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MODELING THE WATER HAMMER IN THE PENSTOCK OF A SMALL WATER POWER PLANT

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Keywords**:** *water power plant, penstock, water hammer*

ABSTRACT

During the commissioning of a small water power plant (SWPP) in Bulgaria, the long GRP penstock was twice broken due to hydraulic transients. The author was assigned with the modelling of the developing water hammer for preventing further damage to the facility. In fulfillment of this task, a special parameter study of the hydraulic transients in the penstock with the particular boundary conditions was performed. As a result, the necessary closure and opening time functions of the operating discharge were defined.

In this presentation, the development of the solution process with the obtained results for this particular task are presented and discussed.

1. Introduction

This investigation treats some problems which arose with the penstock of a small waterpower plant (SWPP) in Bulgaria during the commissioning of regular operation. The GRP penstock was twice broken still during the initial synchronization of the generator of the single unit. Thus, rigorous modeling of the hydraulic transients in the penstock became necessary for formulation of the appropriate opening and closure times of the guide vanes of the installed Francis turbine for all decisive operating modes of the unit and for different initial discharge values. Moreover, these investigations had to be carried out with and without considering of the installed special synchronous outlet valve at the lower end of the penstock. This valve has been installed for controlling of the head amplitudes over the penstock length

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during hydraulic transients following the advice of the turbine manufacturer. However, the present work does not deal with the runaway speed of the generator in the case of load rejection.

2. Problem formulation and modelling approach

The scheme of the considered waterpower system is very simple and represents a concept typical for the small waterpower developments in the last two decades in Bulgaria – a long penstock starts at the water intake and follows the river down to the powerhouse, Figure 1. The main parameters of the waterpower system are as follows:

- Total length of the GRP penstock 6500 m;
- The hydrostatic head is 64 m, the net head for the maximum discharge of 4 m^3/s is 57 m according to the calculated hydraulic losses in the penstock design. Further, in the frame of the performed transient computations, the actual head losses were re-calculated for each particular discharge value.
- The acoustic wave celerity during water hammer in this penstock was assumed 350 m/s based on the supplied strength characteristics and the average diameter (1.5 m) of the GRP penstock. Thus, the reflection time of the water hammer became 37,15 s. This value is too large and requires a very careful and precise formulation of the times for change of the water discharge so that no direct water hammer occurs.
- The computations were performed for all mentioned in the design and operation documentation discharge values (further denoted as Q) and for times of changing these values reaching in the calculations 300 s (without this value being somehow limiting). The minimum such time for discharge change was considered 60 s – i.e. the calculated reflection time with some safety margin. Particular calculations were performed with a time value for change of Q 40 s as well, but these results served only comparative purposes.

For the purpose of the performed analysis, a computational model of the penstock was built based on the Method of Characteristics (MOC) for numerical solution of the governing water hammer equations. The computations were performed by means of the computer program HIUD published in [1] and further specially modified by the author. The following boundary conditions were introduced here:

- At the upper end, (i.e. at the beginning of the penstock): „reservoir with constant water level”;
- At the lower end (i.e. at the end of the penstock at the powerhouse): „turbine of type Francis”.

Of course, in all computational cases regarding the operation of the synchronous outlet valve installed at the lower end of the penstock, Figure 2, the discharge rate of this valve was appropriately modeled additionally to the one of the Francis turbine as well.

All other assumptions and particular details regarding the investigated computational cases are discussed further below in connection with the presented results from the carried out calculations.

Figure 1. Typical reach of the buried penstock

Figure 2a. The branch and powerhouse of the synchronous valve

Figure 2b. The synchronous outlet valve itself

3. Computational cases

3.1. Load rejection for different initial discharge values up to full closure, without synchronous outlet, maximum and minimum head values

In the following Figure 3, the results for maximum head increase in this case are graphically summarized. This representation follows the style introduced in [2] for similar investigation. The closure time values *Ts* [s] of the regulating valve before the turbine vary between 60 s and 300 s. On the horizontal axis, the initial value of the operating discharge is shown.

All these results as well as the ones on the following figures are related to the lower end of the penstock at the powerhouse where the caused by water hammer head changes reach their extreme values.

In the following Figure 4, the results for the obtained minimum head values for this computational case are graphically presented.

3.2. Load increase from standstill up to a certain target discharge value without synchronous outlet, maximum and minimum head values

All other assumptions hold as mentioned above. In this case, the obtained maximum head values did not exceed the hydrostatic head of 64 m anywhere.

The obtained minimum head values in this case are graphically presented in the following Figure 5.

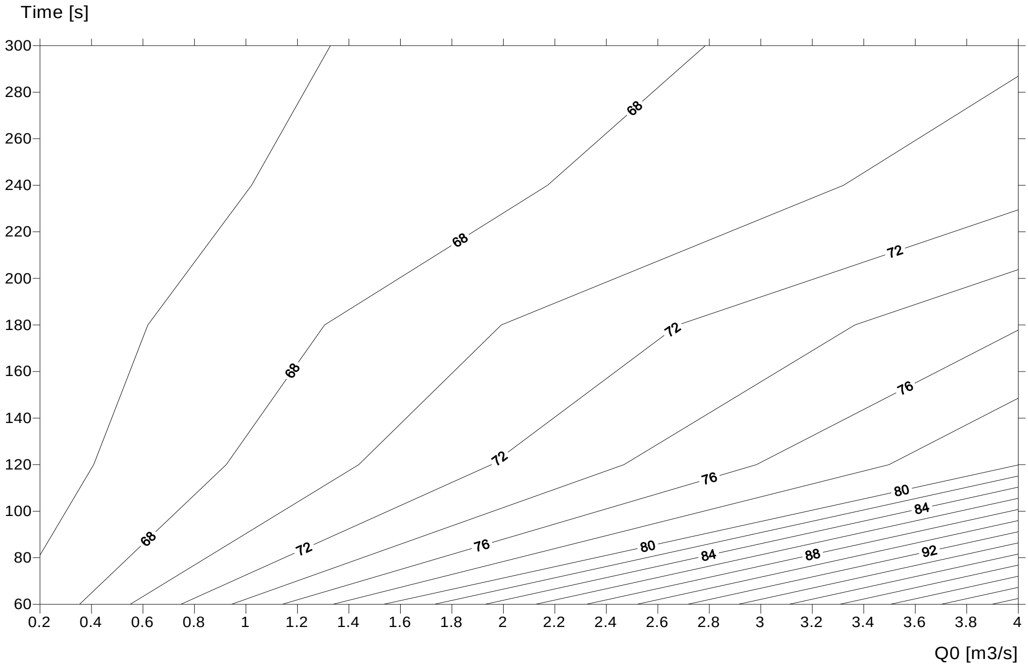

Figure 3. Load rejection, different initial discharge, no synchronous outlet, maximum head values

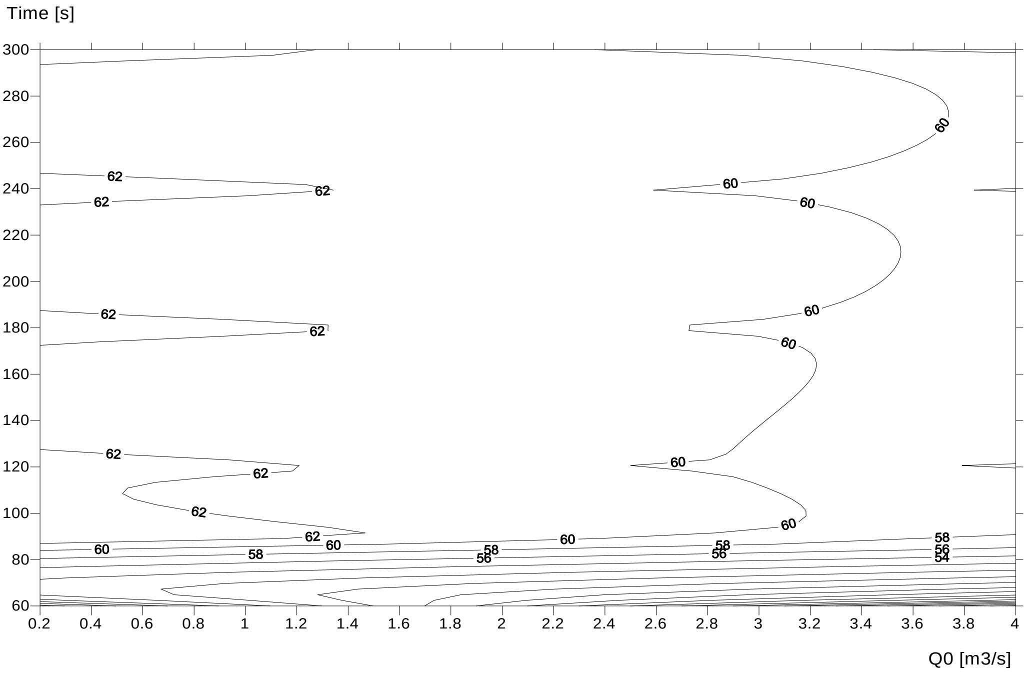

Figure 4. Load rejection, different initial discharge, no synchronous outlet, minimum head values

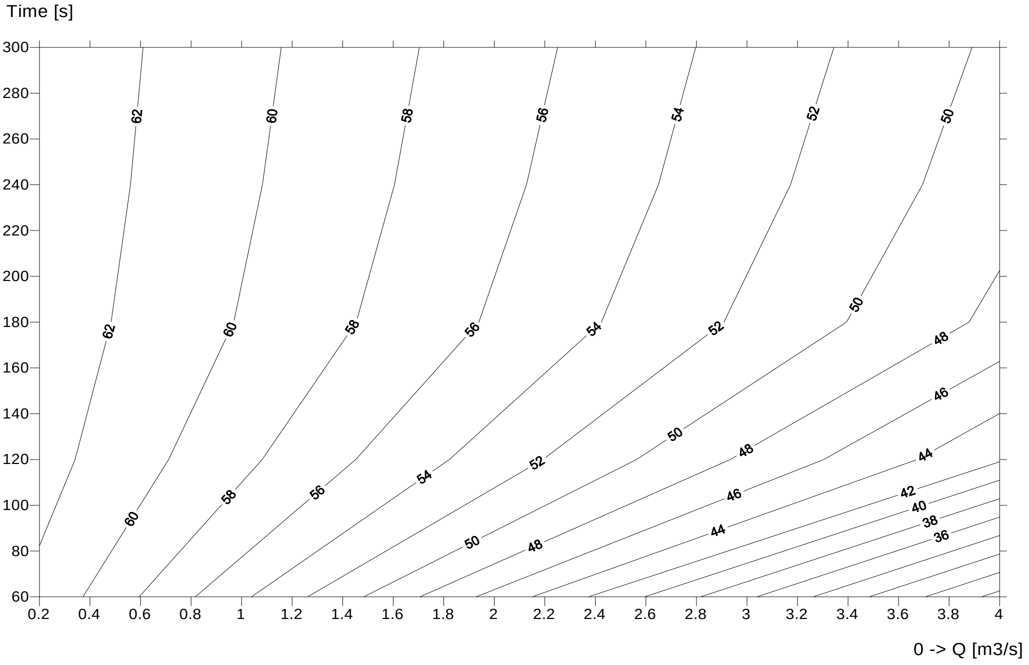

Figure 5. Load increase from standstill, different target discharge, no synchronous outlet, minimum head values

3.3. Load rejection for different initial discharge value, with synchronous outlet designed for *Qsi* = 1,0 m^3/s: maximum and minimum head values

Here, *Ts* [s] is the closure time of the valve before the turbine. For the same time, the synchronous outlet valve opens up to the specified discharge value. *Tsi* is the time for subsequent closure of the synchronous outlet valve. Here, this time was initially assumed to be *Tsi* = 300 s without limiting character of this value.

In the following Figure 6, the results for the obtained maximum head values for this computational case are graphically presented.

3.4. Load rejection for different initial discharge value, with synchronous outlet designed for *Qsi* = 2,0 m^3/s: maximum and minimum head values

In the following Figure 7, the results for the obtained maximum head values for this computational case are graphically presented. All other assumptions hold as specified above.

3.5. Load rejection for different initial discharge value, with synchronous outlet designed for *Qsi* = 3,0 m^3/s: maximum and minimum head values

3.6. Load rejection for different initial discharge value, with synchronous outlet designed for *Qsi* = 4,0 m^3/s: maximum and minimum head values

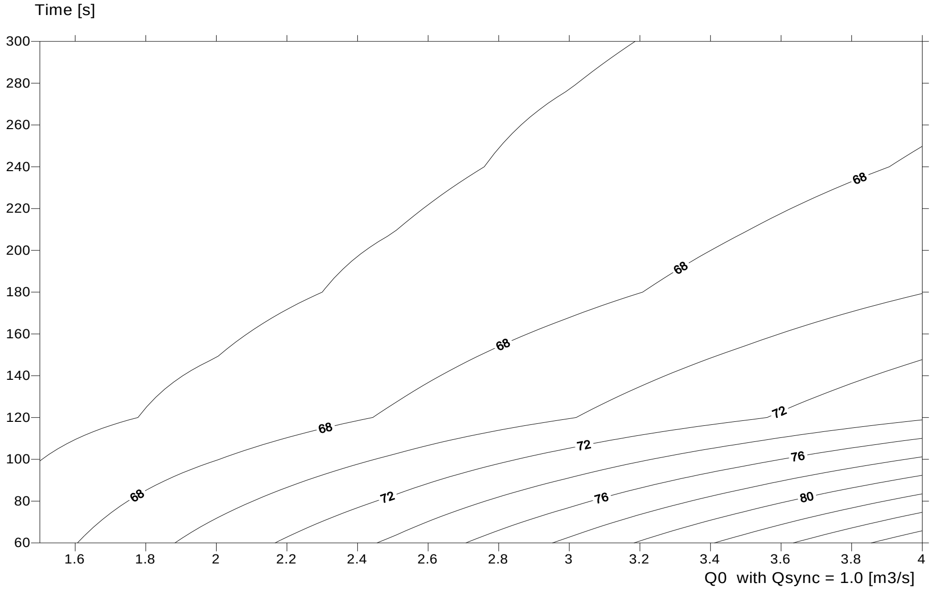

Figure 6. Load rejection for different initial discharge value, with synchronous outlet designed for *Qsi* = 1,0 m^3/s, maximum head values

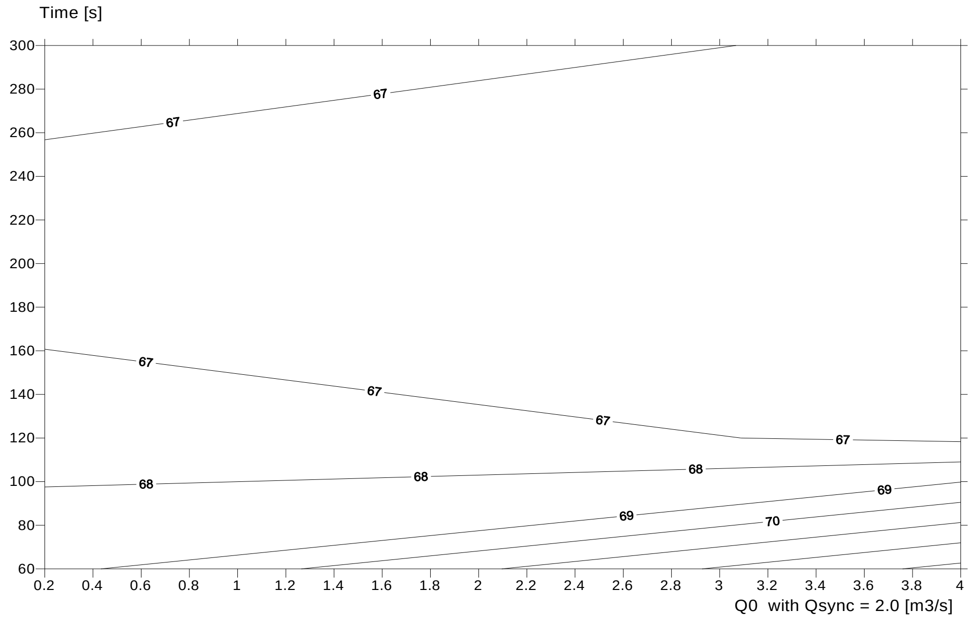

Figure 7. Load rejection for different initial discharge value, with synchronous outlet designed for *Qsi* = 2,0 m^3/s, maximum head values

The results about the maximum head obtained for the computational cases 3.5 and 3.6 did not exceed the corresponding maximum values calculated for the cases 3.3 and 3.4. Hence, their graphical representation here was not necessary.

For computational cases 3.3 to 3.6, the obtained results with respect to the calculated minimum head values, no graphical presentation is given here since these minimum head values either are not below the extreme ones calculated in cases 3.1 and 3.2 or do not fall below the net head of 57 m at all.

4. Analysis of the results, conclusions and recommendations

Based on the carried out calculations of the hydraulic transients for decisive operational cases of the considered here penstock of the power plant, the following main conclusions may be drawn:

- The actual parameters of the penstock (trace, longitudinal section, parameters of the built-in GR pipes etc.) require extremely careful operation of the facility with respect to the operational discharge changes, since the arising hydraulic transients in the penstock due to these parameter sets represent non-typical characteristics differing substantially from the usual penstock structures. Hence, these transients can be very dangerous. The twice broken penstock during commissioning of its operation is unfortunately a sound proof of this statement.
- It could be recognized that the cited equation regarding the water hammer related reserve in the supplied GR pipes specifications was according to the guidelines [3]. The application of this formula to the lower end of the penstock necessarily leads to the necessity of pressure class of the pipes 10 bar. According to the same supplied specifications, however, the installed pipes over the length of the

penstock are of pressure classes 3,5 bar, 6 bar and 7 bar in flow direction, respectively (with respect to the vacuum, the admissible value for all of them is 0,2 bar, i.e. 2 m water column). This means that in fact, there is no available reserve in respect of the pressure (since the hydrostatic head is 64 m). This identification leads to heavy restrictions regarding the times of discharge changes during the penstock operation. Furthermore, the latter identification becomes in contradiction with the prevention of too intensive generator runaway speed (this problem is beyond of the scope of this research but must be implicitly mentioned here).

- The recommended relation for closing of the regulating valve before the turbine in the case of generator load rejection without synchronous outlet valve can be formulated as follows, Table 1. These are the minimum time values. They may be exceeded, but not reduced.

Table 1

Ts [s]	0	75	150	240	290	360	410
Q [m^3/s]	4,0	3,0	2,0	1,0	0,6	0,2	0,0

- The recommended relation for opening of the regulating valve before the turbine (from standstill, i.e. totally closed position) in the case of generator load increase without synchronous outlet valve can be formulated as follows, Table 2. These also are the minimum time values which may be exceeded, but not reduced.

Table 2

Ts [s]	0	60	100	135	225	330	480
Q [m^3/s]	0,0	0,2	0,6	1,0	2,0	3,0	4,0

- The recommended relationship follows for closure of the regulating valve before the turbine in common action with a synchronous outlet valve. Here, the assumption was made that the synchronous valve can work with only one maximum discharge which is reached for the time *Ts* needed by the valve before the turbine to close completely. If this discharge is 1,0 m^3/s, the turbine valve closure (with the simultaneously full opening of the synchronous valve, respectively) will be able to occur for 180 s for all initial discharge values. If this maximum discharge value of the synchronous valve is 2,0 m^3/s, the turbine valve closure will be able to occur for 100 s for all initial discharge values. If this maximum discharge value of the synchronous valve is 3,0 m^3/s, the turbine valve closure will be able to occur for not less than 240 s for all initial discharge values with respect to the minimum head values at the end of the penstock caused by the full opening of the synchronous valve at small operational discharge values. If this maximum discharge value of the synchronous valve is 4,0 m^3/s, the turbine valve closure will be able to occur for not less than 420 s for all initial discharge values due to the same just mentioned reasons. The subsequent closure of the synchronous valve is assumed to occur for 300 s in each of the considered cases, and this is the minimum value of this time.

The laws for discharge change with respect to the maximum head values were formulated according to the pressure class of the installed GR pipes according to the supplied documentation. The corresponding laws with respect to the minimum head values considered the very low slope of the penstock for not crossing it by the pressure line during the development of hydraulic transients. It was assumed that this pressure line does not cross the line defined by the head losses in stationary mode of water flow.

The inability of the turbine supplier to comply with the specified regulation times and the inability of the synchronous valve manufacturer to regulate its operating discharge forced the client to re-construct the lower part of the whole SWPP system.

LITERATURE

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МОДЕЛИРАНЕ НА ХИДРАВЛИЧЕН УДАР В НАПОРНИЯ ТРЪБОПРОВОД НА МАЛКА ВЕЦ

Д. Кисляков[1]

Ключови думи*: *ВЕЦ, напорен тръбопровод, хидравличен удар

РЕЗЮМЕ

При въвеждане в експлоатация на една малка ВЕЦ (МВЕЦ) в България, дългият напорен тръбопровод от стъклопластови (GRP) тръби два пъти се спуква от хидравличен удар. На автора бе възложено моделирането на развиващите се нестационарни процеси на течение в тръбопровода за предотвратяване на следващи аварии. В изпълнение на тази задача бе проведено специално параметрично изследване на нестационарните процеси в тръбопровода при конкретните гранични условия. В резултат на това изследване бяха формулирани необходимите зависимости от времето за изменение на водното количество при отваряне и затваряне.

В настоящия доклад се представят и обсъждат процесът на решение на конкретната задача и получените резултати.

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