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The Semi-Peak-Load Operation of a Canal Regulating Water Power Plant

This paper deals with a description and presents the results of the calculations of possibilities of the semi-peak operation of a canal regulating water power plant. These plants are of a great significance for the electric system. The largest Slovakian canal regulating water power plant is the Gabčíkovo power plant. The semi-peak operation would represent a compromise between the originally designed peak operation and the basically forced continuous-flow operation; where by the existing state of the waterworks on the Danube River would have to be accepted.

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I. INTRODUCTION

Regulating power plants (PP) are of a great significance for the electric system. They can react to changes in the output in a very short period of time and they can adapt their regime to the immediate needs of the mentioned system. Thus they ensure "static" services (e.g. planned power service), as well as "dynamic" services (e.g. taking up steep peak-loads, power reserve and similarly).

The immediate discharge in the river is usually smaller than the total absorption capacity of the PP turbine. The full output can be achieved only when water is taken from the live storage volume of the reservoir above the PP. In this case the discharge regime is regulated. That is why this type of PP is classified as a regulating PP.

If the regulating PP is not located directly at the reservoir, but the water has to be supplied through the diversion channel, the PP is called a regulating PP of the canal type.

The canal regulating PPs can be built as single PPs (one power plant located on one diversion channel), or several may constitute a group (two and more power plants located on one diversion channel).

An example for both mentioned basic types can be found in Slovakia, too. Currently, the Madunice PP and our largest PP in Gabčíkovo are single regulating PPs of the channel type. As for the regulating PPs constituting a group, the following PPs may serve as an example: Hričov - Mikšová 1 - Považská Bystrica. Besides this group there are also three other similar PP groups at the time being on the Váh Cascade [16].

The largest Slovakian canal PP is the Gabčíkovo PP. The installed power plant capacity amounting to 720 MW was determined with respect to the originally designed regulating - peak-load operation. The installed total absorption capacity of the turbines (4,000 m^3s^{-1}, event. 5,000 m^3s^{-1} when the total absorption capacity is overrun) [9] [10] complies with this type of operation. With regard to the fact that the Gabčíkovo PP is the absolutely largest PP in Slovakia, it deserves special attention.

The fact that the Gabčíkovo - Nagymaros waterwork system was not completed in compliance with the originally contracted project (especially the unbuilt surge pond, which should have been created by the Nagymaros stage) does not allow the originally planned peak-load operation of the Gabčíkovo PP. This PP is contemporarily a continuous-flow one. At this type of operation all aggregates can be in operation at once only in exceptional cases. This concerns practically only flood flows exceeding 4,000 m^3s^{-1}. The efficiency of the machinery is thus much lower than the efficiency planned in the project.

The semi-peak operation would represent a compromise between the originally designed peak operation and the basically forced continuous-flow operation, where by the existing state of the waterworks on the Danube River would have to be accepted. Right in the beginning we would like to recall the fact, that the entire Gabčíkovo waterwork, of which the hydro-electric power plant is part, is a multipurpose waterwork. First of all it must protect the adjacent land against floods, ensure the prescribed water offtake and international navigation. In compliance with the Temporary Manipulation Rules [9] [10] the water power utilization can follow only after the afore-mentioned functions are satisfied.

The semi-peak operation applied to the specific conditions of the Gabčíkovo waterwork will be limited to a great extent, even though all the top-priority functions are accepted. We would like to give some possible solutions of the semi-peak operation in this paper, provided that all the other functions of the waterwork are accepted.

The hydraulic conditions in the canal leading to the power plant and in the power plant outlet constitute a significant problem for the semi-peak operation of the Gabčíkovo PP. We have utilized hydrodynamic models developed at our Department [4] [5] [7] for the hydraulic solution of the canal (from Čunovo to the Gabčíkovo PP), data on the power plant outlet were taken from the Temporary Manipulation Rules [9] [10].

We have applied the regulation losses method to the design of the semi-peak operation, as it can be used to optimize the PP operation on the basis of the minimization of losses in the power plant output or power generation.

II. THEORETICAL ANALYSIS OF THE ISSUE

Compared to the continuous-flow operation of the PP, the semi-peak operation is characterized by larger hydraulic losses, especially in the power plant canal and outlet. That is why the total generated power is smaller, even though the water volume remains the same. However, power generation in time zones, in which it is generally more valuated, is higher. And this is the main benefit of a semi-peak operation.

The economic efficiency of the operation of a regulating PP can be resolved by several methods [21]. We have chosen the regulation losses method for further calculations [6] [19] [20] [21] [24].

The regulation losses method is based on the comparison of power generation at the continuous-flow operation of the PP and at the regulating operation (in our case semi-peak operation).

When compared with the continuous-flow operation, losses in the power generation at the regulating operation are called regulation losses.

In the case of a single PP the regulation losses method is used to calculate the appropriate operation of the PP, in the case of several PP (e.g. a group of PP) the method is used to calculate the most convenient type of cooperation between several PP.

The method can be applied to both types of PP, provided that the required output and regulation possibilities of the PP result in the minimum regulation losses. Hence, the minimization of regulation losses is the criterion for the determination of the appropriate type of operation.

The equations for the regulation losses calculation valid generally for a single PP are given below, provided that the following assumptions are satisfied:

- one single PP,
- a two-stage inflow-offtake diagram (it covers the semi-peak operation),
- closed regulation cycle,
- first-order emptying and filling course of the upper reservoir,
- first-order discharge rating curve (given by the discharge coefficient),
- constant total efficiency of the electric energy conversion,
- omission of the losses at the PP inlet and outlet (eventually their inclusion in the total efficiency),
- omission of short-time changes of the water level at the beginning and end of the PP regulating operation (event. when the PP discharge alters).

Regulation losses are as follows:

$$\Delta E = E_P - E_R$$

where:

ΔE	are regulation losses [kWh],
E_P	power generation during the continuous-flow operation [kWh],
E_R	power generation during the regulating operation [kWh].

In order to satisfy the condition of a closed regulation cycle, the basic balance equation must be written in the following form:

$$Q_P * t = Q_{R1} * t_1 + Q_{R2} * t_2$$

where:

Q_P	average natural water inflow [m^3s^{-1}],
t	duration of the regulation cycle [h],
Q_{R1}, Q_{R2}	regulated offtakes through the PP [m^3s^{-1}],
t_1, t_2	duration of operation (halfcycles) [h].

The meaning of the single quantities is evidently shown in the inflow-offtake diagram in Fig. 1.

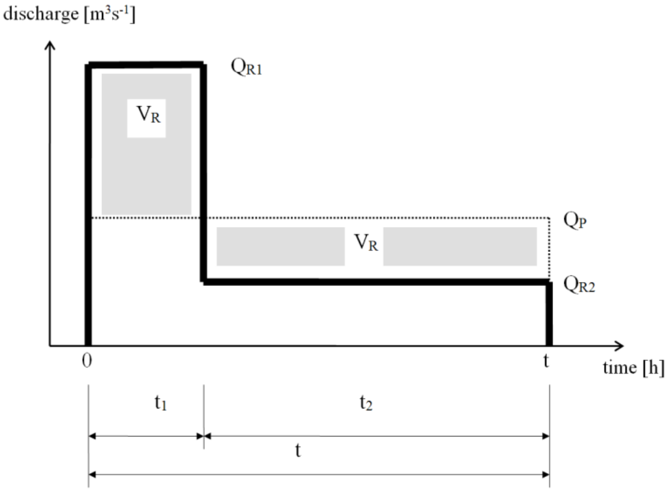

Figure 1.

The power generated in the PP during the continuous-flow operation, which is in compliance with the inflow-offtake diagram given in Fig. 1, is expressed in the following way:

$$E_P = P_P * t = 9{,}81 * Q_P * H_P * \eta * t$$

where:

E_P	total power generation during the continuous-flow operation [kWh],
P_P	continuous-flow operation output [kW],
Q_P	average natural water inflow [m^3s^{-1}],
H_P	average head at the continuous-flow operation [m],
η	total efficiency of the conversion,
t	duration of the regulation cycle [h].

The power generated in the PP during the regulating operation, which is in compliance with the inflow-offtake diagram given in figure 1, is expressed in the following way:

$$E_R = E_{R1} + E_{R2} = 9{,}81 * \eta * \left(Q_{R1} * H_{R1} * t_1 + Q_{R2} * H_{R2} * t_2 \right)$$

where:

E_R	total power generation during the regulating operation [kWh],
E_{R1},E_{R2}	power generation during the regulating

	operation in half-cycles $t_1$or t_2 [kWh],
η	total efficiency of the conversion,
Q_{R1}, Q_{R2}	regulated offtakes through the PP [m^3s^{-1}],
H_{R1}, H_{R2}	average heads at the regulating operation [m],
t_1, t_2	operation duration (half-cycles) [h].

The live storage volume of the reservoir, utilized for the regulation in compliance with the inflow-offtake diagram shown in figure 1, is expressed as follows:

$$V_R = (Q_{R1} - Q_P) * t_1 * 3600 = (Q_P - Q_{R2}) * t_2 * 3600 = Q_O * t * 3600$$

where :

t_1, t_2	duration of operation (half-cycles) [h],
Q_P	average natural inflow during the regulation cycle [m^3s^{-1}],
Q_O	average offtake securing the utilized live storage volume V_R [m^3s^{-1}],
Q_{R1}, Q_{R2}	regulated offtakes through the PP [m^3s^{-1}],
V_R	live storage volume utilized for the regulation [m^3],
t	duration of the regulation cycle [h].

By applying these equations to the first-order discharge rating curve, given by the coefficient of discharge:

$$\alpha = \alpha_1 = \alpha_2 = \frac{\Delta h_{D1}}{Q_{R1} - Q_P}$$

where:

α, α_1, α_2	coefficient of discharge of the PP (average slope of the discharge rating curve within the lower level fluctuation),
Δh_{D1}, Δh_{D2}	swing of the lower level at discharges Q_{R1}, Q_{R2} when compared with discharge Q_P [m],

we obtain the regulation losses equation appropriate for further calculations:

$$\Delta E = 9{,}81 * \eta * \left[Q_P * \frac{\Delta h_H}{2} * t + \alpha * \left(\frac{V_R}{3600} \right)^2 * t * \frac{1}{t_1 * t_2} \right]$$

The solution is demonstrated in Fig. 2.

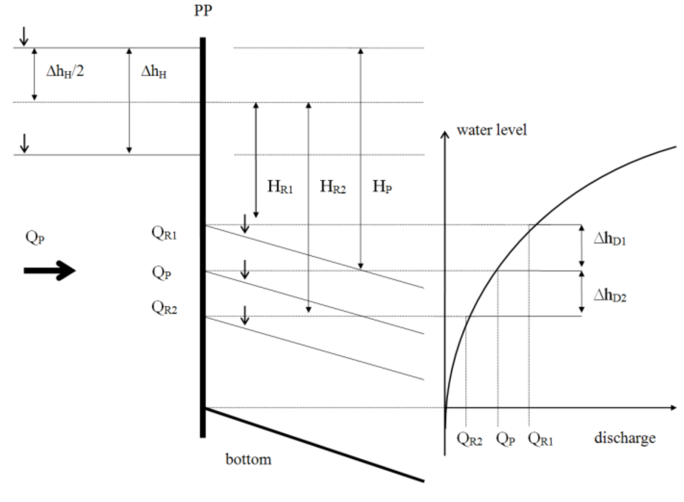

Figure 2.

In the case of the regulating operation of the PP in compliance with the two-stage inflow-offtake diagram the duration of half-cycles t_1 and t_2 can be essentially diverse, provided that $t_1+t_2 = t$. This is in accordance with the diverse losses induced by the canal and PP outlet. We can prove that the minimum losses in the canal and the PP outlet will reach $t_1 = t_2 = t/2$ in the case of the regulating operation. The optimum course of the inflow-offtake diagram corresponds to this fact.

III. APPLICATION TO THE GABČÍKOVO PP

Possibilities of a semi-peak operation of the Gabčíkovo PP are given by the energetic parameters of the PP, hydraulic parameters of the water inlet and outlet, hydrological conditions and the level on which all the other function of the waterwork are safeguarded. We have used the following information for the comparison of various types of semi-peak operation:

- total absorption capacity of the turbines (including the overrunning) $Q_T = 5{,}000$ m^3s^{-1},
- accumulated volumes curve for the Hrušov reservoir, canal and PP inlet in compliance with the Temporary Manipulation Rules [9] [10],
- hydraulic characteristic of the PP outlet (coefficient of discharge) based on the averaged discharge rating curve given in the Temporary Manipulation Rules [9] [10] as $\alpha = 0.0012$ [20],
- total efficiency of the energy conversion on generator terminals which amounts to $\eta = 88.81\%$ based on the information of the Hydro-Electric Power Plants Trenčín control centre (operator of the energetic part of the power plants),
- hydrological data on the average monthly discharges based on the information of SHMÚ as the average monthly discharges over the period of 1901 to 1950,
- actual oscillation of the water level above the Gabčíkovo PP, i.e. including the hydraulic losses between Čunovo and the Gabčíkovo PP.

The semi-peak operation is limited by a whole range of other conditions. We have taken the following ones into consideration:

- maximum decline (oscillation) of the water level in the upper reservoir is0.6 m when gates(?) are dammed at Čunovo - i.e. between two water levels - 131.10 m Bpv (maximum operational level) and 130.50 m Bpv. This corresponds to the accumulated live storage volume V_R = 20.83 mil m^3 (Hrušov reservoir, canal and PP inlet),
- offtakes which cannot be utilized in the Gabčíkovo PP - i.e. idle discharges as the average value $Q_{NEV} = 510$ m^3s^{-1},
- when securing navigation it is necessary to retain a sufficient discharge in the ford section at Palkovičovo, in order to provide a sufficient depth of fairwater. The discharge in this section is given as the sum of the discharges through the Gabčíkovo PP, discharges in the old river bed, which shall be retained after deducting the offtake to the river arms in Hungary, the discharges in our river arms, losses caused by navigation and partially by infiltration. The water balance issue is very complex, its changes are on a seasonal basis and it is in close relation to the groundwater regime. We have considered two ways of securing the depth of fairwater in the ford section for the power generation calculations presented in this paper:
  1. by taking measures in the organization of navigation - i.e.as soon as the discharges in the Danube River below the

watersmeet of the Gabčíkovo PP outlet canal and the old river bed (especially in the case of regulated offtake Q_{R2}) result in a small depth of fairwater in the ford section, navigation through the ford section will be cancelled. When applying this type the energy operation of the Gabčíkovo PP can be fully optimized.

2. by securing a minimum outlet from the Gabčíkovo PP (as long as the hydrologic conditions allow to do so) amounting to 800 m^3s^{-1} (i.e. Q_{R2} = min. 800 $m^3s^{-1} = Q_{OKMIN}$). When applying this type of operation the energy operation of the Gabčíkovo PP cannot be fully optimized.

The following page contains the calculation results for 5 alternatives of the Gabčíkovo PP operation (1 continuous-flow operation = reference alternative and 4 semi-peak alternatives, 2 of them are optimum ones). In the case of the semi-peak alternatives, the live storage volume V_R = 20.83 mil m^3 was fully utilized as long as the hydrologic conditions or other limitations allowed to do so. If it was not possible to do so, we took this fact into consideration when determining the corresponding oscillation of the water levels at Čunovo and above the Gabčíkovo PP. The regulation cycle was a daily cycle (t = 24 h). The calculations were based on monthly time steps.

1. alternative - continuous-flow operation

The 1st alternative represents the continuous-flow operation of the Gabčíkovo PP. We calculated the continuous-flow operation in order to be able to determine the differences in the loss in power generation for various alternatives of semi-peak operation expressed in per cent. The power generation was determined assuming that the water level at Čunovo reaches 131.10 m Bpv - i.e. assuming the maximum operational water level.

2. alternative - semi-peak operation

The 2nd alternative represents the optimum semi-peak operation with $t_1 = t_2$ at a daily regulation cycle. When compared with the continuous-flow operation the optimization was done with respect to minimum losses in the power generation at a semi-peak operation. This type of operation essentially represents also the ideal water economy operation.

With respect to navigation measures in the organization of navigation have to be taken.

3. alternative - semi-peak operation

The 3rd alternative represents the optimum semi-peak operation with $t_1 = t_2$ at a daily regulation cycle. When compared with the continuous-flow operation the optimization was done with respect to minimum losses in the power generation at a semi-peak operation. This type of operation essentially represents also the ideal water economy operation.

With respect to navigation a minimum discharge through the Gabčíkovo PP amounting to Q_{R2} = min. 800 $m^3s^{-1} = Q_{OKMIN}$ has been taken into account.

4. alternative - semi-peak operation

The 4th alternative represents the semi-peak operation with t_1 = 6 h and t_2 = 18 h at a daily regulation cycle. This type of operation represents an operation controlled by the dispatcher. It complies with the needs of the electric system, which are often at variance with the ideal water economy operation. With respect to the fact that times t_1 and t_2 are controlled by the dispatcher, the regulated offtakes Q_{R1} and Q_{R2} depend on the discharge in the Danube River (and thus the PP outputs).

With regard to navigation measures in the organization of navigation are being taken into consideration.

5. alternative - semi-peak operation

The 5th alternative represents the semi-peak operation with Q_{R1} = 3,000 m^3s^{-1} at a daily regulation cycle. This type of operation represents an operation controlled by the dispatcher. It corresponds to the needs of the electric system, which are often at variance with the ideal water economy operation. The fact that the offtake Q_{R1} is controlled by the dispatcher means that the output of the PP is safeguarded to a certain extent during the mentioned offtake. However, the offtake duration depends on the discharge in the Danube River.

Regarding the navigation measures in the organization of navigation are being taken into consideration.

IV. CONCLUSION

The calculation results for the alternatives of semi-peak operation of the Gabčíkovo PP are compared with the continuous-flow operation in the following table:

TABLE I

Alt.	regulation losses	regulation losses	PP maximum output	PP minimum output
	[MWh]	[% from E_P]	[MW]	[MW]
2	68,804.07	3.24	442.05	76.52
3	55,241.68	2.60	442.05	132.43
4	88,766.72	4.18	465.18	102.45
5	109,379.81	5.15	439.10	109.38

When comparing the calculation results we may state, that the regulation losses in the 2nd and 3rd alternatives, which applied the optimum regulation, are lower than in the 4th and 5th alternatives.

However, on the other hand the output amounting to appr. 450 MW (given by the quite large regulated offtake Q_{R1}) is in the 4th and 5th alternatives more secured (in the 5th alternative even all year round, even though in the low-water months only about 3 hours daily) than in the 2nd and 3rd alternatives with optimum regulation.

As has been already mentioned the waterwork is a multipurpose one. Besides the alteration of the energy regime the semi-peak operation of the PP would also directly affect the operation of the waterwork as a whole.

We will give the example of the organization of water offtakes, which have to be ensured by the waterwork. The water offtakes would have to react to the daily fluctuation of the water level at the waterwork (and thus at the offtake facilities). For the water offtakes within the daily regulation cycle must be usually constant.

Navigation is another example. In the case of semi-peak operation of the PP, especially during the low-water months, the regulated offtakes Q_{R2} are relatively small at an optimum regulation. This could not secure safe navigation through the ford in Palkovičovo during the t_2 half-cycle. However, on the other hand regulated offtakes Q_{R1} are higher than the natural water discharge in the Danube River. They would enable safer navigation through the ford in the t_1 half-cycle, and even vessels with heavier loads and a deep draught could pass through the ford in low-water months during the regulated offtake Q_{R1}. This would concern not only the semi-peak operation of the PP, but also increase the navigation discharge in certain daily hours (t_1). This type of operation would, however, require a change in the organization of navigation.

The semi-peak operation of the PP results in the increase of the output and power generation in the peak zones of the electric system daily load diagram. Energy in these zones is generally more valuated than in all the other zones. For instance the maximization of profit may be applied as an optimization criterion besides the applied minimization of losses in power generation. Hence the task becomes a multi-criterion one. Such calculations give a better view of the entire semi-peak regulation of the PP and the semi-peak operation of the waterwork as a whole, whereby all its functions remain maintained and their priorities accepted.

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