

SINNI AQUEDUCT: TRANSIENT ANALYSIS FOR HYDROPOWER ENERGY EXPLOITATION IN WATER SUPPLY SISTEM - CASE STUDY

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Abstract: The paper describes the transient analysis performed within the reviews of the project which refers to the integration of three turbines in a 65 km long, complex geometry, water supply system. The analysis has been performed in order to investigate the compatibility of the installed regulation valves with the new role, assigned to by-pass safety valves by the project. The simulation has been made under different configurations in order to find the most suitable time of wicket gates closure coupled with the opening time of the by-pass valves. Finally the numerical model is used to investigate of the maximum opening time of the by-pass valve compatible with the safe operation of the system.

1 Introduction

Accumulations and water distribution systems are specially interesting due to the possibility of exploiting the available hydropower potential, mainly because of the large volumes of water present in the pipelines. Since the water movement is forced by the gravity forces, implementation of turbines and generators would enable energy production. This operation does not affect water supplying nor water quality [Milićević et al.,2010²]. The exploitation of hydropower potential in the water distribution system is nowadays relatively simple. It consists mainly in replacing the classical energy dissipation devices (such as free drops or dissipation valve) with hydropower turbines.

The installation of an hydropower plant on a water supply network has found a wide usage area in Europe. These facilities have numerous advantages compared to river-type hydropower plants [Kucukali, 2011³]. However, some critical aspects should be considered, such as the compatibility study about the existing scheme and equipment with the insertion of the new turbines or the accurate transient analysis for the system. Indeed, in case of a grid failure and consequently of a load rejection or emergency shutdown, the turbine shut-off has to occur in relatively short time in order to avoid the turbine to stay at runaway speed for too long time. This can generate water hammer in penstock which can lead to dangerous equipment damage and, in the worst cases, to the interruption of the primary functionality of the water system.

Completed in the 70's the Aqueducts of Sinni is one of the most important European waterways. The main line, 65 km concrete and steel penstock, collects from 6 to 16 m³/s of water and it is able to satisfy the drinkable and agricultural needs of Puglia and Lucania regions. The excess head in the system is currently dissipated by two

Johnson valves at the beginning of the penstock. The availability of head and discharge represents a challenge for hydropower exploitation of the system. The possibility to integrate some hydro units in the system is here under investigation.

2 System description

2.1 Current state

The water supply system is composed by a 65 km steel and concrete pipeline with an inner diameter of 3.000 mm.

The whole pipeline is subdivided in 5 branches by means of single and twin surge tanks where free surface condition is guaranteed. Furthermore additional twin surge tanks are placed at the very beginning and end of the pipeline for a total of ten surge tanks distributed along the pipeline (named T1M, T1V, T2M, T2V, T3M, T3V, T4, T4BM, T4BV, T5).

The hydraulic head in each branch is regulated by means of Johnson valves placed between the twin towers that operate as energy dissipation device.

Along the pipeline dozen of intermediate spills are present. In correspondence of that derivations specific minimum hydraulic head must be ensured to guarantee the efficiency of the derivation. Each derivation is equipped by one or more needle valve for the discharge control.

Each tower, exception made of towers T4BM and T4BV, which works as simple piezometers, are specifically designed with funnel-shaped inlet in order to ensure a minimum head in any branch of the system in any condition and to avoid the unwanted emptying of the pipeline during shut-off occurrence.

In the connection between the upstream reservoir (Monte Cotugno Dam) and the first tower T1M there are another piezometer (named TKN0) and two additional Johnson dissipation valves of diameter 1.100 and 1.400 mm (named V1 and V2) currently used to regulate the incoming discharge in the system.

The connection between the reservoir and the piezometer is made by a pressurized tunnel 6.000 mm diameter, the connection between the piezometer and Johnson valve is made by 3.600 mm steel pipe and, finally, the connection between the valve and the T1M by means of a 3.000 diameter steel pipe.

2.2 Project

The current design envisages to integrate some turbines in two different sites along the pipeline.

Site “one” is placed at the very beginning of the pipeline, just after the piezometer of the M. Cotugno reservoir. In the site, two Francis turbines (named T1 and T2) will be installed instead of Johnson valve V1 and V2 and the T1M tower will be by-passed in order to increase the available head for the turbines. The new role of turbine’s by-pass safety valves will be assigned to the valves V1 and V2.

Site “two” is placed in the middle of pipeline where the twin towers T3M and T3V are placed. A single Kaplan turbine (named T3) will be installed in the site, between the twin tower T3M - T3V, and the new role of turbine’s by-pass safety valve will be assigned to the valve V3.

3 Model setup

The analyses were performed in order to study the compatibility of the installed regulation valves with the new role.

One-dimensional simulations have been performed by using free computation software WHAMO under different configurations in order to find the most suitable time combination between turbines wicket gates closure and by-pass valves opening time. Finally the numerical model is used to investigate the maximum opening time of the by-pass valves allowable for the system.

During the simulations, the variation of the hydraulic head in the surge tank and in correspondence of the derivation and the variation of the conveyed discharge in the main pipeline were detected.

Simulation was performed under the main following assumptions:

- Water rejection phenomenon in the turbine was considered negligible;
- Intermediate valves which haven't by-pass functions are not simulated;
- Derivation has a constant flow rate independently by the hydraulic head at the spills;
- Pipe is considered made of homogeneous material;
- Linear valves opening and turbines wicket gate closure.

3.1 System geometry construction

The geometry of the system, from Monte Cotugno reservoir to surge tank T5, was reproduced by using the elements provided by the program such as valve, reservoir and surge tanks. The interconnection of the individual elements was defined by junction, conduit and dummy elements (not physically realistic elements, introduced as simply connector to increase the system flexibility).

Even if the pipeline is actually composed both by steel and concrete pipes, in the simulation it was considered an homogeneous pipe with the weighted average characteristics of the two materials.

Accordingly with the aim of the simulation, the turbines were simulated as simple valves. It permits to simplify the system and to have the possibility to control time closure (valve closure assimilated to the wicket gates closure of the turbine).

In the model there were not represented the Johnson dissipating valves present in the system which will not operate as by-pass valves.

The spills along the pipeline were taken into account by changing the flow conditions. That happens replacing the part of the system downstream the derivation with a constant discharge leaving the system.

The particular geometry of the surge tank inlet (funnel-shaped) was simulated assign to the elevation of the crest of the spillway, which is higher than the bottom of the surge tank, to the corresponding node of the penstock.

3.2 System boundary conditions

A fixed head value was imposed as boundary conditions at the beginning and at the end of the pipeline (M. Cotugno reservoir and T5). The derivation along the pipeline, which consists of additional boundary condition for the system, was considered by decreasing the discharge in the system of a fixed quantity accordingly with the derivation capacity and independently from hydraulic head in correspondence of the derivation itself. This simplifying assumption has been postulated considering the role of the derivation non crucial for the results of simulation.

3.3 Initial conditions

Prior to the transient simulation the program generates automatically the steady state condition according to the specified boundary and operating conditions at time 0. The steady state will be assumed as initial condition for the simulation in term of discharge and hydraulic head along the system.

3.4 Operating conditions

Operating conditions for valves (and turbines) in the system were given in term of discharge by charts representing time versus gate positions and gate position versus discharge coefficient C_q , where the discharge coefficient is related to the formula $Q = C_q \cdot D^2 \cdot (g \cdot \Delta H)^{1/2}$. In the simulations both wicket gate closure and valve opening were considered linear. This assumption was confirmed by the operating chart of both the turbines and of the valves provided by the manufacturer.

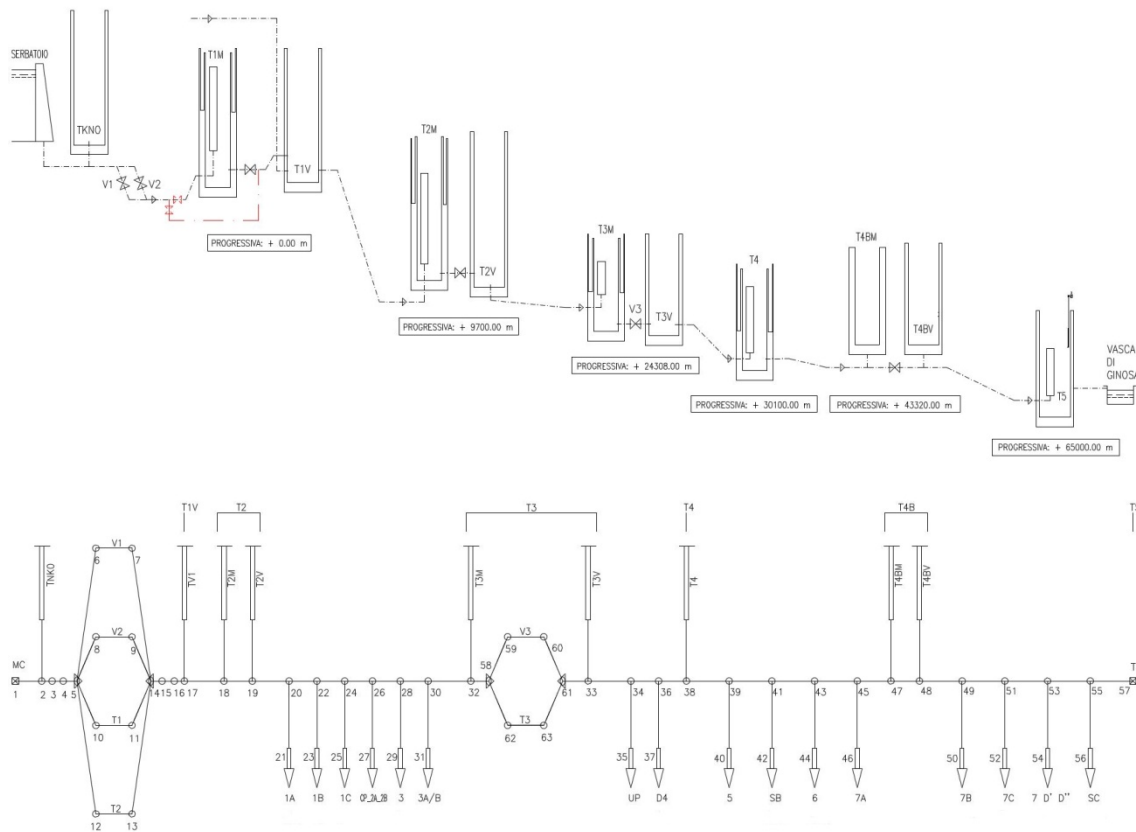


Fig. 1. Geometrical scheme and conceptual model of water system adopted for simulation.

3.5 Simulation

The performed simulations took into account the most severe conditions for the system, which consists in a conveyed discharge at the time of the simulated turbines shut-off equal to $16,6 \text{ m}^3/\text{s}$ entering in the system from M. Cotugno reservoir. It was simulated the simultaneously shut-off of the turbine in site one, while turbine in site two was assumed to work normally and the shut-off of turbine in site two, while turbines in site one was assumed to work normally.

A different combination of wicket gates closure time and valve opening was simulated.

Wicket gates closure time was set up in 22 and 120 seconds, according to the manufacturer suggestion.

For the valves V1 and V2 opening time was set up in 3.600 and 1.800 seconds which are the suitable opening time considering the current actuators (conical worm gear), providing that the possibility to modify the actuators, time opening could be lowered up to 900 s.

For the valve V3 only a simulation with time closure equal to 900 seconds was performed.

The performed simulation plan was able to describe a wide range of situation so that it gives sufficient information to define possible refinements in the analysis.

The total computation time for all the simulations was set up 10.000 seconds in order to keep also track of the stabilization of the system after the shut-off event. Computation delta time was set up equal to 1 second.

For each simulation it has been plotted the water surface elevation in every surge tank and the conveyed discharge in correspondence of the intermediate spills.

Simulation ID	Site	Wicket gates closure time (s)	Valves opening time (s)
T1_22_3600	one	22	3.600
T1_22_1800	one	22	1.800
T1_22_900	one	22	900
T1_120_3600	one	120	3.600
T1_120_1800	one	120	1.800
T1_120_900	one	120	900
T3_22_900	two	22	900
T3_120_900	two	120	900

Table 1: simulations plan.

4 Theory and calculation

The governing equations for the simulated elements used by the program are the following [Fitzgerald et al., 1998¹]:

For conduits

$$\text{momentum: } \frac{1}{g \cdot A} \cdot \frac{\partial Q}{\partial t} + \frac{\partial H}{\partial x} + \frac{f \cdot Q \cdot |Q|}{D \cdot 2 \cdot g \cdot A^2} = 0$$

$$\text{continuity: } \frac{\partial H}{\partial t} + \frac{c^2}{g \cdot A} \cdot \frac{\partial Q}{\partial x} = 0$$

For junction

$$\text{energy: } \frac{1}{g \cdot A} \cdot \frac{\partial Q}{\partial t} + \frac{\partial H}{\partial x} + \frac{f \cdot Q \cdot |Q|}{D \cdot 2 \cdot g \cdot A^2} = 0$$

$$\text{continuity: } \frac{\partial H}{\partial t} + \frac{c^2}{g \cdot A} \cdot \frac{\partial Q}{\partial x} = 0$$

For valves

$$\text{energy: } f(H_i - H_j, Q) = 0$$

$$\text{continuity: } Q_i = Q_j$$

For surge tanks

$$\text{continuity: } \frac{dH}{dt} - \frac{Q}{A} \cdot \left[\frac{1}{g} \frac{dv}{dt} + 1 \right] = 0$$

5 Results

The simultaneous shut-off of the two generating groups in site one cannot be supported by the system if the opening time of the valves is 3.600 seconds. In that case the simulation results indicate the completely emptying of the first tower with a consequently unacceptable air entrance in the penstock.

For the other simulated combination of turbine wicket closure and valve opening time, the results, for both site one and site two, are presented in the table and picture below.

Table 2 summarizes the effects, of the simultaneously turbines shut-off in site one in term of maximum oscillation (positive or negative) of the water surface in the surge tanks. The correspondent variation of conveyed discharge in the main pipeline in correspondence of the first and the last intermediate derivation is reported in Table 4. For what concerns the simulation of the turbine shut-off in site two, Table 3 shows the variation of free surface elevation (max. positive and negative) in the surge tanks immediately upstream and downstream to the turbine. Table 5 shows the variation, referred to the simulated events, of the conveyed discharge in the main pipeline in correspondence of the closest derivation of the site two and in correspondence of the first and last derivations in the system.

Valve opening: 1.800s Wicket gate closure: 22s				Valve opening: 1.800s Wicket gate closure: 120s			
<i>Tower</i>	<i>Distance from turbine</i>	ΔH (m)	<i>T</i> (s)	<i>Tower</i>	<i>Distance from turbine</i>	ΔH (m)	<i>T</i> (s)
TKN0	250 m	8,5	-	TKN0	250 m	2,1	-
T1V	200 m	-18,3	1.084	T1V	200 m	-17,5	1.110
T4BM	43.000 m	-2,8	1.980	T4BM	43.000 m	-2,7	1.007

Valve opening: 900s Wicket gate closure: 22s				Valve opening: 900s Wicket gate closure: 120s			
<i>Tower</i>	<i>Distance from turbine</i>	ΔH (m)	<i>T</i> (s)	<i>Tower</i>	<i>Distance from turbine</i>	ΔH (m)	<i>T</i> (s)
TKN0	250 m	8,5	-	TKN0	250 m	2,0	-
T1V	200 m	-11,0	586	T1V	200 m	-9,9	608
T4BM	43.000 m	-1,4	1.556	T4BM	43.000 m	-1,3	1.584

Table 2: water surface oscillation in the most significant surge tanks in the system due to the shut-off of turbines in site one. Surge tanks reported are the first upstream and downstream of the turbines, and last surge tank in the system. In column T the time from shut-off at which reported oscillation was recorded is presented.

Valve opening: 900s Wicket gate closure: 22s			
<i>Tower</i>	<i>Distance from turbine</i>	<i>+ΔH (m)</i>	<i>-ΔH (m)</i>
T3M	10 m	4,4	3,1
T3V	10 m	-	14,6

Valve opening: 900s Wicket gate closure: 120s			
<i>Tower</i>	<i>Distance from turbine</i>	<i>+ΔH (m)</i>	<i>-ΔH (m)</i>
T3M	10 m	4,2	1,9
T3V	10 m	-	9,2

Table 3: water surface oscillation referred to the steady state conditions in the most significant surge tanks in the system due to the shut-off of turbine in site two. Surge tanks reported are the first upstream and first downstream to the turbine. Times are not reported being the two tower very close to the turbine

Valve opening: 1.800s Wicket gate closure: 22s			
<i>ID</i>	<i>Distance from turbine</i>	<i>ΔQ (m³/s)</i>	<i>T (s)</i>
1A	10.000 m	-3,0	1.087
7B	48.000 m	-1,9	2.250

Valve opening: 1.800s Wicket gate closure: 120s			
<i>ID</i>	<i>Distance from turbine</i>	<i>ΔQ (m³/s)</i>	<i>T (s)</i>
1A	10.000 m	-2,8	1.121
7B	48.000 m	-1,8	2.274

Valve opening: 900s Wicket gate closure: 22s			
<i>ID</i>	<i>Distance from turbine</i>	<i>ΔQ (m³/s)</i>	<i>T (s)</i>
1A	10.000 m	-1,8	979
7B	48.000 m	-0,9	1.831

Valve opening: 900s Wicket gate closure: 120s			
<i>ID</i>	<i>Distance from turbine</i>	<i>ΔQ (m³/s)</i>	<i>T (s)</i>
1A	10.000 m	-1,7	823
7B	48.000 m	-0,8	1.858

Table 4: discharge variation referred to the steady state conditions due to shut-off of turbines in site one. Discharge variations reported are related to the water conveyed by the main pipeline at the section of two of the sixteen spills present along the pipeline and in particular derivations 1A and 7B both downstream to the turbine.

Valve opening: 900s Wicket gate closure: 22s			
<i>ID</i>	<i>Distance from turbine</i>	<i>+ΔQ (m³/s)</i>	<i>-ΔQ (m³/s)</i>
1A	14.000 m	0,9	1,0
UP	4.000 m	3,6	11,1
7B	24.000 m	-	1,5

Valve opening: 900s Wicket gate closure: 120s			
<i>ID</i>	<i>Distance from turbine</i>	<i>+ΔQ (m³/s)</i>	<i>-ΔQ (m³/s)</i>
1A	14.000 m	0,4	0,8
UP	4.000 m	1,4	5,1
7B	24.000 m	-	0,6

Table 5: discharge variation referred to the steady state conditions due to shut-off of turbine in site two. Discharge variations reported are related to the water conveyed by the main pipeline at the section of three of the sixteen spills present along the pipeline and in particular, 1A located upstream to the turbine, UP and 7B located downstream to the turbine.

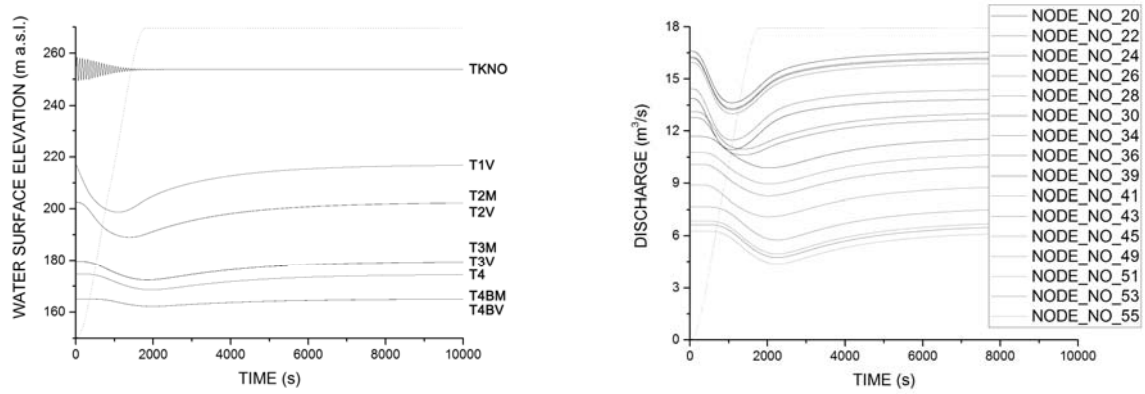


Fig. 2. Free surface level in the surge tanks and discharge in the main pipeline for the simulation corresponding to shut-off of turbines in site one with the following time: 22 s for turbine wicket gate closure and 1.800 s for valve opening. Time of valve opening is plotted with dotted line.

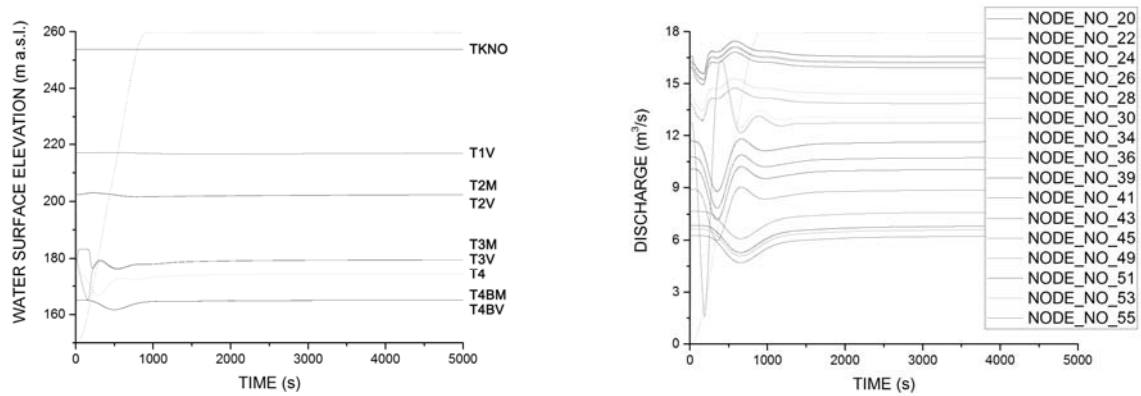


Fig. 3. Free surface level in the surge tanks and discharge in the main pipeline for the simulation corresponding to shut-off of turbine in site two with the following time: 22 s of turbine wicket gate closure and 900 s of valve opening. Time of valve opening is plotted with dotted line.

Figure 2 and Figure 3 show the water surface variation in the surge tanks and the discharge variation in the pipeline at the control sections. Figure 2 is referred to the turbines shut-off in site one considering a turbines wicket gate closure of 22 s and a vale opening of 1.800 s.

Figure 3 is referred to the turbine shut-off in site two considering a turbine wicket gate closure of 22 s and a vale opening of 900 s. Those are the worst case simulated.

6 Discussion

The simulation results analysis shows that the turbines shut-off generates a positive pressure wave upstream and a negative pressure wave downstream of the turbine. The waves travel in the pipeline and they are more and more dissipated by the surge tanks placed along the pipeline itself (Figure 2 and Figure 3).

Furthermore, variation in hydraulic head due to the pressure waves is actually coupled to a variation in the conveyed discharge in the pipeline (Figure 2 and Figure 3).

The simulations results show also that the response time of the system varies between 30 and 60 minutes. This is mainly due to the high length of the pipeline. Actually such high response time can also turn into critical operation problems.

The intensity of the waves depends on the combinations between the turbines wicket gate closure and the valves opening times. In particular the highest wave intensity is registered, at the shortest wicket gate closure time and the longer valve opening time. Therefore, as easily predictable, the worst conditions for the system are related to a turbine wicket gate closure time of 22 s and valves opening time of 3.600. The highest valve opening time allowable in order to avoid air entrance in the penstock is detected in 2.400 s, assuming a turbine wicket gate closure of 120 s.

With reference to the specific turbine shut-off in the site two, considering the combination of turbine wicket gate closure and simulated valve opening time, the results show a strong overflow phenomenon in the closest upstream tower (T3M) which is located only few meters upstream of the turbine.

On one hand, the overflow permits an appreciable cut of the upstream propagated positive pressure waves, on the other hand the magnitude of the phenomenon requires that the overflow is avoided. It has been simulated that without considering the overflow phenomenon, water surface in the tower rises of 10 m in case of wicket gate closure in 120 s and valve opening in 900 s and it rises 20 m in case of wicket gate closure in 22 s and valve opening in 900 s. Those values are actually incompatible with a structural safety of the surge tank tower. In order to avoid overflow phenomena in T3M tower a suitable turbine wicket gate closure has been evaluated in 540 s (9 minutes) considering an opening time of the valve equal to 900s, which is the minimum allowable for this type of valves and actuators.

7 Conclusion

Simulation results are coherent with the classic hydraulic theories which describe transient phenomena in pipelines. The performed model can actually describe correctly the transient phenomena in the pipeline.

Although any structural problems are detected for the pipeline (with except of tower T3M when overflow occurs), considering that the water supply function is the priority, the oscillations generated in the pipeline by turbines shut-off are not allowable with the current opening time of the Johnson valves (1.800 s). Therefore, the recommendation for a compatible hydroelectric generation is to ensure a valve opening time lower than 900 s. At the same time it is essential to ensure the fastest possible turbines wicket gate closure time allowing turbines to sustain the runaway speed for some minutes. The actual Johnson control valves, without any modifications, are not compatible with the new configuration designed for the system. In order to make possible the hydropower exploitation of the system, it will be necessary to modify the actuators of the valve or to proceed to the replacement of the old valves with new ones with adequate opening time. Since we detected high response time of the system to the transitory phenomena, additional study of normal operation conditions is recommended.

References

- [1] R. Fitzgerald, V. L. Van Blaricum, *Water Hammer and Mass Oscillation (WHAMO) 3.0 User's manual*, U.S. Army Corps of Engineers - Construction Engineering Research Laboratories, Vienna, 1998.
- [2] S. Milićević, D. Milićević, R. Milićević, Utilization of hydro power potential already existing water resources and other structures in Serbia, *BALWOIS 2010 – Ohrid, Republic of Macedonia – 25,29 May 2010*
- [3] S. Kucukali, Water supply lines as a source of small hydropower in Turkey: A case study in Edremit, *World renewable Energy Congress 2001 – 8-13 May 2011, Linkoping, Sweden*

Nomenclature

C_q = valve discharge coefficient [-]

D = valve diameter [-]

ΔH = hydraulic head difference between upstream and downstream valve section [m]

H = total head [m]

Q = discharge [m^3/s]

x = lenght [m]

t = time [s]

g = acceleration of gravity [m/s^2]

A = area of pipe [m^2]

D = pipe diameter [m]

f = Darcy – Weisbach [-] coefficient

c = wave celerity [m/s]

v = water velocity [m/s]

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