Energy Conversion and Management 148 (2017) 785–800

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Sensitivity analysis of a Pelton hydropower station based on a novel approach of turbine torque

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ARTICLE INFO

Article history:
Received 19 March 2017
Received in revised form 6 June 2017
Accepted 7 June 2017

Keywords:
Sensitivity analysis
Conversion efficiency
Pelton hydropower station
Penstock
Turbine torque
Nonlinear dynamics

ABSTRACT

Hydraulic turbine generator units with long-running operation may cause the values of hydraulic, mechanic or electric parameters changing gradually, which brings a new challenge, namely that whether the operating stability of these units will be changed in the next thirty or forty years. This paper is an attempt to seek a relatively unified model for sensitivity analysis from three aspects: hydraulic parameters (turbine flow and turbine head), mechanic parameters (axis coordinates and axial misalignment) and electric parameters (generator speed and excitation current). First, a novel approach of the Pelton turbine torque is proposed, which can make connections between the hydraulic turbine governing system and the shafting system of the hydro-turbine generator unit. Moreover, the correctness of this approach is verified by comparing with other three models of hydropower stations. Second, this latter is analyzed to obtain the sensitivity of electric parameter (excitation current), the mechanic parameters (axial misalignment, upper guide bearing rigidity, lower guide bearing rigidity, and turbine guide bearing rigidity) on hydraulic parameters on the operating stability of the unit. In addition to this, some critical values and ranges are proposed. Finally, these results can provide some bases for the design and stable operation of Peltonhydropower stations.

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1. Introduction

With continuous development of China's energy construction, lots of hydropower stations are entering the stage of design, construction and operation in succession [1]. Among them, two terms of hydropower projects are used simultaneously: Small Scale Hydropower and Low Head Hydropower (LHH). For LHH, it is becoming increasingly scarce in China [2]. Water conservancy construction corporations' interest had switched to hydropower sources characterized by high water head and small flow. Pelton turbine has the advantages of simple structure, unlimited installation height and insensitivity of flow changes, compared with Francis turbine and Kaplan turbine applied mostly in hydropower stations [3]. It produces power by utilizing water momentum impinging on bucket mounted on the runner. During this process, water momentum passes its kinetic energy to turbine runner and water with slow speed flows from bucket to air [4]. Utilizing this function, Pelton turbine without gas erosion is widely used in hydropower stations such as Bieudron hydropower station (Design head 1883 m), Yisanhe hydropower station (Design head 861 m) and Tianhu hydropower station (Design head 1022.4 m) [5].

Water resources engineering, an important and challenging subject, has got many contributions in many branch fields, such as the multi-reservoir programming, data preprocessing techniques, stability analysis of hydropower stations and so on. For multi-reservoir programming, a fine-grained parallel algorithm based on Fork parallel framework is proposed to improve the computing efficiency for long-term operation of multi-reservoir hydropower systems [6]. Chen et al. investigate three algorithms, i.e. differential evolution, artificial bee colony and ant colony optimization, to determine the optimal one for forecasting downstream river flow [7]. With regard to data preprocessing techniques, Wu et al. successfully seek a relatively optimal data-driven model for rainfall forecasting from three aspects: model inputs, modeling methods, and data-preprocessing techniques [8], and Wang et al. present an autoregressive integrated moving average model coupled with the ensemble empirical mode decomposition for forecasting annual runoff time series [9]. In addition to stability of hydropower stations, the calculation principles and methods develop very fast in recent years, and we can divide them

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http://dx.doi.org/10.1016/j.enconman.2017.06.019
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into two kinds. The first kind from the perspective of system science is proposing models of Hydro-Turbine Governing Systems (HTGS) considering the design structure of hydropower stations to analyze their stabilities and control methods. In addition to the dynamic stability analysis, for example, Sarasua et al. investigate the dynamic response of a pump storage hydropower station with a long penstock in the generating mode [10]. Guo et al. study the stability of the HTGS using the Hopf bifurcation theory [11]. Xu et al. establish a Hamiltonian model of the HTGS with a common penstock to investigate the dynamic responses under the excitation of stochastic and shock load [12], and then Li et al. analyze the stability of HTGS in load increasing using the Hamiltonian theory [13]. Yu et al. proposean innovative method for solving the coefficient matrix of state equations describing small fluctuations in the penstock [14]. On the other hand, control methods of hydropower stations are proposed to ensure the stable operation of HTGS. For example, Pico et al. present and analyze the dynamic responses of low-frequency oscillations in hydropower stations [15]. Martínez-Lucas propose the power-frequency control method for hydropower stations with long penstocks [16], and then he proposes another frequency control method and applied in a wind-solar isolated system by a hydropower station [17]. Kishor et al. perform the state estimation of the inelastic and elastic fifth order state space model and propose a linear quadratic control approach [18]. Li et al. design a fuzzy-PID controller for HTGS by using a novel gravitational search algorithm [19]. The second kind is a specification of research target key with Shafting System of Hydro-Turbine Generator Unit (SSHTG), which respectively focuses on Hamiltonian modeling and control method design, failure analysis and diagnosis method, vibration characteristics of therotor in thevertical and horizontal direction. For the Hamiltonian method, Zeng et al. successfully established a Hamiltonian model of SSHTG [20] and design a corresponding method for this port-controlled Hamiltonian system [21]. To failure and diagnosis method, Jalan et al. describe a model based technique for fault diagnosis of rotor-bearing system [22]. Xia et al. propose a vibration dynamic modeling method for HGU by using the finite element method [23]. For vibration analysis, Patel studied the influence of a rotor to stator contact on the lateral-torsional coupled vibrations [24]. Bettig et al. studied influences of a great number of inputs including imbalances, rotation speed, guide bearing misalignments, and so on.

In light of the above analysis, models of HTGS and SSHTG essentially study the same thing, namely operating stability and control method, only with different focuses. Specifically, the HTGS focuses more on the design structure of penstock layout and generator speed and ignore the forces acting on the SSHTG, while the SSHTG concerns more with the forces acting on the SSHTG and neglect the design structure of penstock layout and generator speed. In actual operation of thehydraulic turbine, any change of parametersthat must occur in the condition of future's continuous operation, such as hydraulic parameters,mechanic parameters and electric parameters, would probably lead to the instability of the whole system. Moreover, there is, however, not many types of research related to the stability of Pelton hydropower stations, and there are very little papers that can make connections between HTGS (hydraulic factor) and SSHTG (mechanical and electrical factors). Therefore, considering construction structures of Pelton hydropower stations, it is extremely important to define a novel approach that can take into account the effect of the complex forces acting on the shafting as well on its construction structures to investigate the sensitivity of system parameters on operating stability.

Motivated by the above analysis, we can conclude the following three innovations. First, a novelsolving approach of the Pelton turbine torque is proposed, which can make connections between the HTGS (hydraulic factor) and the SSHTG (mechanical and electrical factors). Second, a unified model of the Pelton hydropower station considering the hydraulic-mechanic-electric factors is proposed. Third, the sensitivity of electric parameter (excitation current (i)), the mechanic parameters (axial misalignment (d), upper guide

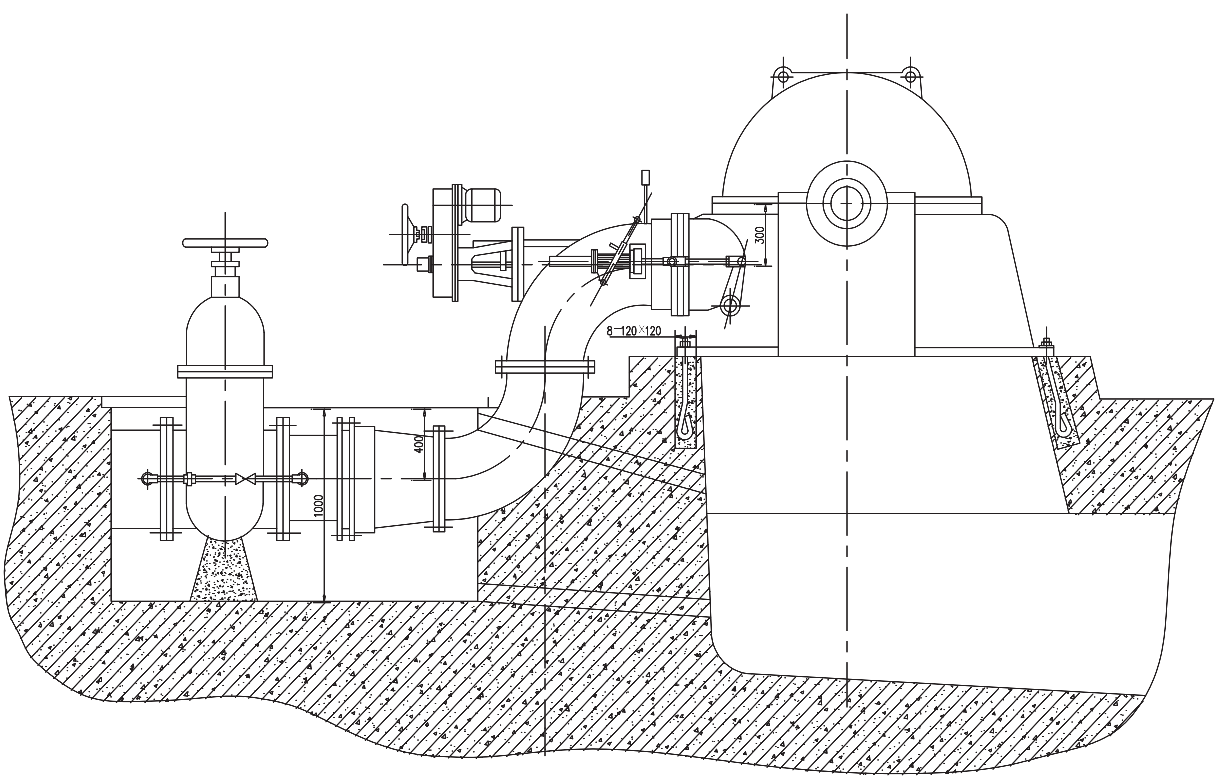

Fig. 1. The layout of a Pelton hydropower station.

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