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Response Time for Primary Frequency Control of Hydroelectric Generating Unit

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Abstract. For evaluating the power quality in primary frequency control for hydroelectric generating units, the power response time is an indicator which is of main concern to the power grid. The aim of this paper is to build a suitable model for conducting reliable simulation and to investigate the general rules for controlling the power response time. Two huge hydropower plants with surge tank from China and Sweden are applied in the simulation of a step test of primary frequency control, and the result is validated with data from full scale measurements. From the analytical aspect, this paper deduces a time domain solution for guide vane opening response and a response time formula, of which the main variables are governor parameters. Then the factors which cause the time difference, between the power response time and the analytical response time of opening, are investigated from aspects of both regulation and water way system. It is demonstrated that the formula can help to predict the power response and supply a flexible guidance of parameter tuning, especially for a hydropower plant without surge tank.

Key words: Primary frequency control; Response time; Hydropower; Governor parameter; Numerical simulation.

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22

23 **1 Introduction**

24 In order to suppress the power grid frequency fluctuation, generating units change their power
25 output automatically according to the change of grid frequency, to make the active power
26 balanced again. This is the primary frequency control. Hydroelectric generating units are suited to
27 undertake the power response in primary frequency control, because of great rapidity and
28 amplitude of the power regulation. Nowadays the power quality of hydroelectric generating units
29 in primary frequency control becomes more and more important, due to the more complex
30 structure of the grid and greater proportion of the renewable intermittent sources. The key of
31 evaluating the regulation quality is the power response time (more details are in Section 2).
32 Therefore, these problems are highly concerned by industry: How do the regulation and water
33 way system affect the response time? How should governor parameter be set to control the power
34 response time?

35

36 To the best of the authors' knowledge, no specific research on response time of primary
37 frequency control exists currently. Simulation and dynamic process analysis of primary frequency
38 control for hydroelectric generating units are treated in e.g. reference [1-4]. The stability problem
39 is discussed in reference [5-7]. Different new controllers or control techniques are studied to
40 improve the dynamic performance of hydropower plant (HPP) in the load frequency control [8-
41 11]. A series of important research activities regarding frequency control were conducted: a
42 complex simulation was performed to investigate an incident of oscillatory behavior in power
43 output of a HPP [12]; A specification was proposed for the transient and steady-state responses of
44 a HPP operating in frequency-control mode. The specification gives a generic definition of how
45 the electrical power should respond to step, ramp and random changes in frequency [13]. Based

on control theory, power response process was deduced by applying the transfer functions and inverse Laplace transform [13]. The idea is a good inspiration to this paper.

Generally speaking, both regulation and water way system directly affects the power response time. Hence the previous research can be extended in two directions, as described below. Aiming at the regulation system, there are several research activities on governor parameter optimization through the preliminary deduction, sensitivity analysis [3] or optimization algorithms [14, 15]. However, the research on the relationship between power response and governor parameter choice is in urgent need. Besides, the former simulations mostly adopt some built-in algorithm directly, for example one of the differential equation solvers in MATLAB, and do not discuss the accuracy and applicability of the solving methods of governor equations. On the other hand, the water way subsystem in most models is relatively simple, which influences the accuracy of power response. Moreover, the influence of surge and water hammer is seldom discussed deeply.

The aim of this paper is to build a suitable model for conducting reliable simulations and to display general rules to obtain a desired power response. Section 2 introduces the test and relevant specifications of primary frequency control, and illustrates the definition and importance of the response time and delay time. Applying Visual C++ 2008, Section 3 presents the modified model of turbine governor with primary frequency control function under guide vane opening feedback control mode. The implementation is based on the existing mathematical model described in [16], which takes into account nonlinear factors such as turbine characteristics and pipeline elasticity. In Section 4, two huge HPPs with surge tank from China and Sweden are applied in the simulation of a step test process of primary frequency control, and the result is validated with data from full scale measurements. Section 5 conducts theoretical analysis and

simulation to study the response time and the influencing factors. The main results are in Section 5. Section 6 draws the conclusion.

2 Test method and specifications of primary frequency control

Strictly speaking, the test of primary frequency control needs to be conducted in every HPP to confirm a set of parameters to meet the requirement of specifications. There are two normal test methods [3]. (1) The first test method is to cut the governor input signal of frequency measurement so that the regulation system is under open-loop control. Then, a required frequency step signal is given, and the active power is recorded to check whether the regulation system meet the specifications of the power grid operator. This test method can yield an accurate result without being influenced by the change of grid frequency, but it nevertheless brings the hidden danger [3] which might be caused by signal errors and wrong parameter settings. (2) The second approach is to keep the units connected to the power system and step change the given frequency of the governor. This method would affect the power system frequency, and the result might has tiny errors because the generator frequency follows the system frequency which is not exactly the rated value (50 Hz). Therefore an accurate simulation is indeed important.

Fig. 1. Illustration of different times under frequency step disturbance

85

86 When the units are operating on 80 % of the rated load, the power response for a 60 second
87 frequency step should meet a series of requirements in accordance with the specifications of
88 China Electricity Council [17]. The most crucial requirements are: the power adjustment quantity
89 should reach 90 % of the static characteristic value within 15 seconds. If the rated head of the unit
90 is larger than 50 m, the power delay time should be less than 4 seconds. In the corresponding
91 European rules, according to the specifications of ENTSO-E [18], the time for starting the action
92 of primary control is a few seconds starting from the incident, the deployment time of 50 % of the
93 total primary control reserve is at most 15 seconds and from 50 % to 100 % the maximum
94 deployment time rises linearly to 30 seconds. There are some differences between these two
95 specifications, but the response time (deployment time) $T_{response}$ and delay time T_{delay} of power
96 response process are the key indicators for both specifications, as shown in Fig. 1. Reference [13]
97 also states similar specifications for these two indicators.

98

99 Another situation applies in the Nordic synchronous grid, where four national transmission
100 system operators (TSOs) cooperate. The TSOs have different criteria, which however can be
101 expected to conform to each other and to the criteria of ENTSO-E in the next few years.
102 Currently however, the Norwegian TSO Statnett has no specific requirements on the response
103 time, but prescribes limits on certain quantities, such as on the delay between frequency deviation
104 and incipient guide vane motion, on the resolution in frequency measurement, on the permanent
105 droop, and on how to measure these parameters [19]. There is also a classification of units based
106 on criteria on governor parameters. Norwegian power plants provide the largest share of
107 regulating power in the Nordic grid. The second largest share comes from Sweden, where the
108 TSO Svenska Kraftnät have demands on response time, but no requirements on details [20]. The

requirements depend on the magnitude of the frequency deviation, and if it exceeds 0.1 Hz, 50 % should be delivered within 5 s, and 100 % within 30 s.

3 Modeling

The modeling and improvement described in this section are based on the software TOPSYS [16], which is developed for analyzing transient processes of HPPs. The basic equations of water conduit and hydraulic turbine behavior in TOPSYS have the following characteristics: (1) Elastic water hammer is adopted in the draw water tunnel, considering the elasticity of water and pipe wall. (2) Characteristic of the penstock is taken into account. (3) Characteristic curve of the turbine is introduced. These are mostly simplified or ignored in the related research. However, the current TOPSYS version cannot simulate primary frequency control. Therefore the governor model is established here to extend the TOPSYS with this supplement implemented in VC++.

3.1 Turbine governor

Generally, there are two control modes for the primary frequency control of hydroelectric generating unit (hereafter referred to as opening control and power control), according to different feedback objects in closed-loop control: guide vane opening and power. The power control mode is also called “power droop”. Since the opening control is the most common one, the model of governor for primary frequency control under opening control is built and described here. The block diagram of a typical PID governor with droop is shown in Fig. 2, and (1) expresses the corresponding differential equation. More exactly, x stands for the relative difference between frequency set-point f_c (commonly 50 or 60 Hz) and generator frequency f_g ; The servomotor stroke or guide vane opening is denoted by y (since these two variables are linearly dependent in this paper, they are actually equivalent). Besides, the dead-band of opening

and frequency are contained in the model. Their effect can be reflected in simulations, but they are omitted in (1) because of their nonlinear nature. The remaining symbols are K_p , K_i and K_d that are standard PID-parameters, b_p denoting droop, and T_y representing lag in main servo motor.

$$b_p K_d T_y \frac{d^3 y}{dt^3} + (T_y + b_p K_p T_y + K_d K_p) \frac{d^2 y}{dt^2} + (1 + b_p K_p + b_p K_i T_y) \frac{dy}{dt} + b_p K_i (y - y_c) = K_d \frac{d^2 x}{dt^2} + K_p \frac{dx}{dt} + K_i x \quad (1)$$

Fig. 2. Block diagram of governor under opening control

3.2 Simplified generator

In the currently relevant simulations, the generator frequency is given directly in the form of a step function, and it does not need to be obtained by a generator equation.

3.3 Engineering case

There are two engineering cases in this paper. Case 1 is a huge Chinese HPP with an upstream surge tank, huge power output and long draw water tunnel. Case 2 is a Swedish HPP with a downstream surge tank and long tailrace tunnel. In both HPPs, there is a surge tank, and the units are under the hydraulic coupling by sharing the same water way. Details of two engineering cases

are found in Appendix A, and two models built by TOPSYS are shown in Fig. 3 and Fig. 4.

Fig. 3 Model of two generating units of case 1 built by extended TOPSYS

Fig. 4 Model of case 2 built by extended TOPSYS

4 Comparison between measurement and simulation

The full scale tests of primary frequency control were conducted within case 1 in January 2013 and within case 2 in October 2013. In this section, the test conditions are selected and compared with the simulation to validate the model. The test conditions are illustrated in Appendix A. The results of measurement and simulation are shown in Fig. 5 - Fig. 8.

For both cases, the computed power response is in good agreement with measurement data, as shown in Fig. 5 - Fig. 8. There is a certain degree of error in the case of power decline, as shown in Fig. 6, and the inferred reason is that the efficiency error of the characteristic curve is larger

164 during the operation with smaller power output. The error in case 1 is slightly larger than which
 165 of case 2, due to a much more rapid movement of opening and power. The slower the transient
 166 process, the more accurate simulation. In general, it turns out to be a reliable model for further
 167 simulation and research.

168

Fig. 5. Power response to a -0.2 Hz frequency step in case 1

Fig. 6. Power response to a +0.2 Hz frequency step in case 1

Fig. 7. Power response to a -0.1 Hz frequency step in case 2

Fig. 8. Power response to a -0.3 Hz frequency step in case 2

169

170 5 Response time of primary frequency control

171 5.1 Time domain analytical solution of opening response

172 The time domain analytical solution of opening response is deduced based on the frequency step

173 test of primary frequency control. The frequency deviation after the dead band is shown in (2).
 174 The input signal $r(t)$ of the second-order system is the step function x , as shown in (3), and the
 175 time when the frequency step starts is regarded as the initial time, 0 s.

$$\Delta f = \begin{cases} 0, & (-E_f \leq f_c - f_g \leq E_f) \\ f_c - f_g - E_f, & (f_c - f_g > E_f) \\ f_c - f_g + E_f, & (f_c - f_g < -E_f) \end{cases} \quad (2)$$

$$r(t) = x = \frac{\Delta f}{f_c} = \begin{cases} 0 & t < 0 \\ A & t \geq 0 \end{cases}, \quad R(s) = \frac{A}{s} \quad (3)$$

176 The transfer function corresponding to (1) is

$$G(s) = \frac{K_d s^2 + K_p s + K_i}{b_p K_d T_y s^3 + (T_y + b_p K_p T_y + K_d K_p) s^2 + (1 + b_p K_p + b_p K_i T_y) s + b_p K_i} \quad (4)$$

177 The “ $b_p K_i y_c$ ” in (1) is a constant term which does not affect the output signal $c(t)$, so it can be
 178 omitted while simplifying the transfer function and re-added in the final expression of the
 179 opening. Besides, K_d is usually set to 0, so the final expression of the transfer function is

$$G(s) = \frac{K_p s + K_i}{(T_y + b_p K_p T_y) s^2 + (1 + b_p K_p + b_p K_i T_y) s + b_p K_i} \quad (5)$$

180 Hence the characteristic equation of the system is:

$$s^2 + \frac{1 + b_p K_p + b_p K_i T_y}{T_y (1 + b_p K_p)} s + \frac{b_p K_i}{T_y (1 + b_p K_p)} = s^2 + 2\zeta \omega_n s + \omega_n^2 = 0, \quad (6)$$

181 where $\omega_n = \sqrt{\frac{b_p K_i}{T_y (1 + b_p K_p)}}$ stands for the angular frequency of un-damped natural oscillation and

182 $\zeta = \frac{1 + b_p K_p + b_p K_i T_y}{2\sqrt{(1 + b_p K_p) b_p K_i T_y}}$ is the damping ratio. It is obvious that ζ is always equal or greater than 1,

183 and therefore the response of the governor system is over-damped, which means that the change
 184 process of output signal is monotonic[21]. It lays a foundation for further research on power

quality.

By applying the transfer function (5) to a step yielding an expected unit change in output, i.e. (3) with $A=b_p^{-1}$, we obtain the Laplace transform of the relative value of the opening signal at any step, cf. (7). Then the relative value of the opening change process can be obtained from the inverse Laplace transform, as shown in (8). To obtain the change process of actual opening, the initial conditions (given opening y_c and amplitude A/b_p) should be considered, then the time domain expression of opening response is acquired, see (9).

$$C(s) = \frac{K_p s + K_i}{s[(T_y + b_p K_p T_y)s^2 + (1 + b_p K_p + b_p K_i T_y)s + b_p K_i]} \quad (7)$$

$$c(t) = 1 - \frac{1}{1 + b_p K_p - b_p K_i T_y} e^{-(\zeta - \sqrt{\zeta^2 - 1})\omega_n t} - \frac{K_i T_y - K_p}{1 + b_p K_p - b_p K_i T_y} e^{-(\zeta + \sqrt{\zeta^2 - 1})\omega_n t} \quad (8)$$

$$y(t) = y_c + \frac{A}{b_p} c(t) \quad (9)$$

Equation (8) shows that the final steady-state value of the relative change process of opening is 1, and the transient component consists of two exponential terms. Since $\zeta > 1$, and especially when $\zeta \gg 1$, we obtain that $\zeta + \sqrt{\zeta^2 - 1} \gg \zeta - \sqrt{\zeta^2 - 1}$. That is to say, for the two exponential terms in (8), the latter attenuates far faster than the former. Hence the latter one can be ignored. The simplified expression of time domain response is achieved by substituting the ω_n and ζ by governor parameters, as shown in (10).

$$c(t) = 1 - \frac{1}{1 + b_p K_p - b_p K_i T_y} e^{-\frac{b_p K_i}{1 + b_p K_p} t} \quad (10)$$

The time when the monotonic output signal $c(t)$ reaches the target value Δ (Δ is set to 90% according to [17]) is

$$t = -\frac{1+b_p K_p}{b_p K_i} \ln \left[(1+b_p K_p - b_p K_i T_y)(1-\Delta) \right]. \quad (11)$$

Equation (11) is the formula for the opening response time of primary frequency control under opening control.

If the parameter T_y is also ignored, equation (1) becomes first-order. The formula for the opening response time can be obtained by applying the same method of Laplace inverse transform as above:

$$t = -\frac{1+b_p K_p}{b_p K_i} \ln \left[(1+b_p K_p)(1-\Delta) \right] \quad (12)$$

It is exactly the same as (11) when $T_y = 0$. Therefore (11) is a general formula including the case when T_y is 0.

5.2 Simulation under different conditions

Simulations under different conditions are conducted in order to analyze the sensitivity of response time with respect to the main parameters. All the simulation and analysis below is done with case 1. The parameters of the simulation is set according to the test condition of the -0.2 Hz frequency step in Section 4, except for the values in Table 1. A model without surge tank is investigated and compared to analyze the influence of surge in upstream surge tank. More exactly, in the model, the surge tank and the upstream pipeline before the tank are replaced by a reservoir, see Fig. 9. Meanwhile, the upstream water level of the simplified model, which affects the water head, is adjusted to ensure that the relation between guide vane opening and power remain the same as in the original model. The simulation results are shown in Table 1.

Fig. 9 The simplified model of HPP without the surge tank

Table. 1 The response time of frequency step under different conditions. T_1 and T_2 are calculated by (11) and simulation respectively, and T_3 is simulated with the simplified model; Response time of opening or power means the time when the opening or power reaches the target value Δ ; All the simulations are conducted with rate limiting which is 12.5%/s.

No.	Parameters					Response time of opening (s)		Response time of power (s)		Time difference ΔT (s)		
	K_p	K_i	b_p	T_y	Δ	Formula, T_1	Simulation, T_2	Without surge tank, T_3	With surge tank, T_4	$\Delta T_1 = T_2 - T_1$	$\Delta T_2 = T_3 - T_2$	$\Delta T_3 = T_4 - T_3$
1	2.00	4.0	0.04	0.020	90%	15.0	14.6	16	21.2	-0.4	1.4	5.2
2	2.00	6.0	0.04	0.020	90%	10.0	9.8	11.4	12.4	-0.2	1.6	1
3	2.00	2.0	0.04	0.020	90%	30.1	29.2	30	232.2	-0.9	0.8	202.2
4	0.20	4.0	0.04	0.020	90%	14.5	15	16.4	21.6	0.5	1.4	5.2
5	10.00	4.0	0.04	0.020	90%	17.2	14.6	16	21	-2.6	1.4	5
6	2.00	4.0	0.02	0.020	90%	29.4	29	29.2	229.4	-0.4	0.2	200.2
7	2.00	4.0	0.06	0.020	90%	10.2	9.8	12	13.2	-0.4	2.2	1.2
8	2.00	4.0	0.04	0.005	90%	15.0	14.8	16.2	21.2	-0.2	1.4	5
9	2.00	4.0	0.04	0.500	90%	15.5	15	16.4	21.6	-0.5	1.4	5.2
10	2.00	4.0	0.04	0.020	80%	10.4	10.2	11.6	12.4	-0.2	1.4	0.8
11	2.00	4.0	0.04	0.020	70%	7.6	7.6	9.2	9.6	0.0	1.6	0.4

The power response time, T_4 , can be expressed as

$$T_4 = T_1 + \Delta T = T_1 + \Delta T_1 + \Delta T_2 + \Delta T_3, \quad (13)$$

where ΔT is the time difference between T_1 and T_4 , as shown in Fig. 1. The differences ΔT_1 , ΔT_2 , and ΔT_3 roughly indicate the time lag caused by different factors. Then T_4 can be analyzed and predicted by investigating the cause and approximate range of the time differences. General trends and some specific results displayed in Table 1 will be explained in sections 5.3 and 5.4.

5.3 Effect of regulation system

1) Governor parameter (T_I)

Equation (11) shows clearly how the governor parameters determine the opening response time, T_I . The values of K_i and K_p play the main role, as shown in Fig.10; b_p affects the adjustment quantity of opening. These three parameters are the major ones, whereas T_y has a limited influence, and target value Δ only decides the calculation range.

Fig. 10. Response time of opening, T_I
($b_p=0.04$, $T_y=0.02$, $\Delta=90\%$)

2) Rate limiting and Numerical algorithm for governor equations (ΔT_I)

There exists a slight difference ΔT_I , between simulated opening response time T_2 and analytical solution T_I , in most cases. However, it turns out to be 2.6 s under a large value of K_p . The error is introduced by the numerical algorithm used to compute the governor output, on the precondition that the rate limiting exists. To investigate this error, the results of different numerical algorithms are compared to the analytical solution and measurement data in this section.

A position-type PID discrete algorithm and a fourth-order Runge-Kutta method are discussed. The former is widely adopted by Programmable Logic Controllers (PLCs) [22], and has a widespread use in HPP. Therefore adopting the position-type PID discrete algorithm in simulation is closest to the actual operating condition. Specifically, disregarding of K_d , (1) was transformed

to (14) through a standard first order difference method [22]:

$$T_y(1+b_p K_p) \frac{y_k - 2y_{k-1} + y_{k-2}}{\Delta t^2} + (1+b_p K_p + b_p K_i T_y) \frac{y_k - y_{k-1}}{\Delta t} + b_p K_i (y_k - y_c) = K_p \frac{x_k - x_{k-1}}{\Delta t} + K_i x_k \quad (14)$$

where Δt is the time step and the subscript k stands for the current step. The fourth-order Runge-Kutta method is applied widely in all kinds of simulation software, and is for example available in MATLAB. The brief principle is illustrated in Appendix B.

The value of K_p is set to 9 and 2 respectively, and the other parameters remain the same as in the test case of -0.2Hz frequency step in Section 4. The rate limiting, which is mostly ignored in former research, is also considered.

Fig. 11. Change process of guide vane opening under different methods. Method 1 and 2 stands for the Position-type PID discrete algorithm and fourth-order Runge-Kutta method respectively; in the figure legend, “RL” is short for rate limiting.

As shown in Fig. 11, without the rate limiting, the accuracy of both two algorithms is verified

because the results are consistent with the analytical solution. However there exists the rate limiting in the actual case, and it will lead to a complex situation. To be specific, when the proportional gain K_p is set to 9, the whole change process of opening obtained by Runge-Kutta method is close to the analytical one and the opening speed is barely limited at the initial stage. As a contrast, the position-type PID discrete algorithm shows a result which sharply diverges from the analytical solution but has a good agreement with measurement data, since it is the method adopted by the real governor. So a key problem is reflected that the actual opening response does not coincide with the analytical solution. Normally the Runge-Kutta method is regarded as a more accurate one, but it reduced the accuracy when modeling the normal governor. While K_p is set to 2, the difference between the results of these two methods is small. In short, the selection of algorithm should follow the actual built-in algorithm of the governor. The default algorithm in some software, such as MATLAB, would probably bring the error especially when K_p or the change rate of input signal is large.

5.4 Effect of water way system

The power response time T_4 is normally greater than opening response time T_2 . The main cause is the hydraulic character of the water way system, including the water hammer and surge in surge tank. Moreover, the turbine efficiency is also a crucial factor which always affects the power output, but it is relatively hard to analyze individually due to the serious nonlinear characteristic.

1) Water hammer (ΔT_2)

Without the surge tank, the time lag between the response time of power and opening is ΔT_2 . Water hammer is the main reason. Turbine efficiency and a minute change of water head can be

considered as secondary reasons. As shown in Fig. 5 and Fig. 6, the reverse power response due to water hammer occurs immediately after the change of opening. It leads to a time delay of the power response.

The key point is how much the water hammer delays the power response, which is rarely discussed before. A similar discussion was conducted in [23], and this section makes a more detailed investigation. The water hammer has a large influence during the first phase [24]. The formula of reflection period of water hammer is

$$T = \sum_{i=1}^j \frac{2L_i}{a_i}, \quad (15)$$

where L is the length of a pipeline, a stands for the wave velocity of water hammer, i represents a specific pipeline and j is the number of pipelines between the turbine and reservoir (or surge tank). The initial value of the reflection period is $T=1.08$ s. The length of the pipeline is changed in order to perform a sensitivity analysis for reflection period of water hammer.

Fig. 12. Power and opening under different reflection periods of water hammer

Fig. 13. Power and surge under parameters of group 3. In the figure legend, “ST” denotes surge tank.

As shown in Fig. 12, the minimum power occurs close to the end of the first phase of water

hammer, and it takes an additional short time for the power to return to the initial value. In other words, the water hammer leads to a delay time T_{delay} which is at least as long as a reflection period T . However the ΔT_2 is hard to predict precisely and may even be less than T , owing to the various factors such as the turbine efficiency and water head. Nevertheless the rough value of ΔT_2 can be estimated according to T , because there is only a tiny difference between these two values.

2) Surge (ΔT_3)

The surge is a primary cause of increase the power response time, in addition to turbine efficiency. Specifically, the power output is adversely affected because the water head changes with the water level fluctuation in the surge tank.

Table 1 shows that the slower the opening response, the greater the influence of the surge (affected by the surge period), and the larger value of the time lag ΔT_3 . Under the parameters of group 3 and 6 which lead to the slowest opening response, the ΔT_3 even exceeds 200s. As shown in Fig. 13, with the surge decline, power reduces before it reaches the target value, and it does not rise up to the target until after half of the surge period. Therefore the surge has a significant effect on power under the opening control mode, and especially when applying the parameters with poor rapidity, the power response time may easily exceed the requirement of specification.

6 Conclusion

This paper describes a model for primary frequency control under guide vane opening feedback control mode. The model, which is one of the main contributions of this paper, is validated with data from full scale measurements. Now it is already incorporated into software TOPSYS and put

into practical application.

Aiming at the response time of guide vane opening, a time domain analytical solution for opening response and a formula of response time, of which the main variables are governor parameters, are derived. The time difference ΔT , between the power response time and the analytical response time of opening, is mainly affected by rate limiting and numerical algorithm (ΔT_1), water hammer (ΔT_2) and surge (ΔT_3). However, the most direct and effective method is still adjusting the governor parameters. Especially for a HPP without surge tank, the ΔT changes within a small range, so the formula of opening response time can also help to predict the power response and supply a flexible guidance of parameter tuning.

Furthermore, this research can be extended in the aspects below: a more complex frequency deviation should be analyzed. The turbine efficiency is a key factor which needs to be further investigated individually. This research only focus on the control mode with guide vane opening feedback, but power droop or more advanced mode should also be studied. Such improvements will possibly make a more comprehensive description and understanding for the dynamic response of hydroelectric generating units in primary frequency control.

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Appendix A.

Table A.1 Basic information of a generating unit of the engineering cases

Parameter	Case 1	Case 2
Rated power (MW)	610.0	169.2
Rated water head (m)	288.0	135.0
Rated discharge (m ³ /s)	228.6	135.0
Rated rotation speed (r/min)	166.7	187.5
Inertia time constant T_a (s)	9.46	4.98
Surge fluctuation period (s)	496.0	390.0

Details of test setup

The tests in both two HPPs are conducted under opening control mode. The table below shows the details of the test setup.

Table A.2 Details of test setup

Parameter	Case 1	Case 2
Upstream level (m)	1639.3	213.1
Downstream level (m)	1332.3	78.3
Initial power (MW)	476.0	135.0 & 23.3
Frequency step (Hz)	-0.2 & +0.2	-0.1 & -0.3
b_p	0.04	0.02
K_p, K_i, K_d	9, 8, 0	1, 0.83, 0
E_y, E_f	0, 0.05	0, 0

Appendix B.

The fourth-order Runge-Kutta method for governor equations

A high-order differential equation, which describes a continuous control system, can be transferred to a first-order differential equation set (state equations), especially when the input of

the equation also contains derivative term [25]. According to (1), when disregarding K_d , the state equations are:

$$\begin{cases} u_1 = y - \beta_0 x \\ u_2 = \dot{u}_1 - \beta_1 x \end{cases} \quad \text{Eq. (A.1)}$$

Under the initial conditions which are $u_1(0)=0$ and $u_2(0)=0$, the results can be obtained by solving Eq. (A.2) with fourth-order Runge-Kutta method.

$$\begin{cases} \dot{u}_1 = u_2 + \beta_1 x \\ \dot{u}_2 = -a_2 u_1 - a_1 u_2 + \beta_2 x \end{cases} \quad \text{Eq. (A.2)}$$

Where $\beta_0 = b_0$, $\beta_1 = b_1 - a_1 \beta_0$, $\beta_2 = b_2 - a_1 \beta_1 - a_2 \beta_0$; $a_1 = \frac{1+b_p K_p + b_p K_i T_y}{T_y(1+b_p K_p)}$, $a_2 = \frac{b_p K_i}{T_y(1+b_p K_p)}$; $b_0 = 0$,

$$b_1 = \frac{K_p}{T_y(1+b_p K_p)}, b_2 = \frac{K_i}{T_y(1+b_p K_p)}.$$

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