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Operation Data Based Modelling and Performance Monitoring of Steam Turbine Regenerative System under Full Working Conditions

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Mathematical modelling of steam turbines regenerative system usually depends on design geometry and characteristics, which may change over long-term operation due to degradation of the system. Performance monitoring based on such models may therefore become less accurate over time. In this paper, we propose an operation data based modelling approach to mathematical modelling and performance monitoring of the system. Operation data are firstly collected over a certain operation period, covering full working conditions. Dominant factor sub-models are then developed for key components of the steam turbine regenerative system to present the performance characteristics, including the heater, turbine stage and pump. The model can then be used for online performance monitoring of the system. This approach enables the possibility of continuous updating the mathematical model of the system for performance monitoring purposes. Finally, a case study is presented, where the proposed method is applied on a 330 MW power plant in Shanxi, China.

1. Introduction

Based on the benefit of reduction of coal combustion in the power plant, the performance monitoring (EPRI, 1984) of key components of the plant is much more essential nowadays, for the purpose of guiding the unit working in a safe and high efficient condition.

Since 1993 ASME published the performance test codes for steam turbines, the performance monitoring methods and techniques have been developed based on the mathematical model of the mechanism (ASME, 1993), and several monitoring software platforms have been made, such as the Turabs system (Johansen, 2004) of Dong energy company in Denmark, the Ebsilon system (Brinkmann and Pawellek, 2003) of Steag company in Germany. The basic idea for performance monitoring is firstly building the mathematical models of the components and the system, then calculating the norm values of the monitored parameters based on the boundary input. And the monitoring is finished by the comparison between the norm value and the measured value, and the deviation would be the foundation to judge whether the components and the system operate normally.

There are mainly two kinds of models for the components and system of thermal power plants: the data-driven model and the mechanical model. Liu et al. (2013) presented an improved probability of support vector regression (PSVR) method for the monitoring condition of the nuclear power plant, and it can be efficiently used for the short-term forecast of the controlled parameters. Hsu et al. (2011) developed a figure based on adaptive prediction and extracted the Non-Gaussian information for the monitoring of the Non-Gaussian process and detection of the slight movement of the performance to improve the capacity of the fault detection in thermal power plants. The researches based on the mechanical model include: Chaibakhsh et al. (2008) who developed a nonlinear mathematical model of steam turbine based on the energy balance and the semi-empirical formula, and the online data is adjusted by the semi-empirical formula and genetic algorithm to obtain the remaining parameters and models. Saari et al. (2014) provided a single heat exchanger model based on effectiveness-number of heat transfer units ($\varepsilon - \mathrm{NTU}$) calculation, and the experimental correction index is used to reduce the gross to obtain a more accurate condenser model under low pressure and temperature. Li et al. (2010) developed a mathematical model to calculate the norm value of the heater's end

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deviation, through the analysis of the structure and the process of the heat exchanger, and the model was tested with the thermodynamic experiment data. For the two kinds of models above, the data-driven model is good at obtaining the solution close to the measurements, instead of the description of components' physical characteristics. On the contrary, the mechanical model focuses on physics but lack of operation data's authentication, and normally the model is not precise enough.

For the modelling and monitoring of the steam turbine in the power plant, nowadays the study mainly focuses on specific operating conditions and system. Modesto et al. (2016) has proposed the potential to increase electricity generation with backpressure steam turbine and condensing steam turbine in sugarcane cogeneration plants, and also a cogeneration plant based on a BIGCC (Biomass Integrated Gasification Combined Cycle). Wu et al. (2015) have proposed the method to select the drivers for pumps and compressors in steam turbine and electric motor, in which the steam turbine is identified to be favorable in the driving system when the environmental impacts are mainly considered. Ahmadpour et al. (2017) have proposed the method to increase the performance of thermo-compressors and steam turbines by volumetric cooling and inlet superheating, which focuses on the performance change from the inner system of the steam turbine.

In order to combine the advantages of both the data-driven and mechanical modelling method, this paper proposes the dominant factor modelling method (Yang, 2005) and apply it into the steam turbine regenerative system. Instead of only study on specific operating conditions, the method is used to build the full working conditions' model of the steam turbine. With the using of real-time operating data of the power plant, the components' mathematical models have been built, which will be more precise. And the models are then used for the performance monitoring, which is realized through the comparison between the measured value and the norm value, calculated with the dominant factor model. The data-driven modelling method enables the possibility of continuous updating of the model, which can ensure a higher accuracy of the performance monitoring.

2. System description and dominant factor model

This paper focuses on the steam turbine regenerative system, which usually includes several parts: heater, turbine stage and pump. Figure 1 represents the system used for the case study.

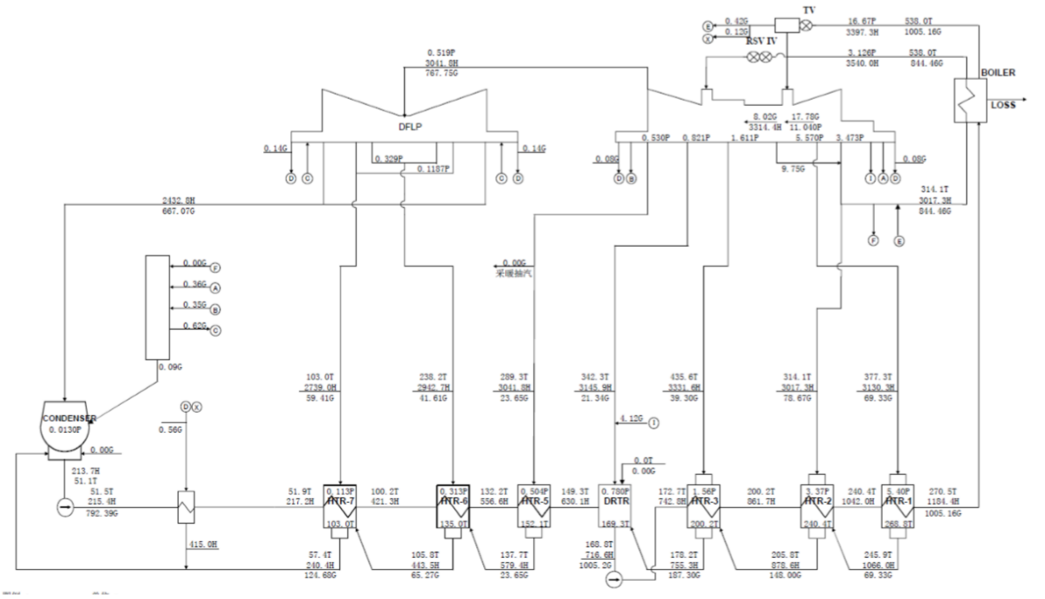

Figure 1: The steam turbine regenerative system for case study, Tongda power unit, Shanxi

For the dominant factor modelling of the components and the system, the characteristic parameters are chosen to represent the operation performance through the mechanical analysis of the components. Then the dominant factors related to the characteristic parameters are determined and the model is finished by the building of the relationship between the dominant factors and the characteristic parameters. For example, for feed water heater the heat exchange coefficient KA is chosen to represent the heat exchange characteristic, the flow rate of feed water m is determined to have the dominant impact on the change of KA through the analysis of the heat exchanger's structure and working mechanism. So as a dominant factor, the relationship between heat exchange coefficient KA and the flow rate of feed water m is found by fitting the curve (Figure 2). Then the dominant factor model can be used for monitoring.

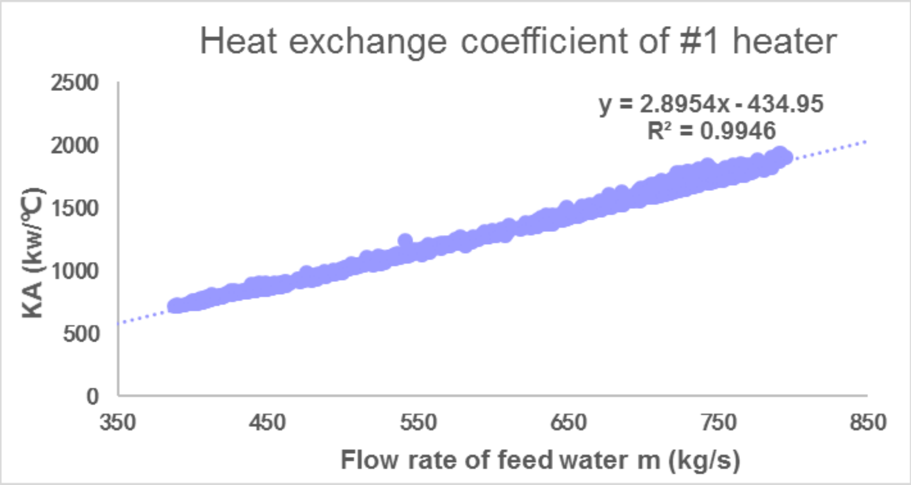

Figure 2: Linear relationship between heat exchange coefficient and the flow rate of feed water

The Figure 3 shows the process of modelling and monitoring. First the online operation data is collected for the modelling. Once the precise model is obtained, i.e. characteristic parameters of components can be represented by the dominant factor, the model can then be used for the calculation of the norm value of the components. Through the comparison between the measurements and the calculation, the operation condition can be judged from the deviation, which means the monitoring can be finished.

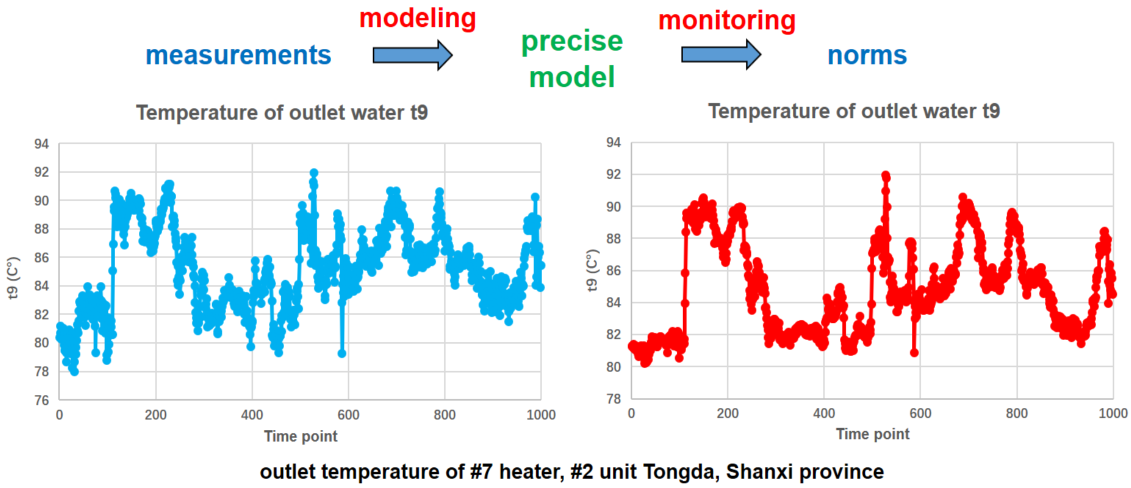

Figure 3: Process of dominant factor method modelling and monitoring

3. Case study and results

The modelling approach has been applied to a 330 MW coal combustion power plant in Shanxi, China, and the steam turbine regenerative system is presented in Figure 1, including 8 stages of steam turbine, 7 steam turbine extractions, 6 heaters and 2 feed water pumps. The components model is firstly built, including the steam stage, the heater and the feed water pump. For the data based modelling method, the measurements include temperature measurements and pressure measurements as follows, which can be directly obtained from the data-base of the power plant.

Firstly, the basic calculations are finished to obtain the characteristic parameters, such as the efficiency and heat exchange coefficient. The calculation is based on the ASME standard, for example, the mass and energy balances of the high-pressure heaters and deaerator are solved with linear equations. And the dominant factor models can be built after the characteristic parameters are determined. Table 1 is the measured variables related to the heater.

Table 1: Measured variables

Variables	Description	Variables	Description
m	Condensing water flow rate	P_w	Pressure of main feed water
T	Temperature of main steam	t2i	Temperature of i^{th} heater's inlet steam
P	Pressure of main steam	t9i	Temperature of i^{th} heater's outlet water
T_re	Temperature of reheat steam	t5i	Temperature of i^{th} heater's drain water
P_re	Pressure of reheat steam	p_b	Back pressure of condenser
t_i_ex	Temperature of i^{th} extraction steam	Pw	Power
p_i_ex	Pressure of i^{th} extraction steam		

3.1 Dominant factor modelling

For the heater, the model establishes the relationship between the heat exchange coefficient KA and the mass flow rate of the feed water m as introduced in section 2. Through the analysis of the structure of the heater, the shell and tube type with superheating, condensing and drain cooling zones, a two-stage model of the heater is introduced. One part is for the heat exchange of superheating and condensing, another is the drain cooling part, and the characteristic can be represented using the following formula:

$$kA = a * m + b \tag{1}$$

Where a and b are the characteristic coefficients, which can be determined by the fitting curve as shown in Figure 4. The linear relationship presenting the heater's characteristics is shown as follows:

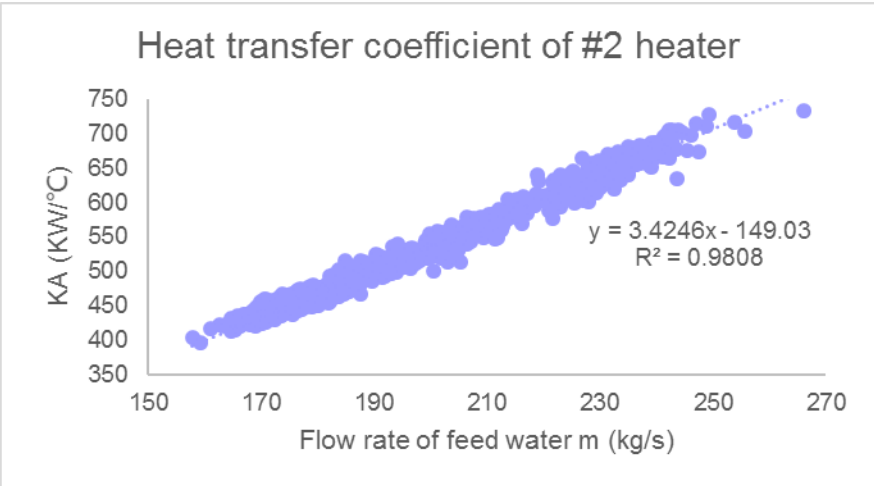

Figure 4: The heat exchange characteristic of heater

For steam turbine stages, the study focuses on the through-flow and efficiency characteristics. To describe the through-flow capacity of the stages, the Flugel equation is introduced, and Flugel parameter is formulated as

$$flu = \frac{G\sqrt{T}}{\sqrt{p_i^2 - p_o^2}} \tag{2}$$

Where G is the mass flow rate, T is the inlet temperature of the stage, p_i and p_o are the inlet and outlet pressure of the stage.

Through the analysis and the fitting curve of Figure 5, the linear relationship between the Flugel parameter and the corrected mass flow rate $\frac{G\sqrt{T_i^2}}{p_o^2}$ is found.

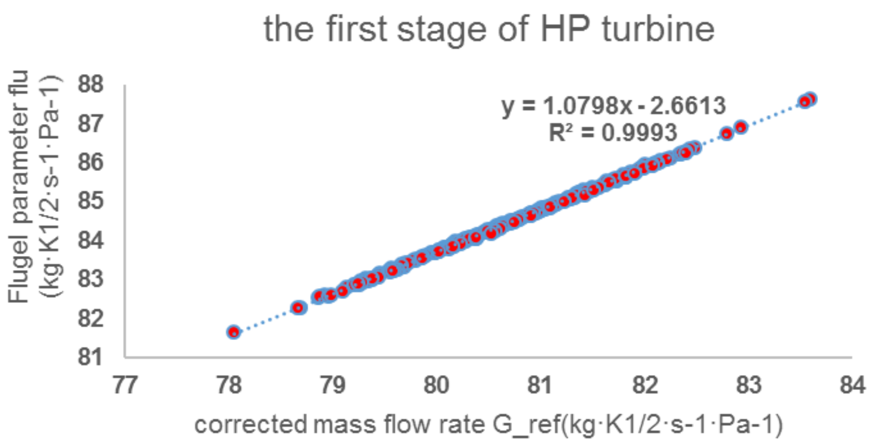

Figure 5: The linear relationship between Flugel parameter and corrected mass flow rate of turbine stage

For efficiency characteristics, the relative internal efficiency can be represented by the dominant factor pressure ratio (pr) and corrected mass flow rate ($gref$):

$$Eff = f(pr, gref) \tag{3}$$

The same with the feed water pump, the performance characteristics can be represented by the pressure rise and the adiabatic efficiency, which can be formulated as follows:

$$\Delta p = f(G, n) \qquad \eta = f(G, n) \tag{4}$$

Where Δp is the pressure rise, η is the adiabatic efficiency, and n is the rotation speed.

After the modelling of the components, the dominant factor model obtained can be used for monitoring.

3.2 Performance monitoring

In this part, the process of performance monitoring of a heater is taken as an example. With the inlet parameters of the heater, such as the temperature and the pressure of the inlet extraction steam and feed water, the outlet parameters can be calculated with the dominant factor models. With Function (1), the heater's characteristic, the heat exchange coefficient can be calculated with inlet feed water. Then solving with the mass and energy balance equation, the outlet parameters are found which include the temperature and pressure of outlet water and drain water of the heater, i.e. the norm value of the heater's outlet parameter. For the monitoring part, the norm values of the components are compared with the measured values to determine whether the components operate normally. The monitoring of the outlet temperature of feed water and exhaust pressure of 1st stage of intermediate pressure turbine is shown in Figure 6, among which the blue points are measurement values and the red points are norm values calculated by models. Then the deviation of the measurement and the norm can be calculated, and through the analysis of the deviation, a maximum deviation can be determined as criteria to judge the components' operation. If the deviation exceeds the maximum deviation, then the outlet parameter is not suitable, and this situation indicates that the component operates abnormally and the performance has changed.

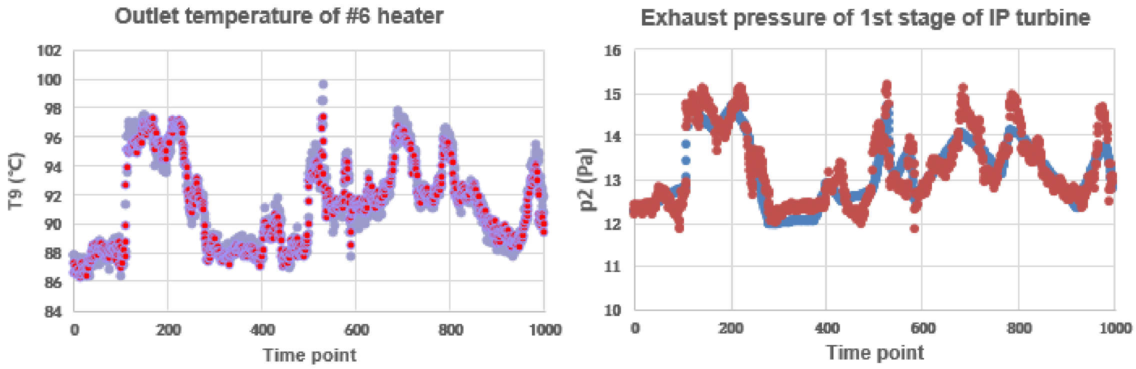

Figure 6: Monitoring of the outlet temperature of feed water and exhaust pressure of 1st stage of intermediate pressure turbine

4. Conclusion

This paper proposes a data based dominant factor modelling method of a steam turbine regenerative system, enabling the continuous updating of the model with the online operation data, which can be used for performance monitoring of power plants.

Firstly, the operation data is collected and the mass and energy balances of the system are calculated to obtain the characteristic parameters of the components, which are considered to represent the operation performances of the components in the system, such as the heat exchange coefficient for heaters and efficiency for stages. Then through the analysis of the structures and operation mechanisms of the components, the dominant factors related to the characteristic parameters are determined, and the relationships between characteristic parameters and dominant factors are found out to finally determine the dominant factor models.

Furthermore, the dominant factor models are used in the monitoring of the system, which can calculate the norm values of components' outlet with the inlet measurements, such as the temperature of the heater's outlet water, pressure of the extraction steam of the stages. And the comparison between the outlet measurement values and the norm values can be used to judge whether the components operate at a normal situation. The deviations can be presented in real-time to monitor the performance change of the components.

Through the case study of the modelling and monitoring process of a real power plant in Shanxi, China, the method proposed in this paper is proved to be useful and applicable in practice. At present the modelling and monitoring method has already been used in the power plant in Shanxi, and also a 1,000 MW power plant in Shandong, China. A real-time operation monitoring platform is built to propose the method and results on-site, which can effectively guide the operation in the power plant.

Acknowledgments

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