The design and estimation of the parameters of the vertical-axial wind-mill electric generating unit for the self-generated power supply of the objects

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Abstract. For the first time the experimental investigation was carried out in the wind tunnel installation to evaluate the influence of the zigzag-shaped wing flaps on the work of the H-Darrieus and circular rotors. It is determined that the rotation frequency of the H-Darrieus rotor increases at the average rate of 19 per cent in the presence of these wing flaps, and the rotation frequency of the circular rotor increases at the average rate of 31 per cent in this case. It will lead to the increase of the power factor. The optimization of the geometrical parameters and the improvement of the blade construction may lead to the increase of the power factor of the H-Darrieus rotor to the point of 0.72, exceeding the maximum possible point 0.45 for the horizontal axial wind-mill electric generating unit. It is appropriate to change over to the single-stage construction of the H-Darrieus rotor with the cross members only at the bottom to connect the rotor to the shaft of the electric power generator and the thin plain bandage for fastening the blades with the wing flaps in the upper part of the rotor. It is practicable to aggregate the H-Darrieus rotors with the circular rotors for activating the rotor at the far less rotation speeds. Such a combined rotor can be used in the systems of electric power supply and heating of different objects.

1. Introduction
In many countries of the world, including Russia, the decentralized systems of power supply come into more common use, including those that use wind-mill electric generating units as the main or auxiliary energy source (WMEGU) [1–4]. Since 1980-s the vertical axial wind-mill electric generating units (VA WMEGU) have been used together with the horizontal axial wind-mill electric generating units (HA WMEGU). The advantage of VA WMEGU in comparison with HA WMEGU is the absence of necessity to use the guidance mechanisms, because the work of these installations doesn’t depend on the wind direction.

VA WMEGU scame into the most common use and they have two main rotor types: with the vertical airfoil blades of the H-Darrieus rotor type and with the vertical semi-cylindrical blades of the cylindrical type. The Savonius rotor can be considered as the special case of the circular type with the diameter of the rotor, not exceeding two diameters of the blade [4–7]. The advantage of the H-Darrieus rotors is their high rapidity, and their disadvantage is the inability of self-starting because of the little starting torque. The advantage of the circular rotors, including the Savonius rotors, is their self-starting ability because of their large starting torque, and the disadvantage is the small rotation speed. The investigation
of the air-flow mechanics of their blades and the energetic characteristics is necessary to improve the constructions of the VA WMEGUs.

The aim of the work is the development of the improved VA WMEGUs on the basis of the analysis of their air-flow mechanical parameter sand the energy efficiency. The main tasks of the work are the analysis of the air-flow mechanical parameters of the VA WMEGUs, the evaluation of their energy efficiency and working out of the practical guidances about the efficiency upgrading of the different types of the VA WMEGUs in the process of designing of their constructions.

2. The analysis of the main air-flow mechanical parameters of the VA WMEGU rotors

According to the majority of the researchers, the rotation of the H-Darrieus rotors is performed by means of the lifting force, originating in the blade airfoil [5-12]. Nevertheless, some authors think that the lifting force originates only on a small part of the circular path of the airfoil blade. The flow-around of the blade by the pulsating flow, which is analogous to the flow, resulting from the interaction of the horizontal air flow with the birds’ waving wing, takes place on the most part of the path. As noted in the works [13–15], such fluctuations are generated by the wing with the width b, fluctuating according to the sinusoidal law with the oscillation amplitude, determined by the formula

\[ A = \frac{D_d}{2Z} \]  

where \( D_d \) is the diameter of the H-Darrieus rotor, m; \( Z \) is the power-speed coefficient, showing the proportion between the blade speed and the wind speed.

The power-speed coefficient can be determined according to the formula

\[ Z = \frac{\omega D_d}{2V} = \frac{\pi n D_d}{60V} \]  

where \( \omega \) is the angular rate of the rotor rotation, \( c^{-1} \); \( V \) is the wind speed, \( m c^{-1} \); \( n \) is the rotor rotation frequency, rpm.

As noted in the work [15] the maximum capacity of the H-Darrieus rotor is achieved at the point of \( Z = 2.5 \), and its geometrical parameters correspond to the wing-width ratio \( 0.2 \leq 2b/D_d \leq 0.3 \). This means that the relative amplitude is \( 1 < A/b < 2 \). Birds’ wings fluctuate with such amplitudes. As the authors of the article suppose, the end members of the blades (wing flaps) of different geometry, similar to the birds' wings, can be used to reduce the wind resistance by means of the loss reduction, caused by the large rotations, formed at the ends of the blades. All the types of the wings, showed in the pictures, mostly have triangular, round or rectangular ends in the end part of the airfoil [17]. Apparently, such wings, enabling to reduce the energy expences during the flight due to the perfect air-flow mechanics, came in to existence due to the long evolution. This experience can be spread on the similar technical objects, such as the blades of the H-Darrieus rotors, the circular rotors and the Savonius rotors.

For the first time the authors carried out the experiments on the laboratory installation, evaluating the influence of the zigzag-shaped airfoils on the work of the H-Darrieus rotor (see figure 1).

Figure 1 shows the aerodynamic axis (tube) 1 with the length of 2.00 rectangular section 0.74x0.46 m, equipped with two fans 2 and the grill for leveling the flow speed. Picture 1b shows the laboratory bench with the H-Darrieus rotor with the diameter of \( D_d = 0.30 \) m, three blades 4 with the sectional width \( b_d = 0.100 \) m, with the sectional thickness \( \delta_d = 0.012 \) m, equipped with the microelectric generator (micromotor) 5, with V-belt multiplying gear 6, with the gearing ratio \( z_m = 7.09 \) for the appropriate increase of the rotation frequency of the electric generator shaft.

The micromotor 5 at nominal voltage 6.0 W had nominal shaft speed 2400 rpm. For measurement of rotating velocity on voltage given by the electric power generator a digital voltmeter -multiple-purpose meter 7 was used. Figure 1c the similar laboratory facility with an H-darrieus rotor is shown with the blades having zigzag-shaped wing flaps 8 with 10 mm height overhangs. Figure 1d shows this facility placed in the aerodynamic axis. There is also axis controller 9 in the form of a frame, made of thick
filaments. By means of the digital anemometer 10 on a bracket (figure 1d), the airspeed was measured in 9 center points of 9 squares 0.10 x 0.10 m in size. By results of these samplings the average air velocity in the midsection of aerodynamic axis $V$ was defined.

Figure 1. Laboratory facility for experiments on rotating velocity of an H-Darrieus rotor:
1 – aerodynamic axis; 2 – fans; 3 – a fence; 4 – blades; 5 – a micro electric power generator; 6 – a V-belt speed up gear; 7 – a digital voltmeter; 8 – wing flaps; 9 – an axis controller; 10 – a digital anemometer.

3 series of experiments by determination of H-Darrieus rotor rotating velocity $n_0$ were conducted in case of a zero blades angle of attack $\alpha = 0^\circ$, rotating velocity $n_1$ in case of an optimum blades angle of attack $\alpha = 4^\circ$ and rotating velocity $n_2$ in case of an optimum blades angle of attack $\alpha = 4^\circ$ in the presence of the zigzag-shaped wing flaps of 10 mm height depending on change of average air speed of The results of experiments on determination of H-Darrieus rotor rotating velocity depending on the blades construction and the air speed are given in table 1. Apparently, in case of average airspeed increase $V$ from 4.1 up to 5.7 m s$^{-1}$, i.e. by 1.4 times rotating velocity $n_0$ increases from 89 up to 245 rpm, i.e. by 2.75 times, rotating velocity $n_1$ increases from 102 up to 290 rpm, i.e. by 2.81 times, and rotating velocity of $n_2$ increases from 130 up to 260 rpm, i.e. by 2.77 times as indicated in table 1. Thus, rotating velocity of $n$ rotor in all experiment series increases in proportion to a cube of average rate of average airspeed increase $V$. In case of an optimum blades angle of attack $\alpha = 4^\circ$ H-Darrieus rotor rotating velocity increases on average by 17 %, and in the presence of the zigzag-shaped wing flaps, 10 mm high, rotating velocity of a rotor additionally increases on average by 19 %. This results from the fact that zigzag flaps break the large eddies which are formed in a stern
of a wing-shaped blades profile in case of their rotation. This effect will lead to the essential growth of energetic efficiency of an H-Darrieus rotor. Thus, it is expedient to position H-Darrieus rotor airfoil blades with an optimum angle of attack \( \alpha = 4^\circ \) and to supply them with the flaps in the form of triangular zigzags. It is also necessary to mark that in the presence of these flaps the H-Darrieus rotor began to be launched independently without use of an additional a circular rotor.

Table 1. H-Darrieus rotor rotating velocity depending upon the blades construction and the airspeed.

| №  | \( V \), m s\(^{-1} \) | \( n_0 \), rpm. | \( n_1 \), rpm. | \( n_2 \), rpm. | \( n_1/n_0 \) | \( n_2/n_1 \) |
|----|-------------------|----------------|----------------|----------------|-------------|-------------|
| 1  | 4.1               | 89             | 102            | 130            | 1.15        | 1.27        |
| 2  | 4.8               | 150            | 169            | 188            | 1.13        | 1.15        |
| 3  | 4.9               | 160            | 182            | 212            | 1.14        | 1.23        |
| 4  | 5.1               | 177            | 209            | 235            | 1.18        | 1.12        |
| 5  | 5.4               | 200            | 243            | 280            | 1.22        | 1.15        |
| 6  | 5.7               | 245            | 290            | 360            | 1.18        | 1.24        |

Average 1.17 1.19

Rotation of circular rotors is carried out at the expense of the difference of head resistance forces operating on the blades located on the different sides from a rotor axis. Authors also made experiments on an impact assessment of zigzag flaps on operation of circular rotors on laboratory facility. See figure 2.

![Figure 2. Laboratory facility for experiments on rotating velocity of a circular rotor: 1 – semicylindrical blades; 2 – rotor shaft; 3 – flatcrossarms; 4 – wing flaps; 5 – aerodynamic axis.](image)

In a figure 2a the laboratory bench of a circular rotor type with a diameter 0.30 m is shown. 3 semicylindrical blades 1 with a diameter 0.10 m have height of 0.20 m and they are attached to a shaft 2 on the top and on the bottom by means of flat cross arms 3. In a figure 2b the same laboratory bench with a circular type rotor with the blades 2 having the zigzag-shaped wing flaps 4 set in aerodynamic axis 5 is shown. Airspeed was determined by the help of the digital anemometer and the coordinate device as well as on earlier described laboratory facility for the research of the H-darrieus rotor rotating speed (see figure 1d), in the figure 2b they are not shown.

Two series of rotating velocity determination experiments were conducted: rotating velocity \( n_0 \) of a circular rotor with semicylindrical blades and rotating velocity \( n_1 \) of a circular rotor with semicylindrical blades that have flaps in the form of triangular zigzags. Results of experiments are given in table 2.
Table 2. Circular type rotor rotating velocity depending on the blades construction and the airspeed.

| №  | $V$, m/s$^{-1}$ | $n_0$, rpm | $n_1$, rpm | $n_1/n_0$ |
|----|-----------------|------------|------------|------------|
| 1  | 2.2             | 25         | 37         | 1.48       |
| 2  | 2.5             | 27         | 41         | 1.51       |
| 3  | 2.7             | 38         | 54         | 1.42       |
| 4  | 2.8             | 44         | 51         | 1.15       |
| 5  | 3.3             | 59         | 69         | 1.17       |
| 6  | 3.5             | 50         | 71         | 1.42       |
| 7  | 3.8             | 68         | 79         | 1.16       |
| 8  | 4.0             | 64         | 82         | 1.28       |
| 9  | 4.9             | 80         | 93         | 1.16       |
|    | Average         |            |            | 1.31       |

It is indicated in table 2 that in case of increase in average airspeed $V$ from 2.2 up to 4.9 m/s$^{-1}$, i.e. by 2.3 times, rotating speed of $n_0$ increases from 25 to 80 rpm, i.e. by 3.2 times, rotating speed of $n_1$, increases with 37 to 93 rpm, i.e. by 2.5 times. Thus, rotating velocity of a rotor $n$ in all series of experiments increases practically in proportion to average airspeed $V$. In the presence of the zigzag-shaped wing flaps of low height 10 mm rotating velocity of a rotor increases on average by 31%. This results from the fact that zigzag flaps break the large eddies which are formed behind the internal surfaces of semicylindrical blades in case of a rotor rotation. This effect leads to the considerable reduction of aerodynamic losses and promotes increase in rotating velocity. It will allow increasing significantly energetic efficiency of a circular type rotor. Thus, it is expedient to supply semicylindrical blades of a circular type rotor with flaps in the form of triangular zigzags. Further the influence of flaps that have different form and size overhangs on the aerodynamic parameters of airfoil blades and the cylindrical form including for Savonius rotors on rotors power factor will be in more detail studied.

To determine the main aerodynamic parameters of a circular type rotor (see figure 3), first of all, it is necessary to get resistance factor of the semi-cylindrical blade $C$ depending on a deflection $\phi$.

![Figure 3](image-url)  

Figure 3. Analytical model of a circular type rotor.

The experiments made by authors of the given article [16] and experiments of other scientists [15], have shown that resistance factor $C$ has the maximum value $C_{max} = 1.76$ at $\phi = 90^\circ$ and the minimum value $C_{min} = 0.42$ at $\phi = 270^\circ$. These values of head drag coefficient can be used when determining of the rotating moment, the power and power factor.
3. Power efficiency assessment of VA WMMEGU rotors usage

The power efficiency of any wind turbine is defined according to [5, 6, 9, 13] power factor (power efficiency or efficiency of wind power)

\[ C_p = \frac{2P_{we}}{\rho V^3 S}, \]

where \( P_{we} \) is the capacity of wind engine, used at WMMEGU, W; \( \rho \) is the air density, kg m\(^{-3}\); \( V \) is the wind speed, m/s; \( S \) is the space, enclosed by wind wheel, m\(^2\).

Power factor \( C_p \) depends on specific speed \( Z \), determined by a formula (2). Parameters \( C_p \) and \( Z \) are the key operational parameters defining perfection of a design and overall performance of the wind turbine. Power factor \( C_p \) has accurately expressed maximum at certain values \( Z \). This maximum value is significantly lower than a theoretical limit of \( C_p^{MAX} = 16/27 = 0.59 \) (so called Betts limit) [5, 9] for HA WMMEGU and fluctuates ranging from 0.15 to 0.50.

However, it is necessary to mark, some scientists in their works and, in particular, Gorelov D.N. [13–15] mark that H-Darrieus blades are streamlined by the pulsating nonstationary flow which arises in case of rotor rotation. As a result of “an ideal H-Darrieus rotors researches, that has only blades and doesn’t have crossarms, creating the additive drag and eddy flows hindering the blades operation the value \( C_p^{MAX} = 0.72 \) [13-15] was received. It is higher than limit value \( C_p = 0.59 \) for an ideal HA WMMEGU rotor.

Maxima of power factors of the modern most perfect H-Darrieus rotors lie in range \( C_p = 0.40 \div 0.47 \) [12–14]. Such elements of construction as crossarms for blades fixing to a rotor shaft exert the strong impact on overall performance of H-Darrieus rotors. In an air flow crossarms are affected by resistance forces which reduce the rotating aerodynamic moment created by blades. Such assessment was made in an experiment [15] in case of tests of 6 propeller two-storey model H-Darrieus rotor. The external blade tips were connected by plane shroud which entered small perturbations to a flow. Therefore the main losses are connected with flow slip of crossarms, located on the rotor midsection between its tiers. Resistance forces in case of flow slip of crossarms were so grand that led to double lowering of the maximum value of the useful output and according to power factor of \( C_p \) which decreased from 0.56 to 0.28, i.e. twice. Thus, in case of a rational choice of crossarm constructions and the systems of blades fixing one can achieve essential lowering of an H-Darrieus rotor energy loss, increasing thereby power factor of \( C_p \), i.e. its energy performance. Therefore it is expedient to switch to a single-tier construction of an H-Darrieus rotor with only bottom crossarms for association of a rotor to a shaft of the electric generator and a thin plane shroud that fix blades in the top rotor part.

The role of an installation angle of airfoil blades is also very important. The authors’ experiments described above showed that increase in blade angle of attack from 0° up to 4° led low-to-high speed transition of an H-darrieus rotor from n0 to n1 on average for 17 % (see table 1). Since the power developed by the wind turbine according to the theory of similarity of rotor machines (pumps, fans, wind turbines) is proportional to rotating speed cubed, the power of the wind turbine increased by 1.6 times, approximately the electrical power factor shall also increase. It is confirmed by the experiments described in the work [15]. Experiments showed that in case of increase in an angle of blades installation \( \alpha \) from 0° to 4° the power factor increased \( C_p \) from 0.40 to 0.61, i.e. by 1.5 times. Thus, in case of an optimum angle of blades installation in 4° one can also achieve essential lowering of energy losses of an H-Darrieus rotating rotor, increasing thereby electrical power factor \( C_p \) by 1.5-1.6 times.

Since the authors’ experiments showed that the use of zigzag-shaped flaps the rotating velocity in addition increases on average by 19 % (see table 1), it will allow to increase respectively the power and the power factor of an H-Darrieus rotor. However the level of increase in power factor of an H-Darrieus rotor requires further researches which are planned by authors.

The fill capacity factor of a airfoil of a rotor \( \sigma \) exerts impact on the power factor of \( C_p \). This factor depends on the relation of chord length \( b \) of an airfoil to diameter of a rotor \( D \). For example, in case of
increase in \( h \) from 0.030 to 0.080 m, and constant diameter of a rotor \( D = 0.65 \) m the fill capacity factor \( \sigma \) increased in the experimental installation [15] from 0.15 to 0.40. Reduction of the fill capacity factor \( \sigma \) leads to increase and offset of a maximum on \( C_P \) power factor towards higher values of speed factors [15]. It can be explained by the fact that increase in speed factor leads to suppression of formation and failure of a dynamic flow from blades to H-Darrieus. Thereby reducing losses and increasing energetic efficiency of VA WMMEGU by 5-18%. It is expedient to apply H-Darrieus rotors with low factor \( \sigma < 0.35 \).

We will execute assessment of energy performance a circular type rotor usage (see figure 3). Its advantage before H-Darrieus rotors is the big running torque of \( M \) and the starting torque of \( M_0 \). It provides a possibility of self-start even in case of small wind speeds. For example, in the authors’ experiments described earlier self-start of a circular rotor was carried out already in case of speed of 2.2 m/c. This rotor has a small amount of semicylindrical blades diameter of \( d = b \) delivered on a rather long distance from a spin axis and factor \( \sigma = 0.3-0.7 \) (see figure 3). The authors showed in the work [16] the relative running torque can be determined by a formula

\[
M^* = M / M_{\text{max}} = 0.50 \frac{C (\sin \varphi + \sin^2 \varphi)}{C_{\text{max}}} ,
\]

where \( d \) is the diameter of the blade, m; \( H, D \) is the height and diameter of a rotor, m; \( \varphi \) is the an angle between the direction of an air flow and the plane passing through the blade tips, degree; \( M_{\text{max}} \) is the maximum torque in case of \( \varphi = 90^\circ \).

Authors in the work [16] also received a formula for determination of power factor of a circular rotor

\[
C_{PK} = 0.25 C_{\text{max}} M^*_c N_b b^* ,
\]

where \( M^*_c \) is the mean value of the relative running torque, nm; \( N_b \) is the number of blades in a circular rotor; \( b^* = d/D \) is the relative width of the semicylindrical blade.

Calculations according the formula (5) showed that with growth of the relative width of the semicylindrical blade \( b^* \) from 0.10 to 0.50 and increase in number of blades from 2 to 6 electrical power factor of \( C_{PKS} \) of a circular rotor increase from 0.018 to 0.226. Thus, it is expedient to increase the number of blades \( N_b \) and their relative width of \( b^* \). The received data approximately correspond to \( C_{PKS} \) values (according to other authors [9, 12, 18]) according to which \( C_{PKS} = 0.15-0.20 \). Since the authors’ experiments showed that use of zigzag-shapedwing flaps of rotating velocity of a circular rotor increases on average on 31% (see table 2), it will allow to increase the power and the power factor of a circular rotor. Thus, according to preliminary estimates of the authors, it is possible to increase power factor of a circular rotor by 31% to 0.20 – 30. However the level of power factor increase in a circular rotor and Savonius rotor requires further research that is planned by authors.

H-Darrieus rotors have rather high frequency of rotation that is convenient for their aggregation with electro and heat generators. The circular rotor have a big running torque and small rotating velocity therefore they can most effectively be applied to the drive of pumps, mills, mechanical heat generators (in the presence of the multiplicator) and other machines. Besides, circular rotors and Savonius rotors can be used as the starting arrangement of an H-Darrieus rotor [8, 9, 15, 16]. In this case diameter of a circular rotor or Savonius rotor according to [15] is connected to an H-Darrieus rotor diameter in a ratio

\[
D_c \leq \frac{Z_0 C}{Z_D} D_b .
\]

On condition of (6) a circular rotor creates the positive running torque for all rotating velocities. Therefore the start of an H-Darrieus rotor can be realized in case of much smaller rotational speeds. Such combined rotor can be grouped with the electric generator and also with the mechanical heat generator and it can be used in electro and heat supply systems of different objects. It can be aggregated with pumps of different constructions and it is used for the rise of different liquids from surface and underground sources, including, for oil production from slits.
4. Conclusion
1. The pilot studies in a laboratory wind tunnel on an impact assessment of zigzag flaps on operation of an H-Darrieus rotor and a circular rotor are executed for the first time. It is set that in case of an optimum blades angle of attack of $\alpha = 4^\circ$ H-Darrieus rotor speed increases on average by 17%, in the presence of the zigzag-shaped wing flaps H-Darrieus rotor speed increases on average by 19%, and a circular rotor on average for 31%. This results from the fact that zigzag flaps break the large eddies which are formed in a stern of a wing-shaped blades profile or behind an external generatrix of semicylindrical blades in case of their rotation. Thus, it is expedient to supply VA WMEGU with the zigzag-shaped wing flaps of low height.

2. Resistance forces in case of flow slip of crossarms were so grand that can lead to lowering of the power factor from 0.56 to 0.28, i.e. twice. Thus, in case of an optimum angle of blades installation in $4^\circ$ and in the presence of the zigzag-shaped wing flaps of low height rotating speed of an H-Darrieus rotor increases that will lead to increase of the power factor. Optimization of geometrical parameters and enhancement of constructions of blades can lead to increase of power factor of an H-Darrieus rotor to the value 0.72 exceeding the greatest possible value 0.45 for HA WMEGU. It will make VA WMEGU competitive about HA WMEGU.

3. It is expedient to switch to a single-tier construction of a rotor to an H-Darrieus rotor with only bottom crossarms for association of a rotor to a shaft of the electric generator and a thin plane shroud that fix blades in the top rotor part. In the presence of the zigzag-shaped wing flaps rotating velocity can increase by 19–31% that will allow to increase overall performance of VA WMEGU constructions. It is expedient to aggregate H-Darrieus rotors with circular type rotors for start of a rotor in case of much smaller rotational speeds. Such combined rotor can be used in electro and heat supply systems of different objects.

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