A novel surface-cluster approach towards transient modeling of hydro-turbine governing systems in the start-up process

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1. Introduction

The transient modeling and simulation of hydro-turbine governing systems is always a challenging problem for researchers [1]. Start-up transient process is an important issue for hydro-turbine governing system (HTGS). During the process, dramatic changes in flow, rotational speed and water head, which make the hydro-turbine governing system unstable and unsafe, are worth studying [2].

The transient process includes small oscillation process and large oscillation process [3–7]. For the first aspect, a lot of achievements have been gained by researchers. For example, Zhang et al. [8] proposed supplementary control strategy of hydro-turbine governor and they proved the effectiveness of the strategy. Khan et al. [9] studied a micro hydropower generation system in Pakistan and CFD analysis of the turbine geometry was carried out to evaluate the optimal recouping of flow properties for maximum electricity generation. Thapa et al. [10] investigated the effects of sediment erosion of turbine components on the flow phenomenon, and developed better design of hydro turbines to minimize those effects. Aggidis et al. [11] presented a technology that can accelerate the development of hydro turbines by fully automating the initial testing process of prototype turbine models and automatically converting the acquired data into efficiency hill charts. However, few researchers have focused on their researches on the transient modeling of the HTGS in the start-up transient process. The conventional research method for the HTGS in the small oscillation process cannot be applied to the large oscillation process especially the start-up process because of the dramatic changes of flow, rotational speed and water head in the start-up process which result in the frequent changes of transfer coefficients [12–14]. The study on the dynamic behavior of the hydro-turbine governing system in transient process is very important for the research on the safe operation and control of the hydropower station system.

To overcome the problem, a surface-cluster method is proposed in this paper. The characteristic equations of the HTGS are improved to describe the frequent changes of transfer coefficients during the start-up transient process. Essentially, the regulation and control of the HTGS is the changing law of the guide vanes. Therefore, the effects of the guide vanes on the dynamic characteristics of HTGS in the start-up transient process are investigated. A new dynamic model of the HTGS which can describe the effect of the guide vanes in the start-up transient process is established. The results of this paper reveal the influence of the guide vane opening law on the transient characteristic of the HTGS in the start-up transient process. Further, to obtain a better dynamic characteristic, the guide vane opening law of the HTGS is improved during the start-up transient process.

To achieve the above goal, this paper is organized as follows: In

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Section 2, the dynamic equations of the hydro-turbine output torque and flow are improved by using the surface-cluster method and the transient dynamic model of the hydro-turbine governing system is established in the start-up process. Section 3 presents the transient characteristics of the transient model in start-up process with different opening laws, and analyzes the effects of the opening law of the guide vanes on the transient characteristics of the hydro-turbine governing system in the start-up process. Finally Section 4 presents the conclusions to this paper.

2. Method

For the condition of rigid water hammer, the Francis turbine is chosen as the research object. The characteristic equation of the HTGS is improved in this section to describe the frequent changes of transfer coefficients in the start-up transient process.

2.1. Conventional characteristic equations of the hydro-turbine

When calculating the hydro-turbine output torque and flow during the start-up transient process, the transient coefficients of the HTGS change frequently [15–17]. This results to the non-negligible accumulated error, as shown in Fig. 1.

The transfer coefficients of the hydro-turbine which are approximately calculated lead to the non-negligible accumulated error in the start-up process. From Fig. 1, when the operating point moves from point a to point b with a fixed rotational speed (x), the increment of torque is \( \Delta m_{ob} = \int_a^b e_x \, dx \) where \( e_x \) is the slope of the a–b curve. Thus, the torque of operating point b is \( m_{ob} = m_{oa} + \Delta m_{ob} \). When the guide vane opening is constant from operating point c to b, the increment of torque is \( \Delta m_{cb} = \int_c^b e_y \, dy \) in which \( e_y \) is the slope of the c–b curve. Therefore, the torque of operating point b is \( m_{ob} = m_{oc} + \Delta m_{cb} \). Due to the approximated values of \( e_x \) and \( e_y \), \( m_{ob} \) may not be equal to \( m_{oa} \). This means that the operating point b has different torque values. More importantly, the accumulated error increases with the changes of rotational speed and guide vane opening in the start-up process. Therefore, the conventional equations of torque and flow must be improved in order to study the dynamic characteristics of the hydro-turbine governing system in the start-up process.

2.2. Improved dynamic equations of the hydro-turbine output torque and flow

To overcome the problem, the dynamic equations of the hydro-turbine output torque and flow are improved by using the surface-cluster method (see Fig. 2).

As shown in Fig. 2, a–b–c–d is the integration path of the torque. Points a, b and c are on surface A and d is on surface B. The path a–b is equal guide vane opening line with the fixed guide vane opening (y) and water head (h). The path b–c is equal rotational speed line with fixed rotational speed (x) and water head (h). The path c–d is changing water head line with fixed guide vane opening (y) and rotational speed (x).

From Refs. [18–20], \( m_t \) is the function of rotational speed, guide vane opening and water head which means \( m_t = m_t(x \; y \; h) \). The torque \( (m_t) \) is a space surface in \( x–y–m_t \) coordinate when water head \( (h) \) is constant. For different water head \( (h) \), the torque \( (m_t) \) is the surface in \( x–y–m_t \) coordinate see surface A and B in Fig. 2. When the torque of operating point a is known \( m_{oa}(x_a \; y_a \; h_a) \), for an arbitrary operating point b, its torque can be written as

\[
m_{ob}(x_b \; y_b \; h_b) = m_{oa}(x_a \; y_a \; h_a) + \int_a^b dm_x = m_{oa}(x_a \; y_a \; h_a) + \int_a^b dm_x + \int_d^c dm_y + \int_b^d dm_t
\]

where \( e_x, e_y \) and \( e_t \) are partial derivatives of the turbine torque with respect to rotational speed, head and guide vane, p.u. Similarly, when the flow of operating point a is known \( q_{oa}(x_a \; y_a \; h_a) \), for an arbitrary operating point b, its flow can be expressed as

\[
q_{ob}(x_b \; y_b \; h_b) = q_{oa}(x_a \; y_a \; h_a) + \int_a^b e_x \, dx + \int_d^c e_y \, dy + \int_b^d e_t \, dh
\]
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