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# Mathematical Modeling and Optimization of Large Thermal Power Installations

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*At present a software package, i. e. a system of computer-aided program generation, has been developed at Melentiev's Energy Systems Institute. It generates a mathematical model of a thermal power installation from simpler models of its elements and technological links among them. The generated mathematical model in turn can form part of the model of a larger installation. Thus, it becomes possible to construct mathematical models of thermal power plants and energy systems. The package is also intended for optimization of parameters of these models by the specially developed algorithm of non-linear optimization.*
*The operating conditions of co-generation plants were optimized by the constructed software package that is based on the computer construction of programs. It allows distribution of thermal and electric loads among the operating facilities of the plant depending on different optimality criteria. Besides, the package identifies the coefficients of mathematical models of the basic facilities of the plant by the results of measuring the parameters of its functioning. The efficiency of the software package was tested on some co-generation plants in Irkutsk region.*

Key words: *mathematical model, optimization, thermal power, CHP*

## Introduction

The existing thermal power plants of different types (steam turbine plants using fossil and nuclear fuel, natural gas combined cycle plants, *etc*.) has difficult internal structure. Valid decisions in designing and operation of such plants cannot be made without using their mathematical models of three types – static models for calculating the parameters and characteristics of the plant's components, static models for calculating the oper-

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ating conditions of the plant at the specified parameters of the components, and dynamic models for calculating the transient and emergency processes.

Studies in the field of computer-based mathematical modeling of thermal power plants have been carried out in the Melentiev's Energy Systems Institute (ISEM) for more than 40 years. They were aimed at creation of especial-purpose system of computer-aided program generation (for the personal computer – SCAPG-PC) for automatic construction of mathematical models of complex thermal power plants and other continuous technical systems [1].

## The software system of computer-aided program generation

Input data for this system include an archive of models of standard components of thermal power plants, a description of links between components of a plant for which the program is generated, and lists of the initial and calculated parameters that are to be recorded in a special input language. The program for the power plant computation is built in Fortran. The SCAPG-PC was applied for generation of tens of models of different types of thermal power plants which are widely used in the technical and economic analysis of a great number of plants.

A special graphic editor has been developed for the graphic display of flow diagrams of thermal power plants. It is aimed at generation of the archives of images of the diagram elements, construction of the flow diagrams from these images, and editing the diagrams contained in the archive (duplication, addition and elimination of elements and production links).

Description of the diagram in the input language of the SCAPG-PC system is automatically formed based on the analysis of graphic display. It includes description of the composition of diagram components, description of the production links between the components, and the command for program generation. The user adds to this command the lists of obligatory and desired initial data and desired calculated variables. Based on this information the scheduler of the computation process determines a sequence of the model operators, a composition of the initial data and iteratively calculated variables, and a start and end of the iterative cycle if available in the model. Then the program text generator constructs the program for calculating the flow diagram of the plant in Fortran.

The array of the numerical initial data is formed from the base of numerical initial data of component models. It contains standard sets of the initial data of components. The generator of the data array analyses the composition of the diagram elements, extracts the required data from the data base, and forms the numerical initial data array to calculate the flow diagram. Further this array can be edited by the user. For the convenient editing the array is supported by the comments with indication of the name for each value and its units.

The results of diagram calculation using the visualizer can be displayed on the flow diagram image by the special windows.

The SCAPG-PC is a very powerful system. It allows create diagram, built program for computation, monitoring data, *etc*. Mathematical models of thermal power plant created by SCAPG-PC may be used for optimization of its existing and future operation modes. The original method is developed for non-linear optimization. This method is first-order gradient method, where objective function and constraints are given implicitly.

Special software system was developed for optimization of operation modes by plant engineers and operational staff. This system has limited functionality compared to SCAPG-PC, but it contains all the tools necessary to optimizing modes, tuning the mathematical models of main equipment of plant, *etc*.

**The software system of optimization of thermal power plants**

The structure of the software system for optimizing thermal power plants (TPP) operation modes is shown in fig. 1. The software system allows the user to enter initial data on the loads of external consumers, on the state of TPP equipment, and so on in convenient form, to obtain calculation results in the form of hierarchically organized technological diagrams and tables, and to carry out calculations for determining the optimal distribution of loads among the TPP power units and identifying the main power-generating equipment [2].

A dedicated informational system for analyzing TPP calculation results has been developed within the scope of the software system. This informational system makes it possible to save optimal operating conditions in a database, to select operating conditions with respect to the main parameters (the TPP electric power output, thermal load, and others), to restore operating conditions for a calculation, to construct graphs characterizing the dynamics of changes in the parameters during operation in the specified modes, and to compare the optimal operating conditions with actual ones (established by the station personnel).

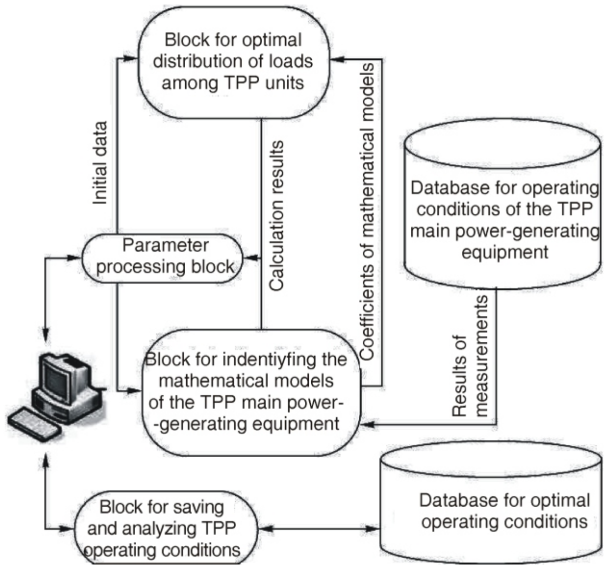


**Figure 1. Structure of the software system**

It should be pointed out that the actual state of TPP equipment varies during operation. For example, the turbine flow path may be clogged with salts, the heat transfer surfaces of the condenser and reheaters may become contaminated, *etc*. The coefficients of the mathematical models describing the elements of main equipment have to be corrected (identified) based on the results obtained from current measurements of their parameters for taking these phenomena into account. Such data can be obtained from tests of power-generating equipment or determined by means of sensors used in a TPP's automated data acquisition and storage system.

An optimization problem of the following form is formulated for identifying the mathematical models of the main power generating equipment at a TPP:

$$\min_{x^i_{nm}n,\, x^i_m,\, \theta} f(y^i, x^i_{nm}, x^i_m, \theta) \tag{1}$$

subject to the conditions

$$\begin{gathered}
H(y^i, x^i_{nm}, x^i_m, \theta) \quad 0 \\
G(y^i, x^i_{nm}, x^i_m, \theta) \quad 0 \\
x^i_{mj} \quad \psi\sigma_{xj} \quad x^i_{mj} \quad x^i_{mj} \quad \psi\sigma_{xj} \\
y^i_{mk} \quad \psi\sigma_{yk} \quad y^i_{mk} \quad y^i_{mk} \quad \psi\sigma_{yk} \\
f^i \quad \sum_{j\;1}^{N} \frac{(x^i_{mj} \quad \overline{x^i_{mj}})^2}{\sigma^2_{xj}} \quad \sum_{k\;1}^{M} \frac{(y^i_{mk} \quad \overline{y^i_{mk}})^2}{\sigma^2_{yk}} \\
f \quad \sum_{i\;1}^{R} f^i
\end{gathered} \tag{2}$$

where $i = 1,..., R$; $j = 1,..., N$; and $k = 1,..., M$. $R$ is the number of operating modes being calculated, $N$ – the dimension of the vectors $x^i_m$, $M$ – the dimension of the vectors $y^i_m$, $x^i_m$ – the vector of measured parameters in the $i^{\text{th}}$ mode that are the input parameters for the mathematical model of equipment, $x^i_{nm}$ – the vector of non-measured parameters in the $i^{\text{th}}$ mode that are the input parameters for the mathematical model and used in optimization calculations, $\theta$ – the vector of coefficients that are determined more exactly in the course of identifying the mathematical model of an installation (the internal relative efficiency of compartments, the throughput capacity of compartments, the efficiencies of regeneration heaters and delivery-water heaters, and like), $y^i_m$ – the vector of measured parameters in the $i^{\text{th}}$ mode that are the output ones for the mathematical model, $^{2}_{xj}$ the variance of the measurement error of $j^{\text{th}}$ component of the vector $x^i_m$, $\sigma^2_{yk}$ – the variance of the measurement error of the $k^{\text{th}}$ component of the vector, $y^i_m$, $f$ – a function that takes into account deviations of the parameters calculated using the mathematical model $(\overline{x^i_{mj}}, \overline{y^i_{mk}})$ from those measured in field equipment $(x^i_{mj}, y^i_{mk})$, and $\psi$ – the factor equal to the number of root-mean-square deviations by which the measured and calculated values of the corresponding parameters may differ from each other (is taken equal to 3).

Means that allow the identification problem to be formulated in a much easier way have been implemented to facilitate the use of the software system for online applications. An interactive diagram of a turbine unit has been developed, in which the points of all possible measurements are indicated, and a set of measured parameters for the mathematical model is assigned for each of these points. A set of actually measured parameters can be specified on this diagram, and relations can be established between the parameters of the mathematical model and measured values of the corresponding parameters of the power unit, which are stored in the database of the system for automated acquisition of the parameters characterizing the operation of power station equipment. These relations are used for automatically constructing the arrays of parameters and the arrays of their measured values and the arrays of measurement error variances. Figure 2 shows an example of a turbine unit diagram on which parameter measurement points are indicated. Application software that allows from 3 to 20 operating modes to be selected has been developed for selecting equipment operating modes to which the mathematical model will be tuned. The system constructed in this way allows mathematical models to be identified in an automated manner and enables the user to establish a set of measured parameters (without participation of the software developer) and completely relieve himself or herself from the need of manually entering measured parameters, feature that not only makes the work easier but greatly reduces the probability of random errors.

Usually the computer codes generated by SCAPG-PC give results with a high accuracy, but they are time-consuming. For multivariant simulations of process schemes for

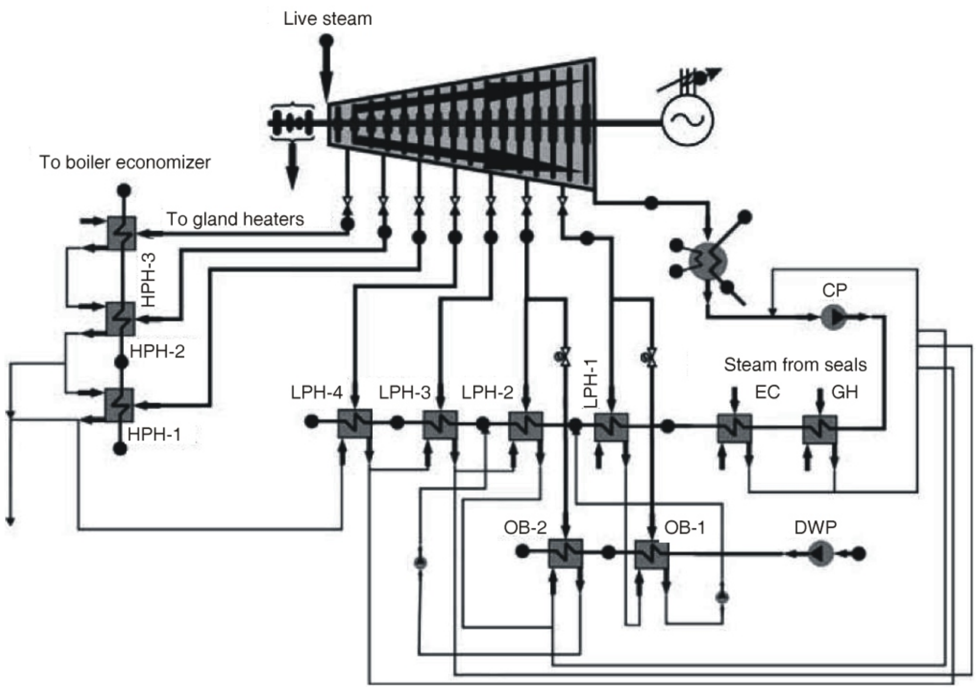


**Figure 2. Schematic diagram of the turbine unit with indicated measurement points**
*HPH – high-pressure heater, LPH – low-pressure heater, OB – delivery-water heater,*
*EC – ejector cooler, GH – gland heater, CP – condensate pump, DWP – delivery water pump*

a power plant, this high computing time is not a barrier. However, this is a problem for optimization of plant operation, when the addressing to calculation of equipment schemes may be as high as hundreds and even thousand iterations, so the issue of model optimization (performance) is the urgent one. There are special mathematical models have being developed to reduce computation time [3].

**Example of optimizing the operating modes of a co-generation station**

The described software system for optimization of operating conditions was implemented for the Novoirkutsk co-generation station (CS) of OAO Irkutskenergo. This cogeneration station is the main source of heat for the Irkutsk district heating system and plays a role in covering the electrical loads of the Siberian power system. The station comprises different types of complex power-generating equipment. Eight power generating boilers with a combined steam output of 4000 t/h and five co-generation turbine units have now been installed at this station. Brown coal is used as the main fuel. The software system is currently passing pilot operation at the Novoirkutsk co-generation station. Figure 3 shows the main window of the software. The tab. 1 gives, by way of comparison, indicators characterizing the actual and optimal operating conditions for two scenarios of the station's thermal and electrical loads. It can be seen from the table that running the station with optimized parameters allows 1.5-1.7% of fuel to be saved.

**Table 1. Comparison of actual and optimal co-generation station operation modes**

| Parameter | Mode 1 | | Mode 2 | |
|---|---|---|---|---|
| | Actual | Optimal | Actual | Optimal |
| CS electric power output, [MW] | 610 | | 547 | |
| Temperature of delivery/return network water, [°C] | 125/70 | | 102/62 | |
| Flow-rate of delivery network water, [$th^{-1}$] | 14310 | | 13940 | |
| Flow-rate of make up water, [$th^{-1}$] | 3245 | | 2795 | |
| Electric power output of turbines, [MW]: | | | | |
| – PT-60-130/13 st. No. 1 | 57 | 45 | 61 | 49 |
| – PT-60-130/13 st. No. 2 | 23 | 46 | 56 | 57 |
| – T-175/210-130 st. No. 3 | 172 | 147 | 167 | 164 |
| – T-175/210-130 st. No. 4 | 166 | 169 | 161 | 173 |
| – T-185/220-130 st. No. 5 | 192 | 203 | 102 | 104 |
| Consumption of fuel by the CS boilers, [tce $h^{-1}$]* | 321.2 | 315.9 | 248.5 | 244.8 |
| Saving of fuel at the CS, [tce $h^{-1}$]* | 5.3 | | 3.7 | |

* tce – tons of conventional fuel

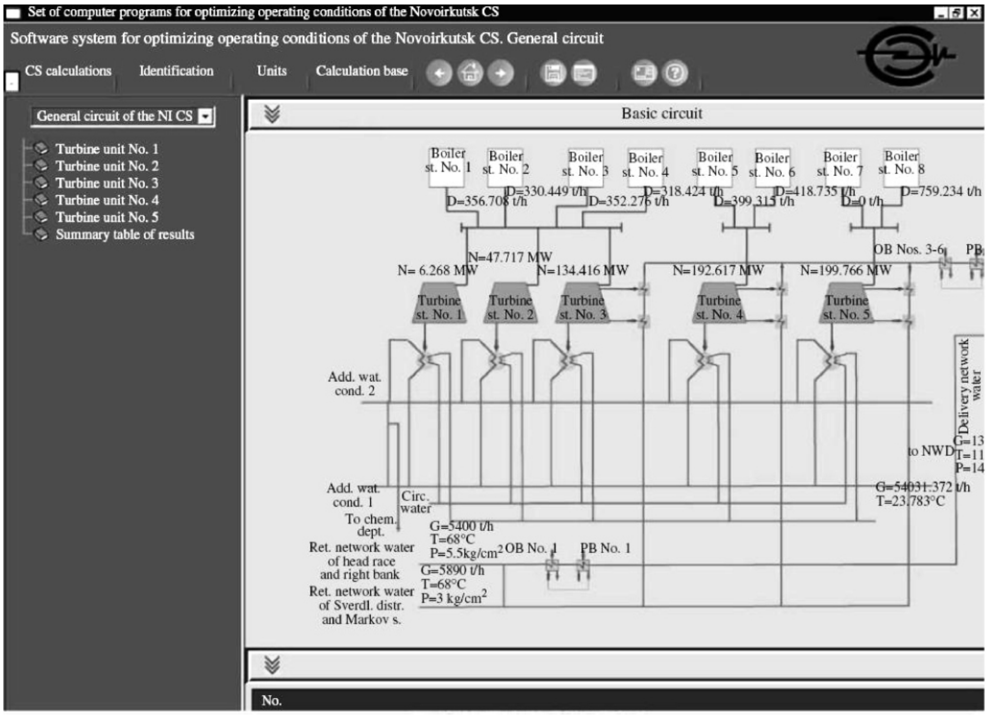


**Figure 3. Main window of the software system**

Figure 4 shows an example of the power performance characteristic of the Novoirkutsk co-generation station constructed using the software system for the operation with a thermal load equal to 4770 GJ/h and temperatures of delivery/return network water equal to 150/70 °C. An analysis of the obtained power performance characteristic shows the following. When the station power output is in the range of 400-480 MW, the CS electric power output increases as a result of a growth in the electric energy generated in the co-generation mode, and when the station output is in the range of 480-640 MW, its electrical power output increases as a result of a growth in the electric energy generated in the condensing mode.

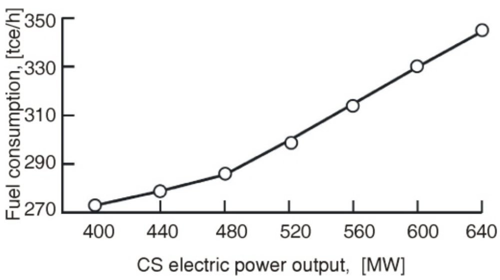


**Figure 4. Power performance characteristic of the co-generation station**

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## Апстракт

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## Математичко моделирање и оптимизација великих инсталација на термоелектранама

У Институту за енергетске системе „Мелентијев” развијен је софтверски пакет, тј. систем рачунарског генерисања програма. Овај систем генерише математички модел термичких инсталација из једноставнијих модела његових елемената и технолошких линкова између њих. Генерисани математички модел може формирати део модела веће инсталације. Према томе, постаје могуће да се на тај начин конструишу математички модели термоелектрана и енергетских система. Пакет такође служи за оптимизацију параметара поменутих модела коришћењем посебног алгоритма за нелинеарну оптимизацију.

Радни услови когенеративних постројења су оптимизовани конструисаним софтверским пакетом који се заснива на рачунарској конструкцији програма. Он дозвољава дистрибуцију топлотних и електричних оптерећења међу инсталацијама унутар постројења зависно од разних критеријума оптимизације. Поред тога, пакет идентификује коефицијенте математичких модела основних инсталација постројења помоћу резултата мерења параметара карактеристичних за њихово функционисање. Ефикасност софтверског пакета је тестирана на неким когенеративним постројењима у региону Иркутска.

Кључне речи: *математички модел, оптимизација, топлотна снага, когенерација*

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