ABSTRACT

to the dissertation for the degree of Doctor of Philosophy (PhD) in specialty 6D071800 – "Electric Power Engineering"

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Dissertation topic: "Studying the efficiency of the electric power generation system of an automatically controlled sailing wind power plant"

Relevance of the study. The environmental situation in the modern world associated with global warming due to greenhouse gas emissions, necessitates replacing fossil fuels with renewable energy sources (RES). In this regard, the use of RES in the form of wind turbines and increasing the efficiency of converting wind energy into electrical energy are of interest. Currently, turbine wind power plants (TWPPs) with horizontal and vertical rotor axes are widely used. A comprehensive and critical analysis of various technical solutions and research in the field of wind energy shows that they are primarily aimed at improving TWPPs. Many studies yield isolated positive results without addressing the main problems. For both types of TWPPs, the unpredictability of wind conditions, the speed and strength of wind gusts, which often change over short periods of time, remains a problem. Furthermore, the lower limit of the wind speed range at which TWPPs operate at rated power is typically quite high: approximately 8 m/s with the maximum efficiency of 0.3. The most suitable alternative to the TWPPs is a small automatically controlled sailing wind power plant (SACSWPP). Its distinctive feature is its design consisting of a six-piece movable parallel manipulator and a swinging wind-powered working element (WE) consisting of an aerodynamically profiled sail that captures wind energy, and a mast rigidly connected to the upper platform of the parallel manipulator. The key advantage of the SWPP is that it operates independently of wind direction and has a power generation system consisting of six electric generators located at the bases of the six manipulator actuators. Therefore, integrated and comprehensive research and development aimed at creating power generation systems for small-scale autonomous wind power sources based on swinging sails located on platforms of parallel manipulators is essential.

This is particularly important for Kazakhstan, which has large areas with low wind speeds and weak energy infrastructure, especially in areas remote from power lines.

The goal and objectives of the study. The SWPP design consists of a manipulator converter (MC) with the SHOLKOR parallel manipulator topology and an end-effector composed of a sail(s) with an aerodynamic cross-section profile and a mast rigidly connected to the SWPP upper platform. Functionally, the conversion of mechanical wind energy into electrical energy is performed by the MC, in which the main unit consists of six actuators, each actuator containing an electric current generator. Thus, the efficiency of the SWPP generation system is determined by the

efficiency of the mechanical energy conversion into electrical energy, which is accomplished by the actuators.

The goal of the dissertation is developing and improving the power generation system for a sail-based wind power plant.

To achieve this goal, the dissertation consistently addresses the following objectives:

• Developing mathematical simulation models for predicting wind speed and direction using artificial intelligence methods based on experimental wind data.

• Developing a methodology for a comprehensive study of the efficiency of a sail-based wind power plant power generation system, including wind forecasting, a power analysis of the structure, and determination of the input power of the actuators during the plan operating cycle.

• Developing and implementing an experimental setup for studying a parallel manipulator actuator with an integrated electric generator and determine its efficiency under laboratory conditions while reproducing the predicted load.

• Developing and studying the structure of the power generation and storage system for an automatically controlled sail-based wind power plant using six synchronous generators and six batteries.

Object and methods of the study. The research object of this dissertation is the actuator of a small automatically controlled sail-based wind turbine. To solve the above-mentioned problems, theoretical and experimental research methods were used, and energy balance equations were obtained for the most functionally important component, the MP actuator, which serves as the source of electrical energy. Using the SolidWorks software, an experimental setup was designed and built to study the efficiency of the wind turbine generation system. The MatLab and the Mathcad software were used for computer modeling of the generation system. Patterns of wind speed and direction changes for various wind conditions (wind speed ranges) were obtained in the form of data arrays. By creating and training a multilayer neural network in the Python, these datasets allowed for predicting the wind conditions at the wind turbine installation site.

Main scientific provisions and research results submitted for defense

- Mathematical simulation models for wind load forecasting using artificial intelligence methods, ensuring the generation of reliable initial data for the experiment.
- Energy efficiency assessment of a parallel manipulator actuator with an integrated electric generator, based on a developed comprehensive analytical and experimental methodology, including input power forecasting, a power analysis of the SWPP design, and laboratory determination of the actuator efficiency.
- A developed system for generating and storing electrical energy, including six synchronous generators and six batteries, along with a battery protection system to protect against deep discharge.

Scientific novelty

- Mathematical simulation models for predicting wind loads for an automatically controlled sail-based wind turbine were developed using artificial intelligence methods. These models allow for predicting wind speed and direction values for further energy analysis of the system.

- A comprehensive methodology for experimentally determining the efficiency of a parallel manipulator actuator with an integrated electric generator was proposed and implemented based on reproducing predicted input power under laboratory conditions.
- The structure of the electric power generation and storage system for a sail-based wind turbine, including six synchronous generators and six batteries, was designed and analyzed. A deep discharge protection system was also developed.

Practical significance. As a result of this dissertation, tools were developed for improving the energy efficiency of a wind turbine power plant (WTPP) by enhancing the efficiency of the MP actuator. These tools were used to develop a pilot design for a small SWPS with the capacity of 5 kW.

Reliability of the results is confirmed by using experimental data as an input for wind analysis. Software was used in the form of modern application packages such as the Python, the Mathcad, and the MatLab. The experimental analysis of the studied object was conducted on a specially designed rig, in which data preparing, testing, and processing of experimental results were performed according to a program using an Arduino controller.

Author's personal contribution. The author personally completed the tasks set out in the dissertation. Specifically, he utilized his skills and abilities in the Python and Mathcad and prepared a sketch in the Arduino IDE development environment. The author developed a comprehensive methodology for conducting an experimental study to determine the efficiency of the SWPP actuator. He designed the test rig, prepared and configured it, and conducted experimental tests to determine the actuator efficiency. In published scientific works, a significant share belongs to the author.

Connection of the dissertation topic with state programs and the university's work plan. This work was conducted at S. Seifullin Kazakh Agrotechnical Research University (Kazakhstan), funded by the IRN grant project AP14869386, "Studying, Developing a Set of Designs, and Creating a Pilot Prototype of an Automatically Controlled Sailing Wind Power Station with an Oscillating Working Element". As part of this project and as a result of the research conducted, a pilot design of the sailing wind power station was designed, and an **implementation certificate was issued.**

Validation of the dissertation results

An article on the results and key findings of the dissertation was published in a journal indexed in the Scopus database with 85th percentiles. Three articles were published in journals recommended by the Committee for Control over Education and Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan. Furthermore, the dissertation materials were included in the Final Report on the topic of IRN grant AP14869386, state registration number 0122PK00575, 2025.

The structure and volume of the dissertation. The dissertation is presented as a 101-page computer text consisting of an introduction, 5 chapters, a conclusion, and 5 appendices. It includes 26 figures, 7 tables, a conclusion, a list of references with 100 sources, and 5 appendices.

The introduction of the dissertation substantiates the relevance of the dissertation topic and formulates the goal and objectives of the study. It presents the main idea, scientific novelty, research results, and publications.

The first section analyzes the existing scientific research in the field of wind energy and the energy sector in Kazakhstan in particular. Based on the analysis of studies from the literature review in the field of electric power and wind energy, the shortcomings of modern wind power plants are highlighted. Given these shortcomings inherent in wind power plants, the dissertation sets the goal of developing and improving a wind power generation system. It proposes using and improving a wind power system by studying and increasing the efficiency of generation and storage systems with six synchronous generators and a calculated number of batteries. This solution is particularly important for Kazakhstan, which has vast territories with low wind speeds and weak energy infrastructure, especially in areas remote from power lines. Therefore, improving automatically controlled wind turbines with oscillating sails by increasing the efficiency of the wind farm's generation system is a pressing and important task in today's environment. For widespread use, wind turbine power plants (WTPPs) must operate at low wind speeds, regardless of wind direction, with high efficiency, that is, with a sufficiently high efficiency. The efficiency of a WTPP largely depends on the efficiency of the key component, the actuator, which directly converts mechanical energy into electrical energy. To evaluate the actuator efficiency, the author proposes using the actuator efficiency metric.

Section 2 of the dissertation focuses on processing experimental data on wind conditions. Since wind conditions are stochastic in nature, the study utilizes an artificial intelligence method to create predictable wind patterns. This section contains research materials on the formation of predicted patterns in wind characteristics (speed and direction). Previously obtained second-by-second wind speed and direction values at a height of 14 meters were used. This extensive Excel database was generated by the controller using measuring instruments. The program written in the Python is then used to extract the previously obtained database and create a database for four wind speed ranges: [0-5], [up to 10], [up to 15], and [over 15]. These databases consist of random values. Therefore, by creating and training a multilayer neural network in the Python, wind speed change patterns for various wind conditions (wind speed ranges) are obtained in the form of data arrays. This data array is then used to calculate the wind power plant's predictable wind speed and to determine the calm and energy periods. The results obtained at this stage are new and can be used by other researchers in relation to any wind power plants, for example, to determine the battery capacity of autonomous wind power plants. It is also possible to use other data as input, for example, data obtained by meteorological stations. A method of determining the calm period is also proposed in this section on predictable wind characteristics. It is shown that determining the maximum calm time allows selecting the capacity of batteries for the storage system of the sailing wind power plant.

In **section 3,** the methodology adopted in this dissertation aimed at an experimental study of the power generation system, continues to be implemented. The problem of simulating the effect of a predicted wind load on a manipulator converter (MC) is solved to determine the predicted input power to the actuator. A previously developed SHOLKOR algorithm for force analysis of the parallel manipulator (PM) is used. Wind characteristics predicted using the Python, as well as design data from a real SWPP prototype, were used as an input for the calculations. The Mathcad software was used for mathematical simulation modeling. The problem was solved in stages: first, a mathematical model was developed for force analysis of the MC using the kinetostatic method. This resulted in a system of equations that allowed determining the components of the reaction forces on six actuators. Next, by examining the kinematics of the working element (WE) consisting of a mast, a sail, and a manipulator, using the homogeneous matrix transformation method, there were determined the increments in actuator carriage displacements for small deviations of the WE from the vertical orientation during forward and reverse pendulum-like swinging motion. The obtained results allowed determining the predicted input power of the selected minimally loaded manipulator during spatial movements of the WE. The minimally loaded actuator was selected because the actuator is evaluated based on its minimum efficiency when generating electric current.

Based on the analytical model of the wind turbine power plant (WTPP) previously developed by the authors, a modified algorithm for the force analysis of a canopy wind turbine power plant (CWTPP) has been developed using the Mathcad software. This algorithm differs in that the input data for this wind situation are the wind characteristics predicted for the given wind situation, obtained in section 2, using the Mathcad function for exchanging information with the Excel spreadsheet program. Furthermore, the initial data for the calculations includes the parameters of a 5 kW WTPP prototype. The developed program allows for the determination of the predicted loads and their powers acting on the input of each of the six actuators depending on the wind characteristics. This program can be further used in strength and reliability calculations for components, assemblies, and the SWPP as a whole. Using the Mathcad program exchange function, the calculated data on the predicted input power at the actuators for various predicted wind speeds and directions is exported to Excel.

In **section 4,** an automatically operating rig for experimental studying the actuator efficiency was designed and proposed. The rig comprises an actuator and a pneumatic system automatically controlled by an Arduino controller, implementing a predicted input load, along with a compressor, as well as control and measuring equipment. Here, the efficiency of the minimally loaded actuator of the wind turbine power plant was experimentally determined to be equal to $\bar{\eta} = 0{,}56 \div 0{,}58$. This result was obtained using previously generated data on the predicted input power, which in turn was obtained through mathematical simulation modeling based on predicted wind characteristics. The experimental study process, as well as data collection and processing, were automated. An Arduino controller and a program developed in the Arduino IDE environment were used for this. To confirm reliability of the obtained results, a histogram and a probability density plot of the efficiency and the Weibull distribution were plotted, which confirmed the experimental results to determine the actuator efficiency. Such an experiment allows evaluating the effectiveness of the selected actuator design parameters. The methodology used opens up opportunities to improve the design of wind turbine power plants by selecting parameters that ensure the highest efficiency in converting wind energy into electrical energy. Overall, it should be noted that a solution has been found to the technical problem of assessing the energy efficiency of wind turbine power plants by experimentally determining the actuator efficiency.

Section 5 of the dissertation notes that a distinctive feature of the studied wind turbine power plant is its actuator power take-off system that consists of two rack-and-pinion transmissions, as well as an electric machine generating electric current. Therefore, this section analyzes the electrical machines, selecting a Naier Wind Power PMSG synchronous generator (1000W 24V/500rpm). Six three-phase synchronous alternating current generators were selected, as generators are installed in each actuator. Because the generator shaft torque is random, electric current generated by each generator differs in characteristics. Therefore, this section presents a schematic diagram of the electrical energy generation and storage system based on the conversion of alternating current to direct current and subsequent parallel connection to a common bus with electrochemical secondary elements. This system, through an output inverter, supplies the consumer with alternating current of the required power. Based on the developed circuit diagram, an experimental model of a power generation and a storage system was developed, including an automatic battery protection subsystem for deep discharge. Tests were conducted on the experimental model. These tests demonstrate that the developed power generation and storage system with a deep discharge protection subsystem can be used in the prototype wind power sail turbine.