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IMPLEMENTATION OF THE HIERARCHICAL APPROACH IN THE MATHEMATICAL MODELLING OF ONCE-THROUGH STEAM GENERATORS

Н.В. Ложечнікова. **Реалізація ієрархічного підходу у математичному моделюванні прямоточних парогенераторів.** Проведено комплексний системний аналіз прямоточного парогенератора, розроблена багаторівнева структура його моделі. Застосування процедури декомпозиції складного об'єкта на початкових етапах моделювання дозволило виділити багатовимірні підсистеми спрямованої дії. Це дає можливість застосування розвинених програмних засобів комп'ютерної імітації. В отриманій структурної моделі виділені підсистеми парогенератора в цілому, підсистеми парогенератора, що включає в себе екранні трубки, сепаратор, змішувач, фільтр, циркуляційний насос, з'єднувальні трубопроводи. Окремо було розглянуто зони екранних трубок, які визначаються станом робочого середовища (зона підігріву з однофазної середовищем, зона випаровування I і зона випаровування II з двофазної середовищем); кінцевомірні моделі секцій екранних трубок зон підігріву та випаровування. Встановлено, що моделі підсистем нульового рівня описуються системами диференціальних і алгебраїчних рівнянь, між внутрішніми змінними яких немає причинно-наслідкових відносин. Будь-яка підсистема першого і вищого рівня може бути представлена підмножиною підсистем безпосередньо нижчих рівнів і безліччю орієнтованих зв'язків між ними. У задачі моделювання прямоточного парогенератора був реалізований принцип рекурентного пояснення. Для опису взаємозв'язків підсистем використані теоретико-множинні, матричні і графічні способи. Показано, що ієрархічні моделі, виявляються формами опису, готовими для реалізації в мовах програмування високого рівня. Використання системного аналізу процесів, технології та конструкції прямоточного парогенератора, а також передбачуваної методології досліджень в тимчасовій і частотній областях, використовуваних розрахункових методів і методів імітації дозволяє вибрати типи і класи математичних моделей, форми їх подання, а також програмні засоби.
Ключові слова: прямоточній парогенератор, математичне моделювання, ієрархічна структура, теплове навантаження, топкова камера, фільтр, змішувач, сепаратор, живильний насос

N. Lozhechnikova. **Implementation of the hierarchical approach in the mathematical modelling of once-through steam generators.** A comprehensive system analysis of a once-through steam generator was carried out as well as a multilevel structure of its model was developed. The application of the procedure of decomposition of a complex object at the initial stages of modeling made it possible to single out multidimensional subsystems of directed action. This makes it possible to use advanced computer simulation software. We distinguished the subsystems of the steam generator as a whole, the subsystem of the steam generator, including the screen tubes, separator, mixer, filter, circulation pump, and connecting pipelines in the resulting structural model. The zones of screen tubes determined by the state of the working medium (heating zone with a single-phase medium, evaporation zone I and evaporation zone II with a two-phase medium), finite-dimensional models of screen tube sections of heating and evaporation zones we considered separately. It was found that the models of zero-level subsystems are described by systems of differential and algebraic equations, between the internal variables of which there is no cause-effect relationship. Any subsystem of the first and higher levels can be represented by a subset of subsystems of the immediately lower levels and a set of oriented connections between them. The principle of recurrent explanation was implemented in the problem of simulating a once-through steam generator. The set-theoretic, matrix and graphical methods are used to describe the relationships between subsystems. It is shown that hierarchical models are forms of description, ready for implementation in high-level programming languages. Systematic analysis of processes, technology and design of a once-through steam generator, as well as the proposed research methodology in the time and frequency domains, the calculation methods and simulation methods used, allows you to select the types and classes of mathematical models, forms of their presentation, as well as software.
Keywords: once-through steam generator, mathematical modeling, hierarchical structure, heat load, combustion chamber, filter, mixer, separator, feed pump

Introduction

Steam generators play an essential role in shaping the dynamic properties of power units. Progress in the field of automation of heat and power plants, improvement of their economic performance largely depend on obtaining reliable information on the dynamic properties of steam generators operating in a unit with a turbine. Modern technical means make it possible to solve many problems of control and automation of control according to the most complex algorithms. But the question remains without an exhaustive answer as to the extent to which new information technologies are able to improve the dynamic properties of once-through power steam boilers, and in what cases do it through

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measures of technical and technological and of a different nature [1]. New knowledge about this class of control and regulation objects is becoming relevant. In other words, new, more detailed mathematical models of steam generators are needed that have an extended area of adequacy, i.e., close to reality for wider ranges of variables and their rates of change.

Hydromechanical instability of a steam generator due to its great practical importance is the subject of extensive research [2]. In most studies on the dynamics of once-through steam generators, it is assumed that the steam-water mixture is homogeneous, which can lead to significant modeling errors [3].

Common to most of the known models is that they are not sufficiently structured. Analysis based on such models is in the nature of a statement and does not explain why the system has certain properties and what needs to be changed to improve them. It is obvious that the practically achievable degree of adequacy of object models also largely depends on the state of information technology.

In the last decade, powerful universal software tools have become widespread, which make it possible to carry out a complex analysis of dynamical systems using mathematical models that are very complex both in structure and in the class of operators and dimensions. Systematical research carried out on new models of once-through steam generators with the help of modern software and interactive capabilities of computers can help in the search and scientific substantiation of recommendations for improving the dynamics of power units.

Along with the potential capabilities of computer technology, which make it possible to build and use for research very complex models of control objects, new problems also appear. The most important of them is the choice of the methodology for mathematical description, analysis and computer simulation of complex systems and its development in relation to the technical objects under study. Another problem is to assess the adequacy of the models and check the reliability of the results of their analysis. In addition, multipurpose tools need to be supplemented with a system of algorithms and programs that provide calculations in a specific subject area.

Thus, the implementation of a multilevel model of a once-through steam generator develops the ideas of a system analysis of complex technical objects in the direction of their constructivization. The use of modern computer technologies will significantly complement the methods for analyzing the dynamic properties of the power unit during its operation both in the basic and in the regulating modes.

Analysis of recent publications and formulation of the problem

The development of hierarchical mathematical models of direct-flow steam generators of power units as control objects and the analysis of ways to improve their dynamic properties using modern means of computer simulation and information processing will solve these problems.

For this, on the basis of the principles of a systematic approach, an analysis of direct-flow steam generators is carried out as control objects, as well as the effects of the environment and the requirements for the functioning of steam generators. The methodology of mathematical description, analysis and computer simulation is selected and specified. The functional-target decomposition of the object and the construction of the hierarchical structure of the model formed by the cause-and-effect interaction of multidimensional subsystems (dynamic aggregates) are carried out. Physical processes in once-through steam generators are studied and the corresponding distributed and concentrated, nonlinear and linearized mathematical models of subsystems are constructed. Models and methods of analysis of once-through steam generators are systematized.

With regard to hierarchical models of steam generators, procedures for analyzing dynamic characteristics are developed and the choice of software for simulating and calculating dynamic systems using hierarchical models is substantiated. The influence of subsystems of various levels and the structure of their interconnections (topology) on stability is revealed, the sensitivity of the dynamic properties of the steam generator to variations in the connections between subsystems of different levels is estimated, the controllability and observability of the steam generator are established, and its properties are estimated along the channels of suppression of disturbances and reproduction of the setting influences.

Once-through steam generator of power units (Fig. 1) are characterized by many advantages in comparison with drum boilers. For example, these are the absence of a thick-walled drum in the steam generator; lower weight and cost of the boiler; smaller water volume of the steam generator.

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These properties make it possible to operate once-through boilers at sub- and supercritical pressures. In addition, changes in the load of once-through boilers can occur at sliding pressure [4].

In the load range from 30 to 85 %, the power unit operates at sliding pressure, while for loads greater than 85 %, the power unit operates at a constant pressure.

The structure of the once-through steam generator includes: vertical pipes of the steam generator, representing the screen of the boiler combustion chamber, separator, mixer, filter, circulation pump and connecting pipelines. Screen pipes on separate walls of the combustion chamber are divided into sections containing several tens of pipes in order to properly select the flow rate of the working substance.

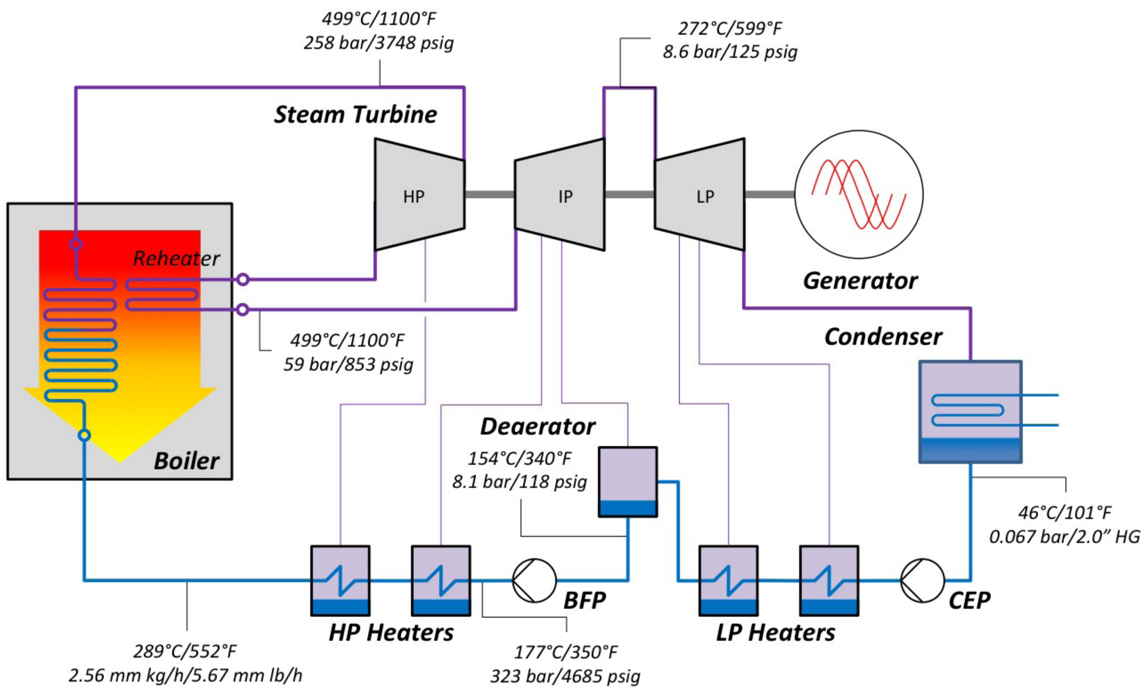

Fig. 1. Simplified power plant with once-through steam generator

Consumers and producers of electrical energy, which are connected by electric power grids, constitute a very complex energy system, consisting of a large number of subsystems with complex dynamic properties [5]. Such subsystems are, in particular, energy blocks, in which, in turn, a large number of complex dynamic processes take place.

For a steam generator operating in a power unit, the power system is the environment. During normal operation, for small deviations of individual values from the steady state values, the boiler is connected to the environment by the following values: boiler outlet pressure, steam consumption at the boiler outlet, signal of the set power of the power unit (set value of the amount of fuel). The steam consumption at the turbine outlet is determined by the sum of the following components: a change in the amount of fuel supplied to the boiler combustion chamber and a change in the pressure at the boiler outlet.

The presented components determine the following dynamic processes characterizing the operation of a steam boiler: "thermal inertia" determines the temporal changes in the steam flow rate at the boiler outlet after changing the set value of the amount of fuel supplied to the combustion chamber and the flow rate of feed water at a constant pressure. These conditions correspond to a situation where the boiler outlet pressure is regulated by acting on the turbine valves. The accumulation capacity determines the temporary changes in the steam consumption at the boiler outlet after a pressure change with a constant fuel amount and feed water consumption. The storage capacity of the boiler is determined by the time constant T_{ak}, which has the meaning of the absorption time of the nominal amount of steam from the heating capacity of the boiler in order to achieve a pressure change of 1 MPa, with the remaining values unchanged. For steam boilers operating on fuel oil and gas, T_{ak} has values in the range of 0.5…2 s/MPa, and for boilers operating on coal – 2…12 s/MPa [6].

The thermal inertia of the boiler is determined by a time constant T_L. For boilers operating on gas and fuel oil, the time constant T_L takes on values in the range of 15…60 s, at the same time for boilers operating on coal – 60…120 s [7].

Steam flow through the turbine valves is a function of the steam pressure at the boiler outlet and the degree of opening of the turbine valves $M_P = f(P, A)$. For small deviations from the steady state, the equation for this dependence takes the form:

$$\frac{\Delta M_P}{M_0} = \left(\frac{\partial f}{\partial P}\right)_0 \frac{P_0}{M_0}\frac{\Delta P}{P_0} + \left(\frac{\partial f}{\partial A}\right)_0 \frac{A_0}{M_0}\frac{\Delta A}{A_0}. \tag{1}$$

In the case when the function is close to linear, equation (1) can be written as follows:

$$\frac{\Delta M_P}{M_0} \cong \frac{\Delta P}{P_0} + \frac{\Delta A}{A_0}. \tag{2}$$

The storage capacity of the boiler allows significant changes in the mass flow rate of steam at the boiler outlet, as well as in the power of the power unit with sharp changes in the degree of opening of the turbine valves. This impact is temporary and enables the power unit to adjust the power and frequency in the power system in the event of rapid changes in energy demand.

The impact on fuel is characterized by slow changes in mass flow rate of steam, which allows the power unit to regulate the power and frequency in the power system with slow changes in energy demand.

When modeling complex objects and control systems, the method of decomposition into subsystems is used, the modeling of which is simpler [8]. The decomposition procedure is carried out as long as it is possible and expedient to determine the models of subsystems of the lowest (zero) level of the hierarchy. Zero-level subsystem models are described by systems of differential and algebraic equations.

As a result of a systematic approach to the analysis of the considered complex control object and the environment of its functioning, a decision is made on the consistent application of informal decomposition in the construction of mathematical and simulation models. Models of an object and its parts are presented as multidimensional subsystems of directed action (aggregates), which reflects the information-algorithmic approach adopted in control theory, and also makes it possible to use advanced software for computer simulation and calculations focused on “causal” models [9].

The purpose and objectives of the study

Models of subsystems of only the 0th level are described by systems of differential and algebraic equations, between the internal variables of which there is no cause-effect relationship. These equations reflect the laws of nature that govern the processes occurring in the steam generator. The l-level model S_l (*1*=1, 2, …) is described as a set of subsystems (*1*-1)-th level and a set of connections:

$$S_l = \left\langle S_{l-1}^i, P_l \right\rangle, \tag{3}$$

where P_l are the connections between subsystems, specified in matrix, set-theoretical or graphical forms on the sets of variables – the components of the vectors of inputs $u_{l-1}^i = (u_{l-1,}^{i,1} u_{l-1,}^{i,2} ...., u_{l-1}^{i,m})^T$ and outputs $y_{l-1}^i = (y_{l-1,}^{i,1} y_{l-1,}^{i,2} ...., y_{l-1}^{i,j})^T$ of the subsystems $i = 1, 2, ..., n_l$.The description of the 0-level subsystems also contains internal variables x_0^i, and the subsystems obtained as a result of topological reduction in the form of a state space are described using abstract variables v_0^i.

Connections of aggregates at this level of the model can be described by the following methods: block-graph (graphical method of representing the structure of the model); description of the operators of individual units; list of input and output quantities of individual units; unit-zero matrix of compounds.

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The proposed matrix, set-theoretical and graphical forms of representation of hierarchical structure models create the prerequisites for the implementation of the principle of recurrent explanation of systems theory. Hierarchical models turn out to be forms of description, ready for implementation in high-level programming languages.

Therefore, the aim of the work is to develop a hierarchical aggregate model of a once-through steam generator of a power unit based on the principles of a systematic approach to the analysis of once-through steam generators and requirements for their operation. And carrying out the functional-target decomposition of the object will allow to build a hierarchical structure of the model formed by the cause-and-effect interaction of multidimensional subsystems (dynamic aggregates).

Hierarchical formalization of the mathematical model of a once-through steam generator

The diagram of the hierarchical structure of the once-through steam generator model, in which special attention is paid to the model of the steam generator, at level 3 is connected with the models of the rest of the boiler devices. The description of the operator of *the steam generator* unit is as follows:

$$[P_{sep}, T_{sep}, H_{sep}, P_{eko}]^T = steamgenerator\ ([q^{\sim}, M_{Sl}, h_{weko}, M_{weko}, M_P]^T)\ . \tag{4}$$

To formalize the description of the model of a once-through steam generator, its structure contains the following subsystems: a mixer, a screen of a combustion chamber, a separator, a supply unit for injection desuperheaters, and connecting pipelines (Fig. 2).

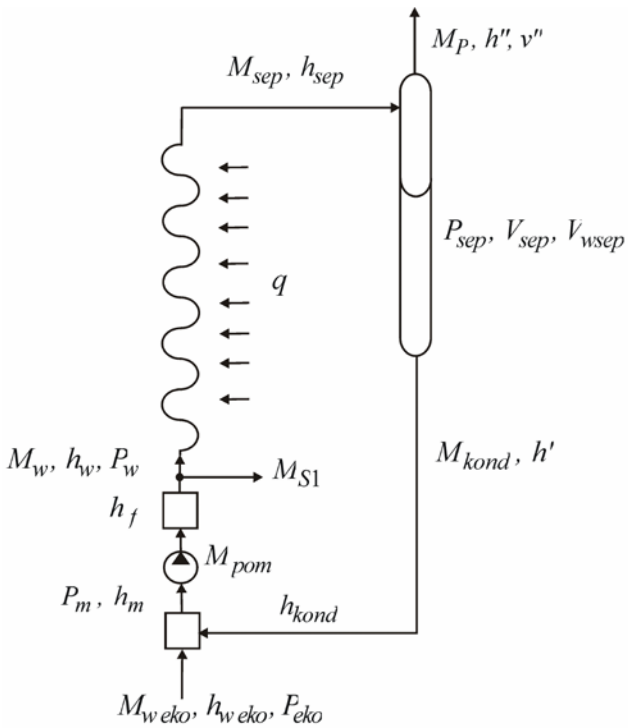

Fig. 2. Simplified diagram of a once-through steam generator

The individual subsystems of the steam generator model can be described by listing the input U_2^i and output vectors Y_2^i, as well as the definition of operators describing the subsystems F_2^i:

– combustion chamber screen:

$$[M^*_{sep}, h^*_{sep}, P_w]^T = steamgenerator.screen\ ([M^*_w, q^{\sim}, h_w, P_{sep}]^T)\ ; \tag{5}$$

– separator:

$$[H_{sep}, P_{sep}]^T = steamgenerator.separator\ ([M^*_{kond}, M^*_{sep}, h^*_{sep}, M^*_p]^T)\ ; \tag{6}$$

– mixer:

$$[h_m, M^*_{kond}]^T = steamgenerator.mixer\,([M^*_{pom}, M^*_{weko}, h_{weko}, P_{sep}]^T)\,; \quad (7)$$

– filter:

$$h_f = steamgenerator.filter\,(M^*_{pom}, h_{wef})\,; \quad (8)$$

– circulation pump:

$$M^*_{pom} = steamgenerator.pump\,([P_{sep}, P_w, H_{sep,} M^*_{kond}]^T)\,; \quad (9)$$

– injection desuperheater feed unit:

$$M^*_w = steamgenerator.injection\,([M^*_{pom}, M_{Sl}]^T)\,; \quad (10)$$

– connecting pipelines:

$$h_{we\,f} = steamgenerator.piping1\,(h_m)\,,\ h_w = steamgenerator.piping2\,(h_f)\,. \quad (11)$$

The structure of the connections of the subsystems in the steam generator model can also be written as a list of the input and output quantities of individual units and the indication of the output quantities that are connected to the individual inputs. These input quantities, to which one of the output quantities is connected, are “internal” variables at this level of the model. The rest of the input quantities form a vector of the model input quantities at this level.

In the case when for the input vectors of individual subsystems it is possible to separate the components originating from the input vectors of other subsystems u^i_{l-1} from the components originating from the environment c^i_{l-1}:

$$Y^i_{l-1} = F^i_{l-1}(u^i_{l-1}, c^i_{l-1})\,, \quad (12)$$

the configuration of connections of subsystems at a given level of the hierarchical model can be described using the matrix *H*, containing the values zero and one [10]. Matrix *H* has size *n***m*, where *n* is the sum of the dimensions of the input vectors of all subsystems, *m* is the sum of the dimensions of the output vectors of all subsystems.

Subsystems of the steam generator model: *mixer, separator, circulation pump, connecting pipelines* do not contain subsystems of the lower levels.

Three subsystems with different properties are distinguished in the model of screen tubes of a once-through steam generator: a *heating zone* located between the inlet section of screen tubes and the section in which the volumetric boiling of water begins (the enthalpy of water takes on a value $h'(P)$) – a section with a coordinate Z_I; *zone of evaporation* I with a high heat load, in which intensive steam generation occurs; the zone extends between the section with the coordinate Z_I and the place where the wall tubes are covered with a wall-mounted superheater; *evaporation zone* II with a low heat load is located between the wall-mounted superheater and the upper collectors of the wall tubes.

The boundary section between the heating and evaporation zone Z_I moves with speed U_I. The description of the subsystems of the steam generator wall tubes takes the following form: *heating zone*:

$$\begin{gathered}[Z_I, U_I, P_{NI}, h_{NI}, M_{NI}, \Theta_{NI}, V_{NI}, P_w]^T = \\ = steamgenerator.screen.heating\,([M_w, q^{\sim}, h_w, \Theta_{NI+1}, P_{NI+1}]^T)\end{gathered}; \quad (13)$$

evaporation zone I:

$$\begin{gathered}[M_{II}, h_{II}, P_{NI+1}]^T = \\ = steamgenerator.screen.evaporationI\,([q^{\sim}, Z_I, U_I, P_{NI}, h_{NI}, M_{NI}, \Theta_{NI}, V_{NI}, P_{II}]^T)\end{gathered}; \quad (14)$$

evaporation zone II:

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$$[M_{sep}, h^*_{sep}, P_{II}]^T = steamgenerator.screen.evaporationII\ ([q^{\sim}, M_{II}, h_{II}, P_{sep}]^T), \tag{15}$$

(the values with the index N_l determine the parameters of boiling water in the boundary section between the zones, the values with the index *II* are associated with the entrance to the evaporation zone *II*, sep – with the entrance to the separator and *w* – with the entrance to the wall tubes).

At the first level of the steam generator model, there are models of individual zones, determined by different types of flow of the working substance in the wall tubes of the once-through steam generator. The individual subsystems of the wall tubes of the steam generator are systems with distributed parameters along one spatial variable (the length of the wall tubes). In the lumped model, the individual zones are divided into finite elements (sections). These sections are described by systems of ordinary differential equations.

The description of individual sections of the heating zone takes the following form: section No. 1

$$[P_1, h_1, M_1, \Theta_1, P_w] = steamgenerator.screen.heating.s_1\ ([Z_I, U_I, h_w, q^{\sim}, M_w, \Theta_2, P_2]^T); \tag{16}$$

section No. *k*

$$\begin{gathered}[P_k, h_k, M_k, \Theta_k] = \\ = steamgenerator.screen.heating.s_k\ ([Z_I, U_I, h_w, q^{\sim}, P_{k-1}, h_{k-1}, M_{k-1}, \Theta_{k-1}, \Theta_{k+1}, P_{k+1}]^T);\end{gathered} \tag{17}$$

section No. *l*

$$\begin{gathered}[Z_I, U_I, P_{Nl}, h_{Nl}, M_{Nl}, \Theta_{Nl}] = steamgenerator.screen.heating.s_{Nl} \\ ([Z_I, U_I, h_w, q^{\sim}, P_{Nl-1}, h_{Nl-1}, M_{Nl-1}, \Theta_{Nl-1}, \Theta_{Nl+1}, P_{Nl+1}]^T).\end{gathered} \tag{17}$$

The description of the individual sections of the evaporation zone I takes the following form: section No. 1

$$\begin{gathered}[P_{od1}, h_{od1}, M_{od1}, \Theta_{od1}, W2_1] = \\ = steam.screen.evaporI.s_1\ ([q^{\sim}, Z_I, U_I, P_{N1}, h_{N1}, M_{N1}, \Theta_{N1}, \Theta_{od2}, P_{od2}]);\end{gathered} \tag{18}$$

section No. *k*

$$\begin{gathered}[P_{odk}, h_{odk}, M_{odk}, \Theta_{odk}, W2_k] = steam.screen.evaporI.s_k \\ ([q^{\sim}, Z_I, U_I, P_{odk-1}, h_{odk-1}, M_{odk-1}, \Theta_{odk-1}, W2_{odk-1}, \Theta_{odk+1}, P_{odk+1}]);\end{gathered} \tag{19}$$

section No. N_2

$$\begin{gathered}[h_{II}, M_{II}, W2_{II}, \Theta_{odN2}, P_{odN2}] = steam.screen.evaporI.s_{N2} \\ ([q^{\sim}, Z_I, U_I, P_{odN2-1}, h_{odN2-1}, M_{odN2-1}, \Theta_{odN2-1}, W2_{N2-1}, P_{II}]).\end{gathered} \tag{20}$$

Description of individual sections of evaporation zone II takes the following form: section No. 1

$$[P_{II}, h_{II1}, M_{II1}, W2_{II1}] = steam.screen.evaporII.s_1\ ([q^{\sim}, P_{II2}, h_{II}, M_{II}, P_{II2}]); \tag{21}$$

section No. *k*

$$[P_{IIk}, h_{IIk}, M_{IIk}, W2_k] = steam.screen.evaporII.s_k\ ([q^{\sim}, h_{IIk-1}, M_{IIk-1}, W2_{IIk-1}, P_{IIk+1}]); \tag{22}$$

section No. N_3

$$\begin{gathered}[h^*_{sep}, M_{sep}, W2_{sep}, P_{IIN3}] = \\ = steam.screen.evaporII.s_{N3}\ ([q^{\sim}, h_{IIN3-1}, M_{IIN3-1}, W2_{IIN3-1}, P_{sep}]).\end{gathered} \tag{23}$$

Mathematical models of once-through steam generators as systems with distributed parameters can be obtained only analytically – on the basis of a priori information about the structure of the object, the physical characteristics of the working means, as well as the laws of mechanics, thermodynamics, etc., written in the form of the so-called balance equations. At the same time, there are very limited possibilities for verifying object models. In particular, using empirical measurement data obtained from a real object in normal operation. Mathematical models of once-through steam generators can be represented in the form of systems of nonlinear differential equations in partial derivatives of hyperbolic type. Currently, there are no general analytical methods for studying this class of models.

Analysis of the results of formalization of the structural elements of a once-through steam generator

Computer simulation is still a universal tool for analyzing the dynamic properties of objects and systems described by nonlinear partial differential equations. This is a powerful research tool applicable to a wide class of models. The fundamental drawback of simulation studies is the extreme concreteness of individual results. From the set of numerical solutions obtained for various initial conditions and external excitations, it is difficult to derive generalizing judgments about the dynamic properties. In addition, numerical methods for integrating nonlinear partial differential equations are based on the discretization of time and space variables, which leads to inevitable errors.

It should be noted that it is not always possible to find ready-made computer simulation programs for mathematical models constructed by the researcher. The development of specialized programs is associated with huge labor costs and is an independent problem. In many practical cases, the use of existing programs for simulating dynamic systems requires modification of the original models. First, the modification can be associated with bringing the systems of differential and algebraic equations into a causal form, which makes it possible to build block diagrams formed by the oriented interaction of directional action elements. Second, the modification may consist in reducing the complexity of a class of models, for example, discretizing spatial variables to obtain systems of ordinary differential equations.

Linearization of nonlinear models makes it possible to apply analytical methods for analyzing dynamic properties, which allow one to obtain general conclusions, although, as a rule, only for local behavior (for example, a judgment about the stability of an equilibrium state).

Modern approaches to modeling complex technical systems combine simulation and analytical calculation methods. Approximation of a distributed model by a system of interconnected lumped elements described by ordinary nonlinear differential equations opens the way to the use of a number of simulation programs. Most of these programs are oriented towards the description language in the form of structural diagrams (directed graphs), i.e. on the so-called causal model. Therefore, the systems of ordinary and algebraic equations obtained as a result of the discretization of the spatial variable must be written in causal form. To determine steady states, that is, equilibrium positions, a system of algebraic equations is written using a nonlinear system, which is solved by numerical methods.

Models with lumped parameters linearized for small deviations from the equilibrium positions make it possible to apply powerful computational methods for analysis, to construct time and frequency characteristics, to calculate the eigenvalues of matrices, to study the controllability and observability of objects, the sensitivity of characteristics, etc.

By equating to zero the time derivatives in the original differential equations of the evaporator, ordinary equations are obtained for a single spatial variable. This makes it possible to construct a time-stable distribution of variables along the tubes of the evaporator screen. For the solution, you can use the MATLAB/Simulink program, supplementing it with the procedure for matching the boundary conditions.

Linearized lumped models can also be obtained by discretizing the spatial variable from linearized distributed parameter models.

Comparison of the equilibrium positions (at zero frequency), frequency and time characteristics, as well as the locations of the eigenvalues of matrices according to particular models obtained in different ways, increases the reliability of models, numerical integration methods and simulation parameters, calculation methods, allows you to select the number of finite-dimensional elements when discretizing distributed models.

Conclusions

A systematic analysis of a once-through steam generator, the effects of the environment on it and the requirements for its dynamic characteristics, as well as an analysis of the potential for information processing with the help of modern computers and software, made it possible to develop a multi-level

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structure of models of this most important technical object of the power industry. The hierarchical structures of the steam generator models are the result of the sequential application of the decomposition procedure for a complex object at the initial stages of modeling.

Models of an object and its parts are presented as multidimensional subsystems of directed action, which reflects the informational-algorithmic approach adopted in control theory. It also makes possible to use advanced software for computer simulation and calculations focused on “causal” models.

In the resulting structural model, subsystems of the following causal levels (from top to bottom) are identified: 3 – steam generator as a whole, 2 – steam generator subsystems (screen tubes, separator, mixer, filter, circulation pump, connecting pipelines); 1 – zones of screen tubes determined by the state of the working medium (heating zone with a single-phase medium, evaporation zone I and evaporation zone II with a two-phase medium); 0 – finite-dimensional models of screen tube sections of heating and evaporation zones.

Models of subsystems of only the zero level are described by systems of differential and algebraic equations, between the internal variables of which there is no cause-effect relationship. Any subsystem of the first and higher levels is described as a subset of subsystems of immediately lower levels and a set of oriented connections between them. Thus, in the problem of modeling a complex object, one of the principles of the systems approach is implemented. It is the principle of recurrent explanation. To describe the interconnections of subsystems, in the terminology of “aggregate conjugation operators”, one can use set-theoretical, matrix and graphical methods. The resulting block graphs have a shape close to the graphical images of the model editors of software such as MATLAB/Simulink. Essentially, hierarchical models turn out to be forms of description, ready for implementation in high-level programming languages.

A systematic analysis of the processes, technology and design of the steam generator, as well as the proposed research methodology in the time and frequency domains, the calculation methods and simulation methods used, makes it possible to select the types and classes of mathematical models, the forms of their presentation, as well as software.

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