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HYDRODYNAMIC ANALYSIS OF WATER HAMMER PHENOMENA IN HYDROPOWER STATIONS UNDER TURBINE EXTREME OPERATING CONDITIONS

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ABSTRACT

This research article investigates transient hydraulic effects, particularly water hammer phenomena, in a hydropower plant (HEPP) through a comprehensive mathematical model and simulation analysis. Utilizing methods of characteristics and FORTRAN programming, the study develops a model that incorporates water hammer considerations, including friction, in the water conveyance system of the HEPP. The system layout encompasses an upstream reservoir, penstock, turbine unit, and downstream reservoir. The research explores the influence of guide vane closure and pressure regulating valve (PRV) opening and closing laws on pressure variations, mass oscillations, and water level fluctuations within the system. Numerical results indicate that PRV failure may not significantly impact turbine speed, but it results in excessive pressure oscillations in the spiral casing head, exceeding allowable pressure control values. The study identifies a critical PRV diameter of 0.6m, causing a maximum pressure in the spiral case of 370m, surpassing the acceptable limit of 250m, with a speed rise rate exceeding 50%. Conversely, a PRV diameter greater than or equal to 0.9m leads to unnecessary water energy loss. The findings emphasize the importance of carefully selecting PRV parameters to optimize system stability and efficiency. The study's comprehensive analysis provides valuable insights into the interplay of various parameters, contributing to a scientific basis for optimizing operational parameters and ensuring reliable and efficient hydropower plant performance.

KEYWORDS: Hydraulic transient, Pressure Regulating Valve, Hydroelectric power plant, Water hammer.

INTRODUCTION

The negative effect of water hammer has been problematic in hydroelectric power plants (HEPP) since the beginning of the first hydropower was created[1]. The collapse of the HEPP facilities due to water hammers generates a severe disaster in the hydropower station (HPS) and sometimes causes the plants' erosion and destruction [2-4]. Water hammer (WH) can be tested by an online examination of equipment performance and understanding of the state of hydropower generation systems [5, 6].

Water hammer in hydropower plants, even with the protection of pressure regulation valves and air chambers, can stem from instantaneous conditions due to sudden changes in the flow of water.

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One significant cause is rapid closure of the pressure regulation valve, creating abrupt variations in pressure within the system. This sudden closure generates water hammer effects, leading to pressure surges that can potentially compromise the integrity of the hydropower plant. Additionally, inadequate sizing or inefficiencies in the air chamber can contribute to water hammer by failing to effectively absorb and mitigate the kinetic energy generated during rapid changes in water flow. Addressing these factors through careful valve control strategies and optimizing air chamber design remains crucial for minimizing water hammer impacts and ensuring the stable operation of hydropower plants.

To control the water hammer in HEPP., any skilled and experienced engineer can easily recognize the location of fault or abnormalities of an HEPP unit before it causes the unit to trip. This can be assessed during the design studies. The safety of HEPP components reduces/avoids maintenance costs and similarly saves resources. The hydraulic researchers recognized the existence of the water hammer effect, but few recognized its catastrophic impact on the environment [7-14]. Some expenses and time are needed to repair and replace pipelines, their components and turbines, and pumps damaged by water hammer[7].

The condition of any component of HEPP is estimated by measuring and testing its behavior at certain water hammer levels. The water hammer influences and affects HEPP components in different factors, such as hydraulic and mechanical factors[15]. Investigating numerous causes and their control at the initial initial phase is essential for HEPP safe and permanent stability operation. Water hammer phenomena are the most dangerous phenomena in HEPP, resulting from the closing of the wicket gate and the sudden opening of wicket gates and sometimes resulting in the loss of life and property.

A water hammer pulsation analysis in an operational HEPP inhibits harmful resonances at power plant stations, so the trustworthiness or availability of the equipment increases. This article presents a full analysis of water hammer occurrence and control.

Nevertheless, several guidelines and standards are associated with the study area, such as IEC 61362 and Pejović et al. [16, 17]. IEC60308 briefly addresses the issue of inexactitude arising from computational programs and computer software packages. The standard acknowledges the inherent challenges and potential inaccuracies that may stem from utilizing such tools in engineering and technical applications, as computational methods play a crucial role in diverse fields, including industry and research. In contradiction, IEC 60041[18] suggests tolerances of pressure pulsation and fluctuation of wave speed in light[16].

Hydroelectric power plants play a crucial role in supporting electrical power grids, particularly in the volatile electricity markets of developing countries. Additionally, they contribute significantly to adapting power output to meet the dynamic demands of energy consumption. [19]. Meanwhile, **hydropower components,** such as the turbine and generator, operate **at maximum power,** load changes, and **the number of startup and shutdown sequences is increasing**. Hydraulic transients describe the disturbance in a fluid when the fluid goes from one **steady-state level to** another [20]. The flow disorders result from **the flow changes**, whereby the water's kinetic energy is transformed into pressure energy[21].

The study focused on the components of hydropower, especially protection devices. In particular, the allowed incremental of the rotational speed (runaway speed), the pressure (water hammer) increase, and the pressure intensity generated in the hydroelectric system and the turbine. Moreover, the FORTRAN programming language is used to simulate the 1-D transient phenomena in hydroelectric plants. M.O.C. was most usually used in water hammer simulation [22]. The various situations for investigation of the negative effect of transient (allowed values of runaway, water hammer, and the guide vanes' minimum closing time).

MODELING OF THE HYDRAULIC COMPONENTS.

Water hammer equation model

In the transient hydraulic calculation, from the continuity equation and dynamic equation of water flow, the fundamental equations of the water hammer can be deduced as follows:

$$\frac{Q}{A}\frac{\partial H}{\partial x}+\frac{\partial H}{\partial t}+\frac{a^2}{gA}\frac{\partial Q}{\partial x}-\frac{Q}{A}\sin\beta=0 \tag{1}$$

$$g\frac{\partial H}{\partial x}+\frac{Q}{A^2}\frac{\partial Q}{\partial x}+\frac{1}{A}\frac{\partial Q}{\partial t}+\frac{fQ|Q|}{2DA^2}=0 \tag{2}$$

Where Q and H are the discharge and head in the pipe, respectively; A is the cross-sectional area of the pipe; x is the distance along the pipe; t is the time; a is the wave velocity of the water hammer; g is the gravitational acceleration; β is the longitudinal slope of the pipe; f is the friction coefficient; D is the pipe diameter. Leaving out minor items in the fundamental equations, hyperbolic partial differential equations are obtained, which can be transformed into ordinary differential equations using the characteristic method. With boundary and initial conditions, pressure and flow during the transient process in the pressure conduit can be calculated [12].

PRV opening model.

The Pressure Regulating Valve opening model determines the controlled mechanism for regulating and adjusting fluid pressure within a system, providing a mathematical representation of the valve's behavior. Spear valves usually control the flow to impulse turbines[23, 24], and the valve suddenly moves to a new position [25]. Bernoulli's equation gives the discharge of the valve through the pipeline.

$$Q = C_d A_0 \sqrt{2gH} \tag{3}$$

Where C_d is the coefficient of the flow rate of the valve, and A_0 is the cross-section area at the entrance of the valve. The range of openings over which the valve controls the flow is essential for sizing pressure-reducing valves and determining the safe closure time for control valves [21].

The Friction and hydrodynamic forces that are required to open or close quarter-turn valves (which rotate 90° like butterfly and cone valves), the friction, and other forces that act on the valve seat and bearing surfaces. The effects caused by the flowing water cause hydrodynamic torque (T)[26]. This torque can be related to the valve diameter (d) and velocity (F) or pressure drop (P) by the following equations[21].

$$C_{tv} = \frac{T}{\rho d^3 v^2} \tag{4}$$

The maximum range of openings over which many valves can accurately and safely control flow is generally between 10 and 90% open [21, 27].

Like pressure regulating valves, dumping devices are established to overcome the excess of high pressure in the system during a positive or negative excursion of the system pressure. Their first working principle is to open at pre-determined system pressure [6] and release some fluid discharge to prevent the high pressure from exceeding a specified standard. However, its second function is automatically re-closing after the average system pressure is restored [27, 28]. The PRV is designed to open fully within an over-pressure of 10% and to offer stable operation over its operating conditions [27, 29, 30].

The pressure-regulating valve as the dumping device relies on dry friction for damping oscillations. It uses lens-shaped friction elements of hard electrographite packed in a chamber between spring-loaded compression elements to force the friction elements against the stem [27, 28]. When, during a transient, the pressure increases and exceeds the calibrated value of the spring, the valve opens, and water outflows [31]. The primary function of pressure regulator devices is to control the pressure of the flowing fluid in systems [32]. In hydraulic systems, these pressure regulator devices are also used to unload the hydraulic machine, such as a pump/turbine, and to maintain system pressure at the expected values.

Governing equations of PRV

The PRV equation comes from the characteristic equations, which are:

$$H_{P1} = C_P - R_P Q_{P1} \tag{5}$$

$$H_{P2} = C_M + R_M Q_{P2} \tag{6}$$

When the nodes of the inlet and outlet of the PRV are (5) and (6), respectively, the formula reflecting the pressure in the inlet and outlet and the flow of the PRV is as follows:

$$Q_{P1} = Q_{P2} = Q_P \tag{7}$$

$$Q_P = f(\tau) D_x^2 \sqrt{H_{P1} - H_{P2}} \tag{8}$$

Where Qst is the discharge of the P.R.V.; Ast is the opening of the P.R.V.; Zst is the diameter of the PRV Solving Equation (5), (6), (7) and (8) simultaneously results in

$$Q_P = \frac{\Delta H_P f(\tau)^2 D_x^4}{2} \tag{9}$$

$$\text{the } \Delta H_P = \sqrt{(R_P - R_M)^2 + \frac{4(C_P - C_M)}{f(\tau)^2} - R_P - R_M +} \tag{10}$$

The valve opening selection and closure time speed are essential for transient control Concerning the water hammer. Other valves, like ball and plug valves, provide comparable performance for the linear valve actuation since most of the flow is reduced during initial valve closure [33]. Monitoring fluid flow in hydraulic systems is essential because the rate (velocity) of the movement of fluid-powered hydraulic machines depends on the pressurized fluid flow rate [34].

Mathematical equations for Turbine draft tube

The draft tube is one of the essential parts of the hydraulic turbine units. The function of the draft tube is to transform the kinetic energy at the runner exit point into potential energy. Therefore, a draft tube increases the turbine's efficiency (raising the runner's head). One of the significant challenges in the turbine is a vortex rope gaseous volume at the off-design operation. The vortex rope is overcome with unwanted periodical pressure pulsations (pressure waves) inside the draft tube. These pressure pulsations produce existing forces that can influence components of all methods of a hydroelectric power plant.

Using a one-dimensional method can be explained as the turbine draft tube model. Designing and modeling the pipeline with a known pressure source excitation in series with two pipes depends on the length and cross-section of the pipeline attained from the draft tube and the wave speed as input parameters.

The vortex rope gas volume modeling is based on the basis that the gaseous volume V relies upon the condition of variables: net head (H) and the flow rate (Q). Gaseous volume changes are given by the periodic flow-rate changes between the two fluid sections limiting the rope[20]

1.1 $$\mathbf{\frac{dv}{dt} = Q_1 - Q_2 = C\frac{dH_2}{dt} + x\frac{dQ_2}{dt}}$$ 1.2 (11)

, Where: $\mathbf{C} = \frac{\partial \mathbf{V}}{\partial \mathbf{H}}$ is cavity compliance and $\mathbf{x} = -\frac{\partial \mathbf{V}}{\partial \mathbf{Q_2}}$ It is the mass flow gain factor. Inertia and friction loss effect of gas volume the area negligible. i.e. $\mathbf{H_1 = H_2}$

Continuity equation $Q_S = Q_P$ (12)

Equations of a characteristic method $C^{+}: Q_P = C_P - B_P H_P$ (13)

Equations of a characteristic method $C^{-}: Q_S = C_M - B_M H_S$ (14)

Flowing equation of turbine $Q_P = Q_{11} D_1^2 \sqrt{(H_P - H_S) + \Delta H}$ (15)

Equations of unitary parameters $n_{11} = nD_1 / \sqrt{(H_P - H_S) + \Delta H}$ (16)

Equations of unitary parameters $M_t = M_{11} D_1^3 (H_P - H_S) + \Delta H$ (17)

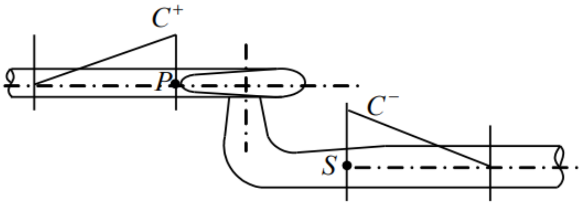

Fig. 1 Illustration of the Francis turbine model

CASE study layout of hydroelectric power plant

Below is the mathematical model of an hydropower plants located in China that comprising an upstream (intake) reservoir, penstock, turbine unit, and downstream reservoir. This study's water hammer phenomena analysis simulates transient hydraulic effects. The subsection number of the water conveyance system is presented in

Fig. *2* Layout of the hydropower plant as a case study

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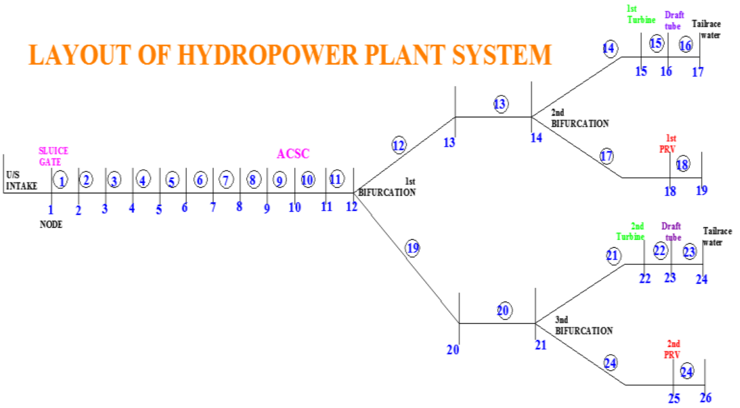

Fig. 2 Layout of the hydropower plant as a case study

This article used characteristic methods to investigate and simulate hydraulic transients in pipeline and hydroelectric power plants. FORTRAN programming language used to build a model that calculates water hammer, including friction.

In this research work, the simulation of transient pressure was divided into water hammer in the conveyance system of hydropower, water level fluctuation in the hydropneumatics tank, and its effects on turbine rotational speed.

NOMENCLATURE

Symbols	Descriptions	Symbols	Descriptions
FORTRAN	Formula translation	**ΔH**	Change in the head, m
A_{in}	Inflow cross-sectional area in m^2	**Δt**	Variation of the time interval
C_d	Discharge coefficient	**ΔV**	Change in fluid velocity, m/s;
A_v	Area of valve opening	**D**	Pipeline Diameter in meter
Q_C	Discharge in the chamber in m^3	**dt**	Change in time in seconds
H.R.	Elevation of the reservoir surface	**f**	Darcy-Welsbach friction factor
a	Characteristic wave celerity of the fluid	**L**	Length of pipeline
A	The cross-sectional area of the tank	**H**	Pressure head or water head
Ap	Cross-sectional flow area m^2	**M/s**	Meter per Seconds
P.D.E.s	Partial Differential Equations	**P**	Pressure head in the pipe
K	Bulk Modulus of Elasticity	$\mathbf{P_{max}}$	the maximum transient pressure
$\mathbf{K_E}$	Loss coefficient for the entrance	$\mathbf{P_{min}}$	the minimum transient pressure
$\mathbf{P_f}$	the pressure at the end of the transient	**A.C.**	Air chamber
$\mathbf{P_i}$	initial pressure at the start of the transient,	**P.R.V.**	Pressure Regulating Valve
V	Velocity along the pipeline (x)	**Q**	Discharge in m^3
Δp	Change in pressure, in Pascal	**T**	Time interval
F_s	Force applied on a surface	**ΔA**	Change in Pressure in Pascal
γ	Fluid density	M.O.C.	Method of characteristic
∂p	Change in pressure	A_0	The cross-section area
ρ	Water density	**H.E.P.P.**	Hydroelectric power plant
HPP	Hydropower Plants	M.O.C.	Method of characteristic
e	Pipe thickness,	$\mathbf{C_d}$	**1.3 Flow-rate coefficient of valve**
ε	1.4 The bulk elasticity modulus for	$\mathbf{H_b}$	Barometric pressure head

Symbols	Descriptions	Symbols	Descriptions
	water		

Table 1: System parameters of the turbine and pipeline system

Parameters for unit -1	Values	Parameters for unit -1	Values
Rated head Hr(m)	199.2	Rated head Hr (m)	199.2
Runner diameter D1(m)	3.5	Runner diameter D1 (m)	2.35
Turbine-rated power Pr (M.W.)	70	Turbine-rated power Pr (M.W.)	34
Nominal flow Qr (m3/s)	39.4	Nominal flow Qr (m3/s)	19.6
Rated speed nr (r/min)	250	Rated speed nr (r/min)	375
Rated point %	93.8	Rated point (%)	93.8
Specific speeds nr (M.kW)	93.6	Typical speeds (M.Kw)	93.6
Specific speed coefficient k	1320	Speed factor (k)	1320
Installation height (m)	1490	Installation height (m)	1490
Moment of inertia (t.m2)	3600	Moment of inertia (t.m2)	7800
Roughness coefficient in the pipe	0.012	Roughness coef. of casing valve	0.011

Pressure and Mass oscillation in the water conveyance system

The HEPP conveyance system's pressure is the algebraic sum of the hammer and hydrostatic pressure when the HEPP station's load rejection transition decreases. The selection of the Pressure Regulating Valve (PRV) diameter in hydropower plants is a critical consideration, as it should neither be too large nor too small. An oversized PRV may lead to excessive pressure drops, resulting in inefficient energy utilization and potential cavitation issues. On the other hand, an undersized PRV may restrict the flow, causing backpressure, decreased efficiency, and increased wear on the system components. The optimal diameter ensures that the PRV effectively regulates pressure, balancing the hydraulic conditions within the system while avoiding unnecessary energy losses and maintaining the overall efficiency of the hydropower plant. Thus, a judicious choice in PRV diameter is essential for achieving optimal performance and longevity in hydropower operations. When the load is discarded in the HEPP station, the unit's guide vane closes quickly, and the pressure regulating valve opens quickly. The reduction of the total flow in HEPP penstock will cause the wave of pressure to rise, as shown in Fig. *3*. The flow pressure in the penstock gradually declines, and the water flow in the diversion tunnel flows into the pressure regulating well, leading to a constant change in water level.

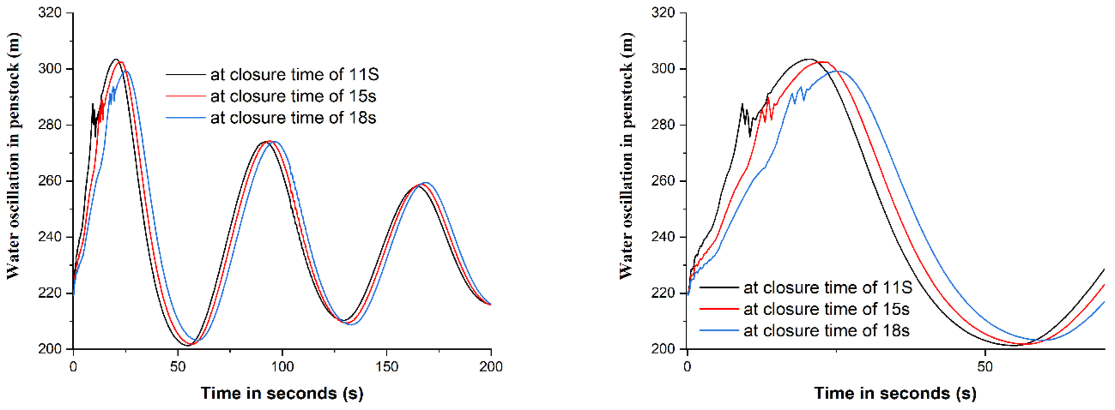

Fig. 3 Mass oscillation in penstock after closure

For HEPP., pressure variation in penstock and limited speed of guide vane change is essential for stable and reliable performance at the varieties for the output power, particularly at load acceptance and sudden shutdown. **Error! Reference source not found.** shows the water oscillation behavior versus closure time responses of the guide vane opening and closing at different times, and the frequency-time response is described. It is clearly shown that, as long as the wicket gate will close after 10 seconds, the pressure rises in the penstock, respectively.

Fig. *4* shows mass oscillation in the throating of ACSC.

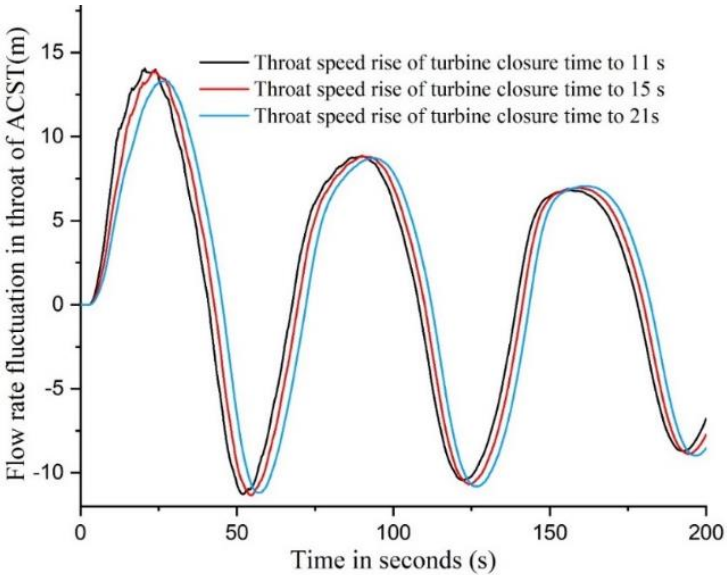

Fig. 4 Flow rate variation of A.C.S.C. throat after closing and opening law

Opening and Closing Law of Wicket Gate and P.R.V.

The water hammer pressure can be diminished while limiting the increase of unit speed by adjusting the guide blade closing rule, which is an easy and effective way. Usually, a straight line is used to establish the governor's reliability in opening and closing the rule when the guide vane and PRV linkage are used. The PRV closing time mainly influences the rising wave pressure at the end of the volute. Nevertheless, when the PRV is kept fully open, the appreciation effect of the volute's end pressure is minimal. Hence, a more diminutive time lag was utilized to reduce water loss.

Meanwhile, when HEPP is equipped with PRV, the closure of the wicket gate is immediately initiated to reduce the rotational speed unit's rising during load rejection; if the (PRV) is inactive during load rejection in a hydropower plant, it is advisable to close the wicket gate gradually. This controlled closure helps mitigate the effects of water hammer, a phenomenon caused by sudden changes in fluid flow that can result in damaging pressure surges. The gradual adjustment of the wicket gate minimizes the abrupt changes in water flow, reducing the likelihood of water hammer and safeguarding the integrity of the hydropower system. This measured approach to wicket gate closure serves as a preventive measure, ensuring a smoother transition during load rejection and enhancing the overall stability of the hydropower plant. In this case, the maximum rotational speed should be controlled to be less than the full runaway rotational speed. For the HEPP with PRVs, to control the pressure pulsation, the wicket fast-closing law is required for a PRV standard opening, while the wicket slow-closing law is for inactive PRVs.

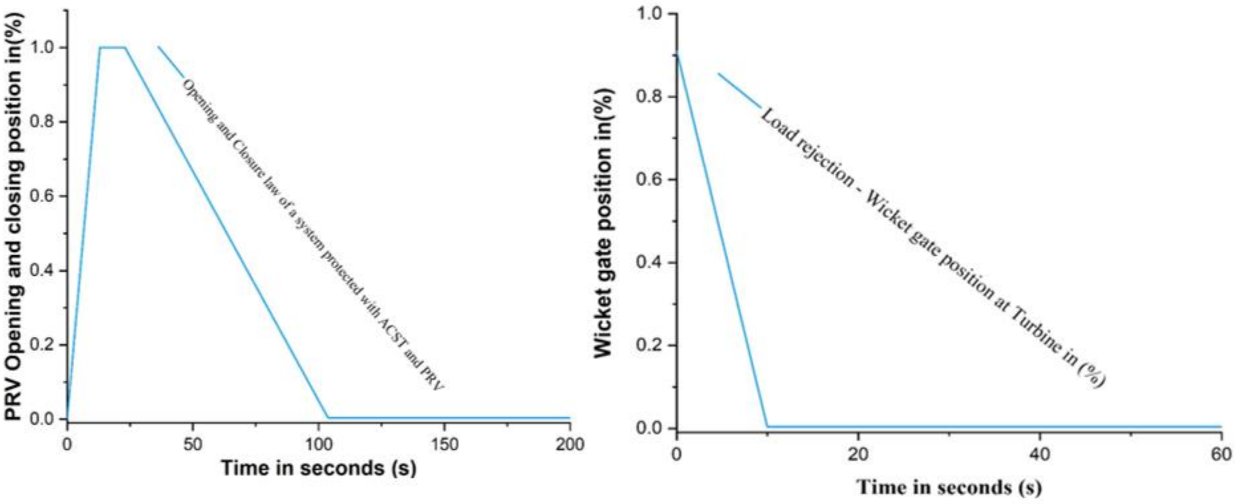

Fig. 5 Opening and closing of pressure regulating valve and Guide vanes closing law

The simulation shows that in the opening and closing laws when the PRV.'s closing time is equal to 10s and 100s, respectively, the maximum pressure at the spiral case is 320 m. To reduce water energy loss, a reasonable closing time of more than 110s would give a better result. The calculation results of opening and closing show that PRV.'s delay time keeping fully open has little impact on the unit speed and the appreciation of spiral case pressure. Therefore, PRV.'s delay time should be decreased to reduce hydraulic interference and water loss.

Throughout the earlier analysis of the guide vane closing time and PRV opening and closing law, the unit guide vane quickly closed, and pressure-regulating the valve's rapid opening time is recommended. The recommended closing time of PRV is equal to 110 seconds, and the delay time of keeping the full open is 11 seconds. Currently, the maximum pressure value at the end of the spiral case is 320m.

Table 2: Different outputs from opening and closing rules of the PRV

Opening/ Closing Law	Max. The pressure of Spiral Case	Max. Speed rise rate (%)	Min. tail water inlet pressure	Max. pressure before PRV (m)	Min. pressure after PRV (m)
1	311.19	40.73	2.96	197.96	3.55
2	304.87	44.06	3.04	197.94	3.82
3	302.34	47.57	3.09	197.61	4.00

As shown in Table 2, the maximum pressure at the spiral case and the unit's maximum speed rise rate have been significantly improved due to the pressure regulating valve's opening, which can meet the maintenance requirements adjustment calculation.

The calculation results indicate that the closing time of the guide vane influences the unit's speed, showing a gradual increase in unit speed with a corresponding extension of the guide vane's closing time. The rotational speed can satisfy the control standard. Because the total overflow of the selected PRV is less than the initially quoted flow of the unit, the closure of the guide vane of the unit will cause the rise of spiral case pressure, and the first wave pressure peak appears at the end of the closure of the guide vane of the unit. Due to the water hammer pressure caused by the valve closing, a new wave of enormous water hammer pressure will appear at the end of the valve closing. Therefore, under the premise that the unit's maximum speed rise rate is less than the control standard, the unit closing law should be extended as far as possible.

Effect of mass oscillation in air cushioning surge chamber

The situations in which the continuum hypothesis is not justified may happen during the sudden opening of the gates when the water pressure falls to the water vapor pressure due to a sudden increase in flow rate. Suppose preconditions for those mentioned above are ensured. In that case, they will be manifested by the interruption of the water column [9]. The basic equation system must be extended by combining appropriate constitutive relationships that introduce the change of phase[10]. Mass oscillation due to different closing times of the wicket gate of the turbine

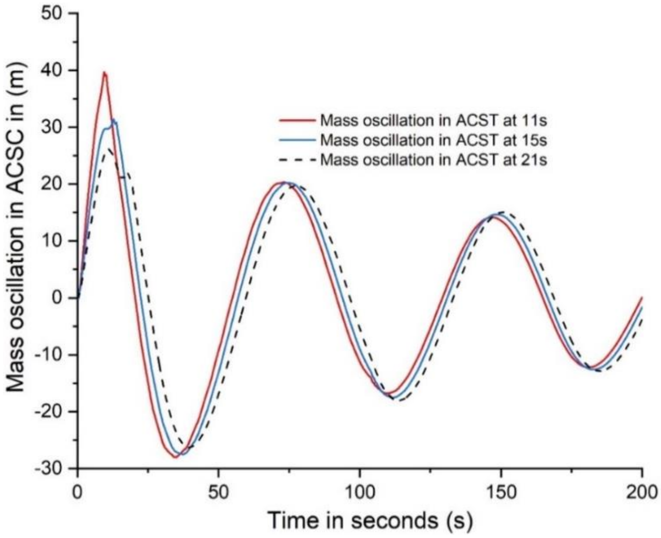

Fig. 6 Mass oscillation in the air cushioning surge chamber

The modeling of water level oscillations in air cushioning chambers is discussed for a typical high-pressure HEPP and the defined flow rate variables in the powerhouse. An approach of incremental integration of the continuity equation has been used in this study. The concept is based on simulating the water entrance to or exit from the air cushioning chamber with a range of fictitious time states. In this way, the variation of water volume Δv that occurs during filling or emptying the air cushion surge chamber in a one-time incremental is subdivided into small equal segments Δvk. The small individual volume of the segment is suddenly discharged into the air cushion surge chamber. The identical variation in water level Δkz is assessed under the hypothesis that the cross-section of the air cushion surge chamber is constant. At that, the air cushioning surge chamber cross-section for the current volume segment Δvk is assumed to be similar to the particularized air cushion surge chamber cross-section.

The alteration in water level corresponds to the gradual decrease or addition of the volume Δvk within the air cushioning surge chamber. The flow rate in the headrace tunnel is determined by maintaining the water level in the air cushion surge chamber. Simulation algorithm results were executed using the Fortran program to generate numerical applications. These techniques were devised to outline the dimensioning method for the air cushioning surge chamber, encompassing scenarios involving water level oscillations following load acceptance and load rejection in the hydropower plant. The method accommodates fluctuations in air cushioning surge chambers, including mass oscillations triggered by variations in the cross-sectional diameter of the air cushioning surge chamber.

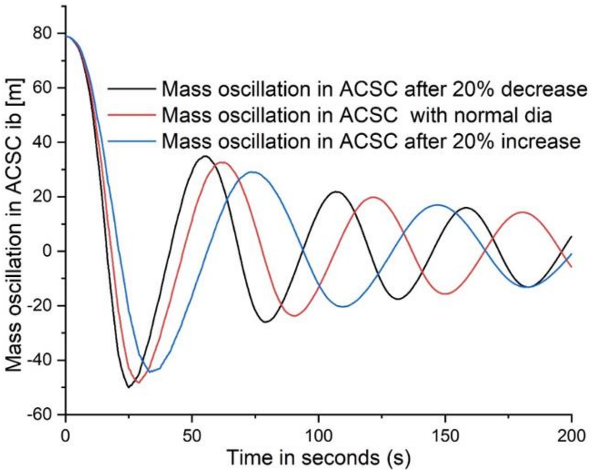

Fig. 7 Water level fluctuation in ACSC due to the air chamber cross-section area variation.

Oscillation results for the initial air cushioning surge chamber geometry prove that the determined closing rate will result in water spilling from the chamber. However, by increasing the diameter, a specific reduction in the maximum amplitude was established, as well as the influence of the change in the air cushioning surge chamber geometry.

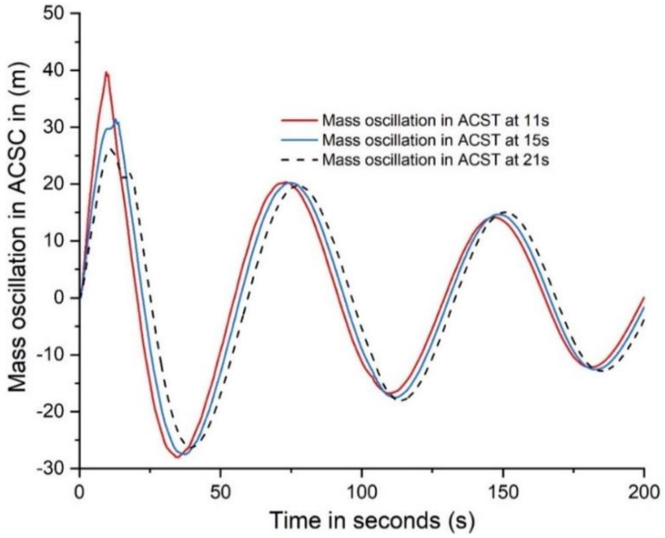

Fig. 8 Change in mass oscillation in ACSC after closure time.

The change in geometry on the oscillation is even more pronounced in the following example. In addition, the guide vane is fast closed in a short time, and the water level of the ACSC changes slightly in the closing process. Therefore, the excessive pressure should be decided by the water hammer pressure. The PRV diameter increase will decrease the water hammer pressure caused by the guide vanes closing and reduce the spiral case's maximum pressure.

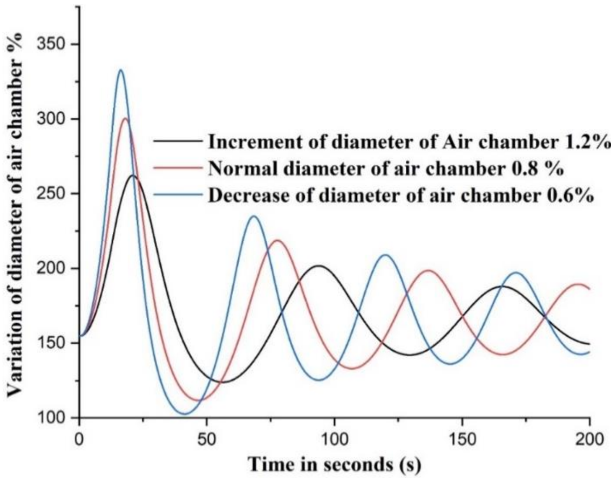

Fig. 9 Water level in ACSC after 11,15 and 21s of closure time and after increasing the ACSC area

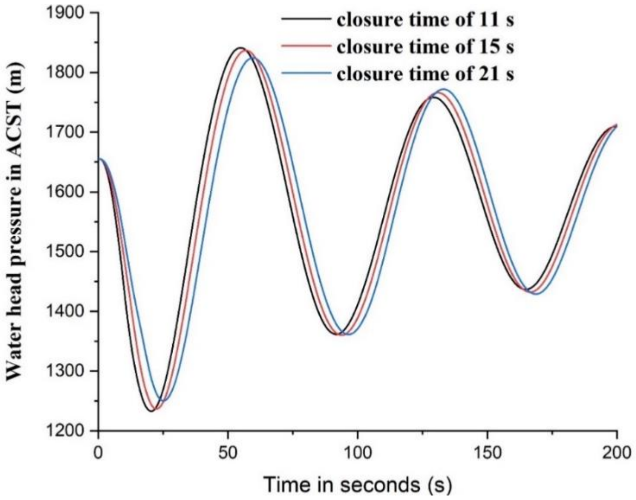

Fig. 10 Water head pressure in ACSC after different closure times

The behavior of the turbine spiral case and PRV during the water hammer

The working condition with the maximum pressure of the volute turbine under the maximum head suddenly dumps the load simultaneously. The guide blade is usually closed and is selected as a working condition. The guide vane of the unit set is completed with a 10s, while the PRV is opened with a straight line of 10s, and after reaching full opening and 10s, the PRV is closed with a straight line of 110s. The simulation results are discussed in
Tabl.

Table 3: Linear closing law for the condition of PRV diameter on pressure rise and speed rise in the turbine’s spiral case.

eter in	Condition of system components after simulation	
	Hydraulic unit two	Hydraulic unit two

	Maximum pressure at the end of the spiral case (m)	Maximum speed rise rate (%)	Maximum pressure at the end of the spiral case (m)	Maximum speed rise rate (%)
0.4	351.230	43.97	325.6663	42.419
0.6	302.348	41.78	304.6763	40.42
0.8	288.299	39.46	290.536	38.443
1	281.545	38.06	283.5051	36.944
1.2	281.376	37.07	283.7291	35.955

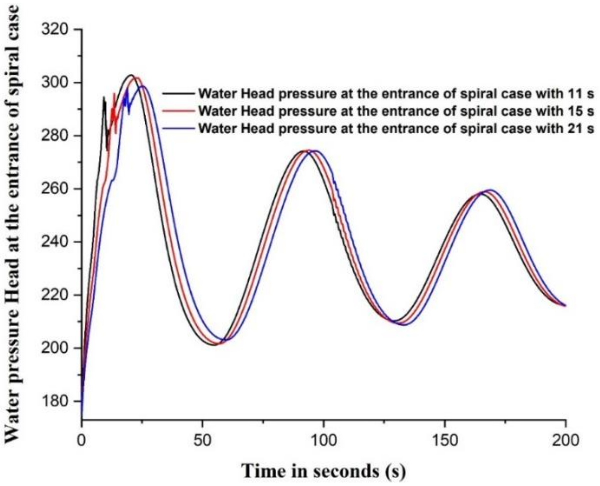

Fig. 11 Pressure fluctuation of turbine spiral case with closure time

Tabl shows how the PRV diameter increases and how the PRV's overflow also increases. The pressure relief effect on the unit's pressure channel during load rejection is even better, so the spiral case of excessive pressure and PRV decreases. According to PRV's selection principle, the appropriate valve diameter should be close to the maximum water hammer pressure generated by the guide vane closing process and the water hammer pressure generated at the end of PRV. This is on the premise that the PRV closing time is not too long. The corresponding safety margin is maintained; the more significant the PRV diameter, the more water it discharges in the same period, so the smaller the rising water level in AC and thus the smaller the hydrostatic pressure. As discussed earlier, the influence of PRV diameter on the maximum pressure of the spiral case in the second wave is uncertain, which is different from the HEPP with only PRV.

Water hammer at turbine draft tube

The flow variation increases the sudden pressure spiral case of the turbine, which mostly appears during the turbine load acceptance and rejection or wicket gate opening and closing. The negative effect of pressure increase in the turbine spiral case is known as a water hammer, whose adverse effects are devastating equipment, broken pipeline systems, and different turbine components. The figure below summarizes the maximum pressure values that might occur during turbine load rejection, affecting the penstock.

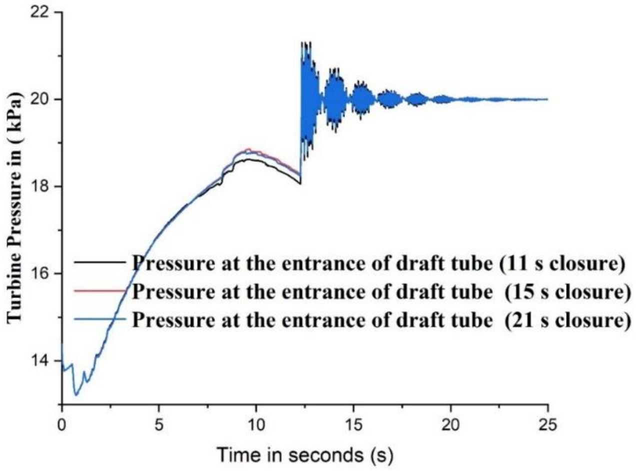

Fig. 12 Turbine pressure variation at the entrance of the draft tube

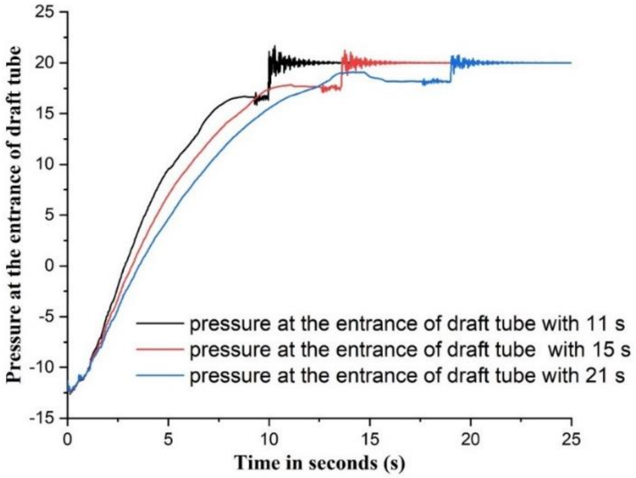

Fig. 13 Pressure rise at the entrance of the spiral case

Effect of turbine rotating speed with different closure time

The PRV diameter on the maximum speed rising rate with the same discharge volume of the conduit in the same condition during turbine load rejection, the PRV diameter; the larger its discharge volume, the less the water is flowing through guide vanes, so the lower the on the maximum rising rate of turbine speed. The more valuable it is to determine whether the larger the PRV diameter will generate the rise of water hammer pressure in the HEPP station, influencing the system's performance.

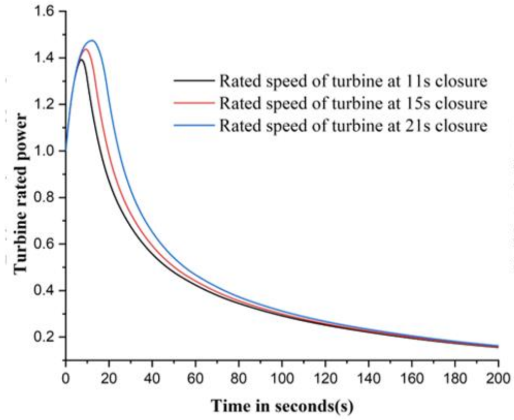

Fig. 14 Rated turbine speed with different closure laws

Based on the simulation, PRV bankruptcy may not significantly impact the turbine speed, but investigation of the spiral casing head as the essential parameter gives excessive pressure oscillations. The PRV failure is examined; in real computations, this regime is negligible, with almost no chance to occur again. However, it describes the most severe spiral casing pressure head raise. Therefore, when the PRV diameter combination is 0.6m, the maximum pressure of the spiral case is 370.m, exceeding the allowable pressure control value of 250m, and the maximum speed rise rate is more than 50%. When the PRV diameter is greater than or equal to 0.9m, the maximum pressure of the spiral case and in front of the PRV is controlled by the highest surge wave in the upstream pressure regulating well, which almost remains unchanged. This indicates that the PRV diameter is too large, and it causes unnecessary loss of water energy. Below, **Error! Reference source not found.** describes the effect of rated power produced during the load rejection.

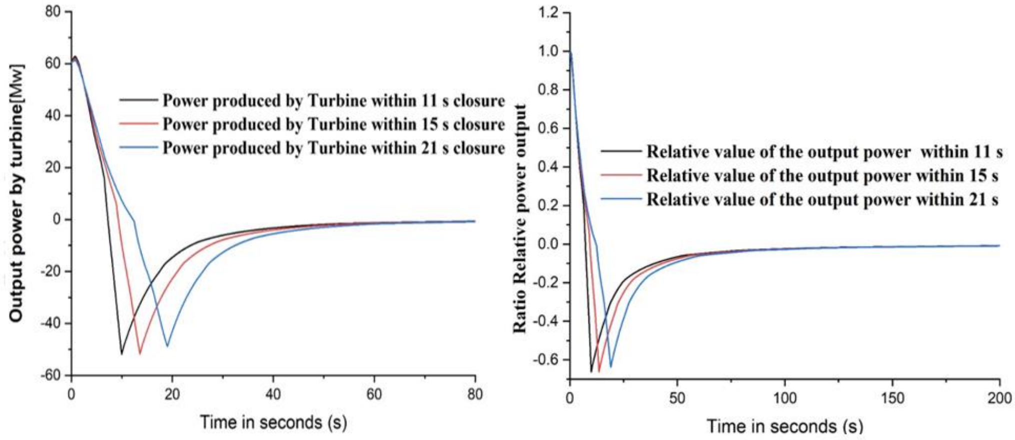

Fig. 15 Effect on power produced during the load rejection

CONCLUSION

In summary, this research article has provided a comprehensive exploration of transient hydraulic effects in a hydropower plant, explicitly focusing on water hammer phenomena. Utilizing methods of characteristics and FORTRAN programming, the study systematically analyzed the impact of guide vane closure and pressure regulating valve (PRV) laws on various system parameters. The simulations highlighted the critical role of carefully chosen parameters, such as PRV diameter and closure times, in optimizing system stability and efficiency. Notably, the research emphasized the importance of adjusting guide vane closing rules and PRV closure times to mitigate water hammer pressures and control unit speed rise during load rejection. The study also delved into mass oscillation effects in air cushioning surge chambers and examined the behavior of turbine spiral cases and PRVs during water hammer events. The insights gained offer valuable recommendations for optimizing closure times and diameters, promoting system stability, and minimizing water energy loss. Specifically, the study suggests a PRV closing time of 110 seconds with an 11-second delay for keeping the valve fully open to reduce pressure pulsations. Additionally, it advocates for a balanced selection of PRV diameters to avoid energy losses and pressure fluctuations. Emphasizing the quick closure of guide vanes during load rejection and the use of straight-line closing laws for both guide vanes and PRVs, these recommendations contribute to the overall optimization of hydroelectric power plant operations, ensuring efficiency, stability, and equipment longevity through informed design and operational practices.

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DATA AVAILABILITY: Some or all data, models, or codes supporting this study's findings are available from the corresponding author upon reasonable request.

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