Operativni režim rada hidroelektrana u kaskadnom sistemu zavisno od potrebe energetskog sistema

Hydro power plants operating modes in a cascade system depending on the needs of the power system

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Apstrakt - Rad prezentira model i metodologija za operativne režime rada hidroelektrana u kaskadnom povezani hidraulični sistem. To uključuje upravljanje vodom proizvodnih i/ili crpnih (pumpne) jedinice, uzimajući u obzir tehničke karakteristike postrojenja elektrana (turbine/generator i pumpe/motorni sistemi), karakteristike rezervoara uzimajući u obzir svu infrastrukturu koja je hidraulično povezana. Svakako tu spadaju i hidrološke prilike i uslove (prirodni priliv i priliv uzvodnih turbina), Cilj operativnih režima rada za hidroenergetske sisteme je imati maksimalan profit od proizvodnje električne energije uzimajući u obzir regionalno okruženje tržišta električne energije, potrebe elektroenergetskog sistema, kao i zadovoljenje tehničkih uslova i istovremeno izbegavanje preliva kolko je moguće. Načini rada hidroelektrana zavise od tržišne cene električne energije, tarifnim modelima i vremenetrajanja svake tarife (bazni, vršni i druge tarife), svakako uzevši u obzir tehničke karakteristike proizvodne jedinice, hidrotehničke uslove, količine akumulacionih rezervoara i drugi uslove. Primena modela će biti prezentovana sa rezultatima na stvarnim hidroenergetskim sistemima koji se sastoje od različiti hidraulični infrastrukturnih elemenata, za različite slučajevima koje zavise od hidroloških uslova i zahteva. Model se može koristiti za izradu preliminarne analize za tehničko poboljšanje hidro-sistema preko dodatnu instaliranu snagu postojećeg sistema. Izabrani rezultati sa analizama biće predstavljeni odgovarajućim upoređivanjem i na kraju sa zaključnim komentarima.

Ključne reči – proizvodnja, hidroelektrana, pumpa, revizibilna, turbina

Abstract- The paper presents the methodology for hydro power plants operation (Long-term and Short-term) in a hydro power cascade system. It includes water managing of generating and/or pumping units taking into accounts technical characteristics of the power plants facilities (turbine/generator and pump/motor systems), reservoirs characteristics considering all hydraulically connected infrastructures which are, as well as the hydrological conditions (for run offs and turbine inflows). The goal of the operation for all hydropower system is to have maximum profit from electricity production taking into account electricity market environment, power system requirements, as well as satisfying technical conditions and at the same time avoiding water spilling as it is maximum possible. Operating modes of the hydro power plants depend on electricity market price, tariff prices and time duration of each tariff (base, peak, and rush hour), technical characteristics of the unit(s), hydro technical conditions, water reservoir's volumes, run off and others.

The application of the model is presented with the results on real hydro power systems consist of different hydraulic connections in various cases depend on hydrological conditions and requirements. The model can be used to make preliminary analysis for additional improvement of hydro systems as having the results for additional installed power of the existing system. The selected output results are presented with appropriated comparing and at the end with conclusion remarks.

Index Terms- generation, hydro, pump, reversible, turbine

I. INTRODUCTION

The paper presents the model for different operation modes of hydraulically connected hydropower system (HPS) consists of reservoirs, pipe connected lines and hydro power plants. The operating modes can be distinguished depend time interval planning (year, season or month for Long Term (LT) and week, few days or a day for Short Term (ST)). The model takes into account the technical specifications and parameters of the whole system such as:

- Volume of the water reservoirs with limitation of minimal and maximum elevation of the reservoirs,
- Turbine units characteristics (flows, power),
- Other technical constraints and specifications of the elements of the hydropower system,
- Connected infrastructure of lines and pipes,

The application of the model is done on the real hydropower system on river Crn Drim, taking into account the existing power

system as well as the other reservoirs and power generation units in new HPPs which are considering to be built in next period.

II. DESCRIPTION OF THE MODEL

The model gives main outputs of hydropower system depend on power system operator requirements and demand, as well as taking into account input of water run offs with respecting the technical conditions of the system. The modeling approaches depend on LT or ST operation modes. In the LT operation modes, the whole considering time period (T) can be a year or few years dividing on months' or weeks' time intervals (t) (depend on availability of hydrological data) and mainly considering the large reservoirs. In the ST operation modes, the whole considering time period (T) can be a week or few days dividing on hourly intervals (t) and mainly taking into account the water management for small reservoirs in daily regulation. The output results from the model are turbine discharges, electricity production of HPPs as well as reservoir level for each time interval (t) of whole considering time period T. In order to simulate the operation regimes of the whole system, it is necessary to know the characteristics of the reservoirs. Modeling of the characteristic of the all reservoirs is done according [4] as two functions, volume dependence of the attitude (1) and vice versa, the attitude dependence of the volume (2).

$$Vol(Att) = 2 \cdot \pi \cdot (A + B \cdot Att + C \cdot Att^2) \quad (1)$$
$$Att(Vol) = g + h \cdot (Vol - d)^e \quad (2)$$

The simulations of the operating regimes has been done taking into account the characteristics of the reservoirs, the water inflows and the turbine characteristics of the HPPs. The inputs in the model are the following: average inflows and run offs for the time intervals, the characteristic of the electric power output P=f (Q_{tur}, H_{gross}) as a function of turbine flow (Q_{tur}) and gross head and the reservoirs characteristics according (1) and (2). For financial analysis it is necessary to have the electricity prices. The following conditions and assumptions are taking into accounts in the model:

- The reservoirs level to be within the allowed limits and avoiding spilling.
- The turbine flow priority is to have maximum revenue from generated electricity according to the electricity market prices for each period of the day.

The output results from the calculations are the following ones:
-Consumed water volume in each time period (year, month, day,…) for each reservoir
-Output power for each time period P(t)
-Electricity generated for each time period W(t)
-Financial profit from the sold electricity FIN
The methodology for operation modes of hydro power plants can be applied in different needs depend on input data and the requirements from the utility or operator of the power plant. Some of the possible application can be done for:
Hydro power systems from simple to complex technical hydraulically configuration and connectivity for different time period of consideration (T) as: few years, a year, season, week, only a day. The period of consideration can be divided on different time intervals Δti, where $T = \sum_{i=1}^{n} \Delta t_i$

III. HYDEO POWER STSTEM OF CRN DRIM

The existing hydropower system (HPS) of river Crn Drim consists of 2 hydro power plants (HPP Globocica 2x21 MW and full turbine discharge of 50 m³/s) and HPP Spilje (3x28MW and full turbine discharge of 108 m³/s), three reservoirs (RES 1- Ohrid lake, RES 2 - Globocica and RES 3 - Debar lake) with main run offs from two rivers (Crn Drim and Radika). HPP Globocica with two units is the first upper stream power plant in HPS Crn Drim is a derivative power plant that uses the water from RES 1 of Lake Ohrid. Each of the two units is 25 m³/s or total of 50 m³/s, with a total installed capacity of 42 MW, have gross head of 108-110 m. The turbine flow from HPP Globocica and the Radika River are the main run offs for RES 3 of Debar Lake as the reservoir of HPP Spilje. Existing HPP Spilje has 3 units, each of 36 m³/s or total of 108 m³/s, with gross head of 80-100 m, and total installed capacity of 84 MW. Figure 1 schematically presents the existing HPS of Crn Drim with planned new hydro power plants and new RES 4.
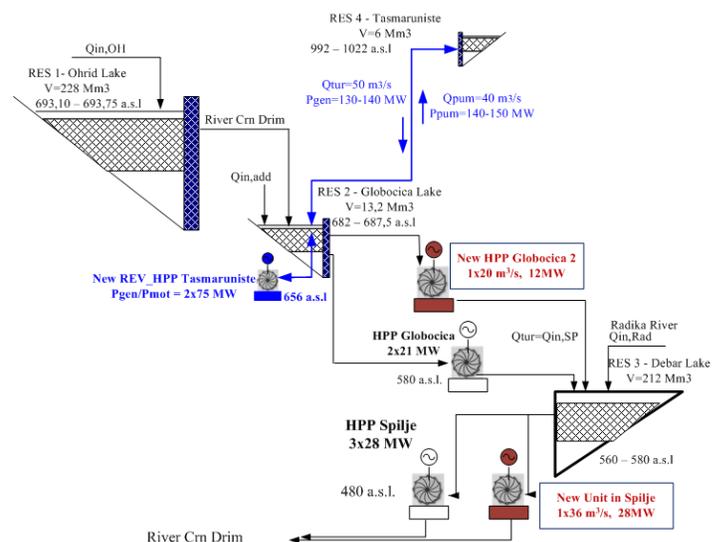

Figure 1. Hydraulically connected HPS of Crn Drim (existing and new reservoirs and units)

The new generating units are in HPP Globocica 2 with a unit of 20 m³/s turbine flow and 12 MW installed power, located in new turbine hall with 70 m gross head. The additional unit in HPP Spilje has 36 m³/s turbine flow and 28 MW installed power the same as the existing ones and located in the same turbine hall [1]. The new reversible (pump storage) HPP Tasmaruniste is added with the upper reservoir RES 4 Tasmaruniste on the Crn Drim system. The others basic technical parameters (from [2] and [3]) as the reservoirs' volumes, attitudes of the turbines, minimum and maximum reservoir levels, turbine flows and installed power are given on the Figure 1. Therefore the whole hydropower system which is considered in this paper, consists of 4 reservoirs with basic information given in Tab.1 and few HPPs with some technical characteristics given on Tab.2.

Table 1. Characteristics of the reservoirs of HPS Crn Drim

	Existing RES1	Existing RES2	Existing RES3	New RES4
Att.max (a.s.l.)	693.75	687.5	580	1022
Att.min (a.s.l.)	693.10	682	560	992
Vol. (10^6 m³)	228.00	13.20	212.00	6.00

Table 2. HPPs Characteristics in HPS of Crn Drim

	No. of units	Q_{inst} (m³/s)	H_{gross} (m)	P_{inst} (MW)
Exist.HPP Spilje	3	108	75-95	84
Exist. HPP Globoc.	2	50	102-105	42
New HPP Spilje 4 unit	1	36	75-95	28
New HPP Globoc. 2	1	20	70	12
New RevHPP Tasmar.	2	Qt=50, Qp=40	305-335	150

The Large reservoirs, RES 1 of Lake Ohrid and RES 3 of Debar Lake are important for long-term analyzes (seasonal, annual and multi-year). The small reservoir RES 2 of Globocica and RES 4 of Tasmarunista can be taken in short-term analyzes as daily, few days or weekly analyzes. The parameters according the formulas (1) and (2) for all reservoirs are given in Tab.3.

Table 3. The parameters for all reservoirs according (1) and (2).

	A	B	C	g	d	h	e
RES 1	1639724	-4863	3,60	675	-3136	0,3	0,5
RES 2	4135	-13	0,01	640	-48	6,1	0,5
RES 3	5790	-23	0,02	500	-194	4	0,5
RES 4	996	-2	0,001	971	-1,2	19	0,5

A. Long term (LT) operation modes of HPS Crn Drim

The simulations for HPS of Crn Drim for LT operation modes are made on the monthly basis time interval (t=1 month) in the whole period of a year (T= 1 year). The main idea of the simulation is to find the operational regimes with maximum financial benefit under new market conditions with electricity prices on the open market with different tariffs (Fig.2).
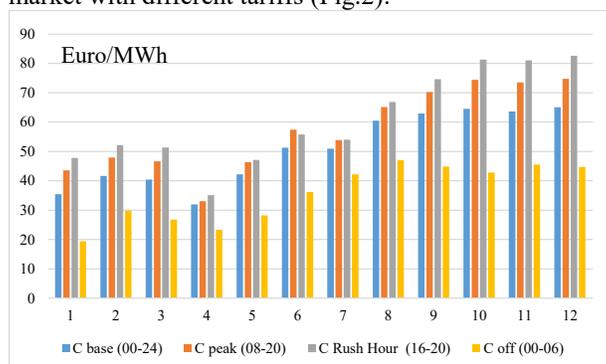

Fig. 2. Daily tariffs and electricity price C (€/MWh) from the HUPEX in 2018

The time periods for each day are divided into 2 groups (tariffs) for Long-term operation modes (Base tariff (C_{base}) and Peak tariff (C_{peak})). The water inflow for HPP Globocica ($Q_{in,GL}$) is predominantly from Lake of Ohrid ($Q_{in,OH}$), and the additional run offs ($Q_{in,add}$):

$$Q_{in,GL}(t) = Q_{in,OH}(t) + Q_{in,add}(t) \qquad (3)$$

The water inflow for HPP Spilje ($Q_{in,SP}$) mainly depends on the turbine flow of HPP Globocica ($Q_{tur,GL}$) and the natural run off from Radika River ($Q_{in,Rad}$):

$$Q_{in,SP}(t) = Q_{tur,GL}(t) + Q_{in,Rad}(t) \qquad (4)$$

According to natural flows from the input hydrological data [2], three characteristic hydrological years have been selected in yearly operating modes: 2001 as dry year representative, 2006 as average year representative and 2013 as wet year representative. Fig.3 and Fig.4 show the monthly water inflows for the reservoirs in HPP Globocica and HPP Spilje respectively, in each of the representative year.
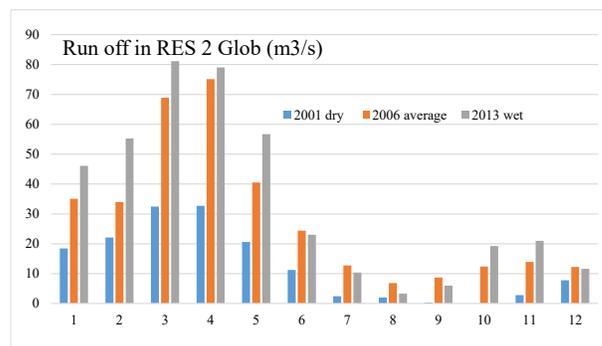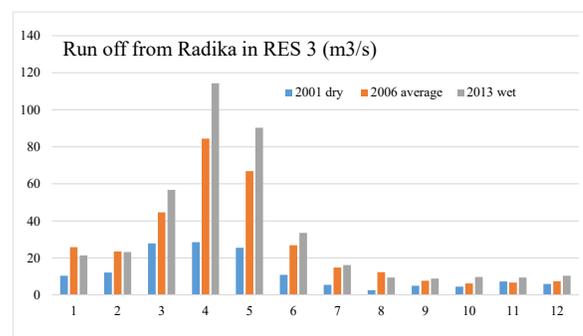

Figure 3. Monthly water inflows for the RES 2 of Ohrid

Figure 4. Monthly water inflows for the RES 3 of Debar Lake from Radika River

The starting value of the reservoirs level in 1st of January is common for all simulations, for Ohrid Lake is 693.3 a.s.l., and for Debar Lake is 563 a.s.l. The simulations are made for three years, dry 2001, average 2006 and wet 2013. The results for the representative of wet year are presented on Fig.5 and Fig.38 as the reservoirs level and the spent volume of water for HPP Globocica (dV_GL) and HPP Spilje (dV_SP) respectively.
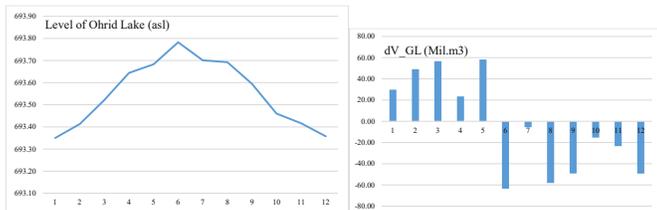
Figure 5. Reservoir level of Ohrid Lake and spent volume of water in HPP Globocica for each month in wet 2013
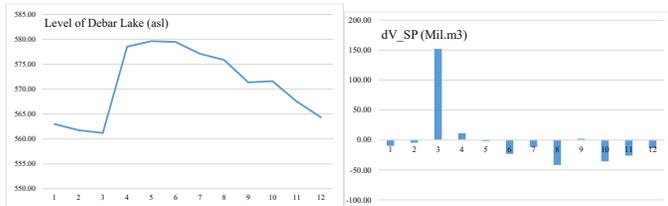

Figure 6. Reservoir level of Debar Lake and spent volume of water in HPP Spilje for each month in wet 2013
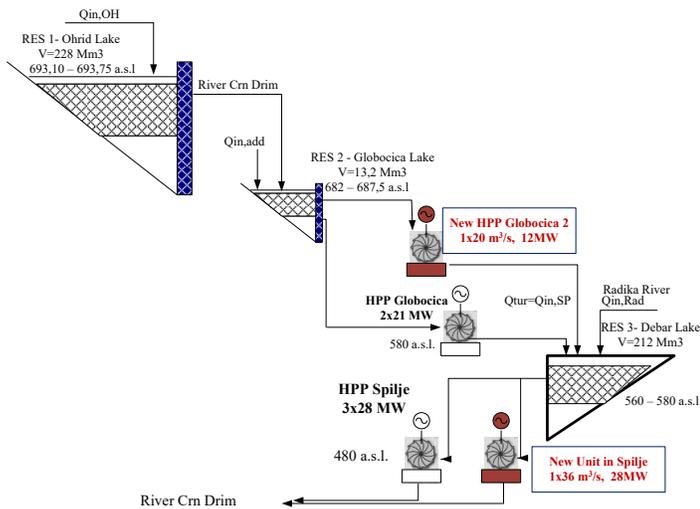

Figure 7. HPS considering for long term (LT) operation modes

For LT operation modes, the reversible HPP Tasmuruniste is not considered, only the conventional HPP Spilje and HPP Globocica (Fig.7). In order to avoid overflowing and spilling, the operation with maximum installed turbine flow for both HPPs is in the first months. The total balance of the both HPPs in the HPS of Crn Drim in generated electricity and financial income from the sold electricity is given in Table 4. The total generated electricity consists of 2 parts, base and peak where the income comes from, and the third part is lost electricity (negative one) because spilling. Therefore, for wet 2013, the all HPPs in HPS Crn Drim give:
• Production of around 658 GWh with total electricity sales of approximately 34.3 million euros.
• Overflow (spillway) of about 36 GWh with a total loss of un-produced electricity of about 1.2 million euros.

Table 4. Generated electricity and financial income for the wet 2013 in case with existing and additional units in HPS Crn Drim

	Generated Electricity W(MWh)			Financial Income FIN (Mil.Euro)		
	base	peak	spill	base	peak	spill
1	0	39717	0	0,00	2,13	0,00
2	0	35525	0	0,00	2,09	0,00
3	31329	23489	0	1,27	1,52	0,00
4	90595	36202	-36202	2,89	1,67	-1,20
5	63037	15665	0	2,66	1,41	0,00
6	35456	27876	0	1,82	2,42	0,00
7	0	26575	0	0,00	1,43	0,00
8	0	43686	0	0,00	2,84	0,00
9	0	32167	0	0,00	2,26	0,00
10	0	33289	0	0,00	3,07	0,00
11	0	31409	0	0,00	3,06	0,00
12	0	31811	0	0,00	3,00	0,00
Sum	220417	377410	-36202	8,63	26,91	-1,20
Total	657990					34,35

Fig.8 gives graphical presentation of the generated electricity in each month for the whole HPS Crn Drim in the wet 2013. The lost electricity because spilling is negative (bellow the apices axis in month of April).
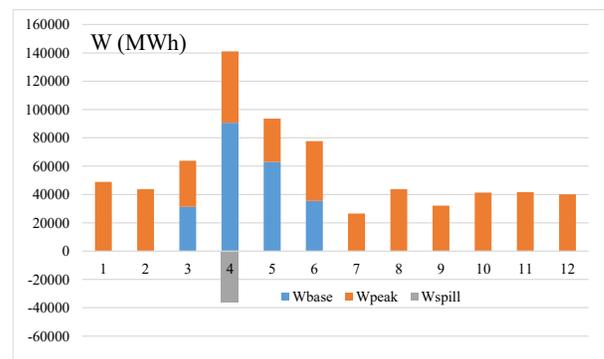

Figure 8. Monthly production for the HPS Crn Drim in wet 2013

According the calculation for all cases and for all representative years, the comparison of the results can be analyzed in order to have answer for the benefit of additional units installed of the HPS Crn Drim, which is very useful for further techno-economic analyzes. Tab.5 and Fig.9 show the generated electricity and lost energy in spilling, for all representative years.

Table 5. Generated electricity and spilled energy in MWh for all cases for HPS Crn Drim

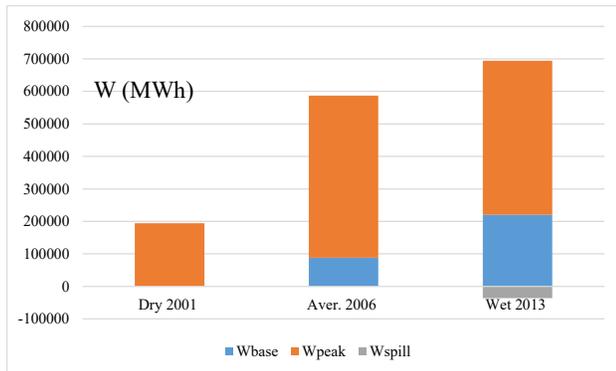|	Dry 2001	Aver. 2006	Wet 2013
W_{base}	0	88440	220417
W_{peak}	194431	498460	473774
W_{spill}	0	0	-36202
Total	194431	586900	657990

Figure 9. Comparing the output energy for all cases

The results show that the increased production and income can be got in additional units in peak tariffs with high prices. The other benefit of additional units is reducing the lost energy of spilling in wet 2013 to 36202 MWh, and the difference goes to additional peak electricity of the system. Tab.6 and Fig.10 give the benefit in Euro from income of generated electricity taking into account the lost energy of spilling.

Table 6. Financial benefit from income (in €) for all cases for HPS Crn Drim

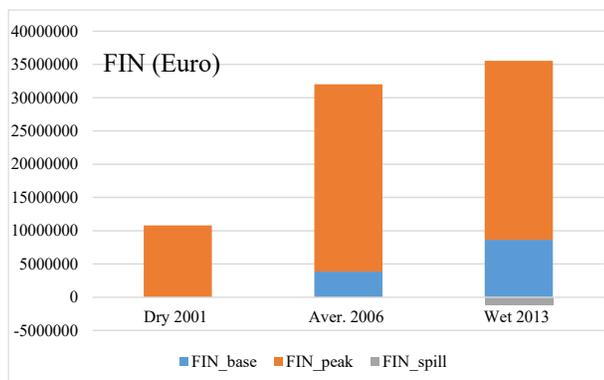|	Dry 2001	Aver. 2006	Wet 2013
FIN_{base}	0	3866861	8634785
FIN_{peak}	10785275	28128836	26909732
FIN_{spill}	0	0	-1196258
Total	10785275	31995696	34348258

Figure 10. Comparing the income (in €) for all cases

The overall benefit for dry 2001 is approximately 10,5 M€, for average 2006 is approximately 32 M€ and for the wet 2013 is approximately 34,2 M€.

B. Short term (ST) operation modes of HPS Crn Drim

The simulation of ST operating modes for HPS of Crn Drim are done for some characteristics days , with the inputs taken from the LT results especially water inflows and turbine discharges. The main point in ST planning is focus on operation of reversible HPP Tasmaruniste with HPP Globocica (Fig.11), as well as the water managing between downstream RES 2 of Globocica and upstream RES 4 of Tasmarunista. The LT operation modes are made on the hourly time interval (t=1 hour) in the whole period of a year (T= 1 day/week…). In this simulations, within the day can be find the operation of turbine mode in the peak and/or rush hours (7-24 h) and pumping mode in off hours (0-6 h).
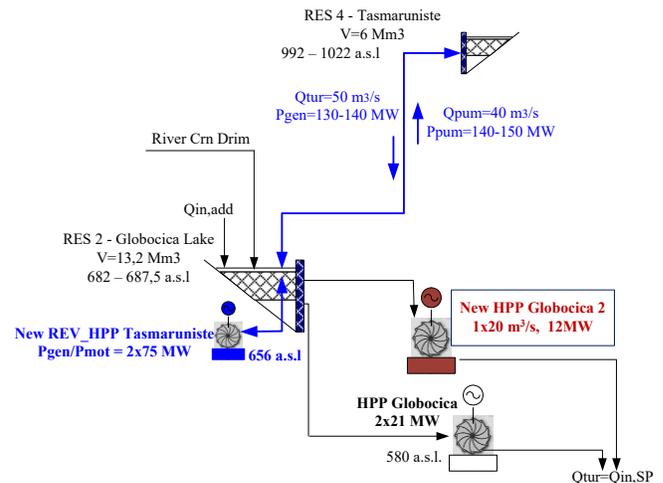

Figure 11. HPS considering for short term (ST) operation modes

According the Study [3], taking into account water losses and efficiencies of turbine and generator, the power output in (MW) injected to the grid in turbine-generation mode for Rev HPP is:

$$P_{gen}(t) = 8,35 \cdot Q_{tur}(t) \cdot H_{gross}(t) \qquad (5)$$

Also, taking into account water losses and efficiencies of pump and motor, the power in (MW) taken from the grid as consumer in pump-motor mode for Rev HPP is:

$$P_{mot}(t) = 11,58 \cdot Q_{pum}(t) \cdot H_{gross}(t) \qquad (6)$$

The time periods for each day are divided into hourly time intervals where for financial analysis it is taken 3 tariffs, night tariff (0-6h) - C_{off}, peak tariff (C_{peak}) and rush tariff (16-20h) (Crush). Fig.12 presents the turbine and pump flows in a day (24 hours) for reversible HPP Tasmarunista in a case of large inflow in RES 2-Globocuca Lake of Qin=32m3/s. The generated power (Fig.13) are from three HPPs (PL1-Globocica1, PL2-Globocica2, and Pg_TAS-Tasmaruniste). The power needs for pumping mode is Pp_TAS.
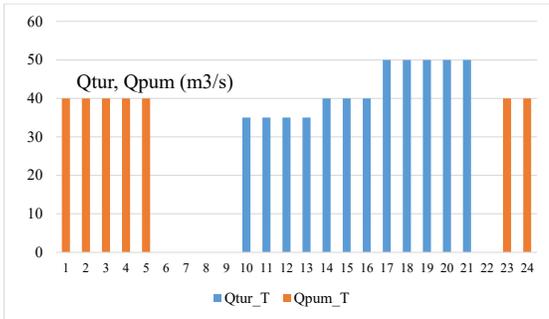
Figure 12. Turbine and pump flows for Rev. HPP Tasmaruniste
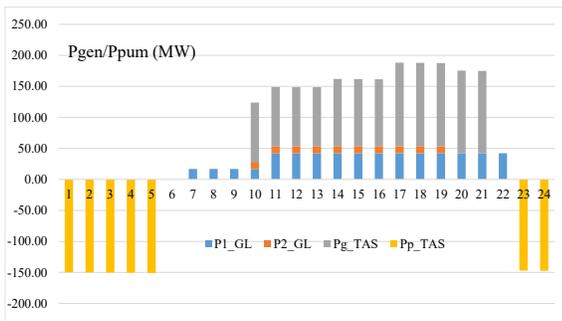

Figure 13. Generated and consumed power for the HPS on Fig.11

The graphs of the water level for upper RES2 – Globocica and downstream RES4 - Tasmarunista are given in Fig.14 and Fig.15
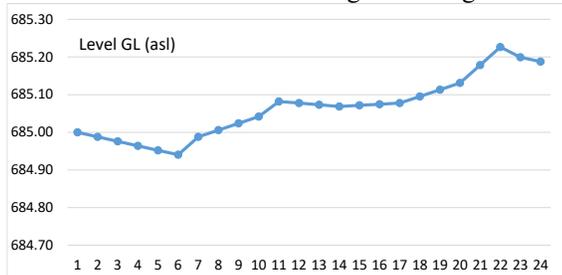

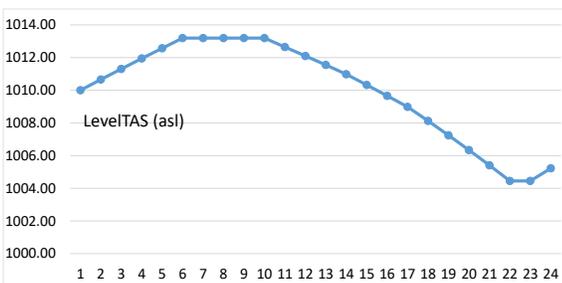Figure 14. Water level for upper RES2 Globocica

Figure 15. Water level for downstream RES4 Tasmarunista

The ratio between the volumes for pumping and for generation electricity is $V_p/V_t=0{,}55$ and for this amount of water, the ratio of the energies needed for pumping and generation is $W_p/W_t=0{,}76$. The other LP simulation is done for 3 days (72 hours) operation mode for a low runoff for RES2 -Globocica Lake which is $Q_{in}=12 m3/s$, and the appropriated results are given on Fig.16 and Fig.17.   The ratio between the volumes for pumping and for

generation electricity is $V_p/V_t=0{,}32$, and for this amount of water, the ratio of the energies needed for pumping and generation is $W_p/W_t=0{,}45$.
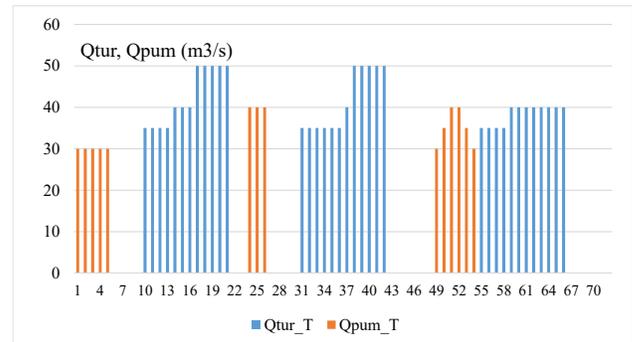

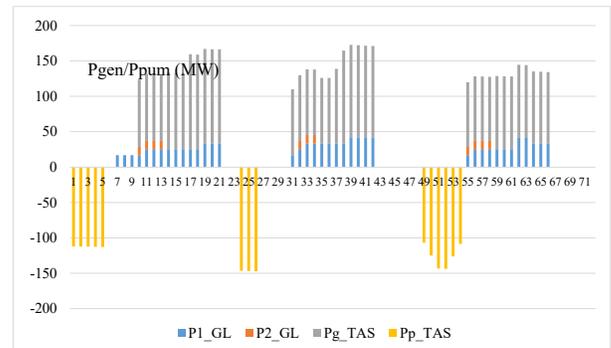Figure 16. Turbine and pump flows for 3 days operation

Figure 17. Generated and consumed power for 3 days operation

The operation mode in each time period of an hour, can be driven by the system operator requirements and electricity demand, but it should be taken the condition of minimum and maximum allowed levels for each reservoir of the system. The design of both reservoirs RES 2 and RES4 are enough for daily-weekly regulations in a system for installed turbine-pump flow of 50 m3/s. This case for ST operation modes does not include the operation mode of HPP Spilje which is down stream of the HPPs Globocica.

IV.   CONCLUSION

The operating modes of the hydropower system depend on the turbine/pump and generator/motor installations for all units in conventional and/or reversible HPP, as well as depend on electricity needs and system operator requirements. Anyway, more units in the HPS means flexible operation of the whole system. For LT operation modes, it can be taken large reservoirs with conventional units, but depend on available data to have in the terms of hydrology (day, week, or month).   For ST operation modes it can be taken the hourly operation for each power unit, with taken into consideration the reversible HPP. In this cases the flexible of the system can be improved in order to have maximum financial profit from electricity generation, but, it is possible for the prices when the ratio between peak tariff and low off tariff are large then the ratio between generated and pumped power for same amount of water or, when $C_{peak}/C_{off}>P_{gen}/P_{pum}$. The benefits of

complex hydropower system operation should be valorized in generated electricity, as well as financial benefit. Some of the additional analysis can be done, such as:

-Higher electricity production as a result of utilization of the overflow spilling water

-Engagement of the units in the periods of high tariffs per day, rather than production as a base plant.

-Opportunity for optimization of the whole system with all units in the HPS,

-Optimizing the HPS and avoid overflows, in order to obtain positive financial effects from the operation the entire hydro system

-Possibility for regulating the water flows of runoffs, as well as regulation of the reservoirs.

The main driven conditions for operation modes of the HPS depend on the complexity of the hydropower system from technical point of view (number of power units and reservoirs with their connectivity), as well as available hydrological data and operator or utility requirements.

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