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An optimization of redundant measurements location for thermal capacity of power unit steam boiler calculations using data reconciliation method

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A B S T R A C T

The optimization of a location of redundant measurements under varying loads for steam boiler of a supercritical power unit using the generalized method of data reconciliation has been carried out. The method of weighted objectives has been applied as a method of optimization. This method reduce the weighted multi-criteria optimization task to task one-dimensional. Measurement values have been determined by numerical experiment and the Monte Carlo method for the designed redundant measurements system. For this purpose, a mathematical simulation model of a supercritical steam power unit with power rating of 900 MW in the *Thermoflex* program has been worked out. In the optimization calculations of location of redundant measurements as an objective functions minimizing the relative standard deviation of a boiler thermal capacity and maximizing the *Kullback-Leibler* divergence have been accepted. In the calculation the measurements were taken into account, which can be located in the water-steam system of the boiler and in the high-pressure heat recovery steam supercritical power unit. The results of calculations confirm the influence of the number of redundant measurements and places of their location in the thermal system of the boiler on the accepted criteria of optimization. Increasing the number of redundant measurements, in terms of the data reconciliation method, leads to decrease the relative standard deviation of the thermal capacity of the boiler and increase the value of *Kullback-Leibler* divergence, i.e.; decrease the information entropy of the measuring system.

1. Introduction

Currently energy conversion processes occurring in the contemporary steam power plants cannot be realized without the automatic supervision and ability to influence of their course. Modern power units are equipped with complex automation and control systems necessary for their proper operation. Increasing the nominal power of a power units and the use of supercritical steam parameters results in complexity of their thermal system [2,9]. For the safe operation of a supercritical coal-fired steam power units a sufficient number of measurements, concerning the technical condition of their equipment and running the processes of energy conversion, is required. Besides of measurement information associated with the control process, the measurement information concerning the supervision of operation has been significantly increased. Currently it enables the usage of a computer systems for decision support in terms of technical control operation and application of advanced methods of engineering analysis. An indispensable element of such systems should be an advanced validation of measurements data from distributed control systems using data reconciliation methods in case of measurements redundancy [1,9,13,17]. Moreover the data reconciliation method should be used in the case of application measurements data in the identification of empirical models, e.g. regression or artificial neural networks [4]. Also diagnosis of complex energy systems as presented e.g. in Refs. [11,12] requires reliable and reconciled operational measurements and unknown values. Only credible measurements data and calculated parameters should be used in this type of applications.

The generalized method of data reconciliation [6,8] could be used at the design stage of redundant measurements system for newly built power units. Number of redundant measurements and

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their location in the thermal system of power units can be optimized from the used criterion point of view. This criterion could be the minimization of uncertainty of the selected parameter which characterize the energy conversion process. Moreover another criterion can be determination of an extremum of parameters which describes in a comprehensive way the measurements system quality after validation his measurements.

The optimization of a location of redundant measurements under varying loads for steam boiler of a supercritical power unit using the generalized method of data reconciliation has been carried out. The method of weighted objectives has been applied as a method of optimization. This method reduce the weighted multi-criteria optimization task to one-dimensional task. The value of the criterion function in this method is the value obtained from the optimization calculation of the considered measurements location configuration for a given number of redundant measurements and for a given power unit load. It has been assumed that for the determination of weights of the objective functions the ordered diagram of real working of power unit will be used.

Measurement values have been determined by numerical experiment and the Monte Carlo method for the designed redundant measurements system. For this purpose, a mathematical simulation model of a supercritical steam power unit with a rated power of 900 MW in the *Thermoflex* program [16] has been worked out. Using simulation model a calculations for different loads of power unit have been performed. In the optimization calculations of location of redundant measurements as an objective functions minimizing the relative standard deviation of a boiler thermal capacity and maximizing the *Kullback-Leibler* divergence have been accepted [3]. This divergence is the criterion which describes the quality of redundant measurement system as a whole [10]. In the calculation the measurements were taken into account, which can be located in the water-steam system of the boiler and in the high-pressure heat recovery steam supercritical power unit.

The proposed algorithm consists in searching of vector of objective function values obtained from all possible solutions of the measurements configuration location in the thermal system of the boiler. The results of calculations confirm the influence of the number of redundant measurements and places of their location in the thermal system of the boiler on the accepted criteria of optimization. Increasing the number of redundant measurements, in terms of the data reconciliation method, leads to decrease the relative standard deviation of the thermal capacity of the boiler and increase the value of *Kullback-Leibler* divergence, i.e.; decrease the information entropy of the measuring system.

2. Principle of data reconciliation

Evaluation of the energy process is carried out by means of its measurements. In reality there are no error-free measurements. The results of measurements contain errors due to inaccuracy of the applied method of measurements, failures of the device or in the signal processing. Such errors are then passed to calculations of unknown values (quantities that are not measured). In thermal engineering in most cases the number of balance equations is larger than the number of unknown values. Hence the surplus equations are not fulfilled because the substance and energy balance equations are not reconciled. The application of the data reconciliation method permits calculations of the measurement corrections so that the all balance equations are fulfilled.

Data reconciliation can be mathematically expressed as a constrained weighted least-squares optimization problem [7,17]:

$$\min\left\{\sum_{i=1}^{m}\left(\frac{\widehat{x}_i - x_i}{\sigma_i}\right)^2\right\} \tag{1}$$

subject to

$$g_l\left(\widehat{x}_i, \widehat{y}_j\right) = 0 \quad for \quad l = 1, \ldots, r \tag{2}$$

The objective function (1) defines the total weighted sum of measurements corrections squares, whereas Formula (2) defines the set of mathematical model constrains. In the thermal engineering these constrains are generally mass and energy balances. Data reconciliation in thermal analysis permits to achieve the following aims [6,7,9,17,18]:

- calculation of the most reliable thermal measurements values,
- unique solution of the most probable unknown quantities in thermal processes,
- an assessment of the accuracy of the corrected results of measurements and of calculated unknown quantities,
- a reduction of uncertainty of measured quantities,
- the control of fulfilling of the assumed measurements uncertainty.

3. Simulation model of the thermal system of power unit

As previously specified, for the designed redundant measurements system, measurement values by means of numerical experiment have been determined. For this purpose, a mathematical simulation model of a supercritical steam power unit with a rated power of 900 MW in the *Thermoflex* program has been worked out. *Thermoflex* is a simulation program dedicated for simulation of power units [16]. Simulation calculations in this program was divided into three parts. In the first one the structure of the power unit is build and values of thermodynamics parameters in particular points of thermal system are assumed, for example: live and reheated steam parameters, pressure in the condenser, ambient parameters, electric power of the turbo-generator, etc. The results of calculations obtained from simulation model were verified by examples presented in the literature and industrial applications. The next step was to transfer this model into off–designed mode which allowed to simulate different loads of power unit and observe the behavior depending on the change of electric power of the turbo-generator. In the last part of simulation the calculations for various loads of the steam power unit have been carried out. The five loads were considered: 60, 70, 80, 90 and 100 percentage of power unit nominal load. Results of this simulation are presented in Table 1.

Considered part of the thermal system of power unit, which is the water-steam boiler system with a high-pressure regeneration and high-pressure part of the steam turbine with marked

Table 1
Selected output data for the simulation calculations.

Parameters	Unit	Load, %				
		100	90	80	70	60
Gross power	MW	900.0	810.4	720.0	630.5	539.8
Gross efficiency	%	46.84	46.46	45.87	45.00	43.92
Net power	MW	842.1	758.9	674.1	589.1	503.0
Live steam temperature	°C	650.0	649.0	649.0	649.8	648.8
Live steam pressure	MPa	30.0	26.9	23.9	21.0	18.2
Reheated steam temperature	°C	670.0	670.0	670.0	669.2	669.1
Reheated steam pressure	MPa	5.9	5.4	4.8	4.2	3.7
Feed water temperature	°C	309.0	304.0	298.0	291.0	284.0