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MASS-DIMENSIONAL CHARACTERISTICS OF WIND-DRIVEN POWERPLANTS WITH HORIZONTAL AXIS OF ROTATION OF WIND WHEEL

Propeller-type wind-driven powerplants with horizontal axis of rotation of the wind wheel is now the most common in Ukraine and abroad. Various structural schemes of such powerplants are known, however, there is no information about their comparative analysis in terms of mass, volume and energy efficiency. In this paper, an attempt of such analysis is undertaken. Following block schemes of wind-driven powerplants of average power were considered:

1) direct-drive scheme (fig. 1, a), in which the wind-wheel 1, usually three-bladed, fixed to the rotating head on top of the tower base, which rotates AC electrical generator 3 by a spindle 2;
2) geared scheme (fig. 1, b), in which between the wind-wheel 1 and the generator 3 there is a gearbox 4, which increases the speed of the generator shaft;
3) turbogenerator scheme (fig. 1, c), providing installation of generators 3 on rotor blades of wind-wheel 1 at equal distances from the axis of rotation, on the shafts of which additional propellers 5 are mounted so that their axes of rotation are perpendicular to the wind direction;
4) the contactless current collector on the basis of an asynchronous machine with wound rotor is introduced in previous scheme, the shaft of which is connected directly to the shaft of the main propeller (fig. 1, d);
5) combined scheme (fig. 1, e), in which the multiplier and a synchronous generator similar are added to elements of the previous scheme alike fig. 1, b.

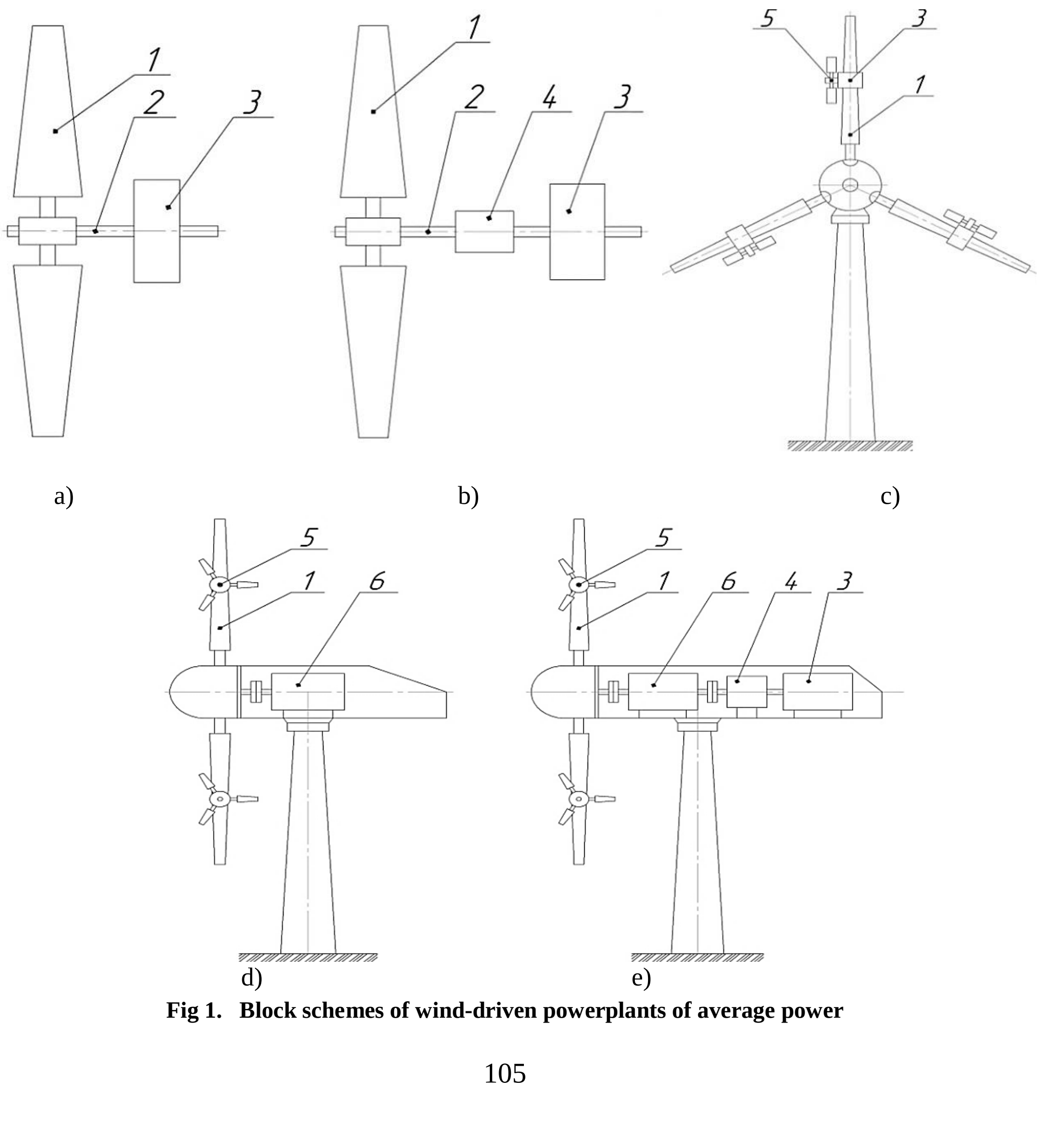

Fig 1. Block schemes of wind-driven powerplants of average power

Production of wind-driven powerplants shown in fig. 1 is the most simple, but because of the relatively low speed of wind-wheel it's necessary to use the generator with large number of pole pairs which has in general considerable diameter and mass. The scheme in fig. 1, b, due to the presence of the multiplier, enables the usage of high-speed generator with a small number of pole pairs and thus with much smaller size and weight than the previous one. But the multiplier with higher gear ratio has a significant size, weight, and requires constant maintenance. The latter reduces the reliability of wind-driven powerplants. The version of the scheme in fig. 1, b, so-called "Multibrid" involves the usage of a single stage gearbox with gear ratio i = 6-10 and multipolar generator with a speed of 100 to 200 rev/min is known and widely used. Compared with basic scheme the gearbox is simplified, but the generator is a little complicated and heavier.

Wind-wheel powerplants, made as shown in fig. 1, c, involves the usage of high-speed generators placed on the main propeller blades which are rotated by counter flow of air that acts on the additional propeller on the axes of these generators. Placing the generators on large radii increases their speed in 10-15 times compared to the speed of the main propeller, eliminating the use of multipliers. But here, for the transmission of electricity to customers from the generators rotating on blades, current collectors are needed, the shaft of which is rotated by the main wind-wheel. If current collectors are contact, the construction is more complicated which decreases the reliability of the wind-wheel powerplant.

Contactless current collector in the scheme on fig. 1, d is a special asynchronous machine with a conventional stator, winding of which is connected with a three-phase power supply network. The rotor winding is made of three identical three-phase windings, each of which is connected to the three-phase winding of the corresponding generator on the blade. Choosing the ratio of the numbers of turns of the phase windings of the stator and the rotor of the asynchronous machine provides a sufficiently high (10 kV) electric line voltage of stator, i.e. machine, except the current collector, also performs the function of enhancing supply transformer.

Implementation of wind-driven powerplants according to the scheme on fig. 1, e, allows to redistribute the power between the generators on its blades and on its axis and obtain two independent sources of electricity and reduce the mechanical stress on blades.

The relative weight and size of the basic elements of considered wind turbines were determined. We assume that the generators installed in swivel head and blades are synchronous and salient-pole. Using the structure of the formula given in [1], and based on the analysis of weight and size of modern synchronous salient-pole generators, a formula to calculate their mass, kg:

$$M_{г} = \frac{7{,}3\cdot 10^4}{\sqrt{p}} D^2 l, \qquad (1)$$

where p - the number of pairs of poles; D, l - the diameter and length of the inductor respectively, m.

The product $D^2 l$ is the so-called dimensional factor $Г_ф$ and can be represented by such relationship [2]:

$$Г_ф = D^2 \cdot l = \frac{6{,}1\cdot 10^3 p'}{K_ф K_{об} F_к \cdot n}, m^3 \qquad (2)$$

where $p' = m_1 E_1 I_1 = m_1 к_н U_1 I_1$ – calculated (internal) generator power, kVA; m_1 – the number of phases; E_1, I_1 – phase electromotive force (EMF) and the current; $K_H = \frac{E_1}{U_1}$ – the coefficient; U_1 – phase voltage; $K_ф$ – the coefficient of the curve shape of the field; $K_{об}$ –armature winding factor of winding; $F_к = \alpha_б B_б A$ – mechanical stress tangent to the circumference of the armature per unit area of the surface, N/m^2; $\alpha_б$ – pole overlap ratio of settlement; $B_б$ - the magnetic induction in the air gap, T; A – linear load of anchor, A/m; n – rotor speed, rev/min.

Taking the value of $K_ф$ = 1.11 (sinusoidal), we wrote the expression for the relative geometric factor:

$$Г'_ф = \frac{Г_ф}{p'} = \frac{5{,}5\cdot 10^3}{к_{об} F_к n}, \frac{m^3}{kVA} \qquad (3)$$

Based on the formula (1) and taking into account the relation (3) we wrote the expression for the relative weight of the generator in the form:

$$m_г = \frac{M_г}{p'} = \frac{7{,}3\cdot 10^4}{\sqrt{p}} Г'_ф = \frac{4\cdot 10^8}{к_{об}\sqrt{p} F_к n} \qquad (4)$$

Formulas (1) and (4) give reliable values of the masses of generators in the power range of 250-1000 kV with rotational speeds of 500 to 3000 rev/min.

The geometrical factor of contactless collector (asynchronous machine) was also considered. During the work of wind-wheel powerplant in the windings of generator armature on the blades occurs EMF with frequency of

$$f_г = \frac{p_г n_г}{60},$$ where $p_г$ – number of pole pairs of the generator; $n_г$ – its speed.

The three-phase currents caused by these EMF create in the rotor' winding of asynchronous machine rotating magnetic flux, which frequency of rotation is equal

$$n_n = \frac{60 f_г}{p},$$ where p is the number of pole pairs of the asynchronous machine.

The rotor itself is rotated by the main wind-wheel with frequency $n_к$ in the direction of rotation of its magnetic flux. Then, the stator's winding of the machine will intersect the magnetic flux with a frequency $n = n_n+n_к$, that causes a variable EMF phase value which is equal to

$$E_1 = 4к_ф f w к_{об} Ф, \quad \text{where } f = \frac{pn}{60} = \frac{pn_n}{60} + \frac{pn_к}{60} = f_г + f_к,$$

w – the number of phase windings; $Ф_м$ – amplitude of the magnetic flux in the air gap, $f_г$ and $f_к$ – EMF frequency components caused by the rotation of the main and additional wind-wheels.

Nominal capacity of asynchronous machine:

$$P^` = m_1 E_{1г} I_1 + m_2 E_{1к} I_1 = P^`_г + P^`_к$$

has two components, respectively to the frequencies $f_г$ and $f_к$ with $P^`_г >> P^`_к$. Taking into account the fact that

$$Ф_м = α_г τ l B_б; \qquad τ = \frac{πB}{2p}; \qquad I_1 = \frac{πDA}{2m_1 w},$$

where τ – pole pitch; l – length of the stator, we get:

$$P^` = 0{,}164 к_ф к_{об} (D^2 l) F_к (n_n + n_к),$$

whence the ratio to calculate the geometric factor will be:

$$Г_ф = D^2 l = \frac{6{,}1 \cdot 10^3 p^`}{к_ф к_{об} F_к (n_n + n_к)} = \frac{5{,}5 \cdot 10^3 p^`}{к_{об} F_к (n_n + n_к)} \tag{5}$$

When wind-wheel powerplant is working on net output, the frequency f of the output voltage of the asynchronous machine has to be equal to 50 Hz, and must satisfy the relation

$$n_n + n_к = \frac{60f}{p} = \frac{3000}{p} = \text{const}.$$

The weight of asynchronous machine in the power range of 315-1000 kW with frequency from 750 to 1500 rev/min is suggested to calculate by formula:

$$M_a = \frac{5{,}8 \cdot 10^4}{\sqrt{p}} (D^2 l). \tag{6}$$

Accordingly, the relative weight will be:

$$m_a = \frac{M_a}{p^`} = \frac{3{,}2 \cdot 10^8}{к_{об} \sqrt{p} F_к (n_n + n_к)}, \frac{кг}{кВт}. \tag{7}$$

Mass-dimensional characteristics of three-bladed wind-driven powerplants with power P = 750 kW at a frequency of rotation of the main propeller $n_к$ = 31.5 / min were calculated. The synchronous salient-pole generator is mounted in rotating head (scheme on fig. 1, a), the frequency of the output voltage of generator is f = 50 Hz. According to the scheme on fig. 1, a, generator must be made with the number of pairs of poles equal to $p = \frac{60f}{n_к} = \frac{60\cdot 50}{31,5} = 100$.

Assume that $\alpha_б$ = 0,75; $B_б$ = 0,9 T; A = $5\cdot 10^4$ A/m, then $F_к$ = 0,75·0,9·5·104=3,4·104 N/m2.

The relative geometric factor is equal to

$$Г_ф^{`} = \frac{5,5\cdot 10^3}{0,92\cdot 3,4\cdot 10^4\cdot 31,5} = 5,6\cdot 10^{-3}\,\frac{м^3}{кВА} \text{ as } к_{об} = 0,92,$$

the relative weight is equal to $m_г = \frac{7,3\cdot 10^4\cdot 5,6\cdot 10^{-3}}{\sqrt{100}} = 41\,\frac{кг}{кВА}$, the total weight of the generator is equal to $М_г = m_г \cdot P = 41\cdot 750 = 30750\ kg = 30,75$ t.

In the scheme on fig. 1, b, the generator with power P = 750 kW is also used, but with a frequency n = 1000 rev/min, that requires the usage of a gearbox with speed ratio $i = \frac{1000}{31,5} = 31,75$. It is obvious that the multiplier must be two-staged. For constructions with cylindrical gearwheels for power comparable to the power of the selected generator, the relative weight of the gear $m_р$ is 16kg/kW [3], and the mass

$$М_р = m_р \cdot P = 16\cdot 750 = 12000\ kg = 12\ t.$$

Regarding the generator accept that $\alpha_б$ = 0,75; $B_б$ = 0,9 T; A = $5,5\cdot 10^4$ A / m, then

$$F_к = 0,75\cdot 0,9\cdot 5,2\cdot 10^4 = 3,5\cdot 10^4\ ^{N}/_{m^2}.$$

Relative geometric factor is

$$Г_ф^{`} = \frac{5,5\cdot 10^3}{0,9\cdot 3,5\cdot 10^4\cdot 1000} = 1,75\cdot 10^{-4}\ m^3/kW,$$

the relative weight is

$$т_г = \frac{7,3\cdot 10^4\cdot 1,75\cdot 10^{-4}}{\sqrt{3}} = 7,4\ kg/kW,$$

the mass of the generator is $М_г = 750\cdot 7,4 = 5500kg = 5,5t$, the mass of the generator and the gear is $M = М_г + М_р = 5,5 + 12 = 17,5$ t.

When the wind-wheel is made according to the scheme (fig. 1, c), three generators are placed on the blades, each with power $P = 250$ kVA and frequency of rotation $п_г = 500$ rev / min (p = 6).

For such generator $F_к = \alpha_б\cdot B_б\cdot A = 0,75\cdot 0,82\cdot 4,3\cdot 10^4 = 2,65\cdot 10^4$ N/m^2,

$$Г_ф^{`} = \frac{5,5\cdot 10^3}{К_{об}\cdot F_к\cdot п_г} = \frac{5,5\cdot 10^3}{0,9\cdot 2,65\cdot 10^4\cdot 500} = 4,6\cdot 10^{-4}\ m^3/kVA,$$

for three generators $3\cdot Г_ф^{`} = 3\cdot 4,6\cdot 10^{-4} = 1,38\cdot 10^{-3}$ m$^3$/kVA, the relative mass of generator is $т_г = \frac{7,3\cdot 10^4}{\sqrt{p}}\cdot Г_ф^{`} = \frac{7,3\cdot 10^4\cdot 4,6\cdot 10^{-4}}{\sqrt{6}} = 13,7$ kg/kVA, weight of three generators is $3\cdot М_г = 3\cdot 13,7\cdot 250 = 10275$ t.

Since the generators are usually low-voltage ($U_н = 0,69$ kV) then a step-up transformer (0,69/10,5 kV) with a nominal capacity of 750 kW is placed in the head.

The relative weight of such transformer is approximately 4.7 kg/kVA, and the total mass is $М_{тр} = 4,7\cdot 750 = 3525$ kg or 3,525 t.

Weight generators and transformer is $M = М_г + М_{тр} = 10,275 + 3,525 = 13,8$ t. Instead of the power transformer the asynchronous machine with phase-wound rotor is used to increase the voltage in the circuit (fig. 1, c). It also serves as a non-contact current collector. Power of machine is 750 kW, synchronous speed $п_г = 1000$ rev/min (p = 3). Assume that $B_б = 0,86$ T; $A = 5\cdot 10^4$ A/m, then $F_к = 0,637\cdot 0,86\cdot 5\cdot 10^4 = 2,75\cdot 10^4$ N/m^2, relative dimensional factor

$$Г_ф^{`} = \frac{5,5\cdot 10^3}{0,9\cdot 2,75\cdot 10^4\cdot 1000} = 2,22\cdot 10^{-4}\ m^3/kW,$$

the relative weight is $\tau_a = \frac{3{,}2\cdot 10^8}{0{,}9\cdot\sqrt{3}\cdot 2{,}75\cdot 10^4\cdot 1000} = 7{,}5$ kg/kW, the weight is $M_a = 7{,}5\cdot 750 = 5625кг = 5{,}625$ t.

The total weight of the generator and the asynchronous machine is $M = M_г + M_a = 10{,}275 + 5{,}625 = 15{,}9$ t.

Assume that in the scheme (fig. 1, d) the power of wind-driven power plants is redistributed equally between generators on the blades and the generator on the axis of the windwheel. Then, for our example, the power of generator on the axis is $P_1 = 375$ kVA, and a power of one generator on the blades is $P_2 = 125$ kVA. The rated speed of the generator on the axis is $п_1 = 1000$ rev/min, and for the generator on the blades – $п_2 = 500$ rev/min.

Assume that $\alpha_б = 0{,}75$; $B_б = 0{,}86$ T; $A = 5\cdot 10^4$ A/m; $К_{об} = 0{,}9$ for the generator, then we obtain $F_к = 0{,}75\cdot 0{,}86\cdot 5\cdot 10^4 = 3{,}2\cdot 10^4$ N/m^2.

The relative dimensional factor

$$Г'_ф = \frac{5{,}5\cdot 10^3}{0{,}9\cdot 3{,}2\cdot 10^4\cdot 1000} = 1{,}9\cdot 10^{-4} \text{ m3/kVA},$$

the relative weight of generator is $\tau_{г1} = \frac{7{,}3\cdot 10^4\cdot 1{,}9\cdot 10^{-4}}{\sqrt{3}} = 8$ kg/kVA, the weight is $M_{г1} = 8\cdot 3{,}75 = 3000$kg or 3 t, the weight of gear is $M_р = \tau_р\cdot P_1 = 10\cdot 3{,}75 = 3750$ kg or 3,75 t. Here $\tau_р = 10$ kg/kW – the relative weight of the gear.

The weight of the generator and gear is $M_1 = M_г + M_р = 3 + 3{,}75 = 6{,}75$ t.

Assume that $\alpha_б = 0{,}75$; $B_б = 0{,}82$ T; $A = 3{,}8\cdot 10^4$ A/m; $К_{об} = 0{,}9$ for generator on blades, then we obtain $F_к = 0{,}75\cdot 0{,}82\cdot 3{,}8\cdot 10^4 = 2{,}3\cdot 10^4$ N/m^2.

The relative dimensional factor $Г'_ф = \frac{5{,}5\cdot 10^3}{0{,}9\cdot 2{,}3\cdot 10^4\cdot 500} = 5{,}3\cdot 10^{-4}$ m^3/kVA; relative weight $\tau_{г2} = \frac{7{,}3\cdot 10^4\cdot 5{,}3\cdot 10^{-4}}{\sqrt{6}} = 15{,}8$ kg / KVA; generator's weight is $M_{г2} = 15{,}8\cdot 125 = 1974кг = 1{,}97$ t; the weight of three generators is $3\cdot M_{г2} = 3\cdot 1{,}97 = 5{,}9$ t.

The total mass is $M = M_{г1} + 3\cdot M_{г2} = 6{,}75 + 5{,}9 = 12{,}65$ t.

If the asynchronous machine is used as a contactless current collector, it is necessary to take into account its mass $M_a = \tau_a\cdot P_1 = 7{,}5\cdot 375 = 2800$ kg or 2,8 t. Then the mass of wind-driven powerplant' elements will be equal to $M_в = 12{,}65 + 2{,}8 = 15{,}45$ t.

In the scheme "Multibrid" on fig. 1, b; a single-stage multiplier with gear ratio i = 6,3 is required. Then rated speed of the generator's rotation should be $п_г = i\cdot п_г = 6{,}3\cdot 31{,}5 = 198{,}45$ rev/min. Assume that $п_г = 200$ rev/min. The number of pole pairs of the generator is $p = \frac{60\cdot f}{п_г} = \frac{60\cdot 50}{200} = 15$. Assume that : $\alpha_б = 0{,}75$; $B_б = 0{,}9$ T; $A = 5\cdot 10^4$ A/m, then $F_к = 0{,}75\cdot 0{,}9\cdot 5\cdot 10^4 = 3{,}37\cdot 10^4$ N/m^2.

The relative dimensional factor is $Г'_ф = \frac{5{,}5\cdot 10^3}{0{,}92\cdot 3{,}37\cdot 10^4\cdot 200} = 8{,}87\cdot 10^{-4}$ m^3/kVA; relative weight is $\tau_г = \frac{7{,}3\cdot 10^4\cdot 8{,}87\cdot 10^{-4}}{\sqrt{15}} = 16{,}7$ kg/kVA; generator's weight is $M_г = 16{,}7\cdot 750 = 12530кг = 12{,}5$ t; the weight of the gear will be about half the amount calculated above because it's single-stage and will be equal to $M_р = 6$ t. Total weight is $M = M_г + M_р = 12{,}5 + 6 = 18{,}5$ t.

Let's consider the question of the efficiency of wind-driven power plants. The coefficient of efficiency of the powerplant (efficiency), shown on fig. 1, a, is calculated according to the formula: $\eta_1 = \eta_к\cdot\eta_г$ where $\eta_к$ – efficiency of wind turbine (propeller): assume that $\eta_к = 0{,}45$ is achievable for the three-bladed windwheels; $\eta_г$ – efficiency of power generator: for low-speed generator with power $S_н = 750$ kVA, $\eta_г = 0{,}95$.

Total efficiency is $\eta_1 = 0{,}45\cdot 0{,}95 = 0{,}427$.

For powerplant on fig. 1, b, the formula for calculating efficiency is $\eta_1 = \eta_к\cdot\eta_р\cdot\eta_г$, where $\eta_р$ – efficiency of reducer. For accuracy class 2 of gear processing, efficiency for one-stage gearbox is 0,98, for a two-stage gearbox – $\eta_р = 0{,}98^2 = 0{,}96$.

For high-speed oscillator is $\eta_г = 0{,}96$, the net efficiency is $\eta_2 = 0{,}45\cdot 0{,}96\cdot 0{,}96 = 0{,}415$.

For the scheme "Multibrid" with one-stage gearbox and low-speed generator – $\eta_3 = 0{,}45\cdot 0{,}98\cdot 0{,}95 = 0{,}419$.

For the powerplant with generators on the blades (fig. 1, b) efficiency is $\eta_4 = \eta_к\cdot\eta_д\cdot\eta_г$, where $\eta_д$ – efficiency of additional windwheels; according to the literature efficiency of $\eta_д = 0{,}85$ is achievable; efficiency of generator with comparatively low power is $\eta_г = 0{,}94$, net efficiency is $\eta_4 = 0{,}45\cdot 0{,}85\cdot 0{,}94 = 0{,}36$. Considering that efficiency of contact collector is $\eta_{кт} = 0{,}99$, then $\eta'_4 = 0{,}36\cdot 0{,}99 = 0{,}356$.

In the schemes described above, while working on a net output, a supply set-up transformer is generally used in generators, which efficiency for power $S_н = 750$ kVA is equal to $\eta_{тр} = 0{,}97$, which we consider calculating the efficiency of powerstation.

For powerplant on the scheme on fig. 1, d, efficiency is equal to $\eta_5 = \eta_к \cdot \eta_д \cdot \eta_г \cdot \eta_а$, where $\eta_а$ – efficiency of asynchronous machine. Let's consider that $\eta_а = 0{,}96$; $\eta_г = 0{,}94$, efficiency $\eta_5 = 0{,}45 \cdot 0{,}85 \cdot 0{,}94 \cdot 0{,}96 = 0{,}345$.

For the combined scheme (fig. 1, e), with the same power of three generators on blades and a generator on the axis of windwheel efficiency is calculated as the arithmetic average of efficiencies of individual units. On blades: $\eta_6' = \eta_к \cdot \eta_д \cdot \eta_{г1} \cdot \eta_а = 0{,}45 \cdot 0{,}85 \cdot 0{,}92 \cdot 0{,}95 = 0{,}33$; on the axis of propeller: $\eta_6'' = \eta_к \cdot \eta_д \cdot \eta_{г2} = 0{,}45 \cdot 0{,}96 \cdot 0{,}94 = 0{,}4$.

For powers considered in this example, принято $\eta_{г1} = 0{,}92$ (on blades); $\eta_{г2} = 0{,}94$ (on the axis), $\eta_а = 0{,}95$ were accepted. Overall efficiency is $\eta_6 = 0{,}5 \cdot (\eta_6' \cdot \eta_6'') = 0{,}5 \cdot (0{,}33 \cdot 0{,}4) = 0{,}368$. The results of the calculations are presented in the table.

Table 1

The results of calculation of wind-driven powerplants' characteristics

№	Structural scheme of wind-driven powerplant	$Г'_Ф$, m^3 / KW	$Г_Ф$, m^3	$m_г$, kg/kVA	$M_г$, T	$M_р$, T	M, T	η, %	Note
1	Direct-drive scheme (Fig. 1, a)	$5{,}6 \times 10^{-3}$	4,2	41	30,75	–	30,75	42,7	–
2	Geared scheme (Fig. 1, b)	$1{,}75 \times 10^{-4}$	0,13	7,4	5,5	12	17,5	41,5	–
3	Scheme with gear "Multbrid" (Fig. 1, b)	$8{,}9 \times 10^{-4}$	0,67	16,7	12,5	6	18,5	41,9	–
4	Scheme with generators on blades (Fig. 1, c)	$1{,}38 \times 10^{-3}$	0,345	13,7	3,425	–	10,275	36,0	–
5	Scheme with contactless current collectors (Fig. 1, d)	$1{,}38 \times 10^{-3}$ $2{,}22 \times 10^{-4}$	0,345 0,166	13,7 7,5	3,425 5,625	– –	10,275+ 5,625=15,9	34,5	Generators Current collector
6	Combined scheme (Fig. 1, e)	$1{,}9 \times 10^{-4}$ $5{,}3 \times 10^{-4}$	0,071 0,198	8,0 15,8	3,0 1,97	3,75 –	6,75+3x1,97 =12,65	36,8	Generators: on the axis on the blades

Findings

1. The wind-driven powerplant constructed according to direct-drive scheme has maximum weight and it also provides the highest efficiency.

2. Schemes with the gearbox and generator on the axis of windwheel allow reducing the mass of wind-driven powerplant two times compared to direct-drive scheme at somewhat smaller value of efficiency.

3. The wind-driven powerplant with generators on the blades of the windwheel has the smallest weight, but its efficiency is considerably smaller than efficiency of the direct-drive and geared schemes.

4. The scheme with contactless current collector will improve the reliability of the wind-driven powerplant and the output voltage while decreasing the weight of its elements in comparison with geared scheme.

5. The combined scheme of wind-driven powerplant allows to reduce the weight significantly in comparison with geared scheme and also receive two independent power sources.

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