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Capacity and Power Characteristics of Disk Generator with Counter-Rotation of Double-Rotor Wind Turbine

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Abstract: This work deals with the transformation of the wind energy into electric one by-the electric generator, when the wind flow gets into its windwheel; the wind flow rotates two windwheels rightabout; one of the wheels is fixed on a rotor, the other one is on a stator, whilst the blades of the first windwheel are turned opposite to the second windwheel and the windwheels themselves are located in different sides of the generator. Mutual rotation of the rotor and the stator rightabout results into the increase of the rotor relative speed in relation to the stator. As the electromotive force of the generator, executed on the constant magnets, is proportional to the rotor angular rotational speed, the mutual opposite rotation of the rotor and the stator results in significant increase of the electromotive force, produced in this way. The carried-out comparative measurements and calculations showed that the first and second windwheels are affected by the forces of coordinate ram pressure and the relation of these forces is $\frac{F_1}{F_2} \approx 0,7 \div 1,0$ (depending on air flow rate).

Key words: Disk generator . mathematical modeling . wind power efficiency . front resistance . double-rotor wind turbine with counter-rotation

INTRODUCTION

Modern energetics passes through a period of rapid development and expectation of inevitable changes. Energy consumption grows, when there are depletion and high prices on the main world resource, providing almost 40% of the world consumption-oil. In modern conditions there is a tendency to increase the share of RES (Renewable Energy Source) usage, which is an alternative to traditional technologies.

Wind is an extensive energy source, which is clean and renewable. Based on its property, wind energy has a potential to reduce the impact on environment, wildlife and human health.

At the present time renewable energy sources are between 15% and 20% of the full energy consumption [1]. Wind transformation energy is a rapid-growing interdisciplinary branch, covering numerous developments in science and engineering. As per American Association of Wind Energy, average set standard increases by 29% each year [2]. In the end of 2009, in the whole world the specified capacity of power energy was more than 159 MW. The predictions as of 2010 were more than 203 MW [3]. Wind energy market increased due to environmental advantages of usage the ecologically clean energy, economic motivation, provided by several state governments [4]. Modeling of a self-starting induction generator for the wind energy and capacity voltage, with changing of mutual induction of the stator and the rotor of the wind aggregate apart from different wind speeds [5]. The rotation of the turbine blades includes two sets of rotors, one behind the other: one rotor runs in clockwise, whilst the other runs in counterclockwise [6].

The task of the described in the work method of usage of the wind energy is the increase of $C_{weu.}$ A technical result of this method is the full usage of wind energy, resulting in the increase of rotor speed in relation to the generator stator at the same speed of the incoming wind flow.

The technical result of the considered method is that in the familiar method of wind energy usage, consisting in transformation of wind energy into the electric one by the electric generator, when the wind flow gets into its wind wheel; the wind flow rotates two windwheels rightabout; one of the wheels is fixed on the rotor, the other one is on the stator, whilst the blades of the first windwheel are turned opposite to the second windwheel and the windwheels themselves are located in different sides of the generator.

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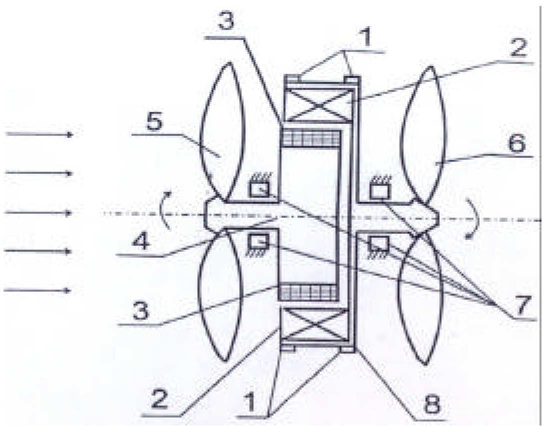

Fig. 1: The diagram of usage of wind energy by means of counter-rotation of two windwheels
1-sliding contacts; 2-stator; 3-rotor magnets; 4-rotor; 5, 6-windwheels; 7-antifriction bearings; 8-stator; (hereinafter the sizes are shown conventionally)

As a result of this technical solution [8], the wind energy is used the most efficiently, resulting in obtaining high speed of rotor running with regard to the stator. It is provided by two windwheels, which are rotated rightabout. After affecting the first rotor blade wheel, the wind flow passes on and rotates the second windwheel of the stator in overside. The wind flow (shown by arrows in the left) goes to the windwheel 5 of the rotor 4, which is rotated in the bearings 7. Along the sides of the rotor disk, there fixed the constant magnets 3, which actuate the electromotive force in the coils 2 of the stator 8. Voltage from the coils 1 is relieved by means of sliding contacts (are not shown in the fig.). The stator 8 can also rotate in the bearings 7. After the wind flow passes the windwheel 5 of the rotor 4, it gets to the second windwheel 6 of the stator 8, the blades of which are turned opposite to the blades of the rotor windwheel 5. Thanks to it, the windwheel 6, fixed on the axis of the stator 8, rotates it rightabout with regard to the rotor.

Mutual rotation of the rotor and the stator rightabout results in the increase of rotor relative speed in relation to the stator. As the electromotive force of the generator, executed on the constant magnets, is proportional to the angular rotational speed of the rotor, the mutual opposite rotation of the rotor and the stator results in significant increase of the electromotive force, produced in this way.

A considered method of wind energy usage is the following. An electric generator with the rotating rotor 3 and the stator 4, with the windwheels of the rotor 5 and the stator 6, fixed on them, has an axis of rotation located in parallel to the air flow direction, where the rotor windwheel is located in front (it shall be noted that the stator windwheel is also possible to be located in front). The sliding contacts are connected to the contact 1 on the stator generatrix 8; the voltage is relieved from them (electromotive force).

To determine the capacity and power characteristics of interaction of the wind flow and the windwheel, a classic theory or the theory of the real wheel by G.Kh.Sabynin is used [7]. The last is also based on the classic theory and differs by including the expenditures on formation of concentrated vortex by wind blade tips to the energy balance of the windwheel and the wind flow.

Let us calculate an ideal wind turbine with two windwheels (a mathematical model of ideal wind electric unit of a new type (WEUNT) in terms of the theory of G.Kh. Sabynin [9, 10].

The theory of G.Kh.Sabynin takes into account the formation of the circular vortex behind the windwheels. In order free steam velocity is V_1 and wind speed behind the wind turbine is V-V_2, vortex rings shall move at the speed of $V-V_2/2$.

Then speed circulation along any contour L equals to:

$$\Gamma = LV - L\times(V - V_2) = LV_2 \qquad (1)$$

Per the unit length is:

$$\frac{\Gamma}{L} - V_2 \qquad (2)$$

Power impulse to form the vortex ring equals to:

$$Fdt = \rho S_2 \times \frac{d\Gamma}{dz} dZ \qquad (3)$$

In a time dt the solenoid length increases by:

$$dZ = (V - \frac{V_2}{2})dt \qquad (4)$$

consequently:

$$Fdt = \rho S_2 V_2 \times (V - \frac{V_2}{2})dt \qquad (5)$$

i.e.:

$$F = \rho S_2 V_2 \times (V - \frac{V_2}{2}) \qquad (6)$$

Then:

$$F = [\rho S_2 (V - V_2)] \times V_2 + \rho S_2 \frac{V_2^2}{2} \qquad (7)$$

An equation in the square bracket is a wind mass, got through the wind turbine:

$$m_1 = \rho S_2 \times (V - V_2) \qquad (8)$$

A value $m_2 = \rho S_2 \frac{V_2}{2}$ is interpreted as an added mass.

Thus:

$$F = (m_1+m_2)\times V_2 \qquad (9)$$

Let us write an energy balance. Energy of the approach flow $(m_1+m_2) \times \frac{V^2}{2}$ was used to form the added mass $\frac{m_2 V_2^2}{2}$; to create the rotation of the wind turbine (force) $F(V\text{-}V_1)$ and the energy, taken away by the flow $(m_1+m_2) \times \frac{(V-V_2)^2}{2}$, i.e.:

$$(m_1+m_2)\times \frac{V^2}{2} = F(V\text{-}V_1)+(m_1+m_2) \times \frac{(V-V_2)^2}{2}+\frac{m_2 V_2^2}{2} \qquad (10)$$

hence, by means of (9) and (10) we obtain:

$$V_2 = \frac{2V_1}{1+\frac{V_1}{V}} \qquad (11)$$

Let us find m_1+m_2:

$$m_1+m_2 = \rho S_2\times(V\text{-}V_2) + \rho S_2\frac{V_2}{2} = \rho S_2\times(V- \frac{V_2}{2}) \qquad (12)$$

or:

$$m_1+m_2 = = \rho S_2 \frac{V^2}{V+V_1} \qquad (13)$$

As:

$$S_2 = \frac{S_1 \times (V-V_1)}{V-V_2} = \frac{(V+V_1)\times S_1}{V} \qquad (14)$$

so:

$$m_1 + m_2 = \rho S_1 V \qquad (15)$$

Then:

$$F = (m_1 + m_2)\times V_2 = \rho S_1 V_1 V_2 \qquad (16)$$

Load factor on the disk surface will be:

$$B = \frac{F}{\rho S_1 \frac{V^2}{2}} = \frac{2V_2}{V} \qquad (17)$$

or:

$$B = \frac{4\frac{V_1}{V}}{1+\frac{V_1}{V}}. \qquad (18)$$

Let us denote $\frac{V_1}{V}$ = e, then:

$$B = \frac{4e}{1+e} \qquad (19)$$

Ram pressure (force) equals to:

$$F = \rho\times S1 \ \frac{V^2}{2}\frac{4e}{1+e} \qquad (20)$$

Shaft power of the wind turbine equals to:

$$N = F\times(V\text{-}V1) = \rho S1 \ \frac{V^3}{2}\times\frac{4\varepsilon\,(1 \quad \varepsilon)}{1+\varepsilon} \qquad (21)$$

C_{weu} equals to:

$$C_{weu} = \xi = \frac{N}{\rho S_1 \frac{V^3}{2}} = \frac{4\varepsilon\,(1 \quad \varepsilon)}{1+\varepsilon}. \qquad (22)$$

Extremum of this equation is observed at e = 0,686, $N_{max} = 0{,}687\rho S\frac{V^3}{2}$, F = 0,586 ρSV².

Let us write the same equations for the second windwheel, located behind the first one.

Speed at the input of the second wind wheel:

$$V' = V - V_2 = \frac{V(V-V_1)}{V+V_1} \qquad (23)$$

So $V' = 0{,}414V_\infty$, consequently:

$$N'_{max} = 0{,}687\,\rho S'_1\ \frac{V'^3}{2} = 0{,}687\,\rho S'_1\ \frac{V_\infty^{\ 3}}{2}\times 0{,}414^3 \qquad (24)$$

i.e.:

$$N'_{max} = 0{,}0487\,\rho\ \frac{S_1 V_\infty^3}{2} \qquad (25)$$

Overall capacity taking into account two windwheels will be equal to:

$$N = (0{,}687+ 0{,}0487)\times \frac{\rho S_1 V_\infty^3}{2} \qquad (26)$$

and overall C_{weu} will be equal to 0,735.

Thus, as per the theory of ideal wind generator of G.Kh.Sabynin, a maximum value of C_{weu} in WEUNT is ξ = 0,735. Theoretical contribution of the second windwheel to C_{weu} equals to the difference 73,5-68,7 = 4,8%.

Let us calculate the same values for the WEUNT by means of the G.Kh.Sabynin theory for the real wind turbine. When calculating the real wind gturbine, both the drag force and the lift force are taken into consideration (Fig. 3).

Lift force, acting on the blade element, equals to:

$$dY = C_Y b dr \frac{\rho W^2}{2} \qquad (27)$$

drag force is the following:

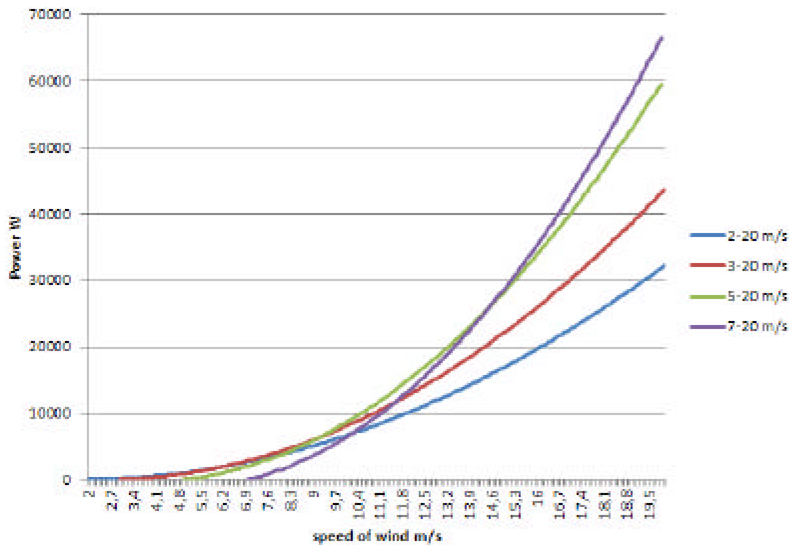

Fig. 2: Capacity characteristic of the double-rotor wind unit

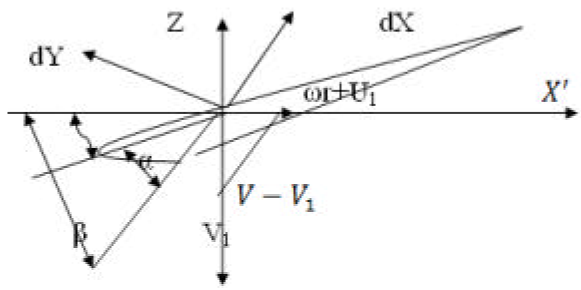

Fig. 3: The forces acting on the wind turbine blade

$$dX = C_x bdr \frac{\rho W^2}{2} \quad (28)$$

where W is a relative speed of wind particles:

$$W^2 - (V - V_1)^2 + (\omega \times r - U_1)^2 \quad (29)$$

speed U_1 is a reaction from the windwheel.

If the air affects on the blade element with the force dF, so the air is affected by the same force, which assigns the speed U_1 to the air.

The force, acting on the blade element (Fig. 4) is written in the following way:

$$2\pi r dr \times (P_1 - P_2) - n \times (dY cos\beta + dX sin\beta), \quad (30)$$

where: n-number of blades; π = 3,14.

Difference of pressures is equal to the ram pressure force, divided by S, i.e.:

$$P_1 - P_2 - \frac{F}{S} - \rho V \times V_2, \quad (31)$$

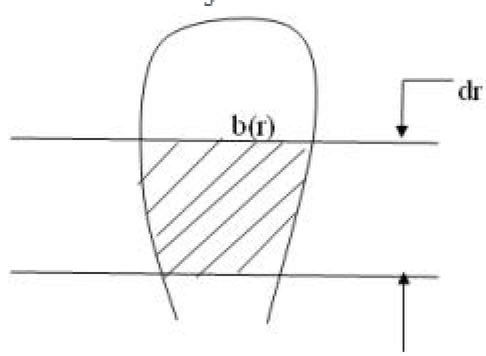

Fig. 4: The blade element

then, taking into consideration (9) and (10), we obtain:

$$2\pi r V \times V_2 = nbC_Y \frac{W^2}{2} \times cos\beta \times \left(1 + \frac{C_X}{C_Y} tg\beta\right). \quad (32)$$

Based on the Fig. 3 it is possible to introduce a notion, named a number of relative modules:

$$ctg\,\beta = \frac{\omega r + U_1}{V - V_1} = Z_U, \quad (33)$$

then:

$$W = (V\text{-}V_1)* \sqrt{1 + Z_U^2}, \quad (34)$$

$$\sin\beta - \frac{V - V_1}{W} - \frac{1}{\sqrt{1 + Z_U^2}}, \quad (35)$$

$$\cos\beta = \frac{\omega r + U_1}{W} = \frac{Z_U}{\sqrt{1+Z_U^2}}. \qquad (36)$$

Let us introduce one more notion $\frac{V_1}{V} = e$ and $\mu = \frac{C_x}{C_Y}$-a reverse quality of the wing (blade), then from (36) we have:

$$n \times b \times C_y = 8\pi r \times \frac{e}{(1+e)\times(1-e)^2} \times \frac{1}{(Z_U+\mu)\times\sqrt{1+Z_U^2}}. \qquad (37)$$

This equation ties the blade width and the lift factor with the deformation of the flow e.

Let us find a torsional force:

$$dF_X = nbdr\frac{\rho W^2}{2}\times(C_Y \sin\beta + C_x \cos\beta) \qquad (38)$$

Introducing μ and Z_U, we obtain:

$$dF_X = 4\pi rd \times \rho \frac{e}{1+e} \times V_\infty^2 \times \frac{1-\mu Z_U}{Z_U+\mu} \qquad (39)$$

When the moment of this force in relation to the axis of the wind turbine is found and multiplied by the angular speed, we obtain an elementary capacity, developed by the blade area 2πrdr, i.e.:

$$dT = dM\omega = 4\pi r dr \frac{e}{1+e} \times \rho V^3 \times \frac{1-\mu Z_U}{Z_U+\mu} \times Z \qquad (40)$$

where: $Z = \frac{\omega r}{v}$. If divide this equation by the elementary energy of the flow $dT_0 = 2\pi rd \times \rho\frac{V^3}{2}$, we obtain:

$$K_{НЭВ} = \xi = \frac{dT}{dT_0} = \frac{4e}{1+e} \times \frac{1-\mu Z_U}{Z_U+\mu} \times Z \qquad (41)$$

This coefficient is a distance function from the rotation axis r. To find the precise full value ξ it is necessary (41) to multiply by r and taking into account the dependency $\mu(r)Z_U$ (r), integrate over r from r_0 to R, where r_0 and r-are the least and the maximum distance of the blade from the rotation axis.

However, as the given functions are not determined, let us use the average values of these parameters.

Let:

$$r = 0{,}6R;\ \alpha = 6^0;\ \frac{nb}{R} = 0{,}81;\ \ell = 0{,}227;$$
$$C_y = 1{,}06;\ \beta = 24{,}3^0;\ \mu = 0{,}037$$

Then: ZU = 2,215 Z = $\frac{0.6wR}{V_\infty}$ = 1.62 and as per the theory of the real wind turbine C_{weu} of WEU (with one) windwheel equals to ξ = 0,489≈0,49.

Taking into account the losses this coefficient increases from 0,467 to 0,487 at ℓ = 0,4 and ℓ = 0,35 respectively.

Setting of Z automatically determines the angular rotational speed $\omega = \frac{2.7V_\infty}{R}$.

For instance, if $V_\infty = 4\frac{m}{c}$, and R = 0,5 m, so ω = 21,6 $\frac{1}{c}$.

Capacity, developed by the wind turbine, if neglect the small quantities, equals to:

$$M = \pi \times R^3 \times \frac{\rho V^2}{2} \times \frac{4e\times(1-e)}{\omega R\times(1+e)} \times \left[\left(1-\frac{r_0^2}{R^2}\right) - 2\mu \times \left(\frac{Z_U}{3} + \frac{1-\frac{r_0}{R}}{Z_U}\right) - \frac{1}{2}\left(1-\frac{r_0}{R}\right)\right] \qquad (2.58)$$

and

$$Z_U = \frac{\omega R}{V-V_1}. \qquad (42)$$

Let us find U_1 and V_1:

$$U_1 = V_\infty \times \frac{e}{1+e} \times \frac{1-\mu Z_U}{Z_U+\mu} \qquad (43)$$

$U_2 = 2U_1$; $V_1 = e\times V_\infty = 0{,}227V_\infty$; $V_2 = 2V1$;
U1 = $\frac{0{,}227 \times 0{,}918}{1{,}227 \times 2{,}252}$ $\times V_\infty = 0{,}05V_\infty$; $U_2 = 2U_1 = 0{,}15V_\infty$.

Let us make the same calculations for the second windwheel:

The speed at the output of the second windwheel: $V' = 0{,}546\times V_\infty$, ($V' = V - V_2$).

The speed U2 helps the rotation, as it slightly increases the angle of attack.

Let us find the angle Δα, on which the angle of attach increases (Fig. 5).

From the Fig. 5:

$$\frac{U_2}{\sin\Delta\alpha} = \frac{\sqrt{V'^2+\omega^2r^2}}{\sin\beta} \qquad (44)$$

Hence:

$$\sin\Delta\alpha = \frac{U_2\sin\beta}{\sqrt{V'^2+\omega^2 r^2}}. \qquad (45)$$

If, the same as for the first windwheel, build $\frac{\omega^2r^2}{V'}$ = 2,7, then sinΔα = 0,039 and Δα = $2{,}24^0$. Thus, if the angle of attach for the first windwheel was 6^0, at the same angle f for the second windwheel it will be $8^015'$. Then C_Y≈1,124 and not 1,07 as per the diagram from [9] and μ = 0,057.

Table 1: Theoretical and experimental values of C_{weu} of WEU and WEUNT

Method of determination	C_{weu} of WEU (with one windwheel), %	C_{weu} of WEUNT (with two windwheels), %	Input of the second windwheel to C_{weu}, %
As per the theory of ideal wind turbine of G.Kh. Sabynin	68,7	73,5	4,80
As per the theory of real wind turbine of G.Kh. Sabynin	49,0	61,4	12,4
Experimentally	47,7	77,9	30,2

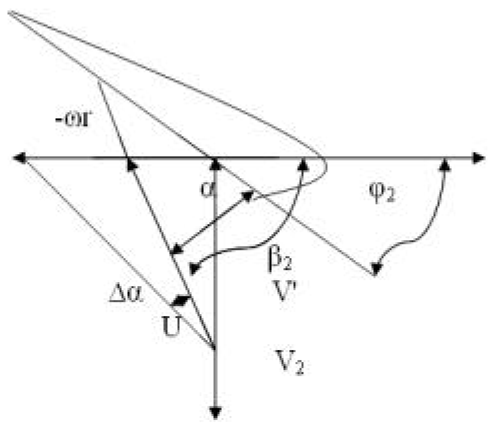

Fig. 5: To calculation of the angle of attack of the second windwheel

Under these conditions e reduces up to 0,19÷0,20.

At this ß = 18,3 + 8,24 = $26,5^0$ and Z_U = ctg ß = 2,006, Z = 2,43 and

$$\xi = \frac{4 \times 0,2}{1,2} \times \frac{0,886 \times 1,459}{2,063} \times 0,417$$

It means that from energy $\frac{mV'^2}{2}$, 0,417 is usefully used.

As V´ = 0,546×V_∞, the usefully used energy by the second windwheel equals to:

$$W_{useful} = 0,546^2 \times 0,417 N_\infty = 0.124 N_\infty \quad (46)$$

So, as per the theory of real wind turbine, the input of the second wheel to C_{weu} WEUNT equals to 12,4%. C_{weu} for the WEU, calculated previously as per the theory of the real wind turbine, equals to 49,0%.

A resultant value for C_{weu} for the WEUNT as per the theory of real wind turbine:

$$C_{weu} = \xi = 0?490 \times 0,124 = 0,614 \quad (47)$$

The results of theoretical and practical evaluations of usage of the wind flow energy in the WEU (with one windwheel) and in the WEUNT (with two windwheels) are shown in Table 1. Theoretical evaluations of input of the second windwheel to C_{weu} of the WEU with two windwheels, obtained as per the theories of ideal and real wind turbines of G.Kh.Sabynin (4,8 and 12,4% respectively) contradict to the obtained experimental data (28,2%).

Thus, by means of the theories of ideal and real wind turbines (as per G.Kh. Sabynin), it is impossible to explain the experimentally obtained effect in the form of the increased value of C_{weu} of the WEUNT. As distinct from the theory, the experiments show a significant increment of electromotive force of the WEUNT due to the work of the second windwheel and therefore the increment of C_{weu}.

However, the obtained experimental results prove the fact, that the second windwheel rotates with significant speed and provides sufficiently great addition to the energy, produced by the WEUNT (with two windwheels).

Efficiency of operation of the disk generator with counter-rotation of two windwheels as compared to the traditional horizontal-axial wind motor can be exemplified by high production of electric energy by vortex rotor wind-power stations, based on the fact, that the average value of speed cubes of different wind flow components is always higher than the cube of average wind speed. The reason of this phenomena in the opinion of the authors [10] is that the averaging of the wind speed results in disregard of wind energy, which are proportional to the wind speed cube, higher and lower than the average value. Therewith, behind the first windwheel, besides the wind flow, coming through its blades, there is one more wind flow, formed by the windwheel itself,working as a fan. This fact is proved experimentally and also the speed of the additional air flow from the rotating windwheel grows with the increase of its rotation frequency.

Besides, let us calculate the force of the ram pressure, acting on the wind motor with horizontal axis of rotation and two windwheels, using the algorithm, suggested in [11].

The first windwheel is affected by the force, determined by:

$$F_1 \quad \rho \frac{V_\infty^2}{2} \times S_1 \times \frac{4e}{1+e} \quad 0,74 \times S_1 \times \frac{\rho V_\infty^2}{2}, \quad (48)$$

where S_1 is an area of the disk surface of the first windwheel; V_∞ is the speed of the wind flow, getting on the first windwheel;

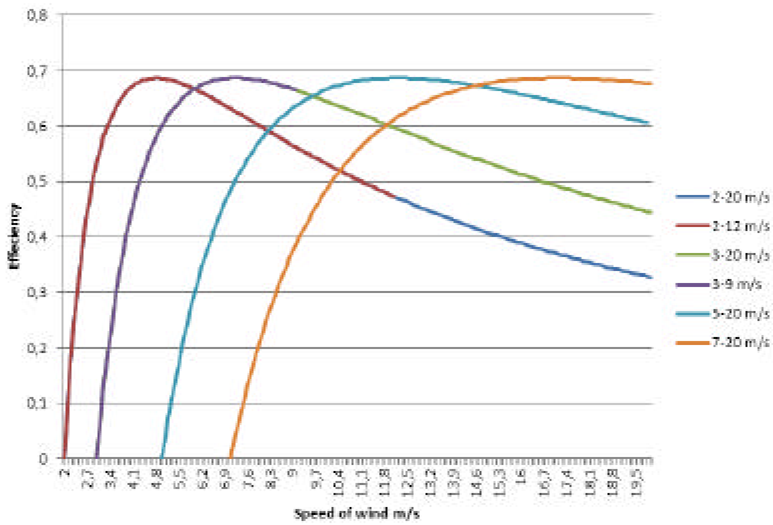

Fig. 6: Dependence of efficiency of the second windwheel on the wind speed

Table 2: Forces of ram pressure on the windwheel of the WEUNT

V, m/s	F1(d1)/F1(d2), H	F2(d1)/F2(d2), H	F(d1)/F(d2), H
2,0	6,8/14,5	1,8/3,9	8,6/18,4
2,5	12,7/28,4	3,4/7,7	16,1/36,1
3,0	22,8/48,9	6,2/13,2	29,0/62,1
3,5	32,3/77,9	8,7/21,0	41,0/98,9
4,0	54,1/116,1	14,6/31,4	68,7/147,5
4,5	75,7/162,5	20,5/43,9	96,2/206,4
5,0	105,6/226,6	28,5/61.8	134,1/288,4
5,5	140,5/301,7	32,0/81,5	172,5/383,2
6,0	182,5/391,2	49,3/105,7	231,8/496,9

The second windwheel is also affected by the force, determined as per the following formula:

$$F_2 = \rho \frac{V_\infty^2}{2} \times S_2 \times \frac{4e}{1+e} = 0{,}74 \times S_2 \times \frac{\rho V_\infty^2}{2}, \qquad (49)$$

where S_2 is an area of the disk surface of the back windwheel.
Total force equals to:

$$F \quad F_1 + F_2 \quad 0{,}94 \times (S_1 + S_2) \times \frac{\rho V_\infty^2}{2}. \qquad (50)$$

Let us use the formulas (2.65) and (2.66) and calculate the forces of the ram pressure F_1 on the first windwheel, F_2-on the second windwheel and $F = F_1+F_2$- on two windwheels for different wind speeds (2-6 m/s) and two values of windwheel diameters (d_1 = 1,5 m and d_2 = 2,2 m) (Table 2).

If we know a mass of the experiment unit and a deflection angle, it is possible to calculate the force of the ram pressure for the first and second windwheels. Affected by these forces the vertical hanger deflects by a definite angle. Simple geometry, values of the deflection angle θ of the vertical hanger from the horizontal, mass values of the hung unit, allow to determine the value of the ram pressure force (F_{rp}):

$$F_{rp} = M_{weu} \times g \times tg\theta \qquad (51)$$

where: M_{WEU} is a mass of unit; g is a gravitational acceleration.

The suggested procedure of determination of the ram pressure force is convenient at small mass of the wind-receiving device (M_{WEU}). The executed comparative measurements and calculations showed that the first and second windwheels are affected by the forces of ram pressure of the same magnitude and the relation of these forces is $\frac{F_1}{F_2} \approx 0{,}7 \div 1{,}0$ (in dependence on the air flow rate).

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