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УДК 621.548

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ANALYSIS OF POWER REGULATION MECHANISMS OF HORIZONTAL-AXIS WIND TURBINES AND PROSPECTS OF THEIR IMPROVEMENT

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Проаналізовано основні типи механізмів регулювання потужності горизонтально-осьових вітроустановок малої потужності. З метою підвищення точності регулювання потужності, ефективності й надійності функціонування вітроустановок у широкому діапазоні швидкостей вітру обґрунтовано необхідність подальшого вдосконалення існуючих механізмів регулювання. Розглянуто перспективи створення комбінованих механічних систем, у яких передбачено можливості одночасного повороту й складання лопатей, повороту (або складання) лопатей і виведення вітроколеса з-під вітру.

Main types of mechanisms of power regulation of horizontal-axis wind turbines of low power are analyzed. The necessity of further improving of existent regulation mechanisms is motivated for the purpose of increasing of accuracy of power regulation, effectiveness and reliability of wind turbines functioning in wide range of wind speeds. The prospects of creation of combined mechanical systems are considered, where the possibilities of simultaneous blades turning and folding, blades turning (or folding) and wind-wheel deflection out of wind direction are provided.

Problem stating. The operation modes of wind turbines (WTs) fall into two types: stationary and transient [1]. In stationary operation modes WTs can be operating during unlimited time spans over the whole life cycle. The shut-down mode and normal (nominal) functioning of WT with partial or full load on the drive shaft may be considered among stationary modes. In transient operation modes WTs can be operating during limited time spans. WT starting, load connection (disconnection), normal and emergency shutdown may be considered among transient modes.

Wind speed time fickleness is one of unfavorable wind energy features. Wind speed can change few times more during several seconds. This situation negatively effects on characteristics of power, generated by WT, and on strength parameters of its various parts (for example, blades). Most WTs are equipped with special regulation systems for ensuring effective and reliable functioning in conditions of changeable wind speed and load on drive shaft. These regulation systems mainly operate at the expense of blades turning and folding or wind-wheel deflection out of wind direction. Usually electric and hydraulic drives are used in regulation systems of WTs of middle and large power (more than 100 kW). Small WTs are equipped with mechanical regulation systems for the purpose of cost reduction of their constructions [2].

WTs with mechanical regulation systems have worse control accuracy and exploitation reliability than WTs with electric or hydraulic drives. However, there are no alternative systems for mechanical regulation in WTs of small power (less than 10 kW) because of their low cost. That’s why the problems of actuation accuracy rising and reliability improvement of mechanical regulation systems are very important.

Analysis of the latest investigations and publications. Much attention in modern technical literature is devoted to problems of improvement of power regulation systems of horizontal-axis WTs [1-7]. Above 500 various companies all over the world handle the problem of creation of new models of WTs. Internationally known European and American companies are “Vestas”, “GE Energy”, “Gamesa”, “Enercon”, “Suzlon”, “Siemens”, “Alstom-Ecotecnia”, “Acciona”, “Nordex” etc. In Ukraine there are not many companies, which handle the problem of WTs development. Well-known Ukrainian enterprises are “Енергодар”, “Світ вітру” (Kharkiv), “Альтекс” (Kyiv), “ЕКО”, “ДКБ Південне” (Dnipropetrovs’k) etc. [2-5].

Most modern investigations and developments are devoted to improvement of commercial WTs of middle and large power (more than 100 kW), which are used for electric energy producing mainly. At that “small” wind energetics develops essentially slower and the problems of improvement of mechanical systems of power regulation of small WTs (less than 10 kW) are disregarded in most cases [8].

We cannot make the most out of world experience of creation and exploitation of WTs of middle and large power taking into consideration low potential of air flows on the territory of Ukraine. Herewith multiblade horizontal-axis WTs of low power are very perspective on huge part of Ukrainian territory. These WTs may be used by isolated (autonomous) users for electric energy generation or in the capacity of direct drives for various industrial and agricultural equipment [8]. Creation of sufficiently accurate, effective and reliable mechanical regulation systems for multiblade low-speed WTs is extremely important problem. And for solving this problem it is necessary to improve WTs construction and develop new methods of conversion of air flow energy.

Formulation of article purpose. Analysis of existent mechanical systems of power regulation of horizontal-axis wind turbines of small power (less than 10 kW). Substantiation of reasonability and consideration of prospects of their development with the purpose of actuation accuracy rising, reliability improvement and efficiency increasing over the wide range of wind speed.

Mechanical systems of wind turbines power regulation. Analysis of power regulation systems of horizontal-axis WTs has presented that three general regulation principles are used nowadays. The first principle is based on using of the effect of aerodynamic lifting force changing on fixed blades with special aerodynamic profile in the issue of wind-wheel rotation frequency changing. This principle is called air flow separation or stalling. The effect of aerodynamic lifting force changing on the unfixed blades at the expense of changing of their attack angle relative to direction of incoming air flow is used in the second principle. The third method of regulation consists in power changing by means of WT blow-off area control [2-4; 6; 7].

Air flow separation or stalling. This regulation method is used in WTs with nominal power less than 0.15-0.12 kW and rotor diameter up to 1.0-1.5 m. For example, this method is used in the model Rutland 913, produced by Marlec Engineering company [2]. Aerodynamic effect of flow stalling on blades is provided by transformation of laminar airflow on their surfaces into turbulent flow, which arises in the issue of blades attack angle changing as a result of wind speed increase (fig. 1). This effect may occur as a result of wind speed increase with steady wind-wheel rotation frequency or in the issue of wind-wheel rotation frequency increase with steady wind speed [2; 6].

The main preference if this method is nacelle construction simplicity, which allows reducing WTs cost and improving its reliability, because the mechanism of power regulation is one of the most frequent sources of failures in WTs operation [2]. Many factors of this effect usage substantially complicate aerodynamic analysis of WT and they should be taken into consideration in process of error calculation: 1) all cross-sections of a blade move with different velocities and have different attack angles when wind-wheel rotating; 2) there are no stable experimental characteristics for separate movable cross-sections of a blade, which can be sufficiently and accurately determined in aerodynamic tunnel. Random dynamic disturbances from wind, construction aeroelasticity, asymmetry of geometrical and mass characteristics of wind-wheel influence on blades; 3) disturbed air flow after a blade have complicated turbulence structure and substantially influence on dynamics of next blade [2-4; 6; 7].

The main faults of regulation by air flow stalling are low effectiveness under wind blast and necessity of permanent load on wind-wheel drive shaft. Wind-wheel quickly loses control and its rotation frequency reaches critical value as a result of exceeding allowable wind speed (even under blast). That's why it is necessary to pay special attention to presence of extra braking system when using this regulation method [2; 6]. WT power fluently rises during the process of regulation by flow stalling in wide range of operation wind speeds and is limited by power of loading device (fig. 2, a) [2].

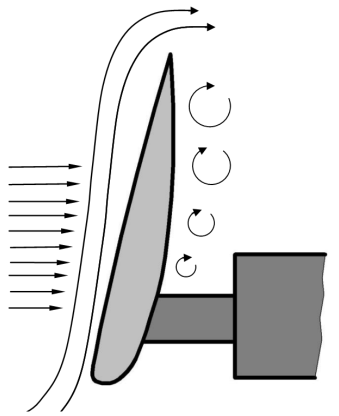

Fig. 1. The scheme of air stalling on WT blades

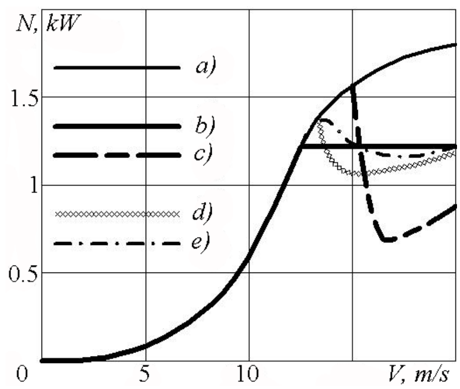

Fig. 2. Characteristics of power regulation methods: a – flow stalling; b – blades turning; c – nacelle sideways turning; d – nacelle backward deflection; e– blades folding

Blades turning. The changing of blades stall angle is very effective method of power regulation of horizontal-axis WTs. Blades revolve on their own longitudinal axes and change attack angles relative to direction of incoming air flow when using this regulation method. The character of blade streamline by incoming air flow changes as a result of blades revolving. The effect of flow stalling appears and causes decreasing of lifting force and WT power [1-7].

Passive control of blades stall angle (without hydraulic, electric or pneumatic drives) is usually used in WTs of small power. Inertial regulation by means of various mechanisms is most high-usage. Usually they are created on the principle of Watt regulator (fig. 3) [2; 6]. It may be presented as weights, which are symmetrically located relative to blade turning axis. Centrifugal forces deflect weights during wind-wheel rotation and they turn blades round longitudinal axes using coupling elements. At that, blades stall angle depends on wind-wheel rotation frequency. For example, inertial control with the help of Watt regulator is used in WTs of Jacobs series, produced by Wind Turbine Industries company [2].

Usage of blades mass by way of Watt regulator is a variation of inertial regulation. At that, blades mass centers are located out of their longitudinal axes. This factor allows moment appearance, which turn blades when rising of wind-wheel angular velocity. For example, this regulation method is used in WTs of Proven series, produced by Proven Energy company [2].

Active regulation of blades stall angle consists in their revolving by electric, hydraulic or pneumatic drives after the command of electronic control system. These regulation methods are more complicated and expensive comparatively to mechanical systems. That's why, they are usually used in WTs of low, middle and high power (more than 20 kW).

When using the regulation method of blades turning, wind speed growth up to nominal value causes smooth rising of WT power to certain maximal quantity and its further keeping at a constant level until wind speed reaches its permissible value (fig. 2, b) [2].

Wind-wheel getting out of wind direction. Power regulation by wind-wheel getting out of wind consists in placing of WT blow-off area under some angle relative to air flow direction. At that, the area of incoming air flow varies within wide limits and lifting force changes also. This effect ensures limiting of WT power during uncontrolled rising of wind speed. This regulation method is the simplest one and it has been used since 19-th century [2-4; 6; 7]. Wind-wheel getting out of wind direction may be realized in several ways: sideways turning (to the right or to the left relative to vertical axis), backward deflection or forward inclination relative to horizontal axis.

Wind-wheel sideways turning relative to vertical axis. This method may be realized in two ways: using of airflow pressure on side blade, connected to nacelle behind wind-wheel (fig. 4) (for example, model Aguasolar 2.5, produced by Aquasolar company), or using of moment relative to vertical axis of nacelle turning, which arises as a result of air flow ram pressure on blades (fig. 5) (for example, in WTs of BWC series, produced by Bergey Windpower company) [2; 6]. Moment arm is an eccentricity, presented by the shortest distance between horizontal axis of wind-wheel rotation and vertical axis of nacelle turning. Wind force, affecting on side blade or wind-wheel, becomes balanced by spring, placed between tail-plane and nacelle [2; 6]. The nacelle turns round vertical axis and tail-plane holds a position at some angle relative to wind direction as a result of blades interaction with air flow. In that way the balance of all forces is kept and nacelle position is fixed for each value of wind speed [2; 6].

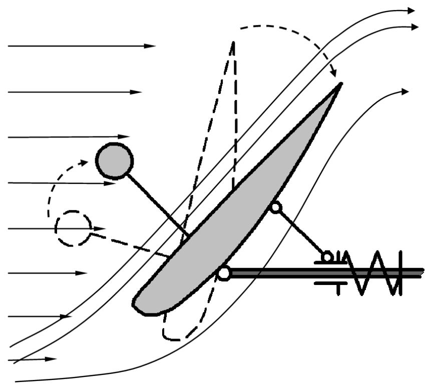

Fig. 3. Principle scheme of power regulation by blades turning

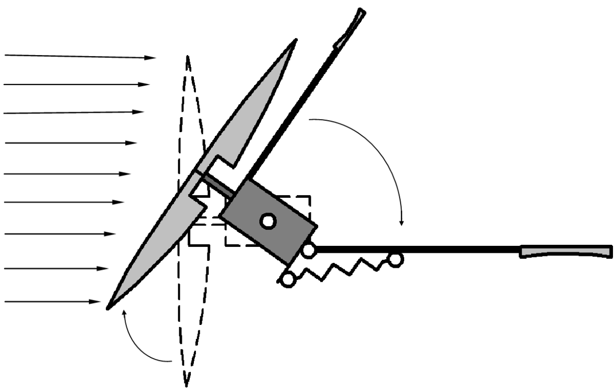

Fig. 4. Principle scheme of the mechanism of wind-wheel sideways turning with the help of side wane

When wind speed increasing, WT power rises to its nominal value and keeps rising until nacelle begins turning sideways and causes nearly stepwise power reduction within limits of 50 % (fig. 2, c) [2]. Thus, WT output power is considerably lower than its nominal value over a large range of wind speed changing. This effect leads to reduction of total amount of energy, produces by WT, and to decreasing of its operation effectiveness [2].

Wind-wheel backward deflection. Wind-wheel getting out of wind direction is realized by means of nacelle deflection as a result of aerodynamic influence on blades (fig. 6). This regulation method is used in WTs with wind-wheels, located before tower from the direction of incoming air flow. Theses wind-wheels use tail-plane for orientation after wind direction and sometimes are called up-wind rotors. Similarly to previous case, this method is realized in reduction of wind-wheel projection area on vertical plane, which is perpendicular to air flow direction. For example, this regulation method is used in model Lakota, produced by Aeromax company [2].

Wind-wheel forward inclination. This method is used in WTs with self-orientating or down-wind rotors (fig. 7). This method uses aerodynamic moment, which appears on a blade, which is perpendicular to air flow direction and placed on vertical beam, connected to nacelle. For example, this regulation method is used in WTs of S series, produced by Appropriate Energy company [2; 6].

As distinct of regulation by wind-wheel sideways turning, the methods of nacelle backward deflection or forward inclination allow reduction of stepwise power decrease to 20 % (fig. 2, d) [2]. Thus, power losses by large wind speed are considerably less.

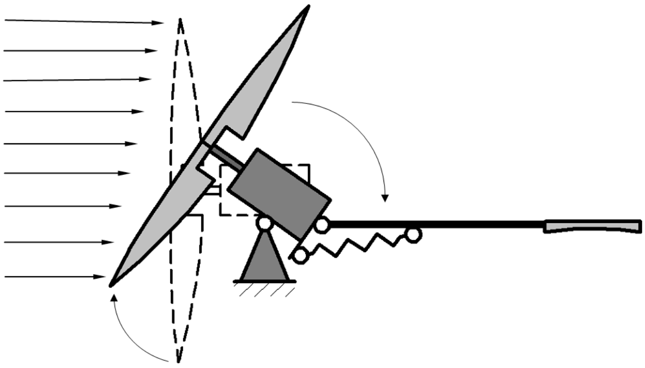

Fig. 5. Principle scheme of the mechanism of wind-wheel sideways turning by means of wind-wheel axis eccentricity

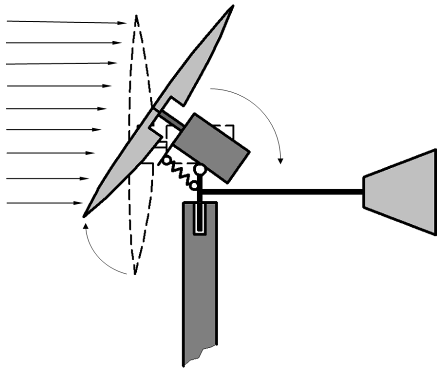

Fig. 6. Principle scheme of the mechanism of wind-wheel backward deflection

Blades folding. Passive blades deflection (folding) in the direction of wind speed vector (fig. 8) is not used so widely as other methods [2]. Under the influence of incoming air flow on blades surfaces, they fold along wind-wheel axis, decreasing its blow-off area and reducing power takeoff. Blades turn into their starting positions with the help of spring elements when reducing wind speed [2; 7]. Power regulation by means of blades folding reduce WT efficiency to some extent in the range of wind speeds, larger than nominal. However, comparing the efficiency of this method and of regulation by means of blades turning (fig. 2, b, e) [2], these two methods are nearly equal and they may be chosen for further investigations as the most effective methods of WT power regulation. For example, this regulation method is used in WTs of BF series, produced by Energotech company [2].

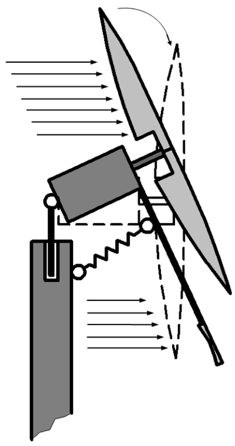

Fig. 7. Principle scheme of the mechanism of wind-wheel forward inclination

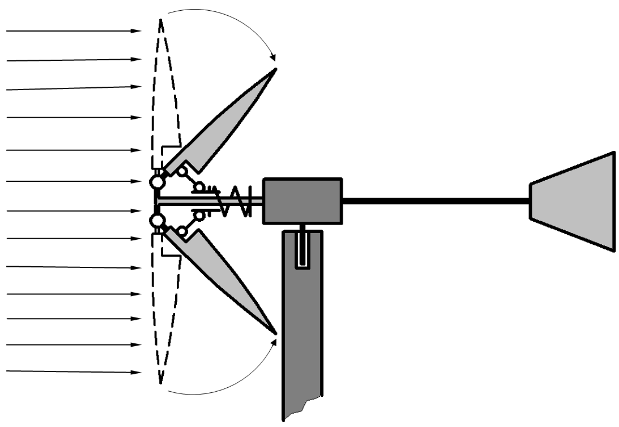

Fig. 8. Principle scheme of the mechanism of blades folding

Prospects of improvement of existent mechanisms of WT power regulation. Vast majority of small WTs (with power of 1-10 kW) are equipped by some power regulation mechanism. It is reasonable to equip low-speed multiblade WTs with systems of power regulation by means of WT blow-off area control. Multiblade WTs have large filling factor of blow-off area. This factor allows effective using of air flow ram pressure on blades surfaces as a driving force for blades folding mechanisms of systems of rotor getting out of wind direction. From the point of view of efficiency and accuracy of regulation it is reasonable to equip high-speed WTs (less than 6 blades) with mechanisms of blades turning. However, from the point of view of construction cost reduction it is reasonable to equip high-speed WTs with mechanisms of rotor blow-off area control.

Thus, creation of combined mechanical systems, which unite mechanisms of blades turning and folding, blades turning (or folding) and rotor getting out of wind direction is one of priority tasks of further development of horizontal-axis WTs constructions. It is planned, that these combined systems will offers all advantages of each regulation method in the future.

Let's consider simplified kinematic diagrams of mechanisms of blades turning and folding of horizontal-axis WT (fig. 9, a, b) [9]. Blades are pivotally connected with rotor hub, which is rotating round horizontal axis. Blades turning into feather position is realized as a result of regulating slider H_1 movement along wind-wheel axis and changing of hinges C and K positions (fig. 9, a). The process of blades folding is realized by means of regulating slider H_2 movement along wind-wheel axis (fig. 9, b). This slider changes blades angular position relative to wind-wheel axis (rotor tapering or conicity) and WT blow-off area by changing positions of hinges N and E .The force of ram pressure is driving force for blades turning and folding in case of passive regulation. When using inertial regulator, the centrifugal force of regulation weights can be used by way of driving force also [9].

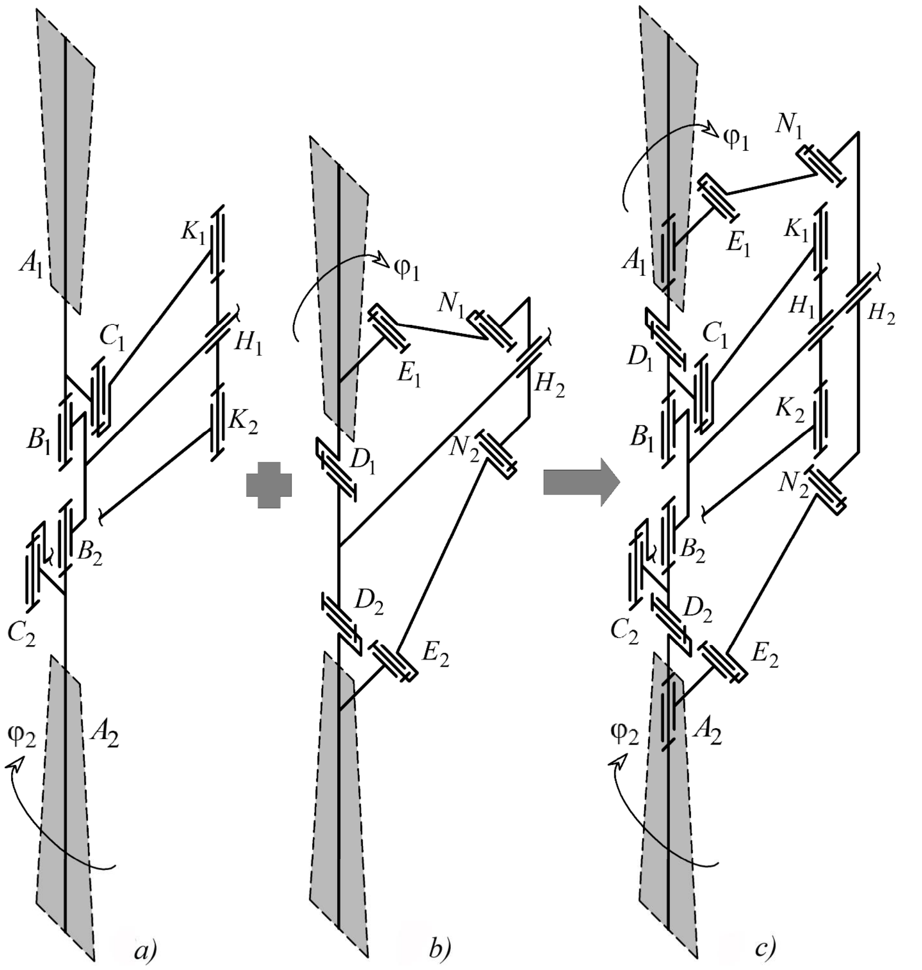

Fig. 9. Kinematic diagrams of the mechanism of blades turning (a), of the mechanism of blades folding (b) and of the combined mechanical system of blades simultaneous turning and folding (c)

Combined mechanical system of blades turning and folding (fig. 9, c) may be received by combining of the mechanism of blades folding (fig. 9, b) with the mechanism of blades turning round their own longitudinal axis (fig. 9, a). The presence of hinges B and D, which are placed on rotor hub when using combined mechanism, allows blades turning round two mutually perpendicular axes. Mentioned movements can be independent, when sliders H_1 and H_2 are not joined or are connected by spring elements. Also these movements can be dependent, when sliders H_1 and H_2 are immovably joined.

Combining of blades turning (folding) system with the mechanism of wind-wheel getting out of wind direction in WT construction (fig. 10, a, b) is another perspective method of horizontal-axis wind turbine power regulation, which can be effectively used by way of anti-storm protection system. In that case, tail-plane joins with nacelle by way of cylindrical hinge and interacts with nacelle through spring element. Wind-wheel can be equipped with side blade P (fig. 10, a), which is used for wind-wheel sideways turning relative to wind direction when wind speed rising over its nominal value. Similar effect can be achieved as a result of wind-wheel axis side-shift relative to tower axis (fig. 10, b) or, in other words, when existing of eccentricity between wind-wheel and tower axes. Side blade size, wind-wheel axis eccentricity value and regulation spring rigidity should be determined depending on wind-wheel and tail-plane sizes and nominal (design) values of wind speed and rotation frequency.

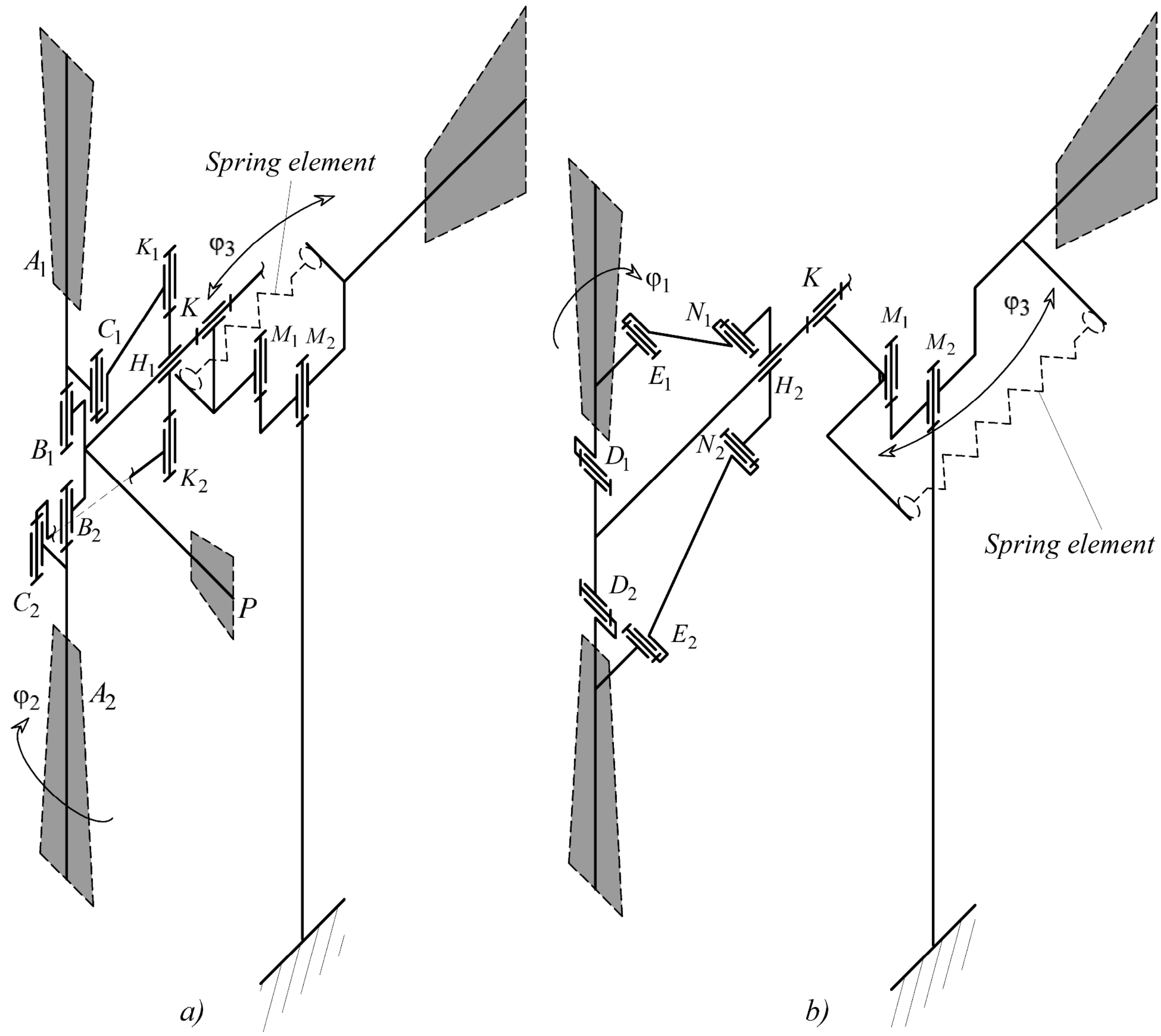

Fig. 10. Kinematic diagrams of combined mechanical systems of simultaneous blades turning and wind-wheel getting out of wind direction (a) and blades folding and wind-wheel getting out of wind direction (b)

Conclusions. Presented comparative analysis of various WT power regulation systems allows drawing such conclusions: 1) regulation systems, operating by way of air flow separation or stalling, are the cheapest and the most reliable ones in comparison with all other systems. However, from the point of view of operation efficiency and accuracy these systems are considerably worse than systems of blades turning and folding; 2) the system of regulation by way of blades stall angle changing is constructively and functionally more complicated and more expensive in comparison with methods of wind-wheel blow-off area changing (sideways turning, backward deflection, forward inclination or blades folding). Also this system requires reliable and qualified service; 3) the system of power regulation by way of blades stall angle changing is the most effective; 4) the mechanisms of power regulation by means of wind-wheel getting out of the wind direction are functionally and constructively less complicated than other mechanical systems. However, their efficiency is considerably lower [1-8]. As follows from the diagram (fig. 11), the amount of WTs with power regulation by flow stalling and by wind-wheel getting out of wind direction decreases when WTs power rising. And at the same time the amount of blades turning mechanisms rises [2]. Mechanisms of blades folding are mostly used in WTs with nominal power less than 10 kW.

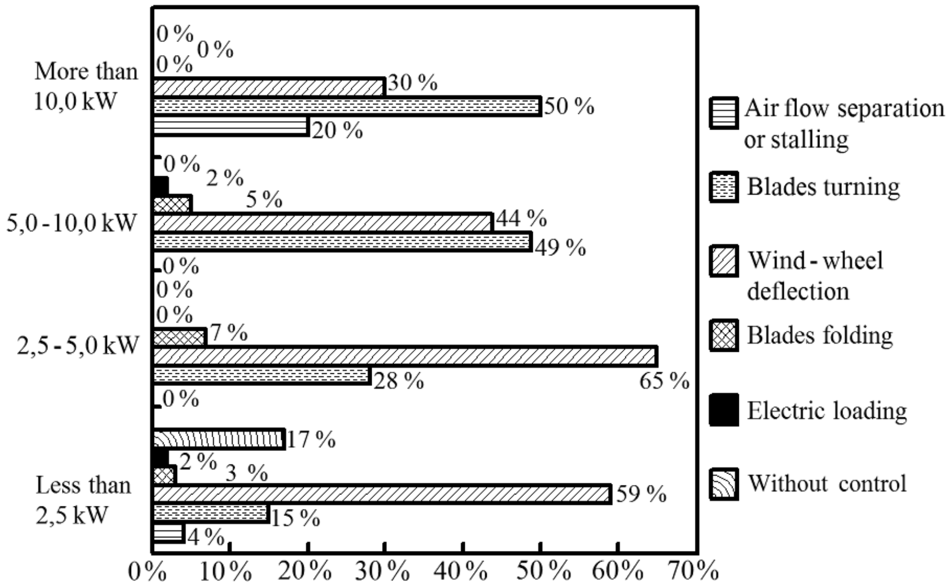

Fig. 11. Diagram of horizontal-axis WTs distribution according to power regulation method

Each regulation method has its own advantages, faults and usage scopes (high-speed WTs with 2-3 blades or low-speed multiblade WTs). When analyzing transient modes of WT operation (especially coherent or storm wind gusts), existent mechanical systems of power regulation are not sufficiently effective taking into consideration large detention lag of their actuation and problems of equipping by effective feedback systems. These problems appear when power regulating according to changing of wind speed or load moment on driving shaft. These problems mainly concern to the systems of wind-wheel getting out of wind direction and cause necessity of usage of extra (friction or electromagnetic) wind-wheel braking systems (blades turning or folding systems etc.). That's why, the expediency of combined usage of blades turning (folding) systems and systems wind-wheel getting out of wind direction is substantiated in the article. It is planned, that these combined regulation systems ensure effective and reliable WTs operating under conditions of coherent and storm wind gusts. At that, simplified kinematic schemes of mentioned mechanisms are proposed and general principles of their functioning are analyzed.

Further investigations provide for creating of mathematical models of WT aeromechanical system with proposed regulation mechanisms, derivation of analytical dependencies for determination of their inertial and rigidity parameters, realization of computer modelling of WT operating in transient modes and substantiation of expediency of usage of proposed regulation mechanisms.

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УДК 621.01.(075.8)

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EXPERIMENTAL RESEARCH OF THE RESILIENT KEY CONNECTIONS STATICS

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Описано методику експериментальних досліджень статики з'єднань з пружними призматичними шпонками, а саме залежності між їх деформаціями, обертальним моментом і розмірами та зроблено відповідні висновки порівняно з теоретичними дослідженнями.

Methods of experimental research of the resilient parallel keyed connections statics are described by showing dependences between their deformations, torque and sizes, and conclusions in comparison with theoretical research are made.

Introduction. The shaft-hub connections with resilient parallel keys transmit torque due to forces of the key deformation. We have obtained theoretical dependences between deformations, torque and sizes of these keys. Therefore, there is a need for experimental verification of statics in such connections.

Recent research and publications analysis. The connections with rigid keys are widely known [1]. In addition, a number of resilient keys for connections of shafts with hubs were developed at the level of patents [2 ... 6]. Use of these keys allows to change the stiffness of the connection and to transmit torque from the shaft to the hub, or vice versa, softer, i.e. without shock, which positively affects the durability of the drive.

Works [7...10] are dedicated to theoretical issues of resilient parallel keyed connections statics. However, these theoretical studies require further experimental research and confirmation of the results.

The aim of this work is to conduct experimental research of statics of resilient parallel keyed connections used to connect various rotation parts during the torque transfer.