0.227$.

Converting the expression (1) to

$$V_H = V_V (h_H / h_V)^m = V_V (h_H / 31.5)^{0.227}, \quad (2)$$

determine the wind speed on the hub height of the

investigated WT.

So, for the hub height, for example, $h_H = 65$ m:

$$V_H = V_V (65 / 31.5)^{0.227} = V_V \cdot 2.06349^{0.227} = V_V \cdot 1.17873.$$

For WT with $h_H = 100$ m

$$V_H = V_V \cdot 3.1746^{0.227} = V_V \cdot 1.29982 \text{ etc.}$$

Using expression (2), it is possible to convert the data of the annual distribution of wind speeds in the region of the AWPS at a height of $h_V = 31.5$ m into the annual distribution of the recurrence of wind speeds at different hub heights of the studied WTs.

The calculation of the annual potential power generation has been carried out according to the formula:

$$Q_n = \sum P_i \cdot T_i. \quad (3)$$

where:

Q_n – annual electricity production (AEP), MW·h;

P_i – generated power in the i -th range of wind speed V_i on the hub height, kW (according to the characteristics of the WT power);

T_i – duration of the wind speed V_i of the i -th gradation.

The duration of the year in hours was 365 days·24 hours = 8760 hours.

As a result of numerical simulation, the following predicted values for generating electricity of 43 megawatt WTs of leading world companies Leitwind, Enercon, Mitsubishi, Vestas and Fuhrlander in wind conditions of the Northern Black Sea region of Ukraine has been obtained (table 1).

The most important distinguishing feature of the obtained parameters is the use of actual multi-year real measurements of wind speeds and the distribution of their probabilities by gradations at the AWPS area. This is precisely their main difference from those hypothetical meanings that various authors used earlier. Therefore, these quantitative parameters are the basis for further computer modeling.

By numerical simulations, a multifactor dependence of the expected calculated electricity generation of a specific WT has been established.

As a result of computer simulations in first time, it has been found that, for example, LTW77 and LTW80 wind turbines with a nameplate capacity of 1.5 MW produce more electric energy than turbine LTW70 with a nameplate capacity of 1.7 MW; turbine E82-2.0 more than turbine E70-2.3; turbines MWT92-2.4 and FL 2.5-100 is more than turbine V90-3.0; and turbine V90-1.8 is more than turbine V80-2.0 (table 1). It follows that when choosing an effective wind turbine, accounting only for the index of its nameplate capacity will lead to significant losses in electricity production.

2.3 Development of a mathematical model of annual electricity production

One of the main goals of the work is a statistical study of the influence of individual parameters (explanatory

factors): rotor diameter, rotor axis height (hub height), nameplate capacity, etc. on the AEP of WT and on the development of a mathematical model (MM) for this dependence. The resulting MM will make it possible to purposefully select on the world market (or design) the most effective WTs for the wind conditions of a particular area during the building of an industrial WPS.

Table 1. WTs performance parameters of some world companies.

Sl. No.	WT	P, MW	D, m	H, m	Q, MW·h	CF, %
1	LTW70	1.7	70	65	4167	28.0
2	LTW77	1.5	77	65	4471	34.0
3	— —	1.5	77	80	4792	36.5
4	LTW80	1.5	80.3	60	4541	34.6
5	— —	1.5	80.3	80	5155	39.2
6	E66	1.8	70	99	5295	33.6
7	E70	2.3	71	57	4564	22.7
8	— —	2.3	71	100	6221	30.9
9	— —	2.3	71	113	6491	32.2
10	E82	2.0	82	78	6284	35.9
11	— —	2.0	82	100	6899	39.4
12	— —	2.0	82	138	7819	44.5
13	MWT92	2.4	92	70	6746	32.1
14	V80	2.0	80	78	5440	31.1
15	— —	2.0	80	80	5599	32.0
16	— —	2.0	80	100	6095	34.8
17	V90	1.8	90	80	6126	38.9
18	— —	1.8	90	95	6599	41.9
19	— —	1.8	90	105	6806	43.2
20	— —	2.0	90	95	6882	39.3
21	— —	2.0	90	105	7171	40.9
22	— —	2.0	90	125	7454	42.6
23	— —	3.0	90	80	7855	29.9
24	— —	3.0	90	105	8497	32.3
25	V112	3.0	112	84	9895	37.7
26	— —	3.0	112	94	10622	40.4
27	— —	3.0	112	119	11269	42.9
28	FL2.5	2.5	80	65	5707	26.0
29	— —	2.5	80	85	6114	27.9
30	— —	2.5	90	85	7297	33.3
31	— —	2.5	90	100	7801	35.6
32	— —	2.5	90	117	8276	37.8
33	— —	2.5	90	141	8852	40.4
35	— —	2.5	90	160	9259	42.3
36	— —	2.5	100	85	8533	39.0
37	— —	2.5	100	100	9049	41.3
38	— —	2.5	100	117	9573	43.7
39	— —	2.5	100	141	10149	46.3
40	— —	2.5	100	160	10548	48.2
41	WTU	3.2	121	90	11665	41.6
42	— —	3.2	121	100	12102	43.2
43	— —	3.2	121	120	12759	45.5

—||— – the same; P – nameplate capacity; D – diameter of the rotor; H – hub height.

At first, a correlation analysis of the statistical influence of all parameters from table 1 on the AEP Q , and then their pairwise influence of one on the other has been carried out [22–25].

The AEP of the turbine Q (MW·h) was considered as an explained variable, and explanatory factors: $X1$ – nameplate capacity (MW); $X2$ – diameter of the rotor (m); $X3$ – the hub height (m); $X4$ – CF (%).

To identify the statistical relationship between all factors of the table 1, we calculated the correlation matrix [22, 23, 25] (for this, the tool “Correlation” from the MS Excel-17 has been used). As a result, the next correlation matrix (table 2) has been obtained:

Table 2. Correlation matrix.

	Q	X1	X2	X3	X4
Q	1				
X1	0.845	1			
X2	0.928	0.765	1		
X3	0.629	0.337	0.373	1	
X4	0.706	0.229	0.676	0.732	1

From this correlation matrix it can be seen that the determining factor in the AEP of a wind turbine Q is the diameter of the rotor $X2$ (correlation coefficient 0.928 – very high correlation); the next effect has the nameplate capacity of the generator $X1$ (correlation coefficient 0.845 – high correlation); then follows CF $X4$ (0.706 – high correlation) and the hub height $X3$ (0.629 – average correlation) [24]. The average and high values of the correlation coefficients between the explanatory factors $X1$ and $X2$, $X2$ and $X4$, $X3$ and $X4$ indicate the possible presence of partial multicollinearity between them [26]. This means that in the further construction of the simplest linear model of multiple regression for the dependence of Q from $X1$, $X2$, $X3$ and $X4$ of the form:

$$Q = Q_0 + a_1X1 + a_2X2 + a_3X3 + a_4X4, \quad (4)$$

partial multicollinearity can lead to significant instability of estimates of the model parameters Q_0 , a_1 , a_2 , a_3 , and a_4 . The instability can result in an increase in statistical uncertainty – the variance of the estimates of the model coefficients, i.e., specific values of the parameters estimates can vary greatly for different samples despite the fact that the samples are homogeneous.

Given the full multicollinearity for a strict linear functional relationship between Q and CF, we exclude $X4$ from the model, which subsequently eliminated partial multicollinearity and ensured the significance of the model by Student. We have:

$$Q = Q_0 + a_1X1 + a_2X2 + a_3X3. \quad (5)$$

As a result of the application of “Regression” tool from MS Excel, the following summary table 3 has been obtained.

The obtained model has a high coefficient of multiple correlation R of the explained variable Q with all the explanatory factors $X1$, $X2$ and $X3$ (0.9939); high coefficient of determination R^2 , normalized to the number of model factors (0.9870); relatively small standard error (272.09 MW·h). The model is significant as a whole according by Fisher ($P_F < 2.04 \cdot 10^{-37}$). The level of significance of the coefficients for explanatory factors by Student is extremely small, that is, MM has no visible limitations.

The obtained MM has the next numerical form:

$$Q = -7126.25 + 1348.594 \cdot X1 + 97.526 \cdot X2 + 28.811 \cdot X3. \quad (6)$$

It has a simple meaning: an increase in WT nameplate capacity by 1 MW leads to an increase in AEP by 1348.594 MW·h; an increase in rotor diameter by 1 m leads to an increase in AEP by 97.526 MW·h; increasing the hub height by 1 m leads to an increase in AEP by 28.811 MW·h. Or equivalent to the output is that an increase in the rated power by 1 MW, that a 14-fold increase in the diameter of the rotor or a 47-fold increase in the hub height.

2.4 Conclusion. Comparison of model studies with results of operation

The reliability and admissibility of accepted idealizations in the development of any dynamic model of a real system can be verified and evaluated only by comparing the results of theoretical studies with experimental data. The industrial operation of the first WPS in the wind conditions of Ukraine provided rich experimental material. In a comparative study, we use the

actual results of their operation to increase the degree of credibility and validity of the conclusions.

Using the first obtained MM (6), we will estimate the possible annual electricity generation by the Dmitrovka Wind Cluster (DWC) of the Ochakov Wind Park (WP), equipped with the 12 WTs FL 2.5–100 for a five-year period (table 4).

At the up part of the table (highlighted in bold), explanatory factors of influence are presented. $X1$, $X2$ and $X3$ for WT FL 2,5–100 and the explained variable is calculated: annual production $Q_M = 8879$ MW·h and CF = 40.5%.

In the down part of the table 5 shown the actual power production Q_O with the actual values of CF [27].

The annual values of Q_O are less than the values of Q_M (and this is quite natural, because downtime is inevitable for all kinds of reasons): a minimum of 11% and a maximum of 18% (an average of 14.4% over 5 years).

Given the real actual values of the availability factor (AF), these ratios decrease from a minimum of 3.4 to a maximum of 14.7 (an average of 8.4% over 5 years), which is a completely reliable result.

Table 3. Regression analysis without CF.

Regression statistics	
Multiple R	0.993937
R-square	0.987911
Normalized R-square	0.986981
Standard error	272.0896
Account	43

Analysis of variance					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Relevance F</i>
Regression	3	2,36E+08	78651579	1062,388632	2,04E-37
The remainder	39	2887278	74032,78		
Total	42	2.39E+08			

<i>Coefficients</i>	<i>Standard error</i>	<i>t-statistics</i>	<i>P-Value</i>	<i>Down 95%</i>	<i>Up 95%</i>	
Y- interception	-7126,25	275,4174	-25,8743	3,62788E-26	-7683,33	-6569,16
$X1$	1348,594	128,4616	10,49803	6,34626E-13	1088,76	1608,43
$X2$	97,52617	4,586866	21,26205	4,66732E-23	88,2483	106,804
$X3$	28,81139	1,762862	16,34353	4,81734E-19	25,2457	32,3771

Table 4. Comparison of the DWC production.

$Q_M, \frac{MW \cdot h}{\%}$	8879	WT FL 2,5-100: $X1 = 2,5$ MW, $X2 = 100$ m, $X3 = 100$ m				
CF, %	40,5	DWC of the Ochakov WP LLC MC «Wind parks of Ukraine», Nikolayev region, Ukraine				
Years of operation	2013	2014	2015	2016	2017	average over 5 years
$Q_O, \frac{MW \cdot h}{\%}$	$\frac{7828}{88,2}$	$\frac{7316}{82,4}$	$\frac{7275}{81,9}$	$\frac{7696}{86,7}$	$\frac{7900}{89,0}$	$\frac{7603}{85,6}$
CF, %	35,7	33,4	33,2	35,1	36,1	34,7
Ratio $Q_M > Q_O$, %	11,8	17,6	18,1	13,3	11,0	14,4
WT availability factor (AF)	0,959	0,890	0,961	0,941	0,921	0,934
Q'_M by AF	$\frac{8515}{100}$	$\frac{7902}{100}$	$\frac{8583}{100}$	$\frac{8355}{100}$	$\frac{8176}{100}$	$\frac{8296}{100}$
Q'_O by AF	$\frac{7828}{91,9}$	$\frac{7316}{92,6}$	$\frac{7275}{85,3}$	$\frac{7696}{92,1}$	$\frac{7900}{96,6}$	$\frac{7603}{91,6}$
Ratio $Q'_M > Q'_O$, %	8,1	7,4	14,7	7,9	3,4	8,4

3 Results and discussion

Comparison of the results of theoretical research and industrial operation is a convincing and indisputable proof of the legality of the computer simulation of MM developed for the first time.

An invaluable practically important feature of the developed MM is the absence of additional direct measurements of various parameters when using it, in particular, it does not require processing of weather data from representative WS, which contributes to a significant reduction in errors. And this is due to the fact that its development is based on actual long-term measurements by the automated system Logger (USA) of wind speeds at the pilot AWPS and the actual power-law index for measuring wind speed by height, which significantly increased the reliability of the calculations.

4 Conclusions

Developed for the first time by the method of computer simulation MM allows:

- quickly and reliably determine the optimal WT in terms of the parameters that are offered on the world market for a specific industrial WPS in a certain area;
- to develop and manufacture the necessary wind turbine in the absence of a world wind turbine with the necessary technical characteristics.

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