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Time Delay Model of the Turbine Pressure Water Conduit: Application to the off-the-grid regime control

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Abstract: The paper presents modeling the hydro-turbine governing system with delay in application to the turbo-machinery control. The delay originates from the wave phenomenon encountered in the pressure water conduit connected to the turbine. To facilitate the PID control tuning the turbine and conduit model is linearized and it results in linear time delay system referred to as the neutral system. Particularly, the disturbance rejection is achieved by the PID control response to varying power loads. Finally, the application example demonstrates the turbo-machinery control in the off-the-grid regime.

Keywords: penstock conduit, turbine, wave phenomenon, neutral system, PID control.

1. INTRODUCTION

In the last decades the hydropower plants became popular in the electricity production due to their nearly zero pollution emissions. Additionally, the hydropower plants serve as backup power supply or off-grid power generation units due to their fast response to peak power loads. Last but not least the low cost of hydroelectric power generation is to appreciate. Hence the hydropower plants are ranging from small over medium to large powerplants. Particularly the small hydropower plants are widely built in order to diversify and localize the overall grid set-up (Kishor, Saini and Singh, 2005; Dal *et al*. 2010). Of course, the large hydroelectric power plants contribute considerably to bulk electricity generation (Huang and Yan, 2009) and this contribution is still increasing (Ren *et al*. 2015).

The renewable energy sources in which the hydropower plants fall require stable and safe operation. This is significant for both the on-the-grid and the off-the-grid regime. In case of the latter, particularly the disturbance rejection has to be guaranteed originating in control response to varying power loads (Li *et al*. 2016; Zhang *et al*. 2015). However, for the stable and safe powerplant operation the model validation of hydro-turbine governing system has to precede the hydro-turbine control design. The hydro-turbine governing system is under impact of hydraulic excitations brought in by the water hammer phenomenon (Bergant, Simpson, and Tijsseling 2006). This phenomenon makes the hydro-turbine governing system complex in behavior.

Essentially, the hydro-turbine governing system is composed of pressure water conduit, turbine, turboalternator and governor. These components are to be modelled for the hydropower system control and optimization. Once the conduit is too long also a surge tank is incorporated into the hydro-turbine governing system. As reported in IEEE Power & Energy Society (2011) lots of yet standardized hydro-turbine models are developed and used in practice. These models result in linear or linearized non-minimum phase systems identified in power industry (Weber and Prillwitz 2003; Kosterev 2004; Holst, Golubović and Weber 2007). After the turbine is connected to the generator the resulting turbo-machinery constitutes a system equivalent (an equivalent machine) to power generation unit. In case of the island operation the equivalent machine was developed earlier (Thorne and Hill 1993). Once the Kaplan turbine is in operation the digital governor is used for the control purpose. As a result, the Kaplan turbine model is non-linear (Brezovec, Kuzle and Tomisa 2006). Since the so-called wave-travelling time, originating from water hammer phenomenon (Bergant, Simpson and Tijsseling 2006; Bostan, Akhtari and Bonakdari 2018), is significant in relation to the machinery inertia time constant the standardized models from IEEE Power & Energy Society (2011) lose the validity. Hence in the case of long conduit the moment and continuity equations describing shock wave in the penstock are included into hydro-turbine and conduit modelling (Voronov1981; Chen 2013; Tenorio 2010; Xu *et al*. 2018). As a result, a non-linear and distributed mathematical model is obtained. A survey on the water turbine models is presented in Kishor, Saini and Singh (2007) and some other works on Francis turbine application are presented in Wang *et al*. (2016) and Liang *et al*. (2017).

Hydro-turbine governing system is modelled with delay, coming from the wave phenomenon in the conduit, and approximated by Padé and *H*-infinity (Kishor, Singh, and Raghuvanshi 2006). However, the Padé approximant of the delay fails in case of small delay that corresponds to the time of pressure wave propagation and reflection. Another delay considered in modelling the hydro-turbine governing system is

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the delay of hydraulic servomotor driving guide vanes (Wang *et al*. 2016).

The paper introduces water turbine and conduit models with delay. These models are linearized and combined each other and facilitate the PID control tuning in the off-the-grid regime. Considering the delay makes the resulting linear time delay system neutral and accordingly demanding turbo-machinery control.

2. MODEL OF LONG PENSTOCK CONDUIT TO THE TURBINE

Radiaxial turbine of Francis type is connected to dam reservoir by a penstock conduit of length L, see Fig. 1, so that operating head H in the turbine inlet is achieved.

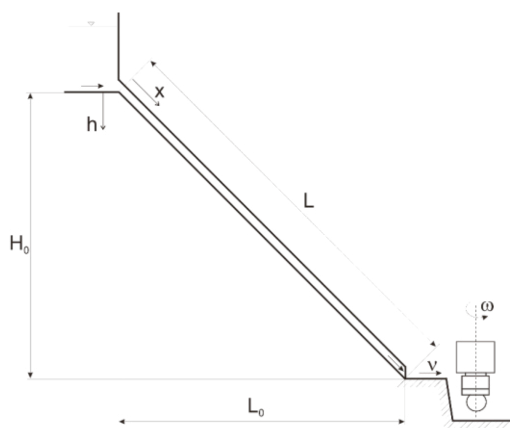

Fig. 1. Scheme of long conduit to the turbine

Cross section area of the penstock F is constant along its length. If friction losses are negligible the following Joukovskii equations for the flow through the penstock hold (Voronov 1981)

$$\frac{\partial h(x,t)}{\partial x} = -\frac{\rho}{a}\frac{\partial q(x,t)}{\partial t} \tag{1}$$

$$\frac{\partial q(x,t)}{\partial x} = -\frac{1}{a\rho}\frac{\partial h(x,t)}{\partial t} \tag{2}$$

where h is the head, q is the flowrate along the penstock, x is length coordinate of the conduit, t is time, ρ is the density, and a is the sound velocity in water. For water density it holds

$$\rho = \frac{aQ_0}{gFH_0} = \frac{av}{gH_0} \tag{3}$$

where g is the gravity acceleration, H_0 is the reference head, Q_0 is the reference flowrate and v is the flow velocity. In comparison with the cross section area of the penstock conduit the change of the dam level is negligible and assumed zero. The transform equations corresponding to (1), (2) with zero initial conditions $h(x,0) = 0, q(x,0) = 0$ are of the form

$$-\frac{\partial H(x,\ s)}{\partial x} = \frac{\rho}{a} sQ(x,\ s) \tag{4}$$

$$-\frac{\partial Q(x,\ s)}{\partial x} = \frac{1}{a\rho} sH(x,\ s) \tag{5}$$

with the solution functions

$$H(x,s) = C_1 \exp(xs/a) + C_2 \exp(-xs/a) \tag{6}$$

$$Q(x,s) = -(1/\rho)\,(C_1 \exp(xs/a) - C_2 \exp(-xs/a)) \tag{7}$$

Zero initial conditions are a real option because head and flowrate variables are introduced as differences from the reference steady state. If the initial flowrate is constant the head difference is zero $h(x,0) = 0$. With respect to their physical meaning integration constants $C_{1,2}$ can be expressed from boundary values of head and flowrate $H(0,s),\ Q(0,s)$

$$H(x,s) = \\ = H(0,s)\cosh(xs/a) - \rho Q(0,s)\sinh(-xs/a) \tag{8}$$

$$Q(x,s) = \\ = Q(0,s)\cosh(xs/a) - \frac{1}{\rho}H(0,s)\sinh(-xs/a) \tag{9}$$

As the upper-level surface area is infinite with regard to the penstock cross section the head boundary condition is zero $H(0,s) = 0$. In addition, the aim is not to assess the values for arbitrary penstock point x but for the endpoint $x = L$. For this point it results

$$H(L,s) = -\rho Q(0,s)\sinh(-\tau s) \tag{10}$$

$$Q(L,\ s) = Q(0,s)\cosh(\tau s) \tag{11}$$

where time constant $\tau = L/a$ is time which takes the sound wave with velocity a to cover the length L. In this way the following relation between $Q(L,s)$ and $H(L,s)$ transforms is as follows

$$H(L,s) = -\rho Q(L,s)\tanh(\tau s) \tag{12}$$

Hyperbolic tangent function is composed of exponential functions with the same argument

$$\tanh(\tau s) = \frac{\exp(\tau s) - \exp(-\tau s)}{\exp(\tau s) + \exp(-\tau s)} \tag{13}$$

Inserting (13) into (12) the transform equation obtains the form

$$H(L,s)[\exp(\tau s) + \exp(-\tau s)] = \\ = -\rho Q(L,s)[\exp(\tau s) - \exp(-\tau s)] \tag{14}$$

Since the products of the transforms with exponentials mean the time shifts of their originals the inverse transform of (14) leads to the following time delay equation

$$h(L,t+\tau) = -h(L,t-\tau) - \rho q(L,t+\tau) + \rho q(L,t-\tau) \tag{15}$$

which in fact, after shifting by $-\tau$, contains one delay -2τ only

$$h(L,t) = -h(L,t-2\tau) - \rho q(L,t) + \rho q(L,t-2\tau) \tag{16}$$

Notice the time delay is linked in a *feedback loop* which means that through the repeated shifts the delayed variable is delayed repeatedly by $t_k = 2k\tau, k = 1,2,3, \ldots$ and so on. Just by this phenomenon the effect of the so-called *wave reflections* is obtained. That is why the solution of equation (16) contains unlimitedly growing number of delayed terms in the explicit solution.

3. LINKING UP THE TURBINE MODEL

Suppose a turbine of radiaxial type is linked up to the conduit at its lower end, i.e. in point $x = L$. For the driving torque M_d of the turbine the following general equation holds

$$M_d = \eta \frac{QH}{\omega} \tag{17}$$

where H is the operating head given by the head difference between the upper water level and the turbine outlet, Q is the flow rate through the turbine. The angular turbine velocity is

ω and η is the efficiency factor. For further development of the model the following relative quantities are introduced

$$h = \frac{H-H_0}{H_0}, \text{ for the head on the turbine,} \quad (18)$$

$$\mu = \frac{M_d-M_0}{M_0}, \text{ for the torque,} \quad (19)$$

$$q = \frac{Q-Q_0}{Q_0}, \text{ for the flow rate through turbine,} \quad (20)$$

$$\varphi = \frac{\omega-\omega_S}{\omega_S}, \text{ for the turbine angular velocity,} \quad (21)$$

where index zero means the reference steady state and ω_s is the reference (synchronous) angular velocity. Assume that these deviations are relatively small in order to achieve a linearized model of the turbine with constant coefficients within the range of variability of these deviations.

The turbine power control is provided by adjusting the guide vanes of the turbine stator whose position u is represented by the relative quantity

$$\frac{u}{u_0} = \frac{Q}{Q_0} = \kappa \quad (22)$$

This control organ is supposed to have linear characteristics. In the steady state the load torque M_z is just outweighed by the driving torque M_d, so that the turbine velocity is constant, particularly in the synchronous operation, $\omega = \omega_S$, in the grid.

With the use of the introduced relative quantities in (18) through (21) the turbine moment equation (17) can be linearized into the following form

$$\mu_d = \kappa h + q - \kappa\varphi \quad (23)$$

This equation is further applied to fulfil the boundary condition and connected with flow rate equation of the form

$$Q = ky\sqrt{H} \quad (24)$$

where k is the proportionality coefficient. In a neighbourhood of a steady state $Q_0,\ y_0,\ H_0$ with regard to conduit model (16) we obtain

$$q = \psi + \frac{\kappa}{2}h \quad (25)$$

where

$$\psi = \frac{\Delta y}{y_0} \quad (26)$$

Inserting (25) into (23) the following equality is obtained for the driving torque

$$\mu_d = \frac{3}{2}\kappa h + \psi - \kappa\varphi \quad (27)$$

Since the reservoir capacity is considered as infinite the form of the conduit model may be assumed as in (12). Inserting the above introduced relative variables the following hyperbolic function relation is obtained

$$h(s) = -\frac{\psi\rho\tanh(\tau s)}{1+0.5\kappa\rho\tanh(\tau s)} \quad (28)$$

Combining the equations (28) and (27) now the final model of the conduit with the turbine is obtained

$$\mu_d(s) = \frac{1-\kappa\rho\tanh(\tau s)}{1+0.5\kappa\rho\tanh(\tau s)}\psi(s) - \kappa\varphi(s) \quad (29)$$

This is a transform equation and it represents the following transfer relation between the control variable ψ and driving torque μ_d

$$W_T(s) = \frac{1-\kappa\rho\tanh(\tau s)}{1+0.5\kappa\rho\tanh(\tau s)} = \frac{\mu_d(s)}{\psi(s)} \quad (30)$$

Hence $W_T(s)$ is the transfer function of the control variable in the penstock conduit. The hyperbolic tangent function is given by exponential function relation (13) and therefore it is further considered in the form

$$W_T(s) = \frac{(1-\kappa\rho)\exp(\tau s)+(1+\kappa\rho)\exp(-\tau s)}{\left(1+\frac{\kappa\rho}{2}\right)\exp(\tau s)+\left(1-\frac{\kappa\rho}{2}\right)\exp(-\tau s)} = \frac{\mu_d(s)}{\psi(s)} \quad (31)$$

This form of the model – after multiplying both numerator and denominator by $\exp(-\tau s)$ – represents a structure of time delay blocks with delay 2τ. Exponential functions in (31) correspond to dead time delays in the original solution

$$(1+\kappa\rho/2)\mu_d(t+\tau) + (1-\kappa\rho/2)\mu_d(t-\tau) = $$
$$= (1-\kappa\rho)\psi(t+\tau) + (1+\kappa\rho)\psi(t-\tau) \quad (32)$$

The time delay term $\mu_d(t-\tau)$ forms a feedback loop which means the existence of all the time growing number of wave reflections again, each in interval of the length 2τ after the previous one.

4. FREQUENCY CHARACTERISTICS OF THE PENSTOCK CONDUIT

The nature of the transfer function (31) is better to recognize from its frequency characteristics, by inserting $s = j\omega$

$$W_T(j\omega) = \frac{(1-\kappa\rho)[\cos(\tau\omega)+j\sin(\tau\omega)]+(1+\kappa\rho)[\cos(\tau\omega)-j\sin(\tau\omega)]}{\left(1+\frac{\kappa\rho}{2}\right)[\cos(\tau\omega)+j\sin(\tau\omega)]+\left(1-\frac{\kappa\rho}{2}\right)[\cos(\tau\omega)-j\sin(\tau\omega)]} \quad (33)$$

This function is periodic with respect to ω. Mapping it in the complex plane results in a circle with centre on the real axis and for arbitrary $\kappa\rho$ intersecting this axis in the points -2 and $+1$ (centre in -0.5). For the variable $\omega\tau$ the characteristics have the period π.

The minimum values $|W|_{\min} = 1$ of amplitude occur for frequencies $\tau\omega = k\pi, k = 0,1,2,\ldots$ and the maxima $|W|_{\max} = 2$ for $\omega\tau = (2k+1)\pi/2, k = 0,1,2,\ldots$ Just the maximum values explain the resonance properties of the conduit for these frequencies. The effect can be experimentally demonstrated by opening the conduit towards outside. The phase characteristics is monotonously decreasing by -2π on each increment of $\tau\omega$ by π.

Short conduit. The transfer function (30) may be substantially simplified if the penstock conduit is relatively short, namely if $|\tau s| \le 0.4$, $\tau = L/a$. In such cases the hyperbolic tangent may be approximated as follows $\tanh(\tau s) \approx \tau s$ and for $|\tau s| \le 0.4$ the error of such approximation of $\tanh(\tau s) \simeq \tau s$ is less than five per cent. Then the function (30) may be approximated by the following rational function

$$W_T(s) = (1-0.5\kappa\rho\tau s)/(1+\kappa\rho\tau s) = \mu_d(s)/\psi(s) \quad (34)$$

This model does not describe the wave effect anymore, however, in cases with $|\tau s| \le 0.4$ this effect is practically negligible. But for longer conduits this approximation is not in place and does not agree with the reality.

5. ISLAND: THE OFF-THE-GRID REGIME OF THE TURBINE

After connecting the turbo-machinery to the grid the speed of this machinery obeys the synchronous grid frequency so that $\omega = \omega_S$ until the on-the-grid regime is disconnected. During this regime own moment of inertia has no impact and machinery velocity is synchronous with the grid frequency. After disconnecting the machinery into the off-the-grid regime the stand-alone velocity control is performed to track the synchronous frequency so that $\omega = \omega_S$. Beside the electric power generation also the moment of inertia is subject to control effort to reject them as disturbances or loads. The complete moment of inertia of the turbo-machinery is summarized into the reduced moment of inertia I_{red} which covers the rotational kinetic energy of both machines. Then in the off-the-grid regime by the difference between the driving (mechanical) torque and the load (generator) torque the angular acceleration of the turbine is exhibited. Hence the mechanical inertia time constant can be expressed from the reference values of the moment of inertia and synchronous angular velocity as follows

$$T_M = I_{red}\omega_S/M_0 \quad (35)$$

For nominal power P_0 of the turbo-machinery and with respect to (17) the relation (35) is next modified

$$T_M = I_{red}\omega_S^2/P_0 \quad (36)$$

The equation for the angular acceleration is achieved after getting together (29) and (31) where (29) is predivided by κ. Such resulting equation is next considered with the inertia of moment effect and generalized to describe not only the machinery dynamics but also the steady-state properties. After multiplying both numerator and denominator of transfer function (31) by $\exp(-\tau s)$ the equation for $\dot{\varphi}$, transform $s\varphi(s)$, results in the form

$$T_M s\varphi(s) + \varphi(s) = \\ = \frac{(1-\kappa\rho)+(1+\kappa\rho)\exp(-2\tau s)}{\left(1+\frac{\kappa\rho}{2}\right)+\left(1-\frac{\kappa\rho}{2}\right)\exp(-2\tau s)} K_r\psi(s) - K_m\mu_d(s) \quad (37)$$

where K_r and K_m are the steady-state gains absorbing $1/\kappa$. Inspecting the form (37) the resulting equation for $\dot{\varphi}$ describes the neutral system with right-hand-part (RHP) zeros. Calling the strong stability condition (Olgac, Vyhlídal, and Sipahi 2008; Vyhlídal and Zítek 2009b) the neutral system is strongly stable if and only if

$$|a_4/a_3| = \left|1-\frac{\kappa\rho}{2}\right| / \left(1+\frac{\kappa\rho}{2}\right) < 1, \kappa\rho > 0 \quad (38)$$

which holds for any finite and positive $\kappa\rho$. The zeros of the neutral system are unstable due to analogous condition to (38)

$$|a_2/a_1| = (1+\kappa\rho)/|1-\kappa\rho| > 1, \kappa\rho > 0 \quad (39)$$

which again holds for any finite and positive $\kappa\rho$. Coefficients $a_i, i = 1,2,3,4$, in (38) and (39) are given as follows

$$a_1 = 1-\kappa\rho, a_2 = 1+\kappa\rho, a_3 = 1+\frac{\kappa\rho}{2}, a_4 = 1-\frac{\kappa\rho}{2} \quad (40)$$

Despite the neutral system (37) has infinite spectra of poles and unstable zeros the strong stability guarantee makes it possible to design successful control, cf. (Wang *et al.* 2017). Nevertheless, to avoid a neutral root chain being close to the imaginary axis and thus preventing these large roots from the deterioration of control performance the neutral PID control loop is assembled and investigated as in Fišer, Zítek, and Vyhlídal (2018).

5.1 PID control of the turbine-generator machinery

Suppose the PID control of the synchronous turbine revolutions under varying electric power generation is aimed. The control feedback considered is as follows

$$\psi(s) = -(r_P + r_I s^{-1} + r_D s)\varphi(s) \quad (41)$$

where r_P, r_I and r_D are the parameters for the PID tuning. Next let it be introduced the loop gains as follows

$$\rho_P = K_r r_P, \rho_I = K_r r_I, \rho_D = K_r r_D \quad (42)$$

Substituting this feedback for the control variable in (37) and after that making some manipulations the neutral characteristic equation results in $M(s) = 0$ where

$$M(s) = \left[\left(1+\frac{a_4}{a_3}\exp(-2\tau s)\right)T_M + \frac{a_1}{a_3}\rho_D + \frac{a_2}{a_3}\rho_D\exp(-2\tau s)\right]s^2 + \left[1+\frac{a_1}{a_3}\rho_P + \left(\frac{a_4}{a_3} + \frac{a_2}{a_3}\rho_P\right)\exp(-2\tau s)\right]s + \frac{a_2}{a_3}\rho_I\exp(-2\tau s) + \frac{a_1}{a_3}\rho_I \quad (43)$$

The characteristic equation of associated difference equation results then in $D(s) = 0$ where

$$D(s) = T_M + \frac{a_1}{a_3}\rho_D + \left(\frac{a_2}{a_3}\rho_D + \frac{a_4}{a_3}T_M\right)\exp(-2\tau s) \quad (44)$$

Both $M(s)$ and $D(s)$ are quasi-polynomials hence both spectra are infinite. Necessary condition of the neutral control loop stability is the strong stability condition as follows

$$\left|\frac{a_2}{a_3}\rho_D + \frac{a_4}{a_3}T_M\right| / \left|T_M + \frac{a_1}{a_3}\rho_D\right| = \beta < 1, \ \rho_D > 0 \quad (45)$$

which holds for positive and bounded ρ_D. Solving equation $\beta = 1$ the upper bound of ρ_D, ρ_{DU}, eventually $r_D = \rho_D/K_r$, r_{DU}, is computed.

The application example of medium hydropower plant is presented in the sequel.

6. APPLICATION EXAMPLE

The off-the-grid regime of turbo-machinery is considered for the water power plant of nominal power 60 MW. All the powerplant data, particularly experimental tests data, have been provided by company ZAT a.s. and in cooperation the developed turbo-machinery model (37) is validated. As a result of the validation the following physical parameters are evaluated, (Kuchař *et al.* 2021),

$$\kappa = 0.8, \rho = 8.5, \tau = 0.125\ s, T_M = 125\ s \quad (46)$$

and the steady-state gains are identified

$$K_r = 11.2, K_m = 8.5 \quad (47)$$

The goal is to tune PID controller to keep the synchronous turbine revolutions despite changes in generated electric power, representing the neutral system disturbance. First of all, based on the strong stability condition given by (45) the upper bound ρ_{DU}, eventually r_{DU}, is evaluated as follows

$$\rho_{DU} = 62.5, r_{DU} = 5.58\ s \quad (48)$$

Then the PID control parameters are tuned by root locus as follows

$$r_P = 15,\ r_I = 7.9\ s^{-1}, r_D = 5.02\ s \quad (49)$$

that guarantee the strong stability because

$$\beta = 0.63 < 1,\ r_D = 5.02\ s < r_{DU} \quad (50)$$

The stability proof is shown in Fig. 2 where the rightmost roots of the characteristic equation, $M(s) = 0$, along with the characteristic roots pertaining to associated difference equation, $D(s) = 0$, are recorded and all these roots lie in the LHP of the complex plane. As a result, fast disturbance rejection with respect to long mechanical inertia time constant T_M is obtained. All the rightmost spectra are computed by the quasi-polynomial root finder (Vyhlídal and Zítek 2009a) and the disturbance rejection response is recorded for the tuning (49) in Fig. 3.

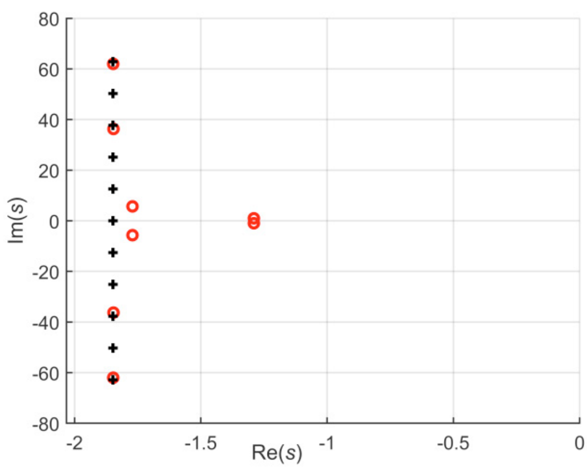

Fig. 2. Rightmost spectrum of (43) denoted by *red o* and associated neutral root chain (*black +*)

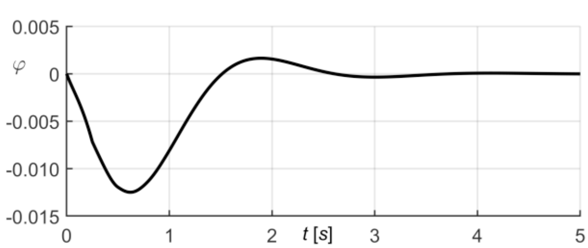

Fig. 3. Disturbance rejection response

In Fig. 3, the considered change in the generated electrical power is 10% increase which is rejected by the PID control with maximum error of turbine angular speed synchronization resulting in the error less than 1.5%. Using the simulator, (Kuchař *et al*. 2021), and its web application[1] the instantaneous power-grid disconnection is recorded in Fig. 4 where μ_d drops from the nominal value to zero. In the simulator the synchronous frequency kept corresponds to $\varphi = 1$ and the PID setting applied is as follows: $r_P = 5,\ r_I = 1.53\ s^{-1}, r_D = 3.05$.

[1] https://aspicc.fs.cvut.cz/turbine

7. CONCLUSIONS

As shown in the presentation the proposed modeling scheme

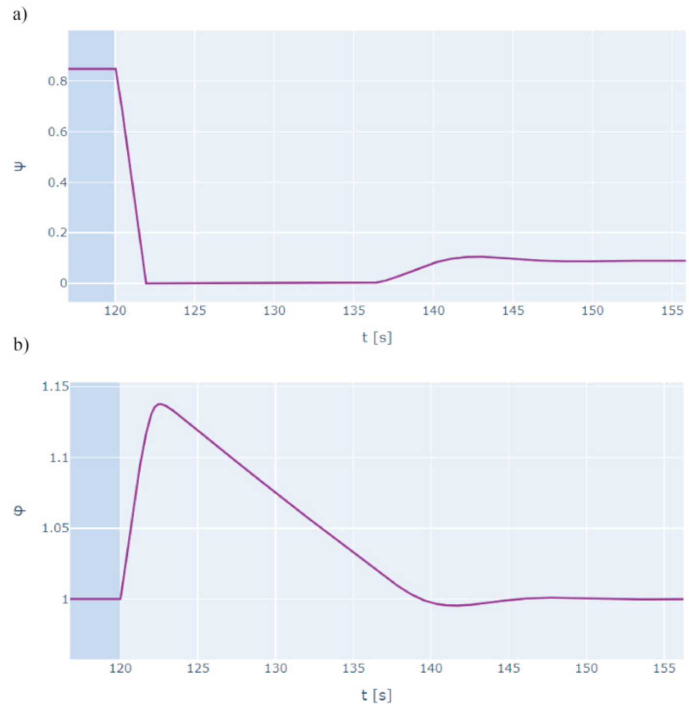

Fig. 4. Power-grid disconnection from nominal power

is particularly suitable for power stations with long conduits where the power house is located separately from the dam and through this arrangement as high as possible head is achieved. Notice that the use of the presented model means that otherwise used Padé approximation is avoided and delays forming the wave phenomenon in the penstock are applied as such. The effect of wave reflections is particularly harmful when the flow is to rapidly reduced and such cases of operation cannot be admitted at all.

As to the neutral kind of stability let be noted that it is brought about by neutral nature of the combined turbine and conduit model and also by the option of ideal PID.

The water turbine with penstock conduit is described by the linear time delay system referred to as the neutral system with RHP zeros. Incorporating the delay into the system validates the model-based PID control tuning for the disturbance rejection in the off-the-grid regime.

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REFERENCES

Bergant, A., Simpson, A., and Tijsseling, A. (2006). Water hammer with column separation: A historical review. *Journal of Fluids and Structures*, 22(2), 135–171.

Bostan, M., Akhtari, A. A., and Bonakdari, H. (2018). Deriving the governing equation for a shock damper to model the unsteady flow caused by sudden valve closure and sudden demand change. *Journal of Water Supply: Research and Technology - Aqua*, 67(2), 202–210.

Brezovec, M., Kuzle, I., and Tomisa, T. (2006). Nonlinear Digital Simulation Model of Hydroelectric Power Unit with Kaplan Turbine. *IEEE Transactions on Energy Conversion*, 21(1), 235–241.

Chen, D., Ding, C., Ma, X., Yuan, P., and Ba, D. (2013). Nonlinear dynamical analysis of hydro-turbine governing system with a surge tank. *Applied Mathematical Modelling*, 37(14-15), 7611–7623.

Dal, M., Kaya, A. M., Aksit, M. F., Yigit, S. K., Kandemir, I. and Yuksel, E. (2010). A hardware test setup for grid connected and island operation of micro hydro power generation systems. In: *2010 IEEE International Energy Conference*. 624–629. IEEE, Piscataway.

Fišer, J., Zítek, P., and Vyhlídal, T. (2018). Neutral PID Control Loop Investigated in Terms of Similarity Theory. In: Insperger T. (ed.), *Proceedings of the 14th IFAC Workshop on Time Delay Systems,* 212-217. IFAC, Budapest.

Holst, A., Golubović, D.-I., and Weber, H. (2007). Dynamic Model of Hydro Power Plant "Djerdap I" in Serbia. In: *International Youth Conference on Energetics*, 1–8. Budapest.

Huang, H.L. and Yan, Z. (2009). Present situation and future prospect of hydropower in China. *Renew Sust Energ Rev*, 13(2009), 1652–1656.

IEEE Power & Energy Society (2011). IEEE Guide for the Application of Turbine Governing Systems for Hydroelectric Generating Units. In: *IEEE Std 1207-2011* (Revision to IEEE Std 1207-2004). IEEE, New York.

Kishor, N., Saini, R. P., and Singh, S. P. (2005). Small hydro power plant identification using NNARX structure. *Neural Computing and Applications*, 14(3), 212–222.

Kishor, N., Saini, R. P., and Singh, S. P. (2007). A review on hydropower plant models and control. *Renewable and Sustainable Energy Reviews*, 11(5), 776–796.

Kishor, N., Singh, S.P. and Raghuvanshi, A.S. (2006). Dynamic simulations of hydro turbine and its state estimation based LQ control. *Energy Conversion and Management*, 47(18-19), 3119-3137.

Kosterev, D. (2004). Hydro Turbine-Governor Model Validation in Pacific Northwest. *IEEE Trans. Power Syst.*, 19(2), 1144–1149.

Kuchař, M., Peichl, A., Kučera, M., Fišer, J., Kulík, P., and Vyhlídal, T. (2021). Hydroelectric Power-Plant Simulator Implemented in Python. In: *23rd International Conference on Process Control*, Slovakia. (accepted)

Li, J. and Chen, Q. (2014). Nonlinear dynamical analysis of hydraulic turbine governing systems with nonelastic water hammer effect. *Journal of Applied Mathematics*, 2014, Article No. 412578, pg. 11.

Li, H.H., Chen, D.Y., Zhang, H., Wang, F.F., and Ba, D.D. (2016). Nonlinear modeling and dynamic analysis of a hydro-turbine governing system in the process of sudden load increase transient. *Mech Syst Signal Proc*, 80(2016), 414–428

Liang, J., Yuan, X., Yuan, Y., Chen, Z., and Li, Y. (2017). Nonlinear dynamic analysis and robust controller design for Francis hydraulic turbine regulating system with a straight-tube surge tank. *Mechanical Systems and Signal Processing*, 85(2017), 927–946.

Olgac, N., Vyhlídal, T., and Sipahi, R. (2008). A new perspective in the stability assessment of neutral systems with multiple and cross-talking delays. *SIAM Journal on Control and Optimization*, 47(1), 327-344.

Ren, J.Z., Gao, S.Z., Tan, S.Y., Dong, L.C., and Scipioni, A. (2015). Role prioritization of hydrogen production technologies for promoting hydrogen economy in the current state of China. *Renew Sust Energy Rev*, 41(2015), 1217–1229.

Sanathanan, C.K. (1987). Accurate low order model for hydraulic turbine-penstock. *IEEE Transactions on energy Conversion*, EC-2 (2), 196-200.

Tenorio, L.A.L. (2010). *Hydro Turbine and Governor Modelling: Electric - Hydraulic Interaction*, MSc. Thesis. Norwegian University of Science and Technology, Trondheim.

Thorne, D. and Hill, E. (1993). Field Testing and Simulation of Hydraulic Turbine Governor Performance. *IEEE Transactions on Power Apparatus and Systems*, PAS-93(4), 1183–1191.

Voronov A. A. (1981) *Fundamentals of Automatic Control Theory. Specific Linear and Nonlinear Systems.* Energoizdat, Moscow, 1981

Vyhlídal, T. and Zítek, P. (2009a). Mapping Based Algorithm for Large-Scale Computation of Quasi-Polynomial Zeros. *IEEE Transactions on Automatic Control*, 54(1), 171 – 177.

Vyhlídal, T. and Zítek, P. (2009b). Modification of Mikhaylov criterion for neutral time-delay systems. *IEEE Transactions on Automatic Control*, 54(10), 2430–2435.

Wang, F., Chen, D., Xu, B., and Zhang, H. (2016). Nonlinear dynamics of a novel fractional-order Francis hydro-turbine governing system with time delay. *Chaos, Solitons & Fractals*, 91(2016), 329–338.

Wang, H., Liu, J., Yu, X., Tan, S., and Zhang, Y. (2017). PID controller tuning for neutral type systems with time delay via dominant eigenvalue assignment. In: *Proc. 29th Chinese Control and Decision Conf. (CCDC17)*, 5592–5597. IEEE, Piscataway.

Weber, H. and Prillwitz, F. (2003). Simulation models of the hydro power plants in Macedonia and Yugoslavia. In: *Proceedings of IEEE Bologna Power Tech Conference*, vol. 3., 982–989. IEEE, New York.

Xu, B., Chen, D., Tolo, S., Patelli, E. and Jiang, Y. (2018). Model validation and stochastic stability of a hydro-turbine governing system under hydraulic excitations. *International Journal of Electrical Power & Energy Systems*, 95, pp.156-165.

Zhang, H., Chen, D.Y., Xu, B.B., and Wang, F.F. (2015). Nonlinear modeling and dynamic analysis of hydro-turbine governing system in the process of load rejection transient. *Energ Conv Manag*, 90(2015), 128–137.