Transient processes and optimization of HPP hydraulic structures

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Abstract. In the scope of Hoabinh HPP extension an additional powerhouse is being designed on the common reservoir with two units 240 MW each and two pressure tunnels 765-785 m long. Due to unfavorable geological conditions the design organization made the decision to abandon the construction of the compensating reservoirs on the tunnels. To reduce the hydraulic hammer the current speed in tunnels was decreased to 3 m/s which is half as much of the speeds normally accepted in energy conduits. The article presents a set of calculations of transient processes required for feasibility study of decreasing the internal diameter of the head conduit in abandonment of the construction of the compensating reservoir. The calculations were performed using the specialized program of calculations of the transient processes of HPP. There were considered the processes of load rejection, frequency regulation in allocation to the isolated energy district and power regulation at constant frequency in the power grid. There is presented the system of limitations of the parameters of transient processes which permitted to justify the decrease in the internal diameter of the conduit from 11.5 to 10.5 m. It is shown that with decrease of the pressure tunnel diameter there are fulfilled the given guarantees of regulation in pressure and in rotation frequency, the conditions of fluctuation stability in frequency regulation, specific speed of power regulation.

1. Introduction
Transient processes – putting into operation, outages, power regulation, load rejection, represent an important part of the flow sheet of power output at HPP. In many respects, they determine the design of hydraulic power structures, the types and parameters of the main equipment, the operation conditions in the power system [1, 2, 3, 4, 5]. The reliable and fail safe HPP operation is considerably ensured by detailed investigation of transient processes at the project designing stage.

2. Methods
The main instrument of investigation of transient processes is their mathematical simulation realized using specialized computer programs. The programs are subjected to rigid requirements: regard to all main influencing factors, the correct choice of turbine characteristics (by specific speed), which would have smaller values of runaway frequency of the runner rotation, extrapolation of the turbine universal characteristics up the to the runaway and braking modes using mathematical methods and practical experience, use of various diagrams of the opening and closing of the turbine wicket gates [2, 6, 7, 8].
In calculation of regulation guarantees the rigid requirements are made to the precision of the results obtained. By maximum pressure in penstocks and in the spiral case this is 5% of maximum head, by the unit rotation frequency – 1% of nominal rotation frequency [6, 8].

3. Research problem

One of the latest tasks there was the optimization of parameters of two headrace pressure tunnels (figure 1) of Hoabinh HPP being designed (extended) in the Socialist Republic of Vietnam. In the tunnels 765 and 785 m long it is normally required the installation of the compensating basins for cushioning a hydraulic hammer in the headrace line [5, 7, 9]. But due to unfavorable geological conditions the compensating basins had to be abandoned and consideration was given to the possibility of the tunnels diameters decrease from the initial value $D_{min} = 11.5$ m.

![Figure 1](image_url)

The salient features of the second Hoabinh HPP are as follows: a) the great depth of reservoir drawdown – 30 m; b) the downstream water level rise by 19 m at release of the design flood; c) the upstream abnormal water level is higher by 5 m than the normal maximum operating level.

In the optimization process consideration was given to four variants of tunnels diameters from 11 to 9.5 m with a pitch 0.5 m, several values of flywheel effect of a generator rotor, various time of the wicket gates closure at load rejection and a number of other factors including use of the movement dampening of the wicket gates at the end of closing.

For the recommended variants of the tunnels diameters apart from load rejections and gaining, consideration was given to the indicators of quality of power regulation, control stability of frequency in idling, operation on an isolated part of the power system [10, 11, 12].

Initial data for simulation: two units of power 240 MW each; maximum, design and minimum heads 106.86 and 70.7 m respectively; design discharge of one unit is 307 m$^3$/s; nominal rotation frequency is 125 min$^{-1}$. The turbine is vertical radial-axial calculated for maximum head 115 m; the runner diameter is 5.65 m.

Tunnel conduits have the reinforced concrete lining. The internal steel sheathing is installed in weak places and in the abutment to the powerhouse.

The following limitations were assigned at the transient processes of load rejection and gaining: the pressure on the spiral case axis is not more than 147.6 m, the rotation frequency at the load rejections is not more than 155%, excess pressure along the route of head conduit and in the draft tube must be ensured in all the transient processes, the vacuum along the head conduit route and in the draft tube is not allowed [3, 8].
Various values of tunnel diameters, stream speeds in them, flywheel masses of the unit rotary parts are easily expressed through time constants (inertia constants) of the pressure system $T_W$, including the spiral case and the draft tube, and the power unit $T_a$.

The inertia constant of the head conduit is designed for the maximum in length branch at the turbine design discharge 307 m$^3$/s and design head 86 m. The inertia constant of head conduits is determined by formula [8]:

$$T_W = \frac{Q_{\text{max}}}{g \cdot H_0} \sum \frac{L_i}{F_i} = 3.35 \text{ s}, \quad (1)$$

where $Q_{\text{max}} = 307 \text{ m}^3/\text{s}$, $H_0 = 86 \text{ m}$, $g = 9.81 \text{ m/s}$, $\sum \frac{L_i}{F_i} = 9.77 \text{ m}^{-1}$ (with regard to the geometry of the water intake, the head conduit of diameter 11.5 m, the spiral case and the draft tube).

The inertia constant of the conduit is relatively small due to the low value of maximum speed 2.96 m/s at the conduit internal diameter 11.5 m.

The unit inertia constant $T_a = 9.29 \text{ s}$ is calculated by formula [8] for the mode of maximum power 240 MW at the value of flywheel effect of the generator rotor 53,166 tm$^2$

$$T_a = \frac{GD^2 n_{\text{nom}}^2}{365000 N_a^2} = 9.2 \text{ s}. \quad (2)$$

Ratio between the inertia constants of the head conduit and power unit $T_W/T_a = 3.35/9.29 = 0.36$ shows that the required values of the regulation guarantees can be ensured without additional measures of decreasing the hydraulic hammer [7, 8].

4. Results

Several series of calculations with parameters variation have been made. Figure 2 shows the extreme parameters curve at maximum load rejection depending on the time of the turbine wicket gates closure for tunnel $D_{\text{tun}}=10.5 \text{ m}$. Figure 3 shows the relation between the indicators of inertia $T_W, T_a$ and the tunnel diameter $D_{\text{tun}}$ under the conditions of the fulfilling of the given limitations in pressure and rotation frequency.

| Inner Diameter of the Tunnel, m | Full Stroke Time of the Servomotor Rod of the Guide Vane for Closing, Ts, s | Maximum Speed of the Unit, rel. | Maximum Pressure in the Spiral Case, m |
|---------------------------------|------------------------------------------|-----------------|-------------------|
| 9.5                             | 16                                      | 1.52            | 115               |
| 10                              | 17                                      | 1.54            | 120               |
| 10.5                            | 18                                      | 1.55            | 125               |
| 11                              | 19                                      | 1.56            | 130               |
| 11.5                            | 20                                      | 1.57            | 135               |
| 12                              | 21                                      | 1.58            | 140               |
| 12.5                            | 22                                      | 1.6             | 145               |

Table 1 shows the inertia indicators $T_W$ and $T_a$ at which there are ensured the required limitations in pressure in the spiral case 147 m and in rotation frequency of the unit $\leq 155\%$ at maximum load.
rejections. For each variant there was determined the optimal time of closure of the turbine wicket gates [6, 8].

Table 1. Relations of parameters for ensuring the given limitations at load rejections 240 MW for tunnel various diameters.

| Tunnel diameter, m | Power tunnel inertia constant, Tw, s | Unit inertia constant, Ta, s | Unit flywheel effect, GD², tm² | Ratio Tw / Ta | Wicket gates closing time, Ts, s |
|-------------------|-----------------------------------|-----------------------------|-------------------------------|---------------|---------------------------------|
| 11.5              | 3.55                              | 10.14                       | 58,000                        | 0.35          | 16                              |
| 11                | 3.8                               | 10.75                       | 61,500                        | 0.35          | 17                              |
| 10.5              | 4.09                              | 11.54                       | 66,000                        | 0.35          | 18.2                            |
| 10                | 4.42                              | 12.59                       | 72,000                        | 0.35          | 20                              |
| 9.5              | 4.8                               | 13.81                       | 79,000                        | 0.35          | 22                              |

Figure 4 gives the example of the processes at maximum load rejection for D_tun=10.5 m, Tw=4.09 s, Ta=11.54 s and Ts=18 s. Shown: the curve of movement of the wicket gates with dampening at the end of closing, change of discharge, change of heads in the spiral case and in the draft tube, the unit rotation frequency and the torque on the turbine shaft.

5. Discussion

The transient processes have the substantial influence on the quality indicators of regulation of the frequency and power [12, 13, 14, 15]. Under consideration is the dynamic system wherein the change of opening of the wicket gates is formed by the turbine automatic regulation system (TARS) and there is the feedback in frequency in the power grid.

In the quality indicators calculations the important is the regard to the hydraulic turbine characteristics and the hydraulic hammer in the head conduits. With the increase in length of the head conduit and in the current speed, the fluctation of the dynamic system is increased and regulation
conditions are impaired [10, 11, 16]. There is the need in higher values of adjustments of TARS stabilizing members.

Regulation quality can be estimated by the transient process whose indicators are as follows [17]:

a) regulation time from the feed of control impact to the end of regulation;

b) overregulation – maximum deviation of the regulated value in the fluctuations process around the finite stabilized value;

c) fluctuation is characterized by the quantity of fluctuations periods of the regulated value during the regulation;

d) static error – deviation of the finite stabilized mode from the given one.

For the conditions of Hoabinh-2 HPP consideration is given to the unit putting into operation with the unit going to idling and the load rejections at HPP allocation to the isolated energy district. The ohmic type of load was accepted. This simulates the most severe conditions of the transient process attenuation. The problem of investigation consists in determination of TARS adjustments leading to the effective attenuation of transient processes (Table 2).

**Table 2.** Turbine governor adjustments ensuring the permissible quality indicators of frequency regulation.

| Adjustment of TARS | At going to idling | At allocation to isolated energy district |
|--------------------|-------------------|------------------------------------------|
| Statism, %         | 5                 | 5                                        |
| Temporary statism isodrome, % | 20   | 40                                        |
| Time constant isodrome, s | 10   | 20                                        |

Figure 5 shows Hoabinh-2 HPP unit going to idling. The process is specified by low fluctuation and goes practically without overregulation; the regulation time was 18 s.

![Graphs and plots related to frequency regulation](image)

**Figure 5.** Unit going to idling.

Figure 6 shows the unit reaction at operation for the isolated energy district – the unit rejects 50% of power. The regulation time is 40 s, fluctuation – 5 half-waves, frequency overshoot – 28%.

Calculations of transient processes and the analysis of frequency regulation quality show that for all the considered conduit diameters there are ensured the attenuating transient processes at adjustments of turbine governors kept within the permissible range of values.
For HPP use is also made of specific quality indicators [8] reflecting inertia characteristics of liquid in the conduit: the power reverse overshoot, that is – power deviation from initial value to the side opposite to the direction of regulation; delay time from the start of regulation to the moment when the power again passes the initial value.

Figure 7 and figure 8 show the modes of the load gain and decreasing by Hoabinh HPP unit at the constant frequency in the power grid. Power regulation quality indicators for extreme value in the range under study of diameters are given in Table 3.

![Graphs](image1)

**Figure 6.** Unit allocation to the isolated energy district with 50% rejection of power.

![Graphs](image2)

**Figure 7.** Load decrease.

![Graphs](image3)

**Figure 8.** Load gain.
The load regulation quality analysis at HPP operation in the power grid shows that the time-lag in change of power is 6-7 s and overregulation is 7-8% (17-19 MW). Such parameters are specific for HPP without Surge Tank.

6. Conclusion
1. With the length of pressure tunnels 765-785 m it is possible to abandon the construction of the compensating reservoir by decreasing the speed in the tunnels to 3 m/s.

2. To justify the possibility of decrease of the diameter of the pressure tunnel it was necessary to do a set of load rejections calculations with determining the regulation guarantees, calculation of modes stability in allocation to the isolated energy district, specific speed calculations and power regulation quality. The load rejection calculations show that it is possible to limit the maximum pressure in spiral case 147.6 m and the unit maximum rotation frequency 155% with the tunnel diameter decrease by increasing a) the flywheel effect of the generator rotor and b) time TS and the mode of closing the wicket gates. With all the considered variants the vacuum along the route is absent.

3. Figure 3 shows how depending on the tunnel diameter it is necessary to change time of closing the wicket gates and the flywheel effect of the generator rotor (and proportional to it the inertia constant of the unit $T_a$), so that to comply with given limitations. It is shown that with the given ratio $T_w/T_a = 0.35 = \text{const}$ to the diameters of the pressure tunnel in the range from 11.5 to 9.5 m there correspond: the closing time from 16 to 22 s, the flywheel effect of the generator rotor from 58,000 to 79,000 tm$^2$, inertia constant $T_a$ from 10.14 to 13.81 s.

4. With allocation of units to the isolated energy district the mode stability can be ensured by adjustments of the turbine governor which do not go beyond the permissible standard values (table 2). In power regulation the regulation time does not exceed 30 s, overregulation is 7-8%, time-lag of power change is 6-7 s.

5. Abandonment of construction of the compensating reservoir permitted to increase the specific speed of frequency and power regulation due to decrease in the proper frequency of pressure fluctuations in HPP pressure system.

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