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Research Paper

Bi-rotor micro hydro power plant for energy supply to isolated consumers

Alaybek D. Obozov [1] *, Ruslan A. Akparaliyev [2], Taalaybek T. Mederov [3], Victor G. Krasnov [4]

[1] ScD, Professor, Director, Research Institute of Power Engineering and Economics affiliated with the National Committee for Industry, Power Generation and Subsurface Management of the Kyrgyz Republic, Bishkek, Kyrgyz Republic
[2] PhD, Deputy Director, Research Institute of Power Engineering and Economics affiliated with the National Committee for Industry, Power Generation and Subsurface Management of the Kyrgyz Republic, Bishkek, Kyrgyz Republic
[3] Senior Lecturer, Department of Renewable Energy Recourses, Razzakov Kyrgyz State Technical University, Bishkek, Kyrgyz Republic
[4] PhD, Associate Professor, Department of Oil and Gas Engineering, Nizhnevartovsk Affiliate of the Tyumen Industrial University, Nizhnevartovsk, Russia
**Corresponding author E-mail: myktarbekjumabaev@yahoo.com*

Abstract

This paper is dedicated to comparative analysis and description of a micro hydroelectric power plant with bi-rotor hydro generator. Based on the characteristics analysis, this paper describes a renewable energy source for a small watercourse; the feasibility of micro hydroelectric power plants with bi-rotor hydro generator is demonstrated. The features of their operation require in-depth research to substantiate parameters of such installations. This paper presents the analysis of the usage of micro hydroelectric solutions with bi-rotor hydro generator. The lattice theory problem was solved, which made it possible to determine the shape of the profile according to a given law of velocity distribution (pressure) on the contour. The experimental stand was developed, and the experiments were conducted to identify the dependence of the frequency of rotation from the flow and the dependence of the rotational frequencies of hydro turbines from various loads. Based on the results obtained, the optimum values of the rotational speed were identified. Presented results of experimental research are of significance and can be applied practically in design of micro hydroelectric power plants with bi-rotor hydro generator.

Keywords: *Bi-Rotor Hydro Generator; Differential Equation; Rotational Flows; Function; Hydraulic Models; Kinetic Energy; Renewable Energy Sources; Velocity Measurements.*

1. Introduction

The use of renewable energy sources (RES) addresses problems of energy supply and environmental protection; it is one of the most intensively developing fields of power generation [1]. It is evident now that the hydrocarbon fuel resources (oil, gas, coal, etc.) are far from infinite given the rate of their consumption, while environmental damage from burning such fuels causes concern to entire humanity due to global climate change. In this situation, extensive use of RES that have enormous potential may provide a solution of environmental problems [2].

Among various RES, the energy of small watercourses is of interest. It appears that the use of the energy of water on hydroelectric plants (HPP) gives the possibility to generate clean electrical power. Micro hydropower industry has been intensively developing along with the large hydroelectric facilities. Advantages of the micro hydropower generation over large hydropower facilitie [3] are low capital investments, shorter construction time and, therefore, faster return on investments; operational independence; and absence of large-scale hydraulic constructions (dams, water intake structures, waste tunnels). Construction of micro and small HPPs does not entail flooding of the lands in estuaries and, finally, the use of local water resources does not require transmission of electricity over long distances, which significantly reduces dissipation of power. In consideration of the above, intensive research aimed at design and development of reliable, highly efficient, and economically feasible micro HPPs has been lately conducted. Such plants became widely used for power supply of isolated low-consuming facilities located in remote areas where the centralized power supply systems are absent. Such objects are forestry farms, remote national parks, villages, small mountain settlements, agricultural farms, mountain tourism facilities, etc.

A significant part of micro HPPs is used on small watercourses, where the steep terrain makes it possible to successfully use such plants at high water head. However, in practice, micro HPPs are often needed at flatlands where it is difficult to obtain high head and construction of dams unjustifiably increases the cost of electricity generation. In this connection, it seems necessary to create a new type of micro HPP that would successfully operate in conditions of low head (1-2 m) and still ensure efficient capacity.

The problem, in this case, is to reach high hydro generator speed because, at low speed, rotation of the hydro turbine is usually not enough to guarantee high rotation speed of the generator. To solve this, a multiplicator is installed between the hydro turbine and the generator; however, it increases the weight, overall dimensions and cost of micro HPPs.

A new approach to the development of low-head micro HPPs that do not require a multiplicator is proposed in this paper. Here, the rotor and the stator of the micro HPP rotate simultaneously in the opposite directions. As known, operation of the electric generator is based on the electromagnetic induction, that is, the electromotive

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force occurs in the generator due to its dynamic interaction with the magnetic field. In a conventional generator, the stator is usually immobile, and the rotor rotates creating current in the winding. The output capacity depends on the frequency of crossing the magnetic field by the rotor windings. Thus, with the rotor and the stator rotating simultaneously in the opposite directions, the frequency of crossing the magnetic field by the rotor windings should theoretically double. Therefore, a doubled relative rotation frequency of the electromagnetic field can be obtained at a lower rotational speed of the turbine.

2. Literature review

Based on the principle of simultaneous rotation of the rotor and the stator, theoretical and experimental studies of the prototype of the bi-rotor micro HPP were conducted. The basic configuration of the prototype is shown in Figure 1.

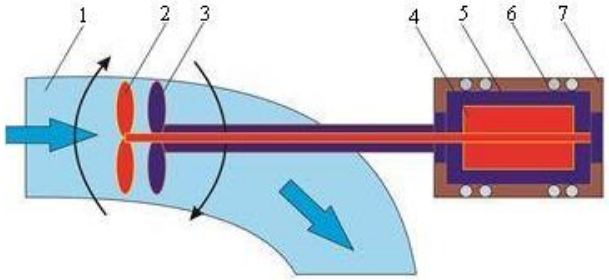


Fig. 1: Basic Configuration of the Bi-Rotor Micro HPP, Where: 1 - Submerged Pipeline; 2 - First Hydro Turbine; 3 - Second Hydro Turbine; 4 - Rotor; 5 - Stator; 6 - Bearings; 7- Housing.

Operational principle the bi-rotor micro HPP is that two working wheels run in one hydraulic flow; at that, the wheels are placed along one axis one after another and rotate in the opposite directions.

Figure 2 demonstrates the basic configuration of another type of bi-rotor micro HPP. The unit consists of pressure water conduit 1, guide vanes 2, hydro turbine with working wheel 3 that is mounted on shaft 4, and outlet pipe 5. Shaft 4 of working wheel 3 is rigidly connected to shaft 6 of generator rotor 7. To drive the stator 9, sleeve-type bearings 8 are installed between the hydro generator and the stator; straight-toothed gear is used. For this, internally toothed gearwheel 10 (driven) with diameter d3 is installed at stator 9. To drive rotor 7 and stator 9 in the opposite directions, gears 11 with diameter d2 are installed between gearwheel 10 of stator 9 and gearwheel 12 (driving) of rotor 7 with diameter dl [4].

The described micro HPP operates as follows: Water flows through the pressure water conduit 1 goes to guide vanes 2, at which point the flow changes speed and direction. Between guide vanes 2 and working wheel 3 of the hydro turbine water is forced to circulate in order to create shock-free incoming flow to the working wheel blades 3 of the hydro turbine. As the water flow interacts with blades 3, the hydrodynamic forces create a torque, and as a result the turbine rotates. Having transferred the hydraulic energy to working wheel 3, the water flows into the tailrace through outlet pipe 5. Working wheel 3 of the hydro turbine converts the hydraulic energy of the stream into the mechanical rotational energy of shaft 4. Further, shaft 6 of rotor 7 that is connected to shaft 4 of working wheel 3 starts rotating and engages gearwheel 12 of rotor 7, which meshes with gearwheels 11 and also starts to rotate them. In their turn, gearwheels 11 grapple with toothed gearwheel 10 of stator 9 and rotate stator 9 in the opposite direction in relation to the rotation of rotor 7 due to internal engagement. The use of direct toothed gear in the hydro generator ensures reliability of the unit and easy assembly and disassembly of the mechanical system.

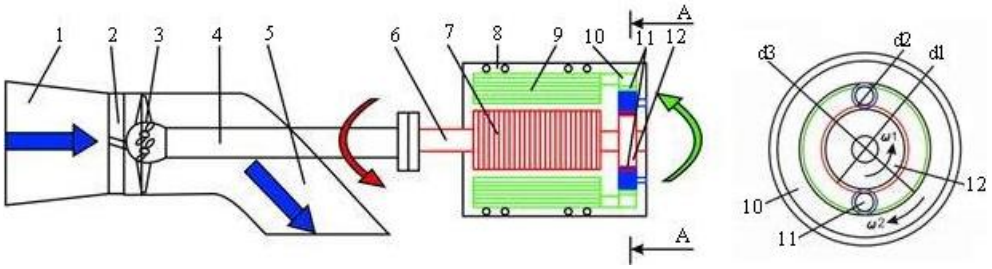


Fig. 2: Basic Configuration of Bi-Rotor Micro HPP.

One of the directions in the development of micro HPPs is the free-flow solution [5] that uses high velocity head of the river flow. In a number of such solutions, the translational motion of the guiding link is transformed into rotary output. At a relatively low speed of the flow, it appears to be difficult to convert mechanical energy into power, which makes the task of using a bi-rotor generator crucial. Possibility of using the bi-rotor generator for such units is explained by the low frequency of rotation of the driven link and the convenience of installation (refer to Figure 3). Shaft 2 of rotor 3 is mounted on the supports of frame 1. Stator 4 is an element of the driven wheel and is mounted movably on shaft 2 of rotor 3. Shaft 2 is provided with current collector 5.

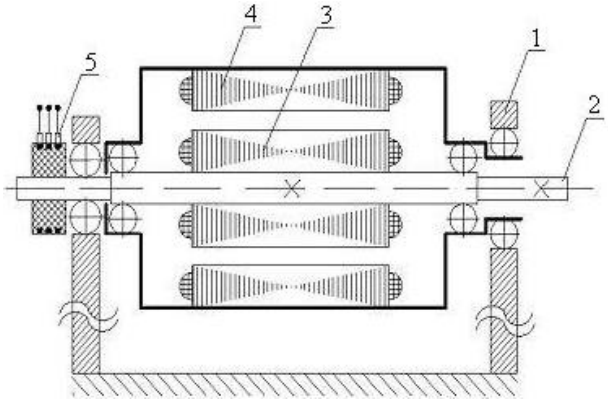


Fig. 3: Configuration of the Free-Flow Micro HPP with A Bi-Rotor Generator on the Driven Shaft.

3. Scope of research

A series of calculations and experimental methods were used in the study, which made it possible to identify the main characteristics of the bi-rotor micro HPP. Using calculations, a design model of the

bi-rotor hydro turbine was developed in order to study the fluid motion pattern and determine its kinematic and hydrodynamic parameters (Figure 4).

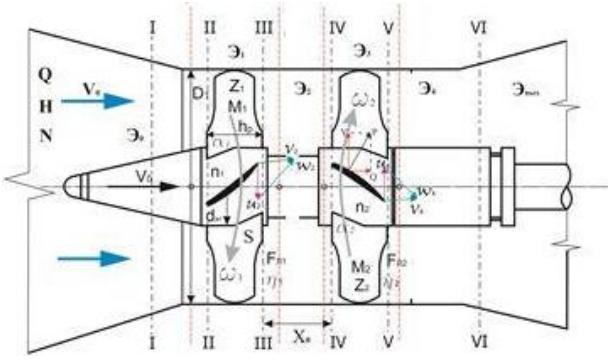


Fig. 4: Model of the Bi-Rotor Hydro Turbine.

Figure 4 demonstrates the principal geometric, hydraulic, kinematic and dynamic parameters: diameters of working wheels D_1, D_2, diameter of sleeve d_{vt}, number of blades Z_1, Z_2, surface area of blades S, operating height of blade h_p, angles of blades α1, α2. The main hydraulic parameters are pressure H, consumption Q, flow capacity N, cross-section area m^2, average flow speed V_0, flow energy in the corresponding sections Э$_i$, coefficient of efficiency of the hydro turbines η_1, η_2, resistance to motion in the working wheel F_{L1}, F_{L2}, circumferential velocities u_1,u_2, relative velocities w_1,w_2 and absolute velocities v_1,v_2. Angular velocities of hydro-turbine rotation ω_1,ω_2 refer to principal kinematic parameters.

Dynamic parameters in the design model are momenta M1 and M2, lifting force Y, resistance force Q, and total power P. All the forces have impact on the blades of the working wheels.

To determine the kinematic parameters of the flow and calculate the geometric parameters of the turbine, the problem of lattice theory was solved. Hence, the shape of profile was determined according to the given law of velocity distribution (pressure) on the contour of the profile. In the general form, solution for the viscous fluid can be sought using the Navier-Stokes equation [6].

$$\frac{\overrightarrow{dv}}{dt} = \vec{F} - \frac{1}{\rho}\text{grad p} + v\nabla^2\vec{\vartheta} \quad (1)$$

Where: $\frac{\overrightarrow{dv}}{dt}$ – total acceleration of a liquid particle; $\vec{F}$ - acceleration from the mass forces; $-\frac{1}{\rho}\text{grad p}$ – acceleration from the pressure forces; $v\nabla^2\vec{\vartheta}$ –acceleration from viscosity forces.

For a plane problem in the projections along the coordinate axes, the equation mentioned above is written in the following form:

$$\left.\begin{aligned}\frac{dv_x}{dt} &= F_x - \frac{1}{\rho}\frac{\partial p}{\partial x} + v\left(\frac{\partial^2\vartheta_x}{\partial x^2} + \frac{\partial^2\vartheta_x}{\partial y^2}\right)\\ \frac{dv_y}{dt} &= F_y - \frac{1}{\rho}\frac{\partial p}{\partial y} + v\left(\frac{\partial^2\vartheta_y}{\partial y^2} + \frac{\partial^2\vartheta_y}{\partial x^2}\right)\end{aligned}\right\} \quad (2)$$

Taking into account that the values of forces due to viscosity are negligible for water, let us use the Euler equation for the motion of an ideal incompressible fluid.

$$\frac{\overrightarrow{dv}}{dt} = \vec{F} - \frac{1}{\rho}\text{grad p} \quad (3)$$

The movement of the liquid in the working wheel is quite complex: when entering the working wheel yet before reaching the blades, the flow moves at a certain speed, in parallel to the axis of rotation of the wheel. Then the flow reaches the blades and channels between the blades. As a result of the interaction of the flow with the blades of the working wheel, the latter starts to rotate acquiring the circumferential velocity (u). The vector of the circumferential velocity is always directed along the tangent to the rotation circle (refer to Figure 5). When a liquid hits the blade, it slides along its surface at a speed (w), which commonly referred to as relative.

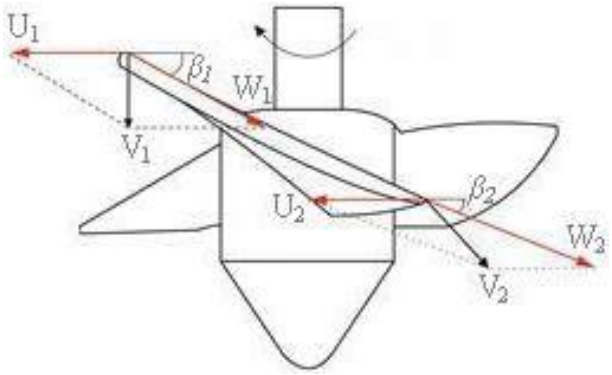


Fig. 5: Speed Distribution in the Axial Working Wheel of the Turbine.

The relative velocity vector is always directed tangentially to the blade surface. Let us denote the circumferential velocity at the entrance to the blade u_1 and at the exit from the blade u_2, and the relative velocity when reaching the blade w_1 and at the exit from the blade w_2. Then, the vectors of the absolute velocity at the input and output of the vane v1 and v2 are respectively determined by the vector sum [6]:

$$\vec{v}_1=\vec{u}_1+\vec{w}_1; \quad (4)$$

$$\vec{v}_2=\vec{u}_2+\vec{w}_2; \quad (5)$$

Thus, the relationship between absolute, circumferential and relative speed is established by a parallelogram or a velocity triangle.

The solution of the problem of calculation and selection of the hydrodynamic parameters of hydro turbines was carried out with the use of FlowVision software product on the basis of the developed model and the calculation algorithm.

When simulating the bi-rotor hydroturbine, the sequence of actions necessary to solve the identified problems was formed. Initially, the model of the hydro turbine in Flow Vision was performed using an external program — a geometric pre-processor. Compass 3D, SolidWorks, AutoCAD are used as such pre-processors; they belong to the Computer-Aided Design family and are widely applicable in scientific and engineering practice.

To study the functioning of the bi-rotor micro HPP, an experimental stand was created as shown in Figure 6 (Mederov, 2016). Experimental stand consists of the following basic elements: 1 - supply pipeline; 2 - valve; 3 - first impeller; 4 - second impeller;
5 – bi-rotor micro HPP; 6, 7 - digital tachometers; 8 - hydro-generator; 9 - panel with load, control unit, ballast, voltmeter and ammeter; 10 - multifunctional measuring device "Metrel"; 11 - oscilloscope; 12 - water meter.

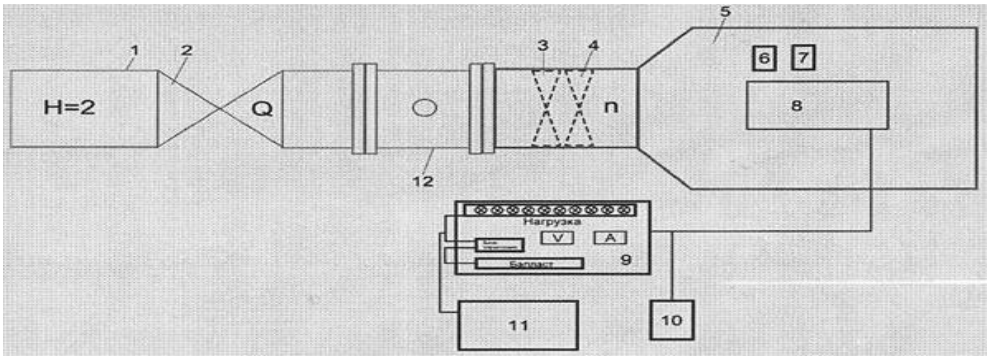


Fig. 6: Experimental Stand.

The experimental operates works the following way: First, the siphon is launched; for that, valve 2 is closed and the vacuum is created at the highest point of the siphon by means of a vacuum pump. The difference between atmospheric pressure on the free surface of water in the channel and the reduced pressure in the upper part of the siphon generates a rise and movement of water along the siphon into the water channel 1. Further, the water flows via a supply water conduit 1, passes through the water meter 12 and comes to the turbine chamber of the tested micro HPP 5 (refer to Figure 6).

First impeller 3 in the turbine chamber rotates clockwise under the influence of the water flow and drives the shaft of the generator. Second impeller 4 rotates in the opposite direction and drives the shaft of the stator. Thus, there is the opposite rotation of two shafts, on which the rotor and the stator are located separately.

After that, having given the energy to the impellers, water flows back to the watercourse through the discharge chamber. Water consumption is regulated by valve 2; hydroturbine rotation frequency is measured by contactless digital tachometers 6 and 7; power, voltage and current are measured with measuring device "Metrel" 10.



Fig. 7: Bi-Rotor Micro HPP During the Test.

4. Results

As a result of the experiments, the following main characteristics were obtained: n = f (Q); n = f (P). The results of the study are shown in Figure 8 and Figure 9.

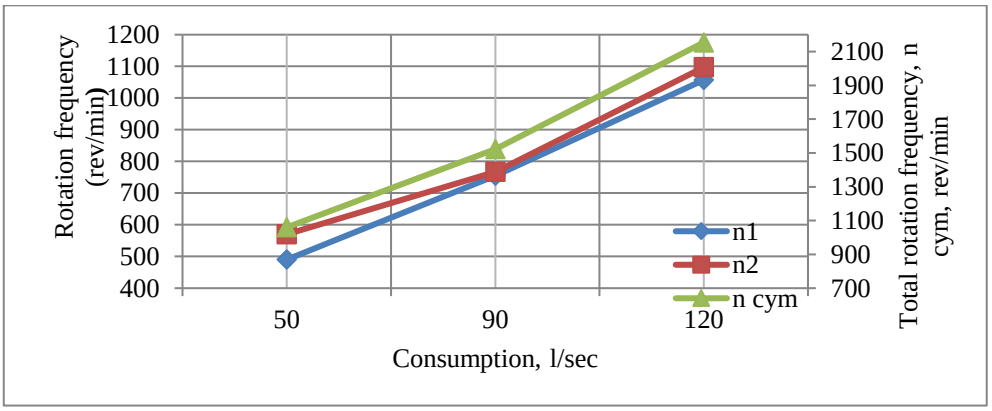


Fig. 8: Dependence between Rotation Frequency and Consumption.

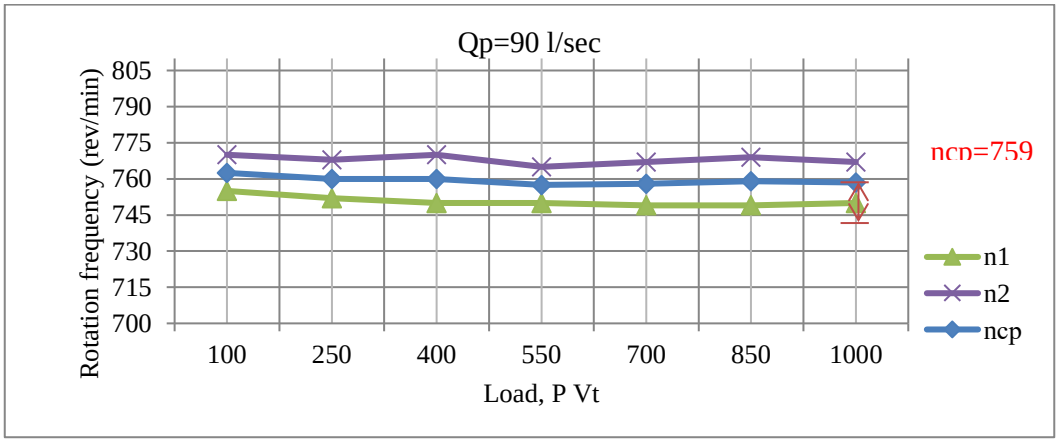


Fig. 9: Graph of the Dependence between the Hydroturbine Rotation Frequency and Different Loads.

5. Findings

The analysis of the obtained results proves that the required design value of the rotation frequency, which is n = 1500 rpm, is achieved at calculated flow rate Q_p = 90 l/sec and corresponds to the required operating conditions of the micro HPP. The change in total capacity corresponds to the estimates. Nominal capacity level is achieved at an average rotation frequency of turbines equal to 759 revolutions.

Notation

$\frac{\overrightarrow{dv}}{dt}$ – total acceleration of a liquid particle (ms-²)

$\vec{F}$ - acceleration from the mass forces (ms-²)

$\frac{1}{\rho}$grad p – acceleration from the pressure forces (ms-²)

$v\nabla^2\vec{\vartheta}$ –acceleration from viscosity forces (ms-²)

v_1 - relative velocity (m/s)

u_1 - circumferential velocity (m/s)

w_2 - absolute velocity (m/s)

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