An Improved Technique For Identification Of Mathematical Models Of Thermal Power Equipment

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***Abstract* — The paper proposes an improved technique for identification of mathematical models of complex thermal power equipment. This integrated technique provides more effective detection of gross errors in measurements of control parameters applied for identification of a mathematical model of studied equipment, validation of the model, correction of errors in the model construction, and an increase in the identification accuracy. Additionally, the paper presents an original approach to considering the effect of a generating unit load on the internal relative efficiencies of turbine compartments, which can be applied to other adjusted coefficients of the mathematical model with nonlinear dependence on equipment operating conditions. The proposed technique was tested on a detailed mathematical model of a 225 MW generating unit. In the paper, the mathematical model identification problem is solved for the generating unit and an example of optimization calculation is demonstrated for the actual operating conditions to decrease specific fuel consumption for electricity generation.**

***Index Terms* — Identification of mathematical models, mathematical modeling, optimization of operating conditions, state estimation.**

I. Introduction

The improvement in the energy and cost efficiency of the main thermal power equipment at thermal power plants is surely a topical and noteworthy objective. It follows from the fact that the thermal power equipment forms the basis for Russia's electric power industry and consumes a considerable portion of mined fossil fuel and other resources [1].

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The thermal power units (TPUs), such as boiler units and steam turbines, are technical systems with rather complex engineering flow diagrams, diverse elemental composition and operating conditions. Hence, the main instruments to study thermal power equipment are the methods of mathematical modeling and optimization of its flat diagrams and parameters.

Note that the equipment efficiency depends on its operating conditions and on-line control. The control efficiency of the main equipment of power plants can be improved by the operating personnel having a "feedback", i.e. the personnel should monitor changes in equipment parameters which are difficult or impossible to be metered directly (fuel consumption, generating unit efficiency, specific fuel consumption, etc.) with change in control actions [2].

The real state of thermal power equipment at thermal power plants (TPPs) is known to change in the process of operation, for example, salt accumulation in the turbine flow part, slagging of the heat-exchange surfaces of the boiler and regenerative heaters, and other changes which influence the equipment operation. Thus, the state estimation of main thermal power equipment is important for the on-line control of power plant operation [3].

II. Literature review

The foundations for application of the methods of mathematical modeling and optimization of thermal power equipment and thermal power plants were laid in the early studies by the researchers from Melentiev Energy Systems Institute. G.B. Levental and L.S. Popyrin dealt with optimization of continuous and discrete parameters of TPUs of different types and flow diagrams, presented automation principles of mathematical modeling of TPUs and described approaches to TPU optimization subject to initial information ambiguity [3, 4]. The methods of mathematical modeling of TPUs were developed by other Russian researchers: F.A. Vulman [5], A.A. Palagin [6], V.M. Borovikov [7].

The state estimation and mathematical model identification were studied by A.Z. Gamm and his colleagues to calculate power system conditions in the context of measurement errors. Approaches to detection of gross errors in measurements (called “bad” data) that are based on the method of test equations are described in [8].

The state estimation and identification of the parameters of mathematical models are also applied to study pipeline systems. In his research, N.N. Novitsky comprehensively analyzes some state estimation problems and methods developed considering specific features of hydraulic circuits [9].

G.V. Nozdrenrko and G.D. Krokhin were the first to deal with these problems in thermal power industry [10, 11]. They proposed a technique for coordination of the heat and energy balance equations to solve the state estimation problems. However, these studies do not state and solve the identification problem of test parameters that cannot be measured directly, and do not examine the interrelation between the optimal solution and an error in measurements.

On the whole, by now a great number of technical and economic studies of energy (and other) facilities have been carried out using the methods of mathematical modeling and optimization. It is worth noting, however, that the indicated studies deal, as a rule, with relatively simple facilities and rather simplified mathematical models as objects of studies.

At present, of great interest are more complex energy facilities, such as combined-cycle gas turbines, multi-purpose thermal power plants producing both electric energy and synthetic liquid fuel, ultra-supercritical steam power plants and others. Usually, the optimization studies of such units involve the method of continuous enumeration of a predetermined set of flow diagrams and parameters [12-14]. The original methods of thermodynamic analysis are applied in combination with rather simple models to upgrade complex TPUs [15-16].

However, the insufficiently extensive use of effective mathematical modeling methods to control operating conditions of TPPs is explained by some difficulties. These are considerable complexity of mathematical models of current TPUs and the need to adjust these models to the actual equipment state changing over time.

Thus, the problems of state estimation of thermal power system operation and identification of mathematical model parameters have not been solved due to the complexity of objects of studies and their mathematical models, and the lack of effective methods, algorithms and computer programs to solve the required mathematical tasks. The results of solving the indicated problems are of importance in themselves and play a large part in solving the TPU control problems, e.g., optimal load distribution among the TPP units and optimal control of TPU and TPP operation.

An up-to-date generating unit installed at the Kharanor condensing power plant (Yasnogorsk settlement in the Trans-Baikal Territory) is taken as the object of the studies. It consists of the 225 MW steam turbine К-225-12,8-3Р with an intermediate steam superheat and the high pressure boiler ЕП-630-13,8-565 БТ with a steam capacity of 630 t/h. More detailed flow diagrams and mathematical models of the turbine and boiler are presented in [17].

The mathematical model of the generating unit was constructed using the software “System of the computer-based construction of programs” that was designed at Melentiev Energy Systems Institute [18]. The calculation scheme of the generating unit consists of 100 elements and 169 ties between them. The obtained mathematical model consists of 1154 input parameters and 1420 output parameters, 40 parameters of which are iteratively calculated and require an initial approximation to be specified.

This study is a continuation of research on identification of mathematical models of the main thermal power equipment at TPPs. The optimization problems were formulated, and some boiler and turbine units and other power equipment were calculated earlier in [18–25].

The software included some techniques designed for identification of mathematical models of energy equipment based on the measurements of the parameters (flow rates, temperatures, pressures, etc.) at different points of the flow diagrams of steam boilers and turbines that were taken during the tests of the studied equipment in several operating conditions [1, 2, 17, 25]. These techniques allow adjusting the mathematical model coefficients so that the results obtained using the mathematical model correspond most accurately to the actual equipment state, which ensures the validity of optimization solutions.

The application of these techniques made it possible to reveal their shortcomings which prevented us from successful identification of the studied equipment model. Firstly, the identification is successful, if there are no gross errors in the measurements of parameters. However, if the measurements in some of the considered operating conditions contain “bad” data with gross errors, the errors are redistributed among different measured parameters in one operating condition and, which is more important, among different conditions. Such redistribution does not enable the erroneous measurement to be uniquely determined and leads to incorrect solutions. Secondly, the indicated techniques do not take into account the errors of the mathematical model itself. The models of main thermal power equipment at TPPs are based on the standard calculation methods and do not always describe real processes sufficiently correctly. This introduces additional errors to be taken into consideration when solving the identification problem.

III. The methodology

In this study, we propose an improved identification technique. It is designed to develop a new integrated approach on the basis of the existing methods for identification of mathematical models. It consists of 3 stages to solve the above problems and improve the accuracy of the mathematical model identification.

The parameters of the mathematical model identification problem can be conventionally divided as follows: the parameters $x_з$ that are measured at the unit and are the input data for the mathematical model; the measured parameters yз that are the output data for the model and the parameters $x_н$ that are not measured at the real unit but are the input data for the model. The array of the adjusted coefficients θ of the mathematical model is selected individually for each model. They are applied to influence the physical processes that occur in the mathematical model elements. Usually, such parameters are the coefficients of thermal efficiency of the boiler heat transfer surfaces, the hydraulic resistances of heat exchangers, the internal relative efficiencies of turbine compartments, and others.

In the first stage of identification, the inaccurate measurements of the parameters are revealed and excluded from further calculations. The inaccurate measurements are the values of the measured parameters that exceed the required accuracy of the measuring instruments applied during the tests. Such measurements can be revealed by minimizing the coefficient ψ (equations 4, 5) for each operating condition of the considered equipment individually. The coefficient ψ corresponds to the absolute maximum relative deviation among the measured parameters. The mathematical statement of the first stage of the identification problem has the form:

$$\min_{X_H^i, X_3^i, \theta, \psi} \psi \tag{1}$$

subject to

$$H(y, x_H, x_3, \theta) = 0 \tag{2}$$

$$G(y, x_H, x_3, \theta) \geq 0 \tag{3}$$

$$x_{3j} - \psi \cdot \sqrt{\sigma_{xj}^2} \leq \overline{x_{3j}} \leq x_{3j} + \psi \cdot \sqrt{\sigma_{xj}^2} \tag{4}$$

$$y_{3k} - \psi \cdot \sqrt{\sigma_{yk}^2} \leq \overline{y_{3k}} \leq y_{3k} + \psi \cdot \sqrt{\sigma_{yk}^2} \tag{5}$$

where H is the function of the equality constraints which includes all equations of the mathematical model and its elements; G is the function of the inequality constraints which takes into account physical and operational limitations on the real equipment operation; ψ is the coefficient equal to the absolute maximum relative deviation of the parameters (the parameters calculated by the mathematical model are with the upper bar, the parameters obtained by measurements on the real equipment are without the bar); σx2, σy2 are the variances of the measurement errors of the vectors xз and yз, respectively.

The indicated variances are determined from the expression:

$$\sigma^2 = \left(\frac{XB \cdot \alpha}{3 \cdot 100} \right)^2 \tag{6}$$

where XB is the upper limit of the instrument range, α is the class of the instrument precision (in %).

The measurement errors in the controlled parameters of a generating unit follow the normal law of error distribution. According to the central limit theorem, the distribution law of the sum of independent random values with finite variances tends to the normal law at the increasing number of summands irrespective of their distribution law [26]. As applied to the measurements, this means that the normal distribution of random errors is typical of the case, where the measurement result is affected by a set of random disturbances and none of them is dominant. The so-called three-sigma rule is applied in this study, since the confidential probability in this case is equal to 0.997, which provides good grounds to state that all possible measurement errors distributed by the normal law do not practically exceed 3 sigma in the absolute value. In equations (4, 5, 10, 11), the multiplier equal to 3 is replaced with the minimized coefficient ψ initially assigned by a big number (50-100). This is necessary to consider both the errors of the applied measuring instruments and the errors of the calculation technique and mathematical models. In the process of the optimization calculation (1) this coefficient tends to the value of 3, however, in practice it often takes somewhat higher value. Thus, this technique enables us to determine an additional error caused by the imperfection of standard calculation methods and by the simplifications of the mathematical model of the studied TPU.

The erroneous measurements can be detected on the basis of the determined active constraint on the deviation of the measured parameter value from the calculated one. The value of the measurements in this constraint can be marked as erroneous and removed from further consideration. The studies have showed that such an approach provides more effective detection of errors in measurements and minimizes redistribution of erroneous measurements among the parameters in different conditions.

In the second stage of the improved identification technique, the mathematical model of the studied equipment is tested for the errors in modeling. The optimization problem is similar to the problem solved in the first stage, only it is solved for all considered conditions jointly.

The study has indicated that solving this problem makes it possible to reveal that the mathematical model provides an incorrect description of the processes taking place in the generating unit. If there is a considerable deviation of parameters from measurements in different conditions of equipment operation, this is indicative of the absence of the required coefficient in the list of those to be specified or the inaccuracy of mathematical model construction, or it may be necessary to take into account negligible heat carrier flows neglected in the stage of mathematical model construction.

In the third stage of the mathematical model identification the following optimization problem is solved

$$\min_{X_H^i, X_3^i, \theta} f(y^i, x_H^i, x_3^i, \theta) \tag{7}$$

subject to:

$$H(y^i, x_H^i, x_3^i, \theta) = 0 \tag{8}$$

$$G(y^i, x_H^i, x_3^i, \theta) \geq 0 \tag{9}$$

$$x_{3j}^i - \psi \cdot \sqrt{\sigma_{xj}^2} \leq \overline{x_{3j}^i} \leq x_{3j}^i + \psi \cdot \sqrt{\sigma_{xj}^2} \tag{10}$$

$$y_{3k}^i - \psi \cdot \sqrt{\sigma_{yk}^2} \leq \overline{y_{3k}^i} \leq y_{3k}^i + \psi \cdot \sqrt{\sigma_{yk}^2} \tag{11}$$

$$f = \sum_{i=1}^{R} \left[\sum_{j=1}^{N} \frac{\left(x_{3j}^i - \overline{x_{3j}^i}\right)^2}{\sigma_{xj}^2} + \sum_{k=1}^{M} \frac{\left(y_{3k}^i - \overline{y_{3k}^i}\right)^2}{\sigma_{yk}^2} \right], \tag{12}$$

where f is the objective function that takes into account the deviations of all parameters calculated by the mathematical model (with the upper bar) from the measurements taken at the real equipment (without the bar), given the precision of measuring instruments used during the tests of the studied equipment; R is the number of calculated conditions; N is the dimension of the vector x_3; M is the dimension of the vector y_3.

IV. Results

The paper presents the calculation results obtained using the proposed improved technique for identification of the mathematical model of thermal power equipment with respect to the above-described generating unit.

The values of the measured parameters at the control points of the flow diagram that are necessary for the mathematical model identification were taken from the sensor readings provided by the engineering personnel of the power plant. The precision class of the applied instruments is 1% for the instruments measuring pressure, 2% for the instruments measuring temperature, 1.5% for the instruments measuring flow rate. The calculations were performed for several selected operating conditions of the generating unit. In one of the conditions, the feed water bypassed a group of high pressure heaters in the turbine. Each condition contained 55 measured values of the parameters at different points of the flow diagram.

The coefficient ψ was minimized in the first stage of the identification procedure. The optimization problem was formulated for each condition individually. The number of optimized parameters was 67, and the total number of inequality constraints was 234. The minimized coefficient ψ considerably exceeded the threshold value equal to three.

In this stage, three measurements in two conditions were revealed to contain gross errors. The first parameter, the steam pressure at the inlet of the 6th turbine compartment, was removed from the calculation in two conditions, and the steam temperature at the outlet from the 3rd turbine compartment-only in one condition.

Validity of the removal of the steam temperature measurement at the outlet from the 3rd turbine compartment can be proved using the *h,s*-diagram of the steam expansion process in the first five compartments for the considered condition which was developed on the basis of the measured values of the parameters. The diagram is presented in Fig. 1. The figures on the plot indicate the number of the turbine compartment with the steam temperature measurement at the outlet. The internal relative efficiency of the turbine compartment above unity (slope to the entropy decrease) is thermodynamically impossible. Consequently, this measurement in the second condition is inaccurate and must be excluded from further calculations.

The steam pressure measurement at the 6th turbine compartment inlet that corresponds to the pressure of steam extraction for the low pressure regenerative heater LPH-3 was tested in a similar way. Based on the measurements it is approximately equal to 2.6 kgf/cm^2. For the given pressure, the saturation temperature is 128 °C. At the same time, the water temperature measurement at the LPH-3 outlet is approximately 140 °C. It is evident that the water flowing through this regenerative heater cannot be heated up to the saturation temperature at the specified pressure. Thus, this measurement must be removed from further calculations.

After removal of the inaccurate measurements, the mathematical model of the studied generating unit was

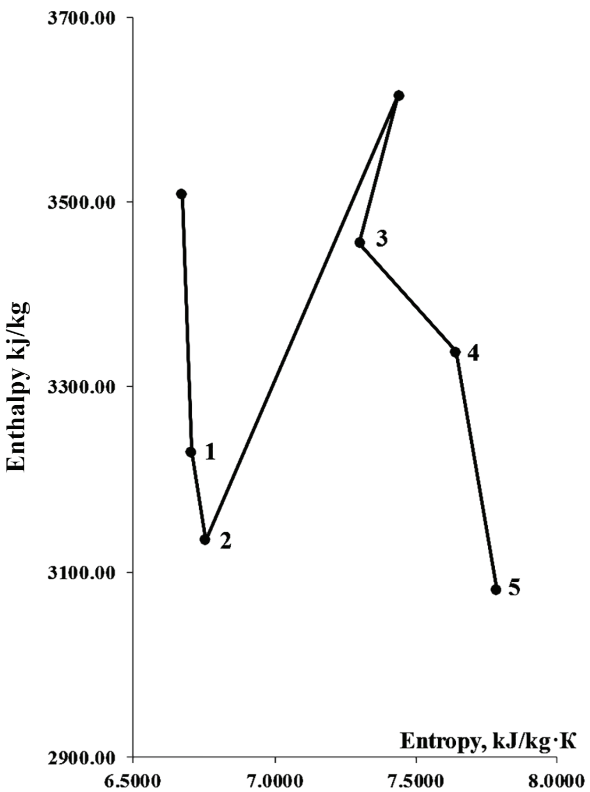

Fig 1. Steam expansion process in the first turbine compartments in the h,s-diagram.

tested for available errors in modeling in the second stage. The optimization problem statement is similar to the statement of the problem solved in the first stage, only it was solved for all considered conditions jointly. The number of optimized parameters in this problem was 82, and the total number of inequality constraints was 605.

An original idea to take into account the effect of change in turbine capacity (or steam flow rate at the turbine inlet) on the efficiency of its compartments was tested in this stage. The internal relative efficiency of turbine compartments is known to be variable and changes its value depending on the turbine load. For example, in the operating conditions close to normal ones it will be higher than in the conditions with a higher or lower load.

A turbine compartment is a group of stages between the steam extractions. The mathematical model of the turbine compartment consists of several equations (13-16). The main calculated parameters of the compartment are the steam pressure P_1 at the inlet, the steam enthalpy H2 at the outlet and the mechanical output N_M of the compartment

The pressure P_1 is determined by the known Stodola-Vlugel formula, where index 1 indicates the parameter values at the compartment inlet, and index 2 – at the outlet. The steam parameters in the nominal (or in some other representative) condition are denoted by the asterisk.

$$P_1 = \sqrt{\frac{G^2 \cdot P_1 \cdot V_1 \cdot \left(P_1^2 - P_2^2\right)}{G^{*2} \cdot P_1^* \cdot V_1^*} + P_2^2} \qquad (13)$$

where P is the steam pressure; G is the steam flow rate through the compartment; V is the specific steam volume.

The enthalpy H_2 is determined by the ideal heat drop, given the internal relative efficiency of the turbine cylinder. The impact of the steam moisture degree on the compartment efficiency reduction is also taken into consideration in the turbine compartments with wet steam formation, where P is the steam pressure; G is the steam flow rate through the compartment; V is the specific steam volume.

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$$H_2 = H_1 - \left(H_1 - H_2^i\right) \cdot \eta_i \qquad (14)$$

where H_1 is the steam enthalpy before the compartment; $H_2{}^i$ is the steam enthalpy at the end of ideal expansion up to the pressure P_2; η_i is the internal relative efficiency.

$$N_M = G \cdot \left(H_1 - H_2\right) \cdot \eta_м \qquad (15)$$

where $\eta_м$ is the mechanical compartment efficiency.

As distinct from all previous studies, the optimized internal relative efficiencies of the turbine compartments were replaced with the quadratic functions, where the ratio of the actual steam flow rate (G) through the compartment to the nominal flow rate (G^*) was used as a variable. The coefficients A, B, C in equation (16) are common for each turbine cylinder (HPC, IPC, LPC), but the coefficients η_i are determined for each compartment depending on the turbine load in different operating conditions

$$\eta_i = A \cdot \left(\frac{G}{G^*}\right)^2 + B \cdot \left(\frac{G}{G^*}\right) + C \qquad (16)$$

An example of the obtained relationship between the internal relative efficiencies of two first turbine compartments and the turbine load is given in Fig. 2.

Moreover, the calculations of the second identification stage showed that some calculated parameters in the deaerator significantly deviated from the measurements. Therefore, it was decided to change the mathematical model of this element by replacing the optimized steam throttling coefficient in the deaerator with the quadratic function of the form $k_Д = A \cdot x^2 + B \cdot x + C$, where x is the live steam flow rate at the turbine inlet that characterizes the turbine capacity; A, B, C are the new optimized coefficients. This change made it possible to adjust the mathematical model of the deaerator in terms of the impact of change in the turbine capacity in different operating conditions, which somewhat improved the accuracy of the generating unit model identification. The indicated changes in the second stage of the identification allowed minimizing the objective function (the coefficient ψ) to the value equal to 3.81, which somewhat exceeded the threshold value but was reasonable.

The optimization problem (equations 7-12) was solved in the third stage. There were 81 optimized parameters, and the total number of inequality constraints was 605. It is worth noting, that the coefficient ψ minimized in the first and second identification stages was excluded from the list of optimized coefficients and fixed. The third identification stage was needed to achieve the maximum possible closeness between the real equipment operation and the calculations on the mathematical model. Objective

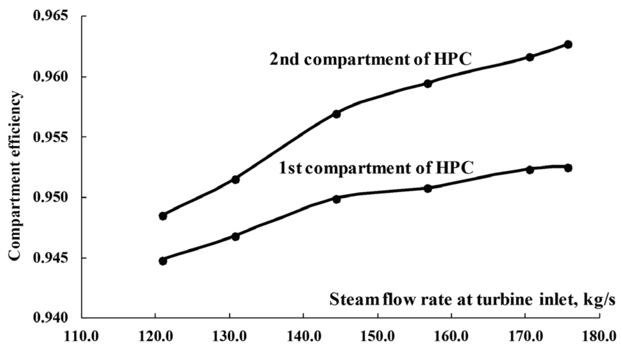

Fig. 2. Relationship between the internal relative efficiencies of two first compartments and load of the turbine

Table 1. Example of generating unit operating conditions optimization

No.	Parameter, measurement unit	Actual condition	Optimal condition
1	Consumption of fuel burnt in boiler, kg/s	34.22	33.38
2	Air-fuel ratio in boiler furnace	1.31	1.205
3	Enthalpy reduction in 1st injection, kcal/kg	8.54	1.27
4	Enthalpy reduction in 2nd injection, kcal/kg	7.29	0.37
5	Enthalpy reduction in 3rd injection, kcal/kg	2.54	2.45
6	Enthalpy reduction in LP injection, kcal/kg	27.93	3.61
7	Feed water pump head, kgf/cm2	168.95	179.11
8	Control action on reheat steam flow rate through 1st stage steam superheater, kgf/cm2	0.673	0.31
9	Water flow rate at condenser inlet, kg/s	10419	9825
10	Specific consumption of coal equivalent for power generation (gross), gce/kWh	305.01	297.89
11	Specific consumption of coal equivalent for power generation (net), gce/kWh	333.39	319.86
12	Gross generating unit efficiency	40.28	41.24
13	Net generating unit efficiency	36.85	38.41

function (12) in this case in contrast to the coefficient ψ was the sum of squared residuals of the parameters in all considered operating conditions of equipment. Correspondingly, in the third stage, we can achieve a reduction in all relative residuals of measured parameters, not only the maximum residual as in the first and second stages. After the identification was completed, the adjusted coefficients θ of the mathematical model were fixed and could not be changed.

Additionally, identification of the mathematical model of the studied equipment allows solving some important operational problems, such as state estimation of thermal power equipment or optimization calculations of flow diagrams and parameters of the studied thermal power plant equipment to improve its efficiency.

The optimization calculation on the identified mathematical model of the generating unit can be presented as an example. Consumption of the fuel burnt in the boiler unit was used as an objective function. An array of inequality constraints consisted of both physical constraints (on the temperature of pipe metal, the mechanical metal stress, the non-negativity of steam flow rates, etc.) and operating constraints (on the temperature of primary and secondary steam, the pressure in the condenser, the turbine capacity). Table 1 presents the values of the optimized parameters (lines 1-9), and the values of the generating unit efficiency (lines 10-13) in one of the considered conditions and in the calculated optimal condition.

The Table shows that changes in the operating parameters of the generating unit make it possible to considerably decrease the quantity of fuel burnt in the boiler with the same power output, which somewhat improves the efficiency of considered generating unit.

V. Conclusions

The paper proposes an improved technique for identification of mathematical models of complex thermal power equipment. The calculations indicate that the technique: a) more effectively detects gross errors in measurements of the control parameters applied for identification of the mathematical model of the studied equipment, assesses its correctness, b) corrects errors in the mathematical model construction and c) improves the identification accuracy.

Moreover, the paper presents an original approach to considering the turbine load impact on the internal relative efficiencies of turbine compartments, which can be applied to other adjusted coefficients of the mathematical model with the nonlinear dependence on the equipment operating condition. As a result, the adjustment accuracy of the mathematical models of TPUs is improved.

The improved technique for identification of mathematical models was tested on the detailed mathematical model of the advanced 225 MW generating unit. The study focused on the identification of a mathematical model of a generating unit and an example of optimization calculation of actual operating condition to decrease specific fuel consumption for power generation.

The mathematical model identification is important and plays an important part in TPU control, including the optimal load distribution among the TPP units and the optimal control of TPU and TPP operation.

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