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Regulation quality for frequency response of turbine regulating system of isolated hydroelectric power plant with surge tank

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ABSTRACT

Aiming at the isolated hydroelectric power plant (HPP) with surge tank, this paper studies the regulation quality for frequency response of turbine regulating system under load disturbance. Firstly, the complete mathematical model of turbine regulating system is established and a fifth order frequency response under step load disturbance is derived. Then, the method of primary order reduction and secondary order reduction, for this complete fifth order system of frequency response, is proposed based on dominant poles. By this method, the complete fifth order system is solved and the regulation quality for frequency response is studied. The results indicate that the complete fifth order system always has a pair of dominant conjugate complex poles and three non-dominant poles. The primary fourth order equivalent system, which is obtained by primary order reduction, keeps the dominant poles almost unchanged, therefore it can represent and replace the complete fifth order system and it is obviously superior to other fourth order systems. The primary fourth order equivalent system is superimposed by two second-order subsystems, one of them is corresponding to two non-dominant real poles (i.e. head wave) and the other one is corresponding to a pair of dominant conjugate complex poles (i.e. tail wave), respectively. In the fluctuation process of frequency response, head wave decays very fast and works mainly in the beginning period while tail wave decays very slowly, fluctuates periodically and works throughout the period. The secondary order reduction of complete fifth order system can be conducted by using the second order system of tail wave, which is the main body of frequency response, to represent the fluctuation characteristics. The most important dynamic performance index that evaluates the regulation quality, i.e. settling time, is derived from the fluctuation equation of tail wave. The different characteristic parameters of turbine regulating system have different influences on the change rules of head wave, tail wave and settling time.

Introduction

One of the main tasks of power system operation is to control grid frequency in the allowable variation range of rated frequency to ensure grid power quality when grid load changes, and load frequency control (LFC) is the primary measure to accomplish this task [1]. In modern power system, hydroelectric power plant (HPP) undertakes the major task of peak modulation (PM) and frequency modulation (FM) due to its characteristic of flexible operation. LFC of hydroelectric generating units is actualized by turbine control system (the core component is governor) [2].

Grid-connected operation and isolated operation are the main operation modes of hydroelectric generating units. The former is the normal and primary operation mode and the later serves in accidental and transient cases.

For grid-connected operation mode, LFC is implemented by the automatic generation control (AGC) system of grid and AGC system of power plant on the turbine control system to accomplish primary frequency regulation (PFR), secondary frequency regulation (SFR) and exchange power control among regional grids, etc. There are considerable researches in this field [3–11]. Some advanced control strategies such as fuzzy control [6,7], robust control [8,9] and intelligent discontinuous control [10] were applied to the design of load frequency controller, and good control effects were achieved.

Under isolated operation mode, the operating conditions of governor are complicated due to the influence of the value of load change and the load characteristics of isolated grid et al. Hence, maintaining the grid frequency within a certain range is indeed a

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challenge. National standard of China [12] stipulates the limit value of decay rate for frequency response of isolated HPP under load disturbance. In practical cases, the frequency response is required to have good regulation quality on the premise of the satisfaction of stability. As to the issue of regulation quality of frequency response, Refs. [13–15] carried out theoretical analysis, model test and numerical simulation on HPP without surge tank, and analyzed the setting and effect of governor parameters; however, there is little research on HPP with surge tank. It is well recognized that surge tank is indeed an important measure of pressure reduction. Since the influence of water-level fluctuation in surge tank, the wave form of frequency response shows the characteristic of head wave and tail wave [16], which is significantly different from the case without surge tank (shown in Fig. 1). The fluctuation characteristics of head wave and tail wave and the effect of system parameters on wave form were analyzed by numerical simulation [16–18]. By solving the fluctuation equation of tail wave, the fluctuation characteristics of tail wave and its relationship with regulation quality were studied [19,20]. It can be found that the researches in Refs. [16–20] exist two major limitations. Firstly, most of the research techniques were numerical simulation. Due to the lack of theoretical analysis, the essence and change rule of regulation quality could not be revealed and recognized clearly. Secondly, in the process of theoretical analysis, the mathematical model of turbine regulating system was simplified too much to reduce the order of overall transfer function, because high order equations, especially fifth-order (or higher) equations, were difficult to analyze theoretically. Specifically, Ref. [19] obtained a second order overall transfer function by assuming that the water-level fluctuation in surge tank was a sinusoidal wave and neglecting the water inertia of penstock and the head loss of entire pipeline; Ref. [20] obtained a fourth order overall transfer function by neglecting the water inertia and head loss of penstock. The complete mathematical model was not established and the simplified models could not represent the original turbine regulating system accurately.

This paper aims to overcome the above two limitations and further study the regulation quality for frequency response of turbine regulating system in isolated HPP with surge tank under load disturbance. There are two motivations: (1) for isolated HPP with surge tank, reveal the relationship between the dominant/non-dominant poles and the different terms of denominator of overall transfer functions, and then establish the corresponding relation between the dominant/non-dominant poles and the head/tail wave of time response of the frequency and (2) propose the method of order reduction for high order system (fifth-order), and then work out the analytic formulae of fluctuation characteristic parameters which evaluate the control quality (the main motivation). The results obtained in this paper can provide a guidance for the improvement of control quality of hydroelectric generator unit with surge tank under isolated operation.

This article is organized as follows. In Section 'Mathematical model', the complete mathematical model of turbine regulating system that includes all subsystems (i.e. headrace tunnel, surge tank, penstock, turbine, generator and governor) is established. In Section 'Derivation of overall transfer function', the overall transfer function is derived from complete mathematical model. In Section 'Primary order reduction of turbine regulating system', the frequency response under step load disturbance is derived from overall transfer function. Then primary order reduction, which overcomes the problem of the solution of fifth order system, is proposed based on dominant poles. In Section 'Regulation quality for frequency response of turbine regulating system', the fluctuation equations of head wave and tail wave of frequency response are solved from the equivalent system obtained by primary order reduction. Based on their fluctuation equations, the formation mechanisms, change rules and relationships with regulation quality of head wave and tail wave are revealed. Then secondary order reduction is proposed based on dominant poles, by using tail wave to represent the fluctuation characteristics of frequency response. According to the fluctuation equation of tail wave, the most important index of dynamic regulation quality, i.e. settling time, is obtained and the effects of influencing factors on settling time are investigated.

Mathematical model

The turbine regulating system of isolated HPP with surge tank is illustrated in Fig. 2, and its complete mathematical model that includes headrace tunnel, surge tank, penstock, turbine, generator and governor can be established as follows:

(1) Controlled system [21–24]

Momentum equation of headrace tunnel:

$$h_F = -T_{wy}\frac{dq_y}{dt} - \frac{2h_{y0}}{H_0}q_y \tag{1}$$

Continuity equation of air cushion surge tank containing state characteristic of gas (conventional open-type surge tank is the special case of air cushion surge tank):

$$q_y = \frac{FH_0}{(1 + mFp_0/\nabla_0)Q_0}\frac{dh_F}{dt} + q_t \tag{2}$$

Momentum equation of penstock:

$$h_F = T_{wt}\frac{dq_t}{dt} + \frac{2h_{t0}}{H_0}q_t + h \tag{3}$$

Moment equation and discharge equation of turbine:

$$m_t = e_h h + e_x x + e_y y \tag{4}$$

$$q_t = e_{qh} h + e_{qx} x + e_{qy} y \tag{5}$$

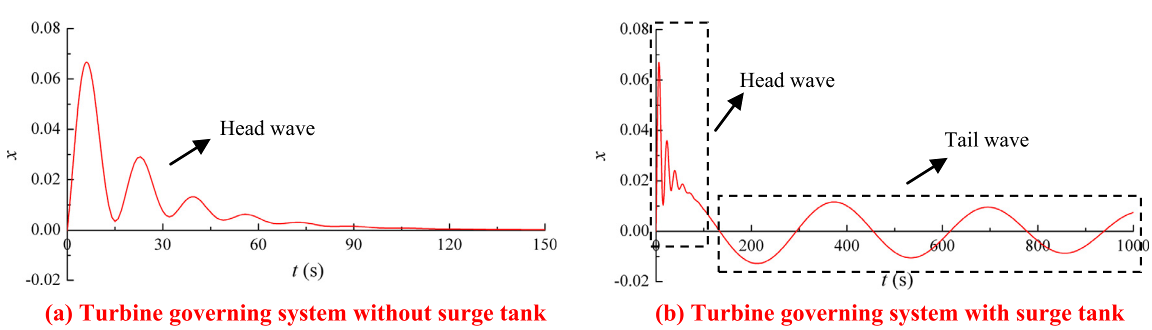

Fig. 1. Head wave and tail wave of time response of the frequency under load disturbance [16].