DEVELOPMENT OF IMPROVEMENT OF MICRO HYDROELECTRIC POWER PLANT FOR WATER FLOWS OF PUMPING DEVICES

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Abstract

The article presents the results of research on the development of a micro hydroelectric power plant adapted to the water flows coming out of pumping devices located in the southwestern regions of Uzbekistan, in particular, in the Bukhara and Kashkadarya regions. An analysis of scientific research on the development of micro hydroelectric power plants with a vertical axis is presented. Empirical equations are given for the dependence of the efficiency of the developed vertical-axis micro hydroelectric power plant on water consumption, changes in water pressure, the angle of inclination of the water flow guides, and propeller-type water wheel blades. A mathematical model of the optimal speed of rotation of the water wheel based on geometric laws has been developed. The maximum efficiency of the hydro turbine is justified, which is 75%, while the angle of interaction of the water flow with the blades of the installation is $\beta=148^o$, the angle of the exit of the water flow from the guide vane $\alpha=53^o$. Also, an improved magnetoelectric generator has been developed to ensure reliable operation of the micro hydroelectric power station in low-pressure watercourses. As a result, it was found that its magnetoelectric power increased by 20%. The possibility of developing a micro hydroelectric power plant with a capacity of 1 ... 50 kW, depending on the flow rate and pressure of the water flow, as well as providing uninterrupted electricity to autonomous consumers located near this station, is substantiated.

Keywords: Pumping device, water flow, water pressure, vertical-axis micro hydroelectric power plant, modeling, water wheel, guide vane, magnetoelectric generator, stator, rotor, winding, pole, electromagnetic power.

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Introduction

Nowadays, ensuring environmental sustainability and energy security, as well as providing an uninterrupted energy supply to autonomous consumers located far from centralized electricity supply systems, is of great importance. One of the main solutions to these challenges is the development and efficiency improvement of energy systems based on renewable energy sources, particularly small-capacity hydropower systems. Scientific research is being conducted on the development of hydroelectric power plants (HPPs), which are more stable compared with other renewable energy sources, to provide autonomous consumers with a continuous supply of electricity [1].

In Uzbekistan, a number of measures are also being implemented to accelerate the development and deployment of energy systems based on renewable energy sources. In order to compensate for energy shortages in different regions of the country through the introduction of renewable energy sources in various sectors of the economy, as well as in the social and housing and communal services sectors, and to implement comprehensive mechanisms for organizing these activities in 2023, it was planned to develop renewable energy facilities with a total capacity of 4300 MW. This included the construction of 103 small-capacity HPPs with a total installed capacity of 235.23 MW by JSC “Uzbekenergo” and business entities in Andijan, Jizzakh, Kashkadarya, Namangan, Samarkand, Surkhandarya, Tashkent, and Fergana regions, with an expected additional electricity generation of 243.56 million kWh in 2023 [2].

Despite the results achieved in the development and efficiency improvement of micro-hydroelectric power plants operating under different water flow conditions, and their use in the design of micro-hydropower plants in areas remote from centralized electricity supply systems, insufficient research has been conducted on the modeling of vertical-axis hydropower systems adapted to variable and low-head pumped-water flows in the south-western regions of the Republic of Uzbekistan. In particular, further research is required to determine the optimal installation angle of the water-wheel blades in order to reduce the hydrodynamic forces acting between the blades and the water flow and to improve the overall operating efficiency of the system. A vertical-axis hydropower device is known to comprise three stationary water-flow guide vanes installed inside a housing, two propeller-type hydraulic turbines mounted on a stationary shaft and capable of rotating under the action of the water flow, and mechanical transmission mechanisms installed on the outer part of the housing and connected to the rotor of an electric generator. This hydropower device makes it possible to continuously generate electricity by utilizing both horizontal and vertical water flows. However, its disadvantages include a complicated structural design and low reliability [3].

A hydropower device for vertical water flows is also known, comprising stationary guide vanes mounted on a vertical stationary shaft to uniformly direct the water flow and a Kaplan-type hydraulic turbine capable of rotation. Such a hydropower device is designed for stable operation under medium-head water flow conditions. Its main disadvantage is its low efficiency when operating under low-head water flow conditions [4].

A vertically installed hydropower device for generating electricity from water flows is known, comprising a stationary housing, a water-flow guide pipe, a water wheel capable of rotation and installed inside a metal pipe, and an electric generator. The disadvantages of this known

hydropower device include high resistance forces generated during the interaction between the water flow and the blades of the water wheel, low operating efficiency under low-head water flow conditions, and low reliability of the electricity generated by the electric generator under variable water discharge conditions [5].
A propeller-type hydraulic turbine hydropower device capable of generating electricity from water flows in water-supply pipelines is also known. It comprises stationary supports attached to a pipe through bearings, with a rotating shaft equipped with a propeller-type water wheel, and chain transmission mechanisms connecting the shaft to the rotor of an electric generator. The disadvantages of this known hydropower device include low efficiency under low-head water flow conditions and low reliability of the electrical energy generated by the electric generator when the water discharge varies [6].

Research objective:
To determine the efficiency characteristics of a vertical-axis hydroelectric power plant operating efficiently under variable and low-head water flow conditions based on mathematical modeling.
As a result of the study, it was determined that in the south-western regions of Uzbekistan, particularly in Bukhara and Kashkadarya regions, the water overflow height on the upstream side of pumping units at facilities of the Amu-Bukhara Machine Canal and the Karshi Main Canal is approximately 0.8–1.6 m, while the water flow velocity ranges from 3 to 5 m/s. Therefore, the development and practical implementation of micro-hydroelectric power plants designed to operate efficiently under these water flow conditions are of significant importance.
The proposed vertical-axis hydropower device comprises a water-flow guide apparatus installed within a movable basin on a stationary shaft, propeller-type water blades mounted on water wheels rotating in opposite directions, a stationary shaft, and a stationary flow-directing apparatus positioned below the first water wheel and above the second water wheel to ensure uniform water-flow distribution. The device also includes an axial permanent-magnet synchronous generator designed to produce high electromagnetic power at low rotational speeds. The generator consists of an armature with copper windings and inductors equipped with permanent magnets. Brushes and commutators are used to extract electrical energy from the axial permanent-magnet generator. The first water wheel is mechanically coupled to the armature of the electric generator, while the second water wheel is mechanically coupled to the generator inductors through belt drives, thereby enabling their rotation in different directions. The hydropower device is securely mounted above the canal water flow by means of a stationary shaft installed on a frame constructed from metal profiles. The proposed vertical-axis hydropower device is designed to operate efficiently under variable and low-head water flow conditions and provides an opportunity to ensure a continuous supply of electrical energy to consumers.

The operating principle of the micro-hydroelectric power plant is as follows. A frame 3 made of metal profiles is securely mounted above the water flow in the canal 2. The water flow is directed through a conduit 4 to the vertical-axis hydropower device 1, which is mounted on the frame 3 by means of a stationary shaft 5. A water-flow guide apparatus 8 is installed inside a specially designed rotating basin 7 to uniformly direct the water flow toward the first water wheel 10. As a result of the uniform distribution of the water flow, the first water wheel 10 begins to rotate steadily in the clockwise direction. A stationary flow-directing apparatus 17 is installed below the first water wheel 10 and above the second water wheel 13 on the stationary shaft 5. This apparatus ensures uniform distribution of the water flow toward the second water wheel 13. Consequently, the second water wheel 13 begins to rotate steadily in the counterclockwise direction, i.e., opposite to the direction of rotation of the first water wheel 10. The first water wheel 10 is mechanically coupled to the armature 22 of the axial permanent-magnet generator 24 through a metal disc 26 and a sleeve 27, while the second water wheel 13 is mechanically coupled to the inductors 19 and 20 of the axial permanent-magnet generator 24 through a flange connection 25. Mechanical power is transmitted from the first and second water wheels to the corresponding rotating components of the generator by means of belt drives 28 and 29. The axial permanent-magnet generator 24 consists of an armature 22 equipped with copper windings 23 and inductors 19 and 20 equipped with permanent magnets 21. The three-phase alternating electrical energy generated by the axial permanent-magnet generator 24 is extracted through the brushes 30 and commutator 31. Due to the counter-rotation of the armature 22 and the inductors 19 and 20 relative to each other, a high electromagnetic power output can be obtained even at relatively low rotational speeds of the water wheels. The operating principle and structural configuration of the developed micro-hydroelectric power plant are shown in **Fig. 1**. A patent for the invention was obtained for the developed device from the Intellectual Property Center of the Republic of Uzbekistan under Patent No. IAP 20230166.

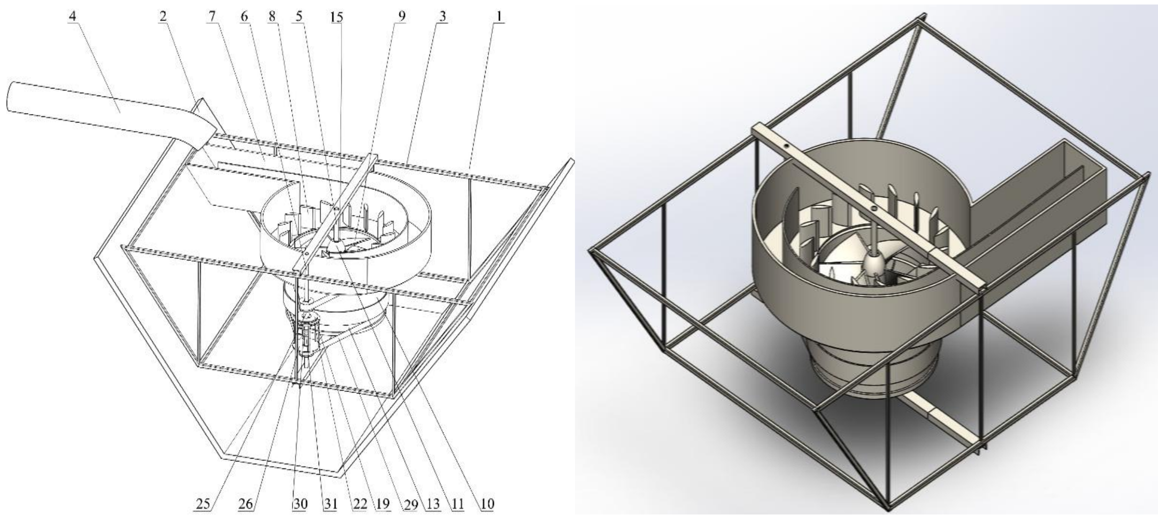


Fig. 1. Improved vertical-axis micro-hydroelectric power plant (IAP 20230166).

The empirical equations describing the dependence of the efficiency of the proposed vertical-axis micro-hydroelectric power plant on the hydraulic head, water discharge, and the installation angles of the water-flow guide vanes and propeller-type water-wheel blades are determined using the following mathematical expressions [7,8,9]:

$$\eta(\lambda_t, Q) = Q \cdot \left[\frac{3{,}33}{2} \cdot \left(\frac{90}{\lambda_t} + Q + 0{,}78\right) \cdot \exp\left(\frac{-50}{\lambda_t}\right)\right] \quad (1)$$

Here, $\lambda_t = \left[\frac{1}{\lambda+0,089} - 0,0035\right]^{-1}$ and $\lambda = \frac{R\cdot A\cdot\omega}{Q}$ is the tip-speed ratio of the blades; Q is the water flow rate, m³/s; R is the outer radius of the water wheel, m; A is the blade area of the water wheel, m²; and ω is the angular velocity of the water wheel, rad/s.

The mathematical expression describing the dependence of the torque of the water wheel on its design parameters is determined as follows:

$$M = \frac{\gamma\cdot Q}{g}\cdot(R_1\cdot c_1\cdot\cos(\alpha_1) - R_2\cdot c_2\cdot\cos(\alpha_2)) \qquad (2)$$

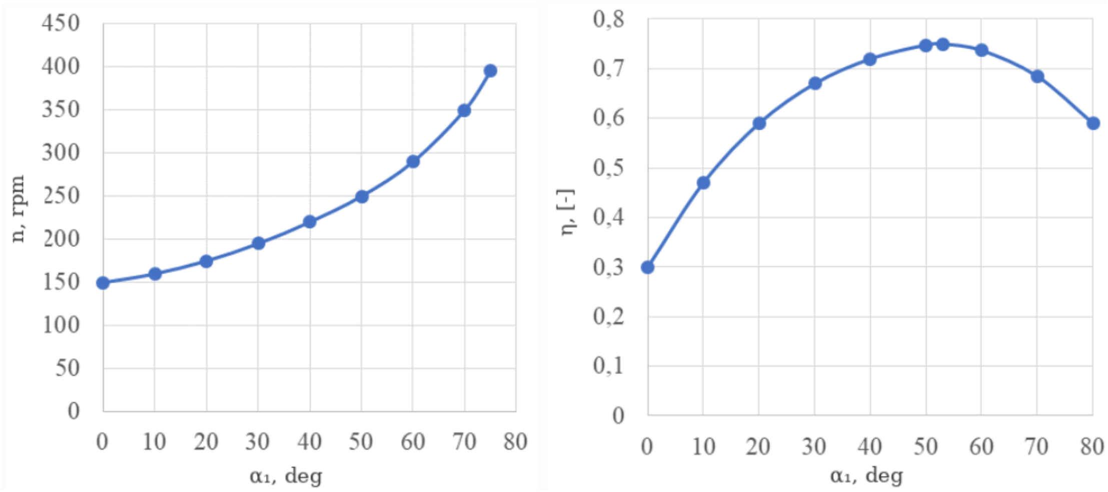
Here, γ − is the specific weight of water, N/m³; g−is the acceleration due to gravity, m/s²; Q− is the water flow rate, m³/s; R_1 − is the outer radius of the water wheel, m; R_2 −is the inner radius of the water wheel, m; c_1 − is the flow velocity at the outlet of the guide vane, m/s; c_2 − is the flow velocity at the outlet of the water wheel, m/s; α_1 − is the outlet angle of the guide vane; and α_2 − is the water-flow outlet angle from the water wheel ($\alpha_2 = 90^0$).

The optimal rotational speed of the water wheel is determined using the following simplified mathematical expression:

$$n_{opt} = \frac{30}{\pi R_1}\cdot\sqrt{\eta\cdot g\cdot H}\cdot\sqrt{1-\frac{tg(\alpha_1)}{tg(\beta_1)}} \qquad (3)$$

Here, g− is the acceleration due to gravity, m/s²; H− is the hydraulic head, m; α− is the outlet angle of the water flow from the guide vane; β_1 − is the water-flow inlet angle at the blades; and η −is the hydraulic turbine efficiency.

Figure 2 presents the efficiency characteristics of the hydroelectric power unit. It was determined that when the water-flow inlet angle at the blades is $\beta_1 = 148^0$,and the water-flow outlet angle from the guide vane is $\alpha_1 = 53^0$ the maximum hydraulic turbine efficiency is 75%, while the optimal rotational speed is 260 rpm.



a) **b)**

Figure 2. Curves of the optimal rotational speed (a) and maximum efficiency (b) of the water wheel of the vertical-axis hydroenergy device

The power of the water flow discharged from the pump units is determined using the following formula [10]:

$$P = \rho\cdot Q\cdot\left[g\cdot H + \frac{v_{in}^2 - v_{out}^2}{2}\right] \qquad (4)$$

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Here, ρ —is the density of water, kg/m³; $v_{in} = \sqrt{2 \cdot g \cdot H}$ — is the flow velocity at the inlet of the rotating water-wheel blades, m/s; g— is the acceleration due to gravity, m/s²; H — is the water pressure head, m; and v_{out} — is the flow velocity at the outlet of the rotating water-wheel blades, m/s.

If the dependence of the flow rate and pressure head of the water flow discharged from the pipe on its velocity is taken into account, the expression can be written in the following form:

$$P = \rho \cdot Q \cdot \left[\frac{Q^2}{2 \cdot S^2} + \frac{v_{in}^2 - v_{out}^2}{2}\right] \quad (5)$$

Here : S — is the cross-sectional area of the water flow, m².

The proposed vertical-axis micro-hydroelectric power plant is primarily designed to utilize water flows discharged from pumping units. Depending on the water flow rate and available head, the power output of the proposed system can be designed within the range of 1…50 kW.

It was determined that $\beta_1 = 148^0$the maximum efficiency of the water wheel of the vertical-axis hydroelectric power plant is 75% when the inlet angle of the water flow onto the blades is , and $\alpha_1 = 53^0$ the outlet angle of the water flow from the guide vane apparatus is .

For hydroelectric power plants intended for application in areas with low-head water flows, the use of electric generators with low rotational speeds increases the operating efficiency and reliability of the systems.

The electromagnetic power generated by a three-phase permanent-magnet generator is determined using the following expression [11]:

$$P_e = \frac{3}{2}\omega[\psi_{PM} + (L_d - L_q)i_d]i_q \quad (6)$$

The electromechanical torque of a generator with p- pole pairs is determined by the following expression:

$$M_e = \frac{3}{2}p[\psi_{PM} + (L_d - L_q)i_d]i_q \quad (7)$$

where: ψ_{PM} – magnetic flux, Wb.

$$\psi_{PM} = \frac{\sqrt{2}E_f}{\omega} \quad (8)$$

The electromagnetic angular velocity when the stator and rotor of the electric generator rotate in opposite directions is determined by the following expression:

$$\omega = p(\omega_{m1} + \omega_{m2}) \quad (9)$$

where: p – number of pole pairs.

Calculation of the armature winding inductance [12]:

The inductance along the d-axis and q-axis is determined as follows:

$$\begin{cases} L_d = m\mu_0 \frac{1}{\pi} \cdot \left(\frac{Nk_w}{p}\right)^2 \cdot \frac{(R_1^2 - R_2^2)}{g'} \cdot k_{fd} \\ L_q = m\mu_0 \frac{1}{\pi} \cdot \left(\frac{Nk_w}{p}\right)^2 \cdot \frac{(R_1^2 - R_2^2)}{g_q'} \cdot k_{fq} \end{cases} \quad (10)$$

where: N — number of turns in one winding; R_1 — outer diameter of the armature, m; R_2 — inner diameter of the armature, m; p — number of pole pairs; k_w — armature winding fill factor; m — number of phases.

Figure 3(a) presents a vertical cross-sectional view of an improved multipole electric generator for a micro-hydroelectric power plant, in which the inductor and armature rotate in opposite

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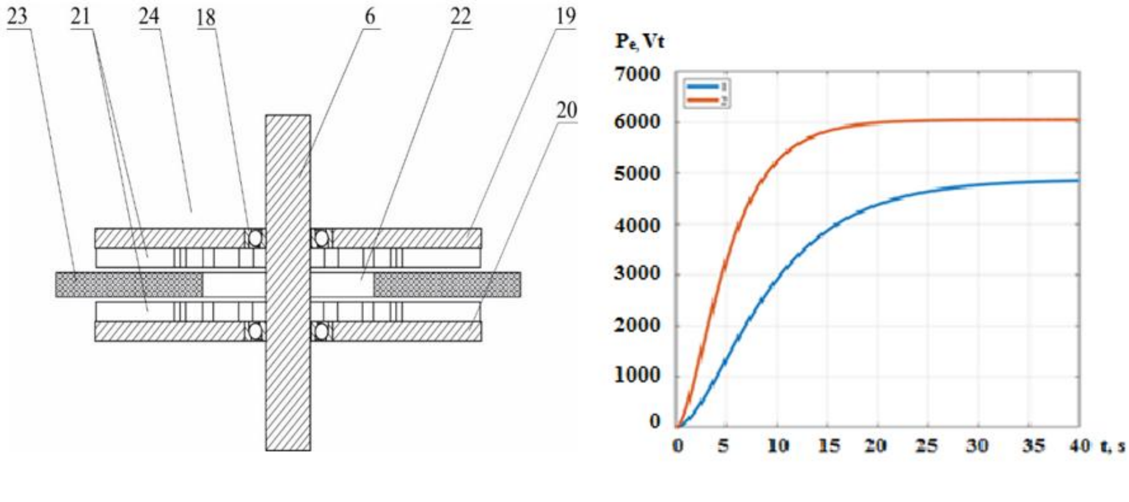
directions relative to each other. This generator is capable of producing a high electromotive force (EMF) at low rotational speeds.



a) b)

Fig. 3. Vertical cross-section of the improved magnetoelectric generator (a); comparative curves of the electromagnetic power of the electric generator (b).

Figure 3(b) compares the electromagnetic power values of the improved multipole magnetoelectric generator. It was found that when the armature and the inductor of the generator rotate in opposite directions relative to each other (Curve 1), the electromagnetic torque and electromagnetic power of the generator increase by 20% compared with the operating condition in which the armature is stationary and the inductor rotates (Curve 2). The electromagnetic power values of the electric generator under dynamic operating conditions at different water-flow velocities were determined using Equation (6).

Thus, the proposed vertical-axis hydroelectric power unit is designed to operate efficiently under variable and low-head water-flow conditions. Owing to the hydraulic turbine efficiency of 75% and the 20% increase in the electromagnetic power of the electric generator under dynamic operating conditions, the reliability and continuity of electricity supply to autonomous consumers can be improved.

Conclusions

1. The developed vertical-axis hydroelectric power unit is primarily adapted to water flows discharged from variable-flow and low-head pumping units. Depending on the water-flow rate and head, the feasibility of developing the unit with an output power ranging from 1 to 50 kW has been substantiated.

2. The modeling results demonstrated that the hydraulic turbine achieves a maximum efficiency of 75% when the inlet flow angle is $\beta_1 = 148^0$ and the outlet flow angle from the guide vane apparatus is $\alpha_1 = 53^0$.

3. It was determined that the developed multipole magnetoelectric generator, designed for efficient operation under variable and low-head water-flow conditions, achieves an electromagnetic power of 6 kW when its armature and inductor rotate in opposite directions relative to each other.

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