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Pico hydro generator as an effective source of renewable energy

Streszczenie. *Artykuł dotyczy piko – agregatu o mocy 1kW: osiowej turbiny wodnej i generatora. W artykule przytoczono przykład osiowej turbiny wodnej z wirnikiem opracowanym z zastosowaniem profilu aerodynamicznego NACA. Przedstawiono konstrukcję pionowej turbiny osiowej. Opisano laboratoryjne stanowisko pomiarowe do badań skonstruowanej i zbudowanej turbiny, napędzającej trójfazowy generator elektryczny. Przedstawiono podstawowe charakterystyki turbiny opracowane dla jej parametrów pracy, przy których osiągnęła najwyższą sprawność oraz podstawowe charakterystyki współpracującego z turbiną generatora. (**Turbina śmigłowa z generatorem efektywnym źródłem energii odnawialnej.)***

Abstract. *The paper presents 1kW pico hydro generator that consists of an axial water turbine and generator. The rotor of the axial water turbine was developed using the NACA aerodynamic profile. The paper describes the construction of a vertical axial turbine and the laboratory stand for the measurement of the developed and constructed turbine powering a three-phase electric generator. The basic turbine characteristics for the highest efficiency parameters and the characteristics of the generator are presented.*

Słowa kluczowe: turbina wodna, energia, generator, ochrona środowiska, cieki wodne. .
Keywords: water turbine, energy, hydro generator, environmental protection, watercourses.

Introduction

Propeller hydro power turbine

The most prevalent natural hydrological conditions in the lowlands, predominating in Central Europe are characterized by low heads in small and medium watercourses flow rates. Such conditions allow for the use of water head energy by means of water wheels, Banks-Mitchell turbines and propeller turbines [1]. Rational locations for these turbines possible installations are largely dispersed so that their powers do not usually exceed several to several dozen kW. Small hydro electric schemes containing generators below 10 MW can be classified as follows:

mini	< 1 MW,
micro	< 100 kW,
pico	< 5 kW.

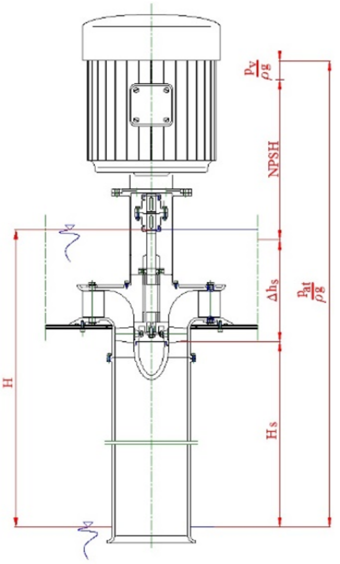

Fig. 1a Set-up of hydro generator - source of supply below turbine

The subject of the paper is the construction , empirical research and assessment of a 1kW pico turbine composed of an axial turbine and generator, designed to use hydropower of watercourses with low head and low discharge.

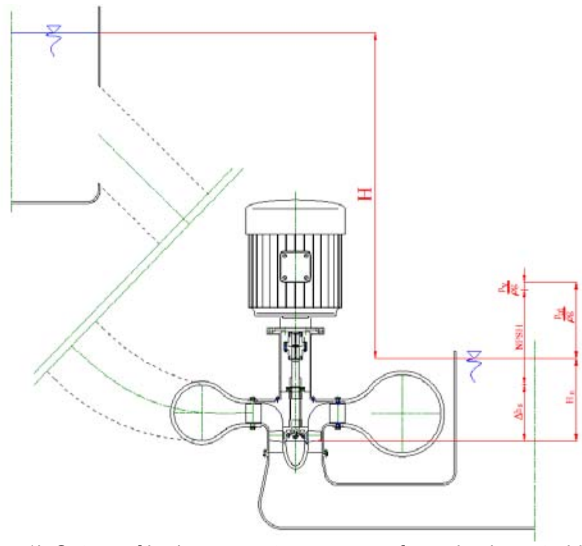

Fig. 1b Set-up of hydro generator - source of supply above turbine

Anti-cavitation surplus and set-up of water turbines.

The smallest water turbines can be installed at the level of the upper tank (Figure 1a), while large ones usually require installation below the water table, in the bottom tank, (Figure 1b). Mini and pico propeller water turbines operating at a several-meter water head have an important advantage as they can work with suction and can be installed at the level of the upper tank, as shown in Figure 1a. This is due to the anti cavitational surplus of the turbine, which in this case is much smaller than the atmospheric pressure. As a result, a few-meter water head allows the turbines to work practically without an inflow, as almost the whole drop occurs in the suction pipe. This construction of the turbine significantly reduces the investment cost.

For the installation of turbine shown in Figure 1a the following condition must be satisfied: the height of suction Hs must be smaller than the height of water H which must be smaller than the height of water column corresponding to the atmospheric pressure pat/ρg. The definition of cavitation properties of water turbine is the same as that of rotation turbines presented in D. Thoma's hypothesis. It follows that the dynamic depression of pressure in the pump or water turbine is proportional to the head and cavitation coefficient. Since the dynamic depression of pressure is practically equal to net positive suction head at the pump inlet or turbine outlet the formula for both machines is written as:

(1) $$NPSH = \sigma_{cav} H$$

where:

(2) $$\sigma_{cav} = f(n_s)$$

where n_s - is the turbine specific speed:

(3) $$n_s = 1{,}166\, nP^{1/2} H^{-\frac{3}{4}}$$

and *P* – turbine power [kW].

Efficiency of water turbines

The construction of power machines results mainly from their efficiency. According to A.M. Chrystjakowa axial pico turbines with rotor diameters <0.46m increase hydraulic losses by several to a dozen or so percent because of the transition to the zone depending on the Reynolds number [2]. Since the diameter of pico turbine rotor d<0,25m, the construction calculations were conducted for $\eta_h = 0{,}75$.

Calculations of the main dimensions of axial turbine rotor

The following values of turbine operating parameters were used for the construction calculations: the quantity of water flowing through the turbine per minute $Q = 4\frac{m^3}{min}$, head $H = 2m$, rotational speed $n = 850\frac{obr}{min}$ .The dynamic specific speed is calculated from the formula:

(4) $$n_s = 3{,}65n\frac{\sqrt{Q}}{H^{0{,}75}} = 476$$

The value of the specific speed indicates that the discussed turbine is an axial one. Further construction calculations for axial pico turbine with the above-mentioned parameters are presented in paper [3].

Blade of axial turbine

The initial shape of the NACA 2412 profile was used to design the blade. The profile is described by the relations of characteristic geometrical dimensions. Figure 2 shows the rotor with four blades. The thickness of the profile was proportionally reduced in relation to that of the NACA 2412 while its length remained unchanged. The height of the blade determined the changes of the maximum thickness of the profile. The profile has the maximum width at the hub end of the blade.

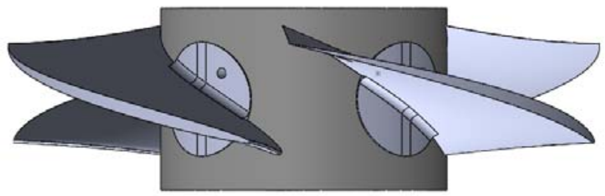

Fig. 2. Hub with blades

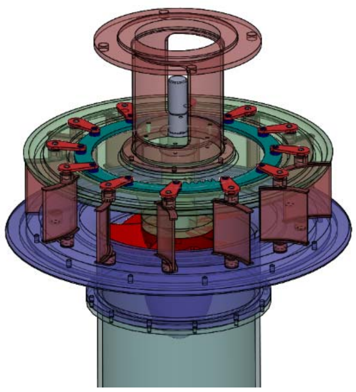

Fig.3. 3D Turbine with a four-blade rotor

The water turbine prototype

In Figure 3 the construction of a prototype axial turbine is shown. The ceramic bearings with water passing through the turbine as a lubricating fluid were used. The longitudinal force was transmitted through the generator bearing. We used an untypical clutch on which the rotating assembly of the turbine was hung on. Successful tests were also carried out on bearings made of stain-less steel alloys washed by flowing water. In this case axial force was transferred by turbine bearings. There was no need for a clutch of special construction. At the inlet to the turbine, a centripetal steering wheel with a profiled, regulated blades was installed.

Materials and Methods

Laboratory test stand

The scheme of the pico-turbine test stand is shown in Figure 4. Considering specific speed and after literature research the authors decided to build the symmetrical inflow channel with one crosswise rib preventing both the formation of vortices and air inflow to the turbine.

The test stand is designed for one turbine size. The proposed shape and dimensions of the inlet channel can be installed under target conditions (e.g., on the stream). Water was delivered to the circuit by means of a centrifugal pump. A draft tube of a constant diameter was manufactured for laboratory tests. In further research, this element should be applied as a diffuser with an appropriate opening angle improving the efficiency of the system.

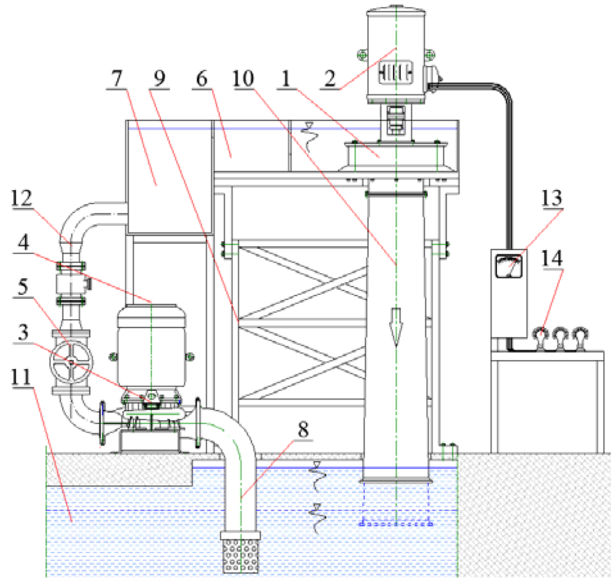

Fig. 4. Water pico turbine and three-phase generator test stand. 1 - turbine, 2 - generator, 3 - supplying pump, 4 - pump motor, 5 - valve, 6 - inflow channel, 7 - buffer, 8 - suction pipe, 9 - load bearing construction, 10 - draft tube of the turbine, 11 - underfloor tank, 12 - discharge pipeline, 13 - electrical meter, 14 - electrical resistor

Measurement method

Water was pumped from the underfloor tank by a centrifugal pump with a rotational speed regulation. It flowed evenly into the turbine through the inflow channel. The incoming water flow was regulated by changing the rotational speed of the supplying pump. The height of water head was regulated by changing the water level in the underfloor tank. The electricity produced by a three-phase generator supplied a set of light bulbs connected in a wye system. In order in to increase the load in each phase, the additional light bulbs were added in series and in parallel. A three-phase generator loading the turbine was used for laboratory tests. The generator was loaded by a set of interconnected bulbs (Figure 5).

Measurement results

The efficiency of water turbine and generator is determined by the measurements of the following parameters: flow rate Q, head H and electrical power P_e. The flow rate was measured by an electromagnetic flowmeter. The value of head was defined as distance between water level in the inflow channel and water level in the underfloor tank. The electrical power was measured by a universal power meter measuring voltage, current and phase angles (threephase system).

Fig. 5. The measurement stand in operation

Measurement of the mechanical parameters (turbine generator in operation)

The Best Efficiency Point for the tested pico turbine at the assumed head H, was characterized by the following parameters:

Head	$H = 2{,}18$ m,
Flow rate:	$Q = 4{,}22$ m^3/min,
Rotational speed:	$n = 859$ rpm,

Measurement of generator's electrical parameters

The measurement was conducted at the electrical side of a generator loaded with electrical resistors and driven by a pico turbine. The three-phase generator, at a rotational speed of n = 859 rpm, was generating electricity with a voltage U = 458 V, and current I = 1.65 A. The measuring instrument measured the changes of the phase shift caused by the load. Electrical power was written as:

(5) $$P_e = \sqrt{3}\, U\, I\, cos\varphi = 1050 \text{ W}$$

and shaft power :

(6) $$P = P_e/Eta_e = 1050/0{,}85 = 1123{,}53 \text{ W}$$

The efficiency of turbine-generator was derived from the hydraulic power supplying the water turbine and the electrical power given back by the generator:

(7) $$\eta_a = \eta_T\, \eta_G = \frac{P_e}{P_h} = 0{,}698$$

The efficiency of pico turbine was defined by the formula:

(8) $$\eta_T = \frac{\eta_a}{\eta_G} = 0{,}821$$

where η_G – generator efficiency

The basic performance curves of picoturbine

The characteristics of the tested pico turbine were elaborated on the basis of Best Efficiency Point parameters and typical curves for water turbines shown in Fig.6.

Generator set-up

The following assumptions were adopted in the generator design:

- power 2 kW
- output voltage 3X350 V
- frequency 50 Hz
- rotational speed 750 rpm

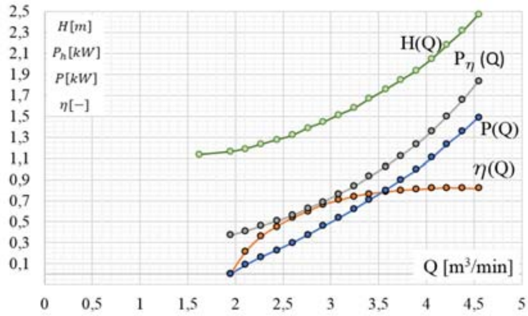

Fig. 6. Characteristics of the tested pico turbine elaborated on the basis of Best Efficiency Point parameters

The stator and rotor stacked cores were made of electrotechnical sheets using the laser cutting method. The generator was built using housing and bearing plates of a typical three-phase a 100 mm lift motor. The generator stator has 36 straight grooves in which a three-phase, eight-pole winding is placed. The rotor is equipped with 8 alternating polarity N38S neodymium magnets of the size 30x20x5 mm. Figure 7 shows a view of the rotor sheet with slots containing magnets. Placing the magnets inside the rotor reduces the induction in the gap, but protects against demagnetization and ensures safe operation of the generator (there is no possibility of breakdown as in the case of magnets glued on the rotor surface and there is no risk of magnets getting unstuck).

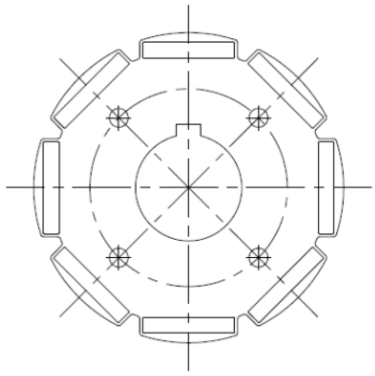

Fig. 7. The shape of rotor's sheet

Different methods of minimizing the cogging torque are used in generators with permanent magnets. [4-11]. In the developed generator the cogging torque was minimized by the use of slanted magnets placed along the length of the rotor. It was done by dividing the rotor into 6 segments shifted against each other by 2^o. Fig. 8 shows the view of the rotor.

Fig. 8. View of the generator rotor with slanted magnets.

In such a design, the individual segments strongly repel each other and therefore it is necessary to connect them with screws as seen in Figure 8. In addition, since magnets in the outer segments are pushed outwards the external, antimagnetic plates visible in Figure 8 are used in order to hold them. The generator stator has straight-teethed slots with a three-phase eight-pole winding placed in them [12-15]. The generator has an aluminium housing typical of an asynchronous motor. The prototype is shown in Figure 9.

Fig. 9. View of the prototype generator

Results and Discussion

Results of laboratory tests

The laboratory tests of the generator included measurements of the cogging torque, and the idling voltage as a function of the rotational speed and the output voltage as a function of the load at the rated speed. The tested generator was driven through the gear by an asynchronous squirrel-cage motor powered by the inverter. The maximum value of the cogging torque was measured using a balanced lever and precise weights. Ten measurements were made at various rotor positions and the arithmetic mean was calculated.

Considering the fact that the machine is multipole, the mean value of the coupling torque is modest and equals 0.37 Nm, which is 1% of the rated torque. It should be emphasized that the results include the frictional moment of the generator bearings. The motor was powered through the inverter, which enabled the regulation of the rotational speed and determination of the generator characteristic at idle. The characteristic was determined in the cold and warm thermal states of the machine. The results of measurements are presented in Table 1 and Table 2.

Table. 1. The results of measurements ϑ_{ot} = 17.6 °C and ϑ_{Cu} = 17.6 °C

ϑ_{ot} = 17.6 °C ϑ_{Cu} = 17.6 °C		
n	*f*	*U*
rpm	Hz	V
113.3	7.55	53.6
230.2	15.35	112.2
305.3	20.35	148.8
404.5	26.97	197.0
498.3	33.22	243.0
596.0	39.73	290.7
700.1	46.67	341.2
750.0	50.00	365.6
800.3	53.35	390.3
898.2	59.88	438.4
1013.5	67.57	494.2

Table. 2. The results of measurements ϑ_{ot} = 17.5 °C and ϑ_{Cu} = 63.4 °C

ϑ_{ot} = 17.5 °C ϑ_{Cu} = 63.4 °C		
n	*f*	*U*
rpm	Hz	V
120.7	8.05	55.1
221.8	14.79	102.2
384.2	25.61	176.9
512.5	34.17	236.5
617.0	41.13	284.6
750.4	50.03	346.2
904.9	60.33	418.2
1011.0	67.40	468.0

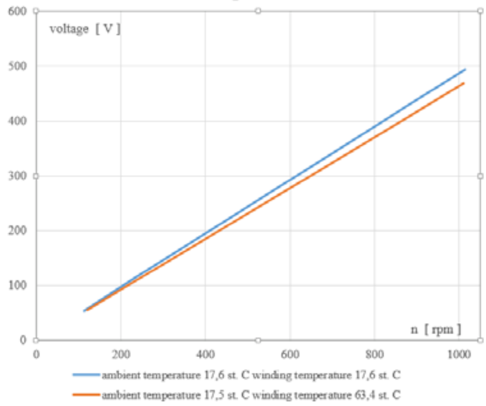

Fig. 10. The dependence of output voltage on rotational speed

Additionally, the waveform of generator output voltage shown in Figure 11 was obtained.

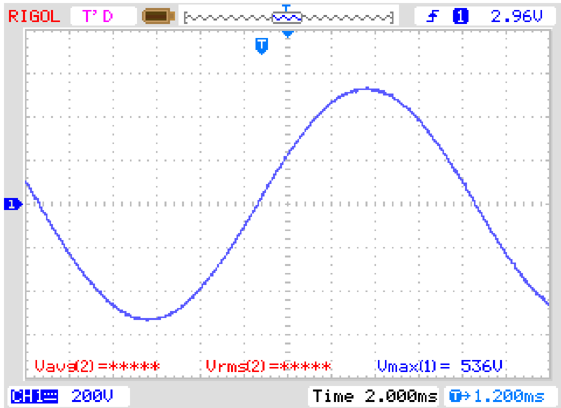

Fig. 11. The waveform of line-to-line voltage for the generator at idle

The voltage has practically sinusoidal waveform. The next stage of the research was to determine the load characteristics, as it provides the best description of power properties of the generator. The characteristics were determined by loading the generator by resistances, symmetrically in each phase. The rotational speed was fixed at 700 rpm as the load current was gradually increased. The characteristic was determined in the warm thermal state of the generator. The results of the measurements are shown in Figure 4.

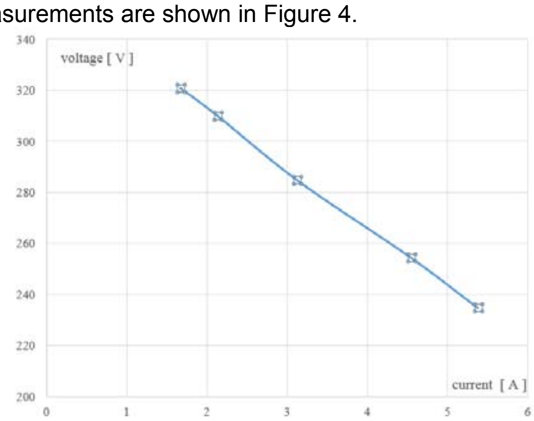

Fig. 12. The dependence of output voltage on load current

Fig.13. View of a turbine-generator set

Conclusion

The tests have shown that if a pico turbine with a rotor diameter of d = 228mm is precisely manufactured and assembled and the appropriate bearings are used, its efficiency may be the same as the one calculated from formula (2). As a result it is not burdened with additional losses caused by the scaling effect. Owing to the use of the algorithm [16] for hydraulic and structural calculations a good agreement of turbine operation parameters assumed for calculations with those obtained empirically was achieved. The application of NACA 2412 as rotor blades profiles proved to be a good solution, which confirms the above conclusion. As indicated previously, the obtained results can be applied in the production of pico turbines and as a model machine investigations for higher capacity turbines. Small hydropower plants equipped with permanent magnet generators achieve higher efficiency compared to power plants with asynchronous machines [6]. The generator discussed in the paper is intended for cooperation with a small water turbine. The constructed pico-hydro generator is presented in Figure 7. The energy obtained from the generator can be transformed and returned to the power grid or used to supply selected receivers. The assumed generator output voltage was untypical due to the maximum allowed input voltage of the inverter.

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