

Research on optimization of hydraulic turbine governor based on PSO algorithm

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Abstract. Due to the complex structure of the turbine control system, poor dynamic performance and difficult stability, the conventional PID tuning method widely used in the turbine governor is becoming increasingly difficult to meet the actual control requirements. Based on the structure and mathematical model of the turbine control system, this paper introduces the PSO (Particle Swarm Optimization Algorithm) to optimize the PID parameters of the turbine governor based on ITAE as the fitness function. The simulation results show that the PSO algorithm is an effective parameter optimization method for the turbine governor, which has better dynamic performance compared with the conventional PID control.

1. Introduction

The turbine regulation system is a non-minimum phase closed-loop system with nonlinear characteristics, time-varying, water hammer effect^[1]. With the emergence of large capacity units and large-scale interconnected power systems and their increased demand for automatic control of power systems, higher requirements are put forward for their control quality^[2].

The traditional PID control parameter tuning method is difficult to improve the control quality, resulting in phenomenon such as overshoot large, long swing time, frequent fluctuations or slow adjustment and so on. Currently, domestic and foreign scholars have done some research on PID control parameter tuning. The Ziegler - Nichols (ZN) integral method is most commonly used. Liu proposes an improved genetic algorithm to optimize fuzzy PID controller of hydropower units^[3], and adaptive fuzzy controller is applied by Zhang to improve the overall performance of hydro-turbine governing system and adjusts adaptively the parameters as the operating conditions change^[4], and the dynamic and static performance of the system is improved. Sun and Fang uses Genetic algorithm and Artificial Fish Swarm algorithm to set the PID parameters of turbine governor, the optimization of parameters is realized effectively^[5-6].

As a new optimization algorithm, Particle Swarm Optimization(PSO) has been applied in the control field^[7-9]. Because of its good performance, PSO has been applied to the hydraulic turbine governing system. In this paper, the particle swarm optimization algorithm is combined with the PID control and use error performance of the control system as the fitness function of the particle swarm algorithm. After several iterations, the optimal parameters of the PID controller are found to improve the control quality of the turbine control system.



2. Mathematical model of hydraulic turbine regulation system

The turbine control system is a closed-loop control system composed of a governor (PID controller) and a regulating object^[10]. The block diagram of the module is shown in figure 1.

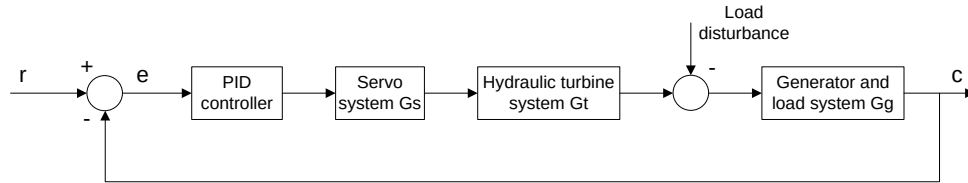


Figure 1. block diagram of turbine control system

In figure 1, the transfer functions of each model controlled are the transfer function of electrohydraulic servo system $G_s(s)$, the transfer function of the water diversion system and the turbine system $G_t(s)$, and the transfer function of the generator and the load $G_g(s)$. The expressions are:

$$G_s(s) = 1 / (1 + T_y s), \quad G_t(s) = \frac{e_y - (e_h e_{qy} - e_{qh} e_y) T_w s}{1 + e_{qh} T_w s}, \quad G_g(s) = 1 / (T_a s + e_n) \quad (1)$$

Where s is the complex parameter. T_y is the relay reaction time constant. T_w is the inertia time constant for the flow. T_a is the inertia time constant for the unit. e_y is the transmission coefficient of the turbine torque to the guide vane opening; e_h is the transmission coefficient of the turbine torque to the head. e_{qy} is the transmission coefficient of the guide vane opening. e_{qh} is the turbine flow on the head transfer coefficient. e_n is the unit self-balancing coefficient. According to the relevant literature, in this paper we select the operating parameters of a hydropower plant as follows: $e_y = 1.0$, $e_h = 1.5$, $e_{qy} = 1.0$, $e_{qh} = 0.5$, $e_n = 1.0$, $T_y = 0.2$, $T_w = 1.0$, $T_a = 3.36$.

3. Particle swarm optimization

3.1. Principle of particle swarm optimization

Particle Swarm Optimization (PSO) is a group intelligent optimization algorithm in addition to ant colony algorithm, fish group algorithm in computational intelligence field. The algorithm was first proposed by Kennedy and Eberhart in 1995. The PSO algorithm is derived from the study of bird predation behavior. When birds prey, the easiest and effective way to find food is to search for the surrounding area of the bird that is closest to food. The PSO algorithm is inspired from the behavioral characteristics of this biological population and is used to solve the optimization problem. Each particle in the algorithm represents a potential solution of the problem, and each particle corresponds to a fitness value determined by the fitness function. The velocity of the particle determines the direction and distance of the particle movement, and the velocity is dynamically adjusted with the movement experience of the particle and other particles, so as to realize the optimization of the individual in the solvable space^[11].

The PSO algorithm first initializes a group of particles in the feasible solution space, and each particle represents a potential optimal solution of the extreme optimization problem. The position, velocity and fitness values are used to represent the particle characteristics. Fitness value is calculated from the fitness function and the quality of value indicates the quality of the particles. The particles move in the solution space and the updation of individual's position is determined by tracking individual extremes (Pbest) and group extremes (Gbest). Individual extremum (Pbest) is the optimal position of the fitness value searched by individual particles. The group extremum (Gbest) refers to the optimal position of fitness for all the particles in the population. When the particle is updated once, the

fitness value is calculated .The Pbest and Gbest are updated by comparing the fitness value of the new particle with the fitness value of the individual extremum(Pbest) and the group extremum(Gbest)^[12].

3.2. Algorithm application

Suppose that in a D-dimensional search space, n particles make up the population $X = (X_1, X_2, L, X_n)$ where the i-th particle is expressed as a D-dimensional vector $X_i = (X_{i1}, X_{i2}, L, X_{iD})^T$ which represents the position of the i-th particle in the D-dimensional search space and also represents a potential solution to the problem. According to the objective function, the fitness value of each particle position X_i corresponds to can be calculated. The velocity of the i-th particle is $V_i = (V_{i1}, V_{i2}, L, V_{iD})^T$. The individual extremum(Pbest) is $P_i = (P_{i1}, P_{i2}, L, P_{iD})^T$ and the group extremum(Gbest) of the population is $P_g = (P_{g1}, P_{g2}, L, P_{gD})^T$.

During each iteration, the particle updates its own velocity and position through the updation of individual extremes and group extremes which can be expressed as follows:

$$V_{id}^{k+1} = \omega V_{id}^k + c_1 r_1 (P_{id}^k - X_{id}^k) + c_2 r_2 (P_{gd}^k - X_{id}^k), \quad X_{id}^{k+1} = X_{id}^k + V_{id}^{k+1} \quad (2)$$

Where ω is the inertia weight; $d=1, 2, L, D$; $i=1, 2, L, n$; C_1, C_2 is a nonnegative constant, called the acceleration constant; k is the current number of iterations; r_1, r_2 is a random number between $[0, 1]$; P_{id}^k is the optimal position for searched for each particle so far and P_{gd}^k is the optimal position searched for the entire particle group so far. In order to prevent blind search of particles, it is generally recommended to limit its position and speed to a certain range.

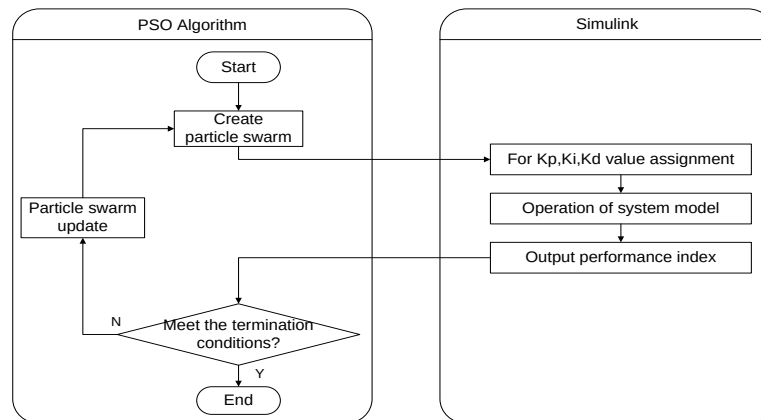


Figure 2. schematic diagram of optimized PID with PSO

The PSO algorithm is as follows:

- Initializing the particle population, randomly generating the location and velocity of all the particles, and determining the particle P_t and G_t ;
- For each particle, the fitness value is compared with the fitness value of the optimal position P_t that the particle has experienced. If it is better, it is used as the current P_t ;
- For each particle, the fitness value is compared with the optimal position G_t that the entire particle group has experienced. If it is better, it is used as the current G_t ;
- Update the speed and position of the particle according to formula (2);
- If the termination condition is not satisfied (usually the default number of iterations and the lower limit of the fitness value), return to step (2), otherwise, exit the algorithm to get the optimal solution. The process of optimizing PID with PSO is shown in figure 2.

4. Simulation analysis

The control system is based on the integral error performance index. The minimization of the integral of time-weighted absolute error (ITAE) is usually referred to literature as a good tuning criterion to obtain controller PID parameters, which is a kind of control system performance evaluation index with good engineering practicality and selectivity. The ITAE performance index is mathematically given by:

$$J = \int_0^{\infty} t |e(t)| dt \quad (3)$$

where t is the time and $e(t)$ is the difference between set point and controlled variable^[13].

Based on the turbine control model, the PID parameter tuning and simulation are carried out by MATLAB-Simulink tool [14]. The Simulink simulation model is shown in figure 2. Particle swarm algorithm is used to iteratively optimize the PID parameters in the model 30 times, the particle size is 100, the inertia factor is 0.6, and the acceleration factor is 1.5.

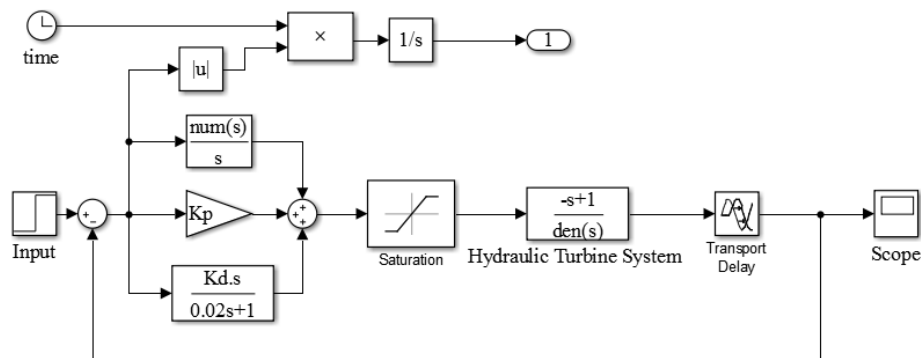


Figure 3. Simulink model of hydraulic turbine system

The PID adaptive parameter tuning curve based on the PSO algorithm is shown in figure 3, the corresponding fitness function during the iteration process shown in Fig.4. The error analysis and comparison of the unit feedback control, conventional PID control, ZN-PID control and PSO-PID (ZN-PID is the commonly used Ziegler-Nichols setting method) are carried out in the same given input. The step response tracking curve is shown in Fig.5. When the number of iterations reaches 15 times, the stability of parameter value and adaptive value is achieved. And the optimal results are $K_p = 2.1725$, $K_i = 1.1106$ and $K_d = 1.0831$ (Final ITAE = 1.0495).

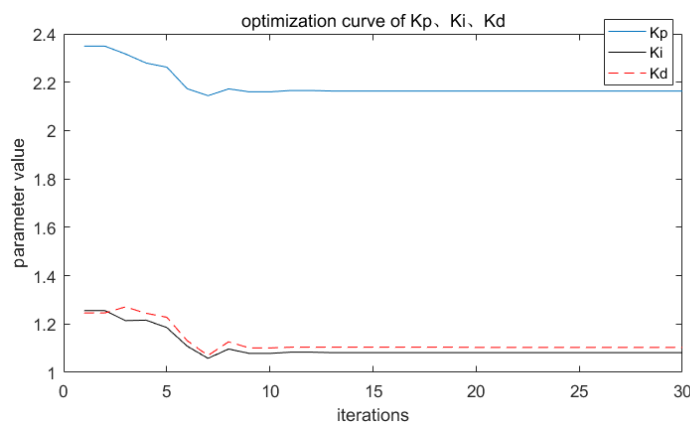


Figure 4. Optimization curve of parameter value

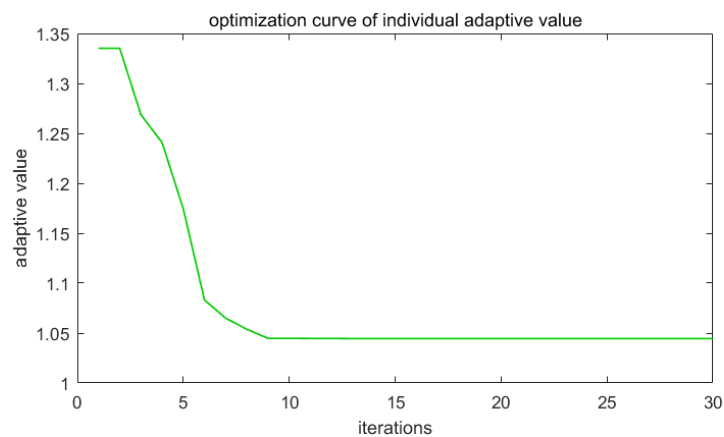


Figure 5. Optimization curve of individual adaptive value

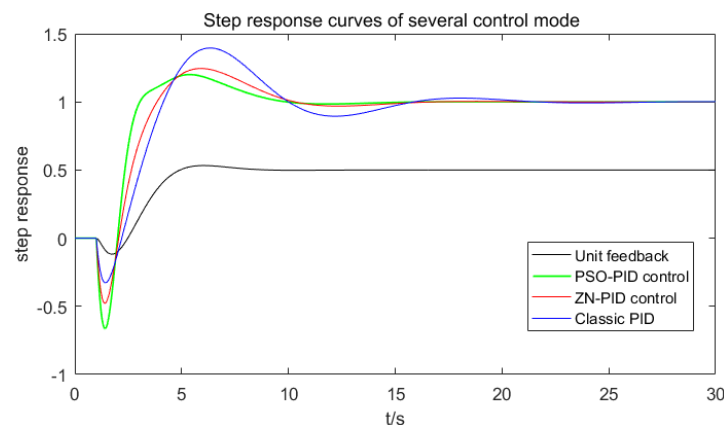


Figure 6. Step response curves of several control mode

The control method is analyzed by simulation results such as step response curve and error analysis. System dynamic performance index is given in table 1.

Table 1. System dynamic performance index

Control method	Rise time/s	Settling time/s	overshoot/%
Classic PID	1.54	14.39	39.6
Ziegler-Nichols PID	1.38	9.24	24.5
PSO-PID	0.72	8.42	20.1

The rise time t_r , adjustment time t_s and overshoot σ are indexes reflect the dynamic performance of the system. It can be seen from the above chart analysis that with the use of PSO to optimize the PID parameters, the commonly used performance indicators are better than the previous PID algorithm. The system response speed with the rise time down to 0.72 seconds, and the adjustment time down to 8.42 seconds. In addition, the system overshoot in the process of running down to 20.1% and the degree of volatility of the system is improved. The dynamic performance has been greatly improved. The only drawback is that due to the inertia of the turbine control system, the 2 seconds at the beginning of the running system, the step response curve appeared a large shock.

5. Conclusion and prospect

In this paper, the PSO optimization algorithm is used to design the PID control parameters of the Hydraulic Turbine Regulating System. Compared with the conventional PID control system, the system in this paper shows good dynamic performance and stability. This shows that PSO optimization algorithm is an effective method for the optimization of PID parameters of hydraulic turbine regulation system. It has certain research significance and application prospect.

The turbine regulation system is a complex nonlinear system. The linear control method based on PID control has some limitations. Combining the PID control with the nonlinear intelligent control method and optimizing the correlation coefficient by using the intelligent optimization algorithm to improve the running performance of the turbine control system, it is the current and future research direction in the field.

References

- [1] Halanay A, Safta C A, Dragoi C, et al. Stability analysis for a delay differential equations model of a hydraulic turbine speed governor[C]. *AIP Conference Proceedings*. AIP Publishing, 2017, 1798(1): 020134.
- [2] Kou P, Zhou J, Li C, et al. Identification of hydraulic turbine governor system parameters based on bacterial foraging optimization algorithm[C]. *Natural Computation (ICNC), 2010 Sixth International Conference on. IEEE*, 2010, 7: 3339-3343.
- [3] Liu H, Zhou J, Wang S, et al. Application of fuzzy PID control system based on improved GA in hydraulic turbine generating units[C]. *Intelligent Control and Automation, 2008. WCICA 2008. 7th World Congress on. IEEE*, 2008: 7790-7794.
- [4] Zhang X Y, Zhang M G. An adaptive fuzzy PID control of hydro-turbine governor[C]. *Machine Learning and Cybernetics, 2006 International Conference on. IEEE*, 2006: 325-329.
- [5] Sun X, Fang H. Speed governor PID gains optimal tuning of hydraulic turbine generator set with an improved artificial fish swarm algorithm[C]. *Information and Automation (ICIA), 2016 IEEE International Conference on. IEEE*, 2016: 2033-2035.
- [6] Fang H, Chen L, Li X. Intelligent optimal tuning of hydraulic turbine governor PID gains based on nonlinear model[C]. *Computer Science and Service System (CSSS), 2011 International Conference on. IEEE*, 2011: 1342-1345.
- [7] XIE Cheng-wang Z O U, Xiu-fen X I A. A multi-objective particle swarm optimization algorithm integrating multiply strategies[J]. *Acta Electronica Sinica*, 2015, 43(8): 1538-1544.
- [8] Liu L, Yan G Y, Lei Y, et al. Optimization design of steering trapezoid mechanism based on an improved particle swarm optimization[J]. *Transactions of the Chinese Society of Agricultural Engineering*, 2013, 29(10): 76-82.
- [9] Hu W, Yen G G, Zhang X. Multiobjective particle swarm optimization based on Pareto entropy[J]. *Journal of Software*, 2014, 25(5): 1025-1050.
- [10] Xu Y Q, Wang Y L. Application of BP Neural Network in Water Turbine Regulating System[J]. *Hydropower Science*, 2017 (7): 176-178. *Engineering*. 2006, 26(8): 66-71.
- [11] Lei G. Application of improved particle swarm optimization algorithm based on average position in parameter optimization of hydraulic turbine governor[C]. *Control, Automation and Robotics (ICCAR), 2017 3rd International Conference on. IEEE*, 2017: 252-255.
- [12] Huang G, Cui J, Chen X, et al. Hydraulic Turbines Vibration Fault Diagnosis by Neural Network Based on Particle Swarm Optimization [J]. *Power System and Clean Energy*, 2009, 4.
- [13] Martins F G. Tuning PID controllers using the ITAE criterion[J]. *International Journal of Engineering Education*, 2005, 21(5): 867.
- [14] Wang Y S, Zheng H L. A New PID Control Method for Hydraulic Turbine Governor[C]. *Applied Mechanics and Materials. Trans Tech Publications*, 2013, 420: 375-380.