Commun Nonlinear Sci Numer Simulat 67 (2019) 192–202

Contents lists available at ScienceDirect

Commun Nonlinear Sci Numer Simulat

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

Research paper

Dynamic safety assessment of a nonlinear pumped-storage generating system in a transient process

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ARTICLE INFO

Article history:
Received 1 September 2017
Revised 8 March 2018
Accepted 11 July 2018

Keywords:
Pumped-storage generating system
Francis turbine
Dynamic safety analysis
Risk probability

ABSTRACT

This paper focuses on a pumped-storage generating system with a reversible Francis turbine and presents an innovative framework for safety assessment in an attempt to overcome their limitations. Thus the aim is to analyze the dynamic safety process and risk probability of the above nonlinear generating system. This study is carried out based on an existing pumped-storage power station. In this paper we show the dynamic safety evaluation process and risk probability of the nonlinear generating system using Fisher discriminant method. A comparison analysis for the safety assessment is performed between two different closing laws, namely the separate mode only to include a guide vane and the linkage mode that includes a guide vane and a ball valve. We find that the most unfavorable condition of the generating system occurs in the final stage of the load rejection transient process. It is also demonstrated that there is no risk to the generating system with the linkage mode but the risk probability of the separate mode is 6 percent. The results obtained are in good agreement with the actual operation of hydropower stations. The developed framework may not only be adopted for the applications of the pumped-storage generating system with a reversible Francis turbine but serves as the basis for the safety assessment of various engineering applications.

1. Introduction

Pumped-storage generating system with a reversible Francis turbine (PSGS) performs as a nonlinear multi-purpose engineering equipment for power production and power consumption, enhancing the efficiency and reliability of electrical power systems [1–2]. Today, the average estimated growth rate of PSGS increases 10% annually in the world, with a total installed capacity of more than 100 GW [3–6]. Pumped-storage power stations are built to improve the maximum usage of thermal and nuclear power as well as to guarantee a high quality of power supply [7].

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https://doi.org/10.1016/j.cnsns.2018.07.025
1007-5704/

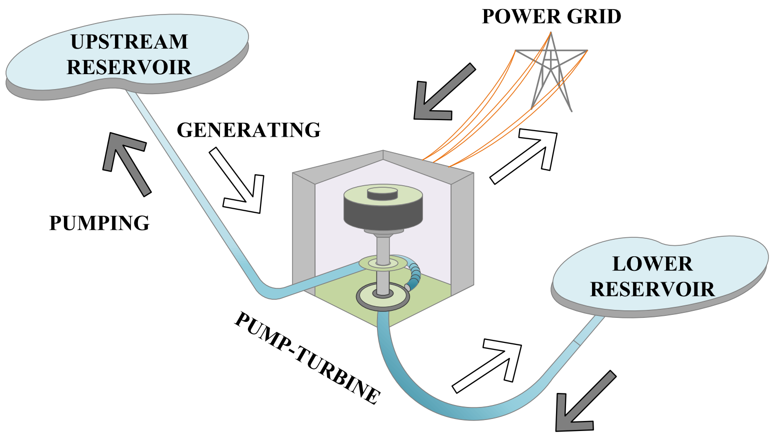

Fig. 1. Schematic working mechanism of an PSGS.

PSGSs are complex nonlinear systems incorporating a great deal of uncertainty in the operation of their hydraulic, mechanical and electrical components [8–11]. Based on five fundamental conditions (i.e., static, generating and pumping condition as well as generating/pumping transfer to phase modulation), PSGSs provide twenty-four switching modes such as start-up in pumping/generating condition switch to shut-down, start-up in pumping/generating condition switch to load rejection, and static switch to pumping condition due to the different demands of the electricity generation in hydropower stations [12–14]. This results in a substantial level of safety challenges such as vibration and water hammer pressure amplitudes in the penstock and draft tube [15–19]. From the operational principle of PSGSs, the above-mentioned safety challenges highlight the need for analyzing the S and inverted-S domains for the operation of pump mode, turbine mode, braking mode in the pumping/generating condition and reversed pump mode. For example, due to the decrease of the pump-turbine flow during the load rejection transient, the generating system can enter the reversed pump mode meaning that the pump-turbine runs in reverse [20]. This in turn causes a higher pump-turbine speed with respect to three different values of the pump-turbine flow. It is therefore considered a hazard, thus, requiring more attention in safety assessment of PSGSs.

Over recent decades, safety assessment methods have been developed in many fields including information science and bioscience. In the case of engineering applications some of these methods can quantitatively describe the uncertainty of the phenomena and provide failure probability of systems or their components [21–23]. In the literatures [24–25], two main approaches are considered for safety assessment, namely static and dynamic processes. The static assessment approach is used to predict the safety property of the system at a certain time, and it cannot better reveal the dynamic behaviors varying with real time. Meanwhile, the static assessment approach may ignore some fuzzy information in the system due to the simple algorithm design. Conversely, the dynamic assessment approach has the ability to quantify dynamic risks in transient processes by updating the information of the critical factors of the system in real time. The static assessment has been widely investigated by previous researchers, while the application of the dynamic approach is relatively limited, mainly due to complexity of the method. Currently, there are copious research outcomes available on PSGSs mainly focusing on dimensional design, hydrological computation, transient simulation and fault diagnosis aspects. However, not many investigations aim at assessing the safety of these systems. Safety assessment of PSGSs aims to predict the failure probability of the system in static and/or dynamic processes enabling the improvement of operation reliability. This requires developing a sound methodology and evaluative standard for an advanced safety assessment, given the complexity of PSGS.

This paper aims at developing a methodology which assesses the dynamic safety of PSGS operations. The novelty of this research is attributed to three components that include: a) proposing a dynamic safety assessment framework for PSGSs, b) conducting the dynamic safety evaluation process and quantification of risk probability values for the nonlinear generating system under different engineered closing laws, i.e. the separate mode operating with a guide vane and the linkage mode operating with a guide vane and a ball valve, and c) utilizing the Fisher discriminant analysis (FDA) method on the basis of actual operating data for the analyses.

2. Pumped-storage generating system with a reversible francis turbine

A pumped-storage generating system with a reversible Francis turbine (PSGS) that incorporates hydraulic, mechanical and electrical components is the complex dual-use equipment as it undertakes the critical tasks of generating power in peak-load hours and pumping in low-load hours. A schematic of PSGS working mechanism is illustrated in Fig. 1.