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Modelling of the Solina-Myczkowce pumped storage power plant

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Abstract

The article presents simulation results of a developed model of PSP Solina. The model was designed and executed in the Matlab – Simulink interface. A modular approach was used to clearly distinguish characteristic elements of the model. Simulations of the model performance were carried out for a period of 365 days. The results were presented graphically. To simplify, the form of criteria defining on/off moments and defining the turbine/pump turbine operating mode was adopted. All constraints arising from the physical parameters and limitations of the cascade objects as well as those arising from the provisions of the current water management instructions for the Solina-Myczkowce cascade were taken into account. The model is a flexible proposal with which to develop and test decision-making mechanisms in the context of energy generation/consumption in operation. Due to the high potential and short on/off times of the turbine sets, the Solina EW plays an important role in the National Electricity System. An important role in the control process of the facility is played by the forecast of both power demand and contingencies. The analyses are supported by many charts and commentary.

Keywords: pumped storage power plants, optimisation, control criteria, multi-purpose water infrastructure

1. Introduction

According to the records of the International Commission on Large Dams, it appears that 70% of large dams and associated reservoirs (out of nearly 28,000 currently in operation) were designed as single-purpose facilities (ICOLD, 2014). Of these, half of the world's single-purpose dams were built for irrigation, followed by power generation, water supply and flood control tasks. A single-purpose facility for the sole purpose of producing electricity is naturally more financially attractive to private investors (such as the negative example of the Diga del Vajont dam, where the pressure of expected profits from the power company led to the facility's disaster). However, reality shows that single-purpose hydropower facilities evolve over time into multi-use facilities. The proper management focus of this evolution allows full utilissation of the benefits and synergies from the multiple tasks performed with a single facility. In today's reality, with the overriding criteria of good ecological status, a sense of social justice and economic efficiency, increasingly expensive and environmentally intrusive water infrastructure is being used for more than one purpose. Justifiably, the term multipurpose water infrastructure water system (MPWI) is emerging (Naughton, 2017). Multipurpose water infrastructure includes all constructed water systems, including dams, dykes, reservoirs and associated irrigation canals and water supply networks, which can be used for more than one purpose in economic, social and environmental activities. There are more than 8,000 large MPWI systems around the world by design, as well as a significant number of systems that operate as multi-purpose although they were initially designed to perform just a single task. Although MPWIs often generate greater economic benefits for communities than single-purpose infrastructure, the interest of potential decision-makers, and subsequently potential investors, to fund multi-purpose projects remains difficult (Naughton, 2017). This is due to the inherent complexity of working with multiple stakeholders, and the need for trade-off solutions of sustainable business models for financing, operation and maintenance, as well as the even distribution of risks among stakeholders in case unforeseen risks and negative externalities arise (Kaczmarek, 2000; Twaróg, 2008). The need has arisen to adjust (evaluate) SPWI (single-purpose water infrastructure) and expand the number of tasks performed by MWPI in the spirit of sustainability requirements. Such an approach makes it possible to increase the economic efficiency of large hydro projects and strengthen their position in the process of water resource management (Drużyńska, 1999; Twaróg, 2009).

The Solina-Myczkowce hydrotechnical facilities have been, since the beginning of their operation, multipurpose hydrotechnical facilities performing the following functions: electricity production, water supply, alimentation, retention, protection of the valley below from flooding, recreation and tourism (Polit. Rzesz., 2001; Dziewański, 2002; Słota, 2000). In the area of electricity production, among the hydrotechnical facilities of the San River cascade, there is the Solina power plant, which is a pumped storage power plant, and the two Myczkowce power plants – a small power plant and a larger derivation power plant.

2. Water management of the cascade

The Solina-Myczkowce cascade performs the following tasks:

- generating power from the retained water;
- protection against flooding on the San River;
- to compensate for the low flows of the San River below the Myczkowce gauge;
- the supply of water for municipal, industrial and recreational purposes.

Water management tasks performed at the cascade require the determination of priorities depending upon the time of year of operation of the power plant (Polit. Rzesz., 2001; Dziewański, 2002; Słota, 2000) . In the period of normal

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operation, the priority is set on the implementation of tasks related to the fulfilment of energy tasks for the NPS, while in the flood period, due to the threat to the public in the valley below and the danger to the cascade facilities (the maximum capacity of the Myczkowce stage is less than the maximum capacity of the Solina stage), the priority must change to flood protection. Any other approach is unacceptable due to the high risk potential accumulated in the Solina-Myczkowce cascade (Polit. Rzesz., 2001; Dziewański, 2002; Słota, 2000). These risks are related to the threat posed by the possibility of facility failure and the occurrence of major floods. Water management and energy management are conflicting goals pursued at the cascade. Protection against flooding and the maintenance of the energy potential require the implementation of conflicting activities that are reconciled by determining priorities, depending on the operating state of the facility, specifically whether the state is normal or emergency. For protection against flooding, it is required to lower the damming to a safe level at the reservoir, as specified in the Reservoir Water Management Instructions for the Solina-Myczkowce Cascade, in order to prepare the so-called flood reserve to cut the peak of the incoming flood wave (Polit. Rzesz., 2001). Maintaining the energy potential comes down to keeping the damming as high as possible, according to the aforementioned Water Management Manual. The goals of the tasks are conflicting, but it is impossible to find a compromise solution here. The only rational solution is to adopt priorities with regard to the way in which water is managed on the cascade (Kaczmarek, 1984; 1960; Malinowski, 1995).

3. Description of selected Solina-Myczkowce Hydroelectric Complex facilities

The Solina-Myczkowce Hydroelectric Complex consists of two water stages (Polit. Rzesz., 2001; Dziewański, 2002; Słota, 2000) :

- Solina water stage,
- Myczkowce water stage.

3.1. Solina water stage

The Solina water stage includes:

- reservoir,
- concrete dam,
- hydroelectric power plant.

3.2. Upper reservoir Solina

The reservoir was created by closing of the valley of the San River with a heavy concrete dam at km 325+400 in 1968. The reservoir is shaped like a large Y, with the dam located at its base. The maximum length along the San tributary is 26.50 km, while along the Solinka. it is 14 km. The reservoir has two main branches and the total perimeter exceeds 150 km. With maximum damming, it accumulates 503.97 10^6 m^3 of water, including a usable capacity of 300 10^6 m^3. The area of the floodplain at the 420 m a.s.l. is 22 km^2. With water damming up to 60 m, the multi-year average flow was determined at Q_0 = 19.6 m^3/s (flow volume V_0=618 10^6 m^3). The Solina reservoir is a reservoir with multi-year outflow equalisation (Polit. Rzesz., 2001; Dziewański, 2002; Słota, 2000).

Table 1. Basic technical parameters of the Solina reservoir (Polit. Rzesz., 2001)

Stacking levels		**[m a.s.l.]**
Highest level of emergency overloading (maximum water level)	maxWL	421.50
Normal water level	NWL	420.00
Minimum water level	minWL	401.50
Capacities		[10^6 m^3]
Total capacity with overstorage	[m a.s.l.]	503.97
Usable capacity	401.5–420.0	275.70
Permanent flood reserve	417.2–420.0	50.00
Forcing flood reserve	420.0–421.5	31.93
Dead volume	401.5	196.34

3.3. Hydroelectric power plant

PSP Solina, is located at the base of a concrete dam. This power plant is a special type of hydroelectric power plant with the ability to pump, as needed, a certain amount of water from the lower reservoir to the upper reservoir. It consists of an underwater section and a machinery hall with an auxiliary building, and has foundations independent of the dam (Polit. Rzesz., 2001) .

The underwater part consists of five blocks:

- two with classical Francis turbines - Blocks 2 and 3,
- two with Francis reversible turbines - Blocks 4 and 5).

In the lowest block of the underwater part, there are turbine chambers, a cable room and auxiliary rooms. Along the block of the power plant, runs a drainage gallery (bottom at the 344.4 [m a.s.l.]) in which drainage equipment, suction pipes and spirals are located. Solina turbine units supply active power to the power system during periods of peak power demand (morning, evening). In addition to active power, they also generate reactive power, contributing to frequency regulation in the system.

Table 2. Parameters of PSP Solina (Polit. Rzesz., 2001)

Power of turbines		**[MW]**
Installed power		(2 x 68) + (2 x 32) = 200
Classic hydro units		
In turbine operation	H_{avg} = 55 m	2 x 68 = 136
Reversible hydro sets		
In turbine operation	H_{avg} = 55 m	2 x 32 = 64
In pumped operation	H_{avg} = 55 m	2 x 30 = 60
Maximum pumping power		69
Turbine gullets		[m^3/s]
Gullet in turbine operation	H = 55 m	(2 x 138) + (2 x 66) = 408
Oesophagus in pump operation	H = 55 m	2 x 52.5 = 105
Characteristic head		
Max GROSS	$H_{brutto\ max}$ = 61 m	(420.0–359.0 m a.s.l.)
Min GROSS	$H_{brutto\ min}$ = 39 m	(401.5–362.5 m a.s.l.)
Pumping shall be carried out only at slopes less than 55.3 m		

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3.4. Myczkowce water stage

The Myczkowce stage includes (Polit. Rzesz., 2001; Dziewański, 2002; Słota, 2000):
- reservoir,
- an earth dam with a concrete overflow section,
- a pressure adit supplying water to the power plant,
- hydroelectric power plant.

3.5. Myczkowiecki reservoir - lower cascade reservoir

The reservoir was created by closing of the valley of the San River with an earth dam in Myczkowce at 319+000 kkm of the San River. It is a daily equalisation reservoir for the intervention-regulatory operation of the Solina power plant and, together with the Solina reservoir, it forms a cascade of reservoirs with strongly interconnected water management. The Myczkowce reservoir is the lower water source for the Solina power plant. The Myczkowce reservoir, due to its small capacity, allows only for daily equalisation of outflow from the Solina reservoir, and for accumulation of water intended for pumping by reversible turbines (Polit. Rzesz., 2001).

Table 3. Basic technical parameters of the Myczkowce reservoir (Polit. Rzesz., 2001)

Stacking levels		[m a.s.l.]
Highest emergency overload level (maximum damming level)	maxPP	363.90
Highest level of usable accumulation		362.50
Lowest level of utility damming, (minimum damming level)	minPP	359.00
Capacities:		[10^6 m^3]
Total capacity with overstorage		10.7
Total capacity	at 362.5 [m a.s.l.]	8.6
Usable capacity	359.0–362.5 [m a.s.l.]	4.4
Forced capacity	362.5–363.9 [m a.s.l.]	2.1
dead volume	359.0–347.0 [m a.s.l.]	4.2

3.6. Characteristic parameters of Myczkowce power plants

The power plant building is located at the end of the adit at the steep slope of the left bank of the San River (km 313 + 400). The basic dimensions of the power plant are: width 21.0 m, length 32.30 m, height 13.0 m. The power plant is equipped with two vertical turbine sets with Kaplan-type turbines, directly coupled to synchronous generators (Polit. Rzesz., 2001; Dziewański, 2002; Słota, 2000) .

Table 4. Table 4. Parameters of the Myczkowce power plants (Polit. Rzesz., 2001)

Turbine powers		[MW]
Installed power		2 x 4.15= 8.3
Turbine gullets		m^3/s
Esophagus installed		2 x 22.5 = 45
Head		[m]
Minimum head		19.2 m
Nominal head		21.7 m
Maximum head		22.7 m
Characteristic head		
Max GROSS	(362.5 – 337.9) [m a.s.l.] Q_{min} = 6.0 [m^3/s]	24.6 m
Min GROSS	(359.0 – 338.7) [m a.s.l.] Q = 45.0 [m^3/s]	20.3 m

4. The catchment area of the Solina-Myczkowce reservoirs

The sources of the San River are located at the 843 m a.s.l. The hydrological network of the catchment area is well developed. The numerous tributaries are typically mountainous in character. The length of the San River catchment along the main channel is 119 km for the Solina reservoir and 6 km for the Myczkowce reservoir. The catchment area for the Solina dam is 1,174.5 km^2. The catchment area for the Myczkowce dam is 1,248 km^2. The Solina reservoir is fed from two major tributaries, the San River and its right tributary the Solinka River. Other major direct tributaries of the Solina reservoir are the Daszówka, Paniszczówka, Czarny, Wolkowyjka, and Krzywy streams (Polit. Rzesz., 2001, Dziewański, 2002, Słota, 2000).

5. The flows

The flows in the line of the Solina dam from the 1969–1994 period of operation are as follows:

Table 5. Flows from the period 1969-2006 (Polit. Rzesz., 2001)

Determination of flow	Flow [m^3/s]
minimum observed – NNQ	0.00
annual average – SSQ	22.70
highest observed – WWQ	1,125.00

The maximum flows with a specified probability of exceedance for the period 1898–1934 for the Solina dam are shown in the table below.

Table 6. Table 6. Maximum flows with specified probability of exceedance from 1898-1934 (Polit. Rzesz., 2001)

Probability exceedance [%]	Flow [m^3/s]
0.01	3,000
0.10	2,250
0.20	1,930
1.00	1,500
5.00	1,000

6. Energy management of the Solina reservoir

Reservoir energy management involves the optimal use of reservoir capacity for power generation in a way that allows (Polit. Rzesz., 2001):

- maintaining an appropriate level of damming;
- securing the possibility of power-plant operation with the guaranteed power supply;
- energy use of the total annual inflow without idle water discharges.

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7. Principles and possibilities of cooperation of the Solina power plant with the NPS

Solina power plant is a CDGU (centrally dispatched generating unit) power plant. It is a pumped storage power plant, operates on retained natural inflow to the Solina reservoir and also serves as an emergency power plant. In addition to scheduled production, the Solina-Myczkowce power plant provides system services for the needs of operators. At any order from the NDC (National Power Dispatch), it is employed for system services (generator operation, pumping operation and compensator operation). The power plant operates in the generator mode during the morning and evening peak periods, off-peak during the low demand period, it operates in the pumping mode. The synchronisation time with the grid is three minutes from startup.

8. Simulation model of the operation of the Solina power plant

The model was developed in the Matlab – Simulink interface. Data of historical inflows to the reservoir (Institute of Engineering and Water Management of PK, now Department of Geoengineering and Water Management) were adopted for the simulation of the model. The power demand data were adopted for a period of the same length. In developing the model, the focus was on the following modules:

- input to the system, which reads information about the power demand of the NPS, the size of the turbine/pump start criteria, and the size of the natural inflow to the Solina reservoir – the natural inflow to Myczkowiec was assumed as a percentage of the natural inflow of the Solina, these quantities can be forecasts;
- building a control signal for reversible turbines (Twaróg, 2009), turning them on and off for both pump and generator operation;
- modifying the control signal (Twaróg, 2009) by limiting the retention of the upper/lower reservoir, possibly due to the impulse of emergency operation, this can be a forecast;
- operation of four turbines in the generator mode and operation of two reversible turbines as pumps;
- economic calculations – revenue-cost, taking into account current energy prices or their forecast;
- an output graphically presenting the results of the simulation or allowing the saving of results in formats such as ASCII.

8.1. Input module

The construction of this module used data:

- power demand quantities (ASCII);
- natural inflow;
- criteria values for the construction of the turbine control signal, turbine on/off values for the generator mode and turbine on/off values for the pump mode.

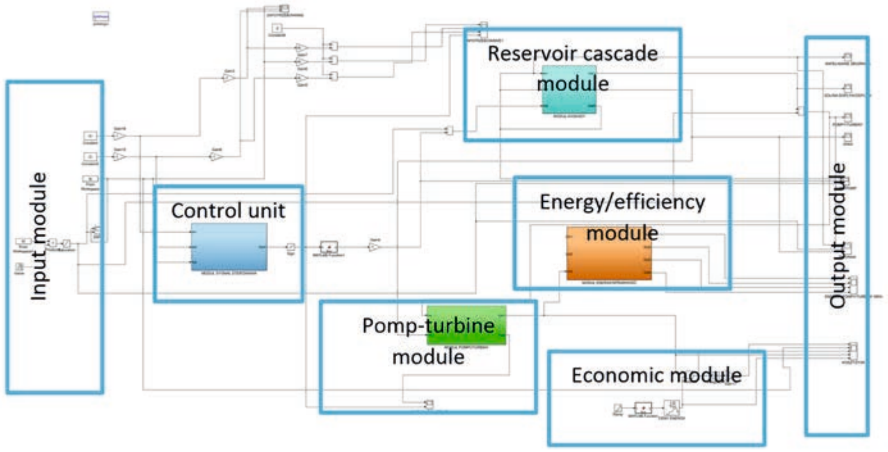

Fig. 1. Simulation model of the PSP Solina operation, Matlab – Simulink [own study]

8.2. Pump-turbine on/off signal building module and operating mode

The signal-building module is based on defined on/off criteria, which are given a priori by the system dispatcher (e.g., NDC-National Power Dispatch), they define the on/off moments and the operating mode of turbines and pump-turbines. The simplest system was adopted and the intersection points of the criteria with power demand information define these decisions. This is an example of a solution that can be modified through forecasts/interventions.

8.3. Modification module for on/off signal and operating mode

The model takes into account the many constraints that are associated with the multipurpose implementation of the cascade's objectives, not only in the energy dimension but also in the area of water management. Constraints arise mainly from the permissible capacities of the two cascade reservoirs, restrictions on the size of idle outflows, the ranges of turbine slopes in the generator mode and reversible turbines for generator and pump operation.

Constraints on the modelling work also arise from the implementation of the contradictory tasks of cascading water management (Twaróg, 2009; Kaczmarek, 1960; 1984; Malinowski, 1995; Słota, 1983; Beibei at all, 2019; Padiyar at all, 2008). In addition, there is a need to take into account so-called intervention, i.e. a change in the operating mode resulting from the needs of the NPS. The interaction of these constraints, scheduled operation and intervention, requires the reconstruction of the system-operation control signal'.

8.4. Turbine/pump turbine operation

The turbine/pump turbine operation module calculates the power and energy of turbines operating in the generator mode and reversible turbines in the generator and pump mode. It takes into account the current fill-level of the Solina reservoir and the Myczkowiecki reservoir.

8.5. Economic module

The economic (financial) module provides assess to the value of revenue from the sale of energy produced and the costs associated with buying the necessary energy for pumping. The cost balance is presented cumulatively.

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8.6. Output module

This module enables the presentation of all quantities that are calculated during the simulation of PSP Solina. At the same time, it is possible to save them in any form.

9. Model simulation results

The results for a 365-day simulation period are presented. Enlarged areas for selected time intervals are shown for readability of the graphs. The graphs are clear and one can intuitively assess the correctness of the working model. The results of the calculations present the relationships between the behaviour of individual objects/modules. The simulation results are presented in detail below and a detailed description of them is included. The simulation results discussed here omit the operation of the two Myczkowce power plants, which do not directly affect the PSP Solina.

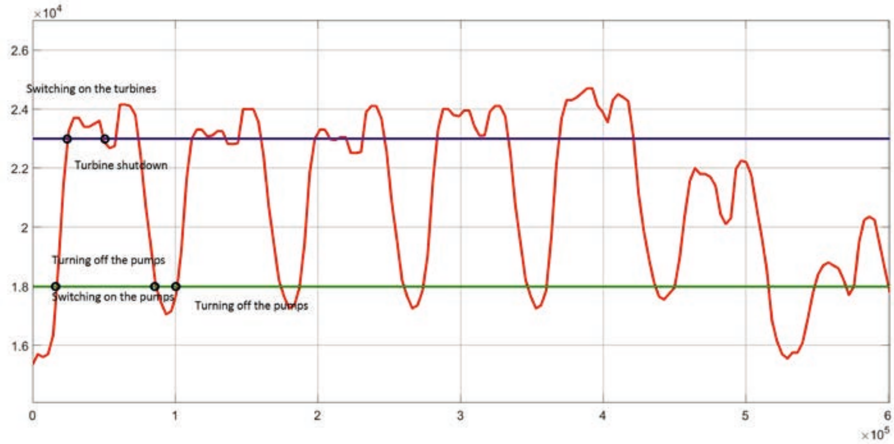

Fig. 2. Determination of switching points from turbine to pumped storage operation and vice-versa against the power demand [own study]

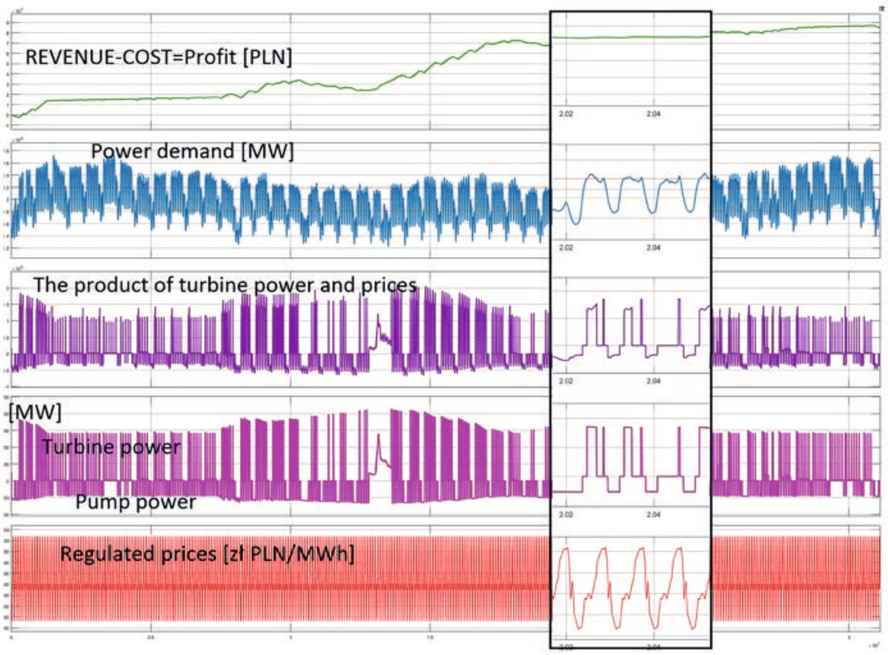

Fig. 3. Regulated energy prices, turbine/pump turbine capacity, product of capacity and energy prices, power demand, pumping cost – cumulative revenue from energy production [own study]

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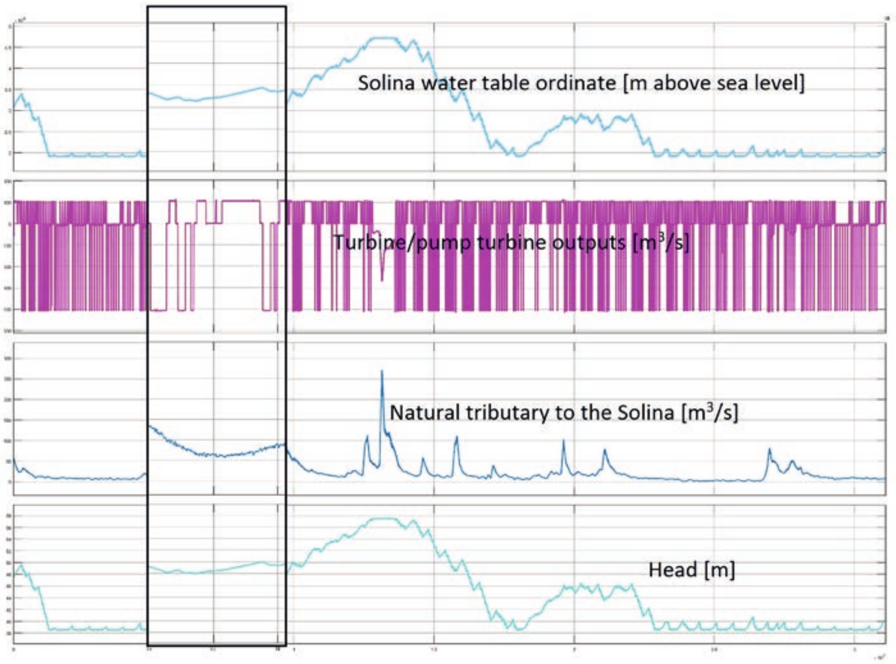

Fig. 4. Slope, natural inflow to Solina reservoir, turbine/pump turbine output, water table ordinate of Solina reservoir [own study]

10. Elements of optimisation

Optimising the operation of single and multi-tank power systems basically involves deciding how much electricity should be generated at each power plant in each time period. The task gets more complicated when dealing with multi-purpose facilities – MPWI. Due to the multi-faceted nature of the control problem of single and multi-tank power systems, the concept of optimal control is difficult to grasp (Twaróg, 2009; Dziewański, 2002; Słota at all, 2000; Kaczmarek, 1984). Decisions made at the reservoir(s) affect the state of the entire water and power system (MPWI) (Słota, 1983), so the criteria used should take into account the broadest possible factors concerning of the decisions made including measures of an economic, ecological and social nature. In the broadest sense, the task of the optimal control of the MPWI system is multi-criteria, random, dynamic, multidimensional and nonlinear (Słota, 1983; Polit. Rzesz, 2001). The opinion is confirmed that the possibility of solving complex problems related to the design and operation of water and wastewater systems (MPWI) by analytical means is limited (Twaróg, 2009; Słota at all, 2000; Malinowski, 1995). Therefore, for even a simple structure, the problem cannot be strictly solved by known methods. Monte Carlo methods have great potential for use in optimising MPWI systems (Twaróg, 2017). These methods cannot only be used in defining forcing in the form of hydrological factors but also in economic, financial and social situations affecting the search for optimal solutions in the area of MPWI design and operation (Twaróg, 2009; Malinowski, 1995; Słota, 1983).

11. Summary

The article presents simulation results of the developed model of PSP Solina. The model was designed and executed in the Matlab – Simulink interface. A modular approach was used to clearly distinguish characteristic elements of the model. Simulations of the performance of the model were carried out for a period of 365 days. The results were presented graphically. To simplify the operation of the model, the form of criteria defining on/off moments and defining the turbine/pump turbine operating mode was assumed. All constraints arising from the physical parameters and limitations of the cascade objects as well as

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those arising from the provisions of the current water management manual for the Solina-Myczkowce cascade were taken into account. The model is a flexible proposal with which to develop and test decision-making mechanisms in the energy area of cascade operation.

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