Influence of the penstock design on the operation of the inlet spherical valves

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Abstract. Spherical valves are supplied for high-head turbines. The drive of spherical valves designed and manufactured by Power Machines/LMZ provides opening by means of servomotors, and closing under the action of the moment created by counterweights.

Selection of parameters for the spherical valve and its design are based on the assumption continuity of the water flow entering the turbine through the penstock. In case, when two or more hydro-units are installed at the HPP, the penstocks usually have pipe bifurcations **(Fig.1).** The design of the penstock should provide a uniform supply of water to all units without spin, rupture of continuity and pulsation. Given in the paper is an example of the HPP with two (2) hydro-units equipped with inlet spherical valves. In the course of operation valve rotor oscillations with different periods in time (T ≈ 15 sec.) were detected. When analyzing, no faults in the valve design and its mechanism of operation were detected.

In the course of the tests, vibration parameters of the spherical valves were determined in the following operating conditions: each of the hydro-units running separately and both of them running simultaneously for different power output values. Based on the test results, operating conditions with maximum vibration of were located. The reasons of surging of perturbing forces acting on the rotor of the spherical valve were detected in the course of analysis of the penstock design. Possibility of accumulation of air at the penstock pipe bifurcations was found. When the air transported by the water achieved its critical value, this air appeared to be the cause of instability in the valve operation. The attention was drawn to necessity of taking into account this circumstance when designing penstock pipe bifurcations.

1.Introduction

It is known [1] that in the course of the water flow through the pipes consisting of various types of connectors and transition portions of rectilinear and bent tubes (in the course of overflowing protruding parts, of separation of the water flow, etc.) vortex zones can be formed. Thus, even a slight change of the inlet section leads to a noticeable change in the conditions of the flow and to an increase in the intensity of the flow turbulence and vortex formation.
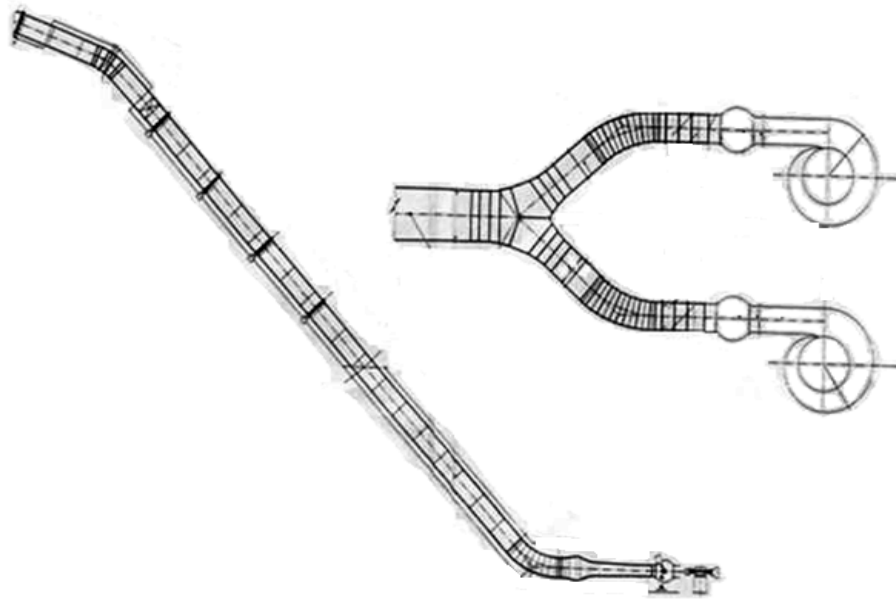
Fig. 1 Pipe bifurcations of the penstock

In engineering practice in the vast number of cases we have to deal with large Re values, in any case, with those that creates a turbulent motion when the inertial forces arising in the flow dominate viscous forces. Especially the role of the forces of inertia increases when the liquid moves through the shaped parts and overflowing different obstacles, so that the law of resistance gets close to quadratic one. Therefore, in the hydraulic formula for the determining resistance are usually given as quadratic ones:

$$\Delta H = \zeta \frac{\omega^2}{2g},$$

where:

ζ- coefficient of hydraulic resistance.

When the water flow turns while ramifying in the penstock pipe bifurcations, centrifugal forces spring up, which leads to the fact that the flow velocity near the inner wall of the pipe increases and the pressure decreases, correspondingly (Fig.2). The opposite phenomenon occurs near the outer wall of the penstock fork: the velocity decreases and the pressure increases. After turning, transition of the water flow into a rectilinear portion is accompanied by the opposite phenomenon: near the inner wall, the velocity decreases (diffuser effect) and near the outer wall the velocity increases (confuser effect), which leads to a separation of the flow from both of the walls.

Moreover, separation of the flow from the inner wall is reinforced due to the tendency of the flow to move rectilinearly by inertia toward the outer wall. The vortex zone resulting due to separation of the flow from the outer wall is negligible. On the contrary, separation of the flow from the inner wall leads to an intense vortex formation.
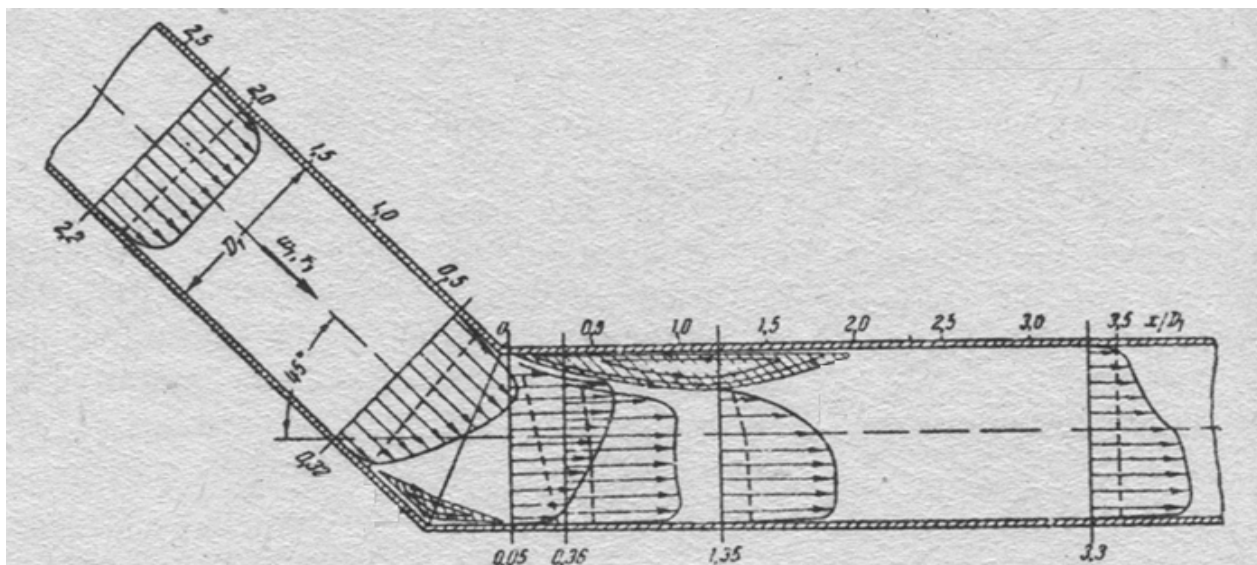
Fig. 2 Process of the vortex formation in the pipe bifurcations of the penstock

Due to the fact that along the diffuser flow velocity keeps decreasing all the time, in the area close to the solid surface of the pipe, the flow velocity falls sharply, decreasing to zero on the surface. When decelerating of the flow, the fluid particles in the a.m. area start moving even slower, and when the flow is sufficiently slow under the influence of differential pressure directed opposite the flow, the particles stop and then start moving in the opposite direction. Thus, near surface the reverse movement of the fluid occurs, though, the outer flow still does not change its direction.

Quantity of decelerated fluid between the wall and the external flow is increasing rapidly and the area of the reverse movement is considerably expanding, till the external flow is completely pushed away from the solid surface. At first, it will lead to thickening of the boundary layer, then to its complete separation from the surface. The sharp boundaries formed between the outer flow and reverse movement area (separation surface) will quickly get folded into a vortex. During the next moments, distortion of the separation surface will occur chaotically, which leads to formation of random of sequences of large and small vortices.

Under the influence of vortices, the separation surface begins to fold reinforcing and making bigger the vortex. Further on, the vortex is carried away along with the flow. After that, the process of the vortex formation in this area repeats again usually in unequal time intervals.

2. Test of hydro units Nos.1 and 2 (HU1 and HU2)

In order to determine the causes of elevated levels of vibration of spherical valve of HU2 (Fig. 3), the tests were carried out on HU1 and HU2 in steady-state operating condition when each of the two units operates separately and when HU1 and HU2 operate simultaneously.
Test results:

Depending on the operating conditions of hydraulic units, pulse repetition frequency was 6 - 8 seconds on HU1 spherical valve, and 12 - 16 seconds on HU2 spherical valve.

In the course of simultaneous operation of hydro-units with maximum power output, maximum vibro displacement peaks of counterweights of HU1 and HU2 spherical valves amounted to 0.8 and 3.0 mm, respectively. After about 2 - 3 seconds of natural damping oscillations vibration levels of HU1 and HU2 spherical valves counterweights becomes approximately ≤ 0.4mm;

In the course of simultaneous operation of two hydro-units at loads 70 ... 100% of the maximum power a sharp increase of the HU2 spherical valve vibration level was recorded;

During operation of one hydro-unit with maximum power (with another unit being shutdown) the value of spherical valves HU1 and HU2 vibrations were approximately equal, and did not exceed 0.4 mm.
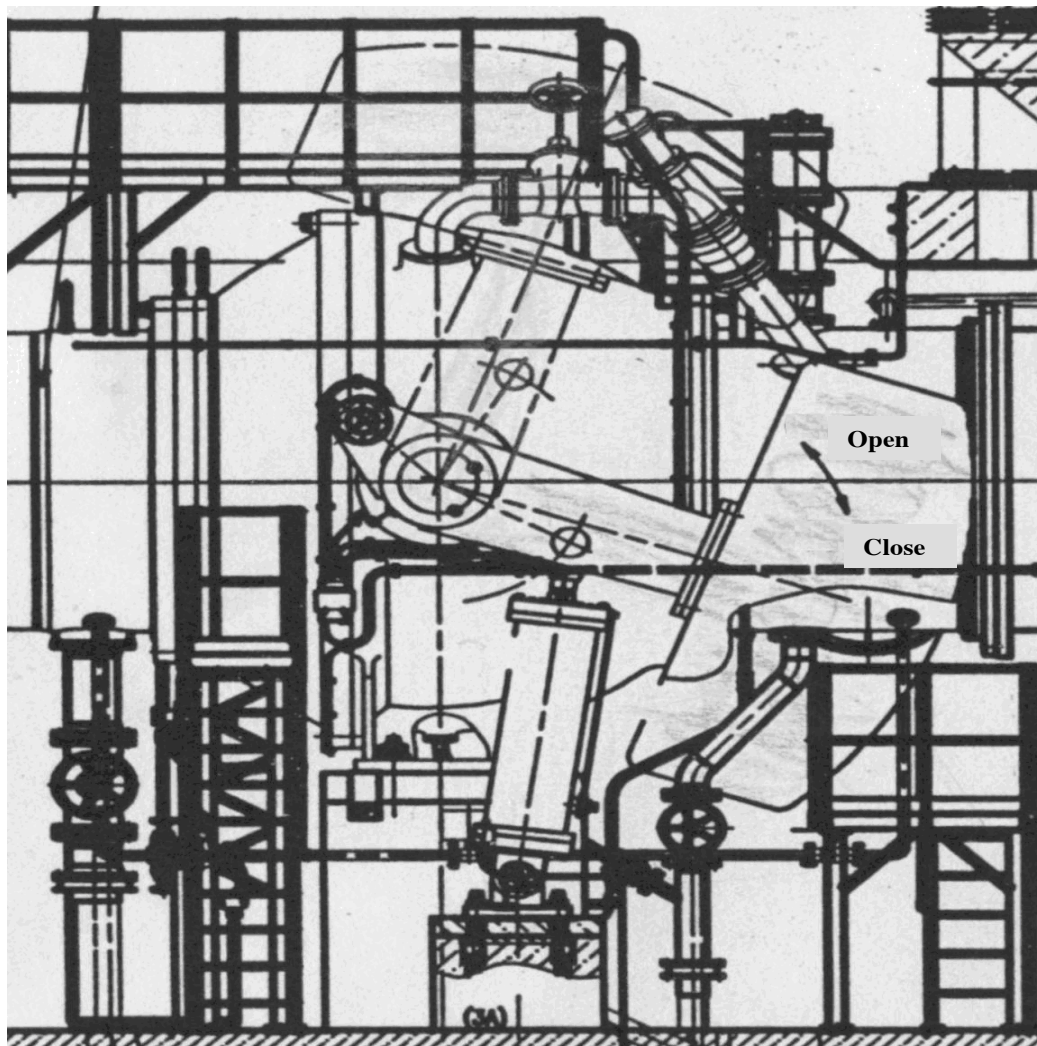
Fig.3 Spherical valve

3. Analysis of test results

3.1 Consider the case when one unit HU1 operates with maximum power output and HU2 is not running.

So we have:

Pa1 = Pa1gen and Pa2gen = 0 - power output of HU1 and HU2;
Pa1gen = η gen Nt1;
Hbr = $^\circ$hwl -$^\circ$twl - gross head;
$^\circ$hwl – head water level;
$^\circ$twl – tail water level;
Ht1 = Hbr - ΔH1;

$\Delta H1 = \zeta \dfrac{\omega l^2}{2g}$ - head losses in the penstock when only one unit HU1 operates (outlet draft tube losses are small);
ζ - coefficient of hydraulic resistance when one unit HU1;

Nt1 = η т ϱ g Hт1 Q1- turbine power;
Nt2 = 0;

η gen - generator efficiency;

η t - turbine efficiency;

ω_1- flow velocity in the pipe bifurcations when one unit HU1 operates;

Q1 - discharge when only one unit HU1 operates.

As mentioned above when one unit HU1 operates at these operating conditions pulsation phenomena in the flow and percussion impulses on the HU1 spherical valve are absent.

3.2 Consider the case of simultaneous operation units HU1 and HU2 at maximum power.

So we have:

Pa1 = Pa1max , Pa2 = Pa2max , Pa max = η gen Nt ,

Ht2 = Hbr − Δ H2 -

Δ H 2 = $\zeta \dfrac{\omega 2^2}{2g}$ – head losses during simultaneous operation of HU1 and HU2 at maximum power;

ω_2 - flow velocity in the pipe bifurcations during simultaneous operation of HU1 and HU2 at maximum power output.

Q2 - discharge through the turbine during simultaneous operation of HU1 and HU2 at maximum power output;

In the course of simultaneous operation of units HU1 and HU2 at the maximum power output, head losses are increasing (as compared to head losses when only one unit is running). Thus, to ensure simultaneous operation of HU1 and HU2 units at maximum power output, there is a need to increase discharge through the turbine until Q2, which leads to an increase of flow velocity until ω_2 and consequently to a change of overflowing conditions in pipe bifurcations of the penstock and conditions of air accumulation and its transportation by the flow.

Based on the results of the tests, impact impulses on spherical valves were registered only during simultaneous operation of units HU1 and HU2 at the loads ranging within 70-100% of the maximum power output.
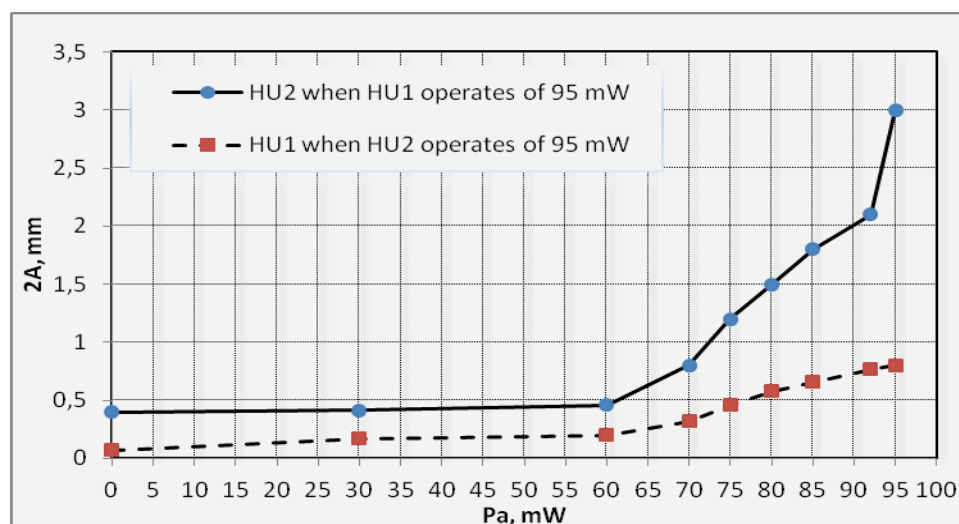

Fig.4 Counterweights vibration during simultaneous operation of HU1 and HU2

From the above it follows that in case of simultaneous operation of units HU1 and HU2 critical flow velocity in the penstock when impact impulses on the HU1 and HU2 spherical valves surge, may be determined as:

$$\omega\, cr \geq 0,7\; Q\; (1 + 2)\, /\, F,$$

where: F - sectional area of the penstock.

Problems of forceful vortex breakdown phenomena when three hydro-units are installed at the HPS with penstock pipe bifurcations have a similar nature [2].

3.3 Analyzing the penstock design

When analyzing the penstock design, it was found that the bifurcation part is located higher than the horizontal portions of the upstream and downstream penstock. Due to this fact, in the proximity of this part air accumulation is possible. When inspecting the inside of the bifurcation wall about $3,5m^2$ with a huge rust stain was detected, which is the testimony of air presence. It is possible that volume of entrapped air came to about $0.3m^3$. Air accumulation, its further transportation by the water flow to the inlet valve area and its dynamic interaction with the elements of the valve might have also the cause of instability of the inlet valve operation.
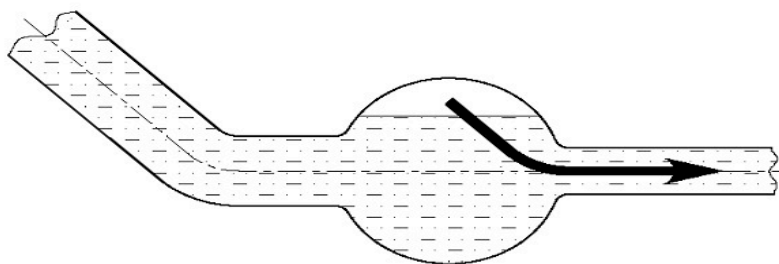

Fig 5 Air accumulation in the pipe bifurcations

4. Conclusion

When designing pipe bifurcations of the penstocks, it is necessary to take into account characteristic structural features of the flow in them and to carry out investigations and model test on two or more hydro-units in simultaneous operation within the whole range of steady state operating conditions to exclude possibility of appearance of non-stationary phenomena in the penstocks and pipe bifurcations.
        Besides, it is necessary to prevent occurrence of conditions when the air starts accumulating in the elements of bifurcations or to provide devices for air exhaust there from.

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