Simulation model of hydraulic turbine speed control system and its parameters identification based on resilient adaptive particle swarm optimization algorithm

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Abstract—A new simulation model of hydraulic turbine speed control system and mathematical models of microcomputer governor is proposed, and to investigate the first and second regulation characteristics of hydraulic turbine speed control system, after hydraulic turbine group connected to the major power systems. Simulation model established and parameters were identified intelligently by using resilient adaptive particle swarm optimization algorithm. The model parameters were finally determined with the measurement and validation and simulation. The first and second regulation process was simulated, the actual test values and simulation result values were compared, and the specific mathematical model was tested and verified. Results show that the simulation and the actual test on site are almost same, the difference of all indicators are less than 0.5%. Simulation model built can reflect the characteristics of speed control system under hydraulic turbine group connected to the major power systems. A reliable method is provided for solving similar hydraulic turbine speed control system model and model parameters measured and identification and verification. The application prospects are good.

Keywords—simulation model of hydraulic turbine speed control system; mathematical model of governor; resilient adaptive particle swarm optimization algorithm; frequency modulation; parameters intelligent identification

I. INTRODUCTION

At present, the governor parameters measured have more theoretical research in foreign countries, such as early least squares of parameter model identification method [1], current fuzzy neural network recognition model and immune algorithm [2]. But all are in research and attempt stage. From research work carried out view, as the regulation systems is in no-load condition or load of stand-alone unit or running into small power system, the adjustment characteristics and mathematical model were focused on. But the research work less involved on the characteristics of the speed control system and the mathematical model of the first and second regulation and the hydraulic turbine speed control systems parameter identification, after the crews are into the large power system. Therefore, the research of mathematical model and model parameters to test and to identify of the hydropower generating units speed control system is an issue with a certain innovative and cutting-edge.

Therefore, the new system simulation model and mathematical models of hydraulic turbine speed control system need to be established based on analysis about control theory, structure, the law of regulation, adjustment parameters of hydraulic turbine speed control system in different conditions and different regulation mode. We will investigate that their model parameters are identified intelligently by using resilient adaptive particle swarm optimization algorithm (RPSO), then measured, checked and simulation calibration. It will be compared and analyzed between the dynamic response process of the output value calculated in every link and the actual testing process on site. The simulation model of the speed control system will be further improved and checked. The first and second regulation process are simulated and tested with the specific mathematical model established and simulation model checked, and then result values of the actual test and simulation are compared, lastly the effectiveness of the specific mathematical models is probed.

II. THE HYDRAULIC TURBINE SPEED CONTROL SYSTEM MODELING AND SIMULATION

A. The mathematical models of the speed control systems

At present, the PID speed control systems accounted for the vast majority in the power plants at home and abroad. According to the principle and structure of the speed control systems [3], in this paper, the parallel PID structure simulation model was set up. Its control block diagram was Figure 1.

The above model reflects comprehensive the characteristics of the first and second frequency modulation of the speed control systems. When the first frequency modulation is carried out, y is unchanged, and Δyc value is zero, the governor carries out PID regulation with frequency offset, at this time the governor is as a value regulator to be used in the regulation systems. If the state deterioration coefficient (bp) is zero, and dead zone is excluded, the PID regulator input value is the frequency difference; the PID regulator output value is ypid, which transfer function is:

\[ G(s) = \frac{ypid(s)}{\Delta F(s)} = K_p + \frac{K_i}{s} + \frac{K_ds}{1+T_ps} \]  

(1)
The input frequency difference of the governor is zero in the course of the second frequency modulation, and the first frequency does not move, so the incremental transfer functions of the $\Delta y_c$ to $\Delta y_{pid}$ is:

$$\Delta y_{pid}(s)/\Delta y_c(s) = 1$$  \hspace{1cm} (2)

If the speed control systems is in a stable condition before the second frequency modulation, and then $\Delta y_{pid} = y_c$ is correct in the adjustment process.

**B. Mechanical hydraulic system model**

1) The first level amplification links

The first level amplification links is made up of the forward integral part and its feedback, whose transfer function is:

$$G_h(s) = 1/(T_v y_1 s + 1)$$  \hspace{1cm} (3)

where $T_v y_1$ is the electro-hydraulic converter time constant; $s$ is the time, Unit is seconds.

2) The second-class electro-hydraulic servo system

The second-class electro-hydraulic servo system is made up of the pressure valve and asymmetric hydraulic cylinder, which displacement control volume of pressure valve spool is the electro-hydraulic converter output displacement; the output displacement of hydraulic cylinder is $y$, whose transfer function is:

$$G_s(s) = y(s)/u(s) = \frac{(K_d/y_n)}{\left(\frac{m}{v_t} + \frac{4\beta c_n}{y_n} y^2 + \frac{mkc}{y_n}\right)}$$  \hspace{1cm} (4)

where $m$ is the load and the total weight of piston, unit is kg; $v_t$ is the total compressed volume of oil, unit is $m^3$; $K_q$ is the flow gain, unit is $m^2/s$; $A_n$ is the effective area of the relay device piston, unit is $m^2$; $\beta_c$ is the elastic modulus of oil, unit is Pa.

Because the generating units work in the low-frequency area, and the natural frequencies of the second order oscillation part in formula (4) is higher, transfer function formula (4) can be simplified to (5)

$$G_s(s) = \frac{y(s)}{u(s)} = \frac{1}{T_y s}$$  \hspace{1cm} (5)

where $T_y$ is the relay device response time.

$$T_y = \frac{du}{d(dy/dt)}$$  \hspace{1cm} (6)

where $u$ is the displacement of the main pressure valve spool. In addition, the startup and shutdown speed of the relay device trip must be limiting.

To sum up, and to consider the impact of mechanical dead zone, the mechanical hydraulic simulation model with the dynamic system is Figure 1.

Relative value of $y$ is the relay device trip in the simulation model of mechanical hydraulic with the dynamic system, its expression is:

$$y = (\Delta y + \Delta y_p + \Delta y_d) \frac{1}{T_v y_1 s + 1} + ((\Delta y + \Delta y_p)K_y) \frac{1}{T_y s} + \frac{1}{T_v y_1 s + 1}$$  \hspace{1cm} (7)

where $\Delta y$ is aperture volume increased or decreased; $\Delta f$ is Frequency difference; $K_y$ is the proportional gain; $K_i$ is integral gain; $K_d$ is the differential gain; $T_v y_1$ is the differential time constant; $b_p$ is state coefficient deteriorated; $T_y$ is the reaction time constant of relay device.

**III. MOLD SIMULATION AND PARAMETER IDENTIFICATION**

**A. Traditional Particle swarm optimization algorithm and disadvantages**

Particle swarm optimization algorithm is global optimization technology that Eberhart R.C. and Kennedy J. (1995) proposed based on swarm intelligence. The optimal solution is found through search for the solution space by the interaction between particles and intelligent.

There are $N$ particles from a community in a D-dimensional search for goal space, one of the $i$th particles represents a D-dimensional vector $X_i = (X_{i1}, X_{i2}, ..., X_{id})$. In other words, the $i$th particles represent position in D-dimensional search for space. Each particle position $X$ is a potential solution. Can calculate its value by $X$ joining into a target function, according to the fitness measure $x$, and to estimate if it is the required solution for the optimal solution. The "flying" velocity of the $i$th particles is also a D-dimensional vector, recorded as $V_i = (v_{i1}, v_{i2}, ..., v_{id})$. The best position of $i$th particles to search is $P_i = (P_{i1}, P_{i2}, ..., P_{id})$, the optimal location of the whole particle swarm is the $P_{gd} = (P_{gd1}, P_{gd2}, ..., P_{gdn})$.

The basic algorithm formula is as follows:

$$v_{id}^{(k+1)} = \omega v_{id}^{(k)} + c_1r_1(P_{id}^{(k)} - s_{id}^{(k)}) + c_2r_2(P_{gd}^{(k)} - s_{id}^{(k)})$$  \hspace{1cm} (9)

$$s_{id}^{(k+1)} = s_{id}^{(k)} + v_{id}^{(k+1)}$$  \hspace{1cm} (10)

where $c_1$, $c_2$ are scaling factors that determine the relative "pull" of the overall best individual particles and the best direction of the particles flying the biggest step; $r_1$, $r_2$ are the random number uniformly distributed in interval $[0, 1]$; $\omega$ is the inertia factor, it can control the speed of the weight, the general $[0, 1]$; $\omega$ will be 0.9 down to 0.1 with the number of iteration increased, this could focus on global search,so that can get high-precision solution.

The PSO algorithm is very easy to implement and rapidness convergence, but there are also shortcomings of the following:

(1) According to the particles are all the particles and their search for optimal solutions to the experience of the direction of "flight", in the larger role of the inertia factor, the particles may be the optimal solution for the lack of sophisticated search and search result in accuracy is low.

(2) By Eq. (9), we can see that all particles have the optimal solution to the direction of "flight", the closer the optimal particles, the smaller speed. All particles are gathered to a point near the extreme in the latter part of PSO. Generally, it is easy to converge to the optimal partial cause of premature algorithm.

**B. The adaptive particle swarm optimization algorithm**

The advanced RAPSO’s method [6] is that to improve the global search capability of PSO, we have to avoid PSO in the latter part of the particle velocity too small. In this paper, the dynamic adaptive fitness transform the speed factor PSO, the particles fly in the direction of the original algorithm, all point to two "extreme." But a new generation of particle positions by the dynamic adaptive transform the speed factor, it is adaptive zoom in or out. Trying to avoid all particles together into a near-maximum in the latter part of PSO and into a local
optimum and premature; At the same time, the implement of adaptive dynamic inertia weight, is for that the reflect of PSO diversity, the average variance of fitness function. Formula is as follows:

\[
\begin{align*}
    (k+1)_{id} &= \mu(k)_{id} + \omega \cdot (k)_{id} - x_{id} + c_1 \cdot r_1 \cdot (k)_{id} - x_{id} + c_2 \cdot r_2 \cdot (k)_{id} - x_{id} \\
    (k+1)_{id} &= (k)_{id} + \mu(m)_{id} - x_{id}, \quad m=1,2,3,\ldots
\end{align*}
\]

(11)

Assume a \(d\)-dimensional search space \(S \subseteq \mathbb{R}^d\), and a swarm with \(M\) particles. The \(i\)th particle is an \(d\)-dimensional vector \(X_i=(x_{i1}, x_{i2}, \ldots, x_{in})^T \in S\). Its position vector is also an \(d\)-dimensional vector \(V_i=(v_{i1}, v_{i2}, \ldots, v_{in})^T \in S\). The previous best position of the \(i\)th particle so far is a point in \(S\), denoted by \(P_{id}=(p_{i1}, p_{i2}, \ldots, p_{in})^T\). The best position among the swarm so far is stored in a vector \(P_{gd}\). According to Eq. (3), the velocity and position can be updated after each iteration. \(W\) is the inertia factor, manipulating the impact of the previous iteration on the current velocity. The symbol with the rest is the same as the former.

Using it for determining the location of the new generation of self-adapting particle zooms in or out. The following identified principles are that a \(V_{1\max}\) (maximum speed) and \(V_{1\min}\) (minimum speed), if \(v_{i}(k)_{id}>V_{1\max}, \mu (m)\) makes the speed smaller of search. If the \(v_{i}(k)_{id}<V_{1\min}, \mu (m)\) makes the speed bigger of search; if \(V_{1\min} < v_{i}(k)_{id}<V_{1\max}\) when their speeds are appropriated, \(\mu (m)\) makes the speed of search \(v_{i}(k)_{id}\) on both sides of the large and small variability, local optimization and avoid premature, particles can be sufficient to search the solution space. Formula is as follows:

\[
\mu (m) = \begin{cases} 
    \left\lfloor \frac{m}{j} \right\rfloor, & v_{i}(k)_{id}<V_{1\min} \\
    \left\lceil \frac{m}{j} \right\rceil, & V_{1\min} \leq v_{i}(k)_{id}<V_{1\max} \\
    m/j, & V_{1\max} \leq v_{i}(k)_{id}<V_{1\max} 
\end{cases}
\]

(12)

C. Mold parameter identification with resilient adaptive particle swarm optimization algorithm design

The simulation model parameter identification of the hydraulic turbine speed control system is a combinatorial optimization problem with a strong bound and nonlinear and multi-stage. Hydraulic turbine governor simulation model parameter identification is to find a set of parameters sequence changed, and to let the average fitness function variance of the simulation values and the governor actual values measured to get to the minimum under bounding to meet a variety of conditions. When solving model with resilient adaptive particle swarm optimization algorithm, a particle can represent an operation strategy of simulation model parameters of the hydraulic turbine speed control system.

(1) Coding of resilient adaptive particle swarm optimization algorithm and the initial particle generation

As solving hydraulic turbine governor simulation model parameter identification with resilient adaptive particle swarm optimization algorithm, \(V^i = (V^i_1, V^i_2, \ldots, V^i_n)\) parameter sequence of each particle position vector represents a solution, \(V^i_k\) is vector elements, which represents the \(k\)th case parameter of the hydraulic turbine governor simulation model parameter; \(v^i = (v^i_1, v^i_2, \ldots, v^i_n)\) is parameter sequence changed of the hydraulic turbine governor simulation model parameter identification, which represents velocity vector. \(v^i_k\) is a velocity vector element, which represents the \(k\)th case velocity of optimization process.

According to the above methods mentioned, randomly generated initial position vector and velocity vector, \(V^i(0) = (V^i_1(0), V^i_2(0), \ldots, V^i_n(0))\) is the initial position vector of the \(i\)th artificial particle, \(v^i(0) = (v^i_1(0), v^i_2(0), \ldots, v^i_n(0))\) is the initial velocity vector of the \(i\)th artificial particle. The initial position vector and velocity vector is \(m\).

(2) Velocity and position update

In order to achieve optimization, particles update their positions and velocities through particles following the current optimal particle. To solve hydraulic turbine governor simulation model parameters with resilient adaptive particle swarm optimization algorithm, the formula of velocity and position replaced is (11).

(3) Fitness function

A characteristic of resilient adaptive particle swarm optimization algorithm is to use the objective function value of the problem resolved to search the next step information related, and the objective function value of the problem resolved is reflected by the individual fitness evaluated. The fitness function is as follow:

\[
fit = \frac{1}{n} \sum_{i=1}^{n} \sum_{k=1}^{p} (y^i_{ik} - y^i_{tk})^2
\]

(13)

where: \(y^i_{ik}\) is the desired output value; \(t^i_k\) is the actual output value; \(p\) is the test time points; \(n\) is the test samples number.

D. Identification results and analysis

The initial inertia factor is \(\omega=0.6\). The initial \(c_1\) is 2 and \(c_2\) is 2.2, \([0, 1]\) is the initial range of \(r_1\) and \(r_2\), \([-3, +3]\) is the initial range of \(C_0\) \([-1, +1]\) is the initial range of \(\omega\), \(M=100\) is particle scale. \(K_{\text{max}}=400\) is the largest number of iterations.

The simulation model parameters are determined by combining with the simulation model parameters value measured and checked. Table 1 show the result identified and confirmed finally on simulation model parameters of the speed control system. Furthermore, according to control strategy of the speed control system, when the speed control system running on the frequency modulation mode or the first frequency modulation function, \(E_j\) is the manual frequency dead-zone, and \(E_i\) is 0, \(bp\) is state coefficient deteriorated, and \(bp\) is 0.04.

We found that the traditional calculation method of the reaction time constant of relay device is mistake in experiment of parameter identification and simulation calculation and measurement and verification. According to traditional methods to calculate, the reaction time constant of relay device is \(T_j=0.05s\). However, if the simulation is carried out by using this value of \(T_j=0.05s\), the simulation results are much different from the measured process. The reason is that the original calculating method is unfit for the current control structure of PID regulator increases follow-up control system.
If according to the inputs relative value of the servo system for conversion, $T_y=0.76s$ is the result recalculated using test data at the scene. The result using this method and the model parameters estimated method with the test data measured is same, and the reaction time constant of relay device is $T_y=0.6s-0.9s$.

### E. PID parameter calibration process simulation

In PID parameter calibration process simulation, inputted the actual step frequency signal at the scene to the machine frequency side of the simulation model by the document to read. Figure 4is parameters checked comparison of PID regulation, where $K_p=4.0$, $K_i=0$, $K_d=0$ and other parameters were determination values in Table 1. In which blue solid line expresses the test curves, the red dotted line expressed the simulation curve. The other two groups of different parameters of the PID regulator were taken to carry out simulation test comparison. From the results comparing of the three groups PID parameter calibration process simulation view, simulation value and experimental value are almost identical. Where: $fx$ expresses the test curves, $fy$ expresses the simulation curve. The two groups of different parameters of the PID regulator were taken to carry out simulation test comparison. From the results comparing of the three groups PID parameter calibration process simulation view, simulation value and experimental value are almost identical. Where: $fx$ is the relative value of the input machines frequency signal of the speed control system; $P$ is the relative value of the output machines power; $y$ is the relative value of the trip of the relay device; $y_{pid}$ is the relative value of the control output of the PID. The same meaning is as the follow.

![PID parameters calibration](image)

The resilient adaptive particle swarm optimization algorithm is suitable for hydraulic turbine speed control system simulation model parameter identification. It can improve its accuracy.

(4) The simulation models and mathematical models of the speed control system built provide an effective and reliable method and means to study the regulation characteristics and the quality of under hydraulic turbine group parallel connection to the major power systems. The method can instruct and approve the speed control system mathematical model established and parameter identified to be used in the power network stability calculation.

### IV. CONCLUSIONS

1. The specific control structures, control law and characteristics of various regulation aspects of speed control system are analyzed. The simulation model of the hydraulic turbine speed control system is established, which is fit for the actual speed control system of hydraulic turbine units used at present. Simulation model block diagram is Figure 2.

2. The specific mathematical model of speed control system has been identified with the means of model parameter identification, the actual test and calibration. The results are shown in Table 1. The simulation results and the actual testing process are basically same, the difference of all indicators are less than 0.5%. Results are very good.

3. The resilient adaptive particle swarm optimization algorithm is suitable for hydraulic turbine speed control system simulation model parameter identification. It can improve its accuracy.

4. The simulation models and mathematical models of the speed control system built provide an effective and reliable method and means to study the regulation characteristics and the quality of under hydraulic turbine group parallel connection to the major power systems. The method can instruct and approve the speed control system mathematical model established and parameter identified to be used in the power network stability calculation.

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