Numerical Modelling and Transient Analysis of a Small Hydropower Plant

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Abstract—**This paper presents the development and evaluation of a mathematical model of the small hydropower plant (SHPP Plavisko), focusing on transient hydraulic phenomena during typical and emergency operational states. The model, created using modular hydraulic and turbine components, simulates the dynamic response of the system under various conditions, including start-up, normal shutdown, generator trip, and emergency closures. The results of numerical simulations are evaluated in terms of pressure transients, turbine rotational speed, and overall system safety. The findings provide valuable insights into the hydraulic design and operational safety of small-scale hydroelectric installations.**

Keywords: Hydropower, water hammer, hydraulic simulation

Introduction

The operation of small hydropower plants (SHPs) involves several transient hydraulic processes that occur during routine and emergency conditions. These include system start-up, shutdown, sudden load rejection, and turbine control manipulations. Although small hydropower systems operate at relatively low heads and moderate flows, improper control or inadequate design can cause dangerous pressure surges or cavitation within the penstock and turbine system.

This study focuses on the small hydropower plant SHPP Plavisko and aims to develop a mathematical model capable of predicting the hydraulic and mechanical behavior of the installation under a range of operational scenarios. The primary objectives were to construct a modular numerical model that accurately represents the hydraulic and mechanical components of the system, to evaluate transient pressures and rotational speeds under different operational states, and to determine safe opening and closing times for turbine guide vanes and valves, ensuring that neither overpressure nor cavitation occurs.

Methodology

The model of the hydropower plant was assembled using predefined computational blocks corresponding to key hydraulic and mechanical components. The upper boundary condition was modelled as a constant head reservoir, followed by a discretized penstock divided into 18 segments. The turbine was represented by a Francis turbine block with two variations: fixed and adjustable guide vane openings. The valve was placed upstream of the turbine, and the turbine shaft was coupled with a synchronous generator operating at 750 rpm.

From several tested solvers, the variable-step solver ode15s proved most stable and efficient. Relative tolerance was set between 10^{-6} and 10^{-9}. The friction factor in the penstock was calibrated to match the design head of 32 m at a discharge of 1.2 m³/s, resulting in $\lambda = 0.016$. The wave speed was calculated as a = 940 m/s.

Model Description

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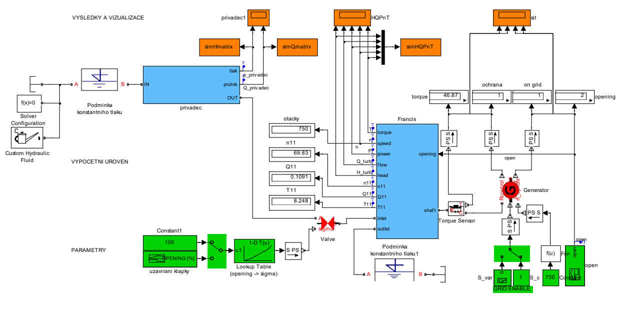

Figure 1 - Simulation scheme of SHPP with long penstock, Francis turbine, main valve and synchronous generator

Simulation Scenarios and Results

Two transition states that occur during normal operation of small hydropower plants were simulated: start-up at full power and normal shutdown. One critical transition state was simulated as a generator failure at full power followed by emergency closure of the control valve.

A. Start-up

Start-up is commonplace and should not critically load the hydraulic system, but it is assessed, nonetheless. Because start-up is driven by progressive guide-vane opening, the adjustable GV model with flow and torque characteristics (Fig. 2) is used.

Procedure used: linear opening to a = 2 over 10 s; generator synchronization to the grid after 60 s; then linear GV opening to full output over 50 s. Opening a = 2 corresponds to Q_{min} = 0.2 m^3/s.

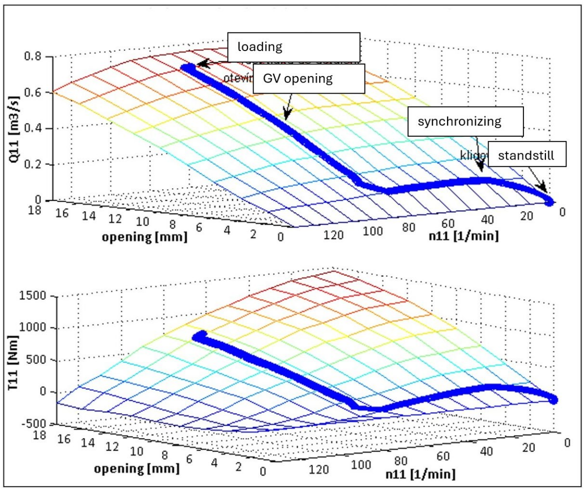

Figure 2 - Simulation of turbine startup and loading

As GV opens, discharge rises and net head across the turbine drops due to hydraulic losses and water inertia. The increase in flow also triggers negative pressure waves (water hammer), but these are quickly damped because the flow is sufficient. Synchronous speed is reached in roughly 50 s from initial opening. Torque peaks shortly after opening begins (rotating mass inertia overcoming); after grid connection torque reflects delivered power plus friction losses. The envelope of pressure minima (Fig. 3) shows no harmful vacuum for the proposed opening law.

GV opening time from zero to a = 2: ⩽ 4 s causes vacuum at least at one penstock location (critical around station 260 m); 10 s is safe with sufficient margin. GV opening from zero to full (a = 16): ⩽ 10 s leads to column separation; 10 – 30 s yields sub-atmospheric but non-cavitating pressures; > 30 s shows no vacuum.

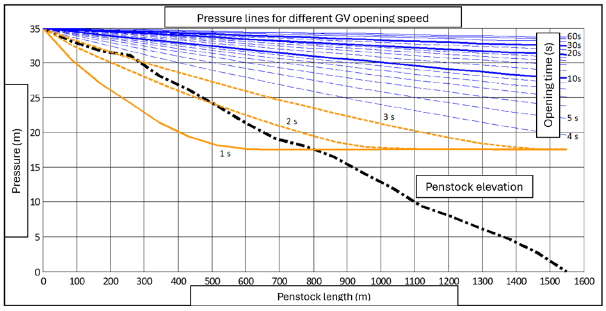

Figure 3 - Minimum pressure lines for different GV opening time

B. Normal Shutdown

A normal stop closes the guide vanes; the generator is disconnected just beforehand by reverse-power protection to avoid motoring. GV closure must avoid excessive surge and prevent vacuum in the penstock.

Design case: linear RK closure from full to zero over 30 s (with the same slope applied for partial-load shutdowns). During closure, discharge and speed decrease; the head upstream of the turbine rises, peaking at full closure. With zero discharge, surge damping is weaker than during start-up. Envelope assessment shows: ⩽ 10 s closure would overstress and cavitate; 11 – 20 s avoids overstress but may draw air through joints; ⩾ 25 s no vacuum. Therefore, 30 s is acceptable with safety margin (Fig. 4).

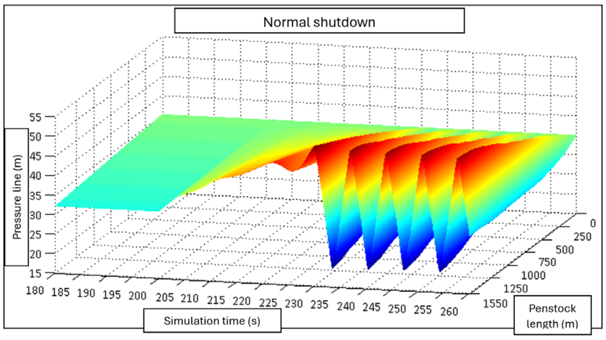

Figure 4 - Pressure as function of penstock length and time

C. Generator trip and GV closure

To avoid prolonged high-speed operation after a trip, a common response is rapid GV closure (Fig. 5). Model: adjustable GV; closure over 20 s beginning effectively at the trip (t = 200 s). The inlet valve remains fully open.

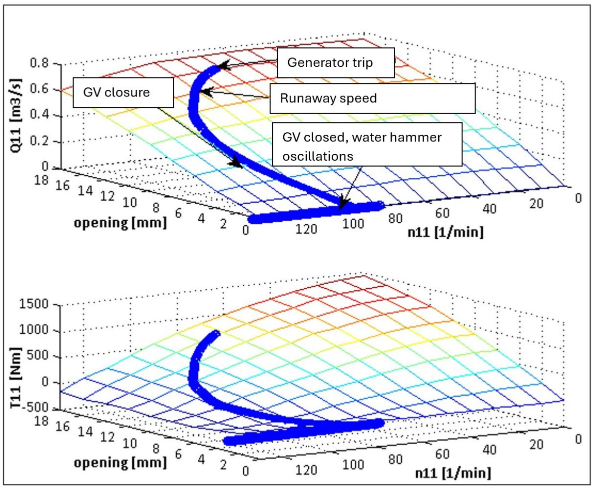

Figure 5 - Simulation of generator trip and emergency GV closure

Here, discharge falls due to both trip dynamics and GV closure, so head rises, and a water hammer develops (Fig. 6). With zero discharge at the end, damping is small. Because turbine characteristics shift with opening, the set accelerates to a higher peak speed than in 5.4.3, reaching about ~1370 rpm, then is hydraulically braked to rest (negative torque/power). Envelope plots show the chosen 20 s closure is safe (Fig. 7): no overstress and no damaging vacuum. Parametrisation indicates: ≤ 10 s causes high-pressure exceedance and cavitation risk; 10–16 s no overstress but vacuum/air-ingress possible; ≥ 17 s no vacuum.

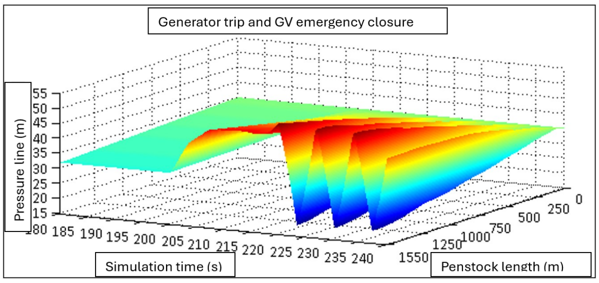

Figure 6 - Pressure as function of penstock length and time

If closure is long enough, the trip-induced wave and the closure-induced wave do not peak simultaneously, increasing slope rather than peak magnitude; this allows shorter safe closure times than normal shutdown.

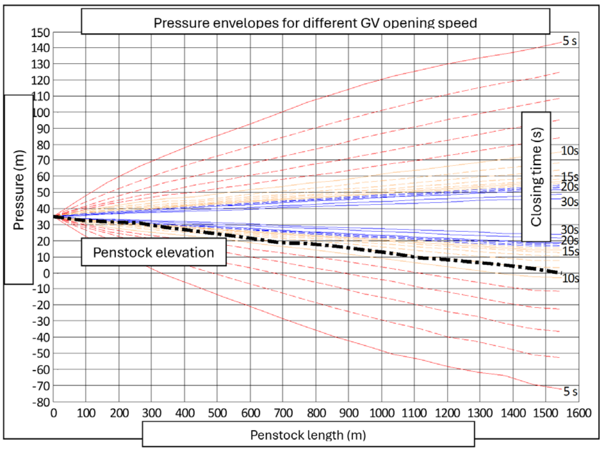

Figure 7 - Envelope of min/max pressure lines for different GV closing times

Discussion

The simulations highlight the importance of control sequences. Start-up and shutdown times critically affect pressure transients. Generator trip events are dominated by mechanical overspeed, whereas combined hydraulic-mechanical interactions occur during emergency closures. Compound valve closure proved an effective compromise between fast response and acceptable hydraulic load.

Conclusions

A detailed numerical model of the SHPP Plavisko hydropower plant was successfully developed. The study confirmed safe operational parameters for start-up, normal shutdown, and emergency states. Closure times longer than 20 s ensure safe hydraulic conditions. The inclusion of an air admission valve downstream of the main gate is recommended to prevent vacuum-induced damage. The model provides an essential tool for transient analysis and design optimization in small hydropower systems.

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References

[1] Josef Záruba: “Water Hammer in Pipe-Line Systems”, Elsevier, 1993

[2] M. Hanif Chaudhry: “Applied hydraulic transients”, Springer, 1987

[3] V. L. Streeter, E. B. Wylie: “Hydraulic Transients”, McGraw-Hill, 1967

[4] C. Nicolet: “Hydroacoustic modeling and numerical simulation of unsteady operation of hydroelectric systems”, EPFL Lausanne, 2007

[5] Nicolet, C.; Allenbach, P.; Simond, J.J.; Avellan, F.: „System Modelling of Hydraulic Power Plants for the Study of Electrical Power System Stability“, Hydro 2005 Conference, Villach, Austria