

Research on Closed-loop Start-Up Process of Hydraulic Turbine Based on Adaptive Variable Parameters of Water Head

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Abstract. The large fluctuation range of the operating head of some hydropower stations has an impact on the arrangement of the starting mode. In order to suppress the influence of the water head on the start-up process, a closed-loop start-up simulation model of a hydro-generator unit is established in this paper, and variable parameter control based on head adaptation is adopted. By comparing the performance indexes of the closed-loop start-up process between the conventional PID control and the adaptive variable parameter control, it is shown that the adaptive variable parameter control based on the head has better dynamic adjustment performance.

1. Introduction

The hydropower unit has the advantages of quick start response and simple adjustment of load. Therefore, it mainly plays the role as peak shaving or frequency modulation unit and rotating standby in the power system, which is also the preferred choice for black start. For example, the Tongren Power Supply Bureau has repeatedly used the Tianshengqiao 2×10000 kW hydropower unit and the Shantou 2×8000 kW hydropower unit as the black start power source. The Triangle Beach 3×5000 kW hydropower unit and the Chunyangtan 4×8000 kW hydropower unit were used as the black start power source in Huaihua, Hunan province [1], restoring the power supply to the grid in a very short period of time. The time required for hydro-generator unit to turn on directly affects the power quality and operational safety of the power system when the system fails and the frequency decreases, and also directly affects the power recovery time and the degree of power outage loss in the event of a system failure resulting in a power outage.

Most small hydropower is run-of-river power station, due to the influence of the season and the weather, the operating head of the hydropower station fluctuates widely, which has a certain impact on the arrangement of the starting mode. Therefore, it is necessary to investigate into the small-scale hydropower start-up control law. Choosing a suitable starting method can reduce the impact of the running water head on the starting process and optimizing the starting control parameters can reduce the adverse effect of the starting law on the dynamic stress of the turbine runner, which can ultimately improve the safety and stability of the power system and the economic benefits of the hydropower station. In order to optimize the control parameters of the closed-loop start-up process, Liu[2] introduced an improved PSO optimization algorithm, to obtain a satisfactory boot performance evaluated by the proposed comprehensive performance index.



In order to further suppress the influence of the water head on the start-up process, this paper establishes a close-loop start-up simulation model of the hydro-generator unit based on Simulink, and proposes a variable parameter control based on the head adaptation. That is, the governor selects different PID parameters according to the current working water head during the start-up process. By comparing the performance indexes of the closed-loop boot start-up process between the conventional PID control and the adaptive variable parameter control, it is shown that the adaptive variable parameter control based on the head achieves a satisfactory boot process under different water heads.

2. Closed-loop start-up process simulation model

2.1. Turbine governor

A parallel PID control regular structure is widely adopted in the turbine governor[3]. Its control law is as follows:

$$y_{pid}(s) = K_p + \frac{K_i}{s} + \frac{K_d s}{T_{1v}s + 1} \quad (1)$$

Where K_p is the proportional gain, K_i is the integral gain, K_d is the differential gain, T_{1v} is the differential link time constant, and s is the pull operator.

The electro-hydraulic servo system of the turbine governor has several structural forms, and its mathematical model is as follows:

$$\frac{y(s)}{y_{pid}(s)} = \frac{1}{T_y T_{y1} s^2 + T_y s + 1} \quad (2)$$

Where T_y is the main relay reaction time constant, T_{y1} is the auxiliary relay reaction time constant, and s is pull operator.

In engineering applications, the nonlinear link of the electro-hydraulic servo system has a great influence on the dynamic quality of the turbine governing system[4]. Hence, a model that incorporates nonlinear factors such as the dead zone of the pressure regulating valve, the stroke limit of the servomotor, and the speed limit has been adopted in this study.

2.2. Pressure water diversion system

The characteristics of the pressurized water diversion system are described by the elastic water hammer theory, whose mathematical model is as follows:

$$G_h(s) = -2h_w th(0.5T_r s + \frac{h_f}{2h_w}) \quad (3)$$

Where h_w is the characteristic coefficient of the water pipe, T_r is the length of the water hammer, h_f is the relative value of the loss along the path, and s is the pull operator.

2.3. Hydraulic turbine.

The physical structure of the turbine is complex, and the external characteristic parameters are nonlinear and time-varying. There are mainly three models, i.e. linearization, nonlinear analysis and model-based comprehensive characteristic curve, respectively. Among them, the hydraulic turbine model based on the model comprehensive characteristic curve can better reflect the dynamic characteristics of the turbine[2], whose mathematical model is as follows:

$$\begin{cases} m = f_M \cdot (h + h_0) / M_{11r} - m_0 \\ q = f_Q \cdot \sqrt{h + h_0} / Q_{11r} - q_0 \\ n_{11} = n_{11r} \cdot (x + x_0) / \sqrt{h + h_0} \\ h(s) = q(s)G_h(s) \end{cases} \quad (4)$$

Where m , q , x , h is active torque, flow rate, speed and working water relative deviation value respectively. The subscript 0 means the relative initial value of each parameter. M_{11r} , Q_{11r} , n_{11r} are unit torque, unit flow and unit speed rating respectively; f_M and f_Q are unit torque and unit flow based on the relationship function of the model's comprehensive characteristic curve, and s is the pull operator.

2.4. Generator

In the analysis of the start-up process, a first-order model that ignores the electromagnetic and power angle characteristics of the generator is usually used, which only considers the equation of motion of the rotor is as follows:

$$J \frac{d\omega}{dt} = M_t - M_g \quad (5)$$

Where J is the unit's moment of inertia, $d\omega$ is the unit's rotational angular speed, M_t is the hydraulic torque of the turbine, and M_g is the unit load torque.

3. The idea of adaptive variable parameters

Usually, the parameters of the turbine governor are optimized by field test in the project, and the results are real and effective. However, in consideration of system conditions and equipment safety and stability, the number of field tests and the conditions that can be tested are limited, and the test period is long. Therefore, it is time-consuming and labor-intensive to optimize the governor parameters only through field tests. In this paper, the variable parameter closed-loop start-up process based on head adaptation is realized through the simulation.

The basic idea of adaptive variable parameter close-loop start-up based on head is:

- (1) Select the typical working conditions of the turbine according to the working head;
- (2) Optimize the parameters of these conditions with the improved PSO algorithm to form an optimized PID parameter table;
- (3) Establish a relationship curve between K_p , K_i , K_d and water head;
- (4) When starting up, get the corresponding parameters according to the current water head interpolation in the relationship curve.

4. Case study

With the Simulink simulation platform, a simulation model is established according to the close-loop start-up process of a mixed-flow hydropower unit.

Basic simulation parameters: $T_w=1.63s$, $T_r=1.81s$, $T_a=5.86s$, $T_y=0.2s$, $T_{y_l}=0.05$.

4.1. PID parameter optimization for starting up

In this paper, the improved PSO optimization algorithm is used to optimize the controller parameters of the close-loop start-up process. Currently used performance indicators are mainly ISE, IAE, ISTE and ITAE. The control system using the ITAE index has the characteristics of fast, stable and small overshoot, and is widely used in the optimization of PID parameters of the turbine governing system[5, 6]. According to the requirements of the actual operation of the hydropower unit, this paper proposes a

comprehensive index based on the ITAE index. In order to avoid the problem that it takes too long time for the unit to reach the rated speed from receiving the power-on command, the t_{SR} limit is added to the performance index. In order to suppress the fluctuation of the unit turning torque and the axial water thrust during the starting process, the maximum head deviation limit is added to the performance index. To achieve a small pressure, change in the unit pressure water conduit during the start-up process, a head deviation integral limit is added to the performance index. In order to avoid over-speed of the unit, a penalty measure is introduced in the performance index, so that once the overshoot is too large, the overshoot limit will be considered.

In summary, the comprehensive indicator expression proposed in this paper is as follows:

$$J_{ZH} = \int_0^{t_u} (|x(t)| + |h(t)|) dt + \delta(\sigma) + w_1 t_{SR} + w_2 |h(t)|_{\max} \quad (6)$$

$$\delta(\sigma) = \begin{cases} 50\sigma & \sigma \geq 1\% \\ 0 & \sigma < 1\% \end{cases} \quad (7)$$

Where t_u is the integral upper limit time, $x(t)$ is the deviation between the actual speed and the desired speed, $h(t)$ is the deviation between the turbine operating head and the initial head, and σ is the unit speed overshoot, $w_1 (=0.1)$, $w_2 (=8)$ are constant values.

In this paper, 10 water head values are selected randomly, and equations (6) and (7) are used as performance indicators of the improved PSO algorithm to optimize the optimal close-loop start-up PID parameters under each head. The optimized PID parameters are shown in Table 1.

Table 1. Optimal start-up simulation PID parameters under each head.

Numble	Relative value of water head	K_p	K_i	K_d
1	1.00	0.9463	0.0787	0
2	0.98	0.9644	0.0823	0
3	0.97	0.9917	0.0850	0
4	0.95	1.0242	0.0900	0
5	0.93	1.0487	0.0954	0
6	0.90	1.0692	0.1047	0
7	0.87	1.0245	0.1101	0
8	0.85	1.0237	0.1156	0
9	0.82	1.0449	0.1251	0
10	0.80	0.9885	0.1319	0

And then, using the spline interpolation, the relationship between K_p and the head is established as shown in Fig. 1. The relationship between K_i and the head is shown in Fig. 2. It can be seen from Table 1 that K_d is always 0, that is, the PI control can obtain better start-up performance during one-stage linear closed-loop start-up process.

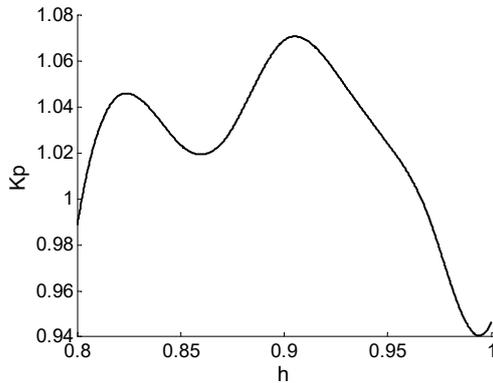


Figure 1. K_p and water head curve.

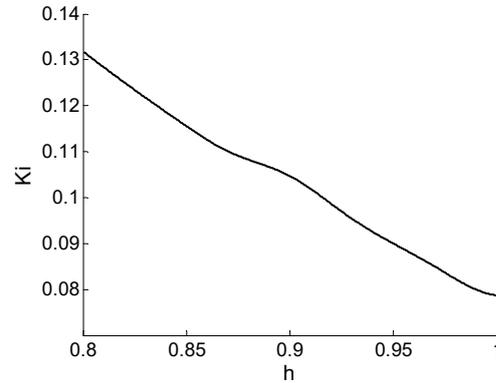


Figure 2. K_i and water head curve.

4.2. Impact of different PID controls on the start-up process

When using variable parameter PID control based on head adaptation, the closed-loop start-up parameter is read in the relationship curve between K_p and the head and that between K_i and the head according to the corresponding working head. When the conventional PID control is adopted, the closed-loop start-up parameter is taken as the optimization parameter under the rated head. When the water head is 0.835, 0.86, and 0.92, the performance indicators of the start-up process under the two control modes are shown in Table 2. The t_{SR} in the table indicates the time when the speed or frequency rises from 0 to less than +1%~-0.5% from the rated value.

Table 2. Comparison of start-up performance indicators of different control parameters.

Water head	control method	K_p	K_i	ITAE	$\sum h(t) $	$ h(t) _{\max}$	σ	t_{SR}
0.835	conventional	0.9463	0.0787	52.006	0.7228	0.1998	0.0000	56.50
	adaptive	1.0397	0.1203	26.019	0.7727	0.2242	0.0020	24.46
0.86	conventional	0.9463	0.0787	45.963	0.7203	0.2028	0.0000	51.64
	adaptive	1.0194	0.1126	25.999	0.7598	0.2226	0.0019	24.41
0.92	conventional	0.9463	0.0787	32.701	0.7145	0.2094	0.0000	30.51
	adaptive	1.0613	0.0983	24.413	0.7551	0.2366	0.0015	24.33

It can be seen from Table 2 that the ITAE and t_{SR} values of the start-up process using adaptive variable parameter control are greatly reduced compared with the conventional control, while other indicators are only slightly increased, which satisfies the balance between rapidity and smoothness. It is also verified that the adaptive variable parameter rules established by simulation can effectively realize the starting up, and improve the adaptability of the closed loop start-up law to the water head.

There may be some differences between the simulation test and the actual project. In literature[7], the relationship between the no-load opening and the head of the Three Gorges left-bank unit and that between the governor optimization parameters and the head are obtained by computer simulation. Then the field test is used to correct the simulation curve, which reduces the number of fields tests and improves the dynamic performance of the turbine regulation system. This provides engineering application support for the adaptive variable-parameter close-loop start-up discussed in this paper.

5. Conclusion

Considering the fluctuation of the operating head of the hydropower station, this paper establishes a simulation model of the close-loop starting process of the mixed-flow hydropower unit. Then the optimized PSO algorithm is used to optimize the relationship between the PID parameters and the water head. Finally, variable parameter PID control based on head adaptation is realized. Compared with the

conventional control, it satisfies the balance between rapidity and stability, and improves the adaptability of the close-loop start-up law to the water head.

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