ANALYSIS OF THE EFFECTS OF CLOSING PROCESS OF GUIDE VANES ON THE WATER HAMMER PRESSURE VALUE OF THE HOUYA HYDROPOWER STATION, LAOS

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Abstract: *This paper presents the numerical simulation results to analyze the effects of the closing process of guide vanes on the water hammer pressure values and fluctuations in the surge tank for the Houya Hydropower Station, Laos. The three processes of opening and closing the unit at the respective durations of 8.2; 8.04 and 7.18s show that the water hammer pressure value increases 60%, 58.2% and 58% respectively. This result shows that it is not possible to have this limited overpressure in 8 seconds closing time with any torque of the unit of* GD^2*. For the selected speed of the machine, it is recommended that the results are satisfactory with 30 seconds closing time. It is also recommended to use the results of vertical pressure distribution along the energy line in case 3 to design the structure of the box channel and steel pipe, ensure no breakage for the box channel and safety for steel pipe.*

Keywords: Numerical simulation, guide vanes, water hammer, hydropower station.

1. INTRODUCTION

Water hammer in hydropower plants is caused by turbine load acceptance and reduction, load rejection under governor control, emergency shutdown and unwanted runaway, and closure and opening of the safety shutoff valve. It induces pressure rise or drop in hydraulic systems, rotational speed variation in hydraulic turbomachinery (pumps and water turbines) and level fluctuation in surge tanks and air chambers (Urbanowicz, 2017).

To control the value of the water hammer control, we had different solutions such as: optimization of closure law of guide vanes; surge control devices (surge tank, pressure regulating valve, flywheel, etc.); redesign of the water conveyance system components (tunnel, penstock); or limitation of operating conditions (limited operating range); addition of flywheel weight to increase the moment of inertia (GD^2) of the rotating components and so on. However, compared to these options, variation of the closure law of guide vane is the most economical option, since the closure law can be modified from the governor without the installation any new equipment in the system (Chen Sheng, 2013; Xiaoqin Li, 2013).

The closure law of guide vane can be linear, curved or the broken line with various stages. Considering the reliability in operation, the curved closure law is rarely used and the broken line closure patterns usually have less than three stages and hence, the two-stage closure law is the most preferred closure pattern for the designer (Cui, 2015). Chen Sheng et al. (2013) studied the effects of the different parameters of two-stage closure parameter on the maximum pressure and rotational speed. Xiaoqin Li et al. (2013) proposed an asynchronous closure of the different wicket gates to control the maximum pressure at the spiral casing. Zhou et al. (2010) used the linear objective function to harmonize the contradiction of maximum pressure and maximum speed for a two-stage closure pattern. Zhou used simulated

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annealing algorithm to find the optimum parameters of closure pattern. Saroj Chalise (2019) focuses on the optimization of two-stage closure pattern of guide vanes with non-linear objective function of two sub-goals. The optimized parameters have effectively harmonized the contradiction of rise of hydrodynamic pressure and rotational speed, ensuring both the target parameters within the permitted scope. Nguyen and Truong (2019) presents the experimental results to investigate the effects of the guide vanes opening on the characteristic curves of a reversible turbomachine, so called Pump as Turbine (PaT) when operating in two modes: pump and turbine. This study builds and evaluates the optimal operating area of the guide vanes for a PaT.

The researches on optimization of closure law and the effect of closure law on the various target parameters (maximum pressure, minimum pressure and maximum rotational speed) are abundant. They also found that for a medium head hydropower plant, the closing process of "slow after fast" is a better option to control the pressure and speed rises, compared to "fast after slow" in a two-stage closure pattern.

The above studies are academic and obvious, but the disadvantage is that the calculation is still based on the empirical formulas and hypothesis. Therefore, the results are less accurate. Some methods consider the calculations of the water hammer pressure and the fluctuation of water level in the surge tank are separate. Especially, many studies can not calculate the complex systems when having many Hydropower Plants on the same water pipeline system, with upstream and downstream surge tanks (such as Huoi Quang Hydropower Plant).

The main attention in this paper focused on the method for controlling changes of shut-off vanes. Cutting off the flow in such a manner that enable to maintain the pressure increases in the target range and to obtain quick stabilization of flow conditions is the most important task of practical realization in this method. In this study, we evaluated the effect of the different guide vanes opening and closing processes on the distribution of the water hammer in the pressure pipes and the fluctuation in the surge tank. Thereby, we also give suggestions and recommendations to improve the capacity of the project's exploitation.

2. THEORETICAL BASIS AND RESEARCH METHOD

2.1 Practical methods for calculating of the water hammer

Water hammer in hydropower plants can be calculated using either elastic or rigid water hammer theory as equation (1) (Ho et al., 2003).

$$\begin{cases} \xi_{n\theta,j+1} - \xi_{(n+1)\theta,j} = 2\mu.\left(q_{n\theta,j+1} - q_{(n+1)\theta,j}\right) - k.q_{n\theta,j}.\left|q_{n\theta,j}\right| \\ \xi_{n\theta,j} - \xi_{(n+1)\theta,j+1} = -2\mu.\left(q_{n\theta,j} - q_{(n+1)\theta,j+1}\right) + k.q_{n\theta,j}.\left|q_{n\theta,j}\right| \end{cases} \quad (1)$$

ξ: Relative water hammer pressure

$$\xi = \frac{\Delta H}{H_o} = \frac{H - H_o}{H_o} \quad (2)$$

μ: first characteristic of the pipeline

$$\mu = \frac{cV_{0\max}}{2gH_o} = \frac{cQ_{0\max}}{2gFH_o} = \frac{T_W}{t_f} \quad (3)$$

q: relative flow rate

$$q = \frac{Q}{Q_{0\max}} \quad (4)$$

H_o(m)- maximum static water column before water hammer occurs; H(m) indicates the water head at the cross-sections; Q_{0max}- maximum flow through the turbine corresponding to the water column H_o at steady mode with the maximum opening of the valve gate or turbine guide vane; Q(m^3/s) indicates the water flow rate at the cross-sections; indexes j, j+1 indicates the position of consecutive cross-sections; symbol θ indicates the time required for water hammer waves to transmit between the two studied cross sections; symbol n is a natural number, representing the generality of the system of equations; $n\theta$, $(n+1)\theta$ indicates consecutive times; F(m^2) is the clear cross-section of the pressure path between the two studied cross sections; c(m/s) is the velocity of the water hammer wave and in the pressure pipe between the two studied cross sections; g is acceleration of gravity; f is the coefficient of friction. Using this system of equations in combination with the initial and specific boundary conditions, we can determine the H, Q characteristics of the unstable mode at any section and at any time.

2.2. Transients software

In the past, it was difficult to simulate water hammer pressure by mathematical algorithm. With the development of the computer, mathematical algorithms become more popular and improved greatly. Numerical simulation has now become the main approach for transient analysis (Triki, 2018; Zhang, 2016). The key of the water hammer calculation is to solve the hyperbolic partial differential equations. Although the water hammer equation is a closed-form equation, no theoretical analytical solution is established at present.

In this research, we have studied and applied the characteristic line method of the water hammer wave transmission equation system, modeled, elementized, and programmed on the computer to solve the above problems at the same time. The programming uses VISUAL BASIC language. The program is increasingly improved with a user-friendly graphic, intuitive interface and fast calculation that helps the consultants save time and effort and improve reliability. This program calculates the flow and torque characteristics of the turbine, the unit adjustment system, the hydraulic and geometrical characteristics of all the parts of the pressure system, the elasticity of water and pipe casing. The program's calculation results serve as the basis for the designer to choose the construction solution, choose a reasonable opening and closing time, arrange the center elevation, the size and structure of the pressurized water lines, design the dimensions and the structure of the surge tank.

There are many hydropower projects that have applied this Transients software to analyze the water hammer pressure and the fluctuation of water level in the surge tank such as: Quang Tri, Huoi Quang, Suoi Sap 3, Ta Co, Za Hung, Nam Pong and others. Compared to the actual operating results, the results from this Transients software are suitable and reliable. Detailed information about this software is presented in the book (Nguyen et al., 2020).

2.3. The linear method for closing the different shut-off vanes

Commonly, there are three patterns: one-phase, two-phase and three-phase. The one-phase has the advantages of simple operation and easy implementation. It only must optimize its closing time, but its optimized space is small and cannot meet the safety requirements of complex working conditions. It can effectively control the increase in water hammer pressure but cannot suppress the increase in speed. The two-phase divides the closing of the guide vanes (wicket gates) from fully open to fully closed into two parts. In each closing period, straight-line sections with different slopes are used. The two-phase is divided into two forms: fast first-and-then-slow and slow-first-and-then-fast, as shown in figure 1.

For conventional turbines, there is a theoretical basis for adopting of fast-first-and-then slow. At the beginning of load rejection, the closing speed of the wicket gates is fast which is beneficial for reducing the increase in speed. When the pressure rise value reaches the specified value, the wicket gates start to close slowly, such that the subsequent water hammer pressure rise rate will not be higher than that at the turning point. Properly selecting the turning point position and the closing speed of the first and second phases can reduce the water hammer pressure and speed rise rate.

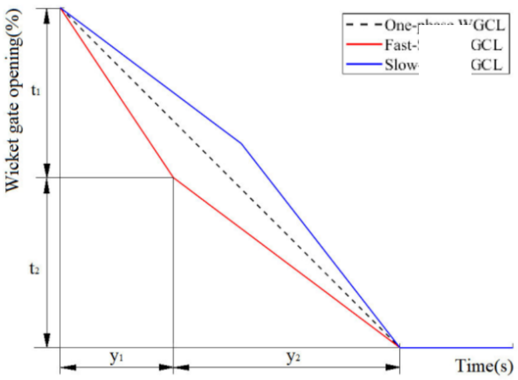


Figure 1. 1-phase and 2-phases

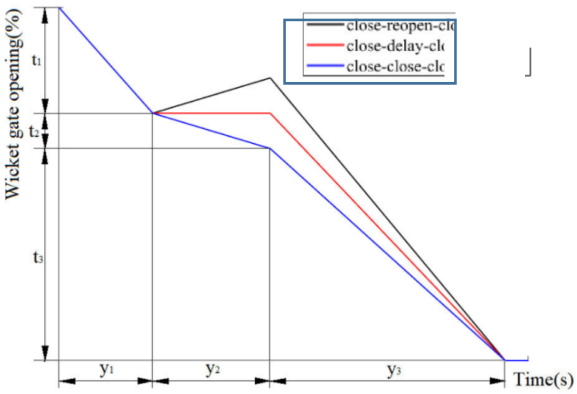


Figure 2. 3- phases

The closing steps of the three - phase are as follows. When the unit changes working conditions, the guide vanes close quickly in the first phase. There are three forms in the second phase: reopened, delayed, and closed. The wicket gates are turned off entirely in the third phase, as depicted in figure 2. This has a flexible adjustment method and can effectively solve the contradiction between different key indicators. However, choosing the turning point time and the opening is challenging.

Table 1. The opening and closing process corresponds to the transition mode

Transition mode of hydropower unit	***Three processes of the opening and closing vane***			
		1	2	3
Case 1	T(s)	0	0.2	8.2
	S(%)	100	100	0
Case 2	T(s)	0	0.2	8.04
	S(%)	98	98	0
Case 3	T(s)	0	0.2	7.18
	S(%)	87.2	87.2	0

Three processes of the opening and closing vanes are shown in table 1. As previously stated the authors recommend that a shortened time of 87.2% and 98% of the full speed stroke should be used when maximum transient pressures are investigated. Table 1 shows guide vanes with different times (8.2s; 8.04s and 7.18s) for the considered emergency shutdown operating regime. The guide vanes closing rule consists of 2 phases:

Phase 1: Delays 0.2s, the guide vanes opening remains constant

Phase 2: The movement to close from initial opening to 0% opening with speed determined by $1/T_s$. The actual closing time of each transition mode then is:

$$T_s^{'} = 0.2 + \frac{S_0 T_s}{100} \tag{5}$$

In which S_0 is the relative initial travel position of secvomotor. The movement to close from initial opening to 0% opening with a specified velocity of $1/T_s$.

2.4 Simulation model

This study applies the calculation method with the parameters of the Houya Hydropower Plant, Laos. The structural parameters of the pressure pipeline system are taken according to the drawings of the section along the energy line (figure 3), with the following basic parameters: Pressure box channel leading from the intake to the surge tank with the length L is 839.2 m; clearance cross section of 3mx3m. The steel pipes leading from the surge tank to the plant and the branch pipes and spiral chambers have the total length of 748.4 m, including 9 sections, with diameters from 3m to 2.8m. The structure of the surge tank is a riser with a clearance of D = 10m (from the height of 309.42m to the height of 329.5m). The elevation of the top of the surge tank is 329.5m. The unit parameters are given below table 2.

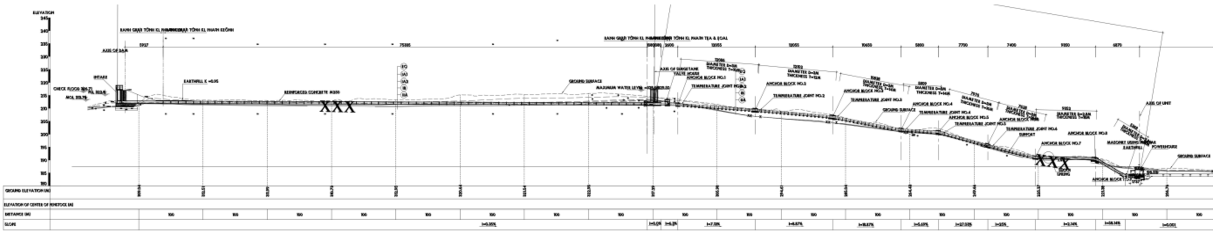


Figure 3. The pipeline system of the Houya Hydropower Station, Laos

Table 2. Parameters of the calculation model - Houya Hydropower Station, Laos

Parameter	**Unit**	**Value**
Rated capacity N	MW	7.5
Overload capacity $N_{\max}$	MW	8.25
Number of units Z		3
Turbine with D_1	mm	1060
Synchronous rotation speed n_{db}	Round/minute	600
Moment of inertia of unit GD^2	$T.m^2$	36

3. RESULTS AND DISCUSSION

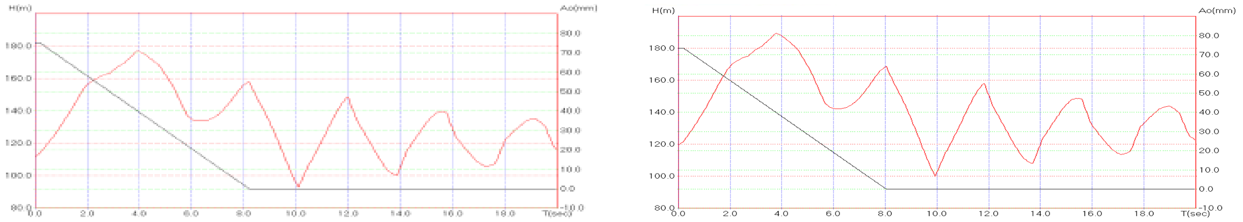
3.1 Effects of the linear method for closing the different shut-off vanes

Figure 4, 5 and table 3 show results of the water hammer analysis for the emergency shutdown of the unit from the maximum load of 7.5 MW. The corresponding unit starting time is T_s = 8.2s; 8.04s and 7.18s and the inertia water time constant is T_w = 0.9s. The results show that the maximum pressure increases for different methods of controlling vane closing with the linear closing of this vane. Due to the influence of the guide vane closing time change of −2% and – 12%, the maximum scroll case pressure head and the maximum speed rise from 50% to 60%.

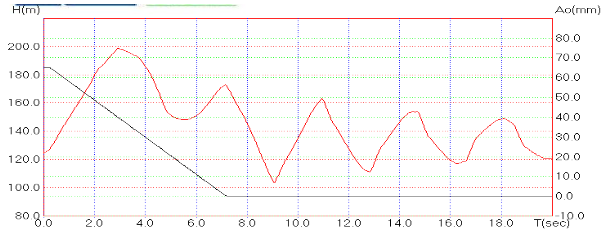
Figure 6 shows the diagram of the distribution of water hammer pressure along the length of the energy line from the inlet - the surge tank - the water divider. The results show that the largest pressure distribution line along the energy line appears in case 3. It is recommended to use the results of vertical pressure distribution along the energy line to design the structure of the box channel and steel pipe, especially the pressurized concrete box channel, ensure no breakage for the box channel and safety for steel pipe. The smallest pressure distribution line along the energy line appears in the case 1. The results of the smallest pressure distribution along the energy line show that the whole line is below the pressure measurement line, ensuring safety without appearing vacuum pressure during operation as well as in the transition mode of the units.

Table 3. Results of water hammer value and different opening options

Case	Water level in the surge tank		Maximum rotation speed n_{max}(rpm)	Maximum pressure of volute chamber H_{max}(m)	Water hammer pressure	
	Z_{thmin} (m)	Z_{thmax} (m)			H_{max} (m)	ξ (%)
1	**311.84**	317.39	925.6	374.38	177.38	58
2	320.14	325.72	**953.5**	386.6	189.6	58.5
3	324.58	**330.08**	930.57	**395.69**	**198.69**	60

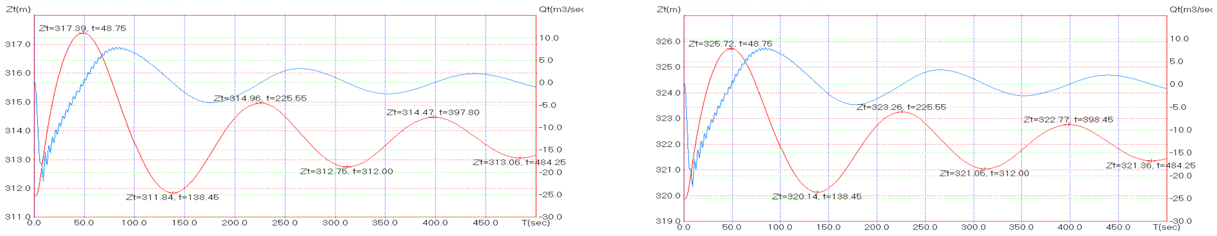


a) Case 1 b) Case 2

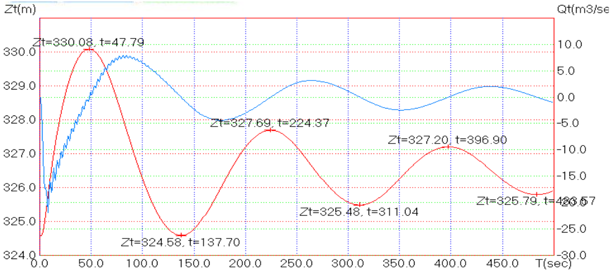


c) Case 3

Figure 4. Diagram of the water hammer pressure with different guide vanes openings options

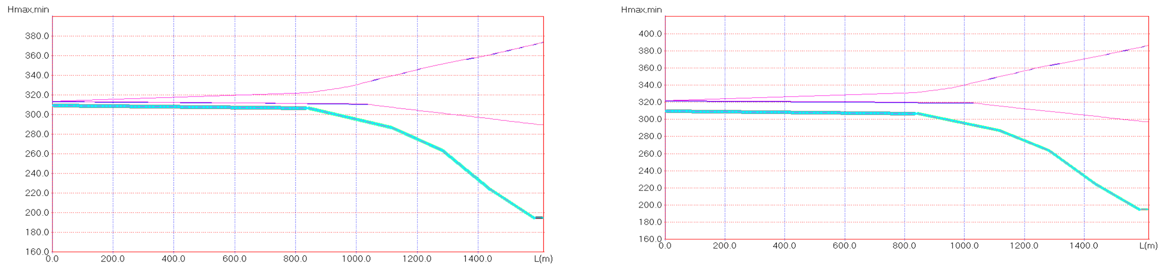


a) Case 1 b) Case 2



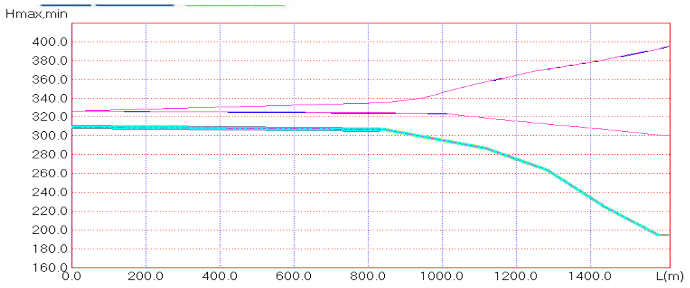
c) Case 3

Figure 5. Fluctuation of water level in the surge tank



a) Case 1

b) Case 2



c) Case 3

Figure 6. Distribution of water hammer pressure along the length of the energy line

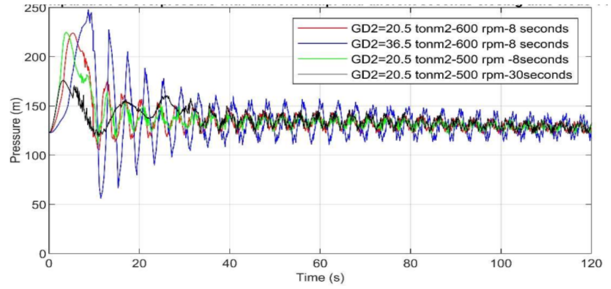


Figure 7. Comparation of overpressure with different rmp and different seconds closing time

The fluctuation gradually dampens which has been shown in figure 7. The result shows that the pressure increases steeply till the time t = 5s and fluctuation starts. It can be seen that the value of maximum pressure along the entire pipeline is nearly 250m which is observed on start of spiral casing at time 13s. Figure 7 shows the temporal variation of the rotational speed of the turbine for closure time t= 6seconds. The result shows that speed rises rapidly soon after the load rejection. The maximum value of the rotational speed is 953.5 rpm.

3.2 Comparison with theoretical calculations math results

Table 4. Comparation of overpressure with different rmp and seconds closing time

DIFFERENT HYPOTHESIS	TRANSIENTS SOFTWARE			THEORETICAL CALCULATION		Error (%)
	Pmax	***H* (m)**	**Overpressure (%)**	***H*(m)**	**Overpressure (%)**	
1. GD^2=36400, 8 seconds closing time and 600rmp.	247.5	126.67	104.83	146.98	121.64	16.81
2. GD^2=20500, 8 seconds closing time and 600rmp.	223.88	103.05	85.29	146.98	121.64	36.35
3. GD^2=20500, 8 seconds closing time and 500rmp.	223.92	103.09	85.32	146.98	121.64	36.32
4. GD^2=36400, 30seconds closing time and 500rmp.	173.99	53.16	44	39.19	32.43	-11.57

Comparison with theoretical calculations math results - Vietnamese standard (Non- Transient Analyses) – by manual (Ho et al., 2003) . The pressure rise maximum is 36.35% with data from theoretical calculations .These differences because of consideration of the surge tank function. In Vietnamese standard, surge tank consider to be used for to reduced 60% of the pressure rise at the turbine point. In fact, the surge tank located in the middle of the pipeline system, and theoretical calculations consider surge tank is the damp (at the reservoir).

It is evident than software results are much more precises, due the capacity of integration with Δt at 0.005s, and not using approximations methodologies. Neverless the results are not really diferente for a problem like the hammer, very sensible to the model boundary conditions and integration parameters. The main difference is produced when it is taken in consideration the GD^2 or the inertia, but it does not change the problem of the transition wave. With this overpressure, the options for this hydropower station are: Check stress design for the pipes, which will be acceptable for steel 250m as it is designed, accepting the 30 seconds time. If not, the 8 seconds time will be considered, and then (i) introduce hammer protection system in the network. (ii) Make reinforcement in the network. The recommendation if to get the number i, due it has not any extra construction or procurement cost.

4. CONCLUSIONS

The paper presented the simulation results to evaluate the effects of the guide vanes closing processes on the water hammer pressure values for the Houya Hydropower Station, Laos. Some specific results are achieved as follows:

(1) The three processes of opening and closing the unit at the respective durations of 8.2; 8.04 and 7.18s show that the water hammer pressure value increases 60%, 58.2% and 58% respectively.

(2) It is not possible to have this limited overpressure in 8 seconds closing time with any GD^2. For the selected speed of the machine, it is recommended that the results are satisfactory with 30 seconds closing time, no with 8 seconds closing time.

(3) The maximum transient overshoot speed of the unit appears in the case 2 with $n_{\max} = 953.5$ rpm. The relative temporary speed is 59%, the above result is acceptable. Thus, the torque of the unit of $GD^2 = 36$ T.m^2 is guaranteed if the closing time of the whole guide vanes journey of $T_s = 8$s is maintained.

(4) The largest pressure distribution line along the energy line appears in case 3. It is recommended to use the results of vertical pressure distribution along the energy line to design the structure of the box channel and steel pipe, especially the pressurized concrete box channel, ensure no breakage for the box channel and safety for steel pipe.

(5) The smallest pressure distribution line along the energy line appears in the case 1. The results of the smallest pressure distribution along the energy line show that the whole line is below the pressure measurement line, ensuring safety without appearing vacuum pressure during operation as well as in the transition mode of the units.

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Tóm tắt:

PHÂN TÍCH ẢNH HƯỞNG CỦA QUY TRÌNH ĐÓNG MỞ TỔ MÁY ĐẾN GIÁ TRỊ ÁP LỰC NƯỚC VA TRONG ĐƯỜNG ỐNG ÁP LỰC CỦA TRẠM THUỶ ĐIỆN HOUYA - LÀO

Bài báo này trình bày các kết quả mô phỏng số để phân tích ảnh hưởng của các quy trình đóng mở tổ máy đến giá trị áp lực nước va và dao động mực nước trong tháp điều áp cho Trạm thủy điện Houya - Lào. Ba quy trình đóng mở tổ máy với thời gian lần lượt là 8.2; 8.04 và 7.18s cho thấy giá trị áp lực nước va tăng lần lượt là 60%, 58.2% và 58%. Kết quả này cho thấy sẽ không đảm bảo được giới hạn giá trị nước va trong thời gian đóng 8s với mọi giá trị của mômen đà GD^2. Với số vòng quay của máy đã chọn, nghiên cứu khuyến nghị rằng thời gian đóng hợp lý là 30s. Đồng thời, nghiên cứu cũng khuyến nghị sử dụng các kết quả về phân bố áp lực nước của phương án số 3 để thiết kế kết cấu cho kênh hộp và đường ống áp lực, đảm bảo kênh không bị vỡ và an toàn cho đường ống thép.

Từ khóa: Mô phỏng số, cánh hướng, nước va, trạm Thủy điện.

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