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ANN Based Modeling and Optimization of Large Pumped Storage Station

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Abstract

Modeling of regulating system of large pumped storage power station with long pipeline and parameters optimization in transient processes are studied in this paper. According to the actual parameters of a certain pumped storage power station, MATLAB/Simulink toolbox is utilized for modeling and simulation of its subsystems. Friction resistance coefficient and water elasticity are taken into consideration in modeling of pressure diversion syste。As to simulate hydraulic vibration characters, BP neural network and RBF neural network are adopted in modeling of pump turbine. Based on the established regulating system simulation model, improved orthogonal experiment method is applied in parameters optimization of no-load frequency disturbance, load disturbance and load shedding transient processes. According to the results, the proposed model reflect the actual characteristics of pumped storage units, and improved orthogonal experiment method is effective in figuring out the optimal parameters group within the given range. This paper provides guidance for modeling of regulating system of large pumped storage units, and set references and theoretical basis for actual optimal control of transient processes in pumped storage units.

Keywords: *regulating system, artificial neural network, modeling and simulation, transient process, parameter optimization*

1. Introduction

Due to its rapid responding, strong load-following capability and reserve capacity, the pumped storage power station has played an irreplaceable and significant role in the electric system. The development of pumped storage power station is not only related to daily electricity consumption, industrial production and social activities, but also to stable operation and long-term plan of electric system.

With the increasing number, capacity and proportion in state grid, problems referred to stability and safety in pumped storage power station are drawing increasingly attention of relevant researchers, thus it is of great importance to study on the system of pumped storage power station [1]. Simulation research on pumped storage power station is able to provide effective technical support to the control of its normal operation and condition switch [2], and can also reduce the costs and risks of various tests so as to find out the features of pumped storage units and improve their safety, stability, flexibility and economical efficiency via optimal control strategy. Therefore, it is quite essential to study the modeling, simulation and optimal control of the regulating system of pumped storage power station by numerical simulation methods.

In this paper, MATLAB/Simulink is used to model the regulating system of a certain pumped storage power station in China, on the basis of which parameters optimization in the transition processes of no-load frequency disturbance, load disturbance and load shedding disturbance are specifically studied.

2. Modeling of Regulating System of Pumped Storage Unit

The regulating system of pumped storage unit is similar to that of a common hydropower station, which is a complex nonlinear closed-loop control system including hydraulic, mechanical and power factors.

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2.1. Structure and Characteristics of Regulating System

Pumped storage unit consist of division system, governor, pump-turbine and generator. More specifically, the regulating system comprises four main subsystems that are pressure diversion system, electro-hydraulic governor, pump turbine and motor-generator.The structure of the system is shown in Figure 1.

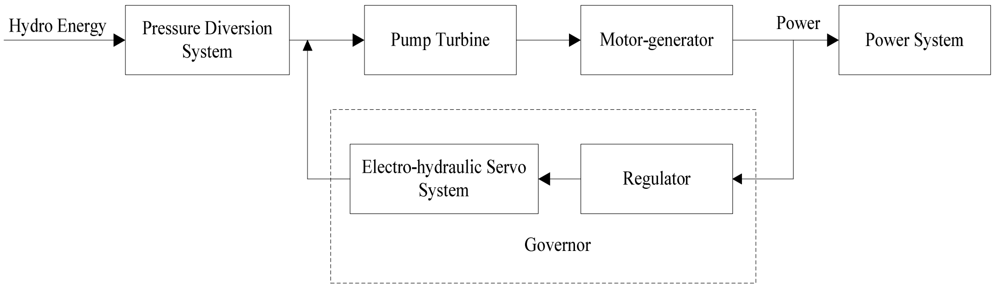

Figure 1. Structure of Regulating System of Pumped Storage Unit

The pumped storage power station studied in this paper has two natural reservoir basins with the fall head of 531 meters. This station consists of two parts, i.e. A and B, both with design head of 517.4 meters and rated flow of 66.2m^3/s, and installed capacity of 1200MW (4*300MW).

2.2. Model of Diversion System

Manifest water hammer effect in the regulating system of pumped storage unit always reduces the output of pump turbine to some extent. More importantly, water hammer effect is contrary to the accommodation of wicket gate, which seriously affects the regulation perform of units. For the modeling of diversion system in pumped storage power station with long penstocks, elasticity of water, pipe wall and influence of hydraulic friction should be considered. Unsteady flow in penstock can be described by the following two differential equations [3].

Momentum equation is below,

$$\frac{\partial Q(L,t)}{\partial t} = gA\frac{\partial H(L,t)}{\partial L} - \frac{fQ^2(L,t)}{2DA} \quad (1)$$

Continuity equation is,

$$a^2\frac{\partial Q(L,t)}{\partial L} = gA\frac{\partial H(L,t)}{\partial t} \quad (2)$$

Where Q is the flow in the pipeline, H is the head of water, L is the length of pipeline, A is the cross-sectional area of pipeline, D is the diameter of pipeline and f is friction loss coefficient.

Then the transfer function of long penstock in pumped storage power station with elastic water hammer is as follows.

$$G_h(s) = \frac{H(s)}{Q(s)} = -2h_w th(\frac{T_r}{2}s) \quad (3)$$

Where Tr is phase length of water hammer and hw is coefficient of pipeline features.

The above function can be transformed into the function below in actual modeling.

$$G_h(s) = \frac{H(s)}{Q(s)} = -h_w \frac{T_r s + \frac{1}{24} T_r^3 s^3}{1 + \frac{1}{8} T_r^2 s^2} \quad (4)$$

With coefficient of friction taken into consideration, it is described as below.

$$G_h(s) = \frac{H(s)}{Q(s)} = -h_w \frac{4f + T_r s + \frac{1}{24} T_r^3 s^3}{1 + \frac{1}{2} f T_r s + \frac{1}{8} T_r^2 s^2} \quad (5)$$

In the diversion system of pumped storage power station with long pipeline, surge tanks are often adopted in the pipeline near the plant house to improve the stability of regulating system [4]. The station studied in this paper is equipped with two throttled surge tanks in both upper side and down side, and corresponding transfer function is as follows [3].

$$G_T(s) = \frac{q_T(s)}{h_T(s)} = \frac{T_h s}{1 + T_q s} \quad (6)$$

Where *Th* is head time constant and *Tq* is flow time constant.

For discussion clarity, this paper is on the basis of a single penstock-single turbine-generator at an isolated network. The diversion system in Plant B is shown below.

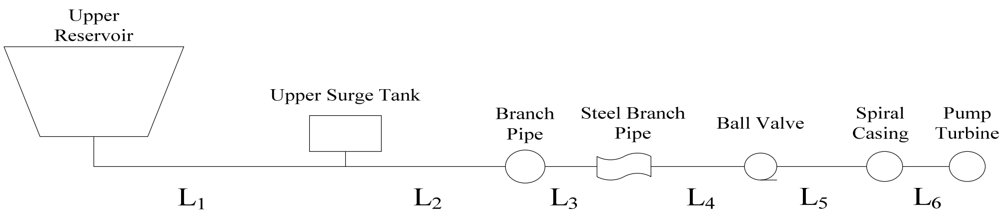

Figure 2. Diagram of Diversion System of Plant B (single penstock-single turbine)

According to relevant data of this power station, parameters of the diversion system can be obtained and shown in Table 1.

Table 1. Parameters of the Diversion System

Pipeline number \ parameter	Tr	hW
1	3.329	0.114
2, 3	1.820	0.115
4, 5, 6	0.279	0.996
Surge tank \ parameter	Th	Tq
Upper surge tank	443.3	171.828

According to the transfer functions and parameters, the simulation model of diversion system of Plant B in MATLAB/Simulink is shown below.

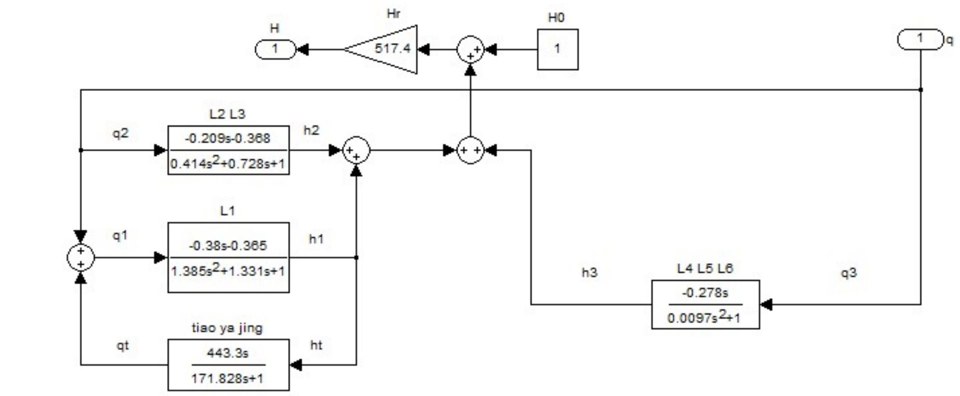

Figure 3. Simulation Model of Diversion System of Plant B

2.3. Model of Electro-hydraulic Governor

The power station in this paper adopts a PID governor manufactured by NEYRPIC French. According to the given structure block, the simulation model of the governor is as in Figure 4.

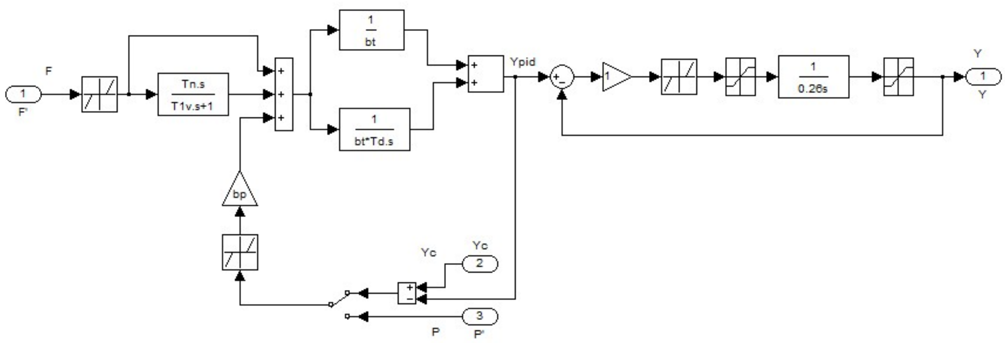

Figure 4. Simulation Model of Electro-hydraulic Governor in Plant B

As shown in the figure, the governing system combines regular parallel PID with differential forward PID, by which the ability of overcoming overshoot is enhanced so as to raise the control quality.

2.4. ANN Based Model of Pump Turbine

As the flow in pump turbine can be quite complex, dynamic performance is often utilized when analyzing transient processes of pumped storage power station. However, there are no effective ways to acquire relevant parameters until now, thus dynamic performance is usually replaced by steady-state characteristics to analyze the dynamic processes. Steady-state characteristics of pump turbine can be described by four-quadrant complete characteristic curve, yet the curve is with serious overlap sections and distinct “S” characteristic in both reverse pump zone and breaking zone, which always result in considerable error in interpolation calculation of the curve.

At present, there are mainly two methods applied in modeling of pump turbine. One is improved SUTER curve method, by which overlaps of “S” zone in complete characteristic curve can be removed thus reducing interpolation errors, but the curve conversion process is rather complicated [5, 6]. The other one is internal characteristic analysis method, which relies much on structure parameters. Using this method, a mass of parameters in pump turbine and initial boundary conditions are needed, yet which are not easy to obtain. In consideration of quite strong nonlinear approximation ability of artificial neural network (ANN), this paper adopts two mostly used networks, i.e. BP neural network and RBF neural network, to fit the nonlinear properties of pump turbine according to the curves of unit discharge *Q11*- unit speed *n11* and unit torque *M11*- unit speed *n11*.

Properties of pump turbine can be expressed by five parameters, i.e. flow *Q*, torque *M*, head *H*, rotational speed *n* and wicket gate opening *Y*, in which *H*, *n* and *Y* are independent while *Q* and *M* can be presented by these three. Hence, ANN based modeling of pump turbine is in fact modeling of a 3 inputs- 2 outputs network.

Taking BP neural network for example, ***newff*** function and LM algorithm are utilized when establishing the BP network due to its fast convergence and small training error comparing with other training algorithms. By comparing the difference between target value and simulation result of different number (i.e. N) of hidden layer neurons, it can be drawn that model of *Q11* is better with *N* = 9. The error value curve of training is shown in Figure 5. The training process of *M11* is similar to that of *Q11* and its model is better with *N* = 8, and the corresponding error value curve is shown in Figure 6.

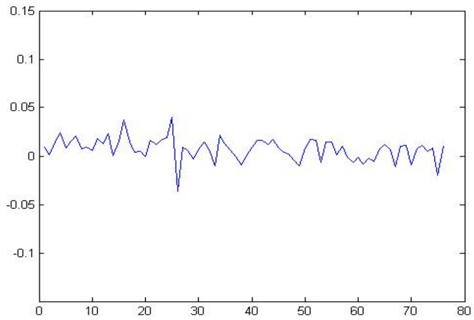

Figure 5. Error Value Curve of Q_{11}

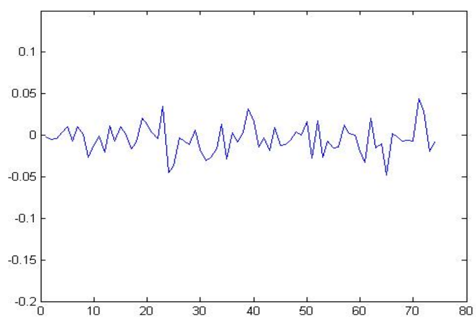

Figure 6. Error Value Curve of M_{11}

As for modeling using RBF neural network, newrb function is chosen to establish the network because it works better with large number of sample as in the case in this paper. By comparing the difference between target value and simulation result of different spread values of radial basis function, it can be drawn that model of *Q11* is better with spread value = 0.49 and model of *M11* is better with spread value = 0.78. The error value curves of *Q11* and *M11* are respectively shown in Figure 7 and Figure 8.

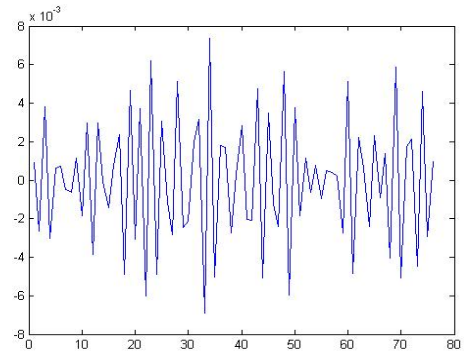

Figure 7. Error Value Curve of *Q11*

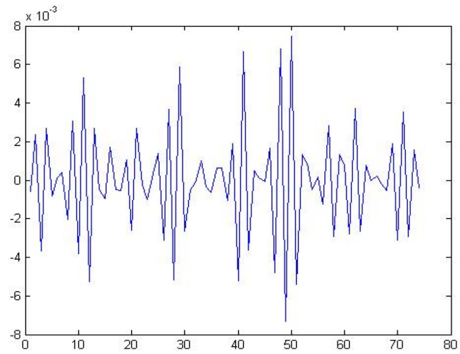

Figure 8. Error Value Curve of *M11*

Through the comparison of modeling of pump turbine using BP and RBF neural network, it can be found that the difference between target value and simulation result is much smaller when using RRF network, so that it can better approach the nonlinear properties of pump turbine. Therefore, models of *Q11* and *M11* using RBF network are selected for simulation tests of the regulating system of Plant B. Simulation model of the pump turbine is shown as follows.

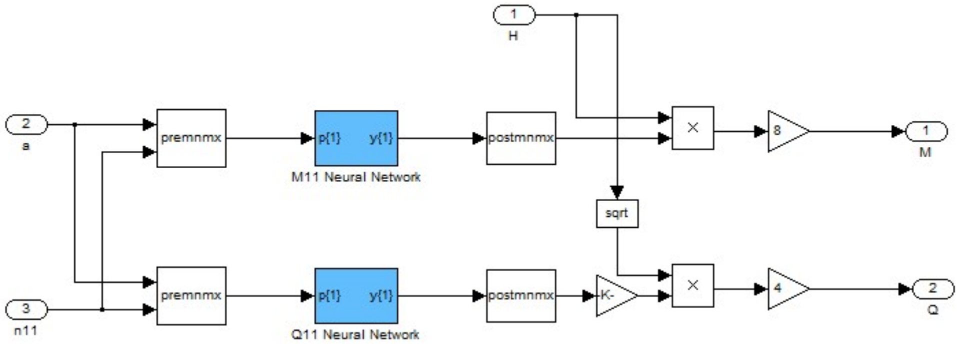

Figure 9. RBF Network Based Simulation Model of Pump Turbine

2.5. Model of Motor-generator

Generally, dynamic properties of generator can be described by a first-order process and its transfer function is as below [7].

$$G_g(s) = \frac{1}{(T_a + T_b)s + e_n} \quad (7)$$

Where, $T_a = \frac{GD^2 n_r^2}{365 P_r}$, named unit inertia time constant, Tb is load inertia time constant, and en is unit synthetic self-regulation coefficient (usually between 0 and 2.0). According to actual data of Plant B, *(Ta+Tb)*= 8.453.

2.6. Model of Regulating System of Plant B

Basing on the above models of diversion system, electro-hydraulic governor, pump turbine and motor-generator, the simulation model of regulating system of Plant B can be acquired by connecting the subsystems and is shown in Figure 10.

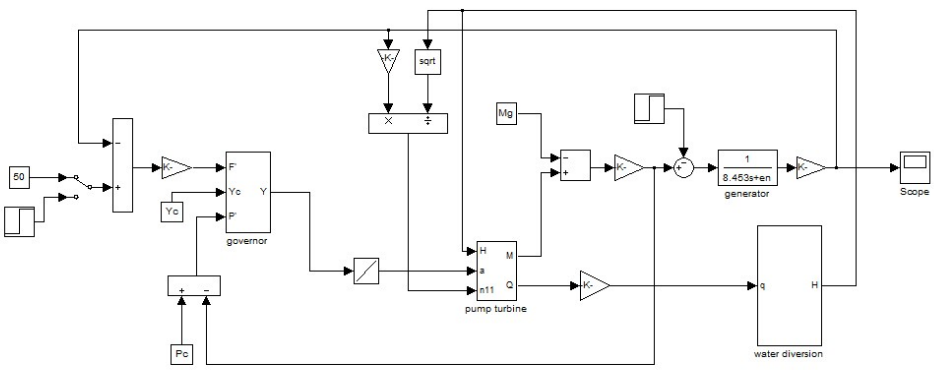

Figure 10. Simulation Model of Regulating System of Plant B

3. Parameters Optimization of Transient Processes

3.1. Common Transient Processes of Pumped Storage Unit

Three common transient processes of pumped storage regulating system are no-load frequency disturbance, load disturbance and load shedding. For no-load frequency disturbance, frequency of the units is given and the task of regulating system is to avoid fluctuation caused by the unsteady flow. For load disturbance, as pumped storage units need to track the change of load rapidly and steadily, the task of regulating system is to keep the frequency of units steady. In load shedding process, speed of the units raises quickly while the wicket gate closing down. Due to self drag torque, speed of the units gradually declines and frequency of the units turns to be at the given point.

3.2. Improved Orthogonal Experiment Method [8-11]

There are three parameters (*bt, Td* and *Tn*) that need to be optimized in transient processes of pumped storage units. Take no-load frequency disturbance test for example, the test is to figure out the optimal group of these three parameters that can make the regulating time *(Tp)* as short as possible and the overshoot *(M)* as small as possible. Test can be arranged by orthogonal experiment table and extremum difference analysis can be used to analyze the test results [12]. Extremum difference analysis table is shown below.

Table 2. Extremum Difference Analysis Table

Indicator / Factor / No.	A		
	T_d	b_t	T_n
I/3	A_{11}	A_{21}	A_{31}
II/3	A_{12}	A_{22}	A_{32}
III/3	A_{13}	A_{23}	A_{33}
Extremum difference	B_1	B_2	B_3

In the table, A_{ij} represents the statistical average of indicator A with the i^{th} factor of j level, B_k stands for the extremum difference of A with the k_{th} factor (i, j, k=1, 2, 3).

Traditional orthogonal experiment method has been proved to be effective in obtaining the optimal group of parameters with dispersed three given levels after nine tests. To gain the optimal group within the given range of these parameters, the method needs to be improved.

Suppose that factor X has three initial levels {x, 2x, 3x}, if the optimal value of X is 2x after the first round of tests, then the new levels of X in the next round of tests should be selected as {1.5x, 2x, 2.5x}. That is to say, set the optimal value of the first round as central level of the next round of test and take half of the difference between levels as the new difference in the next round, then optimal group within a smaller range can be acquired in the next round of test. Tests could be repeated until the result meets the requirements.

3.3. Parameters Optimization of Different Transient Processes

According to relevant data, simulation tests of different transient processes are performed and the results are shown as below.

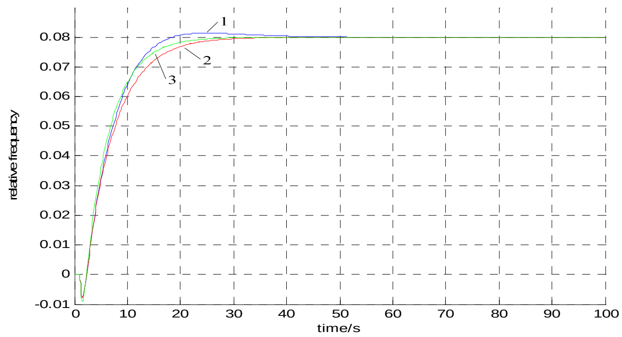

Figure 11. Comparison of Optimization Results of No-load Frequency Disturbance Process

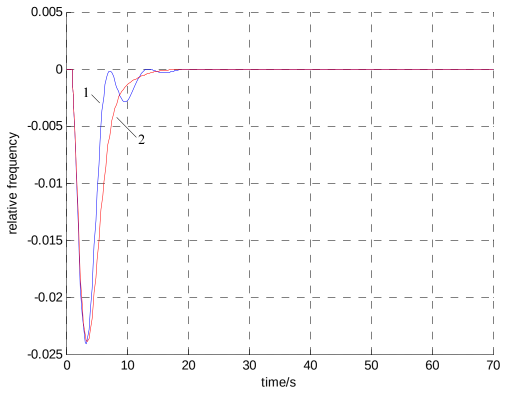

Figure 12. Comparison of optimization results of +10% load disturbance process

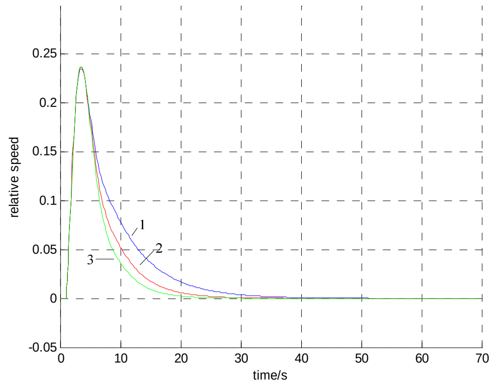

Figure 13. Comparison of Optimization Results of Load Shedding Process

According to these figures, it is evident that improved orthogonal experiment method performs better than traditional method in regulating parameters optimization. Through repeated tests, the range of optimal group is lessened and the regulating system gains better dynamic correspond.

4. Conclusion

The proposed paper is aim to build the model of large pumped storage power station and optimize its transient processes.

According to the characteristics of pumped storage power station with long pipeline, model of its diversion system with elastic water hammer is established, and RBF neural network is adopted to approach the nonlinear properties of pump turbine which proves to effectively reflect characteristics of pumped storage units.

Besides, it is convenient and efficient to figure out optimal group of regulating parameters within the given range by applying improved orthogonal experiment method in simulation tests. Through this way, costs and expense of field tests could be reduced and simulation results shall provide theoretical basis and technical support for parameters adjustment and optimal control of pumped storage units.

Acknowledgements

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