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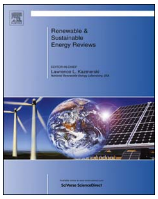

Condition of setting surge tanks in hydropower plants – A review

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ABSTRACT

Hydropower plays an important role in the safe, stable and efficient operation of power systems, especially with current trends toward renewable energy systems. The total global potential of gross, technical, economic, and exploitable hydropower are still enormous in the future, and the developments of new hydropower stations (HPSs) are of great importance. For constructions of new HPSs, the condition of setting surge tanks (CSST) is crucial for various perspectives, e.g. safety, stability and economy of HPSs. In this review, the CSST are summarized and analyzed from the three aspects: regulation assurance, operation stability, and the regulation quality, with an aim of providing a reference and guidance for research and engineering applications regarding surge tanks. Upstream and downstream surge tanks in conventional HPSs and pumped storage power stations are all included. Moreover, a comprehensive comparison of CSST under different conditions is conducted. One of the main focuses of this review is on Chinese studies, for introducing many meaningful results written in Chinese to more readers all over the world.

1. Introduction

Hydropower, as the current largest sustainable energy resource, plays an important role in the safe, stable and efficient operation of power systems, especially with current trends toward renewable energy systems. The total global potential of gross, technical, economic, and exploitable hydropower are still enormous in the future [1], and the developments of new hydropower stations (HPSs) are of great importance, especially in China [2,3].

Nowadays, the size of HPSs and the structure complexity of systems have been increasing. For constructions of new HPSs, rigorous works are necessary for achieving higher performance in safe, stable and economic perspective. An important aspect is to determine whether to set a surge tank (also referred as surge shaft, surge chamber). The purpose of setting of a surge tank is to improve the overall operation performance of a hydropower station (HPS) with a long penstock. A surge tank acts as a fore-bay to reduce the amplitude of pressure fluctuations by reflecting the incoming pressure waves or by storing or providing water, reducing acceleration or deceleration in the tunnel [4]. It can not only ensure the safety of HPSs, but also improve the operation conditions and regulation quality of hydropower units. However, surge tanks are generally large and costly. In particular, for a HPS with a low head, the cost of constructing a surge tank can constitute a significant portion of the entire diversion system. Besides, the setting of a surge tank also brings complexities and increases the construction difficulty [5–7]. Therefore, the condition of setting surge tanks (CSST) has always been a topic of great importance. In recent years, scholars have conducted in-depth research and achieved meaningful results regarding the CSST. In this review, the CSST is summarized and analyzed from the three aspects: regulation assurance (mainly regarding safety aspects and introduced in detailed in Section 2), operation stability, and the regulation quality, with an aim of providing a reference and guidance for research and engineering applications regarding surge tanks. Upstream and downstream surges tanks in conventional HPSs and pumped storage power stations are all included. Moreover, a comprehensive comparison of CSST under different conditions is conducted.

It is worth noting that there are a large numbers of studies conducted by Chinese researchers on this topic during the great hydropower developments in China, but the publications are unfortunately not written in English. Hence one of the main focuses of this review is on Chinese studies, for introducing the meaningful results to more readers all over the world.

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Nomenclature

Symbol description

A_1	cross-sectional area at the draft-tube entrance
a	wave speed
b_t	temporary speed drop
D_1	runner diameter
e_{qy}, e_{qh},e_{qx}, e_y, e_h, e_x	transfer coefficients of the hydraulic turbine
e_g	coefficient of load characteristics
f	correction factor of water hammer pressure
GD^2	generator inertia
g	acceleration due to gravity
H_n	head at time $t = T_n$
H_r	rated head
H_s	draft head of the hydraulic turbine
k	correction factor considering the asymmetric distribution of the velocity at the cross-entrance to the draft tube
K	critical value of $\Sigma LV/H_0$
L	length of the pressure tailrace conduit
L_{w1}	limit length of the tailrace tunnel for FPWH
L_{wm}	limit length of the tailrace tunnel for LPWH
m_{g0}	relative change of load-torque
N	power output of pump-turbine
n_s	specific speed of the hydraulic turbine
n_0	synchronous speed
$n_{1\ n}'$	unit rotational speed at time $t = T_n$
Q_0	steady-state discharge
Q_2	discharge at time $t = T_n$
Q_{min}	minimum discharge
s	Laplace operator
T'	time that the discharge remains unchanged
T_a	mechanical inertia time constant
T_c	delay in the relay device's operation
T_d	dashpot time constant
T_n	rotational speed increase time
T_p	settling time
$[T_p]$	allowable settling time
T_s	effective closing time of wicket gate
T_w	water inertia time constant
T_{ws}	water inertia time constant of the pressure tailrace tunnel
T_z	time corresponds to Q_{min}
$[T_w]$	the allowable value ofT_w
$[T_w]_1$	allowable value of T_w for FPWH
$[T_w]_m$	allowable value of T_w for LPWH
$[T_w]_1$ / $[T_w]_m$	allowable value of$T_w$for FPWH/ LPWH
t	time
t_r	phase length of the water hammer wave
V	flow velocity in the pressure conduit
V_0	initial steady-state velocity in the conduit
V_n	flow velocity in the conduit at time $t = T_n$
V_{w0}	steady-state flow velocity in the pressurized tailrace conduit
V_{wj}	steady-state flow velocity at the entrance to the draft tube
V_1	flow velocity at cross-section 1-1
V_0	initial steady-state flow velocity in the conduit
x	relative speed deviation
$[x_{max}]$	allowable deviation in relative rotational speed
α	relative head loss
β	rising ratio of rotational speed
β_{max}	the allowable value ofβ
ε	rotational speed ratio of hydraulic turbine
ρ_e, σ_e	conduit constants
σ	decay coefficient of the system
ω	angular frequency of the system's damped oscillation
ξ	rising ratio of pressure
ξ_{max}	maximum increase of pressure
$\lvert\Delta\rvert$	allowable fluctuation bandwidth of frequency
∇	installation elevation of hydraulic turbine

2. Studies of CSST based on regulation assurance of a HPS

The first aspect considered in the CSST is the overall safety assurance of the regulation process, which is represented by the term "regulation assurance" in Chinese engineering and research field for over decades. Two main indicators of the "regulation assurance" are the water hammer pressure and the increase of the rotational speed of the generating unit. Safety is obviously the priority for a HPS, and various studies on modelling and simulations of dynamic processes in HPS are conducted to ensure the safety operation, and the influence of surge tanks are considered [8–17]. Hence, the CSST for various cases are reviewed based on regulation assurance firstly in this section.

2.1. Studies of setting conditions of upstream surge tank in a HPS

There are a few international regulations that can be applied to setting conditions of upstream surge tank. For example, it was specified in the HPS design specifications of the former USSR that the setting of a surge tank should be investigated if $\sum LV/H_0 > K$. For HPS in isolated operation or with a capacity greater than 50% of the system capacity, it was suggested that K should be within a range of 16–20. For a HPS with an installed capacity of 10–20% system capacity, $K \geq 50$ has been suggested [18]; The Brown formula states the value of K should larger than15–18. In France and Japan, the CSST is required to satisfy $\sum LV/H_0 > 45$ [18]. Gubin concluded that the CSST should be described in the following form: $T_w = \sum LV/gH_0 > 3\text{–}6$ s [19], where T_w is the water inertia time constant. In the research conducted by Chaudhry, the CSST was defined as $T_w = \sum LV/gH_0 > 3\text{–}5$ s [4]. However, all the above specifications were rough rules of thumb. Different types of hydraulic turbines have varying applicable ranges of water head, such that their requirements regarding the regulation assurance of the HPS will be different.

After the 1970s, it was generally accepted that the setting of a surge tank was related to two parameters: the speed rise of the unit β and water-hammer pressure rise ξ. At the same time, Chinese scholars addressed the feasibility of removing the surge tank from these two parameters [20–22], but they failed to present an explicit expression for the allowable T_w with respect to β and ξ. It was stipulated in [23] that the requirement $T_w > 2\text{–}4$ s is suitable for the conditions of setting an upstream surge tank. With this stipulation, $T_w = \frac{2\xi T_s}{2+\xi}$ was derived on the theoretical basis of the last-phase water-hammer(LPWH) [23,24]. Ding derived a formula for the maximum allowable length of the diversion conduit, based on the first-phase water-hammer(FPWH) [24] and LPWH. The formula was an expression of the maximum pressure increase ξ_{max} [25]. Chen was the first to derive the CSST by simultaneously considering β and ξ, but only the LPWH case was examined [26]. Wang et al. derived the necessary criterion for setting a surge tank based on the allowable value of volute pressure [27]. Nevertheless, they did not consider the value of β. Based on the expressions of β and ξ, Yang et al. derived the computation expression for the value of $[T_w]$ of FPWH and LPWH for an upstream surge tank [28]. First, the expression of the water hammer pressure $\xi = f(T_w, T_s)$ was rewritten as

$$T_s = f_1(\xi,\ T_w) = \begin{cases} \dfrac{\xi+2}{(1+\frac{a}{2L}T_w)\xi} T_w \cdots\cdots\cdots\cdots \text{(FPWH)} \\ \dfrac{\xi+2}{2\xi} T_w \cdots\cdots\cdots\cdots\cdots \text{(LPWH)} \end{cases}. \tag{1}$$