УДК 681.5
DOI: 10.17277/vestnik.2023.01.pp.017-026

ENERGY-SAVING CONTROL OF THE HEATING PROCESS

**S. V. Artemova[1], M. A. Kamenskaia[2],
A. I. Ladynin[1], A. G. Shmeleva[1], Vu Tri Chien[1]**

Department of Informatics, MIREA – Russian Technological University (1), Moscow, Russia; department of Power engineering, Tambov State Technical University (2), art_mari@bk.ru, Tambov, Russia

Keywords: expert system; energy-saving synthesis program; heating dynamic mathematical model.

Abstract: A technique for synthesizing an optimal program for energy-saving control of the heating process using the developed expert system is considered. The analysis and synthesis of the control is based on the method of synthesizing variables, which involves the use of some synthesizing vector, the dimension of which is much less than the dimension of the initial data array of the energy-saving control problem, and which uniquely determines the type and parameters of the control function.

As an example, the paper presents a block diagram of the control of an object, which is a system consisting of a heating element and a metal vessel with water installed on it. For the given system, a model of heating dynamics and an energy-saving control program were obtained, making it possible to reduce power consumption. The implementation of the control program allows saving about 6 % of electricity costs.

1. Introduction

The intensive development of the optimal control theory is usually associated with the Pontryagin's maximum principle, dynamic programming and related studies. This theory serves as a methodological basis for solving various applied problems, related to optimal control, in which the state of the object under study at any fixed moment in time can be defined by a vector in a finite-dimensional space. When using these principles, methods and theories, researchers encountered a number of difficulties caused by the fact that for processes described by infinite-dimensional systems, it is not possible to find a sufficiently universal statement of the problem with complete and verifiable optimality conditions. Even when the specified conditions for the optimality of the problem to be solved were formulated, there were fundamental difficulties in their practical use in finding the optimal control and its approximations [1, 2].

Jumps in operation states during control processes are possible. These changes can possibly affect the initial data array elements of the control problem, such as object model parameters, control action boundaries or time. The control problem itself may also change due to additional restrictions introduction or minimized functional changes. Therefore, an important problem formulation is the correct choice of the control strategy, which is why in addition to the program and positional strategies, energy-saving control system should include such adjustable strategies. We consider the differences between adjustable control strategies and non-adjustable ones. With an unadjusted program control strategy, energy-saving control program, calculated for the initial control time is stored for any changes in the operating states. With an adjustable program strategy, when the operation state event changes, the control program is recalculated. With an adjustable positional strategy, the control function is synthesized again whenever the operation states change.

2. Energy-saving control synthesis

To solve the problems of analysis and synthesis of optimal control of objects, the developed expert system "Energy-saving control of dynamic objects" was used, the block diagram of which is shown in Fig. 1.

The main features of the expert system are as follows:

– dynamics modes of control objects are described by differential equations less than third order;

– energy costs, fuel consumption, control time, etc. are considered as minimized functional, taking into account the integral restrictions on the energy limit or fuel supply;

– control of determining the energy-saving type and calculation parameters is implemented by the program or positional strategies;

– solving problems of identification of control object dynamics models in the form of differential equations with discontinuous right-hand side;

– control devices for microprocessor software development;

– design of algorithmic support for optimal energy-saving control systems to solve direct and inverse problems.

The mathematical basis for the expert system includes several fundamental principles and is as follows:

– analysis and synthesis of complex systems on configurations variety;
– automatic control theory;
– Pontryagin's maximum principle;
– synthesizing devices method;
– interval analysis;
– objects' modeling and identification methods;
– selecting methods of optimal solution.

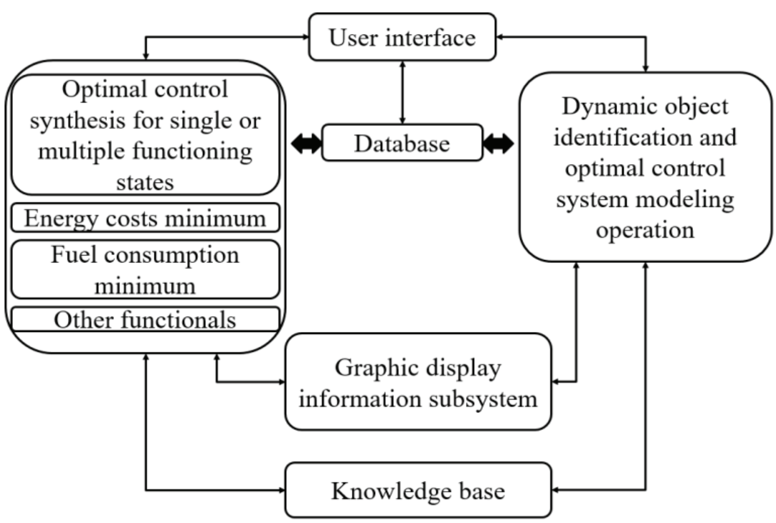

Fig. 1. A structural diagram of the energy-saving control expert system

The functioning of the expert system is based on the problem of optimal control using the technology of intellectualization of solution synthesis by representing the objects of the processes under study through an integrated graph, the vertices of which are at different abstraction levels. Each level is characterized by a number of features, variable laws and principles that describe the behavior of the system. For such a hierarchical description to be effective, models must be as independent as possible for different levels of the system. To distinguish this notion of hierarchy from others, the term "stratified system" is used for it. Abstraction levels that include a stratified description are called strata.

The main goal of solving the problem of intelligent synthesis is to obtain an optimal control that minimizes the given functional. The proposed technology is implemented as an AND-OR graph that meets the task of building algorithms for the synthesis of control of energy-intensive objects.

Search in the state space characterizes the solution of a particular problem as the process of finding the path state graph. In the state space, the vertices of the graph correspond to problem states and represent knowledge frames, the operation of which is implemented using algorithms of functional software modules, while the edges represent the transmitted and received information. The vertices of the graph are proposed to be located at different abstraction levels, making them belong to some strata. Each level represents a stage in the process of solving an algorithmic problem. The introduction of strata makes it possible to identify typical stages of intelligent control synthesis, as well as to optimize search algorithms on the graph, considering only alternative paths in the state space. The hierarchical model is shown in Fig. 2.

The upper layers are designed to identify information models of the analyzed objects and the process model of its technological equipment. The class stratum of optimal control problems characterizes problem-solving features. The modes and goals stratum is designed to determine the appropriate control functionality. Depending on the operating mode of the object, the control goal may change.

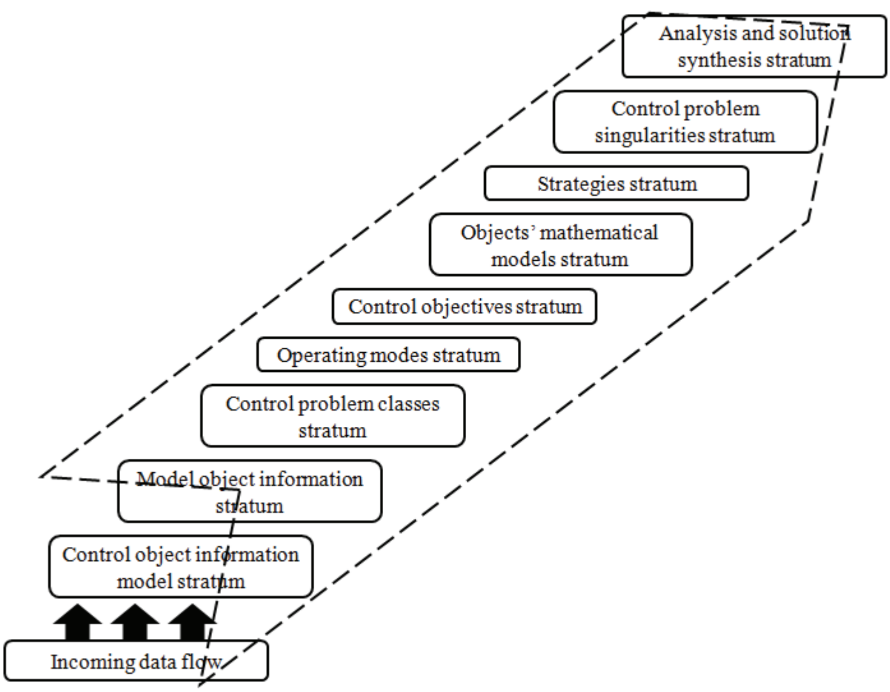

Fig. 2. Strata hierarchical model

The model stratum identifies the mathematical model of the object suitable for solving the control problem. Moreover, module identification procedures make it possible to choose the most adequate model of the control object based on the given experimental data.

The strategy stratum contains strategies for implementing optimal control. The feature stratum contains procedures that allow solving control problems taking into account: integral constraints, control of fixed and non-fixed time intervals as well as the phase coordinate trajectory of the ends of both object models with fixed or interval parameters, taking into account noise.

The analysis and synthesis stratum also contains several procedures: variable synthesis methods, Pontryagin's maximum principle, analytical synthesis of optimal controllers, dynamic programming and several others. The above technology makes it possible to synthesize solutions without decision maker participation.

The presented technology of intelligent synthesis of solutions makes it possible to develop optimal control strategies without the decision makers' participation [3].

3. Model definition

The statement of the energy control problem by systems with distributed parameters was given by A.Ya. Lerner and A.G. Butkovskij. They obtained results on solving a number of problems [2]. When managing such objects, the tasks of creating optimal control systems according to various criteria were solved. A minimized functional that depended on spatial variables, the state function, and control actions distributed in space were considered. In [4 – 6], various EMR set-ups were considered, where the functional of resource or energy costs was minimized:

$$J_{\mathrm{e}} = \int_{t_0}^{t_k} u^2(t)dt \,, \tag{1}$$

where $u(t)$ is controlling action; t_0 , t_k is initial and final value of the time interval.

The problem of optimal energy management can be set in the general form. We assume that $\mathbf{A}$, $\mathbf{B}$ are model parameters matrices; z^0, z^k are the initial and final values of the control vector; $u_{\mathrm{low}}, u_{\mathrm{upp}}$ are control action changes of the lower and upper bounds; n is the dimensionality of vector z.

We define the dynamic model of the object in the form of a system of linear differential equations

$$\dot{z} = \mathbf{A}z(t) + \mathbf{B}u(t), \qquad t \in [t_0, t_k], \tag{2}$$

where by the conditions on the vector of phase coordinates and scalar control are of the form:

$$z(t_0) = z^0 = \left(z_1^0, z_2^0, \ldots, z_n^0\right)^t, \; z(t_k) = z^k = \left(z_1^k, z_2^k, \ldots, z_n^k\right)^t, \tag{3}$$

$$\forall t \in [t_0, t_k]: \quad u(t) \in \left[u_{\mathrm{low}}, u_{\mathrm{upp}}\right]. \tag{4}$$

It is required to minimize the functional:

$$J = \int_{t_0}^{t_k} f_0(u(t))dt \,. \tag{5}$$

It is also required to find such control $u^*(t)$, under which for conditions (2) – (4) functional (5) reaches a minimum on the source data given array:

$$R = \left(\mathbf{A}, \mathbf{B}, u_{\text{low}}, u_{\text{upp}}, z^0, z^k, t_0, t_k\right). \tag{6}$$

For the formulated task above, the function $f_0(u(t))$ defines the cost functional. While minimizing energy consumption, it has the form (1). The described problem (2) – (5) is an optimal control problem with condition on control action that given by a time interval and phase coordinates' vector trajectory fixed ends. Usually, the average temperature of the object under consideration is taken as the first component of the control vector of the thermal object, and temperature change rate, etc. is taken as the second coordinate. In case of electric heating, the voltage or current of networks is taken over as the control.

4. Energy management strategy

There are different strategies for energy management implementing in dynamic modes action control. There are two well-known strategies for optimal control implementation. The first one involves software, in which the optimal program problem is solved by the synthesis of an optimal control scheme:

$$u^*(\cdot) = \left(u^*(t),\ t \in [t_0, t_k]\right),$$

The second one is positional, where synthesizing function determines the control system feedback, i.e.:

$$u^*(t) = s(z(t),\ t_k - t)\cdot$$

The optimal control at each time period is calculated depending on the values of the vector coordinates for the current phase and remaining time.

To solve the problems of analysis and synthesis of optimal control of objects, a developed expert system is proposed, the main features of which are the following:

– dynamic modes of control objects are described by differential equations not higher than the third order;

– energy costs, fuel consumption, control time, etc. are considered as the minimized functionals, taking into account integral limitations on the energy limit or fuel reserve;

– determination of the type and calculation of the energy management parameters is implemented by program strategy or positional strategies;

– the problem of identification of control objects dynamics is solved in the differential equations form with a discontinuous right-hand side;

– software development for microprocessor control devices;

– algorithmic support for designing direct and inverse problems of optimal energy management.

In the designed expert system a mathematical apparatus is used. This apparatus allows determining the function type of optimal energy management and calculating its parameters, change trajectories of the phase coordinates, the energy-saving effect and evaluating the performance of the control algorithm when the initial data is changed by the control data array. To date, the originality of the developed methods and the created knowledge base of the expert system have been confirmed. Manufacturers of equipment for industrial process automation have no information about real-time energy management and control synthesis possibility in various operating states in their product catalogs.

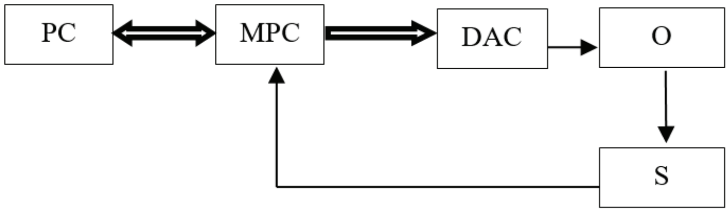

Fig. 3. Control flow chart for heating processes

The synthesis of the optimal program for energy management of the heating process using the proposed expert system was carried out according to the methodology that includes the following steps:

– obtaining experimental data on the dynamics of the heating process of the controlled object for the null CPT model;
– identification of the object model;
– synthesis of an optimal energy-saving program.

Testing of the described methodology was carried out as follows. The system consisting of an electric heating element with a metal vessel with water was used as a control object (O). The control was carried out according to calculated in the energy management PC program, and the microprocessor controller (MPC) performed the obtained program. The information about the object came from the sensors (S) of measured values through the MPC in the PC. Pairing the MPC and the object was carried out using a digital-to-analog adapter (DAC). The control flow chart is depicted in Fig. 3.

During the experiment, two values were measured: the temperature of the water was measured by a thermal sensor and the power consumption was measured by digital electric meter. The digital-to-analog adapter was a powerful thyristor multichannel key, providing contactless electric heater switching sections. The adapter had an input digital register with the possibility of external or internal input data synchronization. The design provided heating of the elements connection with a capacity of up to 3 kW, and also provided for the power stepwise switching possibility with a maximum number of switched channels not exceeding 8.

5. Solving the problem of minimizing electicity costs

According to the method, at the first stage, a heating thermogram was experimentally obtained, at the second stage, the heating model control problem was solved. The heating model type was determined and its parameters were calculated. From the non-optimal heating graph (Fig. 2), it can be seen that the object has a delay in the control channel $\tau = 1$ min. With this in mind, identification of the model dynamics was carried out in a time interval $t \in [1; 10]$. A sufficiently accurate model was proposed in the differential equations form with a discontinuous right-hand side consisting of two zones. The maximum absolute error of which was $E_{\max} = 0.4$ °C.

The first zone of the model $z \in [12.5; 32)$ is described by a real dual integrator:

$$\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -0.48 \end{bmatrix} \begin{bmatrix} z_1(t) \\ z_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0.86 \end{bmatrix} u(t).$$

The second zone $z \in [32; 100]$ is described by a first-order inertial object or an aperiodic link:

$$\dot{z} = -0.002z(t) + 1.423u(t).$$

At the final stage, using the designed expert system, an optimal control synthesis was performed, and the function obtained in this case has the following form:

$$u^*(t) = \begin{cases} 7.5 & t \in [0; 1), \\ 3.82 - 0.13e^{0.48(t-1)} & t \in [1; 6), \\ 3.75 - 0.20e^{0.002(t-6)} & t \in [6; 19.5]. \end{cases}$$

The strategy of the energy-management program was implemented according to the function shown in Fig. 4.

Theoretical calculation results and the experimental function vizualization are shown in Figs. 4, 5.

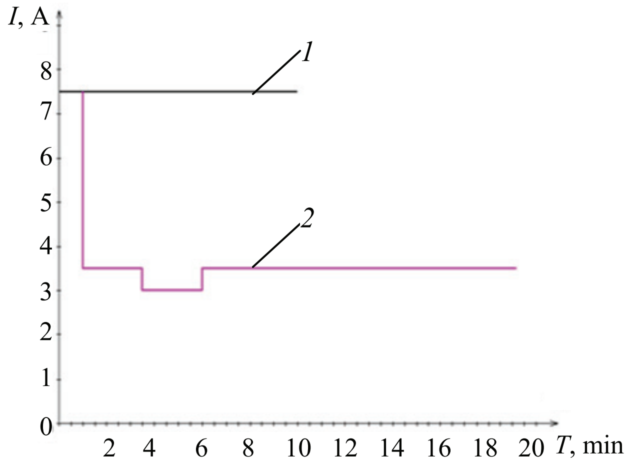

Fig. 4. Heating functions:
1 – non-optimal heating; *2* –optimal heating

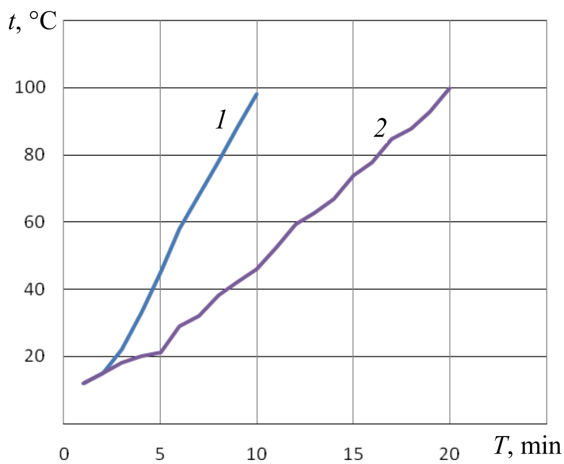

Fig. 5. Heating functions vizualization and optimized heating functions implementation:
1 – vizualization of the experimental data of the heating function;
2 – the experimental data for the optimized heating function

6. Conclusion

Having embodied the obtained energy management function for this system and comparing experiment and analytical calculation results, we can conclude that the maximum absolute error of the experimental thermogram was E_{max} = 2 °C. Comparing the energy consumption at non-optimal (0.245 kWh) and energy-saving (0.230 kWh) heating, we obtained an energy saving about 6 %. It is possible to apply the proposed method of the energy management synthesis, both for household appliances with electric heating (ovens, teapots, coffee pots, boilers, etc.), and for industrial energy-intensive objects (furnaces, extruders, presses, etc.).

References

1. Artemova S.V., Artemov A.A., Kamenskaya M.A. [Visualization of the analysis of energy-saving control of an inertial object of the first order], *Yestestvennyye i tekhnicheskiye nauki* [Natural and technical sciences], 2018, no. 11(125), pp. 366-369. (In Russ., abstract in Eng.)
2. Rokachevskii O.A., Sleptsov V.V., Ablaeva A.E., Kanaev S.A., Moskalenko O.V. Metrological Assurance of the Characteristics of Electric Drives at the Design Stage. *Journal of Physics: Conference Series: II International Scientific Conference on Metrological Support of Innovative Technologies (ICMSIT II-2021).* St. Petersburg, 3-6 March 2021. Krasnoyarsk, 2021, vol. 1889, pp. 042057. doi: 10.1088/1742-6596/1889/4/042057
3. Butkovskiy A.G., Lerner A.Ya. [About optimal control of systems with distributed parameters], *Doklady AN SSSR* [Report of the Academy of Sciences of the USSR], 1960, vol. 134, no. 4, pp. 778-781. (In Russ.).
4. Artemova S.V., Artemov A.A., Kamenskaya M.A. *Metodologiya proyektirovaniya intellektual'noy informatsionno-upravlyayushchey sistemy teplotekhnologicheskimi apparatami: monografiya* [Methodology of designing an intelligent information management system of heat-technological devices], Tambov, Publ TSTU, 2017. 196 p. (In Russ.).
5. Artemova S.V., Artemov A.A. [Energy management of industrial processes (by the example of installations annealing of magnetic circuits)], *Vestnik Tomskogo gosudarstvennogo universiteta* [Reporter of the National Research Tomsk State University, TSU], 2012, vol. 17, no. 5, pp. 1375-1379. available at: http://journals.tsutmb.ru/a8/upload/2018-december/temp.93bd89a87e3874b21c558c2ee8642320.pdf (accessed 02 March 2023). (In Russ.).
6. Artemova S.V. *Informatsionnaya sistema optimal'nogo upravleniya teplotekhnologicheskimi apparatami: monografiya* [Information system for optimal control of heat-technological devices], Moscow, St. Petersburg; Vienna; Hamburg, Publ. MINC [IINC], 2011, 234 p. (In Russ.).

Энергосберегающее управление процессами нагрева

С. В. Артемова[1], М. А. Каменская[2],
А. И. Ладынин[1], А. Г. Шмелева[1], Ву Чи Чиен[1]

Кафедра «Информатика», ФГБОУ ВО «МИРЭА – Российский технологический университет» (1), Москва, Россия; кафедра «Электроэнергетика», ФГБОУ ВО «Тамбовский государственный технический университет» (2), art_mari@bk.ru, Тамбов, Россия

Ключевые слова: математическая модель динамики нагрева; синтез программы энергосберегающего управления; экспертная система.

Аннотация: Рассмотрена методика синтеза оптимальной программы энергосберегающего управления процессом нагрева с использованием разработанной экспертной системы. В основе анализа и синтеза управления лежит метод синтезирующих переменных, предполагающий использование некоторого синтезирующего вектора, размерность которого значительно меньше размерности массива исходных данных задачи энергосберегающего управления и который однозначно определяет вид и параметры функции управления.

В качестве примера приведена структурная схема управления объектом, представляющим собой систему, состоящую из нагревательного элемента и установленного на нем металлического сосуда с водой. Для приведенной системы получена модель динамики нагрева и программа энергосберегающего управления, позволяющая снизить расход электроэнергии. Реализация программы управления позволяет экономить около 6 % затрат электроэнергии.

Список литературы

1. Артемова, С. В. Визуализация анализа энергосберегающего управления инерционным объектом первого порядка / С. В. Артемова, А. А. Артемов, М. А. Каменская // Естественные и технические науки. – 2018. – № 11(125). – С. 366 – 369.

2. Metrological Assurance of the Characteristics of Electric Drives at the Design Stage / O. A. Rokachevskii [et al.] // Journal of Physics: Conference Series: II International Scientific Conference on Metrological Support of Innovative Technologies (ICMSIT II-2021). – St. Petersburg, 3 – 6 March 2021. – Krasnoyarsk, 2021. – Vol. 1889. – P. 042057. doi: 10.1088/1742-6596/1889/4/042057

3. Бутковский, А. Г. Об оптимальном управлении системами с распределенными параметрами / А. Г. Бутковский, А. Я. Лернер // Докл. АН СССР. – 1960. – Т. 134, № 4. – С. 778 – 781.

4. Артемова, С. В. Методология проектирования интеллектуальной информационно-управляющей системы теплотехнологическими аппаратами : монография / С. В. Артемова, А. А.. Артемов, М. А. Каменская. – Тамбов : Изд-во ФГБОУ ВО «ТГТУ», 2017. – 196 с.

5. Артемова, С. В. Энергосберегающее управление технологическими процессами нагрева (на примере установки отжига магнитопроводов). – Текст электрон. / С. В. Артемова, А. А. Артемов // Вестник Томск. гос. ун-та. – 2012. – Т. 17, вып. 5. – С. 1375 – 1379. – URL :http://journals.tsutmb.ru/a8/upload/2018-december/temp.93bd89a87e3874b21c558c2ee8642320.pdf (дата обращения : 02.03.2023.)

6. Артемова, С. В. Информационная система оптимального управления теплотехнологическими аппаратами: монография / С. В. Артемова. – М. ; СПб. ; Вена ; Гамбург : Изд-во МИНЦ, 2011. – 234 с.

Energiesparende Steuerung des Heizprozesses

Zusammenfassung: Es ist eine Methode zur Synthese des optimalen Programms zur energiesparenden Steuerung des Erwärmungsprozesses unter Verwendung des entwickelten Expertensystems betrachtet. Die Analyse und Synthese der Steuerung basiert auf dem Verfahren zum Synthetisieren von Variablen, das die Verwendung eines Synthesevektors beinhaltet, dessen Dimension viel kleiner als die Dimension des anfänglichen Datenarrays des Energiesparsteuerungsproblems ist und der eindeutig Art und Parameter der Steuerfunktion bestimmt.

Als Beispiel ist das Blockdiagramm der Steuerung eines Objekts angegeben, bei dem es sich um ein System handelt, das aus einem Heizelement und einem darauf installiertem Metallgefäß mit Wasser besteht. Für das gegebene System sind ein Modell der Heizdynamik und ein Energiespar-Steuerungsprogramm erstellt, das es ermöglicht, den Stromverbrauch zu reduzieren. Die Implementierung des Steuerungsprogramms ermöglicht eine Einsparung von etwa 6 % der Stromkosten.

Gestion économe en énergie des processus de chauffage

Résumé: Est examinée la méthode de la synthèse du programme optimal de la gestion économisant de l'énergie du processus de chauffage à l'aide d'un système expert élaboré. A la base de l'analyse et de la synthèse de la gestion est la méthode des variables de la synthèse impliquant l'utilisation d'un vecteur de synthèse dont la dimension est beaucoup plus petite que la dimension de l'ensemble de données de base du problème de la gestion économisant de l'énergie, et qui détermine de manière unique le type et les paramètres de la fonction de la gestion.

À titre d'exemple, est donné un schéma structurel de la gestion d'un objet, qui est un système constitué d'un élément chauffant et d'un récipient d'eau métallique monté dessus. Pour le système ci-dessus, est cité un modèle de la dynamique du chauffage et un programme gestion économisant de l'énergie, ce qui permet de réduire la consommation de l'énergie. La mise en œuvre du programme de gestion permet d'économiser environ 6% des coûts d'électricité.

Авторы: ***Артемова Светлана Валерьевна*** – доктор технических наук, доцент, профессор кафедры «Информатика», институт комплексной безопасности и специального приборостроения, ФГБОУ ВО «МИРЭА – Российский технологический университет», Москва, Россия; ***Каменская Мария Анатольевна*** – кандидат технических наук, доцент кафедры «Электроэнергетика», ФГБОУ ВО «ТГТУ», Тамбов, Россия; ***Ладынин Андрей Иванович*** – доцент кафедры «Информатика»; ***Шмелева Анна Геннадьевна*** – кандидат физико-математических наук, доцент, заведующий кафедрой «Информатика»; ***Ву Чи Чиен*** – аспирант кафедры «Информатика»; институт комплексной безопасности и специального приборостроения, ФГБОУ ВО «МИРЭА – Российский технологический университет», Москва, Россия.
