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MINIMIZATION OF POWER FLUCTUATIONS OF WIND POWER PLANTS WHEN CONSTRUCTED IN EXCLUSION ZONES OF ENTERPRISES

Purpose. Development of a methodology for selecting types and quantities of wind turbines built in exclusion zones of industrial enterprises to minimize fluctuations in the power generated by them and increase the efficiency of their use.

Methodology. The work used methods of synthesis of systems, computer modeling in the calculation of the optimal number of different types of wind turbines, methods of combinatorics.

Findings. The developed method for designing wind power plants built in the exclusion zones of enterprises allows determining the required number of different types of wind turbines with different capacities and nominal values relative to the wind speed, which will provide the necessary generated power with minimal fluctuations. This makes it possible to notably reduce the capacity required for the accumulation of excess generation and to significantly reduce the cost of implementing wind turbines.

Originality. The work proposes a methodology for designing wind power plants based on various wind turbines, taking into account their type, power and wind characteristics of the area where the wind power plant is being built. It has been found that the coefficient of fluctuation of the power generated by the wind power plant built on the same type of wind turbines does not depend on the capacity of such a station, nor on the number of wind turbines used, but only on the type of the latter and the wind characteristics of the area where it was built.

Practical value. Wind power plants used at enterprises have significant daily and annual fluctuations in the power generated by them. The proposed approach allows reducing fluctuations of power generated by the station, as well as increasing the amount of electricity generation in comparison with the use of the same type of wind turbines.

Keywords: *wind power plant, power fluctuations, wind characteristics, combinatorial problem, generation, computer modeling*

Introduction. Currently, a complex process of Ukraine's integration into the international economic system is taking place. This path is accompanied by the implementation of global and European standards in various sectors of the national economy. This is especially important for the energy system of our country, since its entry into the pan-European system has a strategic goal of increasing energy security. In this regard, there are a number of global problems, such as reconstruction of existing thermal power units and frequency and power control systems; construction of new substations and power lines, improvement of existing hydro and nuclear power units.

But at the same time, in Ukraine there is also an increase in the number of new generating capacities built on renewable energy sources, which also creates a certain problem – the involvement of additional compensating regulating capacities and energy storage systems in the existing energy system, since the production of "green" electricity is accidental due to the dependence of solar and wind generation on climatic conditions.

As it is known, for almost a decade there has been a steady trend towards the introduction of renewable energy sources into the power supply systems of mining and metallurgical enterprises [1, 2], as well as railway transport, since the latter have a significant amount of electricity consumption [3]. This is also due to the fact that they need to increase their energy efficiency as quickly as possible. The current state of introduction of alternative energy sources to ensure uninterrupted power supply and the functioning of consumers of these and other industrial enterprises also makes it possible to reduce the harmful impact on the environment and increase the reliability of their power grids [4, 5].

Literature review. It is common knowledge that many large enterprises that consume a significant amount of electricity have exclusion zones at their acquisitions unsuitable for agricultural production. The latter, under appropriate meteorological conditions, can be successfully used to place wind power plants on them in an amount that is sufficient to consider them as a powerful additional source of electricity for the enterprise.

For these purposes, iron ore and coal mines, quarries and mining mills as a whole, railway exclusion zones, free areas outside the boundaries of agricultural production, etc., can serve. At all these enterprises, isolated cases of the use of wind turbines are already known, but unfortunately, so far only in pilot versions. And that is in the presence of great opportunities in this regard.

Thus, in mines, in addition to exclusion zones, where sometimes wind turbines are built mainly of horizontal rotation, they are also used inside to utilize the energy from outgoing air flows. It is believed that wind turbines with a vertical axis of rotation are the most suitable for working in the conditions of the ventilation system of these enterprises. It is advisable to place them in the areas of the combination of two air crosscuts [6].

Currently, the electricity generated by such installations is proposed to be supplied not to the power supply system, but to lighting both surface areas and underground workings. The power of the specified consumer is usually 1.6–4 kW. Therefore, the use of wind turbines in this case, unfortunately, is limited to this for now [7].

There are similar examples in railway transport. The idea of direct production of electricity there by wind turbines is not new. So, the authors of the study [8] proposed autonomously powering monitoring devices from a system using wind energy inside tunnels, turning it into electricity. Such a system consists of three components: portable wind turbines, a generator module and an energy storage unit based on a supercapacitor. Its maximum output power can exceed 100 mW.

An equally interesting idea was also implemented in the development of Indian researchers [9], who proposed to install low-power wind generators along the railway track in such a way that they were exposed to a significant wind flow when trains are passing. The resulting electrical energy was used to power both railway signaling devices and nearby residential buildings or, even, small settlements. To do this, it is recommended to use a significant number of wind turbines with a capacity of 400 to 600 W.

Similar proposals for the use of technogenic wind flows in transport for power generation are also considered in the work [10], but all of them are not so attractive compared to the possibility of placing stationary wind turbines in the railway exclusion zone. After all, this makes it possible to create not only additional sources for traction vehicles, but also local power grids to supply a large number of non-traction consumers in a mode separated from the excessively polluted main power grid.

In Ukraine, pilot versions of such systems are implemented at the traction substations Sambir and Stary Sambir of the Lviv Railway. In the first version, 10 kV buses are powered, and in the second – 35 kV [11]. The initial stage of this project for the last case was put into operation in 2014.

The mentioned wind power plant is located on the mountain slopes of the Dniester River, where fairly strong wind flows are formed along it. Their average annual speed exceeds 8 m/s. The plant consists of four generating units based on a Vestas turbine V112 with a rated power of 3450 kW, whose wind wheel has a diameter of 112 m with a hub height of 119 m. The customer hopes that the capital investment for construction in the amount of 20.5 million euros will be returned in 7 years. At the same time, 38 million kWh of electricity will be received annually.

It is also interesting to install wind turbines on the dumps of mining quarries. So, at PJSC "Poltava HZK", where the average annual wind speed is 7.5 m/s, wind generators with a capacity of 50 kW were used [1]. The plant supplies an auxiliary switchgear, the power of transformers of which is 63 kVA. It was, unfortunately, difficult to increase its capabilities and connect it to general power grids.

All considered proposals for the use of wind turbines at these enterprises have a general major drawback – significant daily and annual fluctuations in the power generated by them. And this greatly complicates their integration into the enterprise network. To do this, you need to have either a large excess of electricity, which is eventually lost, or a large capacity for its accumulation.

In both of these cases, the cost of the system increases so much that its practical implementation becomes inadvisable. Therefore, in order to get the possibility of more large-scale introduction of such energy sources at enterprises that have sufficient land plots for this, any real solutions to reduce these fluctuations are relevant without a doubt.

Purpose. The purpose of the work is to develop a methodology for selecting the types and quantities of wind turbines built in the exclusion zones of industrial enterprises to minimize fluctuations in the power generated by the power plant and increase the efficiency of its use.

Results. As noted in [3], it is possible to increase the efficiency of implementation of wind turbines in industrial power networks by compatible use of their different models depending on the peculiarities of wind speed distribution in the area under consideration. This will make it possible to reduce fluctuations in the power generated by wind power plants and significantly increase its overall operation ratio during the year. Therefore, the question of determining the required number of each of the available wind turbines is proposed as a separate optimization task at the design stage of such power sources.

Indeed, now wind turbine manufacturers offer many of their models, different in design, rated power and wind characteristics. On sale there are three types of wind turbines: bladed ones with horizontal and vertical axis and screwed ones in vertical design. All of them have different dependence of generated power on wind speed.

Fig. 1, as an example of this, shows the mentioned dependencies of different models of wind turbines of close rated power: horizontal-axial Euro Wind 5 and Low Wind 48B 5/7 [12] and vertical-axial VAWT-5L-5K-AB [13].

As you can see, they differ not only in the nature of the curves, but also in the nominal wind speeds (12, 13, 15 m/s, respectively). And if we pay attention to wind installations with a capacity of 4, 5, 10, 15 kW, which is offered by the "Energo

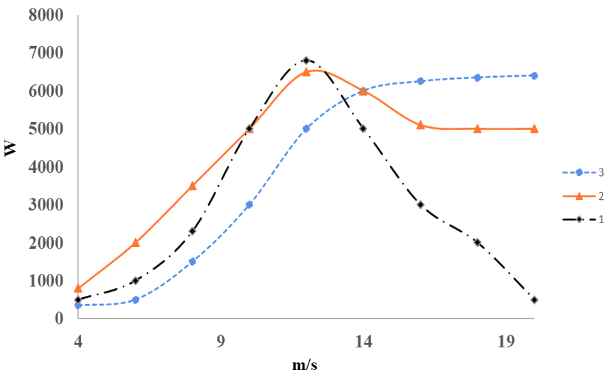


Fig. 1 Dependence of power generated by wind turbines on wind speed:

1 – Euro Wind 5; 2 – Low Wind 48B 5/7; 3 – VAWT-5L-5K

Star LLC" [4], we will see that their specified speeds vary within much larger limits: 5, 8, 10, 12 m/s, respectively.

Table 1 shows the data on other acceptable wind turbine in the case under consideration. Therefore, we will find out the possibility of reducing the power fluctuations generated during the year by a wind power plant consisting of the turbines selected from this list when they are located in the exclusion zones of industrial enterprises. The length of such zones along the perimeter is sometimes up to 25 km. The number of places on them where wind turbines can be located, in each particular case, will depend on the topography of the area and the presence of obstacles to wind flow.

If the total number of places of the wind turbines' specified location at the considered exclusion interval is known and equal to n, and there are m models of wind turbines with different capacities and nominal values of wind speed, which according to the wind characteristics of this area are acceptable for use, then first of all, it is necessary to determine all their

Table 1

Technical characteristics of modern wind turbines suitable for use in the territory of enterprises

No.	Wind turbine model	Manufacturer	Rated		Maximum power, kW	Rotor diameter, m
			Power, kW	Wind speed, m/s		
With horizontal axis						
1	Euro Wind 3	Ukrainian alternative energetics	3.0	12.0	4.0	4.5
2	Euro Wind 5		5.0	12.0	6.4	6.4
3	Euro Wind 10		10.0	12.0	13.0	8.0
4	Euro Wind 15		15.0	16.0	21.0	11.0
5	Euro Wind 20		20.0	13.0	26.5	10.0
With vertical axis						
6	Euro Wind/19	Euro Wind Small Turbines LTD	19.0	12.0	21.0	8.25
7	WS-12/8 kW	Winds IDC Production LTD	8.0	20.0	10.0	2.0
8	WRE 060/6 kW	Ropatec S.P.A.	6.0	14.0	7.2	3.3
9	VAWT-5L-3K	ATMOS-FERA	3.0	12.0	3.6	3.0
10	VAWT-5L-10K		10.0	12.0	12.0	6.0

possible combinations, where the number of each of them will vary from 0 to n. All this applies to combinatorial problems, which are usually solved differently.

As part of the question discussed in this article, the following sequence is proposed for determining the specified sets with a specific amount of each wind turbine in them. So, if we consider all possible combinations $h_i(i=\overline{1,m})$, without taking into account the reality of their location in the places allocated in the exclusion zone of enterprises, then the total number of such combinations can be obtained as follows.

First, it is necessary to form a matrix $m \times n$, the first column of which consists of zero values, which later move to the second, third and subsequent columns. Then in the initial matrix there will be already two columns with zero values that will also gradually move to the right. And then – three, four, etc.

$$\begin{matrix} 0 & 1 & 1 & 1 & 1 \\ 0 & 2 & 2 & 2 & 2 \\ 0 & 3 & 3 & 3 & 3 \\ 0 & n & n & n & n \end{matrix} \quad \begin{matrix} 1 & 0 & 1 & 1 & 1 \\ 2 & 0 & 2 & 2 & 2 \\ 3 & 0 & 3 & 3 & 3 \\ n & 0 & n & n & n \end{matrix} \quad \begin{matrix} 1 & 1 & 0 & 1 & 1 \\ 2 & 2 & 0 & 2 & 2 \\ 3 & 3 & 0 & 3 & 3 \\ n & n & 0 & n & n \end{matrix} \quad \begin{matrix} 1 & 1 & 1 & 0 & 1 \\ 2 & 2 & 2 & 0 & 2 \\ 3 & 3 & 3 & 0 & 3 \\ n & n & n & 0 & n \end{matrix} \quad \begin{matrix} 1 & 1 & 1 & 1 & 0 \\ 2 & 2 & 2 & 2 & 0 \\ 3 & 3 & 3 & 3 & 0 \\ n & n & n & n & 0 \end{matrix}$$

$$\begin{matrix} 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 2 & 2 & 2 \\ 0 & 0 & 3 & 3 & 3 \\ 0 & 0 & n & n & n \end{matrix} \quad \begin{matrix} 1 & 0 & 0 & 1 & 1 \\ 2 & 0 & 0 & 2 & 2 \\ 3 & 0 & 0 & 3 & 3 \\ n & 0 & 0 & n & n \end{matrix} \quad \begin{matrix} 1 & 1 & 0 & 0 & 1 \\ 2 & 2 & 0 & 0 & 2 \\ 3 & 3 & 0 & 0 & 3 \\ n & n & 0 & 0 & n \end{matrix} \quad \begin{matrix} 1 & 1 & 1 & 0 & 0 \\ 2 & 2 & 2 & 0 & 0 \\ 3 & 3 & 3 & 0 & 0 \\ n & n & n & 0 & 0 \end{matrix} \quad \begin{matrix} 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 2 & 2 \\ 0 & 0 & 0 & 3 & 3 \\ 0 & 0 & 0 & n & n \end{matrix}$$

$$\begin{matrix} 1 & 0 & 0 & 0 & 1 \\ 2 & 0 & 0 & 0 & 2 \\ 3 & 0 & 0 & 0 & 3 \\ n & 0 & 0 & 0 & n \end{matrix} \quad \begin{matrix} 1 & 1 & 0 & 0 & 0 \\ 2 & 2 & 0 & 0 & 0 \\ 3 & 3 & 0 & 0 & 0 \\ n & n & 0 & 0 & 0 \end{matrix} \quad \begin{matrix} 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 2 \\ 0 & 0 & 0 & 0 & 3 \\ 0 & 0 & 0 & 0 & n \end{matrix} \quad \begin{matrix} 1 & 0 & 0 & 0 & 0 \\ 2 & 0 & 0 & 0 & 0 \\ 3 & 0 & 0 & 0 & 0 \\ n & 0 & 0 & 0 & 0 \end{matrix}$$

After that, instead of a zero value, value 1 is placed in the first column of the matrix and the sorting is carried out in the same way. The procedure is repeated until n appears in the first column. It is clear that the sum of the obtained values of the number of wind turbines will not be equal to n in all cases (rows of the matrix), and therefore such combinations cannot be practically realized. So, it will be necessary to select only those of them that meet the specified requirement. Fig. 2 shows the proposed algorithm corresponding to the considered sequence.

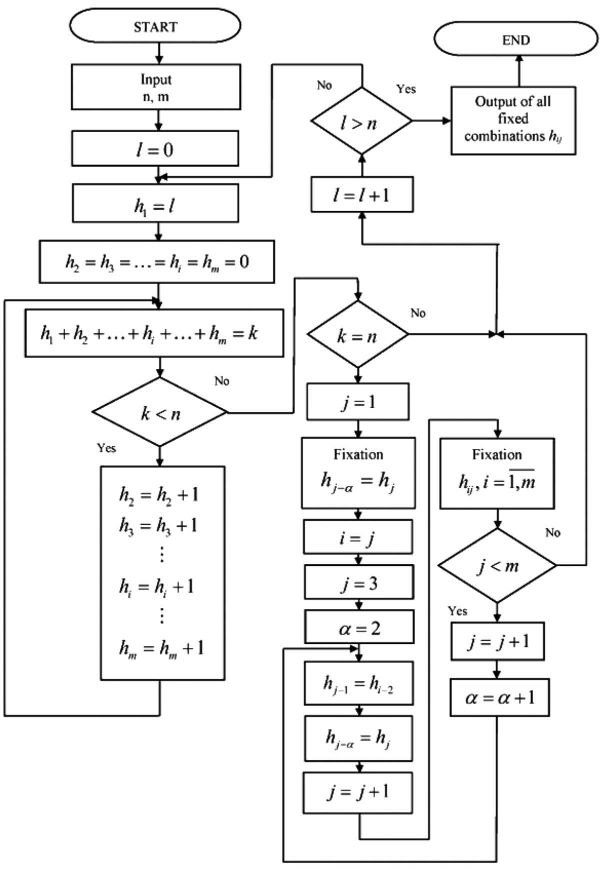


Fig. 2. Algorithm for determining wind turbines combinations with their total number corresponding to their existing locations in the exclusion zone of enterprises

As an example of the application of the specified algorithm, the sequences h_i are considered under the condition that $i=\overline{1,5}$, and $n = 10$. In this case, $P = 989$ combinations can be implemented. With the increase in the number of places for installation of wind turbines to 15, the possibility of choosing an acceptable option increase to 2700. It is obvious that among the obtained ratios regarding the number of different wind turbine models in the wind power plants, only one of the options will be able to meet its required capacity, ensuring the smallest fluctuations in the generation of the latter during the year. It is proposed to determine it using the algorithm presented in Fig. 3. The output data obtained from the calculation is shown in Fig. 4.

The table in Fig. 4 of the example shows the average capacity of five wind turbines P_{ia} $(i=\overline{1,5})$ in the corresponding $\alpha=\overline{1,12}$ months of the year. Here k is the minimum possible value in the given interval of the generated power of 75–90 kW of the fluctuation coefficient of the latter, which is obtained using four Euro Wind 3 units (h) and six Euro Wind 20 units (h). The dynamics of generation of such a wind power plant by months of the year is shown in the last row of the given representation.

In order to obtain the specified information on the P_{ia} capacity, it is necessary to have the results of meteorological observations and determine the annual distribution of the wind speed averaged monthly wind speed characteristic of the area under consideration. For example, near the city of Vasylivka, Zaporizhzhia region, it is characterized by the dependence shown in Fig. 5.

The given distribution indicates that the wind speed in May–August is almost three times less than that observed in October–March. Therefore, when finding out the possibility of autonomous supply of specific consumers of industrial power grids due to energy from such a wind power plant, it is necessary to focus on the possible amount of its generation in the period from late spring to early autumn. And this means that more powerful winter winds, unfortunately, will not be used.

Taking advantage of the latest data and having dependencies on the powers of the i wind turbines, which are consid-

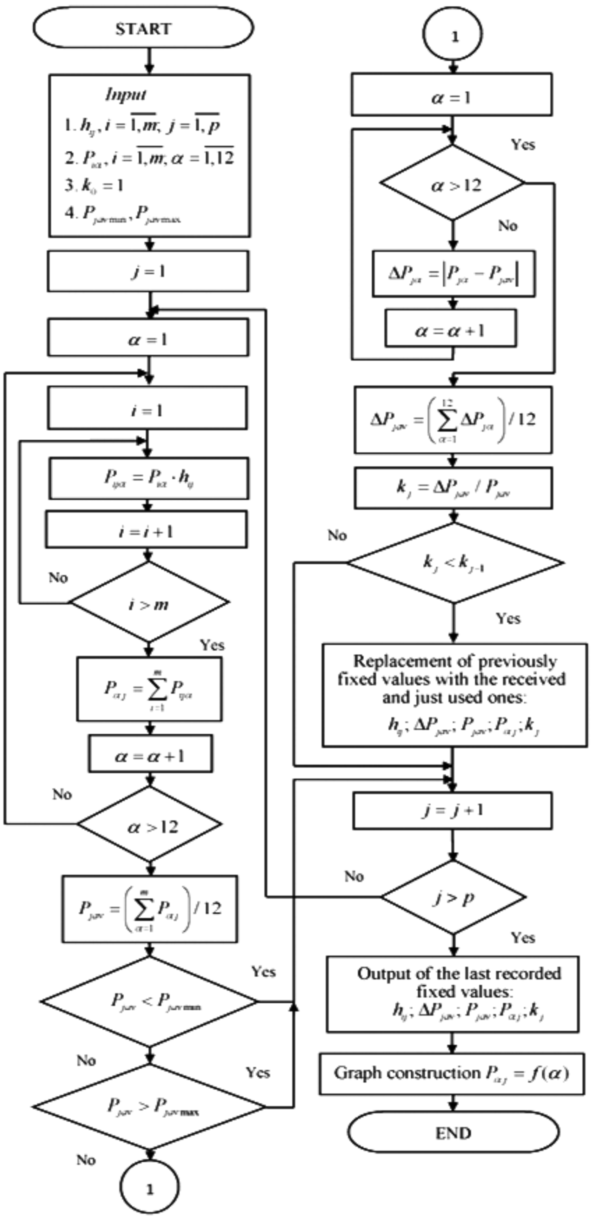


Fig. 3. Algorithm for determining the required number of wind turbines acceptable for the location in the exclusion zone of enterprises for the minimum fluctuations of the power generated by them during the year

Number of locations: 10
Pjcpmin = 75; Pjcpmax = 90
Pjcp = 88,9833333333333; delta Pjcp = 52,3194444444444
k= 0,587969032902541
4 0 0 0 6

Wind turbine model 1	Wind turbine model 2	Wind turbine model 3	Wind turbine model 4	Wind turbine model 5
Euro Wind 3(h)	Euro Wind 5(h)	Euro Wind 10(h)	Euro Wind 15(h)	Euro Wind 20(h)
3,9	6,3	12	19	22,3
2,5	4,1	7,9	20,5	25
3,9	6,2	12	19	22,5
2,9	5,1	9	12,5	13,1
0,5	0,9	1,6	2,1	7
0,2	0,45	0,9	0,5	2,1
0,25	0,5	1	0,6	2,2
0,45	0,8	1,3	2,2	4,1
0,75	1,2	2,5	4	5
3,2	5,2	9,8	15	13,2
4	6,3	12,8	17,5	22
3,8	6	11,8	18,6	21,9

149,4	160	150,6	90,2	44	13,4	14,2	26,4	33	92	148	146,6

Fig. 4. View of presentation of output data for calculations using the developed program

ered, on the speed of wind flow and determine m sequences $P_{ia}(\alpha=\overline{1,12})$. The latest dependencies, which are shown in Fig. 1 in the example of three specific installations, are given

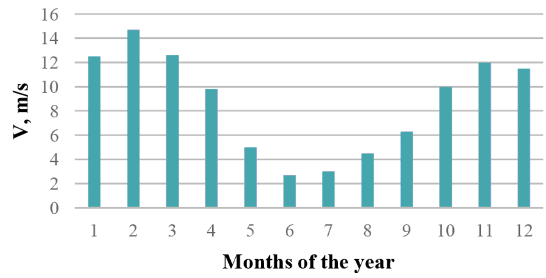


Fig. 5. Annual distribution of monthly averaged wind speed typical for the area near the city of Vasylivka, Zaporizhzhia region

by the manufacturers of such equipment in the relevant technical specifications. The sequences $P_{ia}(\alpha=\overline{1,12})$ obtained in this way with respect to the wind turbines indicated in Table 1 in the case of their location in the above-mentioned area are presented in the same order in Table 2.

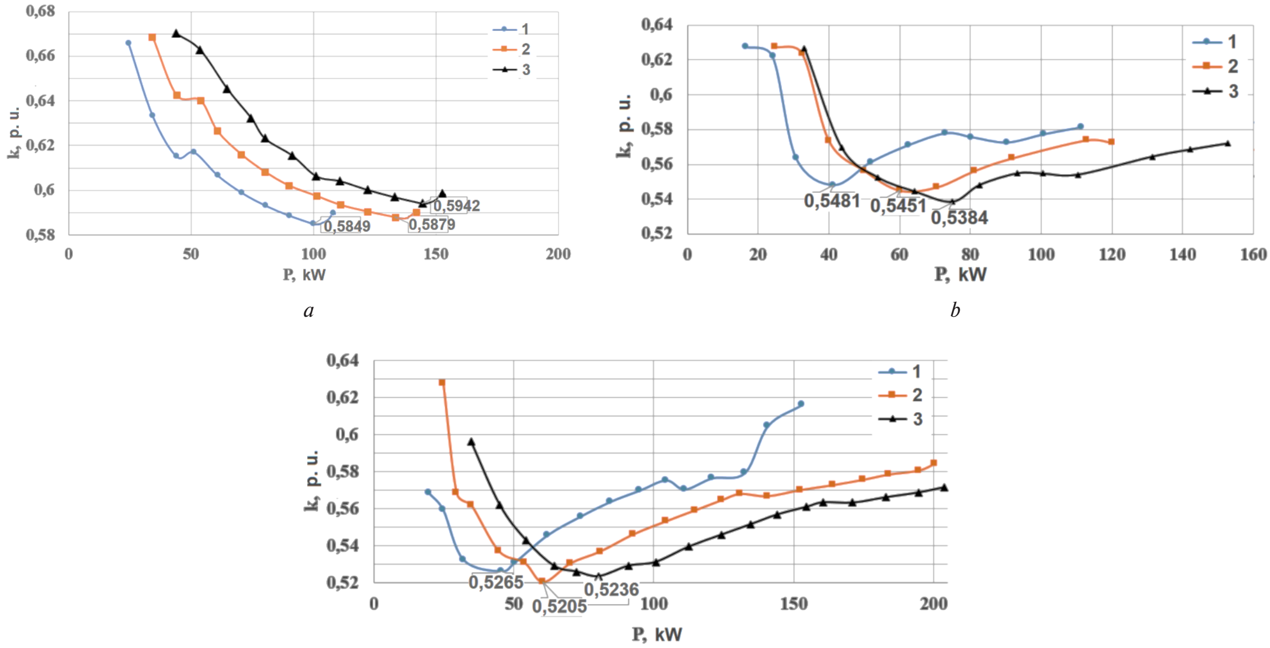
Using the proposed software and the information just mentioned, it is possible to obtain the dependence of the minimum fluctuation coefficients of the power generated by the wind power plant at different averaged values of the latter and different possibilities for certain wind turbines and the number of places for their location in a particular exclusion zone of the enterprise. Fig. 6 shows as an example the following dependencies for 10, 15 and 20 places in the case of using the first five horizontal (*a*), then only vertical (*b*) and, finally, all ten specified in Table 2, wind turbines (*c*). It is obvious that having the information thus obtained and focusing on a given interval of annual average power required by consumers, it is possible to determine the type and number of wind turbines required for this, which will also provide the minimum possible fluctuations in this power during the year.

It can be seen from the above dependencies that when horizontal wind turbines are located at ten exclusion places, the smallest minimum fluctuations in the generated power (k = 0.5849) will be observed for P = 100 kW, with the presence of 15 places (k = 0.5879) – 130 kW, and at 20 (k = = 0.5948) – about 145 kW. If only vertical wind turbines are used or all of them at the same time, these dependencies have a more complex form, but in these cases there are the most favorable values of the generated power, at which its smallest fluctuations will be observed. It should also be noted that in the last two cases the optimal values of the coefficient k decrease, but occur at lower powers – in the range of 40–60 kW.

The distribution by months of the year of possible generation of power by the wind power plant in case of implementation of the obtained nine optimal options is shown in Table 3, and the values of average capacities and their fluctuation coefficients are shown in Table 4. The number of available wind turbines recommended for use in each of these cases (Table 1) is given in Table 5.

Therefore, in conclusion, it can be stated that in the presence of algorithmic and software tools proposed and used as an example in this section, it is possible to calculate the required number of each of the wind turbines types available to wind power plant designers, for the placement of which specific places are allocated in the exclusion zone of the enterprise, and which provide the necessary generated power with its minimal fluctuations throughout the year.

In order to quantify the advantages of the proposed wind power plant design method, a design study was carried out on the values of the fluctuation coefficient of the generated power of a wind power plant, which was built, as usual, on the same type of wind turbines. It is established that it does not depend on the capacity of such a station, nor on the number of wind



c

Fig. 6. The dependence of the fluctuation coefficient of the power generated by the wind farm on its average value per year when using horizontal (a), vertical (b) and both types simultaneously (c) of wind turbines in the presence of such a number of possible places relative to their location (10 (○), 15 (□) and 20 (Δ))

Table 2

Power generated by wind turbines in Table 1 in case of their location in the area under consideration

Wind turbine model as per No. in Table1	Powers by month of year, kW											
	1	2	3	4	5	6	7	8	9	10	11	12
1	3.9	2.5	3.9	2.9	0.5	0.2	0.25	0.45	0.75	3.2	4.0	3.8
2	6.3	4.1	6.2	5.1	0.9	0.45	0.5	0.8	1.2	5.2	6.3	6.0
3	12.0	7.9	12.0	9.0	1.6	0.9	1.0	1.3	2.5	9.8	12.8	11.8
4	19.0	20.5	19.0	12.5	2.1	0.5	0.6	2.2	4.0	15.0	17.5	18.6
5	22.3	25.0	22.5	13.1	7.0	2.1	2.2	4.1	5.0	13.2	22.0	21.9
6	19.1	19.25	19.1	17.1	4.5	1.1	1.2	4.4	7.0	16.1	19.0	18.5
7	2.3	4.1	2.3	1.15	0.2	0.1	0.15	0.35	3.8	1.2	2.1	1.8
8	3.9	6.0	3.9	2.0	0.15	0.1	0.12	0.14	0.5	2.1	3.5	3.4
9	3.1	3.55	3.1	1.5	0.25	0.1	0.15	0.3	0.45	1.75	3.0	2.75
10	10.1	12.0	10.1	6.5	0.5	0.2	0.3	0.4	1.1	6.0	10.0	9.1

turbines used, but only on the type of the latter and the wind characteristics of the area where it was built.

For the wind turbines discussed in Table 1 and wind speed distribution by months of the year shown in Fig. 5, the coefficient has the corresponding values: 0.6781; 0.6544; 0.6563; 0.6903; 0.6143; 0.6146; 0.6773; 0.7706; 0.7252; 0.7574. Therefore, comparing the results with the optimal power fluctuations relative to wind power plants, which are given in Table 4, we obtain the following results.

If only EuroWind 10 wind turbines, which have a value of $k = 0.6303$ in this area, are installed at station 1.1, where this factor has a value of $K = 0.5859$, then the situation with power fluctuations will impaired by 0.0689, that is, by 11.7596 %. In the case of use at power plant 3.2, where 15 different types of wind turbines are installed, and which has the best received fluctuation coefficient of the generated power (0.5205), using the same type of WRE 060/6 kW wind turbines with a vertical axis and the worst values of the specified coefficient ($k = 0.7706$), then its value relative to the power of the entire power plant will increase by 0.2501, i.e., by 48.0499 %.

Therefore, it becomes obvious that depending on the type of wind turbines that is at the disposal of the designers of the power plant and the wind characteristics of the area where they plan to build it, the use of the proposed synthesis method of the latter can reduce fluctuations in the power generated by it from 10 to 50 percent. And this makes it possible to significantly reduce the necessary capacity for the accumulation of excess electricity generated by wind power plants and significantly reduce the cost of its implementation.

An equally important advantage of the considered method for the wind power plant synthesis is also an increase in its generation. Thus, having the power of the above-mentioned station 1.1 by months of the year shown in Table 3, it can be calculated that it is capable of generating 865,382.4 kWh of electricity per year. If they install ten identical wind turbines of the Euro Wind 10 type, the capacity of which by the months of

Table 3

Power values that can be generated by a wind power plant with minimal fluctuations throughout the year near the city of Vasylivka, Zaporizhzhia region

Power, P, kW / Months of the year	The number of places used in relation to the location of wind turbines								
	Wind turbines with a horizontal axis			Wind turbines with a vertical axis			Wind turbines of both types		
	10	15	20	10	15	20	10	15	20
1	167.80	224.10	243.60	64.40	92.70	113.20	63.80	95.30	126.80
2	182.52	240.00	252.50	79.20	114.85	142.60	77.05	118.45	159.85
3	169.20	225.90	245.40	64.40	92.70	113.20	63.90	95.60	127.30
4	100.45	135.30	149.80	48.75	70.45	86.80	43.35	61.05	78.75
5	50.50	66.00	68.50	10.90	16.20	21.20	13.80	21.60	29.40
6	15.30	20.00	21.10	3.10	4.60	6.70	4.30	6.85	9.35
7	16.15	21.30	22.55	3.75	5.55	7.20	4.95	7.75	10.55
8	30.05	39.60	41.85	11.65	17.45	23.20	11.75	17.25	22.75
9	37.25	49.50	53.25	41.70	63.90	88.80	39.80	60.00	80.20
10	102.00	138.00	154.00	46.60	67.50	89.60	92.90	60.90	79.90
11	166.00	222.00	242.00	62.70	90.10	109.60	62.00	92.40	122.80
12	164.7	219.90	238.90	58.70	84.40	102.80	59.00	88.10	117.20

Table 4

Average power and fluctuation coefficient values for wind power plants discussed in Table 3

Indicators	The number of places used for the location of wind turbines								
	Wind turbines with a horizontal axis			Wind turbines with a vertical axis			Wind turbines of both types		
	1			2			3		
	10	15	20	10	15	20	10	15	20
P_{cp}, kW	100.258	133.475	144.454	100.154	60.030	74.850	40.550	60.440	80.321
K, p.u.	0.5859	0.5879	0.5942	0.5849	0.5451	0.5384	0.5265	0.5205	0.5236

Table 5

The number of wind turbines shown in Table 1 used in wind power plants according to Table 3

1		Wind turbine number according to Table 1									
		2	3	4	5	6	7	8	9	10	
Variants of power plants according to the Table 4	1.1	3	0	0	0	7	0	0	0	0	0
	1.2	6	0	0	0	9	0	0	0	0	0
	1.3	11	0	0	0	9	0	0	0	0	0
	2.1	0	0	0	0	0	2	7	0	0	1
	2.2	0	0	0	0	0	3	11	0	0	1
	2.3	0	0	0	0	0	4	16	0	0	0
	3.1	0	1	0	0	1	1	7	0	0	0
	3.2	0	1	0	0	2	1	11	0	0	0
	3.3	0	1	0	0	3	1	15	0	0	0

the year is shown in Table 2, the annual volume of generation of such a station will be 594,720.3 kWh, that is, it will decrease by 270,662.1 kWh, or by 45.5 %.

Conclusions.

1. The existing proposals for the use of wind turbines are quite difficult to integrate into the power network of enterprises due to significant daily and annual fluctuations in the power generated by them.

The proposed method for designing wind power plants built in the exclusion zones of enterprises allows determining the required number of different types of wind turbines with different capacities and rated values relative to the wind speed, which will provide the necessary generated power with minimum fluctuations.

2. Using the proposed method of wind power plant design allows reducing fluctuations of power generated by the station from 10 to 50 %, as well as to increase the volume of electricity generation up to 45 % compared to the use of the same type of wind turbines.

3. This approach allows significantly reducing the capacity required to accumulate excess generation and significantly reducing the cost of wind power plant implementation.

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Мінімізація коливань потужності вітроелектростанцій при їх будівництві в місцях відчуження підприємств

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Мета. Розробка методики вибору типів і кількості вітроелектроустановок (ВЕУ) при їх будівництві в зонах відчуження промислових підприємств для мінімізації коливань згенерованої ними потужності й підвищення ефективності їх використання.

Методика. У роботі використовувалися методи синтезу систем, комп›ютерного моделювання під час розрахунку оптимальної кількості різнотипних ВЕУ, методи комбінаторики.

Результати. Розроблений метод проектування вітроелектростанцій, що будуються в зонах відчуження підприємств, дозволяє визначити необхідну кількість різнотипних ВЕУ з відмінними потужностями й номінальними значеннями щодо швидкості вітру, які забезпечать необхідну згенеровану потужність з мінімальними її коливаннями. Це дозволяє значно зменшити ємність, необхідну для накопичення надлишку генерації, та суттєво здешевити реалізацію вітроелектростанцій (ВЕС).

Наукова новизна. У роботі запропонована методика проектування вітроелектростанцій на різних ВЕУ, що враховує їх тип, потужність і вітрову характеристику місцевості, де будується ВЕС. Встановлено, що коефіцієнт коливань згенерованої вітроелектростанцією потужності, збудованої на однотипних ВЕУ, не залежить ні від потужності такої станції, ні від кількості використаних вітроустановок, а лише від типу останніх і вітрової характеристики місцевості, де вона збудована.

Практична значимість. Вітроелектроустановки, що використовуються на підприємствах, мають значні добові й річні коливання згенерованої ними потужності. Запропонований підхід дозволяє зменшити коливання згенерованої станцією потужності, а також збільшити обсяги генерації електричної енергії в порівнянні із застосуванням однотипних вітроелектроустановок.

Ключові слова: *вітроелектростанція, коливання потужності, вітрохарактеристика, комбінаторна задача, генерація, комп›ютерне моделювання*

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