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

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ABSTRACT

Transient process, an essential condition for the operation of the hydro-turbine governing system, is critical for the safety and stability of a hydropower station. This research focuses on the transient modeling and dynamic analysis of the hydro-turbine governing system in the start-up process. A novel approach is developed to establish the dynamic model of the hydro-turbine governing system in transient process. The flow equation and torque equation were improved to reflect the dramatic changes of system parameters during the start-up process. As a pioneering work, the effect of guide vane opening law on the dynamic characteristics of the hydro-turbine governing system in the start-up process was investigated by numerical simulations. The results of this research can promote the development of transient modeling and performance improvement of hydro-turbine governing systems in transient process.

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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Nomenclature

x	relative deviation of rotational speed, p.u.
q	relative deviation of flow, p.u.
h	relative deviation of water head, p.u.
m_t	relative deviation of turbine torque, p.u.
T_{ab}	hydro-turbine inertia time constant, s
T_w	inertia time constant of penstock, s
y	relative deviation of guide vane opening, p.u.
e_{qx}, e_{qy}, e_{qh}	partial derivatives of the flow with respect to rotational speed, head and guide vane, p.u.
e_x, e_y, e_h	partial derivatives of the hydro-turbine torque with respect to rotational speed, head and guide vane, p.u.
e_n	synthetic self-regulation coefficient, p.u.
w	changing rate of the guide vane, p.u.
m_{g0}	relative deviation of load disturbance, p.u.

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 $\Delta m_{ab} = \int_a^b e_y dy$ where e_y is the slope of a–b curve. Thus, the torque of operating point b is $m_{tb} = m_{ta} + \Delta m_{ab}$. When the guide vane opening is constant from operating point c to b, the increment of torque is $\Delta m_{cb} = \int_c^b e_x dx$ in which e_x is the slope of the c–b curve. Therefore, the torque of operating point b is $m'_{tb} = m_{tc} + \Delta m_{cb}$. Due to the approximate values of e_x and e_y, m'_{tb} may not be equal to m_{tb}. 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 $m_t = m_t(x \quad y \quad h)$. 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 cluster in x–y–m_t coordinate (see surface A and B in Fig. 2). When the torque of operating point a is known $m_{ta}(x_a \quad y_a \quad h_a)$, for an arbitrary operating point d, its torque can be written as

$$\begin{aligned} m_{td}(x_d \quad y_d \quad h_d) &= m_{ta}(x_a \quad y_a \quad h_a) + \int_a^d dm_t = m_{ta}(x_a \quad y_a \quad h_a) \\ &\quad + \int_a^b dm_t + \int_b^c dm_t + \int_c^d dm_t \\ &= m_{ta}(x_a \quad y_a \quad h_a) + \int_{x_a}^{x_d} e_x dx + \int_{y_a}^{y_d} e_y dy + \int_{h_a}^{h_d} e_h dh \end{aligned} \tag{1}$$

where e_x, e_y and e_h are partial derivatives of the turbine torque with respect to the rotational speed, guide vane opening and water head.

Similarly, when the flow of operating point a is known $q_{ta}(x_a \quad y_a \quad h_a)$, for an arbitrary operating point d, its flow can be expressed as

$$q_{td}(x_d \quad y_d \quad h_d) = q_{ta}(x_a \quad y_a \quad h_a) + \int_{x_a}^{x_d} e_{qx} dx + \int_{y_a}^{y_d} e_{qy} dy + \int_{h_a}^{h_d} e_{qh} dh \tag{2}$$

Eqs. (1) and (2) are the improved characteristic equations of torque and flow to describe the dynamic characteristics of the hydro-turbine governing system.

The hydro-turbine governing system is a time-varying system in transient process. In order to describe the dramatic changes of the transfer coefficients in transient process, the surface-cluster method offers a way to calculate the torque and flow in spatial surface. Under this way, the system parameters and transfer coefficients are combined with path integral in transient process. The accumulated errors of the torque and flow are reduced in the transient process because accurate transfer coefficients are used during the calculation.

From Refs. [8–11], the traditional models of the HTGS are difference-equation models. They cannot describe the dramatic changes of

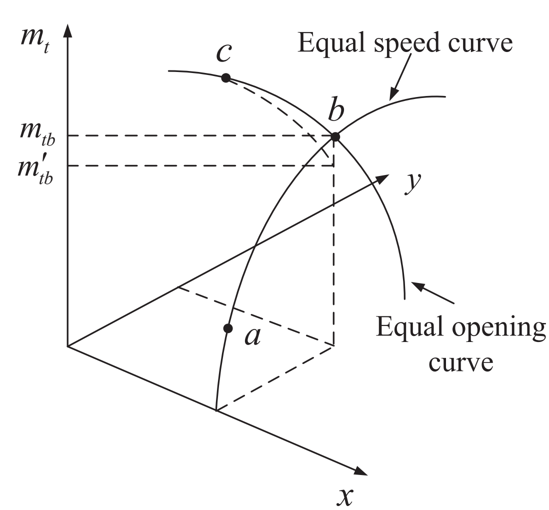

Fig. 1. The accumulated errors of hydro-turbine output torque during the start-up process.