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Response time for primary frequency control of hydroelectric generating unit

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ABSTRACT

For evaluating the power quality in primary frequency control for hydroelectric generating units, the power response time is an indicator which is of main concern to the power grid. The aim of this paper is to build a suitable model for conducting reliable simulation and to investigate the general rules for controlling the power response time. Two huge hydropower plants with surge tank from China and Sweden are applied in the simulation of a step test of primary frequency control, and the result is validated with data from full scale measurements. From the analytical aspect, this paper deduces a time domain solution for guide vane opening response and a response time formula, of which the main variables are governor parameters. Then the factors which cause the time difference, between the power response time and the analytical response time of opening, are investigated from aspects of both regulation and water way system. It is demonstrated that the formula can help to predict the power response and supply a flexible guidance of parameter tuning, especially for a hydropower plant without surge tank.

Introduction

In order to suppress the power grid frequency fluctuation, generating units change their power output automatically according to the change of grid frequency, to make the active power balanced again. This is the primary frequency control. Hydroelectric generating units are suited to undertake the power response in primary frequency control, because of great rapidity and amplitude of the power regulation. Nowadays the power quality of hydroelectric generating units in primary frequency control becomes more and more important, due to the more complex structure of the grid and greater proportion of the renewable intermittent sources. The key of evaluating the regulation quality is the power response time (more details are in Section 'Test method and specifications of primary frequency control'). Therefore, these problems are highly concerned by industry: How do the regulation and water way system affect the response time? How should governor parameter be set to control the power response time?

To the best of the authors' knowledge, no specific research on response time of primary frequency control exists currently. Simulation and dynamic process analysis of primary frequency control for hydroelectric generating units are treated in e.g. Refs. [1–4]. The stability problem is discussed in Refs. [5–7]. Different new controllers or control techniques are studied to improve the dynamic performance of hydropower plant (HPP) in the load frequency control [8–11]. A series of important research activities regarding frequency control were conducted: a complex simulation was performed to investigate an incident of oscillatory behavior in power output of a HPP [12]; A specification was proposed for the transient and steady-state responses of a HPP operating in frequency-control mode. The specification gives a generic definition of how the electrical power should respond to step, ramp and random changes in frequency [13]. Based on control theory, power response process was deduced by applying the transfer functions and inverse Laplace transform [13]. The idea is a good inspiration to this paper.

Generally speaking, both regulation and water way system directly affects the power response time. Hence the previous research can be extended in two directions, as described below. Aiming at the regulation system, there are several research activities on governor parameter optimization through the preliminary deduction, sensitivity analysis [3] or optimization algorithms [14,15]. However, the research on the relationship between power response and governor parameter choice is in urgent need. Besides, the former simulations mostly adopt some built-in algorithm

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directly, for example one of the differential equation solvers in MATLAB, and do not discuss the accuracy and applicability of the solving methods of governor equations. On the other hand, the water way subsystem in most models is relatively simple, which influences the accuracy of power response. Moreover, the influence of surge and water hammer is seldom discussed deeply.

The aim of this paper is to build a suitable model for conducting reliable simulations and to display general rules to obtain a desired power response. Section 'Test method and specifications of primary frequency control' introduces the test and relevant specifications of primary frequency control, and illustrates the definition and importance of the response time and delay time. Applying Visual C++ 2008, Section 'Modeling' presents the modified model of turbine governor with primary frequency control function under guide vane opening feedback control mode. The implementation is based on the existing mathematical model described in [16], which takes into account nonlinear factors such as turbine characteristics and pipeline elasticity. In Section 'Comparison between measurement and simulation', two huge HPPs with surge tank from China and Sweden are applied in the simulation of a step test process of primary frequency control, and the result is validated with data from full scale measurements. Section 'Response time of primary frequency control' conducts theoretical analysis and simulation to study the response time and the influencing factors. The main results are in Section 'Response time of primary frequency control'. The last section draws the conclusion.

Test method and specifications of primary frequency control

Strictly speaking, the test of primary frequency control needs to be conducted in every HPP to confirm a set of parameters to meet the requirement of specifications. There are two normal test methods [3]. (1) The first test method is to cut the governor input signal of frequency measurement so that the regulation system is under open-loop control. Then, a required frequency step signal is given, and the active power is recorded to check whether the regulation system meet the specifications of the power grid operator. This test method can yield an accurate result without being influenced by the change of grid frequency, but it nevertheless brings the hidden danger [3] which might be caused by signal errors and wrong parameter settings. (2) The second approach is to keep the units connected to the power system and step change the given frequency of the governor. This method would affect the power system frequency, and the result might has tiny errors because the generator frequency follows the system frequency which is not exactly the rated value (50 Hz). Therefore an accurate simulation is indeed important.

When the units are operating on 80% of the rated load, the power response for a 60 s frequency step should meet a series of requirements in accordance with the specifications of China Electricity Council [17]. The most crucial requirements are: the power adjustment quantity should reach 90% of the static characteristic value within 15 s. If the rated head of the unit is larger than 50 m, the power delay time should be less than 4 s. In the corresponding European rules, according to the specifications of ENTSO-E [18], the time for starting the action of primary control is a few seconds starting from the incident, the deployment time of 50% of the total primary control reserve is at most 15 s and from 50% to 100% the maximum deployment time rises linearly to 30 s. There are some differences between these two specifications, but the response time (deployment time) $T_{response}$ and delay time T_{delay} of power response process are the key indicators for both specifications, as shown in Fig. 1. Ref. [13] also states similar specifications for these two indicators.

Another situation applies in the Nordic synchronous grid, where four national transmission system operators (TSOs) cooperate. The TSOs have different criteria, which however can be expected to conform to each other and to the criteria of ENTSO-E in the next few years. Currently however, the Norwegian TSO Statnett has no specific requirements on the response time, but prescribes limits on certain quantities, such as on the delay between frequency deviation and incipient guide vane motion, on the resolution in frequency measurement, on the permanent droop, and on how to measure these parameters [19]. There is also a classification of units based on criteria on governor parameters. Norwegian power plants provide the largest share of regulating power in the Nordic grid. The second largest share comes from Sweden, where the TSO Svenska Kraftnät have demands on response time, but no requirements on details [20]. The requirements depend on the magnitude of the frequency deviation, and if it exceeds 0.1 Hz, 50% should be delivered within 5 s, and 100% within 30 s.

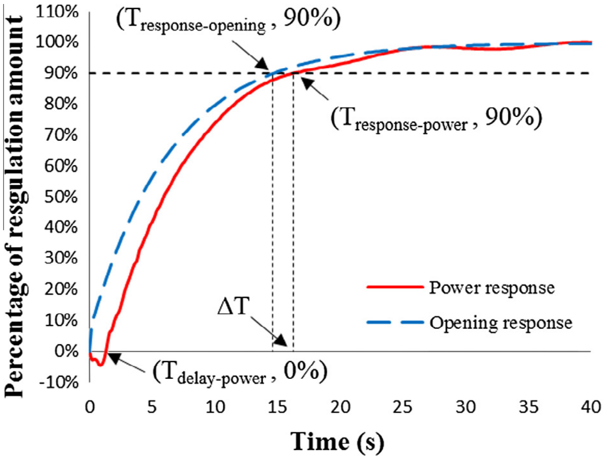

Fig. 1. Illustration of different times under frequency step disturbance.

Modeling

The modeling and improvement described in this section are based on the software TOPSYS [16], which is developed for analyzing transient processes of HPPs. The basic equations of water conduit and hydraulic turbine behavior in TOPSYS have the following characteristics: (1) Elastic water hammer is adopted in the draw water tunnel, considering the elasticity of water and pipe wall. (2) Characteristic of the penstock is taken into account. (3) Characteristic curve of the turbine is introduced. These are mostly simplified or ignored in the related research. However, the current TOPSYS version cannot simulate primary frequency control. Therefore the governor model is established here to extend the TOPSYS with this supplement implemented in VC++.

Turbine governor

Generally, there are two control modes for the primary frequency control of hydroelectric generating unit (hereafter referred to as opening control and power control), according to different feedback objects in closed-loop control: guide vane opening and power. The power control mode is also called "power droop". Since the opening control is the most common one, the model of governor for primary frequency control under opening control is built and described here. The block diagram of a typical PID governor with droop is shown in Fig. 2, and (1) expresses the corresponding differential equation. More exactly, x stands for the relative difference between frequency set-point f_c (commonly 50 or 60 Hz) and generator frequency f_g; The servomotor stroke or guide vane opening is denoted by y (since these two variables