GIDROENERGETIKA//ГИДРОЭНЕРГЕТИКА//HYDROPOWER

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COMPUTER MODELING OF MICRO-HYDROELECTRIC PLANT IN MATLAB/SIMULINK SYSTEM

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Abstract: Introduction. *As a result of the development of economic sectors in our republic, the increase in the standard of living, and the growth of the population, the demand for energy is rising. This situation greatly affects the development of the social and economic spheres, including the level of electricity supply to the agricultural sector of the country. One of the main solutions to mitigate these effects is the development and improvement of the efficiency of energy devices operating on renewable energy sources, particularly small-capacity hydroelectric plants.*

Methods and Materials. *The article presents a 3 kW dual-rotor hydropower device adapted to water flows coming out of pump units used in agriculture, modeled using the Matlab/Simulink software package.*

Results. *According to theoretical and experimental studies, the geometric dimensions of the guide apparatus were determined as follows: outer diameter 1 m, inner diameter 0.5 m, the number of guide vanes 16, the installation angle of the guide vanes β = -17.50, the blade diameter 0.5 m, hub diameter 0.2 m, the number of blades 6, the optimal installation angle of the blades 202.50, and the maximum water consumption rate is 0.24 m³/s. The nominal capacity of the micro-hydroelectric power station was determined to be 3 kW.*

Conclusion. *According to the analysis of the technical and economic indicators of the device, as a result of the practical application of the developed 3 kW vertical axis micro-hydroelectric power station, it is possible to generate an average of 19,500 kWh of electricity per year, save 14.53 tons of conventional fuel, and prevent the release of more than 28.5 tons of carbon dioxide (CO_2) into the atmosphere. The economic efficiency of this micro-hydroelectric power station was evaluated using the "Net Present Value" (NPV) method, with the net present value amounting to 5,500 USD, the static payback period being 1.56 years, and the dynamic payback period being 2.78 years.*

Keywords: *guide vane, dual-rotor hydro turbine, counter-rotating double-rotor axial flux permanent magnet generator, modeling, experiment, net present value (NPV).*

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MATLAB/SIMULINK TIZIMIDA MIKRO GESNI KOMPYUTERDA MODELLASHTIRISH

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Annotatsiya. Kirish. *Respublikamizda iqtisodiy tarmoqlarning rivojlanishi, aholi turmush darajasining o'sishi va sonining ko'payishi natijasida energiyaga bo'lgan talab ortib bormoqda. Bu holat ijtimoiy va iqtisodiy sohaning rivojlanishiga, jumladan, mamlakatning qishloq xo'jaligi sektorini elektr energiyasi bilan ta'minlash darajasiga katta ta'sir ko'rsatmoqda. Ushbu ta'sirlarni bartaraf etishning asosiy yechimlaridan biri sifatida, qayta tiklanadigan energiya manbalari asosida ishlaydigan energiya qurilmalarini, xususan, kichik quvvatli gidroelektr stansiyalarini rivojlantirish va samaradorligini oshirish yetakchi o'rinlardan birini egallaydi.*

Usul va materiallar. *Maqola qishloq xo'jaligida ishlatiladigan nasos agregatlaridan chiqqan suv oqimlariga moslashtirilgan 3 kVt quvvatga ega ikki rotorli gidroenergiya qurilmasini Matlab/Simulink dasturiy paketidan foydalanib modellashtirilgan.*

Natijalar. *Nazariy va eksperimental tadqiqotlar natijasiga ko'ra, yo'naltiruvchi apparatning geometrik o'lchamlari quyidagicha aniqlangan: tashqi diametri 1 m, ichki diametri 0,5 m, yo'naltiruvchi pichoqlar soni 16, yo'naltiruvchi qanotlarning o'rnatish burchagi β= -17,50, pichoqlarning diametri 0,5 m, vtulka diametri 0,2 m, pichoqlar soni 6, pichoqlarning optimal o'rnatish burchagi 202,50 va suv sarfining maksimal qiymati 0,24 m³/s. Mikro gidroelektr stansiyasining nominal quvvati 3 kVt ekanligi aniqlangan.*

Xulosa. *Qurilmaning texnik va iqtisodiy ko'rsatkichlari tahliliga ko'ra, ishlab chiqilgan 3 kVt quvvatga ega vertikal o'qli mikro gidroelektr stansiyasining amaliy qo'llanilishi natijasida bir yilda o'rtacha 19500 kVt·soat elektr energiyasi ishlab chiqarish, 14,53 tonna shartli yoqilg'i tejash va 28,5 tonnadan ortiq karbonat angidrid (CO_2) chiqindilarining atmosferaga chiqishining oldini olish mumkin. Ushbu mikro-gidroelektr stansiyasining iqtisodiy samaradorligi "Sof joriy qiymat" (SJQ) usuli yordamida baholangan bo'lib, unda sof joriy qiymat 5500 AQSh dollariga teng, statik qaytarish davri 1,56 yil va dinamik qaytarish davri 2,78 yilni tashkil qiladi.*

Kalit so'zlar: *yo'naltiruvchi qanot, ikki rotorli gidroturbina, qarama-qarshi yo'nalishda aylanadigan ikki rotorli o'qli oqim doimiy magnitli generator, modellashtirish, eksperiment, sof joriy qiymat (SJQ).*

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КОМПЬЮТЕРНОЕ МОДЕЛИРОВАНИЕ МИКРО ГЭС В СИСТЕМЕ MATLAB/SIMULINK

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Аннотация. Введение. *В результате развития экономических секторов в нашей республике, повышения уровня жизни и роста численности населения спрос на энергию* *увеличивается. Эта ситуация оказывает большое влияние на развитие социально-экономической сферы, в том числе на уровень электроснабжения сельскохозяйственного сектора страны. Одним из основных решений по устранению этих воздействий является развитие и повышение эффективности энергетических установок, работающих на основе возобновляемых источников энергии, в частности, маломощных гидроэлектростанций.*

Методы и материалы. *Статья представляет собой компьютерное моделирование двуроторного гидроэнергетического устройства мощностью 3 кВт, адаптированного к водным потокам, вытекающим из насосных агрегатов, используемых в сельском хозяйстве, с помощью программного пакета Matlab/Simulink.*

Результаты. *Согласно теоретическим и экспериментальным исследованиям, были определены следующие геометрические размеры направляющего аппарата: внешний диаметр 1 м, внутренний диаметр 0,5 м, количество направляющих лопастей — 16, угол установки направляющих лопастей β = -17,50, диаметр лопастей — 0,5 м, диаметр втулки — 0,2 м, количество лопастей — 6, оптимальный угол установки лопастей — 202,50, а максимальный расход воды составляет 0,24 м³/с. Номинальная мощность микро-гидроэлектростанции определена в 3 кВт.*

Выводы. *Согласно анализу технических и экономических показателей устройства, в результате практического применения разработанной вертикальной осевой микро-гидроэлектростанции мощностью 3 кВт можно получить в среднем 19500 кВт·ч электроэнергии в год, сэкономить 14,53 тонны условного топлива и предотвратить выброс более 28,5 тонн углекислого газа (CO_2) в атмосферу. Экономическая эффективность данной микро-гидроэлектростанции была оценена с помощью метода «Чистая приведенная стоимость» (NPV), при этом чистая приведенная стоимость составила 5500 долларов США, статический срок окупаемости — 1,56 года, а динамический срок окупаемости — 2,78 года.*

Ключевые слова: *направляющая лопасть, двухроторная гидротурбина, противовращающийся двухроторный осевой генератор с постоянными магнитами, моделирование, эксперимент, чистая приведенная стоимость (NPV).*

Introduction.

Currently, with the increase in the number of people in the world, global problems such as ensuring the safety of drinking water, food and energy are emerging. In addition, elimination of ecology and energy deficit is also urgent. Important problems such as global warming (drought, sea level rise, melting of glaciers), extinction of animal and plant species, pollution of air, water and land, shortage of natural energy resources during the last 20-30 years showed a serious negative impact of human activity on the balance of nature. As a result, they began to understand the extent of the destruction they had caused and began to look for solutions to environmental problems. One of the main solutions to these problems is to replace traditional energy sources based on organic fuels with renewable energy sources. Increasing the use of renewable energy sources is one of the necessary steps to solve the problems that humanity has created in the last few hundred years [1].

The demand for energy is increasing in our republic as a result of the development of economic sectors, the growth of the population's standard of living and the increase in its number. This greatly affects the development of the social and economic sphere, including the level of electricity supply to the country’s agricultural sector. As one of the main solutions to eliminate these effects, the development and improvement of efficiency of energy devices operating on the basis of renewable energy sources, in particular, small-capacity hydroelectric plants, occupies one of the leading positions. For this, it is important to determine the possibilities of using existing hydroelectric power, to conduct scientific research on the modeling and production of HPPs, which are more stable compared to other renewable energy sources in providing electricity consumers with electricity continuously.

According to the information received from the Bukhara regional branch of "Uzenergoinspeksiya", the economic sectors of the Bukhara region include agriculture, industry, transport, construction, communal household services. Annual electricity consumption of the region in the economic sphere is equal to 3410495 thousand kWh. Figure 1 shows the structure of electricity consumption in Bukhara region by economic sectors. The largest consumption of electricity falls on the agricultural sector.

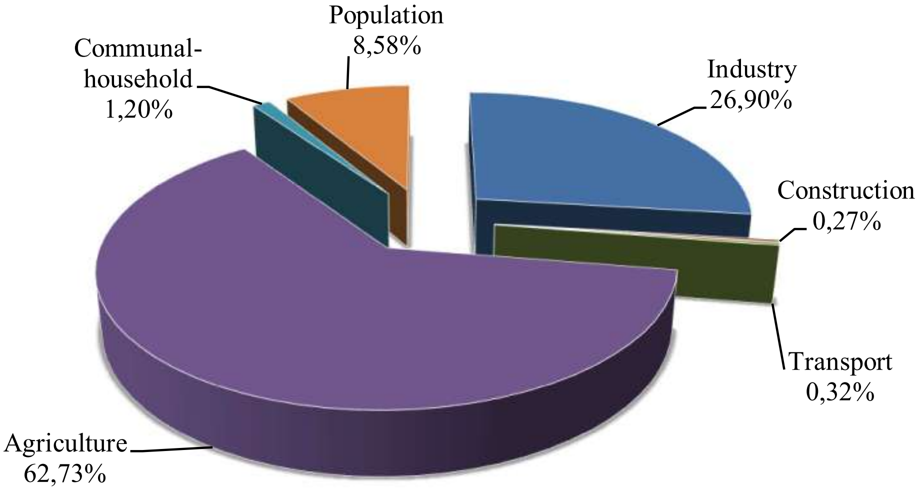


Fig.1. Distribution of electricity in economic sectors of Bukhara region.

Irrigation of the Bukhara region is achieved through pumping stations on the Amu-Bukhara machine canal. This channel starts from the right bank of the Amudarya, 12 km above the city of Chorjoi (Turkmenistan). Passing Kyzylkum, it supplies water to Zarafshan oasis. The 1st line was built in 1965, the 2nd line was built in 1976. The total length is 400 km. The maximum water lifting height is 111 meters, the maximum water transfer capacity is 270 m^3/s. As a result of the commissioning of the Amu-Bukhara magisterial canal, it became possible to irrigate 136,500 hectares of land in the Bukhara region with Amudarya water, which was irrigated from other sources. It was possible to irrigate about 23.8 thousand hectares of new land. The main channel has 65 hydrotechnical facilities, 11 pumping stations (including the Hamza-2 pumping station with 10 pumping units with a power of 12.5 thousand kW each, which raises water to a height of 54 m). This means that the region has high potential for generating electricity using pumped water flows [2].

Currently, there are more than 1,000 electricity consumers (livestock farms, farms, etc.) located far from the centralized power supply in the Bukhara region. About 10 desert and desert tourist zones have been established in order to develop tourism in different regions of the region. They also have the possibility of generating electricity through hydropower devices from the water flows coming out of the pumping units used for water supply. As a result, opportunities are created to use renewable energy sources to achieve energy savings and increase efficiency in agricultural enterprises, in particular, pumping stations.

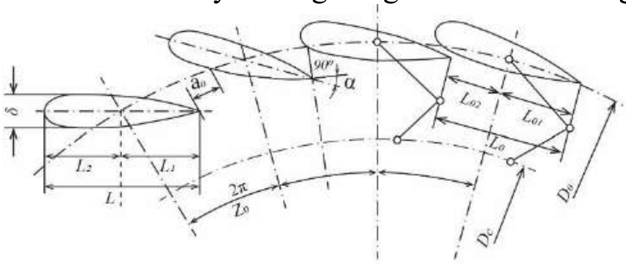
In Uzbekistan, research is being conducted on climate-adapted wind, solar and hydroelectric devices for agriculture [3,4,5,6,7].

The purpose of the research is to develop and justify the parameters of a gravity vortex micro hydroelectric power station adapted to the water flows of pump units intended for irrigation of agricultural fields.

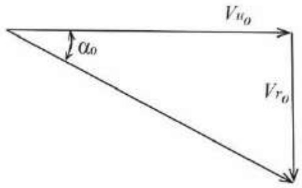
Methods and materials

Methodology of theoretical calculation of the design of the water flow directing apparatus used in the micro-hydroelectric plant

Direction devices serve to direct the water wheel in jet hydro turbines and to adjust the flow of water passing through the turbine. A diverter made of a closed structure can completely stop the flow to the water wheel. The function of adjusting the water flow is performed by a system of paddles arranged along a circle. When the blades are turned, the direction of the water flow coming out of the diverter changes to an angle a (Fig. 2.). Adjustment of the water flow rate in linear hydro turbines is carried out by turning the guide shovels and guide blades.



a)



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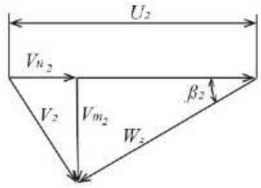


d)

a - guide shovels; b - velocity diagram of the water flow coming out of the diverter; d - is the velocity diagram of the water flow coming out of the water wheel

Fig.2. The main geometric dimensions of the reference deviceю

Figure 2 shows the main geometric dimensions of the guiding apparatus, which consists of the following [8]:

1) the diameter of the circle formed by the guide vanes D_0;

2) number of guide shovels Z;

3) the height of the guide vane b_0;

4) The total length of the tube is L and the length of the inlet part is L_2, the length of the outlet part is L_1 $(L = L_1 + L_2)$;

5) maximum shovel thickness δ;

6) the distance between adjacent shovels is L_0, the distance to the turning axis is L_{01} and the distance after the turning axis is L_{02};

$$L_0 = L_{01} + L_{02} \tag{1}$$

7) the quantity describing the position of the shovels in the closed position relative to the axis of rotation - relative position n_o;

$$n_o = \frac{L_{01} - L_{02}}{2L_0} \tag{2}$$

8) the shape of the shovel (it is often symmetrical)

9) the ratio of the length of the shovel to the length of the gap between the shovels $Z/\ t$ is determined using the diameter of the circle formed by the guide shovels D_0;

10) the diameter of the adjusting circle D_c;

These sizes are unchanged for the same type of guide vanes.

In the process of adjusting the guide apparatus, using the variable a_0, this quantity is called the opening of the guide apparatus and is equal to the distance between the back of any blade and the side blades. The opening of the guide apparatus depends on the size of the turbine and the number of guide shovels. Mathematically, the opening of the guide apparatus a_0 is directly proportional to the diameter of the water wheel and the number of guide shovels is inversely proportional to Z. The turning of the guide vanes is carried out by the adjusting ring, due to the turning, the opening of the guide apparatus a_0 and the surface on which the vanes are located are changed. However, the change in the flow speed when the blades are turned depends mainly on the angle of the water flow direction change α, not on the surface on which the blades are located.

This situation is explained using the fundamental equation of the turbine [8].

$$\eta g H = v_{u1}u_1 - v_{u2}u_2 \quad (3)$$

where, η – the efficiency of the turbine; g – acceleration of free fall, m/s^2; H – hydraulic pressure, m; u_1 – tangential speed at the entrance of the wings, m/s; u_2 – tangential speed at the outlet of the blades, m/s; v_{u1} – speed at the entrance of the wings, m/s; v_{u2} – speed at the exit of the blades, m/s.

The equation of the relationship between the water currents between the guide apparatus and the water wheel.

$$v_{u0}r_0 = v_{u1}r_1 \quad (4)$$

where, v_{u0} – velocity of water flow from the diverter, m/s; r_0 – internal radius of the guiding apparatus, m; v_{u1} – speed at the entrance of the wings, m/s; r_1 – the outer radius of the water wheel, m.

Also, the formulas of the tangential velocities of the water flows coming out of the guide apparatus and water wheels:

$$v_{ro} = \frac{Q}{2\pi r_o b_o} \quad (5)$$

$$v_{m2} = \frac{Q}{F_2} \quad (6)$$

where, Q – flow rate, m^3/s; F_2 – cross-sectional surface of the water wheel, m^2.

Equations (7) and (8) were created by putting the speed values into the basic equation of the turbine based on the speed diagrams in Figure 1.

$$v_{u_1} = \frac{r_o}{r_1} v_{u_o} = \frac{r_o}{r_1} v_{r_o} ctg\alpha_o = \frac{Q}{2\pi r_1 b_o} ctg\alpha_o \quad (7)$$

$$v_{u_2} = u_2 - u_{m_2} ctg\beta_2 = u_2 - \frac{Q}{F_2} ctg\beta_2 \quad (8)$$

where, v_2 – the speed at the exit of the wings, m/s; r_2 – the inner radius of the water wheel, m.

After substitutions, the equation of water consumption was derived.

$$Q = \frac{\frac{\eta g H}{\omega} - u_2 r_2}{\frac{1}{2\pi b_o} ctg\alpha_o + \frac{r_2}{F_2} ctg\beta_2} \quad (9)$$

Thus, the value of water flow rate at a constant speed and pressure depends on the following three quantities: the height of the guide vane b_0, the angle of the water flow from the guide vane α_0 and the angle of the water flow from the water wheel β_2. Water flow control by changing the height of the guide vane b_0 is used only in small power devices. In this case, the guide vane are immovable. Otherwise, it will not be possible to stably control the water flow exit angle. In radial-axis turbines, shovels are usually controlled by changing the exit angle α_0. Water flow control in rotary vane turbines is performed by turning the guide vane and the blades of the water wheel together, that is, by changing the angles α_0 and β_2.

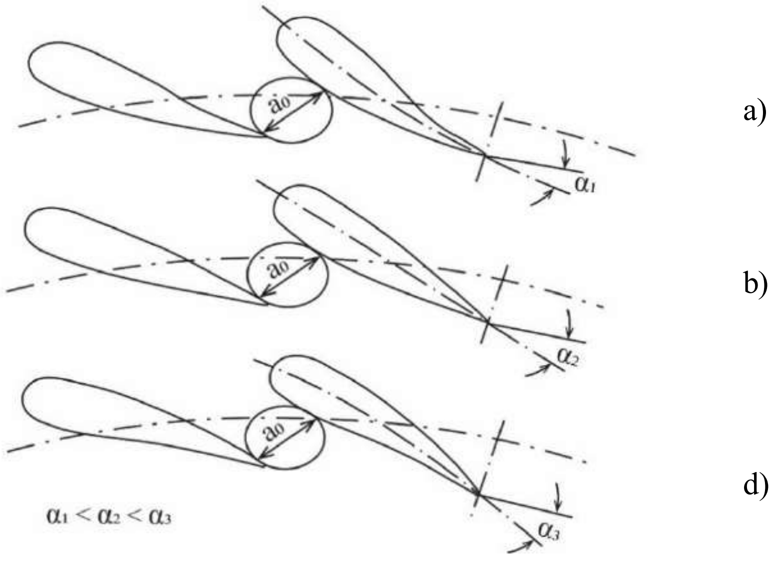
As the current flows around the guide vane of the shovel, the losses are negligible. The main factor affecting the reduction of the efficiency of the steering devices is the reduction of pressure when water enters the shovels. To reduce waste, the guide vane should be designed in such a way that the angle of inclination is optimal in the operating modes of the turbine.

Figure 3 shows the shovels of the guide vane with different shapes:

1) shovels forming a negative curvature angle with the flow directed towards the axis of the turbine (Fig. 3 (a));

2) symmetrical shovels (Fig. 3 (b));

3) shovels forming a positive curvature angle with the flow directed towards the axis of the turbine (Fig. 3 (d)).



a - shovels with a negative curvature angle; b - symmetrical shovels; d - shovels with a positive curvature angle.

Fig. 3. Shovels of the guiding vane of different shapes.

In these shovels, the opening of the guide vane a_0 has the same value, but their exit angles α a have different values (Fig. 4).

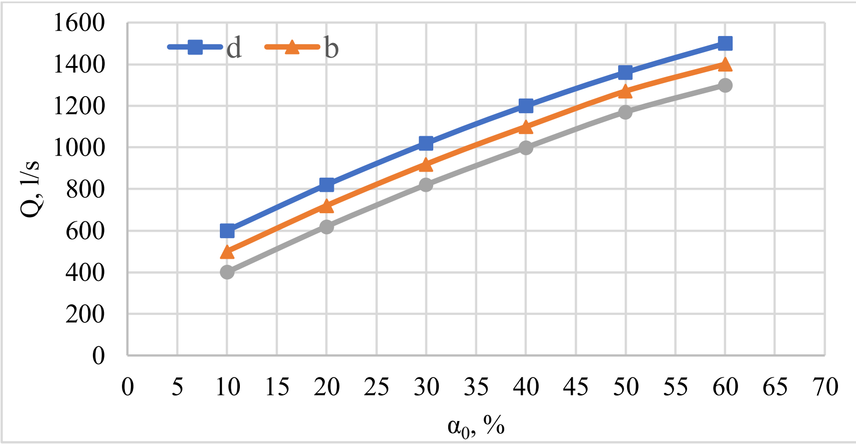


Fig. 4. The graph of the dependence of the water rate from the shovels of the guide vane of different shapes on the opening of the guide vane.

The most current is produced by shovels with a positive curvature angle α_3. As can be seen from the graph in Figure 4, the routers have different transfer capabilities when the value of guide vane opening a_0 is the same. The highest throughput is the throughput of blades with a positive curvature angle. For example, shovels with a negative curvature angle with an opening of 50% will pass a water flow of 1200 l/s, a symmetrical shovels 1300 l/s, shovels with a positive curvature angle 1380 l/s.

Mathematical model of a micro-hydro turbine

The main parameters of small hydropower plants include the installed power, the number of hydro aggregates, the annual amount of electricity produced, the calculated effort, the calculated water rate and the efficiency. The above-mentioned parameters are mainly determined depending on the energy of the water flow expressed through pressure and water rate. A stream of water flowing down a certain slope from an upper level to a lower level has potential and kinetic energies under the influence of gravity and performs certain work, so the water stream can be considered a carrier of certain energy. Part of the energy is used to overcome the friction force inside the water flow and on the walls of the water-conducting structure [9].

We create a mathematical model of the dependence of the vertical axis hydroturbine parameters on the water flow:

From the speed diagram of the vertical axis hydroturbine in Fig. 5, the dependence of the speed of the flow entering the water wheel on the optimal speed is determined.

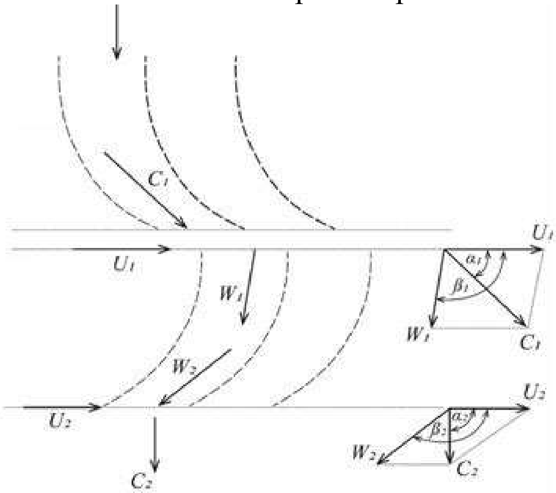


Figure 5. Speed diagram of a vertical axis hydro turbine.

The output power of the water wheel is determined by the following mathematical expression [10,11]:

$$N = \eta \cdot \rho \cdot g \cdot Q \cdot H = \eta \cdot \gamma \cdot Q \cdot H \quad (10)$$

where, ρ – density of water, kg/m^3; g- acceleration of free fall, m/s^2; Q – water flow rate, m^3/s; γ – specific gravity of water, N/m^3.

Angular velocity of the water wheel [12].

$$v_w = \frac{2 \cdot \pi \cdot n}{60} \quad (11)$$

where, n – the rotation speed of the water wheel, rpm.

Expression of power and angular velocity dependence of water wheel torque [13].

$$M = \frac{N}{v_w} \quad (12)$$

Substituting expressions (10) and (11) into expression (12), the expression of the moment of water flow becomes as follows.

$$M = \frac{\eta \cdot \gamma \cdot Q \cdot H \cdot 60}{2 \cdot \pi \cdot n} \quad (13)$$

The dependence of the turbine torque on the structural parameters is determined by the following mathematical expression (this expression is also called the Euler equation) [14]:

$$M = \frac{\gamma \cdot Q}{g} \cdot (R_1 \cdot c_1 \cdot \cos\alpha_1 - R_2 \cdot c_2 \cdot \cos\alpha_2) \quad (14)$$

where, R_1 – the outer radius of the water wheel, m; R_1 – the inner radius of the water wheel, m; c_1 – speed of flow leaving the guide vane or speed of flow entering the water wheel, m/s; c_2 – speed of flow exiting the water wheel, m/s; α_1 –water flow exit angle from the guide vane; α_2 – the angle of exit of the water flow from the water wheel.

As can be seen from the above expression, the water wheel reaches its optimal speed when the exit angle of the water flow from the water wheel is equal to 90^0 ($\alpha_2 = 90^0$). In this case, expression (14) takes this form.

$$M = \frac{\gamma \cdot Q}{g} \cdot (R_1 \cdot c_1 \cdot \cos\alpha_1) \quad (15)$$

First, the tangential velocity of the water wheel is determined as a function of the angular velocity.

$$u_1 = v_w \cdot R_1 \;\text{ or }\; u_1 = \frac{2 \cdot \pi \cdot n_{opt} \cdot R_1}{60} \quad (16)$$

Applying the theorem of sines to the triangle of velocities in the velocity diagram, the dependence of the flow entering the water wheel on the optimum speed of the water wheel is derived.

$$\frac{c_1}{sin(180^0-\beta_1)}=\frac{u_1}{sin(\beta_1-\alpha_1)} \tag{17}$$

$sin(180^0-\beta_1)=sin\,\beta_1$ using the trigonometric formula and expression (16), the expression (17) changes as follows.

$$c_1=\frac{2\cdot\pi\cdot n_{opt}\cdot R_1\cdot sin\,\beta_1}{60\cdot sin(\beta_1-\alpha_1)} \tag{18}$$

We equate expression (13) by introducing expression (18) into expression (15).

$$\frac{\gamma\cdot Q}{g}\cdot\left(R_1\cdot\frac{2\cdot\pi\cdot n_{opt}\cdot R_1\cdot sin\,\beta_1}{60\cdot sin(\beta_1-\alpha_1)}\cdot\cos\alpha_1\right)=\frac{\eta\cdot\gamma\cdot Q\cdot H\cdot 60}{2\cdot\pi\cdot n_{opt}} \tag{19}$$

This equation is simplified.

$$n_{opt}{}^2=\frac{g\cdot H\cdot\eta\cdot 30^2}{\pi^2\cdot R_1^2}\cdot\frac{sin(\beta_1-\alpha_1)}{sin\,\beta_1\cdot\cos\alpha_1} \tag{20}$$

$sin(\beta_1-\alpha_1)=sin\,\beta_1\cdot\cos\alpha_1-cos\,\beta_1\cdot\sin\alpha_1$ subtraction formula for sinusoidal function and $\tan\alpha_1=\frac{\sin\alpha_1}{\cos\alpha_1}$, $\tan\beta_1=\frac{\sin\beta_1}{\cos\beta_1}$ relationships between the trigonometric functions, the optimal rotation speed of the water wheel was created.

$$n_{opt}=\frac{30}{\pi R_1}\cdot\sqrt{\eta\cdot g\cdot H}\cdot\sqrt{1-\frac{\tan\alpha_1}{\tan\beta_1}} \tag{21}$$

2.3. Mathematical model of magnetoelectric axial generator

In developing the mathematical model of the magnetoelectric axial generator, we use the matrix form of the Lagrange formula [15,16].

$$\frac{d}{dt}\psi_{PM}(\varphi)=u+\left\{L\frac{d}{dt}i+R_s\cdot i\right\} \tag{22}$$

We create the following equilibrium equation [17].:

$$J\frac{d^2\varphi}{dt^2}=T_L+T_{em}(\varphi,i_1,i_2,i_3)-D\frac{d\varphi}{dt} \tag{23}$$

Where is the electromagnetic moment:

$$T_{em}(\varphi,i_1,i_2,i_3)=i^T\cdot\frac{\partial}{\partial\varphi}\psi_{PM}(\varphi) \tag{24}$$

where, i – the current passing through the phase windings of the generator, A; u – voltage induced in the phase windings of the generator, V.

$$i=\begin{bmatrix}i_1\\i_2\\i_3\end{bmatrix}\quad and\quad u=\begin{bmatrix}u_1\\u_2\\u_3\end{bmatrix} \tag{25}$$

$$L=L_{\sigma s}+L_s=\begin{bmatrix}L_{\sigma s}&&\\&L_{\sigma s}&\\&&L_{\sigma s}\end{bmatrix}+\begin{bmatrix}L_{11}&L_{12}&L_{13}\\L_{21}&L_{22}&L_{23}\\L_{31}&L_{32}&L_{33}\end{bmatrix} \tag{26}$$

$$\psi_{PM}(\varphi)=\begin{bmatrix}\psi_{PM1}(\varphi)\\\psi_{PM2}(\varphi)\\\psi_{PM3}(\varphi)\end{bmatrix}\quad and\quad R_s=\begin{bmatrix}R_s&&\\&R_s&\\&&R_s\end{bmatrix} \tag{27}$$

The magnetic flux of the "a" phase winding is determined as follows [18].

$$\psi_a(\varphi)=\int_{R_i}^{R_o}w_s\left\{\int_{\frac{-\varepsilon(r)+\alpha_k(r)}{2}+x_a}^{\frac{-\varepsilon(r)-\alpha_k(r)}{2}+x_a}B(x,\varphi,r)\,dx\right\}rdr \tag{28}$$

It is difficult to determine the distribution of the magnetic induction B (x,φ,r) by integrating the expression (28). However, its average value can be determined from the following simplified expression.

The average radius of the inductor is determined by the following formula.

$$r \cong r_s = \frac{R_o + R_i}{2} \tag{29}$$

In the initial state (no induction current in the coil), the current behavior of permanent magnets in the coil "a" is given by the following expression [19].

$$\psi_{PMa}(\varphi) = \sum_{\varsigma \in Q} \psi_{\varsigma}^{PMs} \cdot e^{j\varsigma\ (a-1)\frac{4\pi}{3p} - \varphi\}}$$

where,

$$a = 1{,}2{,}3 \tag{30}$$

The current contribution in the ς^{th} – order harmonic is calculated using the following expression.

$$\psi_{\varsigma}^{PMs} = 2 \cdot B_{\varsigma}^{PM}(r_s) \cdot W_{\varsigma}^{s}(r_s) \cdot r_s \cdot \mathrm{l}_c \tag{31}$$

where, $\mathrm{l}_c = \mathrm{R}_o - \mathrm{R}_i$ - the length of the coil.

The equation for determining the inductance of machine coils [20].

$$L_{ab} = \sum_{v \in P} L_v^{SS} \cdot e^{jv(a-b)\frac{4\pi}{3p_s}}$$

where, $a, b = 1{,}2{,}3$ (32)

Where is an analytical expression of the inductance of a single-phase circuit.

$$L_v^{SS} = \frac{2}{\pi}[W_v^s(r_s)]^2 \cdot r_s \cdot \mathrm{l}_c \cdot \lambda_o \tag{33}$$

The analytical expression of mutual inductance consists of two constituents. The first of them is represented by the scattering of the magnetic current in the active part of the conductor, and the second is the scattering of the magnetic current in the terminals connected to the edge of the coil. Mutual inductance is determined by the following formula [21].

$$L_{\sigma s} \approx 2\mu_o \cdot (w_s)^2 \cdot [(\mathrm{l}_c - \mathrm{a}_{sc}) + (\mathrm{a}_c - \mathrm{a}_{sc})] \cdot 0{,}3 \,/\, p_s \tag{34}$$

Calculation of the electromagnetic power obtained from a generator consisting of three-phase permanent magnets is determined from the following expression [22]:

$$\mathrm{P_e} = \frac{3}{2}\omega[\psi_{\mathrm{PM}} + (\mathrm{L_d} - \mathrm{L_q})\mathrm{i_d}]\mathrm{i_q} \tag{35}$$

The electromechanical torque of the generator with the number of pairs of poles p is determined by the following expression:

$$\mathrm{M_e} = \frac{3}{2}\mathrm{p}[\psi_{\mathrm{PM}} + (\mathrm{L_d} - \mathrm{L_q})\mathrm{i_d}]\mathrm{i_q} \tag{36}$$

where, ψ_{PM} – magnetic flux, Wb.

$$\psi_{\mathrm{PM}} = \frac{\sqrt{2}\mathrm{E_f}}{\omega} \tag{37}$$

The electromagnetic speed when the armature and inductor of an electric generator is reversed is determined by the following expression:

$$\omega = \mathrm{p}(\omega_{\mathrm{m1}} + \omega_{\mathrm{m2}}) \tag{38}$$

where p – the number of pairs of poles.

The moment of inertia of the generator in dynamic modeling is determined from the following expression [12]:

$$\mathrm{J}\frac{\mathrm{d}\omega_{\mathrm{m}}}{\mathrm{dt}} = \mathrm{M_m} - \mathrm{M_e} - \mathrm{k}\omega_{\mathrm{m}} \tag{39}$$

where, J –the moment of inertia of the inductor mass, kg·m^2, $\mathrm{M_m}$ and $\mathrm{M_e}$ – the mechanical and electromagnetic moments of the generator, N·m; k –friction coefficient, ω_{m} – angular speed of the generator, rad/s.

2.4. Evaluation of the economic efficiency of the device implementation

In the world today, the methodology of "Pure Discount" is widely used in the evaluation of projects on the efficiency of power plants. In this case, all costs of the project and future benefits are brought to the value of the time the project is being considered [23].

Net Present Valyu, NPV:

$$\mathrm{NPV} = \sum_{t=1}^{n} \frac{P_t - A_t}{(1+E)^t} - I_0 \quad (40)$$

Levelised Cost of Electricity, LCOE:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + O\ \ t + F_t}{(1+DR)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+DR)^t}} \quad (41)$$

Internal Rate of Return, IRR

$$\sum_{t=1}^{n} \frac{P_t - A_t}{(1+E)^t} = \sum_{t=1}^{n} \frac{I_t}{(1+E)^t} \quad (42)$$

Results and discussions

In Figure 6, a graph of the dependence of the mechanical power of the hydro turbine on the rotation speed and water flow rate was constructed. It was determined that the mechanical power of the turbine changes in the range of 0...2240 W when the water flow rate is 0.15...0.24 m^3/s and the turbine rotation speed is 0...120 rpm.

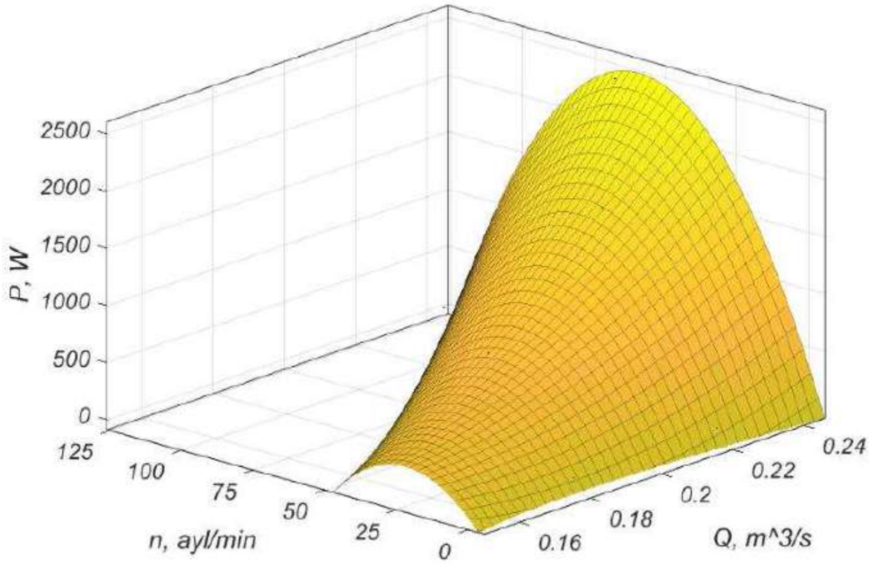


Fig. 6. The graph of the dependence of the mechanical power of the hydro turbine on the rotational speed and water flow rate.

Due to the fact that the flow of water entering the 1st hydroturbine of the proposed vertical axis micro hydroelectric power station from the diverting device is 0.24 m^3/s and the hydraulic head is 1.11 m, the optimal rotation speed of the 1st hydroturbine is 58 rpm and the mechanical power 2238 W will be. On the other hand, since the rate of water flowing into the 2nd hydro turbine is 0.21 m^3/s and the hydraulic head is 0.68 m, the optimal rotation speed of the 2nd hydro turbine is 45 rpm and the mechanical power is 1243 W. It was determined that the total mechanical power transmitted from the mechanical part of the micro hydroelectric power station to the electric generator is equal to 3481 W. With the help of belt transmissions, the rotation speed of the counter-rotating hydro turbines is increased 4 times, and the electric generator reaches a maximum rotation speed of 400 rpm.

In Fig. 7 simulation model for determining electrical and energy quantities of a magnetoelectric generator is built in the Matlab/Simulink application program. Using this model, it is possible to determine the values of armature current, voltage in coils and electromagnetic power. In this case, as the value of water rate changes, the output parameters of electrical and energy quantities also change. Dynamic values of the generator operating mode are presented in the model.

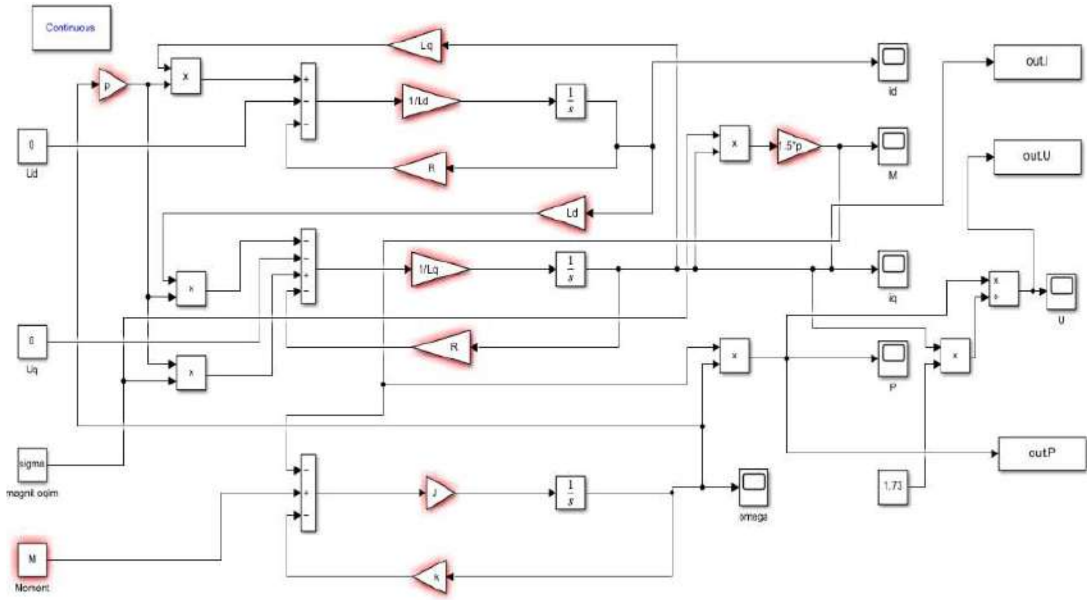
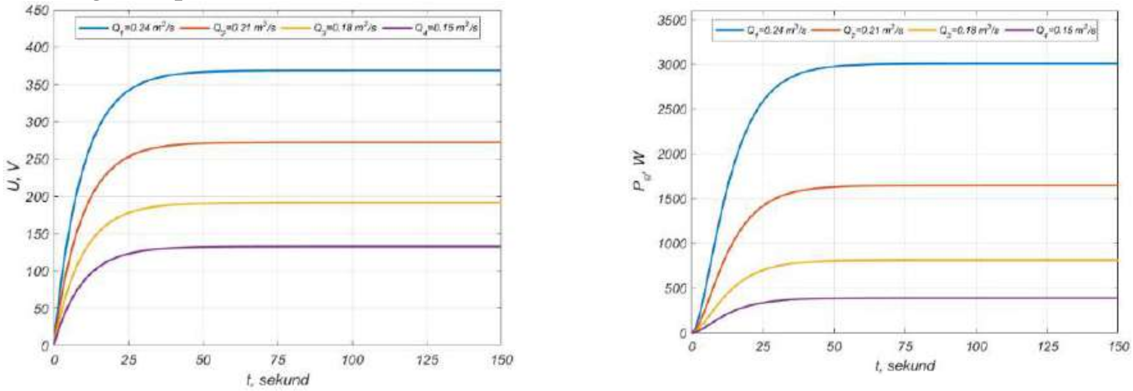


Figure 7. Simulation model of electric generator in Matlab/Simulink application program.

Figure 8 (b) shows the voltage values generated in the armature coils of an electric generator. According to this, it was determined that when the flow rate is 0.15 m^3/s, the voltage in the anchor pipes is 120 V, and when the water flow is 0.24 m^3/s, the voltage in the anchor pipes is 380 V.

The graph in Fig. 8 (b) shows the values of the dependence curves of the electromagnetic power values of the electric generator on the change in water flow rate. Accordingly, it was determined that the electromagnetic power is 400 W when the flow rate is 0.15 m^3/s, and the electromagnetic power is 3000 W when the water flow rate is 0.24 m^3/s.



a) b)

Figure 8. Graphs showing armature current (a), output voltage (b) and electromagnetic power (d) values of generator in dynamic mode in Matlab/Simulink application program.

Based on the processing of the experimental results, a regression equation was obtained that determines the change in the water flow rate and turbine rotation speed of the mechanical power of the hydro turbine.

$$P = 503046012{,}4 \cdot Q^{6{,}16} \cdot n^{-0{,}87} \qquad (40)$$

The following initial conditions are accepted:

(40) for expression: $0.15 \leq Q \leq 0.24$ m3/s; $0<n<120$ rpm.

Figure 9 shows the graph of the regression equation based on processing the results of the experiment.

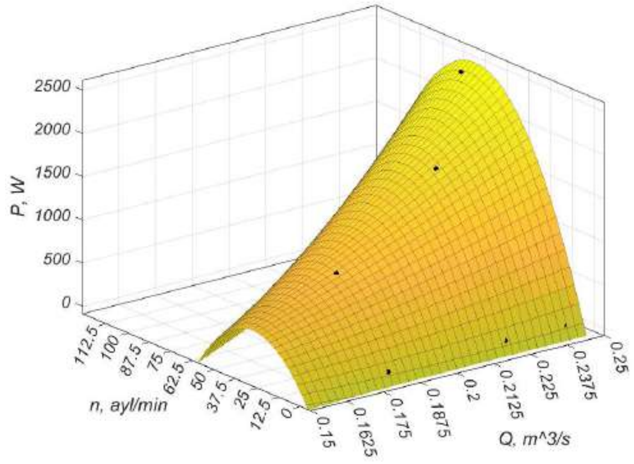


Figure 9. The graph of the regression equation obtained based on the processing of the experimental results.

Adequacy of the regression equation was assessed using Fisher's F-criterion. We compare the calculated values with the values in the table. The significance level is 0.05 and at the number of degrees of freedom γ_1 =63, γ_2 =59, the calculated value of Fisher's F-criterion (F_{cal} =1.03) is smaller than the value in the table (F_{tab} =1.53), so the constructed regression equation is significant. The relative error of the calculation is ± 6 %.

Table 1 shows the technical indicators of the developed vertical axis micro-hydroelectric power plant compared with the closest analog produced in China. According to the results of the comparison, it was found that the efficiency of the developed micro-hydroelectric plant is higher compared to the close analogue when working in low-pressure water flows.

Table 1.

The main comparative indicators of a vertical-axis micro-hydroelectric plant.

№	Technical indicators	Developed vertical axis micro hydropower plant	Vertical axis hydro turbine (China)
1.	Nominal power, W	3000	3000
2.	The range of water flow rate, m^3/s	0,15…0,24	0,014…0,09
3.	Hydraulic pressure, m	0,6…1,1	2…5
4.	Efficiency, %	74,7	68
5.	Phase voltage, V	220 (~)	220 (~)
6.	Phase current, A	4,6	13,6
7.	Device mass, kg	110	155
8.	Device height, m	1,2	1,23

Conclusion.

According to the results of the theoretical and experimental studies, the geometric dimensions of the guide apparatus: outer diameter 1 m, inner diameter 0.5 m, the number of guide shovels is 16, the installation angle of the guide vanes is β= -17.5°, the diameter of the blades is 0.5 m, the diameter of the sleeve is 0.2 m, the number of blades is 6, the optimal installation angle of the blades is 202.5°, and the maximum value of water consumption is 0.24 m^3/s. It was determined that the nominal power of micro hydroelectric power station is equal to 3 kW.

According to the analysis of technical and economic indicators of the device, as a result of the practical use of the developed 3 kW vertical axis micro hydroelectric power station, it was found that it is possible to obtain an average of 19500 kW·h of electricity in one year. The vertical-axis micro-hydroelectric power station was compared with the closest analogue micro-hydroelectric power station, and according to the results of the research, it was proved that the device's performance is high in low-pressure water flows. About 14.53 tons of conventional fuel it was justified that more than 28.5 tons of carbon dioxide (CO_2) were saved and released into the atmosphere. The economic efficiency of the 3 kW vertical-axis micro-hydroelectric plant was evaluated using the "Net Present Value" method, in which the net present value is 5500 $, the static recovery period is 1.56 years and the dynamic recovery period is 2.78 years.

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