DOI 10.51885/1561-4212_2025_4_131
IRSTI 44.39.29

EXPERIMENTAL ANALYSIS OF THE ENERGY EFFICIENCY OF A SAIL WIND POWER STATION ACTUATOR

ЖЕЛКЕНДІ ЖЕЛ ЭЛЕКТР СТАНЦИЯСЫНЫҢ ЖЕТЕГІНІҢ ЭНЕРГЕТИКАЛЫҚ ТИІМДІЛІГІН ЭКСПЕРИМЕНТТІК ТАЛДАУ

ЭКСПЕРИМЕНТАЛЬНЫЙ АНАЛИЗ ЭНЕРГЕТИЧЕСКОЙ ЭФФЕКТИВНОСТИ ПРИВОДА ПАРУСНОЙ ВЕТРОЭНЕРГЕТИЧЕСКОЙ УСТАНОВКИ

K.S. Sholanov [1], N.B. Zhakipov [2], G.Zh. Assainov [3*], B.N. Gorbunov [4], K.M. Tleumbetov [5]
NJSC «Kazakh Agrotechnical Research University named after S. Seifullin», Astana, Kazakhstan
*Corresponding author: Assainov Gibrat Zholamanovich, e-mail: asainovgibrat@gmail.com

Keywords:
Actuator, sail wind power station, parallel manipulator, efficiency, power.

ABSTRACT
The article is devoted to the creation of a system for generating and accumulating electrical energy by the electrochemical method in an autonomous sailing wind power plant (SWPP) with a swinging sail. The (SWPP) uses new equipment and technology to convert wind energy into electricity. The technical feature is that the wind energy conversion uses a parallel SHOLKOR manipulator made up of six actuators with electric current generators. The technological feature of the wind turbine is that the working body that perceives wind energy does not perform rotational motion, but performs spatial rolling in the form of a reverse pendulum. The aim of this article is to create an efficient electrochemical energy storage system generated by a wind-powered sailing power plant, which, as indicated, consists of six 3-phase synchronous alternating current generators. This system provides the consumer with an alternating electric current of the required power through the use of an inverter. Based on the developed scheme, an experimental generation and storage system has been created, containing a subsystem for automatic protection of batteries from deep discharge. The experimental system has been tested for the possibility of functioning. The test results showed that the developed generation and storage system can be used in the created prototype of a sailing wind power plant.

Түйінді сөздер:
Жетек, желкенді жел электр станциясы, параллель манипулятор, тиімділік, қуат.

ТҮЙІНДЕМЕ
Мақала желкенді желкенді жел электр станциясында (ЖЖЭС) электрохимиялық әдіспен электр энергиясын өндіру және жинақтау жүйесін құруға арналған. ЖЖЭС жел энергиясын электр энергиясына айналдырудың жаңа техникасы мен технологиясын қолданады. Техникалық ерекшелігі – жел энергиясын түрлендіруде электр тогының генераторлары бар алты актуатордан тұратын параллель SHOLKOR манипуляторы қолданылады. Бұл технологияны жүзеге асыру үшін кеңістікте тербелетін аэродинамикалық парус (кері маятникке ұқсас) қолданылады, ол бір мезгілде сүйреу және көтеру күштерін қабылдайды ЖЖЭС-тің технологиялық ерекшелігі – жел энергиясын қабылдайтын

жұмыс органы айналмалы қозғалысты жасамайды, керісінше кері маятник түрінде кеңістіктік айналуды орындайды. Осы мақалада жел желкенді электр станциясы өндіретін энергияны сақтайтын тиімді электрохимиялық жүйені құру мақсаты қойылған, оның құрамында алты 3 фазалы синхронды айнымалы ток генераторлары бар. Бұл жүйе тұтынушыны Инверторды қолдану арқылы қажетті қуаттың айнымалы токымен қамтамасыз етеді. Әзірленген схема негізінде аккумуляторларды терең разрядтан автоматты түрде қорғаудың ішкі жүйесі бар эксперименттік генерациялау және жинақтау жүйесі құрылды. Эксперименттік жүйенің жұмыс істеу мүмкіндігіне сынақтар жүргізілді. Сынақ нәтижелері әзірленген генерациялау және жинақтау жүйесін желкенді жел электр станциясының жасалған прототипінде пайдалануға болатынын көрсетті.

Ключевые слова:
Исполнительный механизм, парусная ветроэлектростанция, параллельный манипулятор, КПД, мощность.

АННОТАЦИЯ

Статья посвящена созданию системы генерирования и аккумулирования электрической энергии электрохимическим методом, в автономной парусной ветровой электростанции (ПВЭС) с качающимся парусом. ПВЭС использует новую технику и технологию преобразования энергии ветра в электрическую. Техническая особенность заключается в том, что в преобразования энергии ветра применяется параллельный манипулятор SHOLKOR составленный из шести актуаторов с генераторами электрического тока. Технологическая особенность ПВЭС заключается в том, что рабочий орган воспринимающий энергию ветра, совершает не вращательное движение, а выполняет пространственное качения в виде обратного маятника. В настоящей статье ставится цель создать эффективную электрохимическую систему аккумулирующую энергию, вырабатываемую ветровой парусной электростанцией, имеющей, как указывалось в своем составе шесть 3-х фазных синхронных генераторов переменного электрического тока. Эта система обеспечивает потребителя переменным электрическим током требуемой мощности за счет применения инвертора. На основе разработанной схемы создана экспериментальная система генерирования и аккумулирования, содержащая подсистему автоматической защиты аккумуляторов от глубокого разряда. Проведены испытания экспериментальной системы на возможность функционирования. Результаты испытания показали, что разработанная система генерирования и аккумулирования может быть использована в созданном опытном образце парусной ветровой электростанции.

INTRODUCTION

Due to the adverse environmental climate changes, the widespread replacement of organic fuels with renewable energy sources (RES) is currently relevant. One of the priority RESs is wind power stations (WPS) since wind energy reserves amount to about 1.26 × 10^9 MW (Tong W 2010), which is 20 times higher than all the energy needs of the world. It is known that turbine wind power stations (TWPS) with horizontal (Sutherland 2012 – Anup 2018) and vertical rotor axes, including Darrious and Savonious rotary turbines (Didane 2020 – Banna 2014), are currently widespread in the world. At the same time, an analysis of research in the field of wind energy shows that they are mainly aimed at improving the TWPSs. However, the unpredictability of wind, the speed, and strength of wind gusts, which often change in short periods of time, remains a problem for both types of TWPSs, as well as the fact that the lower limit of the range of wind speeds, at which TWPSs operate with rated power, is typically quite high, i.e. about 10 m/s with a maximum efficiency of 0.3 (Premalatha 2014 – Sholanov 2020). One of the fields in the development of wind energy in recent years is automatically controlled small sail wind power stations (SWPS), as proposed in (Sholanov 2021 – Sholanov 2022). These SWPSs use a new technology for converting wind energy into electrical energy. In order to implement this technology, an aerodynamic sail swinging in space (similar to a reverse pendulum), which simultaneously perceives drag and lift forces, as well as a manipulating transducer (MT) from a parallel Sholkor manipulator, is used (Alzayed 2021). The MT, due to its topology and the design of the working body (WB), composed of a sail, mast, and upper platform of the manipulator, converts wind energy into electrical energy. This is made possible by the fact that the design of the six-movable MT includes six actuators connecting the upper platform to the lower one. Moreover, each actuator includes a semi-active damper system, a power take-off system, and an electric current generator. The studies conducted have shown that small automatic SWPSs (with a capacity of 1-10 kW) may independently generate electric energy when wind speeds change in a wide range, starting from 2.5 m/s and higher, regardless of the wind direction. This feature of the SWPS makes it possible to expand the geography and scope of wind energy applications. It is known that to identify actual problems and analyze potential solutions in wind power stations, power parameters are used, for example, the efficiency of turbines (Chen 2023- Wu 2022). An analysis of these and other studies shows that power indicators are the most effective tool for assessing the energy efficiency of the SWPS. This paper proposes to investigate experimentally the efficiency of the prototype actuator since it is the actuator that is the most responsible unit of the SWPS in terms of functionality, and it determines the energy efficiency of the SWPS as a whole.

The experimental unit (stand) for determining the efficiency of the actuator (Fig. 1) consists of a controlled pneumatic system including a cylinder 1 with a diameter of 125 mm, a rod 3, a device 6 for simulating the load of the working body, as well as a prototype actuator 8 of the prototype SWPS, a compressor 9, and a 500-watt synchronous alternator 15. The unit includes control and measuring instruments, such as reed switch 2, pressure sensor 4, throttle 7, displacement sensor 16, voltage sensor 10, pneumatic distributor 11, Arduino controller 12, and current sensor 14.

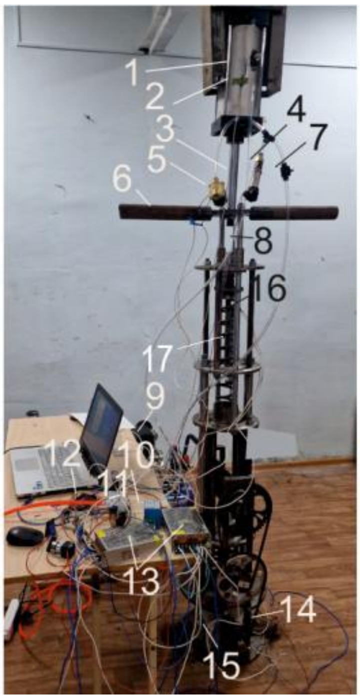


Figure 1. A stand for determining the efficiency of the actuator
Note – compiled by the author based on data from Sholanov, 2024

MATERIALS AND METHODS

The actuator layout included in the stand and the principle of its operation are described in (Sholanov 2020 – Sholanov 2022). The stand also includes a controlled pneumatic system that simulates the power load acting on the actuator from the side of the working body of the SWPS as a result of wind forcing. The load and speed of the actuator carriage in different wind situations are preliminarily determined using the Mathcad software (Sholanov 2020). Figure 2 shows a layout of the pneumatic system in conjunction with the control and measuring instruments. The items in Figure 2 indicate: 1 - double-acting pneumatic cylinder; 2 - 3-position pneumatic distributor; 3 - electromagnet controlling the pneumatic distributor; 4 - throttle; 5 - quick-exhaust valve; 6 - digital pressure gauge; 7 - end sensor; 8 - carriage displacement sensor; 9 – generator devices (CS - current sensor, VS - voltage sensor). The movement of the rod connected to the actuator carriage is set using the end sensor 2 (Fig.1) and is measured by the sensor 16. The power at the actuator inlet is generated by setting the required pressure in the pneumatic system (measured by the digital pressure gauge 6) and selecting the speed of movement of the rod using an adjustable throttle 4. The output power at the outlet of the actuator is determined by the controller according to the data of the digital voltage and current sensor 9, which is generated by the electric machine. The cyclic movement of the pneumatic cylinder rod 1 is provided by the solenoid valves 3 of the pneumatic distributor 2. When the rod reaches the end position, the normally closed exhaust valves 5 are on, and the rod returns to its initial position by restoring the compressed spring 17.

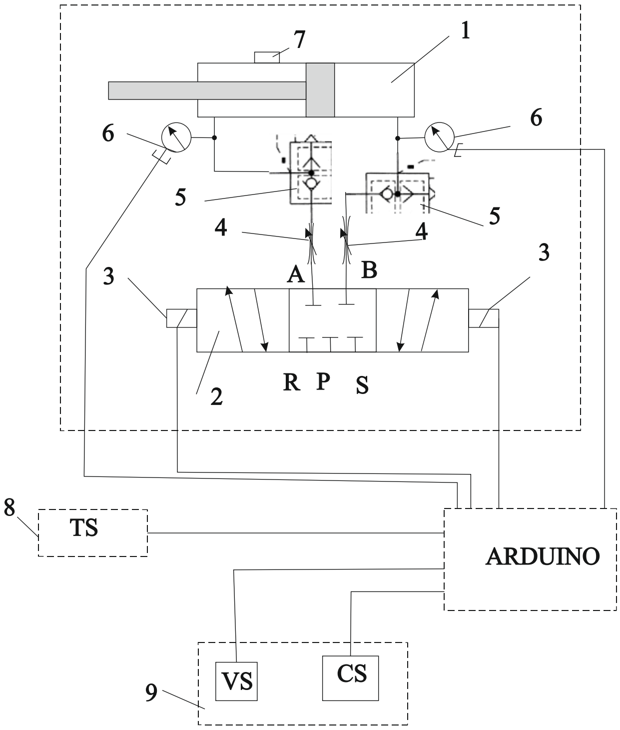


Figure 2. Pneumatic system layout with measuring instruments

Note – compiled by the author based on data from Sholanov, 2023

An experiment to determine the efficiency of the actuator is carried out in the case of an increase in the length of the actuator, at which the upper spring 17 is compressed (Fig. 1). Experiments are conducted for the predicted pattern of changes in wind speed and direction within the selected range (up to 5 m/s) of wind speed changes (Sholanov 2024). The input powers on the minimally loaded manipulator actuator obtained as a result of calculations according to the algorithm and program described in (Sholanov 2020) are used as the initial data. In the experimental unit, the input power (N_i) equal to the calculated one is provided by manually setting the pressure built up by the compressor, as well as the speed of the rod using a throttle. The maximum movement of the rod is set using the end sensor and is assumed to be 60 mm, which corresponds to the deviation of the mast from the vertical by an angle of 2°. The pressure in the pneumatic system is measured by a digital pressure gauge. The force, (P), on the rod is determined on the controller by the expression

$$P = \pi(d)^2/4 \times p, \text{H}. \quad (1)$$

where: d and p – the diameter of the piston and the pressure in the cylinder, respectively. Based on the calculation of the input power for the piston movement cycle;

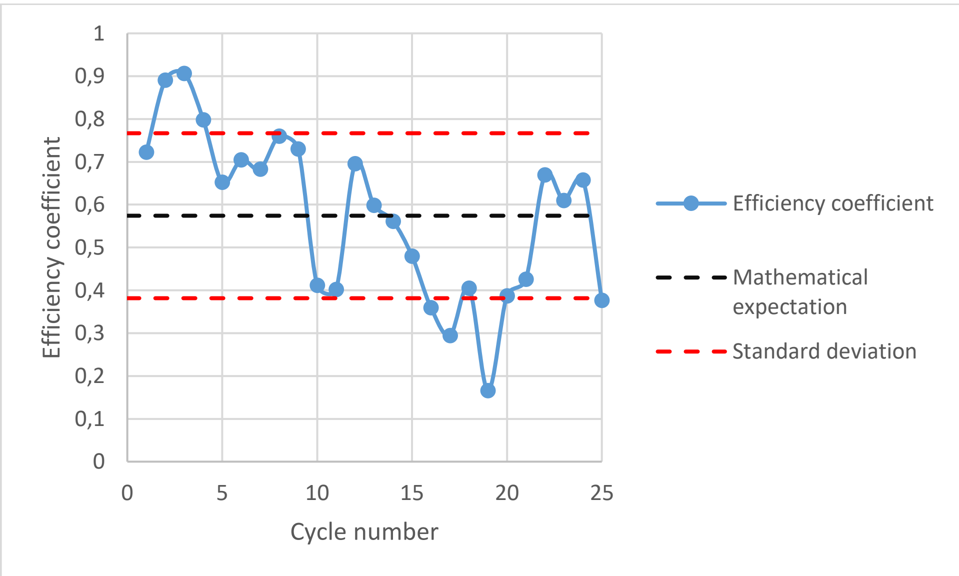
(v_i) – speed of the rod movement is determined from $v_i = N_i/P$ m/s. The time of the piston movement cycle is determined from the ratio t_c=2s/v, s is the carriage stroke;

N_o – the output power, on the actuator is determined as the power of the generated electric current equal to the product of the current measured using a digital ammeter and the voltage measured by a digital voltmeter;

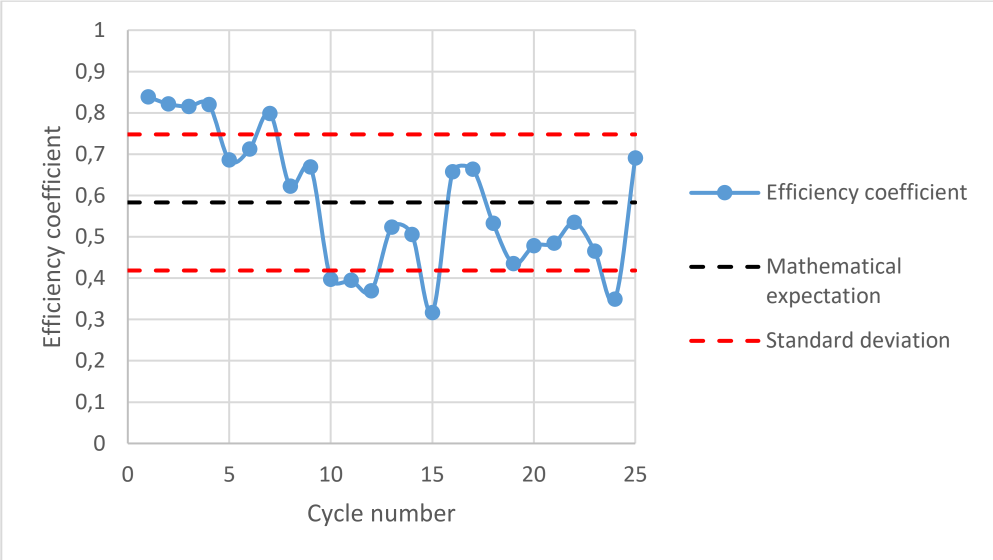
η – the efficiency of the actuator is determined by the ratio of processing and calculation on the controller, $\eta = \frac{N_o}{N_i}$.

RESULTS AND DISCUSSION

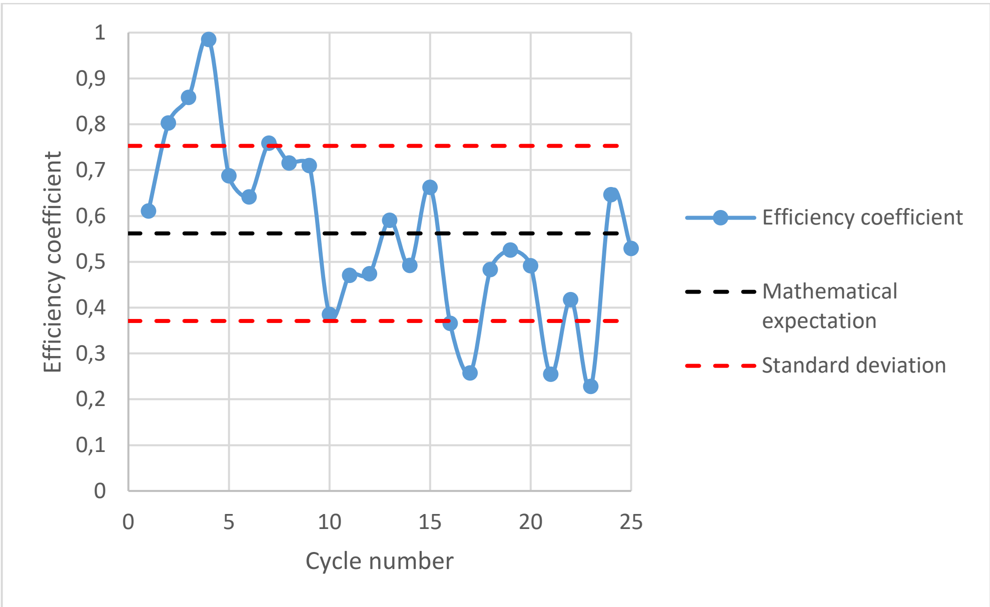
The initial collection and processing of experimental data were carried out by the controller based on measurements of digital sensor data and processing of the input source data. In order to obtain a pattern of changes in the efficiency of the actuator, 50 experiments were conducted. Each experiment included 25 measurement cycles, within which the following summary data were determined: cycle duration time, ms; pressure value, Pa; carriage movement per cycle, mm; voltage of phase 1, V; voltage of phase 2, V; voltage of phase 3, V; current of phase 1, A; current of phase 2, A; current of phase 3, A; pressure per cycle, Pa; applied force per cycle, N; full carriage stroke, mm; carriage speed, m/s; output power per cycle received from the generator, W; input power per cycle during reciprocating movements of the rod, W; efficiency value per experience.



a)



b)



c)

Figure 3. Diagrams of changes in the efficiency of the actuator

Note – compiled by the author based on data from Zhakipov, 2024

Figure 3 shows diagrams of efficiency changes obtained as a result of three experiments, in which, according to the calculation results in each experiment, the input power on a minimally loaded actuator is assumed to be: exp. 1 - N_{in} = 273.79 W, exp. 2 - N_{in} = 159.40 W, exp. 3 - N_{in}= 137.4 W. Similar data was generated in other experiments based on input power values on a minimally loaded actuator. As a result of processing some of the experimental data, taking cycles (*n=25*), diagrams were constructed for three experiments (Fig.3 *a,b,c*) differing in the input power of a minimally loaded actuator, N_k. At the same time, statistical characteristics such as mathematical expectation, $\bar{\eta}$, variance, D, and standard deviation, σ, are also determined (Table 1).

Table 1. Statistical data

k – numbers of experiments	N_k, W	$\bar{\eta} = \frac{1}{n}\sum_{n}\eta_i$	$D = \frac{1}{n}\sum_{n}\eta_i^2 - \bar{\eta}^2$	$\sigma = \sqrt{D}$
1	273.79	0.57420972	0.037091554	0.192591678
2	159.40	0.583135188	0.027115193	0.164666915
3	137.47	0.561884608	0.036480048	0.190997507
Note – compiled by the author based on data from Gorbunov, 2024				

The efficiency values obtained in the three experiments have a fairly large spread of values, confirmed by the indicators of variance and standard deviation. But at the same time, the mathematical expectation of efficiency turned out to be very stable within the range of 0.56-0.58. In order to confirm the reliability of the results obtained, a histogram and graph of the probability density distribution of the efficiency and distribution of the Weibull function (16) with parameters k = 3 (scalability coefficient) and c = 0.641758 (shape coefficient) were constructed.

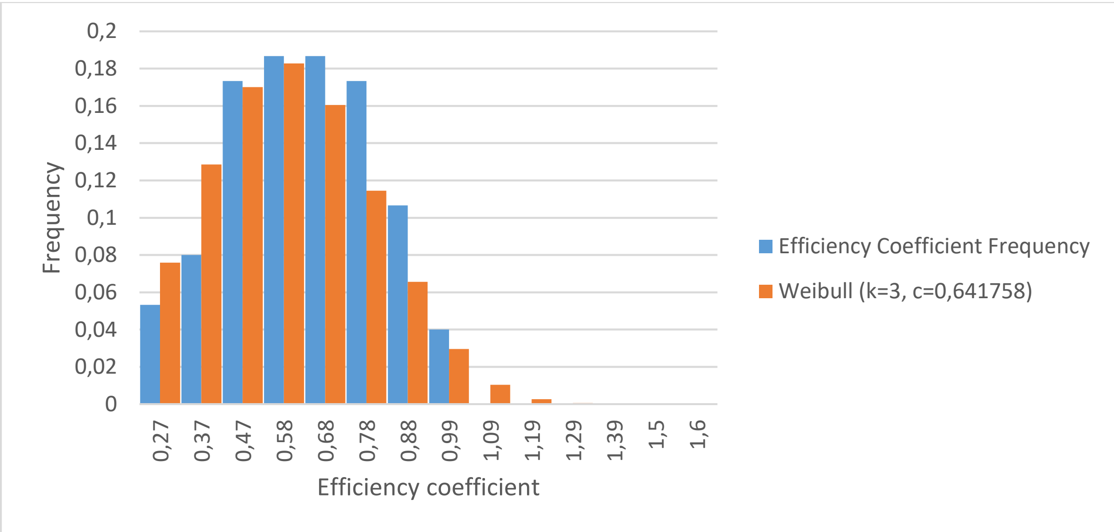


Figure 4. Histograms of the density distribution of efficiency values
Note – compiled by the author based on data from Tleumbetov, 2024

The histograms (Figure 4) indicate the sufficient reliability of the efficiency data, $\bar{\eta} = 0{,}56 \div 0{,}58$.

CONCLUSION

The results of the paper are aimed at obtaining a tool for solving the tasks of improving the design of the SWPS. These tasks are solved with respect to the most functionally important unit, which is the manipulator transducer actuator. The paper proposes to use the energy parameter, i.e. the efficiency coefficient, to assess the design parameters of the SWPS prototype actuator.

In order to solve the task of determining the efficiency value of a prototype actuator, an experimental unit, which includes a prototype actuator, a controlled pneumatic actuator, and control and measuring equipment, was constructed. The efficiency value of the minimally loaded actuator is determined at the experimental unit. For this purpose, the predicted input power is simulated by the pneumatic actuator of the experimental unit, and the power of the electric energy generated by the generator is determined using instruments. As a result of processing the experimental data, a confidence value of the efficiency of the prototype actuator was obtained,

$\bar{\eta} = 0{,}56 \div 0{,}58$. This experiment opens up opportunities to improve the design of the SWPS by selecting the parameters that ensure the greatest efficiency in converting wind energy into electrical energy, the indicator of which is the highest efficiency.

CONFLICT OF INTEREST: The authors declare no conflict of interest.

FUNDING: This scientific paper is the result obtained during the implementation of the project (IRN AP26198145 " Development of Structures, Creation of Modifications and Energy Accumulation Systems for an Experimental Prototype of Automatic Sail Wind Power Station"), funded under the grant by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan.

REFERENCES

Tong, W. (2010). Fundamentals of wind energy. WIT Transactions on State of the Art in Science and Engineering, 44, 3–48. https://doi.org/10.2495/978-1-84564-205-1/01

Sutherland, H. J., Berg, D. E., & Ashwill, T. D. (2012). A retrospective of VAWT technology. SAND2012-0304, Sandia National Laboratories, California.

Anup, K. C., Whale, J., & Urmee, T. (2019). Urban wind conditions and small wind turbines in the built environment: A review. Renewable Energy, 131, 268–283. https://doi.org/10.1016/j.renene.2018.07.050

Didane, D. H., Maksud, S. M., Zulkafli, M. F., Rosly, N., Shamsudin, S. S., & Khalid, A. (2020). Performance investigation of a small Savonius-Darrius counter-rotating vertical-axis wind turbine. International Journal of Energy Research, 44, 9309–9316.

Bhutta, M. M. A., Hayat, N., Farooq Ali, A. U. Z., Jamil, S. R., & Hussain, Z. (2012). Vertical axis wind turbine – A review of various configurations and design techniques. Renewable and Sustainable Energy Reviews, 16(4), 1926–1939. https://doi.org/10.1016/j.rser.2011.12.004

Banna, H. U., Luna, A., Ying, S., Ghorbani, H., & Rodriguez, P. (2014). Impacts of wind energy in-feed on power system small signal stability. International Conference on Renewable Energy Research and Applications (ICRERA), 615-622. https://doi.org/10.1109/ICRERA.2014.7016459

Premalatha, M., Abbasi, T., & Abbasi, S. A. (2014). Wind energy: Increasing deployment, rising environmental concerns. Renewable and Sustainable Energy Reviews, 31, 270–288. https://doi.org/10.1016/j.rser.2013.11.019

Шоланов, К. С., Кабанбаев, А., Абжапаров, К. М. (2020). Исследование и выбор параметров автоматически управляемой ветроэнергетической установки с колеблющимися парусами // Sholanov, K. S., Kabanbayev, A., & Abzhaparov, K. M. *Issledovanie i vybor parametrov avtomaticheski upravlyaemoi vetroenergeticheskoi ustanovki s koleblyushchimisia parusami* [Study and selection of parameters of an automatically controlled wind power plant with oscillating sails] // *International Journal of Renewable Energy Research*. – 2020. – Vol. 11(2). – P. 723–737. https://doi.org/10.20508/ijrer.v10i2.10581.g7947 (In Russ.)

Шоланов, К. С., Мирзабаев, Б. И., Ceccarelli, M. (2021). Расширяемость выработки электроэнергии парусными ветроэнергетическими установками // Sholanov, K. S., Mirzabayev, B. I., & Ceccarelli, M. *Rasshiryaemost' vyrabotki elektroenergii parusnymi vetroenergeticheskimi ustanovkami* [Scalability of electric power generation by sail wind power plants] // *International Journal of Mechanics and Control*. – 2021. – Vol. 22(2). – P. 117–126. (In Russ.)

Шоланов, К., Омаров, А., Ceccarelli, M. (2022). Повышение эффективности преобразования энергии ветра в модифицированной парусной ветроустановке // Sholanov, K., Omarov, A., & Ceccarelli, M. *Povyshenie effektivnosti preobrazovaniya energii vetra v modifitsirovannoi parusnoi vetroustanovke* [Improving the efficiency of wind energy conversion in a modified sail wind turbine] // *International Journal of Mechanics and Control*. – 2022. – Vol. 23(2). – P. 101–110. (In Russ.)

Sholanov, K. S. (2020). Parallel manipulators of robots: Theory and applications. Springer. https://doi.org/10.1007/978-3-030-56073-77

Alzayed, M., Chaoui, H., & Farajpour, Y. (2021). Maximum power tracking for a wind energy conversion system using cascade-forward neural networks. IEEE Transactions on Sustainable Energy, 12(4), 2367–2377. https://doi.org/10.1109/TSTE.2021.3094093

Chen. (2023). A comprehensive overview of power converter applied in high-power wind turbine: Key challenges and potential solutions. IEEE Transactions on Power Electronics, 38(5), 6169–6195. https://doi.org/10.1109/TPEL.2023.3234221

Wu, C., Zhang, X.-P., & Sterling, M. (2022). Wind power generation variations and aggregations. CSEE Journal of Power and Energy Systems, 8(1), 17–38. https://doi.org/10.17775/CSEEJPES.2021.03070

Шоланов, К. С., Токишева, Г. С., Омаров, А. С., Кашкимбаева, Н. М., Исаева, Ж. Р. (2024). Генерация данных для проектирования парусных ветроэнергетических установок // Sholanov, K. S., Tokisheva, G. S., Omarov, A. S., Kashkimbayeva, N. M., & Isayeva, J. R. *Generatsiya dannykh dlya proektirovaniya parusnykh vetroenergeticheskikh ustanovok* [Data generation for the design of sail wind power plants] // *Bulletin of the Toraighyrov University. Energy Series*. – 2024. – No. 2. https://doi.org/10.48081/YRLV5945 (In Russ.)

Bidaoui, H., El Abbassi, I., El Bouardi, A., & Darcherif, A. (2019). Wind speed data analysis using Weibull and Rayleigh distribution functions: Case study: Five cities Northern Morocco. Procedia Manufacturing, 32, 786–793. https://doi.org/10.1016/j.promfg.2019.02.286

Авторлар туралы мәліметтер
Информация об авторах
Information about authors

Шоланов Қорғанбай Сағнайұлы – т.ғ.д, профессор «С. Сейфуллин атындағы Қазақ агротехникалық зерттеу университеті» КЕАҚ, Астана қ., Қазақстан

Шоланов Корғанбай Сағнайевич – д.т.н, профессор, НАО «Казахский агротехнический исследовательский университет им. С. Сейфуллина», г. Астана, Казахстан

Korganbay Sholanov – Doctor of Technical Sciences, professor, NJSC «Kazakh Agrotechnical Research University named after S. Seifullin», Astana, Kazakhstan,

e-mail: sholkor@gmail.com,

ORCID: https://orcid.org/0000-0002-2077-7883,

Нажмитден Жакипов – магистр., аға оқытушы, «С. Сейфуллин атындағы Қазақ агротехникалық зерттеу университеті» КЕАҚ, Астана қ., Қазақстан

Нажмитден Жакипов – магистр., старший преподователь., НАО «Казахский агротехнический исследовательский университет имени С. Сейфуллина», г. Астана, Казахстан

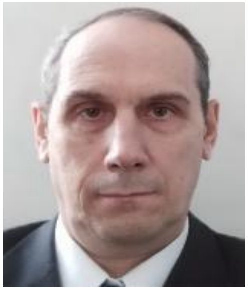
Nazhmitden Zakipov – Master's degree, senior lecturer., NJSC "Kazakh Agrotechnical Research University named after S. Seifullin", Astana, Kazakhstan,

e-mail: nazhmiden@mail.ru,
ORCID: https://orcid.org/0009-0005-7239-2095,

Гибрат Асаинов – PhD, қауымдастырылған профессор м.а, «С. Сейфуллин атындағы Қазақ агротехникалық зерттеу университеті» КЕАҚ, Астана қ., Қазақстан

Гибрат Асаинов – PhD, и.о асс. проф., НАО «Казахский агротехнический исследовательский университет им. С. Сейфуллина», г. Астана, Казахстан

Gibrat Assainov – PhD, Acting Associate Professor, NJSC "Kazakh Agrotechnical Research University named after S. Seifullin", Astana, Kazakhstan,
e-mail: asainovgibrat@gmail.com,
ORCID: https://orcid.org/0000-0002-1330-5909,



Борис Горбунов – т.ғ.к, доцент, «С. Сейфуллин атындағы Қазақ агротехникалық зерттеу университеті» КЕАҚ, Астана қ., Қазақстан

Борис Горбунов – к.т.н, доцент, НАО «Казахский агротехнический исследовательский университет им. С. Сейфуллина», г. Астана, Казахстан

Boris Gorbunov – Candidate of Technical Sciences, Associate Professor, NJSC "Kazakh Agrotechnical Research University named after S. Seifullin", Astana,
e-mail: b.gorbunov@kazatu.edu.kz,
ORCID: https://orcid.org/0000-0002-1719-0715,

Калдыбек Тлеумбетов – магистр., аға оқытушы, «С. Сейфуллин атындағы Қазақ агротехникалық зерттеу университеті» КЕАҚ, Астана, Қазақстан

Калдыбек Тлеумбетов – магистр., старший преподователь., НАО «Казахский агротехнический исследовательский университет им. С. Сейфуллина», Астана, Казахстан

Kaldybek Tleumbetov – Master's degree, senior lecturer., NJSC «Kazakh Agrotechnical Research University named after S. Seifullin», Astana, Kazakhstan,
e-mail: k.tleumbetov@kazatu.edu.kz,
ORCID: https://orcid.org/0009-0009-7666-2346,