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CREATION AND SUBSTANTIATION OF THE MATRIX FOR MODEL SERIES OF TUBULAR PROPELLER TURBINES FOR SMALL HYDROPOWER PLANTS

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Summary. *The paper is devoted to further development of small hydropower on the basis of reliable and cheap unregulated tubular propeller hydroturbines with rigidly fixed operating and guide blades. Such turbines are used mainly at low-pressure small hydroelectric power stations. Their main drawback is the impossibility of generated power regulation. However, solutions that minimize this shortcoming are proposed in this paper. Matrix of 4 model series of tubular propeller hydroturbines has been created. The nomenclature of turbines presented in this matrix is aimed at improving technical characteristics of small hydropower plants and reducing their negative impact on the environment. The rules for equipping machine platforms of low-pressure small hydroelectric power plants with capacity up to 200 kW with models of turbines from the created matrix are proposed, and their technical and environmental justification is performed. According to the recommendations given in the paper, at least two different adjacent turbines from the same model line should be installed at one HPP. The best option is three different adjacent turbines from the same model series, but technical and economic analysis should be performed for more detailed justification of the choice of the number of turbines. This is the subject of our further investigations. The application of scientific and practical results presented in the paper will improve technical characteristics of small hydropower plants with tubular propeller turbines and minimize their possible negative impact on the life of river flora and fauna in lower basin.*
Key words: *matrix, model series, tubular propeller hydroturbine, small hydropower plants, low pressure.*

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Statement of the problem. The change in technological systems, which is currently taking place in Ukraine, poses new challenges to the domestic energy sector and industry. The energy industry requires a wide range of measures to restore and modernize infrastructure facilities of the fuel and energy complex, the spread of information and communication technologies, and the introduction of intelligent networks. At the same time, the efficiency of energy use should be increased, environment-friendly and safe technologies and processes should be introduced, and the share of renewable energy sources should be increased [1]. One of these resources is hydropower of medium and small rivers, which is used by one of the sub-branches of renewable energy – small hydropower. Taking into account the fact that the topography of Ukraine is mainly flat with extensive network of small and medium-sized rivers, our country has great opportunities for the construction of new low-pressure (up to 5 meters of water column, less often – from 5 to 10 m water level) micro-hydroelectric power plants with up to 100 kW capacity, less often – from 100 to 200 kW. At present, such stations are equipped mainly with tubular axial turbines. They are adjustable, partially adjustable or non-adjustable (propeller). In this paper, we will consider only non-regulated turbines, which differ from the other two types of hydraulic machines mentioned above by the highest reliability and the lowest cost. Their main drawback is the impossibility of generated power regulation. However, if the engine room of the micro-hydroelectric power plant is properly equipped and the required sizes of hydroturbines are available, this drawback can be minimized.

Domestic and foreign enterprises produce a wide range of tubular propeller hydroturbines with standard sizes. However, the problem is that some standard sizes of turbines produced by them do not meet the requirements of ensuring the best control characteristics of micro-hydroelectric power plants equipped with such hydraulic machines. The paper is devoted to this problem solution.

Analysis of available investigation results. The paper [2] presents in detail indisputable technical and economic advantages of small hydropower over other sub-sectors of fuel-free alternative energy are presented in detail in paper [2]. One or another advantage provides specific effect(s) indicated in this paper. In addition, the problems arising during the organization of the construction of small hydroelectric power plants, as well as ways to solve them, are presented. But what technical decisions should be made in each specific case are not given. In particular, the issue of building matrixes of turbine models and the issue of selecting turbine models for equipping small hydroelectric power plants are not considered.

Peculiarities of small hydropower in comparison with other branches of renewable energy are described in detail in paper [3]. Program for the development of small hydropower is also proposed, but it has primarily organizational and not technical nature.

In paper [5], the authors note organizational, technical, legal and financial problems of restoration and construction of small hydroelectric power plants in Ukraine. However, their final recommendations are exclusively organizational and not technical: creation and improvement of the legislative framework, development of tax incentives, creation of the conditions for attracting investments in small hydropower, etc.

The experience of «Minihydro» Ltd (Kharkiv) in hydroturbines design, as well as technical characteristics of hydroturbines for small hydroelectric power stations manufactured by this company is highlighted in this paper. Particularly, it is noted that the company produces 5 standard sizes of axial horizontal propeller four-blade tubular hydroturbines with water flow within the range of 0.5÷8.5 m^3/s – T-32, T-50, T-65, T-80, T-90 (the figure in the designation of the turbine model means the diameter of the impeller in centimeters). At present, T-80 turbine is not longer manufactured. Instead, the company is setting up production of T-120 model, which has much higher transmissive capacity and power. On the basis of which initial data the company has chosen the impellers diameters for serial hydroturbines of its own production, the author does not specify. It is also mentioned in this paper that in modern conditions network (non-autonomous) small hydroelectric power plants are forced to operate «following the water flow», that is, they must adjust to the flow of water in rivers, which, according to the data of hydrological services, can change (primarily depending on weather conditions) in sufficiently wide ranges. Therefore, at low-pressure (up to 15 m) small hydroelectric power plants, at least two (or even better - 3 or more) propeller hydroturbines should be installed, but the exact ratio between the diameters of their operating wheels is not indicate by the author (in propeller hydroturbine characterized by simplicity, reliability, speed and high efficiency (the latter, however, applies only to the case when the water consumption by the turbine is equal to the nominal (5%) for the given pressure), it is known that there is no regulation of water consumption). The author also offers to equip low-pressure micro-hydroelectric power stations with sets of replaceable impellers with different geometry of the operating blade apparatus. This solves to some extent the problem of water flow regulation, but at the expense of a certain decrease in the efficiency of the turbine (especially because the guide vane device (when replacing the impeller with another one that has the same outer diameter, but the remaining geometric dimensions are different) is not adjustable). It is worth noting that the company also produces T-32, T-50, T-65 and T-90 hydroturbines with adjustable directional blade device, but they are much more complicated and more expensive than non-adjustable ones. In addition, replacing the impeller of tubular axial hydro turbine manufactured by «Minihydro» Ltd. is rather time-consuming operation that is performed during at least one working day.

The environmental consequences of the operation of 27 small hydroelectric power plants with similar consequences of the operation of 3 large hydroelectric power plants in Norway (the total capacity of both mentioned groups of hydroelectric power plants is approximately the same) are compared in paper [7]. The results of this comparison show that large hydroelectric plants have lower environmental impact than many small-scale projects, but insufficient data accuracy and weak methodological basis introduce uncertainty into the reliability of the research results. If necessary methodology is created, it will be possible to carry out more perfect comparative assessment of the development of small and large hydropower capacities, which will allow better coordination of the goals of energy and environmental policy. Here it should be noted that climate and topography of the territories of Ukraine and Norway are significantly different, so similar comparison for our conditions can show the opposite result. In our work, we try to do our best to reduce the negative impact of low-pressure micro-hydroelectric power plants on the environment to minimum. In order to do this, we create mathematically structured matrix of tubular propeller hydroturbine models and develop clear and understandable recommendations for equipping low-pressure micro-hydroelectric power plants with turbine models from this matrix. Similar investigations have not been carried out in paper [7].

The objective of the paper is to create the matrix of model series of tubular propeller turbines for low-pressure small hydroelectric power plants which operate «following the water flow» (that is, adjust to the flow of water in the river) and transmit all generated electricity to the network at preferential “green” rate, so that they (hydroelectric power plants with the specified turbines)) in the process of operation could provide the best regulatory characteristics and are as «friendly» as possible to river flora and fauna.

Statement of the problem. In order to achieve the set goal, the following problems should be solved:

1. To investigate the existing model series of unregulated tubular propeller turbines for low-pressure micro-hydroelectric power stations, to determine their advantages and disadvantages and, on their basis, to create a number of new mathematically justified model series of such turbines, which should have clear functional relationship between themselves and form the integral structure in the form of a matrix.

2. To propose and substantiate the principles of layout of machine platforms of low-pressure micro-hydroelectric power plants with tubular propeller hydroturbines. The problems to be resolved are the following: a) the number of turbines for machine platform of one HPS; b) standard sizes of turbines for the specified site. These problems should be comprehensively investigated primarily in terms of improving technical characteristics of micro-hydroelectric power plants and minimizing their negative impact on the environment.

Initial data and investigation methods. The initial data of the investigation are domestic and foreign developments in the fields of small hydropower and hydro-turbomachinery. System analysis and system approach are used to create the matrix of model series of tubular propeller hydroturbines. The principles of layout of machine platforms of low-pressure micro-hydroelectric power plants with pipe turbines are formulated using analytical methods.

Conditions and restrictions accepted in the paper. The following restrictions and conditions are accepted in this paper:

1. Only unregulated tubular propeller hydroturbines are considered.
2. Only geometrically similar turbines (the linear dimensions of which are proportional, and the angular dimensions are identical) are considered.
3. The diameters of the operating wheels of hydroturbines are rounded to the whole number with one centimeter accuracy.

4. The designations of the models of tubular propeller hydroturbines in newly created model series correspond to the designations of the turbine models of the same type of «Minihydro» Ltd. (Kharkiv) (for example, in the designation T-90, the letter «T» means «Turbine», and the figure «90» impeller diameter in centimeters).

5. Each newly created model series of tubular propeller hydroturbines is the geometric progression with denominator $2^{1/2}$ (for example, for two adjacent models of turbines of the first series T-23 and T-32 (Table 1), the dependence $23 \cdot 2^{1/2}=32$ is fulfilled).

6. In each newly created model series of tubular propeller hydroturbines, with the same water pressure, any two adjacent turbines differ in the following way: power – by 2 times, water consumption – by 2 times, rotation speed of the turbine shaft – by $2^{1/2}$ times (for example, under the same pressure, the T-32 turbine of the first row has 2 times more power than the adjacent T-23 turbine of the same row; the throughput capacity of T-32 turbine is also 2 times greater than the throughput capacity of T-23 turbine; however, the shaft rotation speed of T-32 turbine, on the contrary, is lower only by $2^{1/2}$ times in comparison with the rotation speed of T-23 turbine shaft).

7. Micro-HPPs with unregulated tubular propeller hydroturbines operate only «following the water flow», that is, they adjust to the flow of water in the river (but not to the consumers needs) and deliver all the generated electricity to the network for sale at preferential «green» rate.

Investigation results. The main result of the investigation is matrix of model series of tubular propeller hydroturbines for small hydropower plants (Table 1).

Table 1

Matrix of model series of tubular propeller hydroturbines (TPHT) for small hydroelectric power plants

No	The title of the model range	TPHT models (the figure in the model designation means diameter of the hydraulic turbine impeller in centimeters) Approximate power of hydroturbines in kW at the same pressure (approximately 3.5 m water level) (power of T-90 turbine is taken as 100 kW)							
1	Model series of TPHT **«Minihydro» Ltd.** (Kharkiv)			T-32 13	T-50 30.9	T-65 52	T-90 100	T-120 178	
2	**The first** TPHT model series (formed by modernization of TPHT model series of «Minihydro» Ltd.)		T-23 6	T-32 13	T-45 25	T-64 50	T-90 100	T-127 200	
3	**The second** TPHT model series (formed on the basis of the first model series using $2^{1/4}$ proportionality coefficient)	T-19 4.7	T-27 9	T-38 19	T-54 38	T-76 75	T-107 150	T-151 300	
4	**The third** TPHT model series (formed on the basis of the second model series using $2^{1/8}$ proportionality coefficient)		T-21 5.2	T-29 10	T-41 21	T-58 41	T-83 83	T-117 165	
5	**The fourth** TPHT model series (formed on the basis of the third model series using $2^{1/8}$ proportionality coefficient)		T-25 8	T-35 16	T-49 31.3	T-69 63	T-98 125	T-139 250	

In Table 1, under the codes of the turbine models, the approximate powers of these turbines in kW for one pressure are given. The turbine power of T-90 model is assumed to be equal to 100 kW. It corresponds to the net pressure of approximately $H_{н}$=3,5 m. Approximate capacities of all other turbine models in Table 1 are accepted for the same numerical pressure value. They (powers) are rounded to the whole numbers for better understanding (with the exception of four values).

The first TPHT model series is formed on the basis of TPHT model series of «Minihydro» Ltd. Small T-23 turbine with 23 cm impeller diameter is added to the existing series, T-50 turbine is replaced by T-45 turbine, T-65 by T-64 turbine, T-120 by T-127 turbine, so that the newly formed series of diameters of hydraulic turbine impellers is the geometric progression with denominator $2^{1/2}$.

Turbines of the second TPHP model series occupy the intermediate position between adjacent turbines of the first model series. For example, under the same pressure, the power of T-90 turbine (series 1) is 100 kW, T-64 (series 1) is 50 kW, and the T-76 turbine (series 2) is 75 kW (this is presented, in particular, by the design feature of the belt Table 1, which corresponds to the second model series).

Turbines of the third TPHT model series occupy the intermediate position between adjacent turbines of the first and second model series, but under the condition that the turbine of the second series is smaller than the turbine of the first series. For example, under the same pressure, the power of T-90 turbine (series 1) is 100 kW, T-76 turbine (series 2) is 75 kW, and T-83 turbine (series 3) is 83 kW (to be more precise, 82.5 kW).

Turbines of the fourth TPHT model series also occupy the intermediate position between adjacent turbines of the first and second model series, but under the condition that the turbine of the second series is larger than the turbine of the first series. For example, under the same pressure, the power of T-90 turbine (series 1) is 100 kW, T-107 turbine (series 2) is 150 kW, and T-98 turbine (series 4) is 125 kW.

Under the same pressure, the ratio of diameters of geometrically similar turbines is equal to the square root of the ratio of powers (and water consumption, see below in this paragraph) of these turbines: for example, for T-90 and T-50 hydraulic machines of TPGT of «Minihydro» Ltd. (Kharkiv) series (Table 1) d_2/d_1=90/50=1.8; $(N_2/N_1)^{1/2}=(100/30.9)^{1/2}$=1.8 (in the above mentioned expressions, symbol d indicates the diameters of the turbines' operating wheels in cm, and symbol N - approximate power of the turbines in kW). Under the same conditions, the rotation speed ω_1 of T-50 turbine shaft is also 1.8 times greater than the similar indicator ω_2 of T-90 turbine (ω_1/ω_2=1.8), and the ratio of water consumption Q_2 and Q_1 is equal to power ratio: $Q_2/Q_1= N_2/N_1$=100/30.9=3.24; $(Q_2/Q_1)^{1/2}=3.24^{1/2}$=1.8.

Recommendations regarding the installation of low-pressure micro-hydroelectric power plants with basic hydraulic machinery equipment. At low-pressure micro-hydroelectric power plants, we recommend to instal two or three (three are better from the point of view of technology and ecology,) tubular propeller hydroturbines. Turbines should be selected from one of the proposed model series (first, second, third or fourth) (Table 1). Both in the first and second cases, all models of hydroturbines at any micro-hydroelectric power plant must be different, but adjacent. This makes it possible to provide better adjustment characteristics of the hydroelectric power plant and at the same time contribute to better preservation of the diversity of river flora and fauna on the the lower basin of the plant. technical and economic justification of the selection of the main hydraulic machine equipment for low-pressure micro-hydroelectric power station is not carried out in this paper, it will be the objective of our further investigation.

Adjustment characteristic of micro-hydroelectric power plant, equipped with two different adjacent tubular propeller hydroturbines of the same model series are presented in Fig. 1, and the same one but with three different adjacent turbines is shown in Fig. 2. Complete set of machine platform according to Fig. 1 provides uniform three-step adjustment characteristic (CC) of micro-hydroelectric power plant with control discreteness δ=33 % and control depth Δ=67 %. Complete set according to Fig. 2 provides much smoother, uniform seven-step CC of micro-HPP with control discreteness δ=14% and control depth of Δ=86%. Seven-step CC makes it possible (compared to three-step CC):

– to adjust the micro-hydroelectric power plant to water consumption in the upper basin of the plant much easier;

– to reduce the frequency of hydraulic units switching, contributing to the increase of their service life and reduce energy consumption for performing the adjustment function (in manual or automatic mode);

– to reduce considerably the negative impact of micro-hydroelectric power plant on the hydrosphere of the lower basin, since the «jumps» of water levels in the lower basin (daily, for two days, weekly, etc.), caused by the operation of hydroelectric power plant, will be much (approximately 2.4 times) smaller.

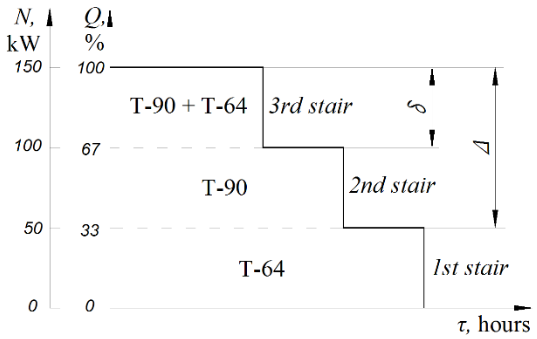

Figure 1. Adjustment characteristic of micro-hydroelectric power plant equipped with two different adjacent tubular propeller hydroturbines T-90 and T-64 of the same (first) model series

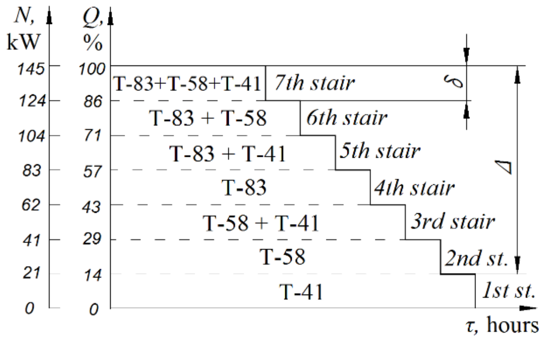

Figure 2. Adjustment characteristic of micro-hydroelectric power plant equipped with three different adjacent tubular propeller hydroturbines T-83, T-58 and T-41 of the same (third) model series

The following notations are adopted in Fig. 1 and Fig. 2: N is the total power of the activated hydroturbines of micro-HPP, kW, for net pressure approximately $H_н$=3.5 m; Q is water consumption by hydroelectric plant, %; τ is time, hours; δ – discreteness of adjustment, %; Δ is the adjustment depth, %.

For better understanding of the presented material, Fig. 1 also shows the example of the complete set of micro-hydroelectric power plant with two adjacent turbines T-90 and T-64 of the first model series (total power – 150 kW), and Fig. 2 – with three adjacent turbines T-83, T-58 and T-41 of the third model series (total power – 145 kW) (Table 1). In these figures, it is also indicated which turbines are turned on to ensure the implementation of this or that «stair» of regulation (for example, in Fig. 2, the implementation of the 5th «stair» of adjustment is carried out due to the switching on two turbines - large one T-83 and small one T-41; the middle turbine T-58 is currently in the disabled mode).

The scientific novelty is that for the first time mathematically structured matrix of models of unregulated tubular propeller hydroturbines for low-pressure micro-hydroelectric power plants has been created. The matrix consists of four rows and six columns (seven columns only for the second row) and contains in total 25 elements. The number of matrix columns can be increased both to the left (decreasing) and to the right (increasing). System analysis and system approach have been used during the creation of turbine models matrix. The matrix has not only theoretical, but also practical significance, since targeting to it makes it possible to avoid numerous mistakes and miscalculations at the design stages of both non-regulated tubular propeller hydroturbines with impeller diameters from 19 to 151 cm, as well as low-pressure micro-hydroelectric power plants based on these turbines. The principles of matrix creation are clear and understandable, in case going beyond its limits, any qualified specialist will be able to expand it competently and, probably, even somehow to improve it.

Conclusions. Matrix of model series of geometrically similar tubular propeller hydroturbines for low-pressure micro-hydroelectric power plants with impeller diameters from 19 to 151 cm has been created. It represents four model series of the specified turbines, each of which (more precisely, the numbers with which the turbine models are encrypted) is geometric progression with $2^{1/2}$ denominator.

It is substantiated technically and ecologically that in the case of using tubular propeller hydroturbines to complete low-pressure micro-hydroelectric power plants, the number of such turbines at one station should be two or three (preferably three). Taking into account the same aspects of the microhydropower operation, in order to execute the specified task, it is necessary to choose different, but adjacent turbines from only one model series. This makes it possible to ensure the best adjustment characteristics of micro-HPP and minimize the harmful effects of micro-HPP on the river flora and fauna (there will be smaller daily «jumps» of water levels in the lower basin, which are caused by the plant operation, (HPP) will adjust to the natural flow of water in the upper basin more accurately).

Matrix of model series of geometrically similar tubular propeller hydroturbines can be considered as a guide to the operation of hydroturbomachinery enterprises whose products are designed for low-pressure microhydropower. One enterprise, no matter how big and powerful it is, should not master the production of all 25 models of hydroturbines that are presented in the matrix. The best option is when there are four enterprises, and each of them takes only one of the four model series of turbines for production development (each enterprise produces another series).

The method of creating the matrix of model series of tubular propeller hydroturbines, which is covered in this paper, can be generalized to other types of hydroturbines.

Prospects for further investigations in this direction are technical and economic substantiation of the selection of the number of tubular propeller hydroturbines (two, three or any other number) for equipping machine platforms of low-pressure micro-hydroelectric power plants.

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СТВОРЕННЯ Й ОБҐРУНТУВАННЯ МАТРИЦІ МОДЕЛЬНИХ РЯДІВ ТРУБНИХ ПРОПЕЛЕРНИХ ТУРБІН ДЛЯ МАЛИХ ГЕС

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Резюме. *Статтю присвячено подальшому розвитку малої гідроенергетики на базі надійних і дешевих нерегульованих трубних пропелерних гідротурбін з жорстко зафіксованими робочими і напрямними лопатями. Такі турбіни використовуються переважно на низьконапірних малих ГЕС. Основним їх недоліком є неможливість регулювання генерованої потужності. Однак у статті запропоновано рішення, які цей недолік зводять до мінімуму. Створено матрицю модельних рядів трубних пропелерних гідротурбін, на основі якої підприємства зможуть налагоджувати випуск технічно й екологічно обґрунтованої номенклатури таких машин. Матриця складається з чотирьох модельних рядів, кожен з яких містить шість моделей турбін (лише другий модельний ряд – сім моделей). Вся матриця містить 25 моделей турбін, але у випадку потреби її можна розширити в бік збільшення або зменшення. Принцип створення матриці полягає в тому, що кожен її модельний ряд є геометричною прогресією зі знаменником* $2^{1/2}$. *У якості початку та членів геометричної прогресії виступають діаметри робочих коліс турбін. Методику створення матриці модельних рядів трубних пропелерних гідротурбін можна розповсюдити й на інші типи турбін. Запропоновано також технічно й екологічно обґрунтовані правила комплектування машинних майданчиків низьконапірних малих ГЕС потужності до 200 кВт моделями турбін зі створеної матриці. Згідно з наведеними рекомендаціями на одній ГЕС повинно бути встановлено не менш, ніж дві різні суміжні турбіни з одного модельного ряду. Найкращий варіант – три різні суміжні турбіни з одного модельного ряду, але для детальнішого обґрунтування вибору кількості турбін ще буде потрібно виконати техніко-економічний аналіз. Це буде тематикою наших наступних досліджень. Використання науково-практичних результатів, викладених у статті, дозволить покращити технічні характеристики малих ГЕС з трубними пропелерними турбінами та звести до мінімуму їх можливий негативний вплив на життєдіяльність річкової флори і фауни у нижніх б'єфах.*

Ключові слова: *матриця, модельний ряд, трубна пропелерна гідротурбіна, мала ГЕС, низький напір.*

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