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EFFICIENCY OF ELECTROMECHANICAL CONVERSION SYSTEMS OF WIND TURBINES WITH AERODYNAMIC MULTIPLICATION

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In this article, we have considered the state of development of high-power horizontal wind turbines. The most common wind turbines for operation with variable wind flow speed usually include a frequency converter to ensure the compatibility of generator with network. It leads to decrease in the efficiency of wind energy conversion system, while the use of direct connection of the generator to the axis of wind wheel leads to a significant increase in the weight and cost of the generator. The wind turbine with aerodynamic multiplication is an alternative to such systems. Its prototype with 750 kW power is manufactured and studied in Ukraine. This wind energy conversion system with the synchronous or induction generators offers the property to generate energy under optimal condition with invariable rotational speed of generator rotor within the wide range of variable speed of wind flow. In this case, it is not necessary to apply the frequency converter that contributes to increasing the efficiency and reducing the cost of wind turbine. As shown, the relative performances of mass, cost and efficiency of generators in proposed system comparatively to conventional one depend on the multiplication factor (i.e. ratio of the rotational speeds of wind turbine and generator). When the power of wind turbines is from 750 to 2500 kW, the multiplication factor is within the limits of 10.72 to 4.75. The theoretical and experimental study shows that the wind turbines with aerodynamic multiplication can be competitive as compared to conventional horizontal wind turbines. This article is aimed to comparative analysis of the quantitative and qualitative characteristics of the equipment used in high-power horizontal wind turbines with direct connection of generators to the axis of wind turbine and in wind turbines with aerodynamic multiplication. References 27, tables 1, figures 6.

Key words: wind turbine, wind energy conversion system, generator, wind wheel, aerodynamic multiplication, frequency converter.

Introduction. The crisis arisen in recent years in the power energy section shows that some countries having lack of energy resources are vulnerable in a sense of misbalanced logistics of power supply. This situation along with environmental problems intensifies the need to develop generation from renewable energy sources such as wind, solar etc.

It should be noted that wind energy possesses the highest potential and is universal. In 2019 the amount of the electricity generated in the world by wind turbines is 52% of total power generation by operated renewable energy sources [1]. Up to date a number of leading foreign countries (Denmark, Germany, USA, China etc.) produce commercially 500÷4500 kW wind turbines. The unique wind turbine with capacity up to 10 MW was put into operation in 2015 [1]. At present the projects with increased power (up to 20 MW) are developed [2, 3].

The competitive firms in the field of wind turbines create the variety of technical solutions. As noted in [1], about 15% of known technical solutions have the industrial realization. The search for rational solutions for increasing the efficiency of wind turbines and above all, for reducing the price-efficiency ratio carries on.

The state of development of wind turbines. There is a variety of technical solutions to realize wind energy conversion system (WECS) in wind turbines. From the standpoint of design type, there are two main types of wind turbines: with horizontal axis of rotation and vertical one. The horizontal axis wind turbines are currently the most extensively used turbines to generate electricity on industrial scale [1–8].

The structure, constructive and schematic features of the wind turbine conversion system depend on its power, designedly permissible wind speed and height of wind wheel arrangement as well as distance of the connection point to power system or consumer. In turn, the wind turbine power depends on the size of the

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blades (i.e. wind wheel diameter), structurally permissible wind speed and mast height, which determine the area, uniformity and kinetic energy of wind flow. The maximal power of wind turbine is determined at wind speed about 12 m/s. If the specified speed of wind flow exceeds 12 m/s, the useful power is stabilized by turning the wind turbine blades. When the wind flow speed is less than 12 m/s, the angle of wind turbine arrangement remains invariable, and the useful power varies cubed proportionality to the wind flow speed.

Depending on the purpose and power, the wind turbines can operate with invariable and variable rotor speed (effective use of wind flow kinetic energy).

Depending on the connection of wind turbine axis to electric generators, there are direct (stiff) connection and connection via a step-up gearbox (multiplier). The stage number of the gearbox depends on the variation range of rotational speed of the wind turbine and generator. The presence of gearbox enables to reduce the mass of generator by increasing the rotational speed; however, it leads to increase of the total mass, operating costs for maintenance and to decrease in the efficiency of WECS. According to [8], the three-stage gearbox for 1000 kW wind turbine has efficiency of 0.95, which significantly reduces the effectiveness of WECS.

As generators, the squirrel-cage or wound rotor induction generators as well as synch generators with permanent magnets and/or excitation windings are usually used in WECS. Particularly in high-power wind turbines (600÷4500 kW), developed by Enercon GmbH, the gearbox-less WECS is used with low-speed generators of 38/22/12 rpm rotor speed for operation under variable wind flow [9]. It should be noted here that the use of slow-speed generators has significant disadvantages. First of all it is the large weight of the generator, which complicates the mounting works especially for high-power wind turbines. Secondly, it is the need to use frequency converters at full power of wind turbines. This leads to a significant increase in the cost of wind turbines.

The power IGBT modules rated 1700 V or more volts and current up to 2000 A are the main component base of frequency converters. The operating voltage for generators up to 2500 kW is 660 V, which allows the use of 1700 V IGBT modules in large scale. For increased power wind turbines, including offshore ones, the voltage increases to 3 kV using special converter circuits in order to reduce losses [7, 10].

Ukraine has all the necessary features for the development of wind energy. Its substantiated potential is at least 16 GW [7, 11]. The development of wind energy is realized by the state program for the construction of wind-power station. As of 2002, the total capacity of wind farms (WF) in Ukraine constitutes 44 MW. These are mainly low-power (100 kW) wind farms constructed according to the documentation of Kenetech Windpower (USA). The Yuzhnoye Design Office (Dnipro, Ukraine) created 200–250 kW domestic plant ABE-250C; on its basis, the pilot Vostochno-Krymskaya WF and Adzhigolskaya WF (Nikolaev region, Ukraine) were built. The feature of these wind turbines consists in the presence of synch generator supplying an industrial network [9].

As of 2019, the 8 powerful wind farms operate in Ukraine; their total capacity comprises 1 GW. 200 MW Prymorska WF and 110 MW Sivash WF are the most powerful wind farms.

Almost a third of the commissioned capacities are in the Zaporozhye region, where 200 MW Botiivska Wind Farm (one of the largest station in Ukraine) is located. The domestic company DTEK Wind Power LLC carried out its implementation and announced a broad program for the construction of a number of wind farms with 14 GW total capacity. The first stage of 90 MW Botiivska WF from 200 MW planned was put into operation in 2012, the second stage was in 2014. The wind farm contains V112-30 type turbines with gearbox and generator with 3 MW single-unit power produced by the Vestas Central Europe.

The search for ways to improve the efficiency of wind turbines led to the idea to create a wind turbine with so-called aerodynamic multiplication (WTAM). This idea is represented in a number of foreign patents for various design and technical solutions [12–15, et al] as well as theoretical studies of similar wind turbines with horizontal and vertical axis of rotation [16, 17], but there is no information on pilot operation of relatively powerful wind turbines of this type. As the main idea of WECS, the turbine generators (so-called secondary turbines) are arranged on the fixed parts of the blades of main wind wheel. Such technical solution provides aerodynamic multiplication to increase the rotational speed of turbine generators and allows supplying the electricity to a network at constant frequency at variable speed of main wind wheel without frequency converter. The distinctive features of this solution as compared with classical design enable to simplify significantly WECS and reduce the cost of wind turbine.

At the end of 2002 the industrial and financial group "Concord" (Dnipro, Ukraine) headed by Ph.D. N.S. Golubenko entered on a project to create the fundamentally new gearbox-less wind turbine of TG-750 type. The Ukrainian patent No. 49970 (application No. 2000031794 dated 2003-03-30) protects its main technical solutions [9, 18, 19, et al]. The development of more powerful WTAM and bringing them to mass production require further experimental and theoretical study of complex multichannel nonlinear conversion system.

The aim of the paper is to carry out the comparative analysis of the quantitative and qualitative characteristics of the equipment used in high-power horizontal axis wind turbines with direct connection of generators to wind turbine axis and in wind turbines with aerodynamic multiplication.

Main results of investigation.

1) Features of wind turbine with aerodynamic multiplication. The sketch of WTAM and turbine generator is shown in fig. 1, *a* and *b*, respectively. Fig 1 presents the blades of main (primary) wind wheel (1), secondary wind turbine (2), generators (3), Nacelle (4), support (tower) (5).

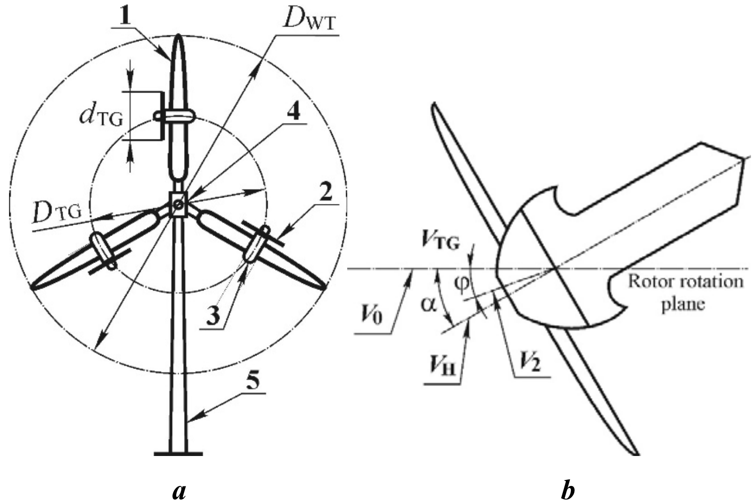


Fig. 1

The generators marked by 3 are arranged on the blades (1) of the main wind wheel at the distance $D_{TG}/2$ from the axis of rotation. Wind turbines 2 are installed on the shafts of the generators. The generators are usually arranged on the fixed parts of the blades. The distance ($D_{TG}/2$) is typically from 0.4 to 0.6 of blade length depending on wind turbine power. The blades are attached to the hub jointed by bearing unit to nacelle 4. The nacelle contains the current collector and hydraulic system for turning the blades, which enable to orient facing to the wind due to electric drives controlled by the control system located at the basement of tower 5.

The feature of this WECS consists in the presence of three channels with two-stage conversion of wind energy. The control of this system is realized in two zones. In the first working zone, the regulation is carried out at a fixed angle of installation of main wind wheel blades. In the second zone, where it is necessary to limit the power taken from wind flow, the regulation is performed by changing the angle of blade arrangement.

In order to regulate this WECS, the stabilization of wind turbines speed can be used by means of controlling the torques of generators.

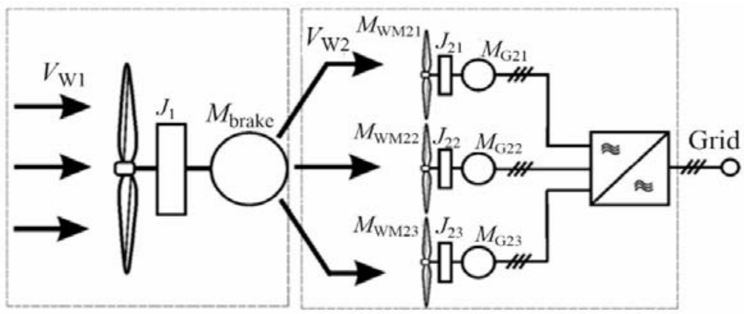


Fig. 2

Fig. 2 shows the functional diagram of WTAM to illustrate the process of wind energy conversion.

The primary wind flow V_{W1} interacts with main wind wheel. The flow transfers the part of kinetic energy to it and drives it to rotate with angular velocity ω_1. The turbines of generators, rotating together with main wind wheel, run orthogonally to the main wind flow at speed:

$$V_{TG2} = \omega_1 \cdot \frac{D_{TG1}}{2}. \qquad (1)$$

The speed of wind flow oncoming on turbines is greater by several fold than the main flow, and the turbines with generators start to rotate with frequency ω_2.

Since the turbine axis is positioned at angle α to the plane of rotation of main wind wheel (see fig. 1, b), the resulting speed and, accordingly, the angle of the flow running on turbine are determined by the following expressions [18]:

$$V_F = \sqrt{V_{TG}^2 + V_{W1}^2}; \quad \varphi = arctg\left(\frac{V_{W1}}{V_{TG}}\right). \qquad (2)$$

The projection of flow running on turbine is equal to

$$V_{W2} = V_F \cdot cos(\alpha - \varphi). \tag{3}$$

It causes the torque:

$$M_{WM_{\mathrm{n}}} = \frac{\pi\rho V_{W1}^3 R_{TG}^2 C_p(Z_2)}{2\omega_{2\mathrm{n}}}. \tag{4}$$

The dynamics of the aeromechanical system is described by the following motion equations (see fig. 2):

$$j_1 \frac{d\omega_1}{dt} = M_{WM}(V_{W1}, \omega_1) - M_{\mathrm{brake}}(P_{W1}, \omega_1) - M_{ML}(\omega_1). \tag{5}$$

$$j_{2\mathrm{n}} \frac{d\omega_{2\mathrm{n}}}{dt} = M_{WML_{\mathrm{n}}}(V_{W2}, \alpha, \omega_{2\mathrm{n}}) - M_{\mathrm{G_n}} - M_{ML_{2\mathrm{n}}}(\omega_{2\mathrm{n}}). \tag{6}$$

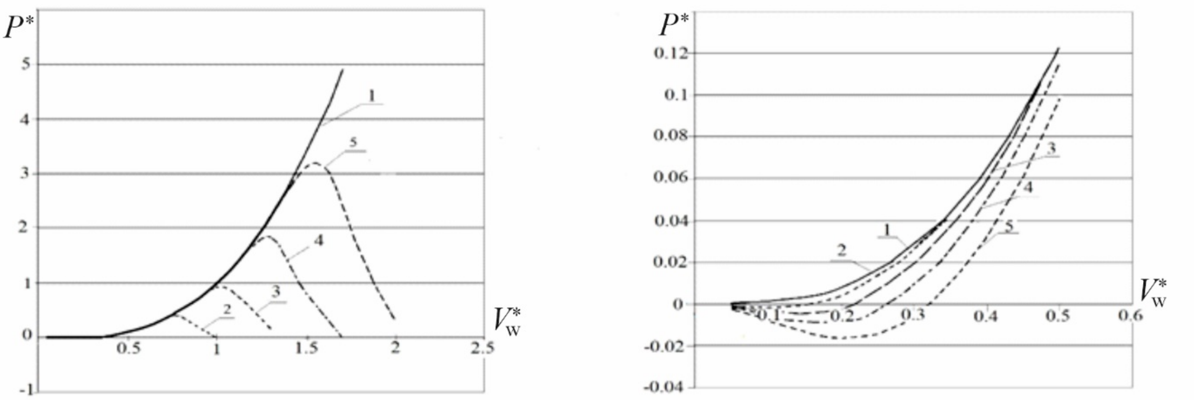
where number *n* (from 1 to 3) in the index indicates the number of power conversion channel; j_1, j_{2n} are the moments of inertia of main wind wheel with wind generators and the wind generator with turbines, respectively; M_{brake} is the total braking torque to be caused by the power take-off by the wind turbines; $M_{\mathrm{ML}}(\omega_1)$, $M_{\mathrm{ML}2n}(\omega_2)$ are the moments of mechanical losses; M_{WM} is the torque of braking the main wind wheel determined by next expression:

$$M_{WM} = \frac{\rho S_{WM} V_{W1} c_P(z_1)}{2\omega_1}.$$

When synch generators are connected to network without converter, they rotate at constant speed due to synchronizing torques, and the frequency of generators is equal to network frequency.

2) Simulation of WTAM conversion systems. The electromechanical conversion system of WTAM was simulated by Simulink software according to expressions (1)–(5), taking into account the balance of wind turbine power and load [20, 26]. The model is constructed with the following assumptions. We neglect the friction moments in the bearings of the main wind wheel and turbines. We also neglect the influence of internal resistances of generators on output voltage due to availability of voltage stabilization at inverter input. The ripples caused by the circuits of rectifiers, inverters are ignored too. The conversion coefficient of wind flow is considered as a constant value. We also assume that the average power of generators is proportional to rotational speed and the total generated power is consumed by a network. In computing the static characteristics, the average generation power is calculated for the period of main wind wheel rotation.

Fig. 3 shows the computational results for electromechanical conversion system WTAM of TG-750 type, namely: the maximum relative power as a function of the relative speed of wind flow as general view (*a*) and in initial section (*b*). The maximum relative power P^* (1), P^* at $\omega_{\text{ст}} = 300$ prm (2), P^* at $\omega_{\text{ст}} = 400$ prm (3), P^* at $\omega_{\text{ст}} = 500$ prm (4), P^* at $\omega_{\text{ст}} = 600$ prm (5) at $C_{\mathrm{p}} = 0{,}48$ are presented in fig. 3.



a ***b***

Fig. 3

The dependencies in fig. 3 show that when the wind flow speed are less than 5–6 m/s (typical for a significant part of time in many regions of Ukraine), the deviation of rated capacity from maximum value is 3–5%. This leads to the reduction of operating efficiency of wind turbine. To increase the power take-off, it should only be reduced the generator speed by half so that this deviation could be minimal. However, in this case, the frequency and magnitude of generated voltage differ from the frequency and voltage of a network.

For their matching, it is necessary to install a frequency converter with installed power in the range of 10 to 20% of rated power.

At the same time, as follows from fig. 3 a, there is a sufficiently wide range of wind flow speed when the operating condition of wind turbine practically does not differ from the optimal one. Thus the effect of auto-stabilization of this WECS under the maximum power take-off operation is evident. To validate the adequacy of the models, we compared the computed static characteristics with the experimental data obtained by TG-750 installation having СГІ-350 generator [21].

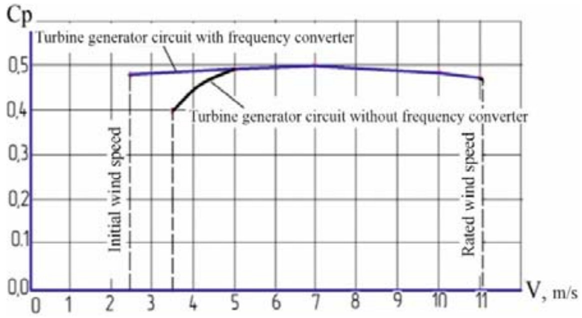


Fig. 4

The dependencies in fig. 4 indicate that the use of frequency converter enables to keep the relative invariability of power factor C_p at V_0 less than 5 m/s and obtain the stable power generation at $V_0 < 3.5$ m/s, i.e. the generation range can be expanded to lower wind flow speed (approximately V_0 = 2.7 m/s) [21].

The comparative analysis of data in fig. 4 (dependencies of main wind wheel efficiency on wind speed for TG-750 typed WTAM), with experimental results confirmed the adequacy of developed model. The error at $V_0 < 5$ m/s does not exceed 10–15% that is explained by the assumptions accepted for simulations.

The creation of pilot plant of TG-750 typed WTAM revealed the fundamental possibility to implement practically the wind turbine of this type. This gives a possibility to start the project for a series of plants with capacity up to 5 MW. The table presents the main technical characteristics of WTAM according to data of Concorde group.

No.	**Parameter**	**Type of wind turbine**			
		TG-750M	**TG-1000**	**TG-2500***	**TG-5000***
1	**Rated capacity, kW**	**750**	**1000**	**2500**	**5000**
2	**Wind speed, m/s**				
	- initial (starting)	2.7	2.7	2.5	2.9
	- rated	10.8	11.9	11.0	12.2
	- maximal operating	25.0	25.0	25.0	25.0
	- ultimate admissible	60.0	60.0	60.0	60.0
3	**Rotor**				
	- diameter, m	58.0	58.0	106.0	124.0
	- number of blades, pcs	3	3	3	3
	- rotational speed, rpm	7.5…27.0	6…28.2	4…15	4…12.9
	- height of rotor axis, m	50.0	50.0	80.0	100.0
4	**Turbine generators**				
	- number, pcs	3	3	3	3
	- number of turbine blades, pcs	6	6	6	6
	- turbine arrangement diameter, m	27.2	27.62	54.0	65.0
	- rated rotational speed of turbines, rpm	375	375	250	150
	Nominal parameters of generators				
	- capacity, kW	250	350	850	1700
	- voltage, V	380	690	690	690
	- frequency, Hz	50	50	50	50

* – project

The circuit containing the frequency converter with grid-controlled inverter was experimentally verified in WTAM of ТГ-750 type.

Due to the synchronizing moments and significant inertial mass of main wind wheel, the control system ensures the stable operation of the generators supplying a network under power balance of the wind flow and electrical load within the wide range of varying speed of wind flow.

3) Selection of electrical equipment depending on WTAM features. In high-power gearbox-less wind turbines the generator play an essential role since its large mass and cost determine in significant degree the energy efficiency of powerful wind turbines. For comparison, let us consider the relationships typical for classical structure of the horizontal axis wind turbine with slow-speed generator and WTAM with the same capacity. As shown in [22], for electrical machines (generators) with similar dimensions at the same current density and electric induction to a first approximation the following relationship is valid:

$$l^4 \equiv \frac{P_{\text{el}}^3}{n}, \qquad (7)$$

where l is the linear dimensions of generators; P_{el} is the electric power; n is the rotational speed of rotor.

Since the mass of the active materials G is proportional to their volume (i.e., l^3), it can be supposed that the losses L and cost C under accepted conditions are proportional to mass G. Then according to [22]

$$\text{G} \equiv \sqrt[4]{\left(\frac{P_{el}}{n}\right)^3}; \quad \text{C} \equiv \sqrt[4]{\left(\frac{P_{el}}{n}\right)^3} \quad \text{L} \equiv \sqrt[4]{\left(\frac{P_{el}}{n}\right)^3}. \qquad (8)$$

Comparing the performances of analogous generators, the total capacity of which is equal to the capacity of single generator and using (8) the relative value of the characteristics are written as:

$$\text{G}^* = \frac{\text{G}_1}{\text{G}_m} \to \text{C}^* = \frac{\text{C}_1}{\text{C}_m} \to \text{L}^* = \frac{\text{L}_1}{\text{L}_m} = = \frac{\sqrt[4]{\left(\frac{P_{el}}{n}\right)^3}}{m \cdot \sqrt[4]{\frac{P_{\text{el}}^3}{m^3 n_m^3}}} = \sqrt[4]{\frac{n_m^3}{m n_1^3}} = \sqrt[4]{\frac{K_{AM}^3}{3}}. \qquad (9)$$

where m = 3 is the number of generators; n_m is their rotational speed; n_1 is the rotational speed of main wind wheel; K_{AM} is the aerodynamic multiplication ratio, expressed as:

$$K_{AM} = \frac{n_m}{n_1},$$

where index m refers to the performances of WTAM generators, index 1 corresponds to the performances of gearbox-less wind turbine generator connected to wind wheel shaft.

Fig. 5 shows the dependences of G*, C*, L* as functions of aerodynamic multiplication ratio K_{AM}: curve 1 is plotted according to (9); dotted curve 2 is constructed for WTAM project (see table).

So the two ways are possible to increase K_{AM} and, as a result, to reduce the mass and cost of WTAM generators. The first is to decrease the rotational speed of main wind wheel ω_1, but in this case, its diameter increases in proportion to the square root of the degree in decrease of ω_1. Note that the decrease of ω_1 for generator located on the wind wheel shaft leads to the increase in its mass. The second way is to increase in the rotational speed of turbine generators ω_2. However, in this case, to keep generated frequency, it is necessary to increase the number of pole pairs of generators that leads to increase in their mass. Then the diameter of turbine reduces inversely.

The choice of K_{AM} is based on the results of the technical and economic comparison of options. When K_{AM} varies in the range from 11.62 to 34.09, the performances G*; C*; L* change from 4.78 to 10.72. This corresponds to the power range from 5000 to 750 kW.

Thus the WTAM conversion system has significant advantages in terms of the main technical and economic performances of generators in comparison with classical gearbox-less WECS.

Relations (9) show a general trend in the use of aerodynamic multiplication, since under increasing capacity for various reasons the similarity of dimensions and other performances is violated.

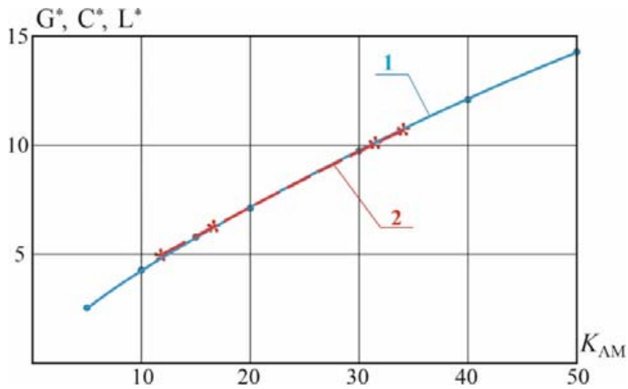


Fig. 5

The losses and thermal behavior of generator, determined by the magnetic flux density in airgap and linear load play the main role in the similarity deviation. The product of these values is proportional to the tangential force F_{k} acting on the surface of rotor (stator) [22]. This fact links the value of moment M of generator with rotor dimensions by [22]:

$$M = \frac{P_e}{n} = \frac{\pi}{2} d_r^2 l_r^2 F_k . \quad (10)$$

where d_r and l_r are the diameter and length of rotor, respectively.

As following from (10): $d_r^2 l_r^2 = \frac{2}{\pi} \frac{M}{F_k}$.

The relation (10) permits to vary the diameter and length of rotor for a certain generator within the limits determined by the ratio of given moments to acceptable tangential force in the construction. This circumstance allows to optimize parameters G*; C*; L* depending on capacity P_{el},. This can violate the numerical value, but not a general trend.

For wind turbines generating power directly into a network, the operating frequency of generator is equal to commercial frequency – 50 (60) Hz.

Under increasing the power of wind turbine, the power of generators increases and the mass of the generator, which affects the mass of the construction and the cost of installation work, present the great restriction.

The generator mass decreases at higher frequency. Under condition of keeping the permissible iron losses, the magnetic flux density should be varied by the following relation:

$$B \equiv 1/f^k ,$$

where k depends on the characteristics of used iron.

In accordance with [22] the performance G for k = 0.65 at constant current density and $n = f$ is determined by

$$G = \frac{\sqrt[4]{P_e^3}}{f^{0.27}} . \quad (11)$$

Therefore, at the same capacity and changing the frequency from 50 to 200 Hz, the mass of generators decreases by 30–40% at the same rotational speed.

The СГІ-350-0,69-50 inductor generator is used in ТГ-750 typed WTAM.

The calculation performed by prof. V.D. Lushchik [23] shows that the increase in frequency of СГІ-350 inductor generator to 125 Hz leads to the decrease in the mass of its active part by factor of 1.66 when the efficiency increases by 3.5%. This permits, at the same mass of generators, to increase their power up to 450 kW. The possibility to create asynchronous-synchronous cascade generators with rated speed of 500/ 300/250/150/100 rpm at frequency of 50 Hz is grounded in [23]. The use of such generators enables to ensure the reduction of weight, depending on capacity, up to 40% compared to induction generators. In addition, this allows solving the problem of starting the wind turbine generator in the mode of induction motor using back-to-back converter depending on electrical circuit (fig. 5).

The presence of a contact-less exciter, due to the combination of stator winding with excitation winding, enables to optimize the voltage of generated power without additional means in basic circuit.

The current trend in the use of permanent magnet synch generators, due to their high efficiency, is correct only for certain design versions. The experimental findings in [24] show that 500 kW synch generators with permanent magnets operating under conditions comparable to the operating conditions of wind turbines, have the same efficiency as squirrel cage induction motor (0.945 at the same speed of 5880 rpm. The weight of synch generator is 7% more than for induction generator. The synch generator with permanent magnets of the same capacity with transverse field at n = 2300 rpm has the efficiency of 0.965 at half weight (400 kg). Note that in this case the use of oil cooling is important for reducing the mass. The developers note that the significant disadvantage of permanent magnet synch generators consists in increased cost and the dependence of the characteristics of permanent magnets on temperature at emergency overloads. The presence of permanent excitation of rotating generators creates the emergency fire hazard at short circuit in stator windings, which can take place until full-stop of wind turbine. This should also be taken into account when designing the wind turbines and generators.

Fig. 6 gives the basic circuits of WTAM for off-line operation with high-frequency generator [27].

Since the generators are located on the blades, the efficiency of WTAM depends significantly on the arrangement of rectifiers (or inverter) as well as their connection circuit (parallel or series). Using 1000 kW wind turbine as an example, the possibility to increase the efficiency by 4.9% is shown because of reducing the losses in connecting cables, if the energy is transmitted by direct current, with simultaneous reduction in cable consumption by 2–4 times [25].

The reduction of power losses in high-power wind turbines is achieved by increase of the output voltage of generators. Due to the presence of three generators in WTAM, the voltage increase is provided by a series connection of rectifiers or back-to-back converter.

When the output voltage of generator is 690, 1050 V, the voltage in the range of 2.7–4.2 kV can be obtained in dc link.

Fig. 6 shows the base circuits of energy conversion in high-power WTAM: *a* – with an uncontrollable rectifier and dc-dc pulse converter; *b* – with pulse converter for stabilization or doubling of voltage; *c* –with inverter according to back-to-back convertor circuit; *d* – with grid-controlled inverter.

The use of pulse converters for voltage stabilization or doubling of voltage gives a possibility to increase the voltage up to 6–10 kV (fig. 6, *b*).

The reduction of frequency converter cost can be provided by using thyristor-based grid-controlled inverters (fig. 6, *d*). The thyristors have the lower voltage drop and significantly lower cost.

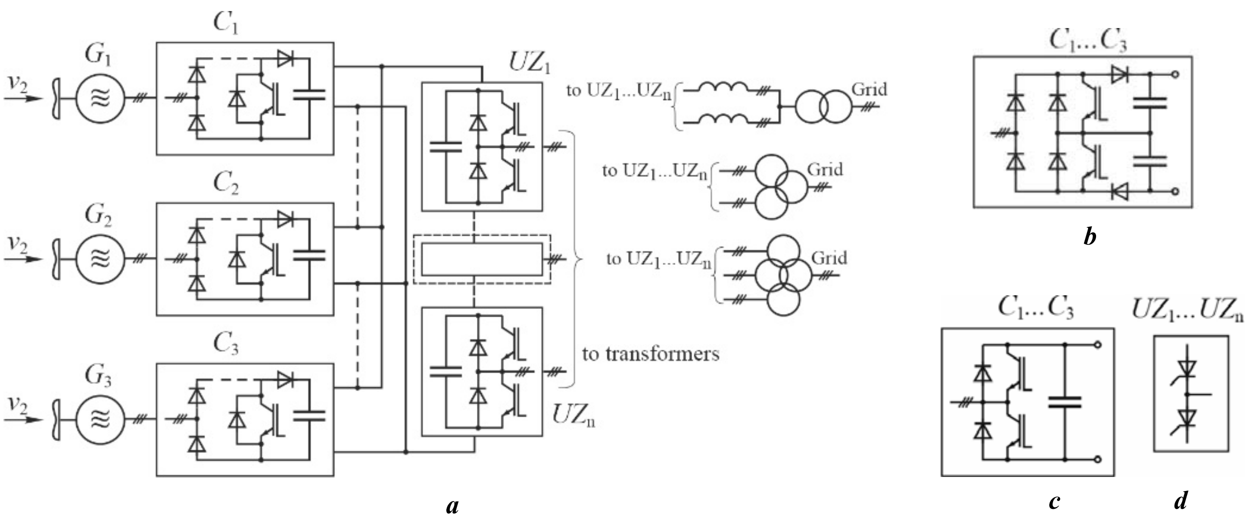


Fig. 6

The high-power wind farms are connected to the networks of 110 and above kV, which have a large distributed capacitance. To compensate this reactance, the shunt reactors are installed at the ends of high-voltage lines. The grid-controlled inverter operating with constant or variable advance angle of trigger β, when it is connected to a network, can be used as a controllable inductance. That permits to reduce the installed power of shunt reactors. The compatibility with a network is attained by using multi-phase (12–24 or more) inverting circuits depending on the power of wind turbine.

Conclusion.

1. The relationships between the quantitative and qualitative characteristics of WTAM and the basic parameters of used equipment are revealed. The recommendations for implementation of the technical solutions that ensure the enhancement of WTAM efficiency and reduction of price are developed.

2. The experimental and theoretical studies show not only the possibility of technical realization of WTAM, but also the fundamental features of its operation, which contribute to reducing the cost, installation costs, operating costs and increasing the efficiency. All this makes it competitive with classical horizontal axis wind turbine.

3. The availability of developed element base (generators, converters, other elements) gives a possibility to accelerate the introduction of these installations into commercial operation.

4. The ways to improve the WTAM are related to the development of aerodynamics of the main wind wheel blades and turbines, the improvement of element base and control algorithms.

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ЕФЕКТИВНІСТЬ ЕЛЕКТРОМЕХАНІЧНИХ СИСТЕМ ВІТРОЕНЕРГЕТИЧНИХ УСТАНОВОК З АЕРОДИНАМІЧНОЮ МУЛЬТИПЛІКАЦІЄЮ

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В статті розглянуто стан розвитку потужних вітроенергетичних установок з горизонтальною віссю обертання вітроколеса. У найбільш поширених вітроустановках зі змінною швидкістю вітрового потоку для сумісності електрогенератора з мережею необхідно встановлювати перетворювач частоти, що призводить до зменшення ККД системи, а використання прямого підключення генератора до осі вітроколеса – до суттєвого збільшення маси і вартості генератора. Альтернативою таким системам пропонується вітроустановка з аеродинамічною мультиплікацією, дослідний зразок якої потужністю 750 кВт виготовлено та досліджено в Україні. Електромеханічна схема такої системи при використанні синхронних або асинхронних генераторів має властивість при постійних частотах обертання ротора генератора генерувати енергію в оптимальному режимі при змінній швидкості вітрового потоку у широкому діапазоні без перетворювача частоти, що сприяє підвищенню ККД та зменшенню вартості електроустановки. Показано, що зменшення відносних показників маси, вартості та ККД генераторів запропонованої та класичної системи залежить від коефіцієнта мультиплікації (відношення частоти обертання вітроколеса та генератора), і в діапазоні потужностей вітроустановок 750÷2500 кВт знаходяться у межах 10,72÷4,75. Теоретичні та експериментальні дослідження показують, що вітроенергетичні установки з аеродинамічною мультиплікацією можуть бути конкурентоспроможними по відношенню до традиційних вітроустановок з горизонтальною віссю обертання вітроколеса. Ціллю поточної статті є порівняльний аналіз кількісних і якісних характеристик використовуваного обладнання вітроустановок великої потужності з горизонтальною віссю обертання і прямим підключенням генераторів до осі вітроколеса, і вітроустановок з аеродинамічною мультиплікацією. Бібл. 27, табл. 1, рис. 6.

Ключові слова: вітроенергетична установка, система перетворення вітрової енергії, генератор, вітроколесо, аеродинамічна мультиплікація, перетворювач частоти.

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