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Process Performance Monitoring and Degradation Analysis

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1. Introduction

The global power sector is facing a number of issues, but the most fundamental challenge is meeting the rapidly growing demand for energy services in a sustainable way. This challenge is further compounded by the today's volatile market - rising fuel costs, increased environmental regulations, etc. Plant owners are challenged to prepare for the impact of future fuel price increases and carbon taxes and consider the value of environmental stewardship. The increasing competition in the electricity sector has also had significant implications for plant operation, which requires thinking in strategic and technical ways at the same time.

Management focus in the past decade has been on reducing forced outage rates, with less attention paid to thermal performance. Energy-intensive facilities seeking to maximize plant performance and profitability recognize the critical importance of performance monitoring and optimization to their survival in a competitive world. It means getting more out of their machinery and facilities. This can be accomplished through effective heat rate monitoring and maintenance activities. At present, it becomes necessary to find an uncomplicated solution assisting thermal performance engineers in identifying and investigating the cause of megawatt (MW) losses as well as in proposing new ways to increase MW output.

In this field of research and engineering, traditional system performance test codes [1] conduct procedures for acceptance testing based on the fundamental principles of the First Law of Thermodynamics. Many scholars have devoted to exergy-based research for the thermoeconomic diagnosis of energy utility systems [2-8], that is, those approaches based on the Second Law of Thermodynamics. In addition, some artificial intelligence model based methods [9-11] are also investigated for the online performance monitoring of power plant. However, some shortcomings also exist for the three kinds of methodologies. As is well known, performance test codes need sufficient test conditions to be fulfilled. It is difficult for continuous online monitoring condition to satisfy such rigorous requirements. Many artificial intelligence based methods may work well on data extensive conditions, but can't explain the results explicitly. Exergy analysis is very valuable in locating the irreversibilities inside the processes, nevertheless it needs to be popularized among engineers.

In this chapter, a novel method is presented, which is deduced from the First Law of Thermodynamics and is very clear and comprehensible for maintenance engineers and operators to understand and make use of. It can also sufficiently complement test codes. The novelty mainly lies in as followings: first, the primary steam flow is calculated indirectly by existing plant measurements from system balance to alleviate test instrument installation and maintenance cost compared with standard procedure. Furthermore, the measurement error can be avoided instead of direct use of plant instrumentation for indication. Second, the degradation analysis technique proposed comes from the First Law of Thermodynamics and general system theory. It is very comprehensible for engineers to perform analysis calculation combining system topology that they are familiar with. Moreover, the calculated results from parameters deviation have traced the influences along the system structure beyond the traditional component balance calculation. Third, the matrix expression and vectors-based rules are fit for computer-based calculation and operation decision support.

2. Foundations for the new analysis method

In nature, the thermal system of a power unit is a non-linear, multi-variable and time-variant system. For the system performance analysis and process monitoring, two aspects are especially important.

First, process performance monitoring requires instrumentation of appropriate repeatability and accuracy to provide test measurements necessary to determine total plant performance indices. Available measurements set must be selected carefully for the proper expression of system inner characteristics. The benefits afforded by online performance monitoring are not obtained without careful selection of instrumentation. Moreover, calculated results are rarely measured directly. Instead, more basic parameters, such as temperature and pressure, are either measured or assigned and the required result is calculated as a function of these parameters. Errors in measurements and data acquisition are propagated into the uncertainty of the resulting answer. Measurement error should be considered combining with engineering availability and system feature itself.

Second, it's hardly possible to solve the hybrid dynamic equations consisting of fluid mechanics and heat transfer for a practical large physical system. From the point of view of system analysis [12], one nature system should be characterized by how many inputs and outputs they have, such as MISO (Multiple Inputs, Single Output) or MIMO (Multiple Inputs, Multiple Outputs), or by certain properties, such as linear or non-linear, time-invariant or time-variant, etc.

The following subsection briefly discusses two fundamental theories, which are employed to cope with issues mentioned above and support the new monitoring and analysis approach proposed in the chapter.

2.1 Measurement error and error propagation

2.1.1 General principles of error theory

Every measurement has error, which results in a difference between the measured value, X , and the true value. The difference between the measured value and the true value is the total error, δ . Total error consists of two components: random error ε and systematic error β . Systematic error is the portion of the total error that remains constant in repeated measurements throughout the conduct of a test. The total systematic error in a measurement is usually the sum of the contributions of several elemental systematic errors, which may arise from imperfect calibration corrections, measurement methods, data reduction techniques, etc. Random error is the portion of the total error that varies randomly in repeated measurements throughout the conduct of a test. The total random error in a measurement is usually the sum of the contributions of several elemental random error sources, which may arise from uncontrolled test conditions and nonrepeatabilities in the measurement system, measurement methods, environmental conditions, data reduction techniques, etc. In other words, if the nature of an elemental error is fixed over the duration of the defined measurement process, then the error contributes to the systematic uncertainty. If the error source tends to cause scatter in repeated observations of the defined measurement process, then the source contributes to the random uncertainty.

As far as error propagation is concerned, for a MISO system, $Y=f(X_1,X_2,\cdots,X_n)$, the effect of the propagation can be approximated by the Taylor series method. If we expand $f(X_1,X_2,\cdots,X_n)$ through a Taylor series in the neighborhood of $\mu_{X_1},\mu_{X2},\cdots,\mu_{X_n}$, we get

$$f(X_1,X_2,\cdots,X_n)=f(\mu_{X_1},\mu_{X_2},\cdots,\mu_{X_n})+\theta_{X_1}(X_1-\mu_{X_1})+\theta_{X_2}(X_2-\mu_{X_2}),\cdots,$$

$$+\theta_{X_n}(X_n-\mu_{X_n}) + \text{higher order terms} \tag{2.1}$$

Where θ_{X_i} are the sensitivity coefficients given by $\theta_{X_i}=\dfrac{\partial Y}{\partial X_i}$. Now, suppose that the arguments of the function $f(X_1,X_2,\cdots,X_n)$ are the random variables $X_1,X_2,\cdots,X_n$, which are all independent. Furthermore, assume that the higher order terms in the Taylor series expansion for $f(X_1,X_2,\cdots,X_n)$ are negligible compared to the first order terms. Then in the neighborhood of $\mu_{X_1},\mu_{X_2},\cdots,\mu_{X_n}$ we have

$$f(X_1,X_2,\cdots,X_n)=f(\mu_{X_1},\mu_{X_2},\cdots,\mu_{X_n})+\theta_{X_1}(X_1-\mu_{X_1})+\theta_{X_2}(X_2-\mu_{X_2}),\cdots,+\theta_{X_n}(X_n-\mu_{X_n}) \tag{2.2}$$

then,

$$\mu_Y=E(Y)\approx f(\mu_{X_1},\mu_{X_2},\cdots,\mu_{X_n}) \qquad \sigma_Y^2\approx\sum_{i=1}^{n}\theta_{X_i}^2\sigma_{X_i}^2$$

In the same way, the total variance associated with a measured variable, X_i, can be expressed as a combination of the variance associated with a fixed component and the variance associated with a random component of the total error in the measurement, that is,

$$\delta=\beta+\varepsilon \tag{2.3}$$

Assuming fixed errors to be independent of random errors and no correlation among the random errors, then the general form of the expression for determining the combined standard uncertainty of a result is the root-sum-square of both the systematic and the random standard uncertainty of the result. The following simple expression for the combined standard uncertainty of a result applies in many cases:

$$\sigma_Y^2=\sum_{i=1}^{n}\theta_{X_i}^2\sigma_{\varepsilon_i}^2+\sum_{i=1}^{n}\theta_{X_i}^2\sigma_{\beta_i}^2 \tag{2.4}$$

The general error propagation rules indicated in (2.4) shows clearly that both systematic error and random error is propagated to the calculated results, approximately proportioning to the partial derivative of each variable. However, θ is determined by system model and the role of the variable in the model. Thus, variables choice becomes one of key steps to control calculation uncertainty.

2.1.2 Characteristics of thermal system measurements

System performance index is calculated as a function of the measured variables and assigned parameters. The instrumentation employed to measure a variable have different required type, accuracy, redundancy, and handling depending upon the use of the measured variable and depending on how the measured variable affects the final result. For example, the standard test procedure requires very accurate determination of primary flow to the turbine. Those are used in calculations of test results are considered primary variables. However, the rigorous requirements make this type of element very expensive. This expense is easy to justify for acceptance testing or for an effective performance testing program, but is unaffordable for online routine monitoring.

In normal operation and monitoring, the primary flow element located in the condensate line is used for flow indication, which is the least accurate and is only installed to allow plant operators to know approximate flow rate. As is well known, fouling issues are the main difficulties for the site instrumentation. Remember that a 1% error in the primary flow to the turbine causes a 1% error in calculated turbine heat rate, that is, 100% error

Variables	Measurement Variation	Heat rate Deviation
Main steam temperature	1°F	+0.07%
Reheated steam (cold) temperature	1°F	-0.04%
Reheated steam (hot) temperature	1°F	+0.05%
Final feedwater temperature	1°F	+0.03~+0.04%
Condensate water temperature (deaerator inlet)	1°F	-0.01~-0.03%
Feedwater temperature (final high pressure heater inlet)	1°F	+0.02~0.04%
Feedwater temperature (first high pressure heater inlet)	1°F	-0.05~0.08%
Main steam pressure	1%	+0.02~0.04%
Reheated steam (cold) pressure	1%	-0.05~-0.08
Reheated steam (hot) pressure	1%	+0.08%
Leakage of High Pressure Cylinder gland steam [a]	1%	-0.0013%
Leakage of Intermediate Pressure Cylinder gland steam [a]	1%	-0.002%
Primary condensate flow[b]	1%	+1%
Power	1%	-1%

Note: a. The leakage quantity is compared with its rated value itself.
b. For comparing, the primary condensate flow is also included.

Table 1. The effect on heat rate uncertainty of variables measurements

propagation. It means the primary flow from existing plant instrument is no longer competent to fulfill the system performance calculation. Selecting new measurements set becomes an imperative for the function.
Fortunately, with the improvement of I&C technology and modernization of power plants, these auxiliary water/steam flow instruments are installed and well maintained, such as secondary flow elements, blow down, drain water, etc. The more existing plant instruments are employed to construct system state equation that lays the foundation for the new methodology proposed in the chapter.
Now, let's focus on the error propagation of these calculation-related measurements. Tab.1 shows the uncertainty propagation of some measurements from a typical larger subcritical power unit. It is revealed that the effect of auxiliary water/steam flow is insignificant compared with these primary variables. On the other hand, most small diameter lines have low choked flow limits; therefore, the maximum flow scenario most likely has a small effect on heat rate.
In a word, a larger measurements set (here, refers to employing more existing plant instrument measurements) and their low uncertainty propagation property are the foundation of system-state-equation-based process performance calculation and system analysis.

2.2 State space modeling
2.2.1 State space model
The state space model of a continuous-time dynamic system can be derived from the system model given in the time domain by a differential equation representation. Consider a general n*th*-order model of a dynamic system represented by an n*th*-order differential equation:

$$\frac{d^n y(t)}{dt^n} + a_{n-1}\frac{d^{n-1}y(t)}{dt^{n-1}} + \cdots + a_1\frac{dy(t)}{dt} + a_0 y(t) = b_n\frac{d^n u(t)}{dt^n} + b_{n-1}\frac{d^{n-1}u(t)}{dt^{n-1}} \cdots + b_1\frac{du(t)}{dt} + b_0 u(t)$$

For simplicity, it is presented for the case when no derivatives with respect to the input, that is:

$$\frac{d^n y(t)}{dt^n} + a_{n-1}\frac{d^{n-1}y(t)}{dt^{n-1}} + \cdots + a_1\frac{dy(t)}{dt} + a_0 y(t) = u(t) \tag{2.5}$$

Then, if the output derivatives are defined as:

$$\begin{aligned} x_1(t) &= y(t) \\ x_2(t) &= \frac{dy(t)}{dt} = \dot{x}_1 \\ &\vdots \\ x_n(t) &= \frac{dy^{n-1}(t)}{dt^{n-1}} = \dot{x}_{n-1} \\ \frac{dy^n(t)}{dt^n} &= \dot{x}_n \end{aligned} \tag{2.6}$$

Then , (2.5) can be expressed by matrix form as:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \vdots \\ \dot{x}_{n-1} \\ \dot{x}_n \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & 0 \\ 0 & 0 & \cdots & \vdots & 1 \\ -a_0 & -a_1 & -a_2 & \cdots & -a_{n-1} \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_{n-1}(t) \\ x_n(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix} u(t) \tag{2.7}$$

$$y(t) = \begin{bmatrix} 1 & 0 & \cdots & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_{n-1}(t) \\ x_n(t) \end{bmatrix} \tag{2.8}$$

Generally, for a MIMO system, the vector matrix expression is given by:

$$\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu} \tag{2.9}$$

$$\mathbf{y} = \mathbf{Cx} + \mathbf{Du} \tag{2.10}$$

Where (2.9) is known as the state equation and (2.10) is referred to as the output equation; $\mathbf{x}$ is called the "state vector"; $\mathbf{y}$ is called the "output vector"; $\mathbf{u}$ is called the "input vector"; $\mathbf{A}$ is the "state matrix"; $\mathbf{B}$ is the "input matrix"; $\mathbf{C}$ is the "output matrix" and $\mathbf{D}$ is the "feed-forward matrix".

System structure properties and inner characteristic are indicated within the matrixes $\mathbf{A}$, $\mathbf{B}$, $\mathbf{C}$ and $\mathbf{D}$, which can also be generally called property matrix. From mathematical perspective, the matrix equations are more convenient for computer simulation than an n*th* order input-output differential equation. But there are many advantages with combining system topology when they are used for system analysis.

2.2.2 System analysis assumption vs. system state space model

Thermodynamics is the only discipline theory to depend on to evaluate the performance of a thermal physical system. Nowadays, balance condition thermodynamics is usually employed for the analysis of such an actual industrial physics system [13]. It mainly comes from as followings:

First, at the steady states, an energy system has the least entropy production, i.e. the lowest energy consumption from Prigogine's minimum entropy production principle. Because there exist many energy storage components in such a complex energy system, it is almost meaningless to assess energy consumption rate under system dynamics.

Second, for such a continuous production system, the actual process with stable condition is much longer than its dynamic process from an engineering perspective. Each stable production process can be regarded as a steady state system. System performance assessment should be conducted at steady-states, which can also transfer from one steady state to another one for responding to production demand.

With the thermodynamic balance condition assumption, a mass and energy balance model can be conducted for each component at steady state of the system. Then the system state equation can be obtained through proper mathematic arrangements guided by system topology. The system state equation is composed of system thermodynamics properties and some auxiliary flows. By comparing the system state equation with the general form of system state space model, a vector based analysis approach is inspired under the required assumption, that is, a linear time-invariant system at steady state.

3. Steam-water distribution equation

The steam-water distribution standard equation for thermo-system of a coal-fired power plant is deduced basing on components balance under the First Law of Thermodynamics.

3.1 The steam-water distribution equation for a typical thermal system

A fictitious system with all possible types of auxiliary system configuration is shown in Fig.1. The dashed beside each heater is used to indicate the boundary of heater unit, which play an important role in the ascertainment of feedwater's inlet and outlet enthalpy. Note that the boundary for the extraction steam of each heater is the immediate extraction pipe outlet of turbine, that is, any auxiliary steams input/output from the main extraction steam

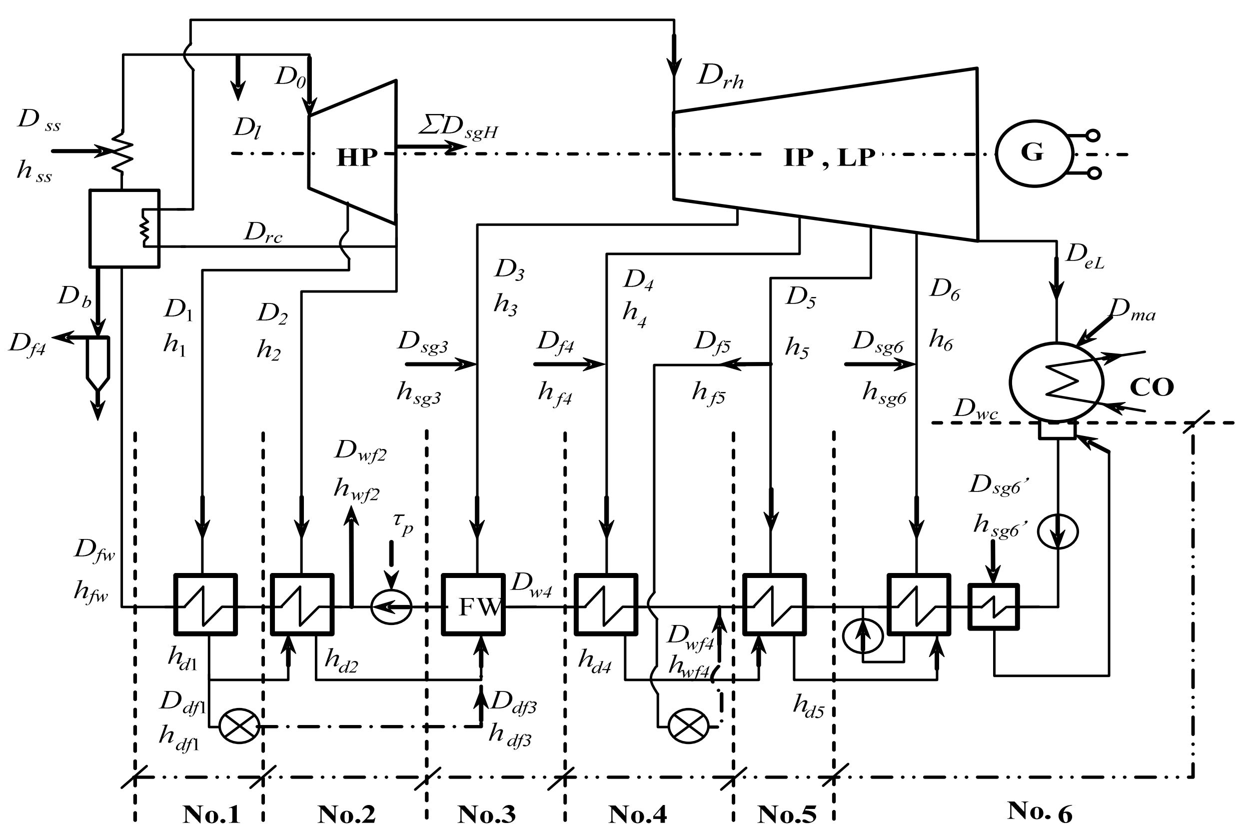

Fig. 1. Typical structure of thermal system (HP: high pressure cylinder; IP: intermediate pressure cylinder; LP: low pressure cylinder; CO: condenser ;G: generator; FW: deaerator)

pipe should be included in the respective heater unit (here, the term 'heater unit' is claimed to refer to the system control volume of heater defined on the above boundary rules.). Conducting mass balance and energy balance for each heater unit as the followings:

No.1:

$$D_1 h_1 + D_{fw} h_{w2} = D_1 h_{d1} + D_{fw} h_{w1}$$

$$\Rightarrow \quad D_1 (h_1 - h_{d1}) = D_{fw} (h_{w1} - h_{w2})$$

$$\Rightarrow \quad (D_1 - D_{df1}) q_1 - D_{df1} (h_{df1} - h_1) = D_{fw} \tau_1 \tag{3.1}$$

No.2:

$$(D_1 - D_{df1}) h_{d1} + D_2 h_2 + (D_{fw} + D_{wf2})(h_{w3} + \tau_p) = D_{fw} h_{w2} + [(D_1 - D_{df1}) + D_2] h_{d2} + D_{wf2} h_{wf2}$$

$$\Rightarrow \quad (D_1 - D_{df1}) \gamma_2 + D_2 q_2 + (D_{fw} + D_{wf2}) \tau_p - D_{wf2} (h_{wf2} - h_{w3}) = D_{fw} \tau_2 \tag{3.2}$$

Where $h_{wf2} = h_{w3} + \tau_p$

No.3:

$$D_3 h_3 + D_{sg3} h_{sg3} + [(D_1 - D_{df1}) + D_2] h_{d2} + D_{df3} h_{df3} + D_{w4} h_{w4} = (D_{fw} + D_{wf2}) h_{w3}$$

$$\Rightarrow (D_1 - D_{df1}) \gamma_3 + D_2 \gamma_3 + (D_3 + D_{sg3} + D_{df3}) q_3 + D_{df3} (h_{df3} - h_3) + D_{sg3} (h_{sg3} - h_3) = (D_{fw} + D_{wf2}) \tau_3 \tag{3.3}$$

where $D_{w4} = (D_{fw} + D_{wf2}) - (D_1 - D_{df1} + D_2 + D_{df3} + D_3 + D_{sg3})$

$h_{df3} = (h_{df3} - h_3) + h_3$ ， $h_{sg3} = (h_{sg3} - h_3) + h_3$

No.4:

$$(D_{w4} - D_{wf4}) h_{w5} + D_4 h_4 + D_{f4} h_{f4} + D_{wf4} h_{wf4} = D_{w4} h_{w4} + (D_4 + D_{f4}) h_{d4}$$

$$\begin{aligned} &\Rightarrow (D_1 - D_{df1}) \tau_4 + D_2 \tau_4 + (D_3 + D_{sg3} + D_{df3}) \tau_4 + (D_4 + D_{f4}) q_4 + \\ &D_{f4} (h_{f4} - h_4) + D_{wf4} (h_{wf4} - h_{w5}) = (D_{fw} + D_{wf2}) \tau_4 \end{aligned} \tag{3.4}$$

Where $h_{f4} = (h_{f4} - h_4) + h_4$

No.5:

$$(D_{w4} - D_{wf4}) h_{w6} + (D_4 + D_{f4}) h_{d4} + (D_5 - D_{f5}) h_5 = (D_{w4} - D_{wf4}) h_{w5} + (D_4 + D_{f4} + D_5 - D_{f5}) h_{d5}$$

$$\begin{aligned} &\Rightarrow (D_1 - D_{df1}) \tau_5 + D_2 \tau_5 + (D_3 + D_{sg3} + D_{df3}) \tau_5 + (D_4 + D_{f4}) \gamma_5 + \\ &(D_5 - D_{f5}) q_5 = (D_{fw} + D_{wf2} - D_{wf4}) \tau_5 \end{aligned} \tag{3.5}$$

No.6:

$$D_{wc} h_{wc} + D_6 h_6 + D_{sg6} h_{sg6} + D_{sg6'} h_{sg6'} + (D_4 + D_{f4} + D_5 - D_{f5}) h_{d5} = (D_{w4} - D_{wf4}) h_{w6}$$

$$\Rightarrow (D_1 - D_{df1})\tau_6 + D_2\tau_6 + (D_3 + D_{sg3} + D_{df3})\tau_6 + (D_4 + D_{f4})\gamma_6 + (D_5 - D_{f5})\gamma_6 + (D_6 + D_{sg6})q_6 + D_{sg6}(h_{sg6} - h_6) + D_{sg6'}(h_{sg6'} - h_{wc}) = (D_{fw} + D_{wf2} - D_{wf4})\tau_6 \tag{3.6}$$

Where $D_{wc} = (D_{fw} + D_{wf2}) - (D_1 - D_{df1} + D_2 + D_{df3} + D_3 + D_{sg3}) - D_{wf4} - (D_4 + D_{f4} + D_5 - D_{f5} + D_6 + D_{sg6} + D_{sg6'})$

$h_{sg6} = (h_{sg6} - h_6) + h_6$

Rearranging（3.1）to（3.6）to matrix equation as (3.7) :

$$\begin{bmatrix} q_1 &&&&& \\ \gamma_2 & q_2 &&&& \\ \gamma_3 & \gamma_3 & q_3 &&& \\ \tau_4 & \tau_4 & \tau_4 & q_4 && \\ \tau_5 & \tau_5 & \tau_5 & \gamma_5 & q_5 & \\ \tau_6 & \tau_6 & \tau_6 & \gamma_6 & \gamma_6 & q_6 \end{bmatrix} \begin{bmatrix} D_1 - D_{df1} \\ D_2 \\ D_3 + D_{sg3} + D_{df3} \\ D_4 + D_{f4} \\ D_5 - D_{f5} \\ D_6 + D_{sg6} \end{bmatrix} + \begin{bmatrix} -D_{df1}(h_{df1} - h_1) \\ (D_{fw} + D_{wf2})\tau_p - D_{wf2}(h_{wf2} - h_{w3}) \\ D_{df3}(h_{df3} - h_3) + D_{sg3}(h_{sg3} - h_3) \\ D_{wf4}(h_{wf4} - h_{w5}) + D_{f4}(h_{f4} - h_4) \\ 0 \\ D_{sg6}(h_{sg6} - h_6) + D_{sg6'}(h_{sg6'} - h_{wc}) \end{bmatrix} = \begin{bmatrix} \tau_1 D_{fw} \\ \tau_2 D_{fw} \\ \tau_3(D_{fw} + D_{wf2}) \\ \tau_4(D_{fw} + D_{wf2}) \\ \tau_5(D_{fw} + D_{wf2} - D_{wf4}) \\ \tau_6(D_{fw} + D_{wf2} - D_{wf4}) \end{bmatrix} \tag{3.7}$$

Substituting the following three equations to (3.7) and rearranging, we get (3.8):

$D_{fw} = D_0 + D_b + D_l - D_{ss}$ (from boiler flows balance)

$N_p = (D_{fw} + D_{wf2})\tau_p$ (the total enthalpy increase by feedwater pump shaft work)

$Q_{sg6'} = D_{sg6'}(h_{sg6'} - h_{wc})$ (the heat inputted by the turbine shaft gland steam heater)

In (3.8), $q_{df1} = h_{df1} - h_{d1}$; $q_{df3} = h_{df3} - h_{w4}$; $q_{sg3} = h_{sg3} - h_{w4}$; $q_{f4} = h_{f4} - h_{d4}$; $q_{sg6} = h_{sg6} - h_{wc}$; $q_{f5} = h_{f5} - h_{d5}$; $\tau_{wf2} = h_{wf2} - h_{w3}$; $\tau_{wf4} = h_{wf4} - h_{w5}$.

$$\begin{bmatrix} q_1 &&&&& \\ \gamma_2 & q_2 &&&& \\ \gamma_3 & \gamma_3 & q_3 &&& \\ \tau_4 & \tau_4 & \tau_4 & q_4 && \\ \tau_5 & \tau_5 & \tau_5 & \gamma_5 & q_5 & \\ \tau_6 & \tau_6 & \tau_6 & \gamma_6 & \gamma_6 & q_6 \end{bmatrix} \begin{pmatrix} D_1 \\ D_2 \\ D_3 \\ D_4 \\ D_5 \\ D_6 \end{pmatrix} + \begin{bmatrix} q_{df1} &&&&& \\ \gamma_2 & 0 &&&& \\ \gamma_3 & \gamma_3 & q_{sg3} &&& \\ \tau_4 & \tau_4 & \tau_4 & q_{f4} && \\ \tau_5 & \tau_5 & \tau_5 & \gamma_5 & q_{f5} & \\ \tau_6 & \tau_6 & \tau_6 & \gamma_6 & \gamma_6 & q_{sg6} \end{bmatrix} \begin{pmatrix} -D_{df1} \\ 0 \\ D_{sg3} \\ D_{f4} \\ -D_{f5} \\ D_{sg6} \end{pmatrix} +$$

$$\begin{bmatrix} 0 &&&&& \\ \gamma_2 & 0 &&&& \\ \gamma_3 & \gamma_3 & q_{df3} &&& \\ \tau_4 & \tau_4 & \tau_4 & 0 && \\ \tau_5 & \tau_5 & \tau_5 & \gamma_5 & 0 & \\ \tau_6 & \tau_6 & \tau_6 & \gamma_6 & \gamma_6 & 0 \end{bmatrix} \begin{pmatrix} 0 \\ 0 \\ D_{df3} \\ 0 \\ 0 \\ 0 \end{pmatrix} + \begin{bmatrix} 0 &&&&& \\ \tau_2 & \tau_{wf2} &&&& \\ \tau_3 & \tau_3 & 0 &&& \\ \tau_4 & \tau_4 & \tau_4 & \tau_{wf4} && \\ \tau_5 & \tau_5 & \tau_5 & \tau_5 & 0 & \\ \tau_6 & \tau_6 & \tau_6 & \tau_6 & \tau_6 & 0 \end{bmatrix} \begin{pmatrix} 0 \\ -D_{wf2} \\ 0 \\ D_{wf4} \\ 0 \\ 0 \end{pmatrix}$$

$$-(D_b + D_l) \begin{pmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \\ \tau_5 \\ \tau_6 \end{pmatrix} + D_{ss} \begin{pmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \\ \tau_5 \\ \tau_6 \end{pmatrix} + \begin{pmatrix} 0 \\ N_p \\ 0 \\ 0 \\ 0 \\ Q_{sg6'} \end{pmatrix} = D_0 \begin{pmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \\ \tau_5 \\ \tau_6 \end{pmatrix} \tag{3.8}$$

For a more general system, i.e. there are r auxiliary steams and s auxiliary waters flowing in/out heater unit, t boiler blown down or other leakage flows. Then a general steam-water distribution equation can be got:

$$[\mathbf{A}]\ [\mathbf{D}_i]+\sum_{k=1}^{r}[\mathbf{A}_k]\ \left[\mathbf{D}_{fik}\right]+\sum_{j=1}^{s}\left[\mathbf{T}_j\right]\ \left[\mathbf{D}_{wfij}\right]-(\sum_{m=1}^{t}D_{bm})[\boldsymbol{\tau}_i]+D_{ss}[\boldsymbol{\tau}_i]+\left[\boldsymbol{\Delta}\mathbf{Q}_{fi}^{0}\right]=D_0[\boldsymbol{\tau}_i] \tag{3.9}$$

Equation (3.9) can be written simply as：

$$[\mathbf{A}]\ [\mathbf{D}_i]+[\mathbf{Q}_{fi}]=D_0[\boldsymbol{\tau}_i] \tag{3.10}$$

Where,

$$[\mathbf{Q}_{fi}]=\sum_{k=1}^{r}[\mathbf{A}_k]\ \left[\mathbf{D}_{fik}\right]+\sum_{j=1}^{s}\left[\mathbf{T}_j\right]\ \left[\mathbf{D}_{wfij}\right]-(\sum_{m=1}^{t}D_{bm})[\boldsymbol{\tau}_i]+D_{ss}[\boldsymbol{\tau}_i]+\left[\boldsymbol{\Delta}\mathbf{Q}_{fi}^{0}\right] \tag{3.11}$$

$\left[\boldsymbol{\Delta}\mathbf{Q}_{fi}^{0}\right]$ is the vector from pure heat imposed on the thermal system. For example, $\left[\boldsymbol{\Delta}\mathbf{Q}_{fi}^{0}\right]=[0\quad N_p\quad 0\quad 0\quad 0\quad Q_{sg6}']$ in the demonstration system showed in Fig.1.

In (3.10), $[\mathbf{A}]$ is the character matrix consisting of the thermal exchange quantity (q,γ,τ) in each heater unit. $[\mathbf{D}_i]$ is vector consisting of the extracted steam quantity and $[\boldsymbol{\tau}_i]$ is enthalpy increase of feeedwater (or condensed water) in each heater unit. D_0 is the throat flow of turbine inlet. $[\mathbf{Q}_{fi}]$ can be regarded as a equivalent vector consisting of the thermal exchange of all auxiliary steam (water) flow or external heat imposed on the main thermal system (here the main thermal system means the thermal system excluding any auxiliary steam or auxiliary water stream).

3.2 The transform and rearrangement of system state matrix equation of a general power unit

According to total differential equation transform, equation (3.12) can be obtained from equation (3.10), where the infinitesimal of higher order is neglected.

$$[\Delta\mathbf{A}][\mathbf{D}_i]+[\mathbf{A}][\Delta\mathbf{D}_i]+[\Delta\mathbf{Q}_{fi}]=D_0[\Delta\boldsymbol{\tau}_i] \tag{3.12}$$

Then,

$$[\Delta\mathbf{D}_i]=[\mathbf{A}]^{-1}\left[D_0[\Delta\boldsymbol{\tau}_i]-[\Delta\mathbf{A}][\mathbf{D}_i]-[\Delta\mathbf{Q}_{fi}]\right] \tag{3.13}$$

Considering the linear characteristics of the thermal system under a steady state, the system keeps its all components' performance constant while suffering the disturbance inputs coming from auxiliary steam (water) or external heat. That is, the thermal exchange of unit mass working substance in each heater unit is constant, then, the followings can be declared,

$$[\Delta\mathbf{A}]=\mathbf{0}\ ,\ [\Delta\boldsymbol{\tau}_i]=\mathbf{0}$$

So equation (3.13) becomes,

$$[\Delta \mathbf{D}_i] = -[\mathbf{A}]^{-1}[\Delta \mathbf{Q}_{fi}] \tag{3.14}$$

Doing total differential equation transform and neglecting the infinitesimal of higher order, and the equation (3.11) becomes,

$$\begin{aligned}[\Delta \mathbf{Q}_{fi}] &= \sum_{k=1}^{r}[\Delta \mathbf{A}_k]\left[\mathbf{D}_{fik}\right] + \sum_{k=1}^{r}[\mathbf{A}_k]\left[\Delta \mathbf{D}_{fik}\right] + \sum_{j=1}^{s}\left[\Delta \mathbf{T}_j\right]\left[\mathbf{D}_{wfij}\right] \\ &+ \sum_{j=1}^{s}\left[\mathbf{T}_j\right]\left[\Delta \mathbf{D}_{wfij}\right] - \Delta\left(\sum_{m=1}^{t} D_{bm}[\boldsymbol{\tau}_i] + D_{ss}[\boldsymbol{\tau}_i] + \left[\Delta \mathbf{Q}_{fi}^{0}\right]\right)\end{aligned} \tag{3.15}$$

Under the same assumption as (3.14),

$$[\Delta \mathbf{A}_k] = \mathbf{0}\,,\ \left[\Delta \mathbf{T}_j\right] = \mathbf{0}\,,[\Delta \boldsymbol{\tau}_i] = \mathbf{0}$$

Thus, the equation (3.15) becomes,

$$\begin{aligned}[\Delta \mathbf{Q}_{fi}] &= \sum_{k=1}^{r}[\mathbf{A}_k]\left[\Delta \mathbf{D}_{fik}\right] + \sum_{j=1}^{s}\left[\mathbf{T}_j\right]\left[\Delta \mathbf{D}_{wfij}\right] \\ &- \sum_{m=1}^{t}\Delta D_{bm}[\boldsymbol{\tau}_i] + \Delta D_{ss}[\boldsymbol{\tau}_i] + \Delta\left[\boldsymbol{\Delta} \mathbf{Q}_{fi}^{0}\right]\end{aligned} \tag{3.16}$$

3.2.1 Definition of thermal disturbance vector

Each item in (3.16) is discussed in detail as followings:

First, the item $\sum_{k=1}^{r}[\mathbf{A}_k]\left[\Delta \mathbf{D}_{fik}\right]$ can be rearranged as,

$$\sum_{k=1}^{r}[\mathbf{A}_k]\left[\Delta \mathbf{D}_{fik}\right] = \sum_{k=1}^{r}\Delta D_{f1k}\begin{bmatrix} a_{1k} \\ a_{2k} \\ \vdots \\ a_{ik} \end{bmatrix} + \ldots \sum_{k=1}^{r}\Delta D_{fik}\begin{bmatrix} a_{1k} \\ a_{2k} \\ \vdots \\ a_{ik} \end{bmatrix} \tag{3.17}$$

Where the subscript i stands for the number of heater unit (such as i =8 for a 600MW power unit with eight heaters), and $k = 1 \sim r$, stands for the number of auxiliary steam imposed on the No. i heater unit.

The equation (3.17) is the sum of numbers of items, and each item is the product of a coefficient and a vector. The coefficient is mass quantity of auxiliary flow, which is positive for flowing in and negative for flowing out the thermal system.

The configuration of the vector takes on some well-regulated characteristics, which is exposed in details as followings.

The item $[\mathbf{A}_k]$ is a lower triangular matrix, and the vector $\begin{bmatrix} a_{1k} & a_{2k} & \cdots & a_{ik} \end{bmatrix}^T$ is shaped by system topology configuration. It consists of the heat exchange quantity in the each heater unit along with the (virtual) path from the access point of the auxiliary steam till hot well, such as the auxiliary D_{f21} in Fig.2, whose access point is the steam extraction pipe of the No.*2* heater unit. It hasn't direct heat exchange with the No.1 heater, so the corresponding item a_{11} =0, and along with the dashed (see Fig.2), its heat exchange quantity in No.2 is q_{f21} , and γ_3 in No.3 heater respectively. After the closed heater No.3, it is confluent with condensed water, so the heat exchange quantity is regarded as τ_4. That is, the vector becomes $\begin{bmatrix} 0 & q_{f21} & \gamma_3 & \tau_4 \cdots & a_{i1} \end{bmatrix}^T$. Because the dashed flow path may not be a real flow path of the auxiliary steam considered, it is also called "virtual path" for the convenience to construct the vector for analysis.

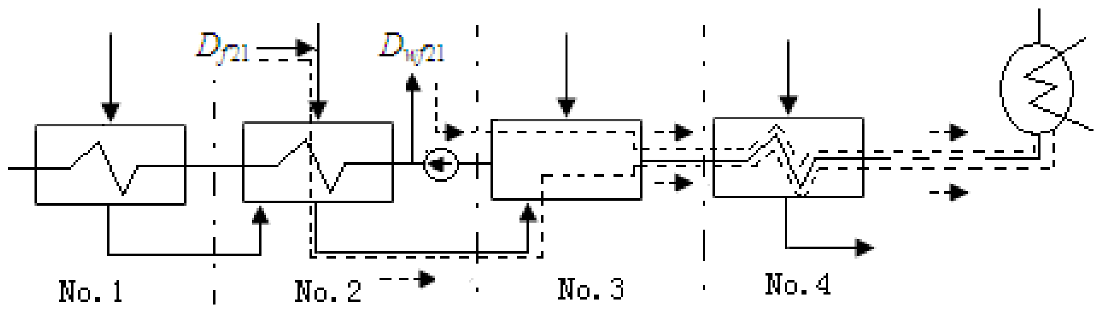

Fig. 2. The schematic illustration for thermal exchange vector of auxiliary steam and water

Second, the item $\sum_{j=1}^{s}\left[\mathbf{T}_j\right]\left[\Delta\mathbf{D}_{wfij}\right]$ denotes the thermal disturbance quantity resulted from the auxiliary water flowing in (out) feedwater (condensed) water pipe of all heater units. It is similar with auxiliary steam disturbance except for their flow path. As these auxiliary water are all from or to the water side of the thermal system, their thermal exchange quantity are the enthalpy increase τ_i in each heater unit, such as the auxiliary water D_{wf21} in Fig.2, whose thermal disturbance vector is,

$$\begin{bmatrix} 0 & \Delta\tau_{wf21} & \tau_3 & \tau_4 \cdots & \tau_i \end{bmatrix}^T$$

In this system, $\Delta\tau_{wf21} = \tau_p$,which belongs to the thermal exchange with No.2 heater unit.

Third, $\Delta\left[\mathbf{\Delta Q}^0_{fi}\right]$ is the pure heat disturbance, such as pump work, heat transferred by gland heater and so on, whose elements are the direct energy quantity exchanged on the corresponding heater unit.

Finally, the other items in $[\Delta\mathbf{Q}_{fi}]$ are these water flowing in (out) system from boiler side directly, such as continuous blow down, desuperheating spray flow and so on. According to the construction rules for the flow path, their thermal disturbance are regarded as spreading over the entire regenerative heating system. So the thermal exchange of each of them with the heater units is fixed as $\begin{bmatrix} \tau_1 & \tau_2 & \tau_3 & \tau_4 \cdots & \tau_i \end{bmatrix}^T$.

In summary, the vector $\left[a_{1k}, a_{2k}, \cdots, a_{ik}\right]^T$ is defined as the *thermal disturbance vector*, which is constructed through indentifying the (virtual) flow path of the auxiliary flow considered from its access point till the hot well. Its elements assignment is equal to the heat exchange with each heater unit along with its (virtual) flow path.

3.2.2 Definition of main steam vector

The matrix $[\mathbf{A}]$ is also shaped by system topology configuration as a lower triangular matrix. Inspired by the feature of the *thermal disturbance vector,* it is revealed that the same rule works for the element vector of $[\mathbf{A}]$. For example, in Fig.1 the second extracted steam's access point is the No.*2* heater unit. It hasn't direct heat exchange with the No.1 heater, so the first element is 0. Along with the (virtual) flow path from the access point till the hot well, the heat exchange quantity in No.2 is q_2, γ_3 in No.3, and τ_4, τ_5, τ_6 in the No.4, No.5, No.6 heater respectively. The column vector of $[\mathbf{A}]$ is called as the ***main system vector*** for convenience of equations construction.

3.3 Deduction of system output equations for an thermal power unit

3.3.1 The equation for power output of system

1. The power output equation for the ideal Rankine cycle is:

$$N = D_0(h_0 - h_c)$$

2. For the ideal reheat Rankine cycle:

$$N = D_0(h_0 - h_{eH} + h_r - h_c)$$

3. For the actual cycle of power plant:

Defining $\sigma = h_r - h_{eH}$ gives

$$N = D_0(h_0 + \sigma - h_c)$$

When certain steam $x(D_x, h_x)$ leaves from HP (High Pressure Cylinder), the power output decrease is, $N_x = D_x(h_x + \sigma - h_c)$, and when it leaves from IP(Intermediate Pressure Cylinder) or LP (Low Pressure Cylinder), the power output decrease is $N_x = D_x(h_x - h_c)$ .For generalization, the uniform term $h_x{}^{\sigma}$ is defined as followings:

When the steam leaves from HP：

$$h_x{}^{\sigma} = h_x + \sigma - h_c$$

When the steam leaves from IP or LP:

$$h_x{}^{\sigma} = h_x - h_c$$

For an actual thermal system, the steam leaving from turbine consists of all kinds of extraction steam for heaters and leaking steam from shaft gland. Thus, a complete power output equation for an actual system is obtained according to mass and energy balance.

$$N = D_0(h_0 + \sigma - h_c) - \sum_{i=1}^{p} D_i h_i^{\sigma} - \sum_{n=1}^{u} D_n h_n^{\sigma} + D_{rs} h_{rs}^{\sigma}$$

Written in matrix form:

$$N = D_0(h_0 + \sigma - h_c) - [\mathbf{D}_i]^T[\mathbf{h}_i^\sigma] - [\mathbf{D}_n]^T[\mathbf{h}_n^\sigma] + D_{rs}h_{rs}^\sigma \tag{3.18}$$

Where n stands for number of shaft gland steams, and $h_{rs}^\sigma = h_r - h_c$.

3.3.2 The equation for the heat transferred by boiler

The equation for the heat transferred by boiler for the ideal Rankine cycle is:

$$\dot{Q} = D_0\left(h_0 - h_{fw}\right)$$

For the ideal reheat Rankine cycle:

$$\dot{Q} = D_0\left(h_0 + \sigma - h_{fw}\right)$$

For an actual system, considering all kinds of steam that are not reheated and all kinds of working substance flowing out of and into system from boiler side such as continuous blow down, periodical blow down, the steam for soot blower system, desuperheating spray flow and dereheating spray flow, etc., then the complete equation for the heat transferred by boiler becomes (3.19).

$$\begin{aligned}\dot{Q} = {} & D_0\left(h_0 + \sigma - h_{fw}\right) - \left[\mathbf{D}_i\right]_{c'}^T\left[\boldsymbol{\sigma}\right]_{c'} - \left[\mathbf{D}_n\right]_{d'}^T\left[\boldsymbol{\sigma}\right]_{d'} + \\ & D_{ss}\left(h_{fw} - h_{ss}\right) + D_{rs}\left(h_r - h_{rs}\right) + \sum_{m=1}^{t} D_{bm}\left(h_{bm} - h_{fw}\right)\end{aligned} \tag{3.19}$$

3.4 The analytic formula of heat consumption rate

According to (3.10), $[\mathbf{D}_i]$ can be obtained.

$$\left[\mathbf{D}_i\right] = \left[\mathbf{A}\right]^{-1}\left[D_0\left[\boldsymbol{\tau}_i\right] - [\mathbf{Q}_{fi}]\right]$$

The actual power output can be acquired from site wattmeters, then D_0 and $\left[\mathbf{D}_i\right]$ can be obtained from simple iterative calculation using system state equation and equation (3.18). Substituting $\left[\mathbf{D}_i\right]$ into the equation (3.19), then the equation of heat consumption rate $\hat{q}$ can be immediately obtained by $\hat{q} = 3600\dot{Q}/N$.

4. Degradation analysis using state space method

4.1 The state space perspective of thermal system state equation

In our domain, the steady state performance is evaluated for thermal energy system, that is, the dynamic process is neglected and it is focused on the performance evaluation at one steady state. So, equation (3.10) can be regarded as the steady state equation of (2.9). The item $[\mathbf{Q}_{fi}]$ can be regarded as the input vector from auxiliary steam-water flows or the pure heat disturbance. Thus, the next step is to find the output matrix $\mathbf{C}$ and the feedforward matrix $\mathbf{D}$ for system output.

4.2 Deduction of two property vectors

The increment vector of system output can be obtained through equation (3.18) and (3.19).

$$\Delta N = -[\Delta \mathbf{D}_i]^T[\mathbf{h}_i^\sigma] - [\Delta \mathbf{D}_n]^T[\mathbf{h}_n^\sigma] + \Delta D_{rs} h_{rs}^\sigma$$

$$\Delta \dot{Q} = -[\Delta \mathbf{D}_i]_{c'}^T [\boldsymbol{\sigma}]_{c'} - [\Delta \mathbf{D}_n]_{d'}^T [\boldsymbol{\sigma}]_{d'} + \Delta D_{ss}(h_{fw} - h_{ss})$$
$$+ \Delta D_{rs}(h_r - h_{rs}) + \sum_{m=1}^{t} \Delta D_{bm}(h_{bm} - h_{fw})$$

Then, the matrix equation can be expressed as,

$$\begin{bmatrix} \Delta N \\ \Delta \dot{Q} \end{bmatrix} = -\begin{bmatrix} h_1^\sigma & h_2^\sigma & \cdots & h_i^\sigma \\ \sigma_1^c & \sigma_2^c & \cdots & \sigma_i^c \end{bmatrix} \begin{bmatrix} \Delta D_1 \\ \Delta D_2 \\ \vdots \\ \Delta D_i \end{bmatrix} + \begin{bmatrix} -\sum \Delta N_n + \Delta N_{rs} \\ -\sum \Delta Q_{d'} + \Delta Q_{rs} + \Delta Q_{ss} + \Delta Q_{bm} \end{bmatrix} \tag{3.20}$$

Where, the change of constant items is zero. $\sum \Delta N_n$ and ΔN_{rs} are the change of power output by turbine gland steam and reheater spray water respectively. $\sum \Delta Q_{d'}$, ΔQ_{rs} , ΔQ_{ss} and ΔQ_{bm} are the change of boiler heat by HP turbine gland steam, reheater spray water, desuperheating water and boiler blow down respectively.

$$\sigma_i^c = \begin{cases} \sigma & i \le c' \\ 0 & i > c' \end{cases}$$

Replacing the items in the equation (3.20) with the equation (3.14), and defines,

$$[\boldsymbol{\eta}_i \quad \boldsymbol{\xi}_i]^T = \begin{bmatrix} h_1^\sigma & h_2^\sigma & \cdots & h_i^\sigma \\ \sigma_1^c & \sigma_2^c & \cdots & \sigma_i^c \end{bmatrix} [\mathbf{A}]^{-1} \tag{3.21}$$

Then, equation (3.20) becomes,

$$\begin{bmatrix} \Delta N \\ \Delta \dot{Q} \end{bmatrix} = [\boldsymbol{\eta}_i \quad \boldsymbol{\xi}_i]^T [\Delta \mathbf{Q}_{fi}] + \begin{bmatrix} \Sigma \Pi_N \\ \Sigma \Pi_Q \end{bmatrix} \tag{3.22}$$

Where $\begin{bmatrix} \Sigma \Pi_N \\ \Sigma \Pi_Q \end{bmatrix} = \begin{bmatrix} -\sum \Delta N_n + \Delta N_{rs} \\ -\sum \Delta Q_{d'} + \Delta Q_{rs} + \Delta Q_{ss} + \Delta Q_{bm} \end{bmatrix}$.

The matrix $[\boldsymbol{\eta}_i \quad \boldsymbol{\xi}_i]^T$ just is the transfer matrix of auxiliary thermal disturbance $[\Delta \mathbf{Q}_{fi}]$. It is a constant matrix under a certain steady state of the system. The another item of equation

(3.22) can be regarded as feedforward matrix, which reflects those auxiliary steam or water imposing directly on the system output, such as HP turbine gland steam, spray water.

4.3 The advantages of transfer matrix and thermal disturbance vector for system analysis

So far, we have deduced the transfer matrix $\begin{bmatrix} \boldsymbol{\eta}_i & \xi_i \end{bmatrix}^T$, the main system vector, the thermal disturbance vector and other vectors. The new analysis method can be called vector-based method. The advantages for analyzing a thermal energy system are as followings:
Firstly, it unifies all the analysis formulas for all kinds of auxiliary steam (water) disturbance or pure heat disturbance. That is, we need not to memorize the different formula for different disturbance or to try to discern all its possible results imposed on the system, which may be only competent for an experienced engineer merely.
Secondly, the analysis process can be greatly simplified in terms of different auxiliary flow concerned. For instance, if the whole system is analyzed, that is, the full path of a certain auxiliary steam or water is considered from the source to the destination, so the forward matrix item in equation (3.21) should be considered enough. Otherwise, if only the regenerative heating system is focused on, the necessary calculation is just the product of a constant vector and the thermal disturbance vector of the corresponding auxiliary steam (water) or pure heat disturbance, which can be constructed easily from equation (3.16) and Fig 2.
Thirdly, for certain device performance degradation, only a few local properties are changed and the linear assumption is still satisfying. Thus, equation (3.22) can also be used. such as, terminal temperature difference of heater. Their equivalent thermal disturbance $[\Delta \mathbf{Q}_{fi}]$ can be obtained through local balance calculation and equations rearrangement.

5. Case analysis

In order to demonstrate the availability of state space method for the performance analysis of a thermal energy system, the example for an actual 600MW coal-fired power unit is presented. Its system diagram is showed with Fig.3.

Heater No.	h_i **(kJ/kg)**	tw_i **(kJ/kg)**	ts_i **(kJ/kg)**
1	3126.6	1201.1	**1077.3**
2	3013.9	1052.6	**880.8**
3	3325.5	863.51	**764.4**
4	3147.0	725.9	
5	2948.2	569.3	**458.1**
6	2761.9	435.8	**373.4**
7	2640.8	351.3	**277.7**
8	2510.0	255.9	
other Properties (kJ/kg)	h_0**=3394.1;** h_r**=3536.4;** h_c**=2340.4;** h_{cw} **=140.7;** τ_b**=25.3;** h_{drum}**=2428.73**		

Note: h_i is the enthalpy of th ith extracted steam; tw_i is the enthalpy of output water of th ith heater; ts_i is the enthalpy of the drain water of of the ith heater; h_0 is the enthalpy of the main steam; h_r is the enthalpy of the reheated steam; h_c is the enthalpy of the exhausted steam of turbine h_{cw} is the enthalpy of the condensed water; τ_b is the enthalpy increase in feedwater pump; h_{drum} is the saturated enthalpy of drum water

Table 2. System properties under rated load

5.1 The demonstration of calculation process

There are six key steps to accomplish a certain disturbance analysis as followings:

1. According to the construction rule of the *main system vector*, the matrix [A] can be constructed with the parameters given in Tab.2.

$$[\mathbf{A}]=\begin{bmatrix} 2049.3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 196.5 & 2133.1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 116.4 & 116.4 & 2561.1 & 0 & 0 & 0 & 0 & 0 \\ 195.1 & 195.1 & 195.1 & 2577.7 & 0 & 0 & 0 & 0 \\ 133.5 & 133.5 & 133.5 & 133.5 & 2490.1 & 0 & 0 & 0 \\ 84.5 & 84.5 & 84.5 & 84.5 & 84.7 & 2388.5 & 0 & 0 \\ 95.4 & 95.4 & 95.4 & 95.4 & 95.7 & 95.7 & 2363.1 & 0 \\ 115.2 & 115.2 & 115.2 & 115.2 & 137.0 & 137.0 & 137.0 & 2369.3 \end{bmatrix}$$

2. Referring to (3.18), (3.20) to construct the vector $\left[h_1^\sigma, h_1^\sigma, \cdots, h_i^\sigma\right]$ and $\left[\sigma_1^c, \sigma_2^c, \cdots, \sigma_i^c\right]$.

$$\left[h_1^\sigma, h_2^\sigma \cdots h_i^\sigma\right] = [1308.7 \quad 1196.0 \quad 985.1 \quad 806.6 \quad 607.8 \quad 421.5 \quad 300.4 \quad 169.6]$$

$$\left[\sigma_1^c, \sigma_2^c, \cdots, \sigma_i^c\right] = \left[522.5 \quad 522.5 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0\right]$$

3. The transfer matrix $[\boldsymbol{\eta}_i \quad \xi_i]^T$ can be obtained from equation (3.21) with the parameters in Tab. 2.

$$[\boldsymbol{\eta}_i] = \begin{bmatrix} 0.5139 \\ 0.4856 \\ 0.3374 \\ 0.2878 \\ 0.2297 \\ 0.1674 \\ 0.1230 \\ 0.0716 \end{bmatrix} \qquad [\xi_i] = \begin{bmatrix} 0.2315 \\ 0.2449 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

4. The disturbance vectors can be formed from the equation (3.16) according to its (virtual) flow path, such as the auxiliary steam L, where there isn't heat exchange with heater No.1, No.2 and No.3, the heat exchange with the No.4 heater is $(h_L - tw_5)$ and then become confluent with condensed water through a virtual path to condenser. Thus, for unit quantity of flow, its thermal disturbance becomes,
$[\Delta \mathbf{q}_{fi}]_L = [0,0,0,2440.5,133.5,84.5,95.4,115.2]^T$.
5. Calculating the feedforward item $\begin{bmatrix} \Sigma \Pi_N \\ \Sigma \Pi_Q \end{bmatrix}$ through finding out the source and destination of the auxiliary steam L.
6. Calculating the system output increment that caused by the auxiliary steam L with equation (3.22).

The analysis results for almost all kind of auxiliary flows can be found in Tab.3.

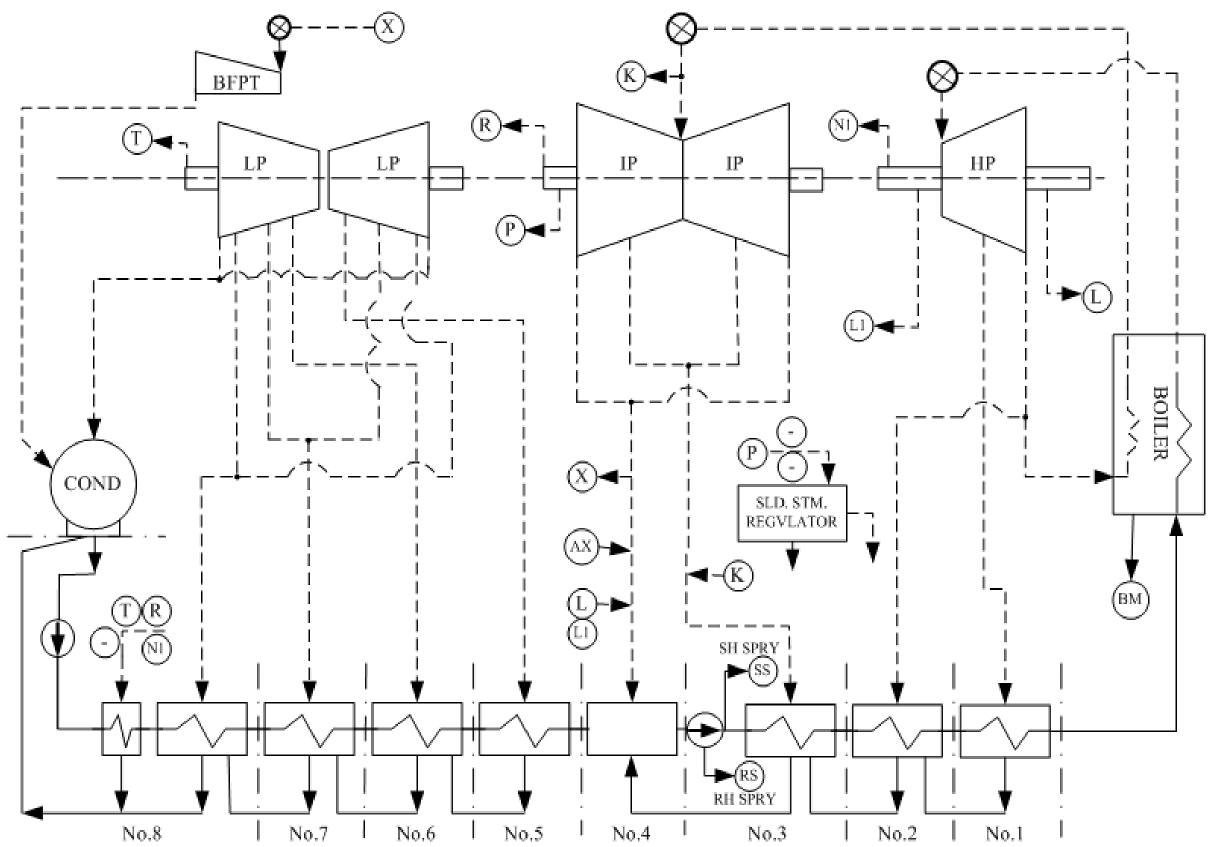

Fig. 3. The thermal system diagram of a 600MW power unit

Aux. No.	enthalpy (kJ/kg)	Quantity Increment[2] (t/h)	Thermal disturbance vector $[\Delta \mathbf{q}_{fi}]$	Power increase by THR (kW)	Power increase by $\Sigma\Pi_N$ (kW)	Total increment of power ΔN (kW)	Total increment of boiler heat $\Delta\dot{Q}$ (kJ)
L	3009.8	0.331	$[0,0,0,2440.5,\tau_5, \tau_6, \tau_7, \tau_8]'$	70.532	-109.5886	-39.056	-48.04
L1	3317.3	0.292	$[0,0,0,2748.0,\tau_5, \tau_6, \tau_7, \tau_8]'$	69.399	-121.618	-52.219	-42.38
N1	3317.3	0.013	$[0,0,0, 0,0, 0, 0,3176.6]'$	0.8211	-5.4145	-4.5934	-1.89
SS	751.2	10.0	$[0,0,25.3, \tau_4,\tau_5, \tau_6, \tau_7, \tau_8]'$ $[\tau_1,\tau_2, \tau_3, \tau_4,\tau_5, \tau_6, \tau_7, \tau_8]'$	572.285	0	572.285	1473.9
RS[1]	738.55	40.0	$[0,0,12.65, \tau_4,\tau_5, \tau_6, \tau_7, \tau_8]'$	-1268.1	13289.0	12021.0	31087.0
K	3536.4	0.742	$[0,0,2772, \gamma_4,\tau_5, \tau_6, \tau_7, \tau_8]'$	217.707	-246.509	-28.802	0
R	3147.0	0.02	$[0,0,0, 0,0, 0, 0,3006.3]'$	1.1955	-4.4811	-3.2856	0
P	3147.0	0.114	$[0,0,0, 0,0, 0, 0,0]'$	0	-25.5423	-25.5423	0
X	3147.0	6.495	$[0,0,0, 2557.7,\tau_5, \tau_6, \tau_7, \tau_8]'$	-1455.2	0	-1455.2	0
AX	2176.2	10.0	$[0,0,0, 1606.9,\tau_5, \tau_6, \tau_7, \tau_8]'$	1464.5	0	1464.5	0
T	2340.4	0.104	$[0,0,0, 0,0, 0, 0,2199.7]'$	4.5488	0	4.5488	0
BM	2428.73	5.0	$[\tau_1,\tau_2, \tau_3, \tau_4,\tau_5, \tau_6, \tau_7, \tau_8]'$	-450.583	0	-450.583	1817.1

Note: 1. The reheater spray water has an analogy to a low pressure parameters cycle attached to the main steam cycle. Its equivalent efficiency is only 38.67% from the calculation above.
2. The quantity increment of auxiliary flow is ten percent of its rated value except for SS, RS, AX and BM.

Table 3. The results of whole system analysis with kinds of auxiliary thermal disturbance

5.2 Discussion on the calculation results

The fourth column in the Tab.3 consists of the thermal disturbance vector of each auxiliary flow from the definition in the section 3.2.1. For example, there are two thermal disturbance vectors for the desuperheating water, because it imposes two thermal disturbances on the thermal system, one is flowing out the feedwater pipe and another is flowing in boiler. The auxiliary steam P doesn't directly flow into the thermal system, so its thermal disturbance vector becomes zero vector from the rules given in the section 3.2.1.

The fifth column is the power increment obtained from the first item on the left of the equation (3.22), where the flow path from condenser's hot well through regenerative system and boiler till the inlet of turbine is named as thermal heating route (THR), that is, every thermal disturbance vector arises from the THR.

For single auxiliary flow, the matrix equation becomes the product of two vectors plus some simple items, that is, $\Delta N = [\boldsymbol{\eta}_i]^{\mathrm{T}}[\Delta \mathbf{q}_{fi}] + \Sigma\Pi_N$ and $\Delta \dot{Q} = [\boldsymbol{\xi}_i]^{\mathrm{T}}[\Delta \mathbf{q}_{fi}] + \Sigma\Pi_Q$. The calculation for every auxiliary flow obeys the rules, which greatly alleviate the difficulties for engineers to memorize many specific formulas.

The specific performance deviation caused by each auxiliary flow deviation can be obtained directly from the total increment of power (ΔN) and the total increment of boiler heat ($\Delta \dot{Q}$). The total deviation comes from the mathematical summation of them. They are identical with those calculated by traditional whole system thermal balance calculation.

6. Conclusion

Process performance monitoring is an overall effort to measure, sustain, and improve the plant and/or unit thermal efficiency, maintenance planning, etc. The decision to implement a performance-monitoring program should be based on plant and fleet requirements and available resources. This includes the instrumentation, the data collection, and the required analysis and interpretation techniques, etc. [14]. This chapter starts from the point of view of system analysis and interdisciplinary methods are employed. Based on vector method of linear system, the new performance monitoring and analysis methodology are proposed, which is intended to achieve an online monitoring/ analysis means beyond traditional periodic test and individual component balance calculation. The main features are as followings:

1. According to error propagation rules and the characteristics of the objective thermo-system, a larger measurements set is adopted to avoid using the primary flow as a necessary input for process performance evaluation, which is impossible to get an accurate calibration for continuous monitoring demand. So good ongoing maintenance of these existing plant instruments and some supplements for traditionally neglected flows measurements may greatly contribute to the achievement of the new methodology, i.e. process performance monitoring is also a kind of management.
2. The system state equations reveal the relationship between the topological structure of thermo-system of a power plant and its corresponding mathematic configuration of steam-water distribution equation, which are deduced for a steady-state system beyond simple mass and energy balance equations, though they are all from the First Law of Thermodynamics
3. The analytic formula of heat consumption rate for thermal power plant indicates that the current heat consumption rate of system can be determined by the system

structure and its thermodynamic properties, as well as all kinds of small auxiliary steam/water flows. It can be easily programmed with the date from existing plant instruments.

4. Based on the research into the assumption for system analysis, the idea of state space model analysis is imported from control theory. The two important vectors, that is, transfer matrix is worked out, which reflects the characteristic of the system itself and hold constant under a steady state condition. Therefore, the system outputs increment is regarded as the results of the disturbance input imposed on the system state space model.
5. The thermal disturbance vector, main system vector, etc. are the new practical approaches proposed here. The regulations to construct these vectors are very comprehensible and convenient, which closely refer to system topology structure and greatly simplify the system analysis process against the traditional whole system balance calculation.
6. The transfer matrix is no longer suitable for the calculation under the circumstances with large deviation of system state or devices degradation, where the current system properties have to be reconfirmed. However, the system state equation holds for any steady state. The vector based method works well on a new reference condition.

In a word, the linearization technique is still an indispensable method for the analysis of such a complex system.

Nomenclature

D mass flow rate, kg/s

h specific enthalpy of the working substance, kJ/kg

N_p total enthalpy increase by feedwater pump shaft work, kJ/kg

N power output, kW

q heat transferred by extracted steam per unit mass in heater. For the closed feedwater heater unit, it is equal to the specific enthalpy difference of inlet steam and outlet drain water. For the open feedwater heater unit, it is equal to specific enthalpy difference of inlet steam and the heater unit's inlet feedwater, kJ/kg

Q rate of heat transfer, kW

$\dot{Q}$ rate of heat transfer by boiler, kW

$[\mathbf{Q}_{fi}]$ equivalent vector consisting of the thermal exchange of all auxiliary steam (water) flow or external heat imposed on the main thermal system

$\hat{q}$ heat consumption rate, kJ/kW.h

γ heat transferred by drain water per unit mass in heater. For the closed feedwater heater unit, it is equal to the specific enthalpy difference of the upper drain water and its own drain water. For the open feedwater heater unit, it is equal to the specific enthalpy difference of the upper drain water and the heater unit's inlet feedwater, kJ/kg

τ specific enthalpy increase of feedwater through the heater unit, kJ/kg

τ_p specific enthalpy increase of feedwater through pump, kJ/kg

σ specific enthalpy increase of reheated steam, kJ/kg

Subscripts

0 primary steam
b boiler blowdown
c last stage exhaust steam.
c' total number of the extracted steam leaving before reheating.
d drain water of heater
d' total number of shaft gland steams of HP.
df auxiliary water flow out of or into drain pipe
eH exhaust steam of HP
f auxiliary steam flow out of or into extraction pipe or
fw feedwater
i series number for heater unit
l leakage of steam or water
r reheated steam
rs dereheating spray water
ss desuperheating spray water
sg shaft gland steam
w feedwater or condensate water
wf auxiliary water flow into or out of feed water pipeline
wc condensate water from hot well
x all kinds of steam leaving from turbine

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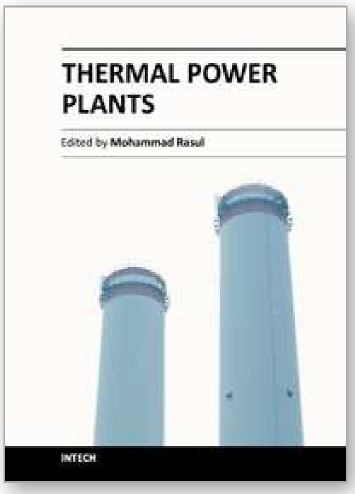

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Thermal power plants are one of the most important process industries for engineering professionals. Over the past few decades, the power sector has been facing a number of critical issues. However, the most fundamental challenge is meeting the growing power demand in sustainable and efficient ways. Practicing power plant engineers not only look after operation and maintenance of the plant, but also look after a range of activities, including research and development, starting from power generation, to environmental assessment of power plants. The book Thermal Power Plants covers features, operational issues, advantages, and limitations of power plants, as well as benefits of renewable power generation. It also introduces thermal performance analysis, fuel combustion issues, performance monitoring and modelling, plants health monitoring, including component fault diagnosis and prognosis, functional analysis, economics of plant operation and maintenance, and environmental aspects. This book addresses several issues related to both coal fired and gas turbine power plants. The book is suitable for both undergraduate and research for higher degree students, and of course, for practicing power plant engineers.

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