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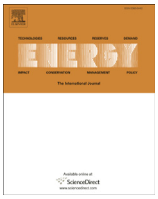

Inequality constrained nonlinear data reconciliation of a steam turbine power plant for enhanced parameter estimation

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ABSTRACT

Measurement errors inevitably exist amongst on-line measured data in steam turbine power plants. Problematic steam turbine isentropic efficiencies and turbine expansion curves are therefore obtained in the existence of measurement errors. Data reconciliation is widely used for uncertainty reduction of measurements and parameter estimation. Inequality constraints or bounds are rather necessary in some cases to adjust parameter estimates to be physically meaningful. In this work, we apply an inequality constrained nonlinear data reconciliation approach to the thermal system of a power plant, and compare its effect with equality constrained approaches. Case studies using performance test data and operational measurement data of a real-life 1000 MW steam turbine power plant are provided. The necessity and difference brought by inequality constraints are also discussed. Corrected expansion curve with reasonable enthalpy–entropy relationships and better estimates of isentropic efficiencies are obtained after implementation of inequality constraints. Results show that uncertainties of most measured parameters are reduced by 30–80 percent, and uncertainty of the calculated exhaust steam enthalpy is reduced by 22 percent.

1. Introduction

Steam turbine performance is essential to heat efficiency and reliability of power plants. Performance monitoring and fault diagnosis are widely used to enhance the performance of power plants [1–6]. For performance monitoring purposes, turbine expansion curve and stage isentropic efficiencies are usually calculated and analyzed [7]. Problematic results can be obtained using on-line measured data in the existence of measurement errors. Besides, the effect of performance monitoring methods also strongly depends on the accuracy of on-line measured data [8]. However, due to harsh working conditions and limited measurement instruments, accuracy of measured data is usually non satisfactory and measurement error inevitably exists. Therefore, studies aiming at improving accuracy of measured data are essential to performance monitoring of power plants [9].

In power plant thermal system, parameters are related to each other through physical constraints such as material or energy balances. Given a set of such system constraints, a minimum number of error-free measurements is required in order to calculate all the system parameters and variables [10]. If there are more measurements available than the minimum number during the on-line measuring process, *i.e.*, the system is overdetermined, thus spatial redundancy exists in the measurements. A data processing technique named data reconciliation makes use of process model constraints and obtains estimates of process variables by adjusting process measurements so that the estimates satisfy the constraints, assuming sufficient measurements exist [10]. It can also be used for gross error detection and identification together with statistic test methods [11]. Another type of redundancy is temporal redundancy, which is beyond the topic of this work.

It is common in industries that there are insufficient and incorrect measurements. Inaccurate measurements have negative impact on the accuracy of reconciled results after data reconciliation. Furthermore, if there are insufficient measurements, and fewer variables are measured than necessary to determine the system, no correction to erroneous measurements is possible via data reconciliation. In this underdetermined system, the values of some variables can be estimated only through other means unless additional measurements are provided.

Numerous studies have been developed on theories and applications of data reconciliation, and this technique has been widely

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used in industries, such as chemical and process industries [12–16]. In the power plant industry, data reconciliation has been conducted on nuclear [17–19], gas turbine or combined cycle plants [20–22] and steam turbine power plants [23–30] in previous studies. These researches have shown the ability and potential of data reconciliation for accuracy improvement and gross error detection of measured data.

In the abovementioned studies, equality constrained equations are mostly introduced and applied in a data reconciliation problem. However, in some cases equality constraints cannot satisfy the demands and it is necessary to impose inequality constraints or bounds on the variables. For example, when reconciling flows and temperatures in heat exchanger networks, it is possible that the estimates violate thermodynamic feasibility, such as temperature estimate of the hot stream being lower than the corresponding cold stream temperature estimate [10]. In order to combat this, inequality constraints should be imposed to adjust parameter estimates to be physically meaningful.

Early in 1990s, theories and methods had been proposed for inequality constrained data reconciliation [31,32]. Solution techniques for this problem were also developed, including general purpose nonlinear optimization technique, sequential quadratic programming method, generalized reduced gradient method [10] and so on. Based on these achievements, applications of inequality constrained data reconciliation are performed in many studies, as follows. Kadu et al. [33] applied a modified unscented recursive nonlinear dynamic data reconciliation approach for solving large scale state estimation problems. Prata et al. [34] developed the simultaneous robust data reconciliation and gross error detection through particle swarm optimization for an industrial polypropylene reactor. Miao et al. [35] studied simultaneous data reconciliation, joint bias and leak estimation based on support vector regression for a linear recycle system and a nonlinear heat-exchange network. Zhang et al. [15] studied the correntropy based data reconciliation and gross error detection for nonlinear dynamic chemical processes. Bounds or inequality constraints of reconciled parameters were taken into consideration in these studies.

Amongst the abovementioned studies, few researches investigate the necessity of the implementation of inequality constraints, and the difference brought by them compared with equality constraints. It is not always necessary to introduce inequality constraints because of the improved complexity and large amount of calculation. Therefore, the balance between introducing more inequality constraints and the increased complexity should be carefully considered.

Furthermore, applications of the inequality constrained data reconciliation to steam turbine power plants are quite limited, especially using the real-life measurement data from power plants. In a steam turbine power plant, problematic steam turbine isentropic efficiencies and turbine expansion curves are rather frequently obtained due to the existence of measurement errors amongst on-line measured data. These less accurate estimates of parameters have negative effects on the reliability of performance monitoring and fault diagnostic systems. Given the fact that accuracy of measurement equipment is difficult to improve once installed within a thermal system, it is necessary to apply the inequality constrained data reconciliation in these circumstances by imposing inequality constraints to the problematic variables based on steam expansion physics. However, research and application concerning this topic are rather insufficient in previous studies.

Therefore, in this work we present an inequality constrained nonlinear data reconciliation framework and provide case studies on a real-life 1000 MW ultra-supercritical coal-fired steam turbine power plant with performance test data and operational measurement data. A comparison of this inequality constrained approach with equality constrained approach is presented, together with discussions on the difference brought by the

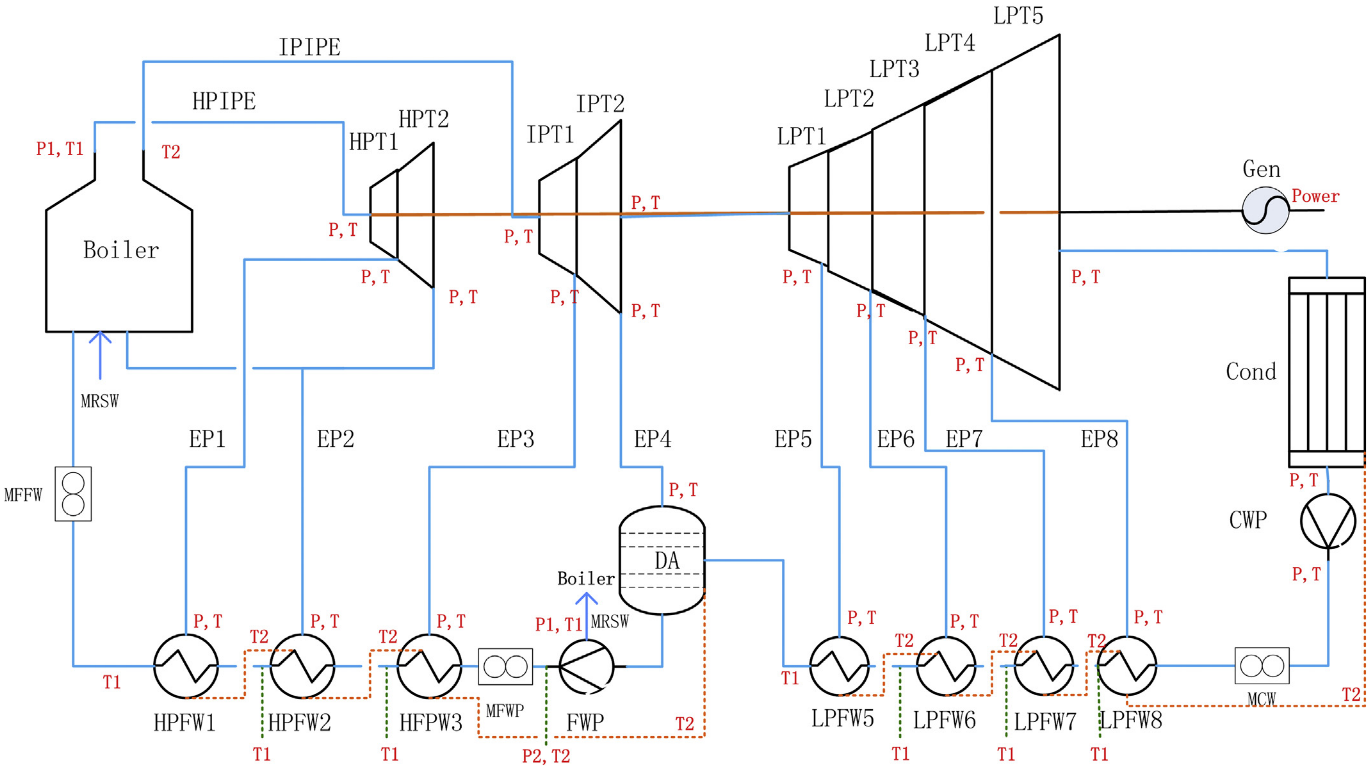

Fig. 1. An illustration of the thermal system of a coal-fired steam turbine power generation unit.