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Exploitation Criteria for Installed Discharge at SHPP

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Abstract:

The water management organization, under the leadership of PC "Strezevo", provides water for irrigation and process water for industrial enterprises, using water from reservoir Lake Strezevo. Water from the reservoir is distributed to consumers through energy use. Two small hydro power plants are installed, one SHPP Strezevo with three identical turbine units installed and second SHPP Exploitation Minimum, with one turbine. The technical parameters of the turbine units are different. In exploitation, all four turbine units are connected to one water supply system. This water supply system is characterized by the specificity that it should always deliver the required discharge to consumers, while managing the turbine units to provide maximum energy efficiency at the flow required, depending on the water level in the reservoir. The required operating conditions of the turbine units deviate from the standard turbine control procedure, which makes the optimization method specific. The optimization model for determining the parameters of exploitation of turbine units takes into account: water level in the accumulation, technical performance of individual turbine units (represented by the hill diagram), limitation of the minimum flow of turbine operation, limitation of turbine opening (openness of the wicket gate), as well as the limitation due to installed power. The optimization criterion is to provide the maximum opportunity for individual or joint operation of turbine units. The output part of the optimization is the setting of the operating mode for each turbine unit. For the time being, correlation calibration settings of the model have been made the base of exploitation period, and the next exploitation period for proving the model is yet to come.

Keywords:

Exploitation Discharge, Run-Of-River SHPP, Energy Production, Economy Index

1. Introduction

The Strezevo hydraulic system has been in operation for more than 30 years. Water from the "Strezevo" accumulation is distributed to the users via a concrete inlet duct,

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which feeds the main and section pipelines, as well as a branched detailed pipeline network that extends to the surface for irrigation.

The basic activity of PC "Strezevo" is providing the necessary quantities of water for irrigation of part of agricultural land Pelagonija, (20,200 ha net land) supplementing the required quantities of untreated water for the needs of PWC "Vodovod" - Bitola, providing technological water for the needs of industry (TPP "Bitola", Factory for Yeast and Alcohol, Dairy Bitola, Factory for Fruit and Vegetable and for the needs of individual farmers and other water users).

View map of the wider geographical area and catchments of the Strezevo hydro system. The overview map shows the objects that are part of the Strezevo hydro system:

- the catchment area along with the alimentary canal and the Shemnica River that supply the lake with water,
- accumulation of about 118 million cubic meters of water,
- the dam "Strezevo" with the accompanying facilities,
- main supply channel,
- a detailed pipeline network,
- water supply intakes for TPP "Bitola",
- center for dynamic regulation (office building)

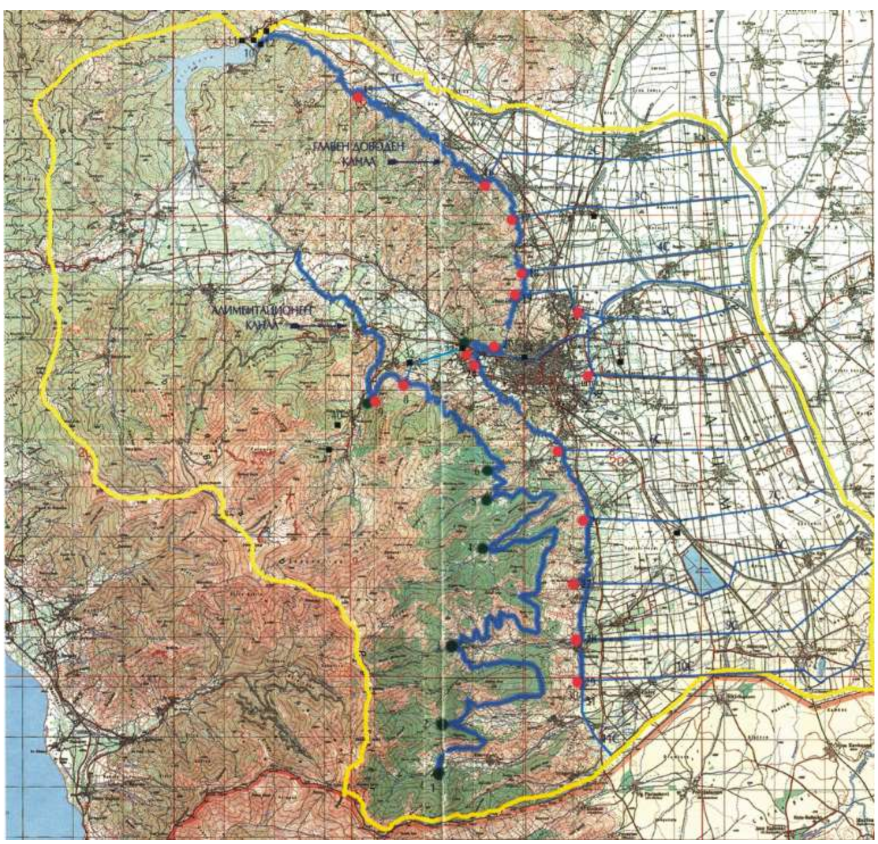

Fig.1. Map of the area and catchment basins of the hydro system "Strezevo"

On the dam "Strezevo", in the water discharge system to the consumers, two SHPP were built:

- SHPP "Strezevo", built and commissioned in 1992, consisting of three Francis turbines, with 3x800 kW power and 3x (1000-2800) l/s discharge, adjusted to the needs of the customers and the level of accumulation.
- SHPP“Exploitation Minimum”, built and commissioned in 2011/2012 consisting of a Francis turbine, with a power of 340 kW and a flow rate of 400-1200 l/s, depending on the water demand of the customers and the level of accumulation.

The turbine units of the two SHPPs are installed on a common penstock. A scheme of connection of the turbine units to the penstock is shown in Figure 2.

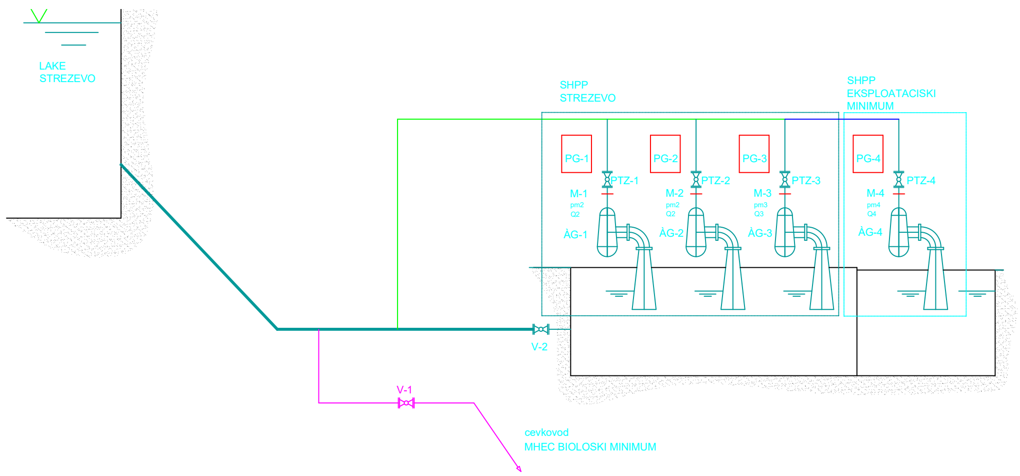

Fig. 2. Scheme of connecting the aggregates to the penstock

Fig. 3. Power house of SHPP Strezevo

Fig. 4. Power house of SHPP Exploitation minimum

1.1. Energy production

On the base of annual energy production for the exploitation period (2012-2019) by simultaneous operation of the two constructed SHPPs, diagram where effective annual power generation by each SHPP are presented, is defined, fig 5. The effective annual energy production as a cumulative value from constructed SHPP, is presented with dash line. On base of exploitation results, it can be concluded that energy production varied through the year and depends on discharge to the consumers.

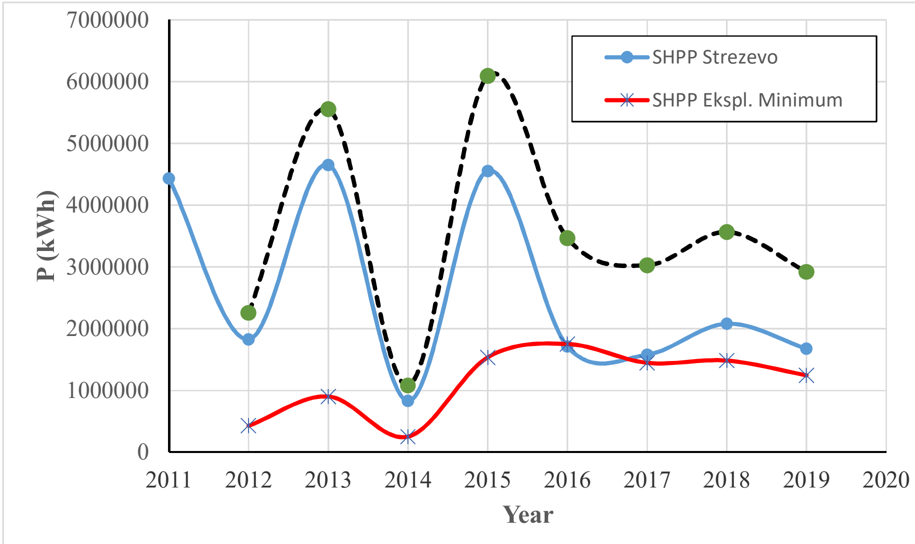

Figure.5. Effective Annual Power Generation per SHPP (2012-2019)

If SHPP Strezevo and SHPP Exploitation Minimum treated as a hydro node for energy production, then ratio in energy production (sum of both) than participation of each SHPP in energy production (ratio Phec/P_{hj}) are given on diagram fig.6.

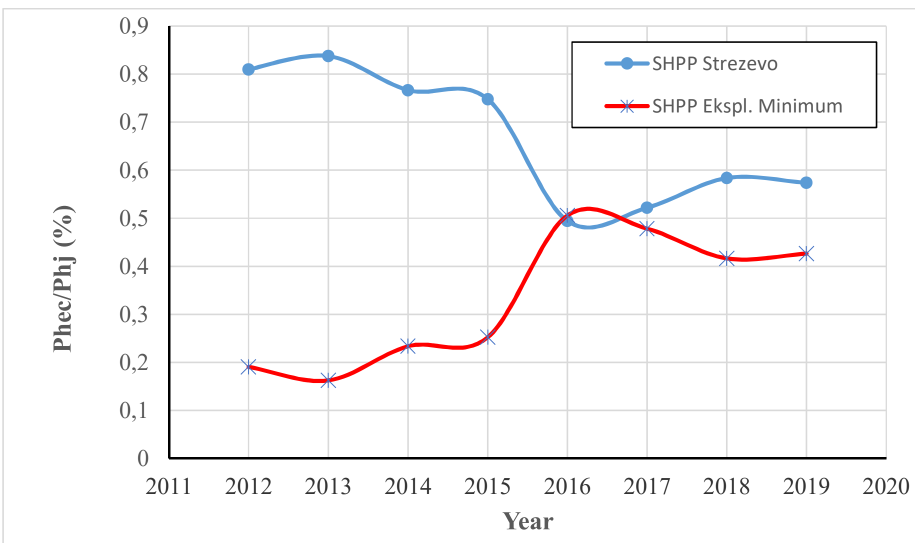

Fig.6. Participation of individual SHPPs in electricity production

Taking into account that SHPP Strezevo and SHPP Exploitation Minimum are installed on the same penstock, they use the same water potential, they have dominant ration in energy production and can work as one hydro power node, but the nominal discharge is different, then it is logical to be established one control system which will include all turbines and to obtain the best energy production and efficiency of the SHPP.

The operating parameters of the units at the two plants depend on the discharge to be consumed by the customers and the level of water in the reservoir. In the past exploitation period of units, the selection of the number of units in exploitation and the adjustment of the operating parameters are performed by the operator in the plants on the base of experience. The system technical capabilities and mode of exploitation of the system is predetermined for the presence of an operator in the process of exploitation and active participation of a person at terrain. Such a condition is required during the exploitation of two SHPPs: SHPP Strezevo and SHPP Exploitation Minimum, as they are also regulatory authorities for discharging the required amount of water from the Strezevo accumulation to all water users (such as TPP Bitola, PWC "Vodovod", industry, irrigation, etc.), and are at the same time energy facilities that provide the energy efficiency of the hydro system.

In order to enable maximum production of electricity from the discharged water, a calculation model has been developed to determine the optimal adjustable operating parameters of the turbines at the SHPP "Strezevo" and the SHPP "Exploitation Minimum" in the parallel work. In this paper, a numerical model is presented to determine the optimal operating parameters of the turbines depending on the needed flow to be discharged and the level of water in the accumulation in order to obtain maximum electricity production and best efficiency.

2. MODEL FOR DETERMINING BEST OPERATING PARAMETERS OF THE TURBINE UNITS

A numerical model for determining the best operating parameters of the turbines, in order to obtain the maximum power output at a defined flow rate and a trough elevation of the water level in the reservoir, was developed in the Microsoft Office Excel software package.

The model takes into account three main parameters, presented on block diagram):

- Technical characteristics of the turbine
- Hydraulic conditions of water supply system (penstock and branches) and tailrace
- Boundary conditions with initial parameters for water level in accumulation and discharge of water to the users, working conditions of aggregates and variance of the calculation model

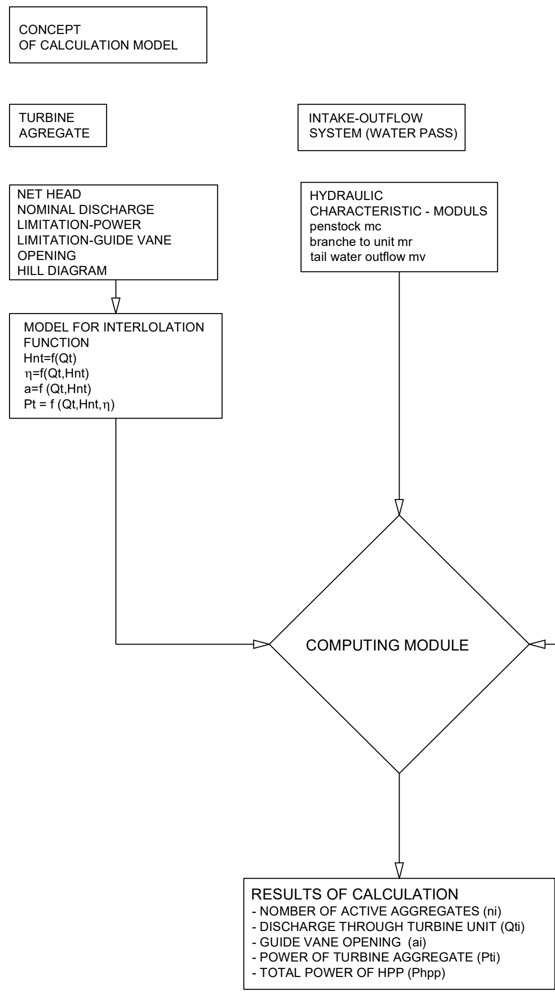

Fig.7. Block diagram of calculation model

2.1. Turbine unit-description

The basis for the development of the calculation model for turbine unit are the matrix presentation of functional dependency between discharge-head-efficiency (Table 1) and the matrix presentation of functional dependency between discharge-head-guide vane opening (Table 2), obtained from the operational turbine exploitation diagram (hill diagram) shown in Figure 8.

To obtain the functional dependence of the turbine efficiency on the discharge and net head ($\eta = f(Q, H_n)$), as well as the functional dependence of the guide vane openings of the regulation apparatus vs the discharge and the net head ($a = f(Q, H_n)$), the interpolation of the matrices with an eighth degree polynomial equation by discharge and net head, using the least squares method is performed, i.e.:

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$$\eta = b_0 + \sum_{i=1}^{8} b_i Q^i + c_0 + \sum_{i=1}^{8} c_i H_n^i \quad (1)$$

$$a = d_0 + \sum_{i=1}^{8} d_i Q^i + e_0 + \sum_{i=1}^{8} e_i H_n^i \quad (2)$$

where b_i, c_i, d_i and e_i are derivate coefficients of polynomial functions

Table 1: Matrix presentation of discharge-head-efficiency

Discharege (m^3/s)	Head (m)									
	16	**19.1**	**22.2**	**25.3**	**28.4**	**31.5**	**34.6**	**37.7**	**40.8**	**44**
3	0.7	0.75	0.8	0.82	0.85	0.86	0.87	0.88	0.88	0.88
2.9	0.73	0.78	0.81	0.84	0.87	0.88	0.88	0.889	0.88	0.88
2.8	0.76	0.81	0.83	0.86	0.88	0.89	0.9	0.898	0.89	0.89
2.615	0.81	0.83	0.86	0.88	0.90	0.90	0.90	0.905	0.896	0.89
2.43	0.815	0.85	0.88	0.905	0.912	0.911	0.91	0.9	0.892	0.883
2.287	0.8	0.84	0.87	0.89	0.89	0.9	0.89	0.89	0.88	0.868
2.144	0.78	0.825	0.855	0.87	0.88	0.885	0.88	0.873	0.862	0.853
2.001	0.75	0.805	0.838	0.853	0.862	0.863	0.862	0.855	0.848	0.84
1.858	0.7	0.775	0.815	0.836	0.845	0.848	0.843	0.84	0.833	0.828
1.715	0.65	0.74	0.775	0.81	0.82	0.825	0.82	0.81	0.805	0.78
1.572	0.55	0.68	0.735	0.775	0.78	0.785	0.78	0.775	0.765	0.755
1.429	0.45	0.61	0.675	0.725	0.75	0.75	0.75	0.735	0.725	0.685
1.286	0.43	0.55	0.62	0.67	0.69	0.69	0.695	0.68	0.65	0.625
1.143	0.3	0.45	0.5	0.585	0.61	0.615	0.605	0.6	0.58	0.56
1	0.2	0.35	0.45	0.5	0.52	0.53	0.52	0.5	0.48	0.41

Table 2: Matrix presentation of discharge-head-guide vane opening for turbine at SHPP "Strezevo"

Discharege (m^3/s)	Head (m)									
	16	**19.1**	**22.2**	**25.3**	**28.4**	**31.5**	**34.6**	**37.7**	**40.8**	**44**
3	1.48	1.4	1.3	1.24	1.16	1.09	1.04	0.98	0.91	0.865
2.9	1.43	1.36	1.26	1.18	1.1	1.05	0.99	0.93	0.88	0.84
2.8	1.4	1.3	1.22	1.12	1.05	1	0.93	0.88	0.84	0.8
2.615	1.32	1.22	1.15	1.05	0.985	0.92	0.86	0.825	0.785	0.75
2.43	1.27	1.15	1.085	0.99	0.9	0.845	0.8	0.765	0.72	0.7
2.287	1.12	1.09	1	0.9	0.845	0.79	0.75	0.715	0.68	0.655
2.144	1.11	1	0.92	0.845	0.79	0.74	0.69	0.66	0.635	0.605
2.001	1.04	0.925	0.855	0.785	0.73	0.68	0.645	0.62	0.585	0.56
1.858	0.97	0.887	0.79	0.725	0.67	0.625	0.59	0.565	0.535	0.505
1.715	0.9	0.8	0.73	0.66	0.615	0.57	0.54	0.505	0.48	0.46
1.572	0.82	0.72	0.665	0.6	0.55	0.515	0.48	0.45	0.435	0.415
1.429	0.75	0.65	0.59	0.545	0.5	0.45	0.42	0.39	0.375	0.35
1.286	0.66	0.585	0.535	0.48	0.43	0.39	0.35	0.33	0.31	0.285
1.143	0.59	0.525	0.475	0.41	0.35	0.32	0.29	0.27	0.255	0.25
1	0.53	0.46	0.41	0.34	0.3	0.27	0.265	0.25	0.24	0.225

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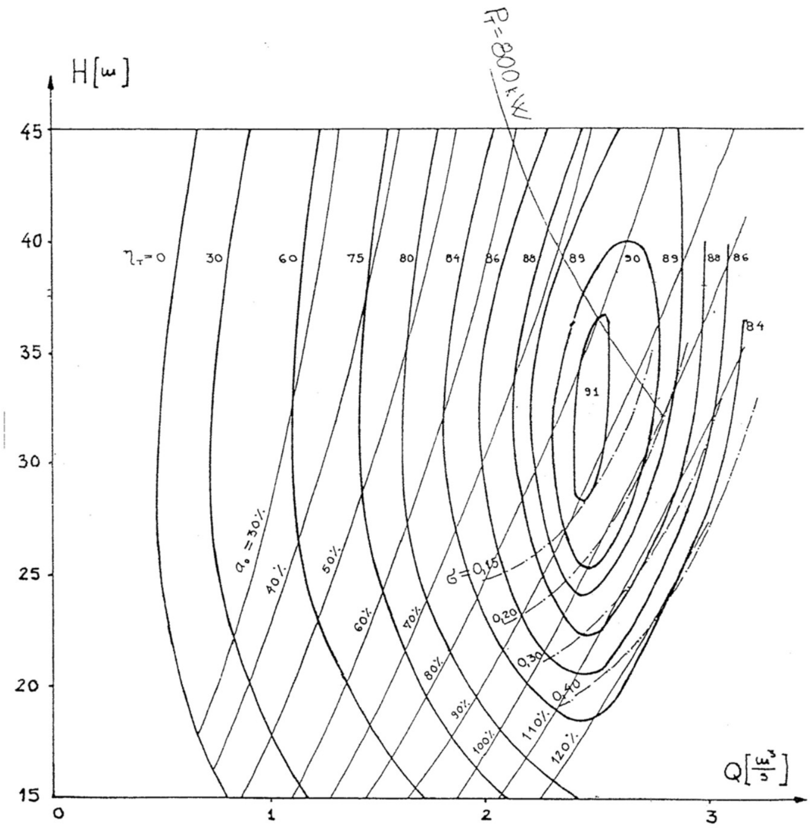

Fig. 8. Exploitation hill diagram of the turbine at SHPP "Strezevo"

2.2. Hydraulic characteristic of water supply system-description

In addition to the stated matrices, the basis of the model are the loss coefficients in the penstock, branches to the turbines, obtained by measuring the losses at different flow rates. The scheme of measurement is given on fig.9.

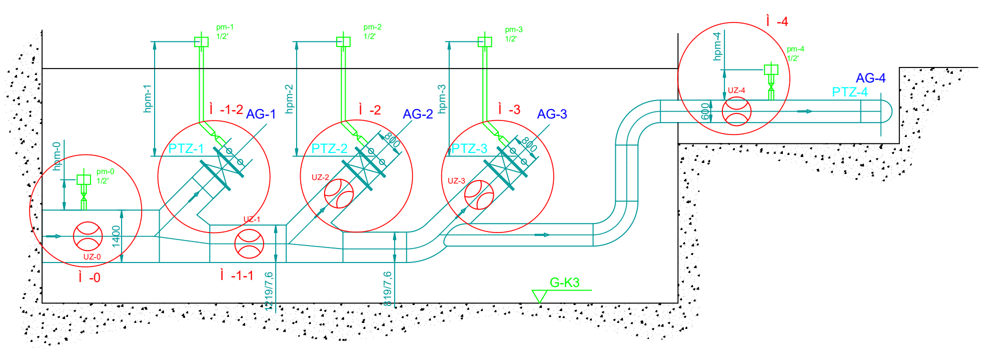

Fig.9. Scheme of measuring sections

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Fig.10. Branches to the turbine unit

The measurement procedure was done according to IEC 60193. In the same time pressure and discharge were detected. The discharge was measured with ultrasonic (mobile) flow meters, placed at different cross sections (where it was possible to install) of the pipe branches.

a) measuring pressure and discharge b) data acquisition device

Fig.11. Measuring devices at unit -4

The hydraulic characteristic of water supply system was divided in parts:

- hydraulic characteristic of pipeline
- hydraulic characteristic of branches to the turbine
- hydraulic characteristic of the tailrace

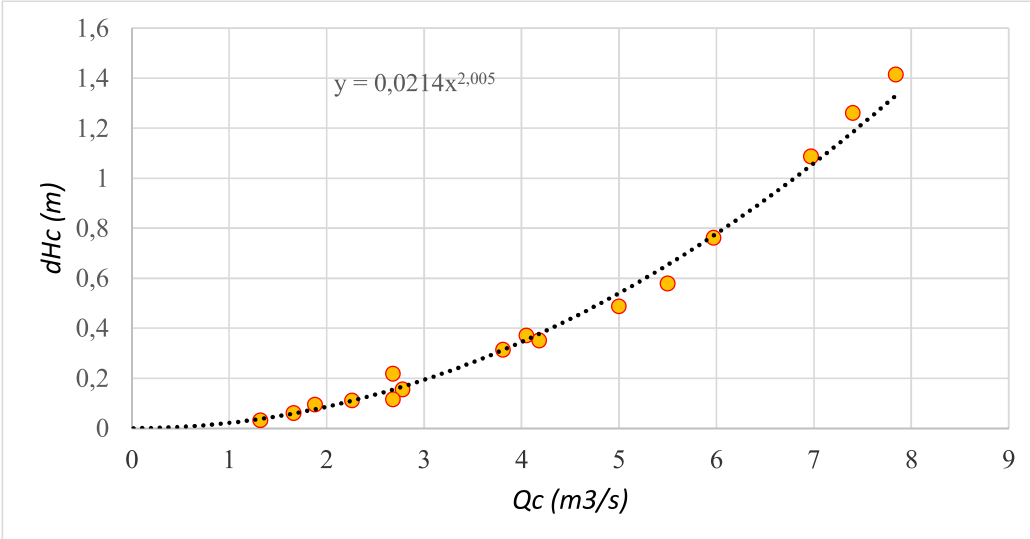

Fig.12. Hydraulic characteristic of pipeline

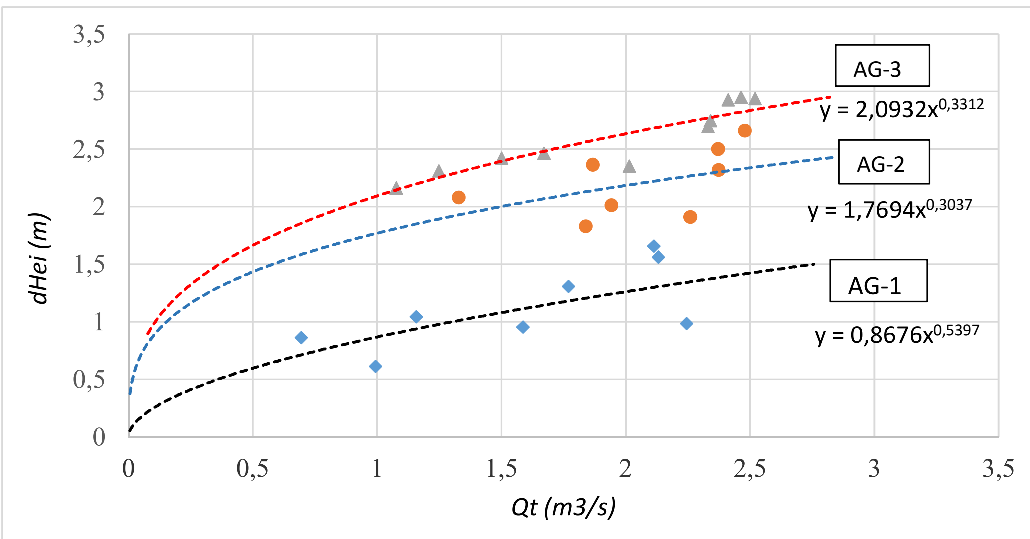

Fig.13. Hydraulic characteristic of the unit branches

Fig.14. Tailrace of SHPP

Net head for the operating conditions are defined by the coefficients of the individual sections of the penstock, branches to the turbines and the hydraulic characteristic of the tailrace.

$H_n = H_b - (m_1 + m_{ov})Q_{vk}^2 - m_i Q^2$ - net turbine head
H_b *(m)* - gross head
Q_{vk} *(m^3/s)* - total flow that is released into HPP
m_1 - loss coefficient in the pipeline
m_i - branch loss ratio to appropriate turbine
m_{ov} - loss ratio in tailrace

2.3 Exploitation conditions

The basic parameters used to select the turbine aggregate sharing mode are the height of the water level in the water intake (*Hel*) and the required water flow to be delivered to users (*Qkor*).

With the model, the optimal turbine operating parameters are determined for the following variance of operating modes:

- Symmetrically Loaded Aggregate Mode (Throughout the aggregates the flow is changed and a regime with maximum total power is adopted).
- Asymmetric Load Aggregate Mode a certain number of units are maximally loaded and one unit is charged to the required flow rate.
- Priority Aggregate Mode in SHPP "Exploitation Minimum", an aggregate that is always maximally loaded because it has a lower installed flow.
- Maximum Load Aggregate Mode a certain number of aggregates are maximally loaded and excess water is discharged through the by-pass drain
- Selection of aggregates not to be burdened, i.e. which should not be powered, i.e. serviced.

2.4. Computing module

From the interpolation equations obtained for the efficiency of utility and openness of the guide vane, and depending on the level of water in the accumulation, dependencies of power vs. discharge (eq.3), discharge vs. power (eq.4), openings of the guide vane vs. discharge (eq.5) and discharge vs. the openness of the guide vane (eq.6) are determined in the model, i.e.:

$$P_t = b_0 + \sum_{i=1}^{8} b_i Q^i \quad (3)$$

$$Q = c_0 + \sum_{i=1}^{8} c_i P_t^i \quad (4)$$

$$a = d_0 + \sum_{i=1}^{8} d_i Q^i \quad (5)$$

$$Q = e_0 + \sum_{i=1}^{8} e_i a^i \quad (6)$$

Depending on the level of water in the reservoir and the quantity of water to be discharged, the model calculates:

- Discharge (with Equation 4) and the guide vane opening (with Equation 5), in case when the net head is greater than the nominal net head of the turbines (*turbine limited power mode*).
- Discharge (with Equation 6) and power (with Equation 3) in case when the net head is greater than the nominal net head of the turbines (*maximum open mode of the turbine guide vane*).

3. Criteria and Defining working of units

Regulation of the flow through the turbines in both power plants is done depending on the need for water to consumers and the water level in the reservoir.

In order for the turbines to operate in optimal mode, i.e. in case of a certain flow of water that should be discharged to the consumers, the production of electricity to be maximum, software has been developed for selection of the optimal operating mode of the units in both power plants.

Input data in the software are:

- Transit elevation of the water level in the reservoir
- Required water flow to be discharged to consumers
- Functional condition of the units in both power plants (for units that are not in reparation, the software indicates: unit is serviced - yes).

From the entered input data we get:

- Maximum possible flow through the power plants, i.e. maximum flow that can be discharged through the aggregates.
- Possible choice of the unit in SHPP "Exploitation minimum" as a priority, i.e. always discharge water into the system through this unit.

The communication with the calculation model is via the input and output data mask shown in Figure 15.

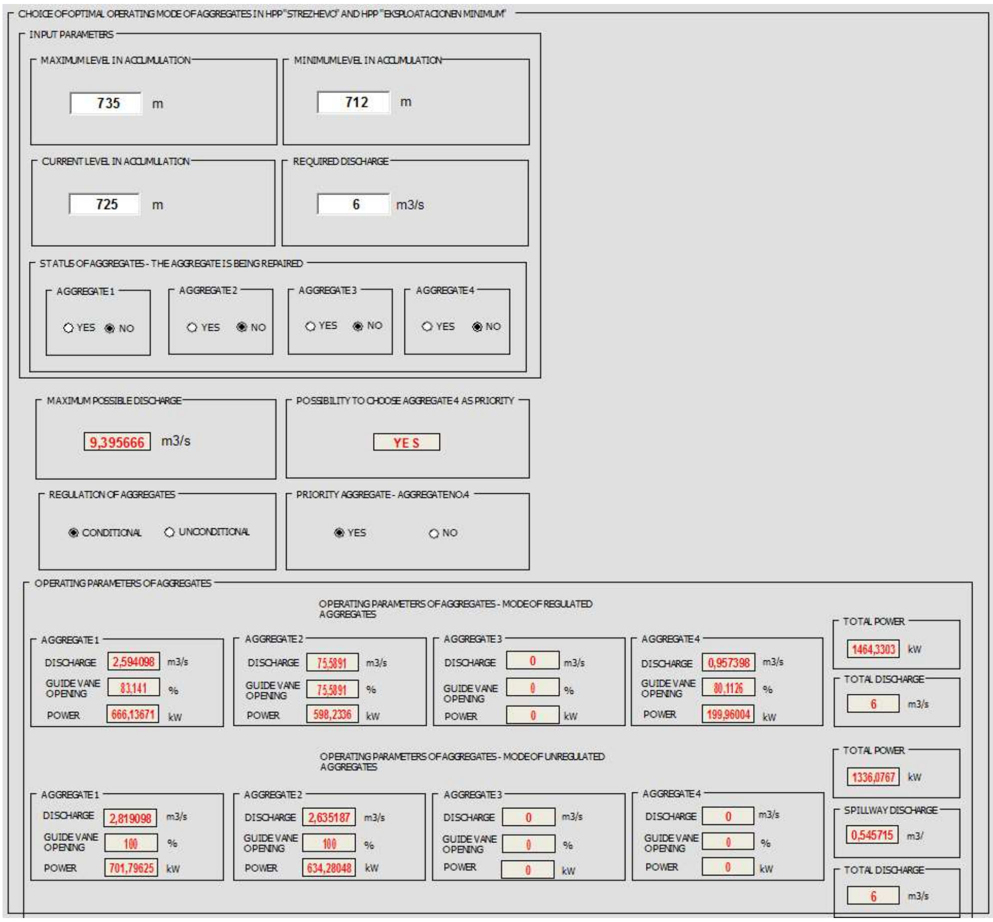

Fig. 15. Model mask with input and output data

The values given to the output worksheet of the calculation model are the result of variant solutions contained in the calculation model. Since the model calculates several variant solutions and conditions of regulation of turbine units and their choice of work, the working mask proposes three solutions, ranked according to the criterion:

- the most favorable energy solution: with proposed variant openness of the guide vanes and the number of turbine units in operation
- alternative solution: second ranked solution that is calculated inside the model, and according to the total power of SHPP, with the proposed variant openness of the blades of the conducting apparatus and the number of turbine units in operation
- priority AG-4: solution when in the operation priority is given to the active state of the turbine unit from SHPP Operation minimum,

The concept of representing the output computational quantities through the guide vane opening and the power of the turbine unit has been adopted due to the way in which this computational software will be used. Namely, the application of the software is to give information to the operator from the dispatch center, according to the conditions of operation of the system (level of water in accumulation and required flow to the user) to define the conditions for adjusting the guide vane openness of the dispenser or control to set the power of the turbine unit.

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The concept of computing software is not set for automated operation of the system, but as an auxiliary tool for the operator.

3.2. Model testing

3.2.1. Limits of the hydro-node regulation zone

Based on the calculation model, the maximum discharge that can be regulated through SHPP at different water levels in the water intake are defined. For a given water level in the water intake, up to the maximum flow rate of the SHPP, the joint operation of the turbine units can be optimized, while for the required water discharge to the user greater than the maximum permeability, the turbine units are fully open and the required excess discharge can be provided by discharging from by-pass of the system.

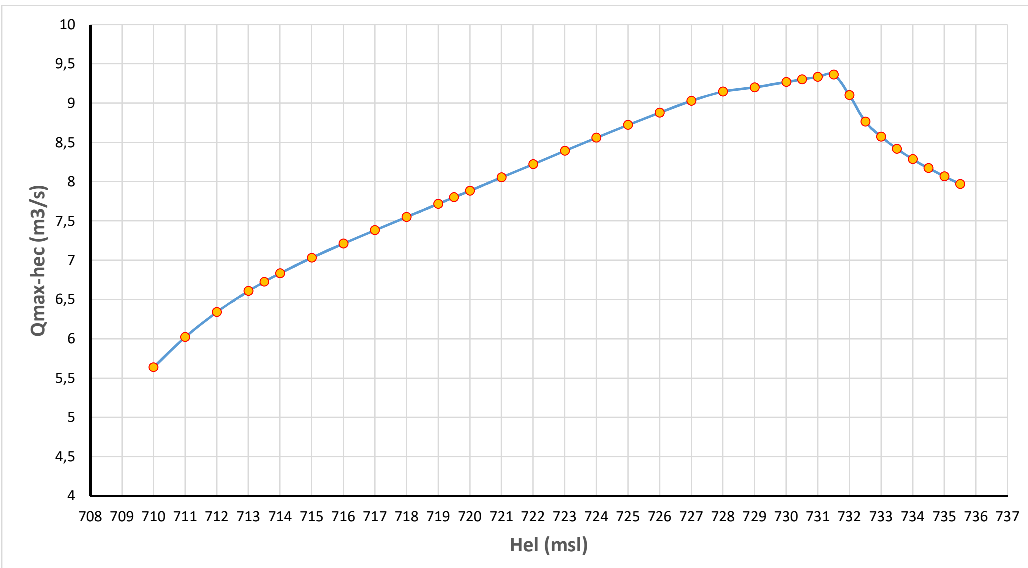

Fig.16. Maximum discharge through the SHPP for different levels in the reservoir

The limitation of the maximum discharge through the SHPP originates from the technical limitations that the turbine units have in terms of permeability through the opening of the wicket gate, i.e. through the limitation of the power of the turbine generator. Therefore, the zone of regulation of turbine units from SHPP is represented by the impact of these two technical limitations of the equipment, up to the water level in the reservoir 728 msl, the limitation is the permeability of the wicket gate (100%), while for higher elevations of water, the power limit is already active.

3.2.2. Comparison of exploitation and calculated parameters of the aggregates

In the current exploitation of the Strezevo hydro system, the selection of the number of units in operation and their load is done by the operator in the power plants depending on the flow to be discharged, the water level in the accumulation and the experience of the operator. Because the production of electricity in SHPP "Exploitation Minimum" is at a privileged price, during the operation of the system the unit in this plant is maximally loaded.

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In order to check the model, which determines the parameters of the units for obtaining maximum electricity production, simulations were performed for previously realized operating modes of the units, depending on the number of activated units, the flow to be discharged and the level of water in the reservoir. The comparative data from the realized operating modes and the calculated data with the model for selection of optimal parameters are given in fig.17.

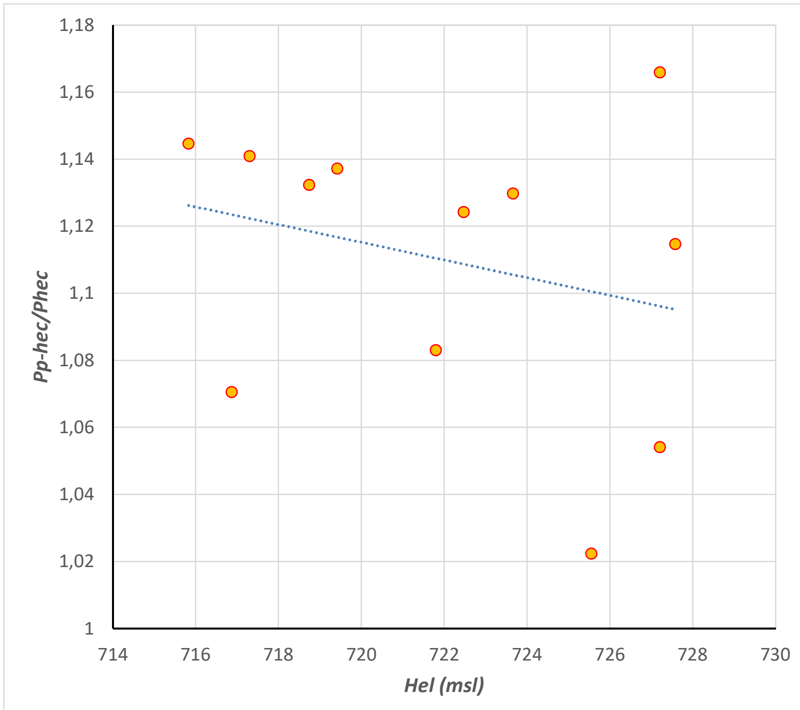

Fig. 17. Relative relation of calculated and realized exploitation of the hydro power-node

From the obtained data, if the adjustment of the units is done according to the parameters obtained from the model, a higher electricity production will be obtained for all the compared operating modes of the system. Initial estimates indicate that by applying the results obtained from the calculation model, they will provide to increase in energy production by about 10-14% depending on the water level in the reservoir.

4.Conclusions

Testing of the developed model for determining the optimal operating parameters of the turbines in SHPP "Strezevo" and SHPP "Exploitation minimum" when discharging water from the accumulation, shows that its development and implementation are justified.

For complete verification of the model, it is necessary in the second phase of its development to:

- Perform additional measurements of the losses in the branches of each of the turbines, depending on which units are loaded and determine the coefficients of resistance to be incorporated in the model.

- Test the model in operating conditions, i.e. to compare the total electricity produced according to the set parameters of the generators by the operators and according to the set parameters obtained from the model.

To verify the software, it is necessary to perform its wiring through:

- Detailed measurements of losses in the branches to the aggregates, under different operating modes.
- Level measurements in the drain, under different operating modes.
- Control measurements of the openness of the conducting device in all units.

This conclusion should be confirmed by the implementation of the model in the operating conditions of the system, i.e. by comparing the parameters set by the operator and the parameters obtained from the model.

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