LIFE CYCLE MANAGEMENT OF CONSTRUCTION FACILITIES

УПРАВЛЕНИЕ ЖИЗНЕННЫМ ЦИКЛОМ ОБЪЕКТОВ СТРОИТЕЛЬСТВА

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Original Empirical Research

Life Cycle Analysis of Construction Facilities Using the Eexample of Wind Power Facilities

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Abstract

Introduction. Construction plays a major role in the economy of the Russian Federation contributing to sustainable development and improving the living conditions of the population. Modern construction facilities include residential and commercial buildings, municipal and infrastructural structures such as roads and bridges, as well as industrial and energy facilities, including wind power facilities. Wind energy is becoming an important part of the construction industry, contributing to innovation and technological progress. As objects of the construction industry, wind power facilities go through their life cycle which includes the main stages: design, construction, operation and disposal (renovation). Each stage requires effective management to ensure reliable operation and safety of the facility. Thus, in order to ensure the future generation of environmentally safe energy by a wind power plant, it becomes necessary to analyze the planned construction site and, as a result, manage solutions at the design and construction stages. During such an analysis, it becomes possible to identify potential problems during the operation phase of a wind power facility. These include, first of all, wear, corrosion of structural elements and frostbite of the blades. These problems are the reason for the decrease in performance and service life of the object. The aim of the work was thus to search for the possibility of extending the service life in the life cycle of wind power facilities by solving the problem of blade icing at the design and construction stages.

Materials and methods. The research is based on the method of analyzing the life cycle of construction facilities, including the systematization and optimization of their management processes. The model of the life cycle of wind power facilities, developed by the author earlier, helped to identify the problems of the facility's operation phase. The most significant problem that significantly affects the duration of the operation phase is the problem of blade icing. An analysis of the life cycle of a wind power facility has shown that it is advisable to ensure a successful solution to this problem at the design and construction stages of the facility. The data of the conducted analysis of the problem are based on the research results of domestic and foreign authors.

As a result, a generalization and systematization of existing anti-icing methods was carried out, on the basis of which a new method of implementation was set forth and an appropriate work methodology was developed. Such a solution, envisaged at the design stage of the construction facility, will enable one to successfully manage its life cycle, and, in particular, the operation stage.

Results. Throughout the course of the research, the author has been able to increase the duration of the operation stage in the life cycle of wind power facilities. To this end, an analysis of the life cycle of construction facilities was carried out, during which the causes affecting the life of the facility were identified. The most significant reason leading to a sharp reduction in the service life of the construction site is the problem of icing of the blades during the cold season.

Based on the analysis of operating conditions, the causes of icing of the blades of wind power structures have been determined, the basic principles of anti-icing protection have been established, and a new method for solving this problem using UAVs (unmanned aerial vehicles) has been set forth, as well as a technique for applying hydrophobic coatings to prevent the icing process. The implementation of the research results will ensure the required performance, which, in turn, will increase the service life of the wind power plant.

Discussion and conclusion. Successful lifecycle management of such construction facilities as wind power plants requires attention not only at the stage of operation of the facility, but also at the stages of design and construction. The key task of the operation stage of a wind power facility is to ensure the necessary productivity and increase the service life of the facility. This can be solved by carefully analyzing the life cycle and preventing future operational problems at the design and construction stages. The method set forth in the study to combat blade icing can be implemented not only for existing wind power plants that do not have special anti-icing systems, but also for projected facilities. Moreover, the suggested solutions for combating icing of the blades can be included in the design documentation as mandatory types of work carried out during the construction phase, as well as subsequently during the operation phase with a certain frequency.

Solving the problem at the design stage of the facility will ensure an increase in productivity and an increase in the service life of a wind power plant operating in cold and humid climates. Thus, the results of the study provide a theoretical basis for managing the life cycle of wind power facilities, as one of the promising construction projects.

Keywords: life cycle, construction sites, wind power facilities, anti-icing of blades, hydrophobic coatings.

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Оригинальное эмпирическое исследование

Анализ жизненного цикла объектов строительства на примере ветроэнергетических сооружений

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Аннотация

Введение. Строительство играет ключевую роль в экономике Российской Федерации, способствуя устойчивому развитию и улучшению условий жизни населения. Современные строительные объекты представляют собой жилые и коммерческие здания, коммунальные и инфраструктурные сооружения, такие как дороги и мосты, а также промышленные и энергетические объекты, включая ветроэнергетические сооружения. Ветроэнергетика становится важной частью строительной отрасли, способствуя инновациям и технологическому прогрессу.

Как объекты строительной отрасли ветроэнергетические сооружения (ВЭС) проходят свой жизненный цикл, включающий основные этапы: проектирование, строительство, эксплуатацию и утилизацию (реновацию). Каждый этап требует эффективного управления для обеспечения надежного функционирования и безопасности объекта. Так, для обеспечения в будущем генерации экологически безопасной энергии ветроэнергетическим сооружением возникает необходимость анализа планируемого объекта строительства и, как следствие, управление решениями еще на этапах проектирования и строительства. В ходе такого анализа появляется возможность выявить потенциальные проблемы этапа эксплуатации ветроэнергетического сооружения. К ним прежде всего можно отнести износ, коррозию конструктивных элементов и обморожение лопастей.

Данные проблемы являются причиной снижения производительности и срока службы объекта. В связи с этим целью работы являлся поиск возможности увеличения срока эксплуатации в жизненном цикле ветроэнергетических сооружений за счет решения проблемы обледенения лопастей на этапах проектирования и строительства.

Материалы и методы. Исследования базируются на методе анализа жизненного цикла строительных объектов, включающем систематизацию и оптимизацию процессов управления ими. Модель жизненного цикла ветроэнергетических сооружений, разработанная автором ранее, помогла выявить проблемы этапа эксплуатации объекта. Наиболее значимой проблемой, существенно влияющей на продолжительность этапа эксплуатации, является проблема обледенения лопастей. Анализ жизненного цикла ветроэнергетического сооружения показал, что обеспечить успешное решение этой проблемы целесообразно на этапах проектирования и строительства объекта. Данные проведенного анализа проблемы базируются на результатах исследований отечественных и зарубежных авторов.

В результате произведено обобщение и систематизация существующих методов борьбы с обледенением, на основе чего предложен новый способ реализации и разработана соответствующая методика выполнения работ. Такое решение, предусмотренное еще на этапе проектирования строительного объекта, позволит успешно управлять его жизненным циклом и, в частности, этапом эксплуатации.

Результаты исследования. В ходе проведенных исследований автором достигнута цель — увеличение продолжительности этапа эксплуатации в жизненном цикле ветроэнергетических сооружений. Для достижения поставленной цели проведен анализ жизненного цикла объектов строительства, в ходе которого выявлены причины, оказывающие влияние на срок эксплуатации объекта. Наиболее значимой причиной, приводящей к резкому сокращению срока службы объекта строительства, является проблема обледенения лопастей в холодный период года.

На основе анализа условий эксплуатации определены причины обледенения лопастей ветроэнергетических сооружений, установлены основные принципы защиты от обледенения и предложен новый способ решения этой проблемы с применением беспилотного летательного аппарата (далее — БПЛА), а также разработана методика нанесения гидрофобных покрытий для предотвращения процесса обледенения. Внедрение результатов исследования позволит обеспечить требуемую производительность, что, в свою очередь, увеличит срок службы ветроэнергетического сооружения.

Обсуждение и заключение. Успешное управление жизненным циклом таких объектов строительства как ветроэнергетические сооружения требует внимания не только на этапе эксплуатации объекта, но и на этапах проектирования и строительства. Ключевая задача этапа эксплуатации ветроэнергетического сооружения — обеспечение необходимой производительности и увеличение срока службы объекта — может быть решена путем тщательного анализа жизненного цикла и предотвращением будущих проблем эксплуатации еще на этапах проектирования и строительства. Предложенный в исследовании способ борьбы с обледенением лопастей может быть внедрен не только для существующих ветроэнергетических сооружений, не имеющих специальных систем против обледенения, но и для проектируемых объектов. Причем предлагаемые решения для борьбы с обледенением лопастей могут быть включены в проектную документацию как обязательные виды работ, осуществляемые на этапе строительства, а также впоследствии — на этапе эксплуатации с определенной периодичностью.

Решение проблемы на этапе проектирования объекта позволит обеспечить повышение производительности и увеличение срока службы ветроэнергетического сооружения, функционирующего в условиях холодного и влажного климата. Таким образом, результаты исследования представляют собой теоретическую базу для управления жизненным циклом ветроэнергетических сооружений как одних из перспективных объектов строительства.

Ключевые слова: жизненный цикл, объекты строительства, ветроэнергетические сооружения, борьба с обледенением лопастей, гидрофобные покрытия

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Introduction. Construction is one of the major sectors of the country's economy playing a key role in its sustainable social and economic development and improving the living conditions of the population. Modern construction industry facilities are made up of a diverse range of structures with each having its unique role in the infrastructural development of society. These include residential and commercial buildings, infrastructure facilities such as roads, bridges, and tunnels, as well as industrial structures. Recent years have seen special attention paid to wind power facilities becoming increasingly crucial in sustainable development and the search for alternative energy sources. Wind power facilities not only help reduce dependence on fossil fuels, but also minimize the environmental footprint by providing clean and renewable energy. Their integration into the construction industry opens up new avenues for innovation and technological progress making wind energy a key element of modern construction practice. Like any other construction projects, wind power facilities go through a specific life cycle including a few key stages: design, construction, operation and liquidation or renovation. Each calls for thorough management and control for ensuring efficiency, safety and durability of structures. At the design stage it is thus important to account for climatic conditions, topography, and potential wind resources to maximize productivity of structures to be built in the future. The construction phase of wind power facilities calls for the use of high-quality materials and advanced technologies to guarantee reliability and stability of structures. The operation of wind power plants is a crucial stage, since their economic feasibility and environmental efficiency are dependent on it. Regular maintenance and monitoring of equipment condition can serve to prevent breakdowns and extend the service life of structures. The liquidation or renovation stage involves either dismantling outdated structures or upgrading them to improve efficiency. This is similar to the life cycle of other construction projects where it is also critical to account for aspects of sustainable development and minimize environmental impact. The tasks of managing the life cycle of wind power facilities at each stage are thus unique and call for a variety of approaches and solutions. At the same time, it is to be noted that to maximize the efficiency of generating environmentally friendly energy by wind power facilities in the long term, it is necessary to perform a comprehensive analysis of a facility being planned at the initial stages of its life cycle. This entails implementing a comprehensive approach to managing design and construction solutions as early as at the stage of designing and constructing a structure. Performing such a multifactorial analysis enables potential problem areas to be encountered during the operation of the construction site to be pinpointed.

The most major factors include:

– mechanical wear of structural elements;

– corrosion impacting metal components;

– icing of the rotor blades, particularly at low temperatures;

– degradation of electronic components under the influence of aggressive external factors.

The impact of these negative factors causes a considerable decrease in the operational characteristics of a facility, including a decline in power output and a reduction in maintenance intervals. In the long term, this involves a decrease in the overall efficiency of a wind power plant and calls for extra costs for maintenance and restoration.

Timely identification and consideration of potential problems at the early stages of the life cycle of a facility enable it to develop preventive measures to improve the reliability and durability of a structure, which in the long run optimizes the operational characteristics of a facility throughout its entire period of operation.

One of the major problems having a considerable impact on the life of a wind power plant is the icing of the blades. This problem seems to be crucial for facilities situated in regions with a cold and humid climate (Fig. 1). This curbs the efficient energy production (with ice thickness up to 30 cm power generation is reduced by 80 %) resulting in an imbalance due to the uneven distribution of ice on the blades, heavier structure and reducing the efficiency of rotation [3]. As a result, there is accelerated wear of the equipment: a shift in the center of gravity, increased load on the rotation mechanisms and mechanical damage to the surface of the blades. Icing might thus lead to malfunctions and need for premature maintenance [4].

Icing, which is the deposition of ice on the streamlined parts of a wind power plant commonly takes place during fogs, rains or sleets. At the same time, sufficient conditions to induce icing are high humidity, negative air temperature and low temperature of the working surfaces [5].

Fig. 1. Example of icing on a wind turbine blade

An essential parameter inherent to blade icing is the icing intensity, i.e., the thickness of the ice forming per unit surface area in contact with precipitation [6]. There are three degrees of icing intensity:

– mild icing, which is an accumulation of ice caling for no considerable effort to be eliminated. It does not pose a severe threat to wind power plants;

– moderate icing when the rate of ice accumulation is still not sufficient to seriously impact the safety and stability of wind power plants;

– severe icing, which is a large-scale accumulation of ice likely to cause a noticeable loss of wind turbine rotation speed. This degree of icing intensity will be crucial in terms of safety and involve serious economic repercussions (reduced productivity, increased maintenance costs and shorter service life of equipment).

Given the significance of the issue of icing on the blades of wind power structures, the scholarly community sets forth a few of strategies to reduce the negative impact of ice formations [7, 8]. Modern anti-icing methods comprise:

– the use of heating systems in the turbine design or heating elements at the ends of the blades. By means of maintaining temperatures above zero, the aerodynamic properties of the blades are retained and the stable operation of the wind power plant is ensured in icing conditions;

– the use of hydrophobic plastic in the design of the blades reduces the adhesion of water and mineral particles to the surface. Moisture retention on the blade surface is thus curbed and icing is less likely;

– applying special coatings to the blades of a wind power plant to create a protective layer. Such coatings have properties preventing ice structures from forming;

– mechanical de-icing using climbing equipment or a lift, as well as ice removal from a helicopter using hot liquids. However, this method enables one to address the problem of icing in the short term and calls for considerable organizational costs.

Based on the analysis of modern anti-icing methods, applying special coatings to the blades of a wind power plant can be regarded as the most efficient solution. This method of anti-icing is fairly simple to use, has lower energy consumption compared to heating systems, provides relatively long-term protection, retains aerodynamic characteristics of an object and causes almost no changes to the mass of the blades.

However, accounting for the size of wind power facilities and the need for repeated and routine application of special coatings, choosing the way of implementing this method is still a considerable problem.

Materials and Methods. The ongoing study relies on a methodology for analyzing the life cycle of construction facilities including a comprehensive systematization and optimization of managing all stages of a life cycle of a structure [9].

The model of the life cycle of wind power facilities previously developed by the author enabled a detailed analysis of potential problems that might occur during the operation of a facility [2]. Among the factors identified, special attention was given to blade icing, which has a considerable effect on the duration and efficiency of the operational stage.

The analysis of the life cycle of a wind power facility has indicated that the most appropriate solution is to address the problem of icing at the initial stages of the design and construction of a facility. The empirical foundation of the research relies on the analysis of the results of the studies by domestic and foreign researchers in the field. Through the course of the research, the existing anti-icing methods were classified making it possible to come up with an innovative approach to solving this problem and design an appropriate methodology for implementing anti-icing measures.

Implementing the suggested solution in the design concept of a construction facility will be conducive to effective management of a life cycle of a wind power facility prioritizing its operation efficiency.

Research Results. The problem of anti-icing of wind turbine blades can be successfully addressed by means of applying hydrophobic coatings to create a protective layer and prevent ice formation. These coatings are typically designed using materials with micro- or nanostructures lending the surface extremely high water-repellent properties [10]. Microstructures on the coating surface contribute to water droplets not being able to be evenly distributed over the surface, but instead forming into balls and roll off, carrying moisture with them and preventing ice formation.

In order to address the problem of icing of wind turbine blades, two compositions (Silokor-Anti-Ice and graphene) were chosen, which, owing to their physical and chemical characteristics and the capacity to sustain hydrophobic properties for a long time, are best suited for appropriate climatic operating conditions of wind turbines. The major components and chemicals comprising Silokor-Antiled are siloxane polymer (the major component providing the hydrophobic properties of the coating), solvents for polymer dilution, technological additives improving the performance of a coating and fillers enhancing the mechanical properties of a coating [11].

Unlike Silokor-Antiled, graphene is a two-dimensional allotropic modification of carbon comprised of carbon atoms arranged in a hexagonal crystal lattice [12]. Graphene consists exclusively of carbon atoms. Each has 6 electrons: 2 in the inner shell and 4 in the outer one. Graphene is thus chemically identical to diamond and graphite, since it is made up of the same carbon atoms. However, the difference in physical properties is owing to their special spatial arrangement. It is thanks to this feature that the material *posseses* unique properties such as hydrophobicity, high strength and electrical conductivity. Hence it can also be employed to combat icing of wind turbine blades.

For the preferred choice of the composition, a comparative analysis was performed shown in Table 1.

Table 1

Comparative analysis of hydrophobic compositions for combating anti-icing of wind turbine blades

Index	Hydrophobic composition	
	«Silokor-Anti-Ice»	Graphene
Durability	Long service life provided there is appropriate surface preparation and application	High durability owing to its strength and resistance to external influences, suitable for extreme conditions
Economic effectiveness	A more cost-effective solution, particularly for large facilities	High cost of production and application
Environmental friendliness	It contains solvents, which might call for additional disposal and safety measures to be taken	An environmentally friendly material provided that safe production and application methods are utilized
Compatibility with surfaces	Suitable for metal, concrete, painted and other surfaces	Diverse, can be applied to a variety of materials, including complex and delicate surfaces
Light transmission	High light transmission coefficient, which might be critical for some types of applications	Does not affect light transmission, can be used in transparent coatings
Application and treatment	Easy to apply owing to a two-component system. Calls for thorough surface preparation prior to application	A more complex application procedure commonly calling for the use of specialized methods

Analyzing the data in Table 1, it can be concluded that Silokor-Antiled composition might be the preferred choice for most applications due to its accessibility and effectiveness. Graphene may actually be an optimal solution for specialized and high-load operating conditions, where its unique properties can be enhanced. Both compositions are successfully utilized to protect pitched roofs, gutters, mast structures from icing, for processing ceramic and polymer tiles, slate [11]. Given such a wide range of applications, these compositions can be considered for protecting the blades of a wind turbine in constantly recurring cycles of freezing and thawing. On top of that, the results of the analytical studies have confirmed that coatings using graphene are extremely promising. For example, Rice University scientists have proposed graphene nanoribbons should be employed as an effective de-icer for various surfaces including airplane wings, power lines, and helicopter blades [13, 14]. Graphene nanoribbons make up a bond in a composite by conducting an electric current through the material with a minimum load. The resulting electrothermal heat results in heating of an object surface. Meltwater forms between the surface and the ice in the course of melting allowing the ice to be removed without having to wait for the process to come to an end. Graphene coating is thus a promising material that can be applied to the surface of wind turbine blades or alternatively, graphene nanoribbons can be used reducing the likelihood of icing on the work surfaces and thus prolonging the service life of a facility.

As the application of hydrophobic coatings in this work is considered on an already erected and functioning wind turbine, there is a task of arranging this process. Instead of human labor or the use of bulky aircraft, coatings can be provided using an unmanned aerial vehicle (UAV). The integration of UAVs in the field of high-altitude work would enhance the efficiency of maintenance of wind turbines, since this field is poorly developed these days. Despite the time limitations of the use of UAVs for peaceful purposes, this tool remains extremely promising for tackling a whole host of tasks.

The suggested method of applying hydrophobic coatings to the surface of the blades of a wind turbine entails the selection of an appropriate UAV, as well as the development of a procedure for performing operations.

In order to implement spraying of hydrophobic compositions, the aircraft must be designed for suspended equipment to be set up on its body. The most suitable option is thus an agrotron which can be equipped with a suspension system for both sowing and spraying fields. In terms of of anti-icing, suspended spraying equipment will be employed to apply hydrophobic compositions to the surface of a wind turbine.

In order to apply hydrophobic compositions to the blades of a wind turbine, the following fly-around scheme can be employed (Fig. 2).

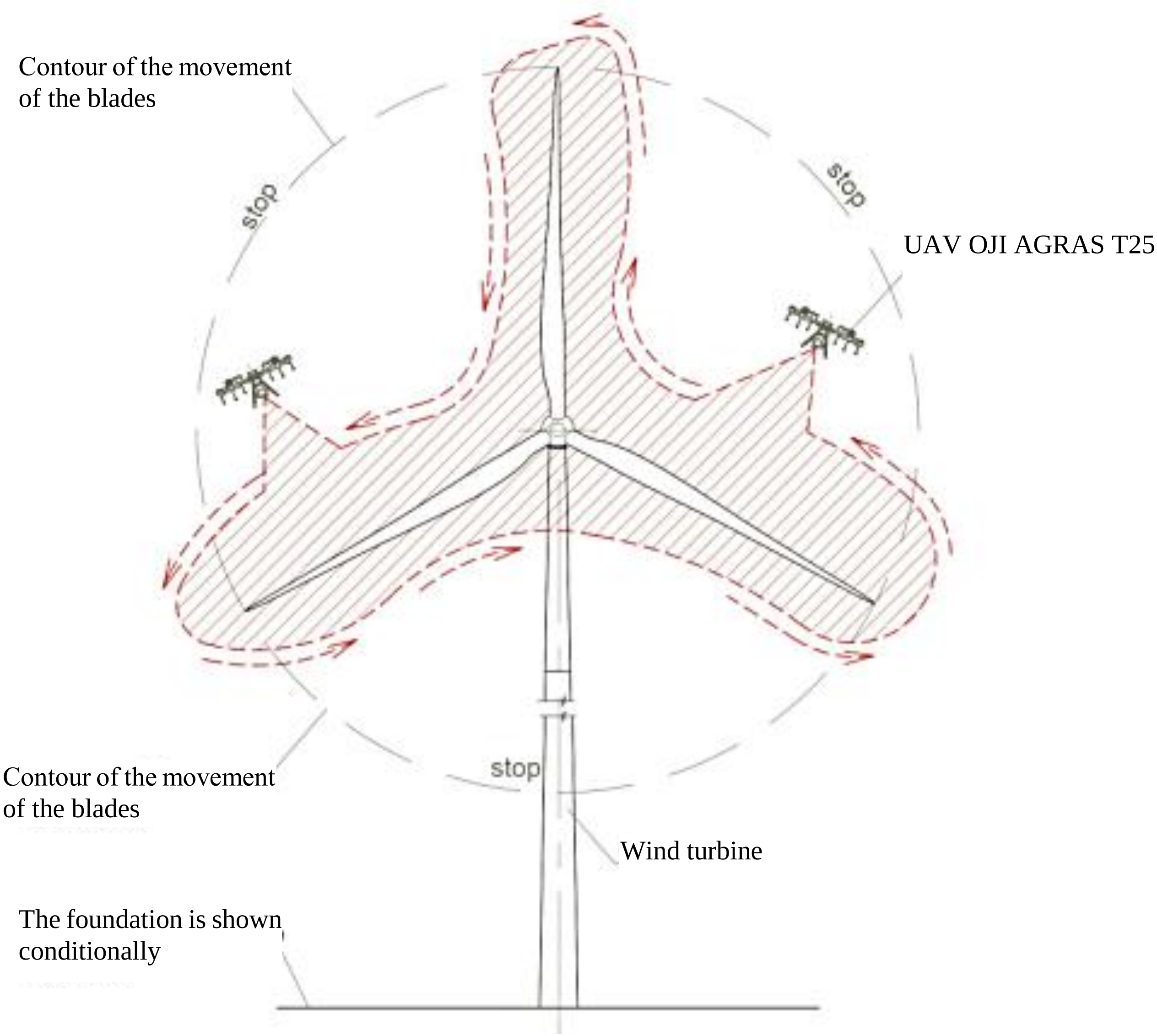

Fig. 2. Fly-around scheme for the treatment of blades with hydrophobic coatings using UAVs

The OJI EAGLES T25 UAV designed for agricultural needs was considered as an example. The device is capable of carrying up to 25 kg of useful load allowing it to be used for spraying large volumes of material. The time spent in the air is 15 minutes, and the control range is about 5 km enabling the operator to freely move and control the device at a long distance. A special feature of this UAV model is a high-precision spray system that ensures uniform distribution of the substance.

The device is also equipped with modern sensors and navigation systems, including GPS allowing it to closely follow set itineraries and avoid obstacles on the way. Agrotron can be equipped with multispectral cameras and sensors to collect data on the state of a coating assisting in making more informed technical decisions.

Based on the analysis of existing anti-icing methods and accounting for the flaws of current approaches in the context of the above problems, a technique for applying hydrophobic compositions to the surface of wind turbines using UAVs has been developed. The suggested methodology includes the following steps:

Preparing and collecting weather data. Prior to applying a hydrophobic composition to the blades of a wind turbine, up-to-date weather data, including wind speed, air temperature and humidity must be collected. These parameters are key to ensure the safety of UAV operation and the quality of surface treatment.

Preliminary fly-around of the wind turbine with photofixation. Possible places of ice formation as well as damage and problem areas must be identified. At this stage, hard-to-reach areas can also be evaluated and the flight time can be recorded.

Selecting and preparing a hydrophobic composition. Based on the characteristics of a wind-generating facility, climatic data and criteria in Table 1, an informed choice of hydrophobic materials should be made. Next, the solution is prepared and the ingredients are mixed in a prepared container.

Assembling and preparing the UAV. If necessary, an unmanned aerial vehicle equipped with a spray system should be assembled and refueled. All the elements must be in good order and set up properly.

Flying around the wind turbine and applying a hydrophobic coating. The hydrophobic anti-icing coating is applied in a few stages until a layer thickness of 50-70 mkm is achieved.

Stage 1. Controling the UAV with a complete fly-around of the wind turbine according to the scheme (Fig. 2) and applying the first layer of coating by means of a pneumatic method. An important task is to ensure the composition is distributed evenly over the surface of the blades.

Stage 2. Drying of the first layer within 15 minutes and applying the second layer of the hydrophobic composition in a similar manner ensuring the material is distributed evenly over the surface.

Stage 3. After complete drying, there is a fly-around of the wind turbine and the third coating layer is applied.

Controling the coating quality. To control of the coating quality visually for defects, it is necessary to fly around the wind generator with photo (video) fixation. If defects are detected, adjustments must be made by applying another layer of a hydrophobic coating.

Documentation and reporting. Work progress must be reported including the time and date of the work, weather conditions, the selected composition of a hydrophobic coating and all the stages of applying the composition to the working surfaces of the wind turbine.

Discussion and Conclusion. Effective management of the life cycle of wind power plants as capital construction objects entails the use of an integrated approach combining management decisions at all the stages: from the design concept to operational monitoring.

The primary objective of the operational period of a wind power facility is to enhance productivity while increasing its operational life. This is achieved by means of a preventive analysis of potential operational risks and their mitigation at the initial stages of the life cycle of a facility. The developed methodology for combating icing of blade elements is indicative of the diversity of its application both in existing wind power structures that are not equipped with specialized de-icing systems and for promising projects. At the same time, the complex of de-icing measures can be assigned in the design documentation as imperatives both at the construction stage and as part of routine operation maintenance.

Introducing preventive measures at the design preparation stage ensures a considerable increase in the service life of wind power facilities operated under adverse climatic conditions with high humidity and low temperature conditions. The results obtained throughout the study are thus a theoretical and methodological foundation for implementing multidimensional lifecycle management of wind power facilities positioned as an essential segment of the modern construction sector.

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