The widespread use of electricity determines the development of new methods for effective control of electrical energy consumers in the face of changing constraints. A model of a decentralized control system for a group of electric room heaters based on the collective behavior of automatic machines interacting with a random environment with a limited resource distribution is studied.

The considered problem differs from the known ones in that the distribution participants are limited in the use of the resource by the "all or nothing" condition. This means that each electric heater at the current time can use a fixed amount of energy resources or refuse it, and the third is not provided. The decision to connect the heaters to the electrical network is made when performing the Nash equilibrium. The Nash equilibrium condition in this work means that the unused power of the electrical network is lower than the power of any heater not connected to the electrical network.

The self-organization procedure of a group of electric heaters is studied. A model of a control system for electric heaters has been developed with the task of distributing a limited resource of electrical energy based on Nash equilibrium, using the principles of decentralized control, information technologies for the development and implementation of control actions by a group of heaters. The experiments carried out have confirmed the effectiveness of a decentralized electric heating control system and allow us to recommend it for practical use. It is shown that the proposed approach opens the way to the construction of cost-effective intelligent electric heating systems

Keywords: decentralized control system, limited resource distribution, collective behavior of automatic machine, electric heating

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IMPROVING THE EFFICIENCY OF ELECTRICAL ENERGY DISTRIBUTION WITH DECENTRALIZED ELECTRIC HEATING CONTROL BASED ON NASH EQUILIBRIUM

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1. Introduction

In Europe, for example, the share of residential buildings with electric heating is at least 30 % in France, Germany, and Sweden. In England and Finland, electric heating is generally the main type of heating in all types of buildings [1]. In Norway, the share of electric heating reaches 70 %. In France, where nuclear energy is highly developed, more than 90 % of new and under-construction buildings are heated from electricity. Electric heating schemes are used differently. In Germany, for example, preference is given to common household electric boiler houses. In France, Norway, Finland – electric convectors. In Ukraine, in cities such as Kamenskoe – 240 thousand inhabitants, Nikopol – 120 thousand inhabitants, Manganets – 50 thousand inhabitants install individual electric heating in apartment buildings [2].

Modern means of direct electric heating are gaining more and more popularity. This type of heating works well with intelligent indoor climate controls. The obvious advantages of direct electric heating are: the ability to quickly selectively heat individual zones, heat mobility, and environmental safety. No other heating system can provide an equivalent level of comfort, efficiency, safety, and reliability.

The limited capacity of the electricity supply network prevents the widespread use of direct electric heating more than the high cost of electricity. For example, for most rooms in multi-storey buildings, power output is limited to 5 kW. The uncontrolled switching on of three heating devices with a capacity of 1.5 kW each can lead to an unacceptable overload of the power supply network, given the operating conditions of other household electrical appliances. This, in turn, will lead to an emergency power outage of the room. This problem can be solved by ordering (synchronizing) in time the states of electrical heating devices. Direct electric heating must be controlled. This means that at each moment the total power of the switched-on heating devices should not exceed the level of the permissible power, which changes randomly due to the switching on and off of various electrical devices. An example of the synchronization of the operation of two electric heaters, switched on and off by their thermostats when the set temperatures are reached, is shown in the diagrams in Fig. 1.

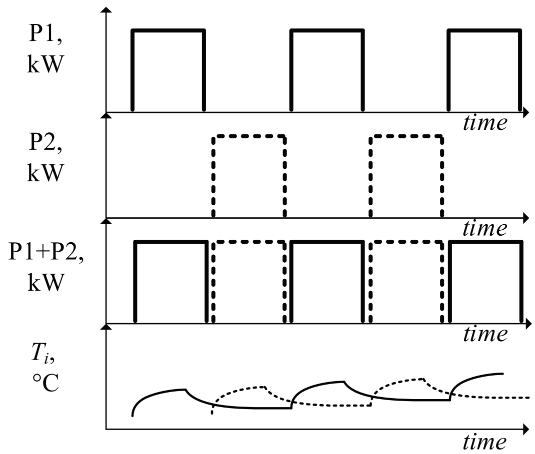

Fig. 1. Limiting the power of direct electric heating by synchronizing the switching on and off of heating devices

From the diagrams given (Fig. 1), it can be seen that in the absence of mutual synchronization, the maximum power consumed for heating would reach 3 kW, while in the presence of synchronization, it is only 1.5 kW. Exceeding the permissible power limit can be avoided if the operation of heating devices is synchronized not only with each other but also with other energy consumers in such a way as to automatically redistribute electricity. The possibility of implementing such an automatically controlled process is due to the inertia of electric heaters and intermittent operation of household electrical appliances (refrigerator, iron, washing machine, etc.).

Therefore, it is relevant to study the principles of self-organization of a "smart" electrical network with a decentralized distribution of limited power of electrical energy. The results of such studies can be useful for solving the problems of distributed direct electrical heating.

2. Literature review and problem statement

Centralized limited resource distribution methods use various mathematical laws. These include: PID control, optimal control, nonlinear adaptive control, predictive control, intelligent control based on artificial neural networks, fuzzy sets, genetic algorithms, etc. [3–14]. An example of a method of centralized control of the distribution of limited power of electrical energy for electrical heating of rooms/water is considered in [3]. A feature of the proposed method is the presence of one central control unit in the system, a predetermined power rating of each heater, and the priority of the sequence of connecting the heater to the electrical network. This solution requires additional expenditure of working time to adjust the operation of the central unit when the number of used heaters, the power of an individual heater, and the priority of the heater are changed.

The solution to the problem of optimal distribution of hot or cold air in an energy-efficient building is presented in [4]. The considered air heating and cooling system contains a central source of air heating/cooling, regulators for controlling the distribution of heated/cooled air for each zone where the air temperature is stabilized. Each regulator maintains duct pressure and directs cooled/heated air to the area. A decentralized and distributed algorithm is designed to correctly adjust the airflow for each heating zone. There is no general power limitation in the system for generating hot/cold air, and there is no measurement or prediction of disturbances. The model of the control system is based on solving the problem of resource distribution using the gradient method, without taking into account the mutual heat exchange between neighboring zones.

There is an interesting work [5], in which the problem of centralized distribution of limited power of electrical energy for heating rooms using fuzzy sets is solved. The paper discusses two limitations: the maximum power consumption of electrical energy and the achievement of set temperatures in the heating zones. Each heater contains a temperature sensor and is wirelessly connected via the Zigbee network. The system architecture contains a central control module, a set of heaters, and a power-saving distributed algorithm for distributing heat output for each heater. The work [6] considers the heating control system with power limitation, using groups of heaters with given priorities. A low-priority heater can access to the rest of the resource after higher-priority heaters.

In [7], a centralized control system for the distribution of energy generated by different sources connected into one system is considered. The system contains many optimization variables combined into one criterion for the cost function. In [8], a real-time power distribution system in a group of networks is considered. The system contains a power limitation. Optimization is performed based on Lyapunov's theorem. In [9], a multiparameter model of heating bulk materials, including those with fuzzy parameters, which are easily estimated by people, but difficult to measure technically, is considered, contains an integral criterion for assessing quality. For a system where a person subjectively evaluates the quality of heating (heating), the use of this technique will optimize resource distribution. The paper [10] discusses the use of heat pumps to recover heat from water and mine air. The paper uses classical methods of parameter analysis, the system of a specific enterprise, and methods of the modern theory of automatic supervisory control of distributed systems. In [11], to optimize the room heating control system, an analysis of the dynamic characteristics of water heaters was carried out. A model of the heat transfer process for a water heater in the space of a mathematical model has been developed. In [12], to improve the quality of the nonlinear thermal process control system, neuro-fuzzy filters were used to predict the state. The work [13] considers the architecture of the water heating control system. The control system is divided into three levels. Each level solves the problem of optimizing the use of resources and coordinating with the center to avoid conflicts. In [14], an expert system for controlling the microclimate of rooms based on neural networks and fuzzy inference of the Sugeno type is considered. The results of the study of the effectiveness of the application of the expert system are presented. It is shown that the use of the developed system provides a reduction in energy consumption up to 23.4 %.

Analysis of the literature suggests that it is appropriate to conduct studies of the decentralized model room heating control system (Fig. 2) to test the efficiency of electric power resource distribution procedures. Important elements of the control system are smart connectors (smartcones), and a network controller that measures the current load of the power supply network and calculates the current level of electricity allowed for power consumption.

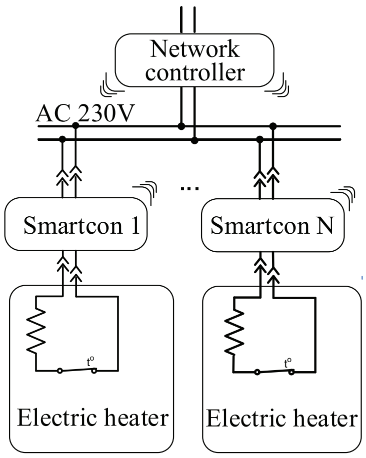

Fig. 2. Structure of a decentralized room heating control system

Smart connectors connect heating devices to power outlets. The smart connector automatically recognizes the load of the controlled heater before it is connected to the power supply. Exchange of information between the smart connectors and the network controller can be performed by wire power network using PLC protocols and data transmission via wireless environment Wi-Fi. Through a collective exchange of information, smart connectors reach an agreement on participation in the heating process. In this case, a subset of heaters is formed, the total power of which does not exceed the permissible limit at a given time. The heaters are switched off by their thermostats when the set temperatures are reached.

3. The aim and objectives of the study

The aim of the study is to increase the efficiency of using electrical energy for room heating with a variable limit of power from the standpoint of the theory of collective behavior of automatic machines in a random environment [15].

To achieve the aim, the following objectives were set:

– to develop a procedure for the operation of a model of a decentralized control system for room heating;

– to study the procedure of the model of a decentralized control system for room heating.

4. Development of a procedure for the model of a decentralized space heating control system

The object of the study is the process of room heating control with electric heaters.

The subject of the study is methods and models for electric heaters control.

The principle construction of the decentralized control system is based on theoretical models of collective behavior of machines interacting with a random environment during the distribution of a limited resource [16, 17]. The problem differs from the known ones in that the participants of distribution are limited by a local condition of the "all or nothing" type. This means that each electric heater at the current time can use a fixed amount of power resource or refuse it, and the third is not given. In the process of self-organization of the system, the initial set of distribution participants is divided into two subsets due to preliminary decisions made by smart connectors. The network controller reports to the network whether there is an excess or shortage of resources. If, based on the results of a preliminary decision, an excess of the resource remains in the network, the choice of those smart connectors that have decided to connect their heaters is confirmed. Otherwise, the choice of those smart connectors that have decided to turn off their heaters is confirmed. Those smart connectors that have not received confirmation are returned to the drawing of the resource. The process of decomposition of heaters into subsets of on and off ends when the Nash equilibrium is reached. This equilibrium is characterized by the fact that the rest of the resource cannot be used by any of the distribution participants.

Let there are a certain number of m objects (heaters) – resource consumers. Each (i-th) object is characterized by power $w_i \geq 0$. It is assumed that the objects under consideration cannot act as regulators. This means that there are only two possibilities for them. They are connected to the power supply network and create a load $w_i \geq 0$ in it, or they are not connected at all. If the resource is sufficient to cover the power of all heaters $W \geq \sum_{i=1}^{m} w_i$, then they all use it, obtaining an effect in the amount of $\psi_i = \psi(w_i)$, otherwise, when $W < \sum_{i=1}^{m} w_i$ a distribution problem arises, some of the objects must be disconnected from the resource. In this case, the disabled objects incur losses in the amount of $f_i = \psi_i - \lambda w_i \geq 0$, where λ is the resource price. It is required to select the composition of the group of connected objects $\alpha_1, \alpha_2, \ldots, \alpha_i, \ldots, \alpha_m$, $\alpha_i \in \{0,1\}$ in such a way that the damage associated with the refusal of the resource

$$F = \sum_{i=1}^{m} (1 - \alpha_i) f_i \quad (1)$$

was minimal, and the total request for the resource did not exceed the set limit

$$W \geq \sum_{i=1}^{m} \alpha_i w_i (\Delta t), \quad (2)$$

where α_i is a boolean variable that takes the value 1 or 0 depending on whether the i-th object receives the required amount of resource or not.

Strictly speaking, this problem belongs to the class of exponentially complex discrete programming problems. However, for heaters, it can be modified by changing the objective function. Smart electric heaters, distributing limited electrical power among themselves, do not pursue the goal of maximizing the effectiveness of its use, but only strive to establish the Nash equilibrium in the network. When equilibrium is established, the heaters that receive the resource cannot refuse it without reducing the total effect of its use. None of the heaters that remained not connected to the power supply network can use the remaining undistributed resource due to its smallness. The operating procedure for the decentralized space heating system model is presented below.

1. Measurement of the current load of the power network W^*.

2. Determination of resource imbalance $\Delta W = W_{max} - W^*$.

$$UN=\begin{cases}0, & \Delta W<0.\\ 1, & \Delta W\geq 0.\end{cases}$$

3. Smartcones poll. We get:

$$H_1, H_2, \ldots, H_i, \ldots, H_n.$$

$$w_1, w_2, \ldots, w_i, \ldots, w_n.$$

$$T_1^*, T_2^*, \ldots, T_i^*, \ldots, T_n^*.$$

4. Determining the amount of the resource to be allocated

$$LW=\begin{cases}\Delta W, & UN=1.\\ \sum_1^n H_i w_i+\Delta W, & UN=0.\end{cases}$$

5. Determination of the current priorities of smartcones

$$\lambda_1^*=\frac{\frac{T_1}{T_1^*}}{\sum_1^n \frac{T_1}{T_1^*}}\cdot\left(1+\frac{t}{\tau}\right);\ t=\begin{cases}1+t, & H_1=0.\\ 0, & H_1=1.\end{cases}$$

$$\lambda_n^*=\frac{\frac{T_n}{T_n^*}}{\sum_1^n \frac{T_n}{T_n^*}}\cdot\left(1+\frac{t}{\tau}\right);\ t=\begin{cases}1+t, & H_n=0.\\ 0, & H_n=1.\end{cases}$$

6. The decision to participate in the distribution (b_i=1)

$$b_1=UN\oplus H_1;$$

…………………

$$b_n=UN\oplus H_n.$$

7. Setting the initial state of the heater control trigger (C_i=10 – turn on the heater; C_i=01 – turn off the heater; C_i=00 – do not change the state of the heater)

$$C_1=00,\ \ldots\ldots\ C_n=00.$$

8. Initial resource price

$$\Lambda=\langle\lambda^*\rangle=\frac{\sum_1^n \lambda_i^*}{n}.$$

9. Resource request (a_i=1)

$$a_1=\begin{cases}1, & (\lambda_1^*\geq\Lambda)\&(b_1=1)\&(C_1=00).\\ 0, & (\lambda_1^*<\Lambda)\vee(b_1=0).\end{cases}$$

…………………………………………

$$a_n=\begin{cases}1, & (\lambda_n^*\geq\Lambda)\&(b_n=1)\&(C_n=00).\\ 0, & (\lambda_n^*<\Lambda)\vee(b_n=0).\end{cases}$$

10. Determination of the current balance of the distributed resource

$$D=LW-\sum_1^n a_i w_i.$$

11. Decision making (C_i=10 – turn on the heater; C_i=01 – turn off the heater; C_i=00 – do not change the state of the heater)

$$\begin{cases}\text{If } D\geq w_1,\text{ and } a_1=1,\text{ then } C_1=10.\\ \text{If } D\geq w_1,\text{ and } a_1=0,\\ \text{then waiting for a new value } \Lambda, C_1=00.\\ \text{If } D<w_1,\text{ and } a_1=0,\text{ then } C_1=01.\\ \text{If } D<w_1,\text{ and } a_1=1,\\ \text{then waiting for a new value } \Lambda, C_1=00.\end{cases}$$

$$\begin{cases}\text{If } D\geq w_n,\text{ and } a_n=1,\text{ then } C_n=10.\\ \text{If } D\geq w_n,\text{ and } a_n=0,\\ \text{then waiting for a new value } \Lambda, C_n=00.\\ \text{If } D<w_n,\text{ and } a_n=0,\text{ then } C_n=01.\\ \text{If } D<w_n,\text{ and } a_n=1,\\ \text{then waiting for a new value } \Lambda, C_n=00.\end{cases}$$

12.

$$\begin{cases}\text{If } \forall_i(C_i\neq 00),\text{ then goto 1}.\\ \text{If only for one value } k(C_k=00)\\ \text{and } UN=0,\text{ then } C_k=01 \text{ goto 1}.\\ \text{If only for one value } k(C_k=00)\\ \text{and } UN=1,\text{ then } C_k=00 \text{ goto 1}.\\ \text{If more then one value } k(C_k=00),\text{ then goto 13}.\end{cases}$$

13. Request for resource (a_i=1)

$$a_1=\begin{cases}1, & (\lambda_1^*\geq\Lambda)\&(b_1=1)\&(C_1=00).\\ 0, & (\lambda_1^*<\Lambda)\vee(b_1=0).\end{cases}$$

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$$a_n=\begin{cases}1, & (\lambda_n^*\geq\Lambda)\&(b_n=1)\&(C_n=00).\\ 0, & (\lambda_n^*<\Lambda)\vee(b_n=0).\end{cases}$$

14. Determining the price of a resource

$$\Lambda=\frac{\sum_1^n a_i\lambda_i^* w_i}{\sum_1^n a_i w_i},\ \text{go to 10.}$$

Symbols used in the description of procedures of the decentralized control room heating system:

W^* is a current load (power) averaged by a sliding window for 1 min;

W_{max} is a maximum permissible load;

UN is a pointer to the load imbalance sign;

H_i is a heater condition: H_i=1 – switched on, H_i=0 – switched off;

w_i is heater power;

LW is the amount of available resource;

T_i^* is the current temperature in the area of the heater;

T_i is the set temperature in the area of the heater;

λ_i is the initial priority of the heater;

λ_i^* is the current priority of the heater;

$\langle \lambda^* \rangle$ is the average level of current priority;

a_i is a resource request (a_i=1);

Λ is the price of the resource;

D is the remainder of the resource after satisfying all requests;

t is the period of the current time, the countdown of which begins from the moment the heater is turned off;

τ is a constant that determines the rate of increase of the current priority;

b_i is a decision on participation in the distribution (b_i=1 – decision to participate, b_i=0 – decision not to participate);

C_i is a heater control command.

5. Results of the study of the operating procedure of the model of the decentralized control system of room heating

To study the procedure for the self-organization of a network of smart heaters and check the efficiency of its functioning, a simulation model of a decentralized direct electric heating system has been developed. A three-room apartment on the first floor of a multi-storey building was chosen as a heated object. The simulation takes into account heat losses through window openings, through the floor and ceiling, walls and doorways. Also, insignificant heat emission in heated rooms from various unregulated sources is taken into account. To heat the apartment, four standard electric heaters are used – two 1,000 W and two 1,500 W. The heaters are combined with smartcons and a network controller into a decentralized control system via wireless communication channels (Fig. 3).

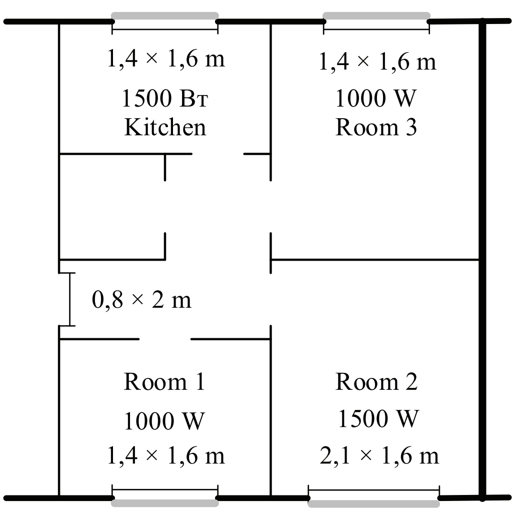
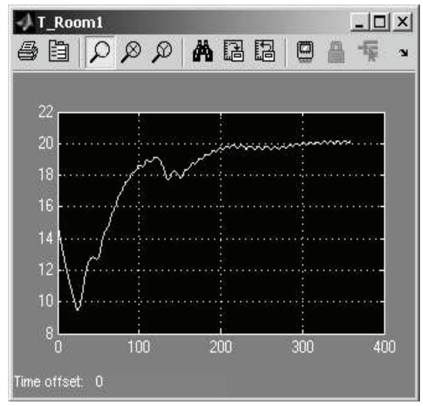


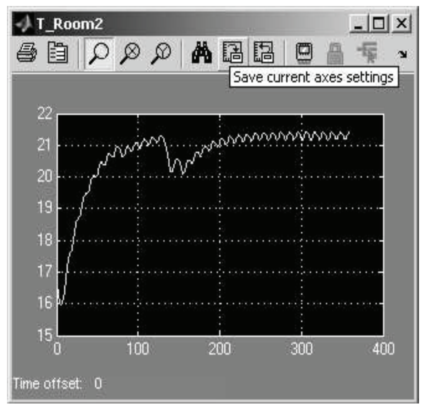
Fig. 3. Layout of heaters in the apartment

A simulation model of thermal processes in the zones of operation of electric heaters, the results of modeling the process of distribution of thermal power and maintaining comfortable temperatures in heated rooms are given in [18]. Graphs of temperature changes in the zones of operation of electric heaters at an outdoor temperature of minus twenty degrees Celsius are shown in Fig. 4.

Below are oscillograms (Fig. 5) of the total power consumption at the specified temperature conditions. It can be seen that the power limit is not exceeded due to the timing of the included heater groups.



a



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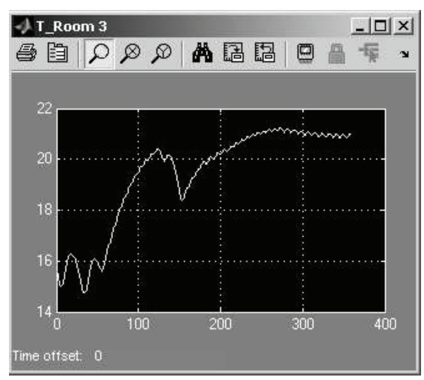
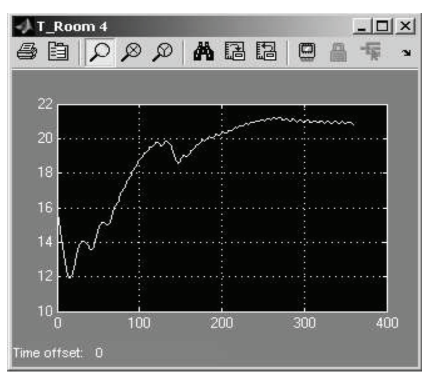


c



d

Fig. 4. Results of simulation of thermal processes in the zones of action of electric heaters: *a* — temperature in the kitchen, *b* — temperature in room 1, *c* — temperature in room 2, *d* — temperature in room 3

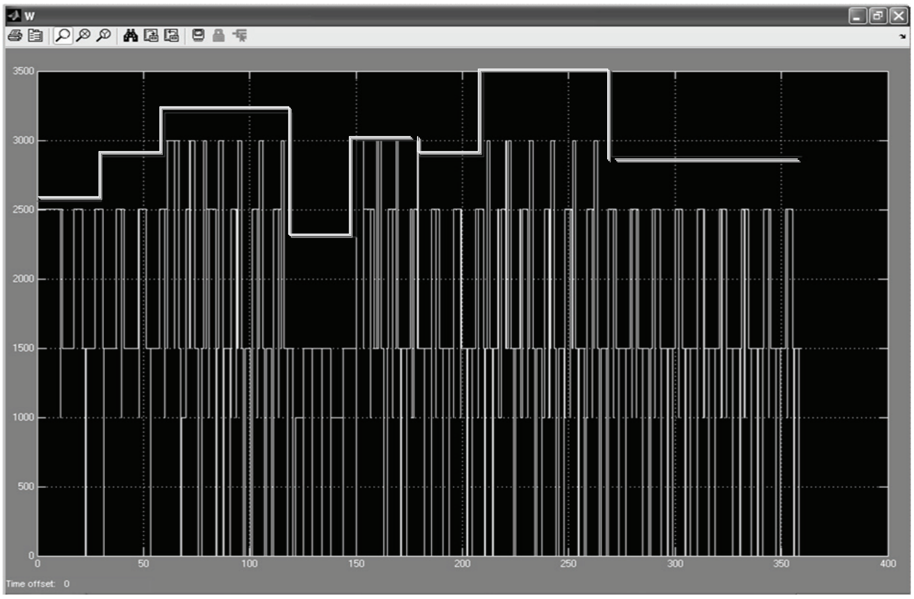


Fig. 5. Total power of the electric heaters network (the diagram of the maximum power allowed for use by the heaters is shown by the bold white line)

It can be seen that the decentralized control system for electric heaters provides heating of the air in the rooms and maintaining temperatures in them at the level of 18–21 degrees with a changing limit of the permissible power of electrical energy. The cost of electricity consumed (at an outdoor temperature of minus 20 degrees Celsius), extrapolated to a calendar month, was € 63, while the centralized supply of heat energy for an apartment of 60 sq. m would be € 76.

6. Discussion of the results of the study on improving the efficiency of electrical energy distribution during electrical heating control

A procedure has been developed for the operation of a decentralized control system for electric heating of rooms with a variable power limitation, which differs in that when the control actions are performed by a group of heaters, the damage associated with the failure of the heater to access the resource (1) and the total resource limitation (2) for all heaters are estimated. Control (on/off) of electric heaters is modeled by modified finite state machines with bilinear tactics. The decision to connect the heaters to the electrical network is made when performing the Nash equilibrium. The Nash equilibrium condition in this work means that the unused power of the electrical network is lower than the power of the heater not connected to the electrical network.

The study showed that the procedure for the operation of the decentralized control system for space heating with the distribution of a limited resource with local restrictions of the “all or nothing” type provides a given temperature distribution (Fig. 4) and monitors the limitation of power consumption at a given level (Fig. 5).

Application of the developed procedure for decentralized control of room heating simplifies the setup of the whole system. The heating system of any size with this structure and procedure is conveniently configurable if the user makes changes to the settings of individual heaters, including turning on/off the heater. The decentralized heating control procedure has the function of self-organization and is linked with the structure of the system (Fig. 2), which contains several loops for monitoring and controlling the state of the heaters. At the network controller level, the current network load is measured, the damage/benefit (1), the power balance (2) of the planned solution of the smartcon level are calculated, and then the calculation results are informed to all smartcons. The functions of control, identification of the values of the heater parameters have been transferred to the smartcon level. The smartcon initiates the participation of the heater in obtaining the resource of electrical power, and, based on the numerical calculation of the network controller, makes a decision on the control of the heater.

Thus, the developed procedure for the decentralized control of room heating, in comparison with the centralized one, has a distributed functionality, since the structure of the system contains several loops for monitoring and controlling heaters, which simplifies operation when the conditions of the control object change: limiting the power of electrical energy, the number of heaters, the values of heater parameters.

During the study, the following parameters were unchanged: the number of heaters, the power value of each heater, the priority of the heaters, the set value of the air temperature near the heater. The power limit was in the range up to 4500 W.

The disadvantage of this study may be that all heaters have the same priority. This leads to approximately uniform heating of the air near the heaters, while the user can be near one of them. Prospects for future research are associated with practical research of prototypes of decentralized control systems for electric heaters of various sizes and purposes.

A model of a control system for electric heaters has been developed with the task of distributing a limited resource of electrical energy based on Nash equilibrium, using the principles of decentralized control, information technologies for the development and implementation of control actions by a group of heaters.

Practical novelty is in the developed procedure for the self-organization of heaters with decentralized distribution of limited power of electrical energy.

7. Conclusions

1. A procedure has been developed for the operation of a model of a decentralized control system for electric room heating, which takes into account the changing conditions of the control object (limiting the power of electrical energy, the number of heaters, their parameters) and uses the Nash equilibrium principle when performing control actions by a group of heaters.

2. The study of a model of a decentralized control system for room heating demonstrated air heating to specified tempera-

tures, also for a room with an area of 60 sq. m, the cost of electricity consumed (at an outdoor temperature of minus 20 degrees), extrapolated to a calendar month, was €63, while for centralized heat supply it would be €76. This indicates that the proposed approach is cost-effective and opens the way to the use of decentralized control systems for electric room heating.

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