Multi-unit modular wind farm for areas of low wind potential

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Abstract. Many dispersed sites are remote from the power grid in agriculture. The centralized power supply of these objects with electric energy from the power grid is unprofitable. During the year, tests were conducted in full-scale conditions of wind power plants with different parameters under conditions of power shortage. The article proposes the development of a multi-unit wind power plant with an additive block, where the energy from multiple winds receiving devices is summed. The article shows that the wind turbine operates in a stable mode in an extended range of wind speeds of 4500 hours per year and generates rated power even in conditions of power shortage due to energy storage and operation of the wind turbines with different parameters. It is two times longer than the power of the wind turbine with separate generators during the year. Studies have shown that at low wind speeds of 4-5 m/s, a 1 kW wind power plant generates up to 840 W at wind speeds of 4-6 m/s, the efficiency of a multi-unit wind power plant is 4 times higher than the overall efficiency of individual wind power plants operating on their own generators.

1. Introduction

Existing wind power stations with a capacity of up to 20 kW operate efficiently at average wind speeds of 6.5-7 m/s. Most Russian territory has the average periodic wind speeds of less than 4-5 m/s. High-speed few-blade wind turbines, designed for speed ratio of $Z=6-9$, in areas with an average annual wind speed of 4-7 m/s operate in the design mode of about 152 to 720 hours or from 2 to 8 % per year [1]. Wind turbines are designed for a narrow range of wind speeds. To develop a power supply module, it is necessary to expand the range of wind speeds used, since about 80% of the time the wind speed is less than 5 m/s [2].

The purpose of this work is to study the operation of wind turbines with different parameters and to compare the power generated by a multi-unit installation working in additive mode and the sum of the power generated by individual wind turbines with the same parameters in a wide range of wind speed.

2. Materials and methods

The concept of multi-rotor wind turbines is increasingly found in world research and development in the field of wind energy. For example, researchers from the Indian Institute of technology, Aarhus (Denmark), Durham (UK) and Stanford (USA) universities model the aerodynamics of multi-rotor wind turbines using high-resolution digital modeling. They have found that a wind turbine with four rotors on a single foundation creates less turbulence and has higher energy production [3]. Since 2016, the Danish company Vestas has conducted 2.5-year tests of a 900 kW multi-rotor unit equipped with four V29-225kW wind generators with a rotor diameter of 29 m at a test site located near Roskilde (East of Denmark) [4]. An increase in capacity of 1.5% was noted during the tests. Also in 2014, the French company New Wind presented the concept of the wind turbine “Arbre à Vent” in the form of a tree equipped with vertical mini-turbines that can produce up to 3 kW even at low wind speeds [5].
The idea of a multi-wind installation is not new. The multi-wind frame wind farm of A. G. Ufimtsev is well known. Having 10 wind wheels mounted on a single frame, each wind wheel is connected to a separate generator by a gearbox. There are also known variants of other inventors, where the wind wheels are connected by long shafts to a single generator [6]. The patent study shows that the presented concepts of multi-wind turbines are aimed at increasing the efficiency of large megawatt wind power plants and increasing the ability to resist wind gusts [7].

Currently, a multi-unit wind installation that operates in an additive mode under a power shortage of one of the wind turbines is being developed. It is considered possible to connect wind turbines with different parameters with a generator using an additive module.

The essence of the multi-unit installation is that the mechanical energy from some wind receiving devices with different parameters is hydraulically summed in an additive block. The summed energy is transferred to the electric generator. The power of the planned installation is 1 kW. Such a system works in an extended range of wind speeds because the wind receiving devices with different parameters at different wind speeds and the accumulation of energy will compensate the lack of power at one of the wind receiving device. For example, if the wind speed is 5 m/s, a low-speed unit will produce 70% of the rated power, a high-speed one will produce 10% and a three-blade one will produce about 20%. In total, one will get 1 kW and the losses on the power generator will be minimal. In addition, the excess energy in the form of hydraulic energy of the working fluid is sent to the accumulator. Figures 1 and 2 show conventional schemes of wind turbines with separate generators and a multi-unit installation.

Figure 1. Design of wind turbines with separate generators: 1 – wind receiving devices, 2 – generators, 3 – accumulator.

Figure 2. Scheme of a multi-unit installation with a single generator: 1 - wind receiving device, 2 – hydraulic block, 3 -accumulator, 4 – generator.

Figure 3 shows a multi-unit modular installation under development, which is being installed in the wind farm of the FSBSI FSAC VIM in Istra, Moscow district, Russian Federation.
Figure 3. Experimental sample of multi-unit wind farm.

At the wind farm of the Federal Scientific Agroengineering Center “VIM” in Istra, Moscow region, during the year, research was conducted on the operation of wind turbines of different parameters. Observations were made on the operation of 3-, 6-, 9-blade horizontal-axis and 6-blade vertical-axis wind turbines with diameters of 2, 3, 3.9, 4.15 m, with a nominal generator power of 1 kW. There were recorded simultaneously the power generated by the wind turbine on the generator shaft and the rotation speed of the wind turbine depending on the wind speed.

The obtained data are grouped by wind speed from 4 to 14 m/s, and the average annual values of the generated capacity are calculated by groups.

Using the obtained data, calculations of the power of the installation were performed. The output power of the wind receiving device $P$ (W) is calculated using equation 1:

$$ P = \xi \rho V^2 S $$

(1)

$\xi$ – wind power utilization factor;  
$\rho$ – air density 1,225 kg/m$^3$;  
$S$ – wind turbine area, m$^2$;  
$V$ – wind velocity, m/s.

$$ S = \pi D^2 $$

(2)

$D$ – wind turbine diameter, m.

Output power of the generator $P_G$ (W):

$$ P_G = P \eta $$

(3)

$P$ – Output power of the wind turbine, W;  
$\eta$ – generator efficiency, %.

Output power from the generator of a multi-unit wind turbine $P_M$ (W):

$$ P_M = \sum P \eta_h \eta_G $$

(4)

$P$ – Output power of the wind turbine, W;  
$\eta_G$ – generator efficiency, %;  
$\eta_h$ – hydraulic block efficiency, %.

The rotation speed of the wind turbine $n$ [rpm] is calculated using the equation:

$$ n = 60VZ\pi R $$

(5)

$Z$ – speed ration;  
$R$ – wind turbine radius, m;  
$V$ – wind speed, m/s.
Along with this, calculations were made for the number of hours a year the wind installation and individual units will operate at full capacity, i.e. generate 1 kW of electricity. With an average wind speed of 4 m/s in the Istrinsky district of the Moscow region, where tests were conducted, according to the wind repeatability table of M. M. Pomortsev [8]. The wind speed is less than 5 m/s for about 5062 h a year, the wind speed is 5 m/s for about 1445 h, the wind speed is 6 m/s for about 315 h, the wind speed is 7 m/s for about 230 h, the wind speed is 8 m/s for about 110 h, the wind speed is 9 m/s for about 50 h and the wind speed is 10 m/s for about 20 h. The article presents the calculations of excess energy storage. In the case of multi-unit installation, accumulation is hydraulic, the mechanical energy from the wind receiving devices converts to the hydraulic energy by the pumps and directs it to the accumulator, where the summation of energy occurs, and the surplus energy is stored. Accumulation and storage of excess energy of wind power plants with separate generators are electric using batteries.

3. Results and discussion

Table 1 shows the data obtained over the one-year data collection on the generated power of 3-, 6-, 9-blade horizontally-oriented and 6-blade vertically-oriented wind turbines. The diameters of the wind wheels are 2, 3, 3.9 and 4.15 m. The wind energy utilization coefficient of 3-, 6-, 9-blade horizontally-oriented and 6-blade vertically-oriented wind turbines are equal to 0.4, 0.35, 0.3 and 0.28.

Table 1. Powers of wind units with separate generators.

| v (m/s) | Unit power (W) | Generator output power (to the load and the battery) (W) | Sum of generator outputs (W) | To the battery (W) |
|--------|----------------|----------------------------------------------------------|----------------------------|-------------------|
| 3-blade horizontal | 6-blade horizontal | 9-blade horizontal | 3-blade vertical | 6-blade horizontal | 9-blade horizontal | 6-blade horizontal | 9-blade horizontal | 6-blade horizontal | 9-blade horizontal |
| 4 | 48 | 94 | 140 | 148 | 14 | 0 | 28 | 0 | 42 | 0 | 44 | 0 | 129 | 0 |
| 5 | 94 | 183 | 273 | 289 | 28 | 0 | 55 | 0 | 82 | 0 | 87 | 0 | 252 | 0 |
| 6 | 162 | 316 | 472 | 500 | 49 | 0 | 95 | 0 | 142 | 0 | 150 | 0 | 435 | 0 |
| 7 | 257 | 502 | 750 | 794 | 15 | 0 | 301 | 0 | 450 | 0 | 476 | 0 | 1000 | 0 |
| 8 | 384 | 750 | 1120 | 1185 | 23 | 0 | 450 | 0 | 672 | 0 | 711 | 0 | 1000 | 0 |
| 9 | 547 | 1068 | 1594 | 1688 | 49 | 0 | 961 | 0 | 1000 | 0 | 1000 | 519 | 1000 | 519 |
| 10 | 750 | 1465 | 2187 | 675 | 0 | 1000 | 31 | 1000 | 968 | 1000 | 1286 |
| 11 | 998 | 1950 | 2910 | 898 | 0 | 1000 | 75 | 1000 | 619 | 1000 | 1374 |
In the case of individual units, losses on the generator are about 70% at wind speeds up to 7 m/s and are about 40% at wind speeds of 7-8 m/s due to the low power generated on the wind generator shaft, the rpm is not enough for the generator to operate at full power. At a wind speed of 9 m/s, losses in the generator are 10%. At the same time, in the case of individual wind farms, excess generated capacity is not used.

Table 2 shows the of the multi-unit wind power plant at different wind speeds.

Table 2. Powers of multi-unit wind power plant.

| v m/s | Wind receiving device power, W | To the battery, W | Power taking into account losses in hydraulic, W | Generator output power, W |
|-------|-------------------------------|-------------------|-----------------------------------------------|--------------------------|
| 4     | 570                           | 0                 | 553                                            | 506                      |
| 5     | 890                           | 0                 | 875                                            | 840                      |
| 6     | 1450                          | 290               | 1378                                           | 1000                     |
| 7     | 2303                          | 1143              | 2188                                           | 1000                     |
| 8     | 3439                          | 2279              | 3267                                           | 1000                     |
| 9     | 4896                          | 3736              | 4651                                           | 1000                     |
| 10    | 4401                          | 3241              | 4181                                           | 1000                     |
| 11    | 5858                          | 4698              | 5565                                           | 1000                     |
| 12    | 1296                          | 136               | 1231                                           | 1000                     |
| 13    | 1648                          | 488               | 1565                                           | 1000                     |
| 14    | 2058                          | 898               | 1955                                           | 1000                     |

The losses of the multi-unit plant are 15%, 5% at the hydroelectric unit and 10% at the generator since the energy summed in the additive block is transferred to the generator. Up to 6 m/s, the plant generator also does not work at full power, so the efficiency is about 70-80%. The output of the generator does not reach the rated value at wind speeds of 4-5 m/s, but more than 2 times higher than in wind turbines with individual generators, as can be seen from figure 4: at wind speeds up to 7 m/s, the power of the multi-unit wind turbines is approximately 2-3 times higher than the sum of the powers of the individual wind turbines.

The multi-unit plant works at full capacity at an average wind speed of 4 m/s for about 4500 hours per year, including the use of accumulated energy. This is 51% of the total time of the year. At a wind speed of 4-5 m/s, the multi-unit plant produces up to 840 watts. Under the same conditions, separated wind farms in total provide 1 kW of electricity for only 1185 h (13%), which is 3-4 times less.

The calculation of the operating time of wind power plants at 4, 5 and 6 m/s shows that in wind installations with separate generators (table 1) the amount of electricity generated is 130 W, at 5 m/s - 250 W and at 6 m/s - 435 W. The multi-unit installation produces 500 W of electricity at 4 m/s, 840 W at 5 m/s, and 1 kW at 6 m/s when up to 300 W is accumulated (table 2). To compensate for the lack of energy at 4-5 m/s, it is possible to use the excess energy in the form of working fluid energy from the accumulator.
In wind power plants with separate generators at 4-5 m/s, only multi-blade wind receiving devices work fully, but they produce small power due to the low wind power utilization, which is insufficient for the generator operation. Wind farms in total accumulate up to 200 kWh per year. Accumulation is possible from 9 m/s.

According to the wind repeatability of M. M. Pomortsev, it is known that the average speed of 4 m/s is observed 1610 h per year, 5 m/s is observed 1445 h and 6 m/s is observed 1070 h. To calculate the operating time \( T, \text{h} \) of wind turbines with separate generators and multi-unit installation, we use the equation 6:

\[
T = t_1 + t_2 + t_3
\]  

\( t_1, t_2, t_3 \) - the number of hours per year with a certain wind speed of 4, 5 and 6 m/s according to M. M. Pomortsev.

For example, for multi-unit installation \( T=1610+1445+1070=4125 \text{h} \). To compensate for the lack of energy at 4-5 m/s, it is possible to use the excess energy in the form of working fluid energy from the accumulator.

In wind power plants with separate generators at 4-5 m/s, only multi-blade wind receiving devices work fully, but they produce small power due to the low wind power utilization, which is insufficient for the generator operation: \( T=t_3=1070\text{h} \).

The annual accumulated energy \( Q, \text{kWh} \) is calculated using equation 7:

\[
Q = \sum P_i t_i
\]

\( P_i \) - power at a certain wind speed from tables 1 and 2, W;
\( t_i \) - number of hours per year with a certain wind speed according to M. M. Pomortsev, h.

Multi-unit installation accumulates 2619 kW h of energy per year: \( Q=290w*1070H+1143w*640H+2279w*315h+3736w*152h+3241w*52H+4698w*26h=2619\text{kw*h} \).

Wind farms with separate generator in total accumulate up to 200 kWh per year. Accumulation is possible from wind speed of 9 m/s.

![Figure 4. Comparison of capacities of a multi-unit and three separate wind farms with losses taken into account.](image)

**4. Conclusion**

At low wind speeds, the torque and rotation frequency of low-blade wind receiving devices are low, therefore the frequency of the generator and the efficiency are low. However, summing energy of the individual units with different parameters that work efficiently at different wind speeds by using the additive unit, one can power the generator with energy from a number of wind receiving devices using hydraulic motors in an additive block, increasing the speed and efficiency of the generator, keeping the rotation speed at nominal.
Calculations have shown that the wind power plant at an average wind speed of 4 m/s operates at full capacity of 4500 hours per year or 51% of the total time of the year. At 4-5 m/s, the multi-unit installation produces up to 830 watts. Under the same conditions, wind farms with separate generators in total provide 1 kW of electricity for only 1185 h (13%), which is 4 times less than the wind installation and there is no possibility to use the energy reserve.

At the same time, 2619 kWh of energy is accumulated in multi-unit installation, and it is possible to accumulate it at a wind speed of 6 m/s. If there is a shortage of wind power, the accumulated energy compensates for the lack by maintaining a constant power output of the generator.

References
[1] Kharitonov V P 2010 Osnovy Vetroenergetiki [Fundamentals of Wind Energy] (Moscow: VIESKH)
[2] Dorjiev S S, Bazarova E G, Pimenov S V, Rozenblum M I 2018 J Phys Conf vol 1111 012053
[3] Hovgaard T G, Jørgensen S B and Jørgensen J B 2013 Wind Energ. vol 00:1–12
[4] Vestas Multi Rotor concept demonstrator at Risø Available at: https://www.vestas.com/~media/files/multirotor%20fact%20sheet/ (accessed 15 February 2020)
[5] The Wind Tree Available at: https://newworldwind.com/en/wind-tree/ (accessed 25 January 2020)
[6] SHefter YA I Rozhdestvenskiy I V 1957 Izobretatelyu o Vetrodvigatelyakh i Vetroustanovkakh [To Inventor About Wind Turbines and Wind Units] (Moscow: Ministry of Agriculture publ.) chapter 2 pp 35–36
[7] Patents RF no. 2187019 2002, no. 2239092 2004, no.2581304 2016, no.2366829 2009, GB no. 2443886 2016, EP no.1407139 2009
[8] Pomortsev M M 1894 O Zakone Raspredeleniya Skorostey Vetra [On the Law of Distribution of Wind Speeds Units] (St Petersburg: Marine Government Printing House) Chapter 2 pp 35–36