Water hammer effect in the spiral case and penstock of Francis turbines

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Abstract. Sudden pressure increases in the penstock or spiral case of a hydraulic turbine are the effect of sudden flow variation that occur during transient processes of type opening / closing or load rejection of the hydro unit. The consequence of the pressure rise in the spiral case and penstock is the water hammer phenomenon, whose effects can be devastating in some cases, up to breaking pipes and calamities produced in the area. This paper aims to analyze the method of calculation of the maximum pressure values that might occur in load rejection situations to a hydraulic turbine, in spiral case and in penstock, conditioned by the limiting of the values of the over speed and measures of limiting the increase in pressure in conjunction with limiting the increase in speed in these specific processes. As an example, we studied and analyzed the situation of a hydroelectric power plant equipped with a 7.8 MW Francis turbine without pressure regulator and the inflow surge. The results of analytical calculation overlaid on the experimental measurements performed during the performance tests of the hydro unit lead to the conclusion that the calculation algorithm proposed has been chosen correctly and the 2-stage closing law of the wicket gate promoted in this case is effective in such situations.

1. Introduction

The impermanent regime of fluid dynamics is a frequent event, met during operation of hydraulic installations which are carrying fluids under pressure [1], [2], [3], [4]. It appears whenever the dynamic regime is varying very fast, meaning whenever changes occur in the flow limiting conditions, such as opening or closing a valve, stopping or turning on pumps, rejecting air, water pipe breaking, so on [5],[ 6].

Such an impermanent regime can introduce important mechanical stresses in the system. The motion of the fluid in the pipes may cause an over-pressure, capable to emulate several or tens of times the operating pressure. Also, an important depression can be expected. In both cases partial damages or even the total destruction of such an installation can occur [7], [8], [9].

The motion of the fluids in the pipes in impermanent regime can be of a slow or fast variation, depending on the relative speed of changing the limit conditions of the system [10], [11].

The more the variations are slower in time, the more the wave character is reduced. The movement becomes increasingly more oscillating in mass and compressibility and plays a less important role. To the limit, for very slow movements varying in time, the compressibility can be neglected and it can be reached the simplified model of the incompressible fluid which can however be used only in this case, of the very slowly varying in time movements.
The quick variation impermanent movement phenomena will be referred to as "water hammer effect" and the slow variation will be called "oscillation in mass movements". Parts, fittings or installations that are required in order to control the water hammer phenomena will be called "protection devices" [12].

The effect of increasing the pressure in a pipe or chamber due to rapid flow changes is called in technical terms "water hammer". Water hammer represents a very destructive force that can appear in any pumping system where the rate of flow is varying abruptly in operation from different reasons. Most of the engineers recognize the existence of water hammer effect, but few realize its destructive impact. In fact, too much time and many expenses have been spent repairing pipelines and damaged pumps and valves because of water hammer. Thus, it is essential for an engineer to know exactly when to expect water hammer occurrences, how to estimate the maximum pressure rise, and if possible, how to provide a solution in order to reduce the maximum pressure rise up to a safe limit.

The water hammer phenomena have a wave characteristics. Any change of limiting conditions in any point of the pipe, is causing local variations in flow and pressure, changes which are transmitted from point to point, with a finite speed called propagation speed, due to the elasticity of the fluid and of the material of the pipe, forming plane waves of flow and pressure.

In water hammer case, the propagation speed practically merges with celerity, namely the propagation speed in the fluid at rest [16]. Of course, there are many methods of calculating the maximum values of pressure attainable in transitory processes [13], [14], [15], as well as we can find many solutions for limiting the effects of water hammer. In all these cases, the solution is to be determined, from case to case, according to the technical characteristics of the hydraulic system in which the phenomenon may occur.

Since we cannot establish a clear demarcation between the fast and slow water motion (pressure variation) and we cannot decide for sure whether the simplified model can be applied, it is recommended that in all cases to apply only the precise model of the compressible fluid.

This paper proposes to take the fast varying phenomena only, meaning the water hammer effects that appear in spiral case of the Francis turbines or in the penstocks from the hydro arrangements without surge tank.

2. Analytical approach to the phenomenon

This paper shows the case of impermanent phenomena that occur during transitory processes of the stopping with load rejection of a hydro power plant equipped with one Francis turbine powered by a single penstock with a diameter of 1.2 m. The water intake of the penstock is placed into a polder made on the derivation from a river with almost constant flow. The arrangement is placed on the Tana River in Kenya.

2.1. Initial data

Technical characteristics of the hydro unit (head, flow, power) are mentioned in Table 1. Supplementary necessary information to operate the calculation [17]:
- Hydro unit runaway speed: \( n_{\text{rs}} = 610.9 \text{ rpm} \)
- Generator inertia momentum: \( G\ell^2_{\text{generator}} = 150 \text{ tm}^2 \)
- Turbine inertia momentum: \( G\ell^2_{\text{turbine}} = 7.3 \text{ tm}^2 \)
- The function \( f=f(\sigma) \)
- The experienced function \( T_s=f(Tw) \)
- Maximum over speed: 150\% at nominal speed
- Maximum overpressure: 130\% at nominal head
### Table 1. Technical data for the Francis turbine

|   | Q (m³/s) | H_{netto} (m) | P (Kw) | n(rpm) |
|---|----------|---------------|--------|--------|
| 1a| 16.5     | 52.45         | 7913   | 333.33 |
| 1b| 13       | 54.05         | 6315   | 333.33 |
| 1c| 9        | 55.39         | 4019   | 333.33 |
| 1d| 7        | 55.89         | 2865   | 333.33 |

#### 2.2. Calculation Hypothesis
In the present calculation there were assumed the following hypothesis [17]:
- Correctly operation of the speed governor which leads to perform the closing time which was taken into consideration;
- Linear closing lure of the wicket gate;
- Hydraulic hammer;
- \( g = 9.777 \text{ m/s}^2 \) (value for Equator area)

#### 2.3. Calculation algorithm
The first step of calculation is determining \( L_{v\text{tot}} \) according to the equation (1):

\[
L_{v\text{tot}} = \sum L_{v\text{ad}} + \sum L_{v\text{cs}} + \sum L_{v\text{st}}
\]

It is taken into account the length and the speed that are specific to the 2 segments of the hydraulic circuit, namely: penstock and spiral case.

The calculation algorithm determines the following variables:

a) \( \rho \) – Allievi constant according to the equation:

\[
\rho = \frac{a \cdot V_m}{2g H_n}
\]

where:
- \( V_m \) = the medium water speed (m/s)
- \( a \) = speed of water hammer pressure wave (1425 m/s according to the nomogram for the situation of metallic pipes and in the case in which the ratio D/wall width = 10…15)
- \( g \) = acceleration of gravity (m/s²)
- \( H_n \) = nominal head (m)

b) \( T_w \) (sec) - inertia time constant of the water masses in the penstock according to:

\[
T_w = \frac{\sum L_{v\text{tot}}}{g H_n}
\]

c) \( \sigma \) = coefficient of overpressure in the penstock (no dimensional) according to

\[
\sigma = \frac{T_w}{T_i}
\]

while \( T_i \) is the closing time of wicket gate (s).

The closing time is chosen according the imposed limit for speed rise in many variants according to the results shown in Table 1.2

d) \( T_r \) - reflection time of the pressure wave is calculated according to the equation:

\[
T_r = \frac{2 \cdot L_{v\text{ad}}}{a}
\]
e) In the first part of the wicket gate closing, the pressure rise coefficient $\zeta_1$, is calculated with the equation:

$$\zeta_1 = \frac{2 \cdot \sigma}{1 + \rho t_0 - \sigma}$$

(6)

where $t_0 = 1$ for load rejection from the rated power.

f) After a number of phases had been passed, the limit of the pressure rise coefficient is almost reaching the limit value $\zeta_m$ and further remain constant. The constant $\zeta_m$ is derived as:

$$\zeta_m = \frac{\sigma}{2} \left( \sqrt{\sigma^2 + 4 + \sigma} \right)$$

(7)

In case of a sudden closing of the wicket gate after a load rejection from the rated power, the pressure rise coefficient on the installation is divided between the construction elements as follows:

g) For a pressure rise in the penstock the rise coefficient is calculated according to the equation:

$$\zeta_{ad} = \frac{\sum L_{\text{viald}}}{\sum L_{\text{tot}}} \cdot \zeta_m$$

(8)

h) For a pressure rise in the spiral case the rise coefficient is calculated with the equation:

$$\zeta_{cs} = \frac{\sum L_{\text{viald}} + \sum L_{\text{vics}}}{\sum L_{\text{tot}}} \cdot \zeta_m$$

(9)

i) The effective pressure rise in the penstock $\Delta H_{ad}$ is calculated with the equation:

$$\Delta H_{ad} = \zeta_{ad} \cdot H_n$$

(10)

j) The effective pressure rise in the spiral case is calculated from the equation:

$$\Delta H_{cs} = \zeta_{cs} \cdot H_n$$

(11)

k) The pressures in the penstock and in the spiral case are:

$$H_n + \Delta H_{ad} = H_n (1 + \zeta_{ad})$$

(12)

$$H_n + \Delta H_{cs} = H_n (1 + \zeta_{cs})$$

(13)

The permissible limit values of over pressure in the penstock and spiral case are closely linked to the limit values allowed for hydro unit over pressure from technical and economic reasons. In such a situation, treatment of water hammer phenomenon cannot be done without taking into consideration the packaging of the machine in the worst case of load rejection, usually from the maximum value of power that can be given by the power plant.

The over speed is calculated by equation:

$$\Delta n = -1 + \sqrt{\frac{364 \cdot P \cdot T_{na} \cdot f}{G D^2 \cdot n^2}} + 1$$

(14)
where $T_{ia}$ (sec) - closing time of the wicket gate up to the no load position and it will be calculated with the equation:

$$T_{ia} = 0.9 \cdot T_i$$ \hspace{1cm} (15)

- $P$ - turbine output (Kw)
- $f$ - corrective coefficient of speed rise
- $GD^2$ - fly wheel moment of the generator and turbine ($tm^2$)
- $n$ – hydro unit speed (rpm)

2.4. Establishing the proper solution for avoiding overpressure and over speed

According to Table 2, results:
- It can be inferred it is an indirectly water hammer, namely the head maximum rise appear at the end of wicket gate closing curve ($\zeta_1 < \zeta_m$ and $Tr < Ti$)
- For a closing time of 7 seconds, the head maximum rise in the penstock is of 12.5 m and in the spiral case is of 15.26 m
- For the same closing time $T_i = 7$ s the hydro unit speed maximum rise is of approx. 53\% (see Figure 1- law no. 1)
- The highest value of the head and speed rise are reached when the unit is loaded at rated power ($P = 7913$ Kw).

Because the over speed value goes beyond the admissible value (50\%) it is adopted the solution of closing the wicket gate in two steps (see Figure 1 – law no. 2), as follows:
- First step of closing has influence upon the over speed value, it is active up to 30\% opening in a time $T_{i1}$ of 5 seconds;
- The second step of closing goes from 30\% up to the end of the stroke in a time of $T_{i2} = 12$ seconds.

Taking into consideration the input data and the calculation hypothesis mentioned above, further in the following tables are centralized the values of the calculated parameters with the equations already presented in Table 3.

In such a situation there are guaranteed the following:
- The maximum value of the over speed will not go over 50\%;
- The maximum value of overpressure will not go over 30\%;

| Parameter | MU |
|-----------|----|
| $P$ (Kw) | 7913 |
| $H_m$ (m) | 52.45 |
| $Q$ (m$^3$/s) | 16.5 |
| $L_{ad}$ (m) | 238.46 |
| $L_{Vad}$ (m$^2$/s) | 891.39 |
| $L_{q}$ (m) | 10.565 |
| $L_{Vq}$ (m$^2$/s) | 65.79 |
| $L_{ST}$ (m) | 54.52 |
| $L_{VST}$ (m$^2$/s) | 29.56 |
| $L_{Total}$ (m) | 303.545 |
| $L_{VTotal}$ (m$^2$/s) | 986.75 |
| $V_m$ (m/s) | 2.99 |
| $A$ (m/s) | 850 |
| $P$ | 2.47 |
| $Tr$ (s) | 0.71 |
| $T_W$ (s) | 1.92 |
| $T_i$ (s) | 7 |
| $\Sigma$ | - | 0.27 | 0.18 | 0.148 | 0.107 |
The closing diagram of the wicket gate is given in Figure 1.

### Table 3 Values calculated for closing law no. 2

| Parameter       | MU   |
|-----------------|------|
| P (Kw)          | 7913 | 6315 | 4019 | 2865 |
| Hn (m)          | 52.45| 54.05| 55.39| 55.83|
| Q (m³/s)        | 16.5 | 13   | 9    | 7.00 |
| L_rad (m)       | 238.46| 238.46| 238.46| 238.46|
| L_Vrad (m³/s)   | 891.39| 594.26| 486.21| 378.15|
| L_cs (m)        | 10.565| 10.565| 10.565| 10.565|
| L_Vcs (m³/s)    | 65.79 | 43.58 | 35.2 | 21.9 |
| L_ST (m)        | 54.52 | 54.52 | 54.52 | 54.52 |
| L_VST (m³/s)    | 29.56 | 20.31 | 15.21 | 12.95 |
| L_total (m)     | 303.545| 303.545| 303.545| 303.545|
| L_Vtotal (m³/s) | 986.75| 680.37| 567.22| 412.1 |
| V_m (m/s)       | 2.99 | 1.98 | 1.63 | 1.302|
| A (m/s)         | 850  | 850  | 850  | 850  |
| P               | 2.47 | 1.57 | 1.31 | 1.01 |
| Tr (s)          | 0.71 | 0.71 | 0.71 | 0.71 |
| T_W (s)         | 1.92 | 1.27 | 1.04 | 0.75 |
| T_total (s)     | 17   | 17   | 17   | 17   |
| T li (s)        | 5    | 5    | 5    | 5    |
| T_2i (s)        | 12   | 12   | 12   | 12   |
| Σ               | 0.11 | 0.07 | 0.06 | 0.04 |
| ζ_l -           | 0.16 | 0.123| 0.136| 0.112|
| ζ_m -           | 0.11 | 0.07 | 0.06 | 0.04 |
| H_add/Hn (m)    | 10.6 | 6.7  | 5.8  | 3.9  |
| H_nes/Hn (m)    | 11   | 7    | 6    | 4    |
| GD² (tm²)       | 157.3| 157.3| 157.3| 157.3|
| t_i (s)         | .5   | .5   | .5   | .5   |
| -                | .33  | .28  | .25  | .18  |
| Δn/n (%)        | 0.9  | 7.3  | 1.2  | 4.7  |
2.5. The technical solution applied to avoid water hammer effect

In order to avoid the phenomenon of water hammer, in case in which the hydro power arrangement has no surge and no pressure regulator fitted to the inlet of the spiral case, given that the automatic speed governor is of the type digital and electro-hydraulic, it was used an electro-hydraulic system installed on the closing pipe and controlled by the same PLC that implemented in digital equipment.

The system consists of several hydraulic elements from Bosch, adequate for necessary flow used for closing the wicket gate in the calculated time.

The reason for which it was proposed this solution of 2-stage closing is as follows:
- The first part of the closing to be as fast as possible in order to avoid overpressure, having in attention that over speed has the biggest gradient immediately after the disconnecting of the main circuit breaker (the 5 s time corresponds to the rise limitation of the speed up to 150% from the rated speed).
- The second part of the closing should be as smooth as possible, having in attention that over speed is not increasing anymore and we have in intention to avoid water hammer (the total time of 17 s is fitted for an overpressure of 130% from the maximum static head).

The inflection point in the closing law of the wicket gate is an adjustable variable by application software in this case, depending on the current position of the wicket gate, but it can be realized through a mechanical cam, adjustable as position, tightly connected of the servomotor piston of the wicket gate. Of course, we can use as input data too, the instantaneous value of the speed, but in such a case should be adopted a different software implemented algorithm or a different hydraulic actuation system corresponding to the proper law that intended to be implemented.
3. Experimental measurements (records)
Checking the analytical calculation results was made in site during commissioning tests.

The present diaphragm on the hydraulic control circuit of the wicket gate has a 2 mm hole. The closing time for the wicket gate (Figure 3) was recorded as almost 17 s (the same value as it was calculated in the design). The changing point of the two slopes is around 35% of total opening. So, for the first slope (from 100% to 35%) we have around 5 s and for the second slope (from 35% to 0%) we have around 12 s (according to designed value).
We recorded exactly the total stroke of the wicket gate servomotor. It is 260 mm for 100% of opening. The wicket gate opening temporized time (increasing/decreasing from keys) from 0% to 100% is around 50 sec. (0.01%/5.6 ms scan time). It was done the test of closing the wicket gate through de-energizing the safety valve by losing power supply to the solenoid valves hydraulic block.

There were performed the load rejection tests for 75% and maximum power obtained. Following we will present some conclusions resulted from the records. The over speed and overpressure values which were recorded are according to the closing law. This closing law is performing the most optimal situation regarding the rise of the speed and of the pressure in the spiral case. The maximum power can be reached in the range 75-78% opening of the wicket gate (see records). The maximum power obtained was 7.3 MW, with the line voltage of approx. 10.5 kV, the water pressure in the spiral case of 5.3 bar.

3.1. Recording for STOPPING LOAD REJECTION at 75% of nominal power
The values resulted from the records for over-speed and overpressure are:
- Over-speed: 126 % from nominal speed
- Pressure rise in the spiral case: 118.8 from static head
- Wicket gate closing law: Inflection point is set at 32% and the total closing time of the wicket gate is 8 s, suitable to the opening on which the load rejection occurred.)

Figure 4. Record of closing time of the wicket gate
3.2. Recording for STOPPING LOAD REJECTION AT MAXIMUM POWER

The values resulted from the records for over-speed and overpressure are:

- Over-speed: 142.6% from nominal speed (This value is obtained in case of remaining in no load regime, and it is not under guarantee)
- Pressure rise in the spiral case: 129.2 % from static head
- Wicket gate law: Inflection point is set at 32% and the total closing time of the wicket gate is 9.5 seconds, suitable to the opening on which the load rejection occurred.)
Figure 6. Stopping Load rejection from maximum power (left image); Over-speed: 140.9 % (right image middle); Pressure rise in the spiral case: from 4.95 bar to approx. 6.4 bar (right image down); Wicket gate law (right image up)

4. Conclusion
Following the completion of the hydraulic 2-stage closing system it was harmonized the allowable values for pressure rise or speed rise to load rejection from nominal power, transient phenomenon that occurs frequently in hydropower units operation.

The calculus algorithm is our own and uses equations taken by the studied bibliography.

As seen from the analysis of recordings that made, the values of interest, namely over speed and over pressure so as the closing time of the wicket gate did not exceed the values which calculated.

In those circumstances the penstock and the whole arrangement can operate safely even after a simplified calculation, if calculation assumptions are chosen appropriately.

Graphs realized to the commissioning tests of the hydro unit shows the 2-stage closing law of the wicket gate and the operation times realized by adjusting the holes of the diaphragms from the return pipe are very close to analytical calculation results.

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