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Estimation of exhaust steam enthalpy and steam wetness fraction for steam turbines based on data reconciliation with characteristic constraints

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ABSTRACT

Wetness fraction of exhaust steam is important to the economy and safety of steam turbines. Due to lack of commercially available measurement technologies, it is usually obtained from model based calculation via other measurements. However, accuracy of relevant measurement data is usually unsatisfactory due to limits of measuring instruments, and data reconciliation can be applied to improve the accuracy of these measurements. Traditionally, balance constraints of steam turbines are mostly considered in data reconciliation, and results of previous studies illustrate that there is still potential for further improvement. In this work, we present a generalized data reconciliation approach with both balance and characteristic constraints for estimation of wet steam parameters in steam turbines, with case studies on a real-life 1000 MW coal-fired power plant. Results show that uncertainty reduction is enhanced for all measurements. Better estimates of exhaust steam enthalpy and steam wetness fraction can be therefore obtained after data reconciliation.

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1. Introduction

Wetness fraction of exhaust steam from low pressure cylinders (LPC) is an important parameter closely related to the economy and safety of steam turbines (Wang et al., 2002), because the occurrence of condensation phenomena in wet steam two-phase flow would reduce the steam turbine efficiency, result in corrosion damage of turbine blades, and threaten the power unit safety (Li et al., 2012). However, on-line measurement of the steam wetness fraction of the LPC has been a difficult task for a long time (Xu and Yuan, 2015), therefore many methods have been investigated to determine the steam wetness fraction, such as numerical simulation (Sun et al., 2015; Du et al., 2013), artificial neural network (Wang and Song, 2012), and steam turbine modeling (Xu and Yuan, 2015; Zhang et al., 2007).

Accuracy of measurement data is essential to the effect of these methods and estimates of steam wetness fraction. However, accuracy of on-line measured data is usually unsatisfactory due to measurement errors and uncertainty of measuring instruments (Jiang et al., 2014a). Consequently, data preprocessing techniques aiming at reducing uncertainty of measurements and unmeasured parameters are of great interest to steam turbines. Data reconciliation is a technique explicitly making use of system constraints and redundant measured data to obtain better estimates of system parameters and reduce the effect of random errors (Narasimhan and Jordache, 1999). It adjusts system measurements according to their uncertainties to satisfy the constraint equations of system, and provides better estimates of parameters without measurement.

Since 1960s, a number of studies have been conducted on theories and applications of data reconciliation (Kuehn and Davidson, 1961), and up to now this method has become an important data processing technique with wide applications in industry, including chemical reaction process (Prata et al., 2009; Zhang and Chen, 2014; Srinivasan et al., 2015; Zhang and Chen, 2015; Özyurt and Pike, 2004), mineral and metal processing (Vasebi et al., 2012a; Vasebi et al., 2012b; Vasebi et al., 2014), refinery plants (Zhang et al., 2001), absorption refrigeration system (Martínez-Maradiaga et al., 2013), recycle system (Miao et al., 2011), and so on.

Besides, data reconciliation has also been applied to power plants, including nuclear power plant (Langenstein, 2006; Valdetaro and Schirru, 2011), gas turbine power plant (Chen and Andersen, 2005; Martini et al., 2013), combined cycle plants (Gülen and Smith, 2009), and steam turbine power plants. Fuchs (2002) studied the data validation method to increase the accuracy of calculated steam turbine exhausting steam enthalpy and heat rate on the basis of acceptance tests and simulation data. Zhou et al.

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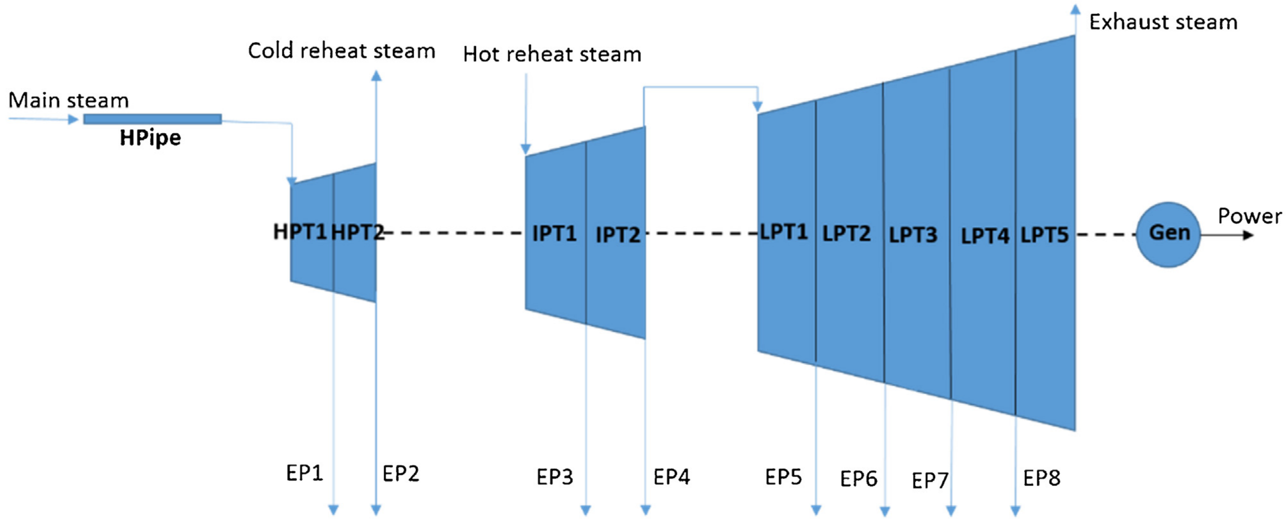

Fig. 1. An illustration of the steam turbine system of a 1000 MW coal-fired power plant.

(2012) provided accurate parameter estimates for the spraying water system in a coal-fired power plant by developing a simultaneous data reconciliation and gross error detection method. Jiang et al. (2014d) applied the data reconciliation approach to reduce the uncertainty of primary flow measurements and heat rate of steam turbine, and presented a serial elimination strategy to detect gross errors in measured data (Jiang et al., 2014a). Besides, a mathematical method based on data reconciliation to evaluate the minimum isolable magnitude for a gross error to be isolated from another with a required probability for steam turbine power plants was put forward by Jiang et al. (2014c). Guo et al. (2016a) presented an overall thermal system approach for better results of data reconciliation for steam turbine power plants, and proposed an inequality constrained nonlinear data reconciliation approach to correct the expansion curve of steam turbine and obtain better estimates of isentropic efficiencies (Guo et al., 2016b).

In most previous studies, balance constraint equations of steam turbines are usually considered in a data reconciliation problem. Characteristic constraint equations are additionally conditional equations in the so called generalized data reconciliation (Szega, 2009). Introduction of characteristic constraints helps to improve redundancy of the system, thus improving the effect of uncertainty reduction by data reconciliation. In reconciliation of measurements in thermal power unit, these characteristic constraints can include equations of steam flow capacity in turbine and its internal efficiency, the equation of pressure drop in pipelines and heat flow in regenerative heat exchangers (Szega and Nowak, 2013). Jiang et al. (2014b) applied characteristic constraints of pipelines as well as heat exchangers, and proposed a data reconciliation approach for integrated sensor and equipment performance monitoring for steam turbine power plants. Badyda (2014) introduced characteristic constraints of steam turbine and applied data reconciliation to correct the measured steam mass flows, close the mass balance and converge the calculated capacity to the measured generated electric capacity. Szega and Nowak, (2013) used additional equations of conditions in the generalized method of data reconciliation for optimization of measurement placement in redundant measurement system in power units.

For the abovementioned studies, applications of characteristic constraints in data reconciliation are carried out with simulation data, while the application and validation in a real-life power plant using on-line operational data are rather insufficient. Besides, applications of the generalized data reconciliation considering characteristic constraints to the estimation of wet steam parameters of LPC, such as steam wetness fraction are quite limited to the author's knowledge.

Therefore in this work, we introduce characteristic constraints as well as balance constraints of steam turbines in data reconciliation and apply to the steam turbine system of a real-life 1000 MW ultra-supercritical coal-fired steam turbine power plant by using design data as well as on-line operational measured data. Two case scenarios are constructed respectively (Case A and Case B). In Case A, data reconciliation are carried out with design values at different loads (100%, 70%, 50% and 40%) to theoretically investigate the effect of generalized data reconciliation considering characteristic constraints of steam turbines. In Case B, data reconciliation is carried out with 551 groups of operational measured datasets in steady state in a real-life power plant. Firstly, we describe the steam turbine system and methodology of the generalized data reconciliation method. Secondly, uncertainty reduction results of measurements in two cases are presented and discussed. Finally, we evaluate and analyze the estimates of exhaust steam enthalpy and steam wetness fraction for LPC after data reconciliation.

2. System description

2.1. System configuration

An illustration of the steam turbine system of a 1000 MW coal-fired ultra-supercritical power plant is shown in Fig. 1.

In this study, a steam turbine consists of a high pressure cylinder (HPT1 and HPT2), an intermediate pressure cylinder (IPT1 and IPT2) and two low pressure cylinders (LPT1, LPT2, LPT3, LPT4 and LPT5). Turbine stages are determined by eight extraction steam flows (EP1, EP2, EP3, EP4, EP5, EP6, EP7, and EP8), and extraction steam flows are used to heat feed water. Main steam from the boiler enters the steam turbine through high pressure steam pipes (HPipe) and expands in turbine stages to generate power. Eventually, exhaust steam from the final turbine stage of LPC is condensed in a condenser.

2.2. Measured parameters and measurement uncertainty

A list of measured parameters in the system and their corresponding descriptions are shown in Table 1. Pressure, temperature, and flow rates are measured in the system.

Since we only focus on the steam turbine system in Fig. 1 in this work, the mass flow rates of eight extraction steam flows are

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