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Model experiments and study on regulating stability of isolated hydropower plants

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Abstract. Hydropower shoulders a large portion of the regulation and balancing duty in many power systems all over the world. The stable regulation of hydropower plants (HPPs) is a conventional and crucial research topic, and many meaningful studies have been carried out by theoretical analysis and numerical simulations; however seldom experimental works on this issue are reported. This paper investigates stability of isolated HPPs based on model experiments on an integral experiment platform for transient processes of pumped storage plants in Wuhan University. Theoretical stability analysis is conducted based on Routh–Hurwitz stability criterion, and the stability region of the model power plant is obtained. The experiment results validate the theoretical analysis on the system stability, and the instability of the hydropower system due to poor settings of speed governor parameters are captured and demonstrated. This work presents initial results of experimental study on oscillation characteristics and regulation performance of HPPs for power system stability.

1. Introduction

Hydropower shoulders a large portion of the regulation and balancing duty in many power systems all over the world. The fast and stable regulation of hydropower plants (HPPs), including pumped storage power plants, is a conventional and crucial research topic; many meaningful studies have been carried out by theoretical analysis and numerical simulations [1-9]; however seldom experimental works on this issue are reported, and on-site tests on operating stability in real HPPs is also not a common practice due to safety risk.

This paper investigates stability of isolated HPPs based on model experiments on an integral experiment platform for transient processes of pumped storage plants in the State Key Laboratory of Water Resources and Hydropower Engineering Science of Wuhan University. In this work, the pumped storage units are operating in generation mode in the experiments, and the study objective is hydropower generation system. Theoretical stability analysis is conducted based on Routh–Hurwitz stability criterion, and the stability region of the model power plant is obtained.

In Section 2, the basic information of the experiment platform is presented. In Section 3, the method of theoretical stability analysis is introduced. In Section 4, the results of model experiments



and theoretical stability analysis are compared and analysed. In Section 5, the main works and conclusions of this paper are summarized.

2. Integral experiment platform for transient processes of pumped storage plants

The photo and illustration of the experiment platform are shown in Figure 1 and Figure 2, respectively, and its nine sub-systems are presented in Table 1. Detailed introduction of the experiment platform can be found in [10].



Figure 1. Photo of the experiment platform for transient processes of pumped storage plants.

Table 1. Nine sub-systems of the experiment platform.

| No. | Sub-systems | Descriptions |
|-----|---------------------------|---|
| 1 | Waterway system | Scaled model of real waterway system in HPPs: a key to study the hydraulic characteristics of hydropower systems |
| 2 | Model units | Including two sets of reversible pump-turbines and motor generators |
| 3 | Circulating water | Providing circulating water for the model experiments |
| 4 | Speed governor system | Main inlet valve control, power and frequency control, automatic generation control, start-up and stop control, and emergency shutdown of the units |
| 5 | Electrical control system | Excitation control, synchronization and protection of the generator-motors |
| 6 | Electrical load | Providing R-L-C load for the model experiments under isolated operating condition |
| 7 | Converter and commutation | Enabling variable-frequency start-up and switch between pumping and generation of pump turbines |
| 8 | Measurement system | Fast acquisition, processing and analysis of various physical quantities for the model experiments |
| 9 | Monitoring system | Operation instruction, data acquisition and processing, safety monitoring for the model experiments |

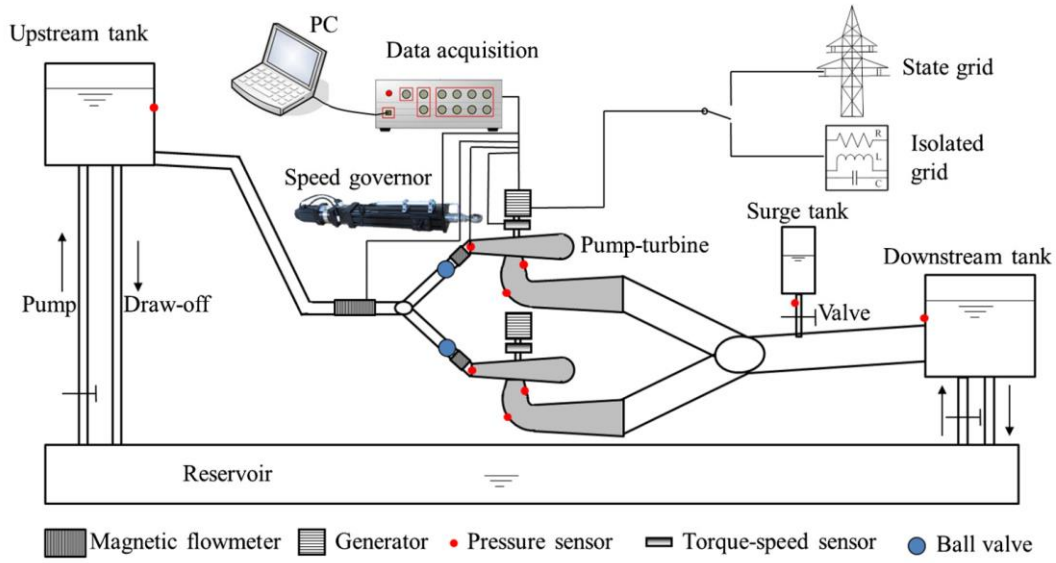


Figure 2. Illustrations of the experiment platform.

3. Method of theoretical stability analysis

In this section, standard mathematical model and method of theoretical stability analysis are briefly introduced. Routh–Hurwitz stability criterion is adopted to investigate the stability of the model power plant. The mathematical model of the model power plant is a linear time-invariant SISO system, which described in the following equations. All the symbols for variables in this paper are presented in Appendix.

The transfer function describing the pipeline is

$$G_p(s) = \frac{h(s)}{q_t(s)} = -\frac{T_w s}{1 + 0.5T_e^2 s^2} \quad (1)$$

The transfer function of the pump turbine and the waterway system is

$$G_T(s) = \frac{m_t(s)}{y(s)} = \frac{e_y + (e_{qy}e_h - e_y e_{qh})G_p(s)}{1 - e_{qh}G_p(s)} \quad (2)$$

The transfer function of the first-order generator model is

$$G_G(s) = \frac{x(s)}{m_t(s) - m_g(s)} = \frac{1}{T_a s + e_n} \quad (3)$$

$$e_n = e_x + D_t \quad (4)$$

The transfer function of the PI speed governor in frequency control mode is

$$G_F(s) = \frac{y(s)}{x(s)} = -\frac{K_p s + K_i}{(T_y + b_p K_p T_y)s^2 + (1 + b_p K_p + b_p K_i T_y)s + b_p K_i} \quad (5)$$

The overall transfer function for describing the system is

$$G(s) = \frac{x(s)}{m_g(s)} = -\frac{G_G(s)}{1 + G_F(s)G_T(s)G_G(s)} \quad (6)$$

The detailed introduction of implementing Routh–Hurwitz stability criterion for similar cases can be found in [6, 11].

4. Results of model experiments and theoretical stability analysis

In this section, the results of model experiments and theoretical stability analysis are compared and analysed.

4.1 Operating conditions and settings

The parameter settings of the mathematical model for theoretical stability analysis are calculated based on the practical conditions and previous studies [10], and the values are given in Table 2. Other parameters of the experiment platform can also be found in [10].

Table 2. Parameter settings of the mathematical model for theoretical stability analysis.

| Parameters in the mathematical model | | Pump-turbine characteristics | |
|---|---------|------------------------------|---------|
| Time constant of water column elasticity, T_e | 0.057 s | e_y | 0.9 pu |
| Water starting time constant, T_w | 0.31 s | e_x | -0.8 pu |
| Servo time constant, T_y | 0.1 s | e_h | 1.45 pu |
| Mechanical time constant, T_a | 4.0 s | e_{gy} | 0.66 pu |
| Damping coefficient, D_t | 0.9 s | e_{gx} | 0.1 pu |
| Turbine governor droop, b_p | 0 | e_{qh} | 0.9 pu |

Only one pumped storage unit is operating and in frequency control under generation mode, forming a single-machine isolated system. In each experiment case, a step change of pure resistance load from 75% to 70% happens at 5.0 seconds, and there are in total 34 cases presented in this paper, as shown in Figure 3.

4.2 Results

Based on the Routh–Hurwitz stability condition, the stability region of the isolated model power plant is achieved, as shown in Figure 3. For the experiment results, the governor parameter settings of the 34 cases are demonstrated as scatters in the K_p - K_i coordinates in Figure 3, and representative time domain plots of rotational speed are presented in Figure 4 and Figure 5. The cases are categorised as the following three groups.

(1) “Stable cases” are for the normal cases under which the system keeps stability under the step change of 5% electrical load, as shown in the blue squares in Figure 3 and the cases “ $K_p = 1$ ” and “ $K_p = 6$ ” in Figure 4.

(2) “Unstable cases” means that the system loses stability and the speed fluctuation diverges, as shown in the black crosses in Figure 3 and the cases “ $K_p = 8$ ” in Figure 4 and the case “ $K_p = 7$ ” in Figure 5. Generator tripping is manually conducted after the divergence of speed fluctuation occurs for the sake of safety.

(3) “Sustained oscillating cases” are not strictly defined here, and they are for intermediate cases under which the speed fluctuation continuously for a relatively long time, as shown in the red circles in Figure 3 and the cases “ $K_p = 7$ ” in Figure 4, the case “ $K_p = 4$ ” and “ $K_p = 6$ ” in Figure 5. The governor parameter of sustained oscillating cases in the K_p - K_i coordinates are located closely to the boundary of stability region.

In short, the measurements have a good agreement with the theoretical stability analysis, especially for the overall shape of the stability region, which is a core for the regulation performance of the hydropower system. Inherent deviation between the theoretical stability region and measured fluctuations is observed, e.g. the case “ $K_p = 1$ ” in Figure 4 can be deemed as stable, while the governor parameter setting is out of the stability region; it is because of the ignored nonlinear factors in the theoretical model, measurement errors, etc., and further study needs to be conducted.

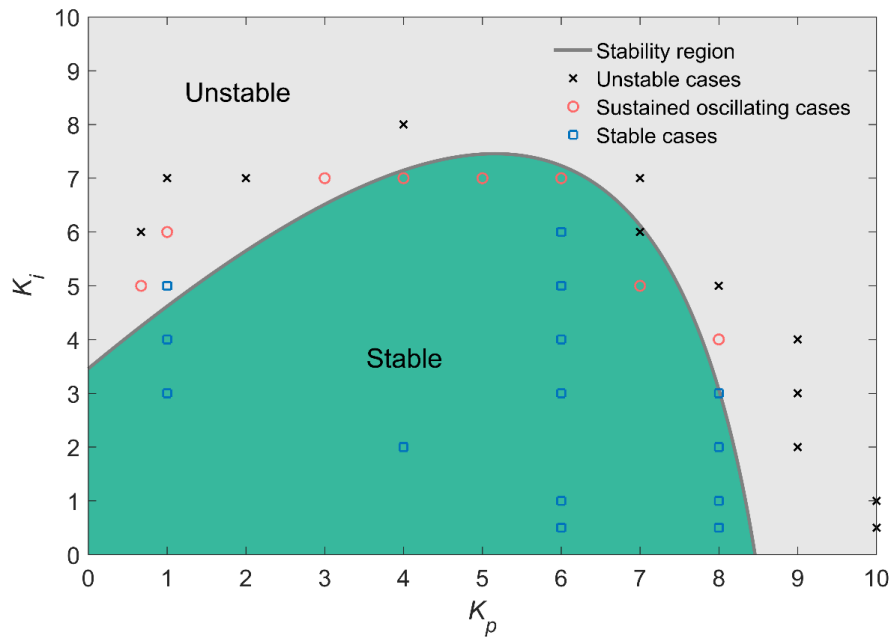


Figure 3. Stability region in K_p - K_i coordinates and settings for experiment cases.

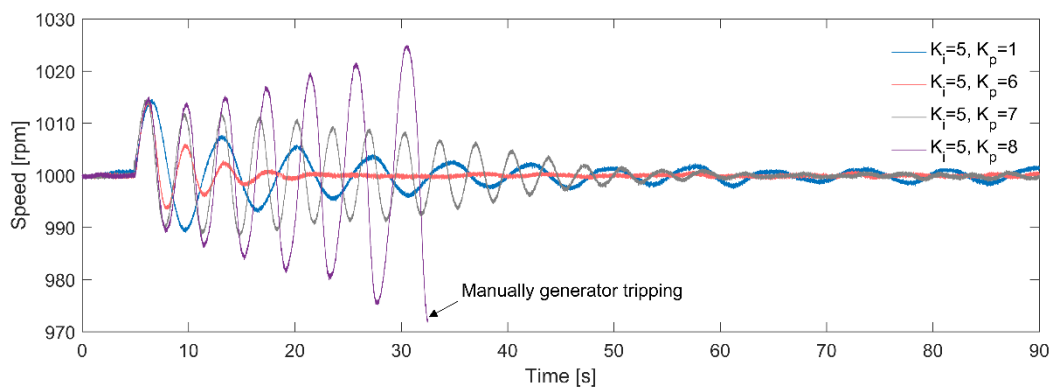


Figure 4. Measured rotational speed for experiment cases ($K_i = 5.0$).

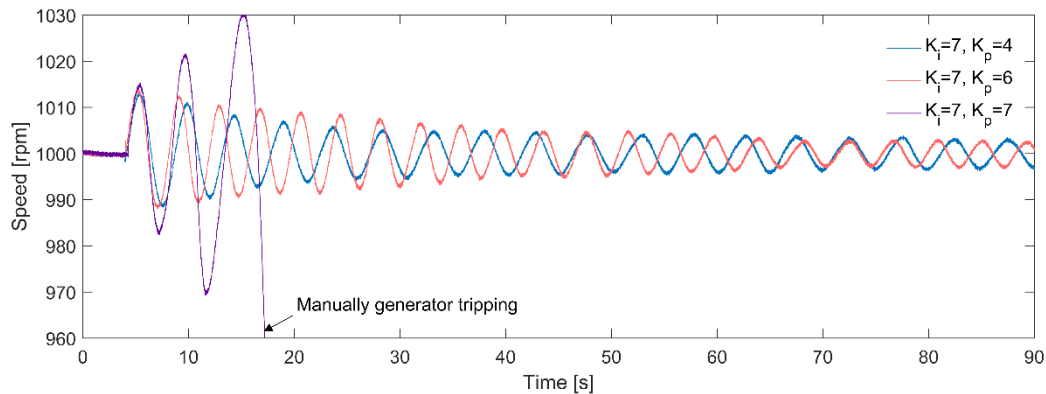


Figure 5. Measured rotational speed for experiment cases ($K_i = 7.0$).

5. Conclusions

In this study, stability of isolated HPPs is investigated based on model experiments on an integral experiment platform for transient processes of pumped storage plants in Wuhan University. Theoretical stability analysis of the model power plant is also conducted based on Routh–Hurwitz stability criterion.

The results show the overall good agreement between the measured cases in different governor parameter settings and the stability region from theoretical stability analysis. The instability of the hydropower system and the sustained oscillation of generator rotational speed, due to poor settings of speed governor parameters, are captured and demonstrated.

Inherent deviation between the theoretical analysis and measured results is observed, due to ignored nonlinear factors in the theoretical model, measurement errors, etc., and further study needs to be conducted. A long-term goal of the study is to thoroughly investigate the oscillation characteristics and regulation performance of HPPs for power system stability.

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Appendix

Nomenclature

| | |
|--------------------------|---|
| b_p | turbine governor parameter (droop) |
| D_t | damping coefficient |
| e_y, e_x, e_h | partial derivative of turbine power output with respect to guide vane opening, speed and head |
| e_{qy}, e_{qx}, e_{qh} | partial derivative of turbine discharge with respect to guide vane opening, speed and head |
| e_n | a synthetical damping coefficient |
| m_g | electromagnetic torque |
| m_t | mechanical torque |
| K_i | speed governor parameters: for integral term |
| K_p | speed governor parameters: for proportional term |
| s | Laplace operator |
| T_a | mechanical time constant |
| T_e | time constant of water column elasticity |
| T_w | water starting time constant |
| T_y | servo time constant |

| | |
|-----|--------------------|
| x | rotational speed |
| y | guide vane opening |

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