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Francis Turbine and Governor Improved Models Considering Step Closing Law of Guide Vanes for Power System Stability Analysis

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Abstract

The Francis turbine governing system models in PSD-BPA can't precisely reflect the actual characteristics. Endeavor was done in this paper to solve the problem. An improved model of actuating mechanism was developed, which could reflect the step closing characteristic of hydro guide vanes. The effect of the inflection point value of actuating mechanism on load rejection was analyzed based on simulation. The non-linear Francis turbine model with power versus gate position module was researched in this paper. Based on field test, comparisons of simulation results with measured data were presented. The analysis demonstrates that the improved models of Francis turbine and governor proposed in this paper are more realistic than the models of BPA, and can be applied in power system simulation analysis better.

Keywords

Francis Turbine, Governor, Actuating Mechanism, Step Closing Law, Improved Models, Power System Stability Analysis

1. Introduction

As an indispensable part of hydropower generating units, hydro turbine governing system plays an important role in sticking up for power system stability in China. The studies on power system stability are relying on models to correctly predict system response to disturbances specified in the reliability criteria. Therefore, more precisely modeling of hydro turbine governing system can't afford to be neglected in the research field of coordinated optimization between generator units and grid. Its important application value is self-evident.

There has been endeavor in modeling of hydro turbine and governor system, but more in-depth study is necessary. Different types of turbine models were given in [1], but the Francis turbine model was not validated based on field test. Common types of actuating mechanism models were analyzed in [2], which was of great reference value. The PID controller model developed in [3] had been incorporated into PSD-BPA and applied.

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An actuating mechanism model considering dead zone and saturation modules was given in [4], which was more accurate than the linear model, but it couldn't reflect the two-segment closing characteristic of hydro guide vanes in practical engineering [2], leading to inaccurate simulation results in large oscillation condition.

This paper develops an enhanced actuating mechanism model including two-segment closing device module. Then the load rejection study demonstrates that different inflection points have significant influence on the unit's dynamic performance. The Francis turbine model considering nonlinear relationship between gate position and turbine power is researched. Based on measurements taken at field test, including the actuating mechanism open/close test and the power-raising test, models validation is presented.

2. Francis Turbine and Governor Models

The block diagram of **Figure 1** shows the basic elements of a Francis turbine-governor system within the power system environment.

In **Figure 1**, w_{ref} is frequency refrence, P_{ref} is power refrence, y_{ref} is gate position refrence, y_{PID} is the outprt of PID Micro-computer based governor, y is gate position, h is the head at the turbine admission, q is turbine flow rate; P_m is mechanical power; w is frequency; P_e is electrical power.

2.1. Micro-Computer Based Governor Model

Recently in China, the regulating method of hydro turbine micro-computer based governor is Proportional- Integral-Derivative. The governor consists of PID controller and actuating mechanism. The PSD-BPA PID controller model [3] is used to represent the PID controller in this paper.

In practical engineering, the actuating mechanism of the governor incorporates step closing device. In the emergency of guide vane closing, step closing device devides the guide vane closing process into two sections, and the closing rate of each section is different. Given this fact, an improved actuating mechanism model considering step closing characteristic was developed and shown in **Figure 2**.

In **Figure 2**, T_y is the actuating mechanism time constant. T_1 is the time constant of the delay module, and T_2 is time constant of the feedback module.

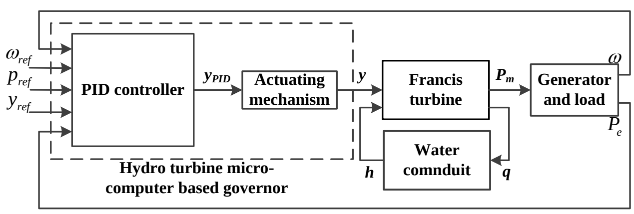

Figure 1. Block diagram of Francis turbine and governor.

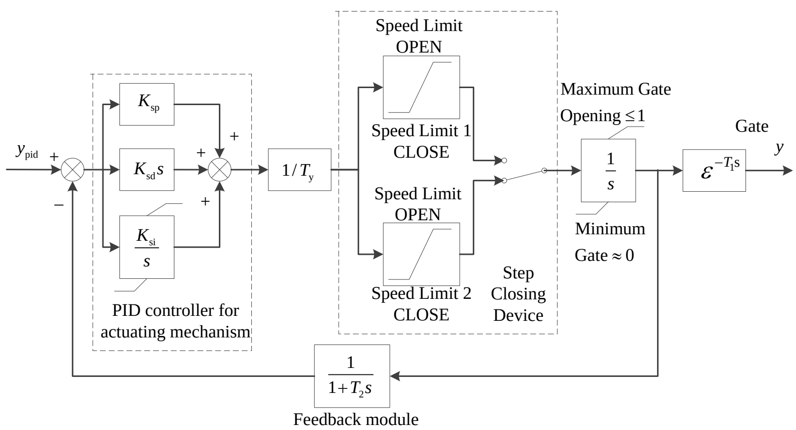

Figure 2. Governor's actuating mechanism model considering the step closing law of hydro guide vanes.

2.2. Francis Turbine Improved Model

Neglecting the head loss due to friction in the conduit, no load flow and speed deviation damping effect, the per unit flow rate through the turbine and the per unit turbine power are given by:

$$q = y\sqrt{h} \tag{1}$$

$$p_m = qh \tag{2}$$

This model achieves a compromise between simplicity and capturing essential behavior for large-scale studies. But nonlinear turbine effects can't afford to be neglected. Based on this type of model, a module should be incorporated in to reflect the non-linear relationship between gate position and turbine power [1].

In **Figure 3**, H_0 is the static head of water column, G(s) is the transfer function of turbine conduit.

The non-linear relationship between gate position and electrical power is given by:

$$P_m = f(y) = a_1 \cdot y^3 + a_2 \cdot y^2 + a_3 \cdot y + a_4 \tag{3}$$

where, a_1, a_2, a_3, a_4 are the coefficients for curve fitting.

2.3. Turbine Conduit Model

For simple water conduit no more than 800 m length, the elasticity of the steel in the conduit and the compressibility of water can be ignored. Using the rigid model of water column is adequate:

In **Figure 4**, T_w is the water time constant in the conduit. T_w can be identified based on the particle swarm optimization algorithm. The fitness function is given by:

$$fitness = \frac{1}{N}\sum_{k=1}^{N}\left[y(k) - y_0(k)\right]^2 \tag{4}$$

where N is sampling number, and $y(k)$ is the output of the model used for simulating, and $y_0(k)$ is the measurements recorded at field test.

3. Simulation Studies

Xiaowan hydroelectric power station is on the Lancang River in Nanjian County, Yunnan Province, southwest China. It is the third largest hydroelectric power station in China. The models validation is combined with measurements at Xiaowan hydroelectric power station.

The simulation and analysis of load rejection are presented in chapter A. Then the validation of actuating mechanism model and Francis turbine model is made in chapter B and chapter C respectively. Chapter A and chapter C use the same simulation system. The general view of the simulation system is shown in **Figure 5**.

The synchronous machine 5 orders practical model and a simplified voltage regulation and excitation system model [5] were used to simulate the generator and excitation system.

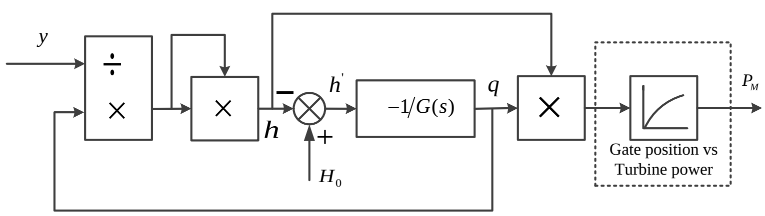

Figure 3. Francis turbine model with mechanical power versus gate position module.

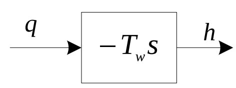

Figure 4. Non-elastic water column model.

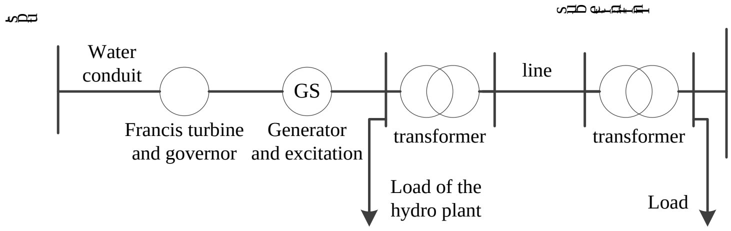

Figure 5. Simulation system general view.

3.1. Simulation of the Two-Segment Closing Characteristic of Actuating Mechanism

In the load rejection study, the simulation system is shown in **Figure 5**. The length of the water conduit of Xiaowan hydroelectric power station is no more than 800 m. Thus the rigid model of water column was applied. The actuating mechanism model developed in this paper and IEEE nonlinear turbine model were used to represent the turbine-governor.

Different value of inflection point was set respectively in order to study the influence of the two-segment closing characteristic. The generator trips when t = 8 s. The 100% load rejection simulation results are shown in **Figure 6**.

It can be seen from **Figure 6**:

There is an observable difference between the simulation results of four types of inflection point value. With the increasing of inflection point setting value, the over-speed event will be more serious during the load rejection. The dynamic time lasts longer and the maximum deviation of the frequency excursion increases. The same phenomenon resulting from serious over-speed happens in the dynamics of other electrical quantities, including generator voltage, rotor angle, electrical power.

3.2. Validation of the Actuating Mechanism Model

The actuating mechanism model in **Figure 2** and BPA model were applied to the actuating mechanism open/close test of Xiaowan Unit #2. The recorded output of PID controller was used to drive the model response. **Figure 7** shows the comparison of simulated and recorded responses.

It can be seen from **Figure 7**:

1) Both of the improved model and the BPA model can correctly simulate the gate-opening process, and the response of the improved model is more accurate.

2) The measured governor response (gate position) and the simulated response of the improved model are in very close agreement in the process of gate-closing, while the BPA model can't reflect the step closing characteristic.

3) The actuating mechanism closes the guide vane according to speed limit of each section. And the inflection point value of Xiaowan 2# unit is 0.13.

3.3. Validation of the Francis Turbine and Governor Models

The validation is based on power-raising test of Xiaowan 2# unit.

The rated head of the turbine is 216 m, and the rated power is 700 MW. The actual head is 171 m, and the maximum power is about 470 MW.

#2 unit online, 210 - 350 MW power-raising test was conducted by stepping the power reference, using type TCFZ-35A multifunctional tester for hydro turbine governing system to record the input signal of governor, step responses of relative variables, including gate position and electrical power. The actual power reference signal is shown in **Figure 8**.

In the simulation, the rigid model of water column was used, and four model combinations were applied to represent the turbine-governor system:

Combination 1: The Francis turbine and governor improved models proposed in this paper;

Combination 2: IEEE nonlinear turbine model and the improved actuating mechanism model in **Figure 2**;

Combination 3: BPA ideal turbine model and the improved actuating mechanism model in **Figure 2**;

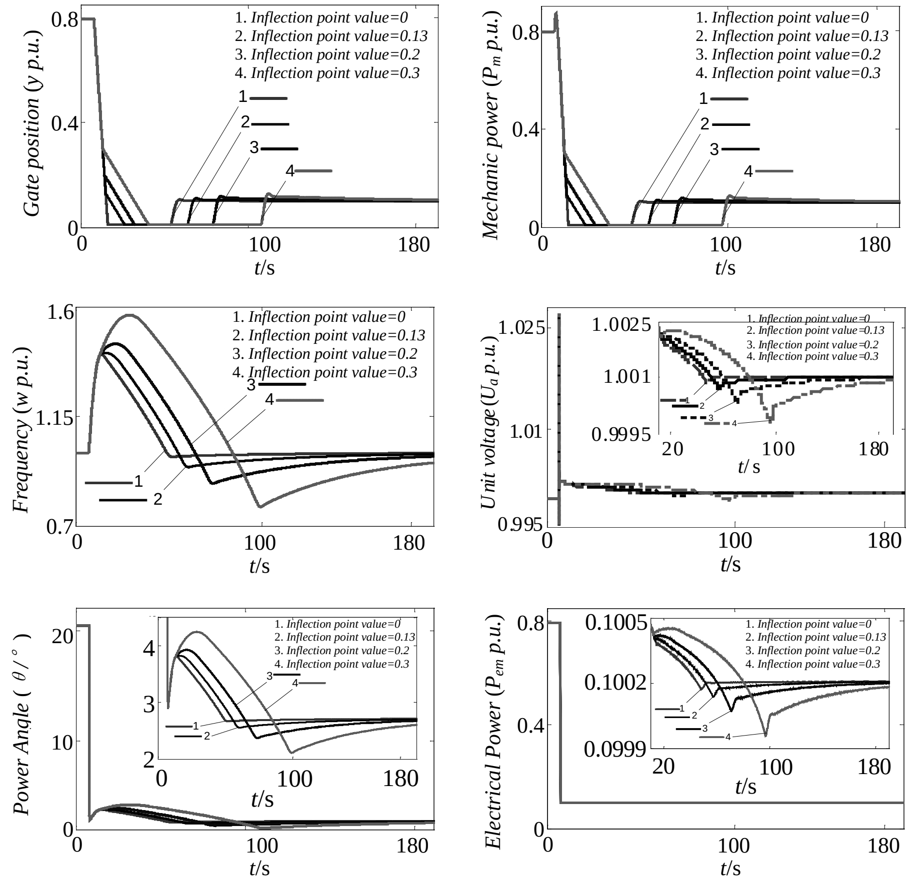

Figure 6. Simulation results of load rejection.

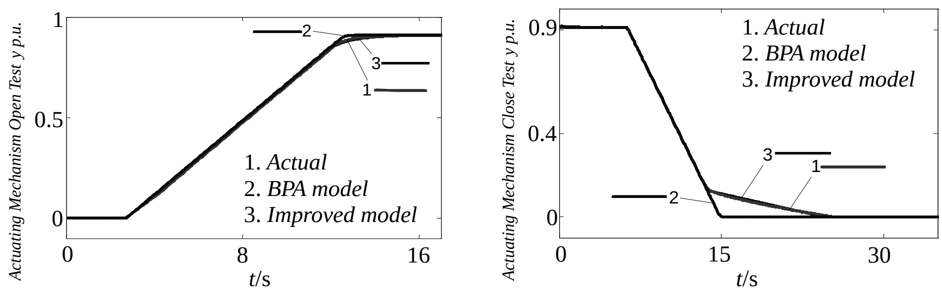

Figure 7. Simulation results of positive and negative step disturbance.

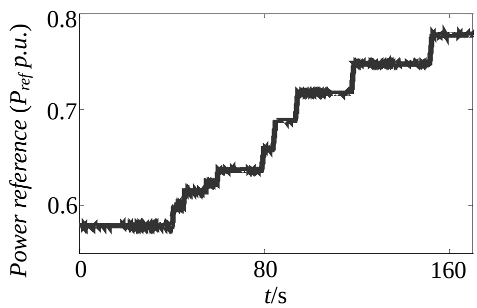

Figure 8. Power reference signal.

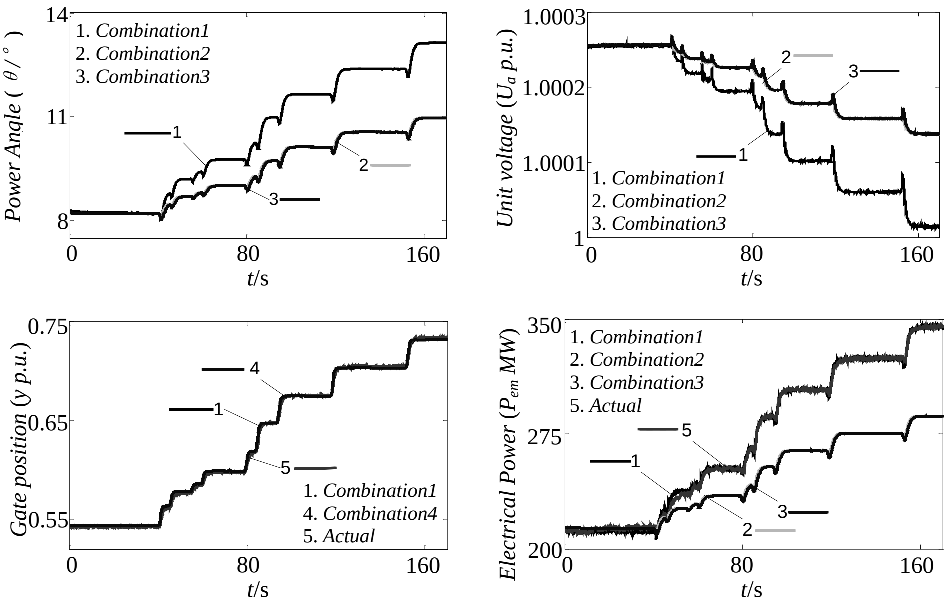

Figure 9. Francis turbine and governor models' simulation results.

Combination 4: Francis turbine model in **Figure 3** and BPA governor model.

Through curve fitting, the non-linear relationship between gate position and power was got, and the coefficients in (3) are: $a_1 = 6.2891$, $a_2 = -12.2513$, $a_3 = 8.8952$, $a_4 = -1.9222$. And T_w is 1.825 s, identified by the particle swarm optimization algorithm.

Figure 9 shows the comparison of simulation result.

The simulation results in **Figure 9** validate the Francis turbine and governor models proposed in this paper. It can be seen from **Figure 9**:

1) Both of the improved actuating mechanism model and BPA model can simulate the response correctly when the fluctuation of gate reference signal is small.

2) Large head variations clearly can have a major impact on the total response of generating unit. Thus the non-linear relationship between gate position and power will strongly influence the amount of power response. That is the reason why the response of ideal turbine model in BPA or IEEE nonlinear model without this modeling addition is significantly in error in simulation, while the measured power response and the simulated response of the improved Francis turbine model are nearly identical.

4. Conclusions

1) The improved model of actuating mechanism can reflect the two-segment closing law of hydro guide vanes and obtain the correct response in simulation for Xiaowan hydro generating unit, overcoming the disadvantage of actuating mechanism model in PSD-BPA.

2) In load rejection studies, the setting value of inflection point will strongly influence the governing system responses, including gate position, turbine power and frequency. With the increasing of inflection point setting value, the over-speed event will be more serious during the load rejection.

3) The Francis turbine model considering nonlinear relationship between gate position and electrical power, compared with the ideal hydro turbine model in PSD-BPA, captures the responses of Xiaowan hydro generating unit more accurately. The Francis turbine and governor improved models considering two-segment closing law of hydro guide vanes can be applied in power system simulation analysis better.

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