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CLASSIFICATION OF HEATING CONDITIONS IN TERMS OF SMART CONTROL OF INDOOR HEATING WITH THE USE OF UNCONTROLLED ELECTRIC HEATERS

Purpose. To reduce specific energy consumption for heating municipal and industrial buildings by introducing smart indoor temperature control taking into consideration individual dependences of characteristics of each person as a consumer of energy resources on specific heating conditions.

Methodology. The energy-efficient and smart control of indoor heating is based on the fact that a control system is to elaborate and provide a compromise solution as for comfortable perception of proper conditions of someone's staying indoors and minimum consumption of energy resources. To do that, first of all the problem should be solved concerning recognition of different heating conditions by a smart control system aimed at providing a process of system learning and database formation. To complete this task, the parameters of one-dimensional dynamic models describing heat-exchange processes are proposed to be used as the information signs for the classification of situations in terms of heating relative to the uncontrolled electric heaters; the input value is the heater capacity, and the output value is the air temperature within the local indoor zone. Within the framework of the development of a method for classifying indoor heating conditions, dependences of the parameters of dynamic models of local indoor heating zones on the characteristics of local heating zones were analysed. Besides, certain regularities of a control process for heaters were determined; that helped provide accurate identification of the models of local heating zones without considerable changes in a preset temperature mode. Computational experiments made it possible to evaluate the accuracy of determination of information signs for the classification of heating conditions while representing real characteristics of indoor heat-exchange processes.

Findings. The studies resulted in the development of a method for identifying dynamic properties of indoor heat zones for the cases of using uncontrolled electric heaters with two states.

Originality. For the first time, certain regularities have been identified concerning a capacity control process for electric heaters with two states and a process of temperature measurement within the local indoor zones. The regularities made it possible to determine the parameters of dynamic models of indoor heat-exchange processes with high accuracy and without considerable changes in the preset temperature mode, and to use these parameters as information signs while classifying the heating conditions.

Practical value. The obtained regularities of the processes of heater control and temperature measurement allowed developing a method for identification of dynamic properties of local indoor heat zones, which makes up the basis for a classification procedure of heating conditions.

Keywords: *energy-efficient heating of buildings, smart control, classification of heating conditions*

Introduction. Currently, the improvement of Ukrainian energy system is among the most important strategic missions of the national security being the required condition to reduce power sector dependence upon other countries. The above-mentioned is supported by the provisions of the developed Energy Strategy of Ukraine up to 2035, and approved by the order of the Cabinet of Ministers of Ukraine of 18.08.2017 No. 605-p. The problem should involve integrated approach; moreover, it has to be solved simultaneously and co-ordinately through several planes. One of them is active and deep implementation of the current information technology in the process of electric energy distribution and consumption by industrial enterprises as well as municipal objects as a part of a *Smart Greed* concept. Topicality of the tendency to solve the problem of energy system improvement is supported by the recent dynamics analysis of energy intensity of GDP in the developed EU countries [1] which showed its sharp 10.2 % decrease in the period of active implementation of energy saving IT inclusive of *Smart Greed*. On the other hand, our country has substantial potential to decrease energy intensity of GDP since the index is more than twice higher to compare with similar EU index [1].

Taking into consideration climate problems, global tendency of the century is the so-called green energy as well as efficient and environmentally friendly ways of its use. The tendency is demonstrated by each industry of highly developed countries using energy. Housing and communal services are also involved because energy-efficient indoor heating is quite a topical problem in view of significant power intensity of the process.

As for the share of electric indoor heating, the developed countries differ from Ukraine in its greater portion since for a long time they have had a fully-fledged market of energy resources where gas is far from being a cheap power source [2]. In this context, the electric heating cost is comparable with the gas heating price [3]. However, electric heating has no necessity to develop and maintain inside gas supplying system. In addition, electric indoor heating is combined perfectly with green energy as well as more environmentally friendly energy use. Particularly, it concerns the rapidly developed methods for efficient conservation of green electric energy [4]. Another important advantage of electric indoor heating is its better adaptability to the implementation of smart power networks using a *Smart Grid* concept. Currently, there are numerous hardware and software platforms to solve the problems of smart control of electric heating [5]. They help measure the consumed power by each heater, inside temperature, and control every heater separately. There are no such ready decisions for buildings where gas is applied to heat water as a coolant; hence, it will need greater expenditures connected with the development of a smart power network.

Consequently, for the developed countries (including Ukraine), taking care of their energy security strengthening, near-time outlook is to use indoor electric heating since it will be more promising approach. Thus, to be at the leading edge of IT, favouring the improved efficiency of electric indoor heating, is really topical scientific and research tendency.

Unsolved problem. The problem to control human assisted energy consumption by a building or apartment for the purpose of ensuring more economical electricity use is solved under the *Smart Home* concept or *Micro Smart Grid* concept. According to the first concept, separate class of systems has been developed to control energy consumption in a house, i.e. *Smart Home Energy Management* (SHEM) [6]. The second concept involves the development of relatively small smart power networks within a building (i.e. *Micro Smart Grid*) whose mission is to control electricity distribution and use by the whole building as well as by individual consumers in its smaller segments to improve power quality as well as energy efficiency of a building and single households.

Initially, a *Smart Grid* concept was applied to large electricity consumers [7]. For instance, paper [8] considers algorithm of the distributed control of electric energy consumption based upon a game theory to decrease the top demand by a group of residents. The user is a cluster of devices; a problem is how to distribute electricity among the apartments or buildings rather than among the devices.

Nevertheless, wide use of IT for buildings has helped apply the *Smart Grid* ideas for separate households or apartments.

Paper [6] mentions that search for efficient approaches concerning electricity consumption within SHEM and Micro Smart Grid systems is still a topical problem since no available solution can provide minimum power use if indoor temperature is comfortable. The situation turned out to be difficult due to complex mathematical description of a human understanding of being indoors in terms of comfort. Hence, search for a compromise solution in terms of inside comfortable temperature as well as minimum energy consumption for heating becomes more complicated.

Another reason is complexity of mathematical apparatus describing dynamics of indoor thermophysical processes from the viewpoint of heating condition classification. An approach to solve a problem of efficient indoor power consumption control, described in paper [9], serves as a model. According to the approach, algorithm of the energy consumption control involves a complex and multicomponent mathematical model describing thermophysical process for inside heating. The model is required to forecast time of each heater connection to the electric grid. Moreover, the model involves a number of input data characterizing type of a building, parameters of premises, environment etc. Complexity of the model needs much time to collect sufficient data array updating its numerous parameters. Due to the fact, use of such complex mathematical models of thermophysical processes indoors during heating process control prevents smart energy networks from quick response to short-term changes in the electricity consumption nature or heating conditions.

Thus, there is a problem to search for a new approach as for the development of smart energy networks controlling indoor heating able to response quickly to changes in the inside environment and find a compromise solution concerning the comfort of a specific person being in the specific premises, on the one hand, and minimum energy consumption, on the other hand.

Literature review. Recently, such technologies of Industry 4.0 as Internet of Things, Artificial Intelligence, and Big Data have been widely used to control climate inside buildings of industrial enterprises as municipal objects. An example of Industry 4.0 technology use to control indoor climate is given in paper [5]. It is a system of interaction between sensors, operating mechanisms, and other data sources for multiple home automation. The system is called qToggle. It operates using capacity of flexible and powerful application programming interface (API). The majority of devices, applied by qToggle, are based on ESP8266/ESP8285 chips and/or on Raspberry Pi boards. Smartphone app has been designed helping users control a series of home appliances and sensors.

The developed system controls indoor temperature to maintain thermal comfort and save electric energy. In such a case, the system of self-operating temperature regulators offers the following benefits: anytime and anywhere access and control of indoor temperature within the help of qToggle in a mobile phone. Hence, the system foresees that it is human who has to adjust self-operating temperature regulators so as to achieve thermal comfort and energy saving. The manipulations should be performed for each specific situation from the viewpoint of heating conditions. Consequently, the so-called human factor, being actually one of the key reasons of the unjustified increase in energy consumption for heating of buildings, cannot be ruled out completely.

Similar disadvantage is also observed in paper [10], where a system of a smart home control is Bluetooth-based. In this context, users may utilize app for mobile phones Android to control both home appliances and indoor temperature. For the purpose, IoT technology is used based upon Bluetooth.

Paper [11] represents the algorithm to control power consumption by electric heaters with the help of artificial intelligence based upon a theory of collective behaviour. Nevertheless, the considered algorithm needs temperature setpoint as the input data preventing the system from control of changes in energy efficiency of indoor heating. Moreover, the criterion cannot be taken into consideration by a control algorithm. The disadvantage is also typical for a solution to design a system of indoor heating control described in paper [12] where the problem how to coordinate timely operation for maximum use of electric energy provided for the heating is solved based upon a collective behaviour theory. However, the control algorithm does not involve a criterion characterizing specific electricity consumption for indoor heating.

Another solution, concerning smart control of indoor heating, foresees use of the specific systems as a part of a *Smart Home* concept, i.e. systems controlling inside heating being *Home Energy Management System* (HEMS). Paper [13] proposes a system to control home energy (HEMS-IoT) whose aim is improvement of comfort and safety of smart homes with simultaneous energy saving. For this reason, HEMS-IoT applies IoT, big data technologies, and machine learning to manage energy consumption. To develop models of consumer behaviour and energy consumption and classify buildings in terms of the energy use within HEMS-IoT system, machine learning algorithm J48 and API Weka were applied. Operation of HEMS-IoT system results in the formulation of energy saving recommendations based upon user preferences; to do that, such software tools as RuleML and Apache Mahout were used.

Analysis of paper [13, 14] showed that the represented classification of the consumed energy efficiency can take into consideration neither complexity nor individual perception of comfort by each user to be inside depending upon the processes taking place in the building. Thus, there are no components in the models of consumer behaviour taking into consideration individual perception of comfort. Moreover, impact of the processes on the components has not been analyzed. For instance, a range of comfortable temperatures and the range connection with heating conditions have not been identified for each user. In addition, learning algorithms cannot accomplish tasks as for the classification of heating conditions for further accurate forecasting aimed at the specific user of the range of comfortable temperatures

Unsolved aspects of the problem. Consequently, the overview and analysis of the latest solutions and achievements in the field of smart homes and smart electric grids show that the concepts are still under formation. Hence, numerous problems have not been solved involving future studies and research. Actually, the only problem is solved, i.e. development of a software and hardware platform to build smart home or smart power grid. Currently, the platform helps accumulate large amounts of data in the form of dozens of physical quantities, measured in the homes, or security videos. However, solving problems of the data processing and developing algorithms of system learning in a smart home as well as algorithms of making decisions by the systems are at an early stage.

Description of the research methods. The real-time experiments have helped obtain acceleration curves in terms of various heating conditions. According to the experimental curves, identification was made to obtain the parameters of dynamic models of local zones of indoor heating for various heating conditions. Dependence of the model parameters of local heating zones upon the thermophysical parameters of the zones was determined. Actual characteristics of indoor heating zones as well as results of statistical processing of the experimental acceleration curves have helped develop a complex simulation model describing a procedure to control the indoor heat-exchange processes. Using the model, dependence of accuracy of the parameter identification of the dynamic models of local heating zones upon the algorithm parameters to control heaters and temperature measurement was studied. The study helped define regularities of control of the binary electric heater capacity as well as a temperature measurement process within the indoor local heating zones making it possible to determine the parameters of dynamic models of the zones accurately and without significant changes in the specified thermal behaviour.

Purpose. The purpose is to decrease specific energy consumption to heat up municipal objects as well as industrial objects while implementing intellectual indoor temperature control taking into consideration individual characteristic dependence of each human as an energy consumer upon the specific heating conditions.

Presentation of the main material. To substantiate information characteristics aimed at classification of situation from the viewpoint of indoor heating, in-situ analysis of static and dynamic specifications of heat-exchange processes was carried out.

Thus, to define a *heater-room* correlation model as a control object with the room division into several heating zones, real experiment was conducted based on Room 1409 in building 7 of Dnipro University of Technology (dimension of the room is 4 × 4.5 m; floor-ceiling distance is 2.5 m).

The experiment idea is as follows. Window and door opening resulted in the room cooling down the exterior temperature being 16 °C for the experiment. Then, a heater and temperature indicators were placed in the premises (Fig. 1).

After that, a 2 kW heater was turned on with full power. The temperature in four heating zones in which the room was divided conditionally, was measured every 30 seconds.

The analysis of the experimental acceleration curves, shown in Fig. 1, helps draw conclusions concerning the structure of dynamic models of local heating zones:

1. Each temperature of heating zones works for stable values; hence, there is no zero root in a characteristic equation (the object has no astatism properties).

2. For the zones, more distancing from the heater, a temperature starts increasing with a time lag; hence, the model structure involves transportation lag.

3. Intensity of the temperature increase in time decreases monotonously during the whole transition period; hence, one can predict that a characteristic equation of the transition function of a control object has one real negative root.

Taking into consideration the conclusions concerning the structure of dynamic models of local indoor heating zones in terms of experimental acceleration curves, shaped during long-term temperature observations (for six months of cold season) the models were identified parametrically. Analysis of the parametric identification results has helped demonstrate the following dependencies of the model parameters upon the heating conditions:

- an intensifying factor characterizes the energy amount required to vary thermal behaviour. It depends upon the changes in thermal behaviour as well as upon the changes in the environment (for instance, changes in atmospheric temperature) as well as upon the changes in characteristics of premises (for instance, extra source of thermal energy in the form of direct sun beams). Moreover, the model parameter varies if local indoor heating zone undergoes changes;

- a time constant as well as transportation lag of the dynamic models of local heating zones characterizes a transition period of thermal behaviour from one static state to another. To a far greater degree, within a short time interval the parameters characterize changes in the local heating zone. During a longer time interval, conclusions made for intensifying factor are similar for them.

To classify the situations from the viewpoint of indoor heating conditions relying upon the substantiated information features, a method was developed to identify dynamic characteristics of indoor thermal zones if uncontrolled electric two-state heaters are applied.

The method is based upon a two-stage identification procedure in a narrow range of temperature values with the pulse-time modulation of a managing signal for a full experimental acceleration curve obtained to define dynamic characteristics of the local indoor heating zones. For this purpose, three states of a heater control are introduced:

1) on-off regulator operations where the heating zone is not identified;

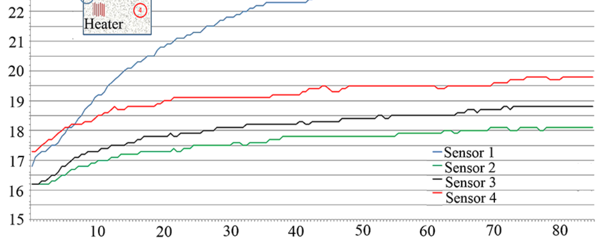

Fig. 1. Experimental acceleration curves in terms of indoor temperature

2) stage one of a heating zone preparation to be identified is required to determine a test managing signal as well as point one of a static characteristic of the control object;

3) stage two of a heating zone preparation to be identified is required for shaping the experimental acceleration curve.

The identification procedure of dynamic characteristics of the local indoor heating zones in the municipal objects is described with the help of a transition graph shown in Fig. 2.

Condition for transition *1* in Fig. 2 is non-fulfilment of initiation of the heating zone identification (there is no permission by a high-level system). Action of transition *1* is permission for an on-off regulator to operate.

Condition for transition *2* is to initiate the heating zone identification (there is permission by a high-level system). Operation of transition *2* is to decrease temperature setpoint by 1 °C for an on-off regulator with the view of transition to a low temperature range while identifying.

Condition for transition *3* is non-fulfilment of transition to identification stage two (power and temperature samples were not formed during stage one). Transition *3* operation is formation of the temperature and power samples during identification stage one.

Condition for transition *4* is fulfilment of transition to identification stage two (termination of sample formation during stage one). Transition *4* operation is a shift from an on-off regulator to a pulse-width control signal generator.

Condition for transition *5* is non-fulfilment of formation of output data termination for the heating zone identification (formation of samples during identification stage two). Transition *5* operation is formation of the temperature and power samples during identification stage two.

Condition for transition *6* is termination of the output data formation to identify a heating zone. Operation of transition *6* is initiation of an identification procedure. The identification procedure is followed by the reset of all intermediate timers and variables, and timer start to determine time of last identification of a heating zone. In addition, reverse transfer takes place to an on-off regulator with a temperature setpoint specified by a user.

To analyse and prove efficiency of the proposed method identifying dynamic characteristics of the indoor thermal zones, mathematical support for the smart energy grid was developed in the form of imitational model of local system for automatic temperature control within the local heating zone described by [15]. Based upon the model, regularities of temperature changes with time were obtained as well as heater capacity helping observe stages of procedure identifying dynamic characteristics of the local heating zones relying upon the proposed method (Fig. 3).

State one in Fig. 3 corresponds to a static state of a smart energy grid at the previous level of a temperature setpoint (the state duration depends upon the specified accuracy of the average value determination). Within the graph section shown by Fig. 3, any temperature dynamics is possible in the range of ±0.5 °C. The range was accepted by default; however, further studies are required to analyse dependence of the degree of human comfort to be indoors upon the value. State one in Fig. 3 also corresponds to state one of a transition graph demonstrated in Fig. 2.

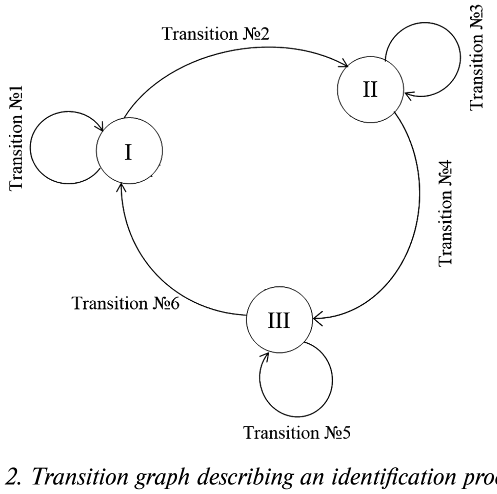

Fig. 2. Transition graph describing an identification procedure of dynamic characteristics of the local indoor heating zones

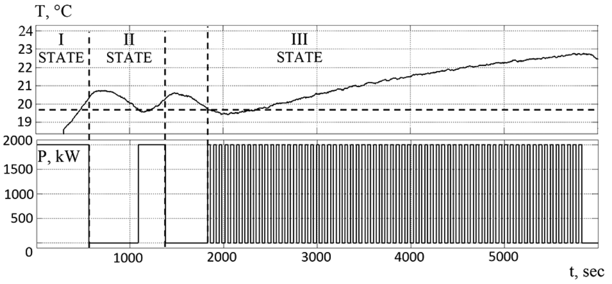

Fig. 3. Time variations of air temperature in a local indoor heating zone (Figure above) and capacity consumed by a heater (Figure below)

State two in Fig. 3 corresponds to the intermediate static condition of the smart power grid introduced artificially to minimize a range of temperature variations within a local heating zone around the specified temperature setpoint. For the purpose, temperature is reduced by 1 °C (the value was accepted by default; however, further studies are required to analyse dependence of the degree of human comfort to be indoors upon the value). Then, it is maintained within the lowered ±0.5 °C range until the accurate average temperature and capacity heater values are determined. The abovementioned is required for more exact determination of an intensifying factor of a transfer function involving at least two points within the operating static characteristic of the control object. State two in Fig. 3 corresponds to state two of a transition graph in Fig. 2.

State three in Fig. 3 corresponds to a dynamic condition of the smart energy grid. Within the graph section, a heater should consume as much electricity as it is required for the temperature of a local heating zone to achieve +2–3 °C (of setpoint) temperature at the end of state three. The level was accepted by default; nevertheless, it needs further clarification in the process of computational experiments based on the identification accuracy, involving perturbation, depending upon the analysis of dependence upon it. Since the start of state three of the grid informs on the average electricity value only for one point on the static characteristic, in relative units the electricity amount should be increased by 20–30 % of the average power value determined during state two of the grid. Extra studies of temperature increase in the local heating zone are required depending upon the value of relative electricity growth for various sections of the static characteristic as well as for heating conditions. In the graph section in Fig. 3, capacity dynamics within a short time interval should provide the required electricity amount. In addition, a discrete managing signal has to be rather short to provide a correct shape of the experimental acceleration curve (its substantiation needs further study on the identification accuracy dependence upon the parameter taking into consideration the fact that too short period results in frequent on/off heater switching, which is also undesirable procedure).

Fig. 4 represents one of the identification effects of dynamic characteristics of the local indoor heating zone based upon the proposed method using software and mathematical support of a smart power grid developed as a part of the research.

Top right of Fig. 4 shows that relative match index between the experimental acceleration curve and a model graph, calculated as the normalized standard deviation of the graph coordinates on the coordinate axis, is 95.83 % if complete match is

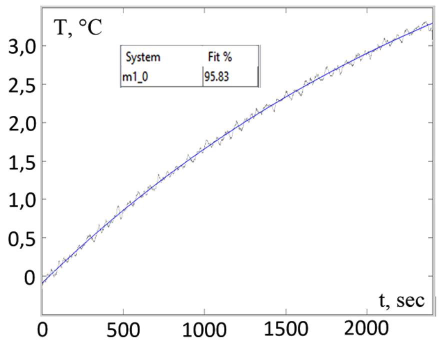

Fig. 4. Identification outcome of dynamic characteristics of local indoor heating zone

100 %. Hence, in terms of experimental data, structural identification of the dynamic model of a heating zone is of high accuracy.

To support efficiency of the proposed method, the simulation results were analysed comparatively as long as the imitational model of the local heating zone and the model, obtained as a result of identification of dynamic characteristics of a heating zone, based on the developed method, were used. For the purpose, the models were compared in terms of the output value (Fig. 5).

To evaluate a coincidence degree of the graphs in Fig. 5, two temperature samples in the local heating zone were formed corresponding to the graphs. Relative to them, the normalized standard deviation, being 93.6 %, was defined. In such a way, the research results helped get an idea of high accuracy while determining dynamic characteristics of the local indoor heating zones with the use of the proposed method.

Conclusions. In the process of identifying dynamic characteristics of the local indoor heating zones based upon the proposed method, the following features and regularities of the procedure have been defined consideration of which will help make it more accurate:

1. If 100 % step signal is supplied for identification (i. e. if a heater is constantly turned on with full power), then a short time period will demonstrate an integrating link, being the initial section of aperiodic process, and information criterion intensifying it. As the experiments demonstrated, the criterion remains almost unchangeable in the context of varying heating conditions. Consequently, in terms of discrete objects, inclusive of the heater, minor changes in the managing signal are analysed using pulse-width modulation. For the purpose, duty cycle of a managing signal is determined previously for the current thermal behaviour in terms of –1 °C temperature of a setpoint to reduce fluctuation around the setpoint. Then, the duty cycle of a managing signal increases by 0.04–0.1 (further studies are required as for the parameter changes depending upon the heating conditions as well as human comfort to be indoors).

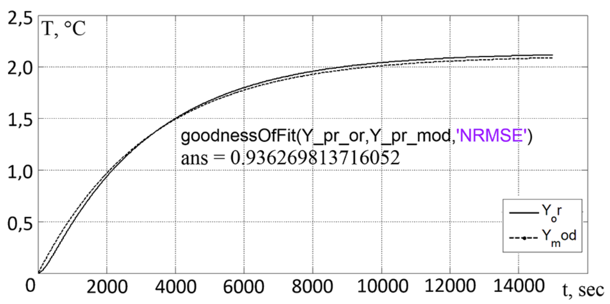

Fig. 5. Graphs of temperature time changes in the local indoor heating zone (solid line), and the model, determined with the use of identification of dynamic characteristics of a heating zone involving the proposed method (dotted line)

2. Specific feature of the identification procedure during stage one (previous thermal behaviour) is as follows. In the context of such correct determination of an intensifying coefficient, the amplified sample of a managing signal should be formed right within the period. Otherwise, a significant error will take place. Moreover, if identification stage two (supply of a pulse signal with the increased duty cycle) starts immediately after the managing signal at stage one (100 % are supplied), then substantial misshaping of the experimental acceleration curve happens. As a result, a time constant is determined with a considerable downward error. Hence, the sample formation in terms of temperature (which should also be done right within the period) has to be started and terminated when the temperature drops (i. e. the zone cools down). Since the controlled value varies in time with lag relative to the managing signal, then samples of both managing and manageable values are formed within different time intervals with different conditions. After the sample is formed in terms of capacity, the managing signal turns out to be blocked for the correct formation of the manageable value. The abovementioned will provide the zone cooling in the near future as well as faster transition to stage two.

3. Duration of identification stage three (Fig. 3) should be studied additionally concerning its optimum value as well as dependence upon other factors (it has to be minimal to shorten identification period but rather adequate for high accuracy).

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Класифікація умов опалення при інтелектуальному керуванні опаленням будівель із використанням некерованих електронагрівачів

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Мета. Зменшення питомих енерговитрат на опалення будівель об'єктів муніципалітету та промислових об'єктів за рахунок уведення інтелектуального керування температурами у приміщеннях з урахуванням індивідуальних залежностей характеристик кожної людини, як споживача енергоресурсу, від конкретних умов опалення.

Методика. В основу енергоефективного та інтелектуального керування опаленням будівель закладено пошук і забезпечення системою керування компромісного рішення стосовно комфортного сприйняття людиною умов перебування у приміщеннях і мінімального споживання енергоресурсів. Для цього насамперед повинне бути вирішене завдання розпізнавання системою інтелектуального керування різних умов опалення з метою забезпечення процесу навчання системи й формування бази знань. Для вирішення цього завдання по відношенню до некерованих електричних обігрівачів у якості інформаційних ознак для класифікації ситуацій з точки зору умов опалення запропоновано використовувати параметри одномірних динамічних моделей, що описують теплообмінні процеси, вхідною величиною яких є потужність обігрівача, а вихідною – температура повітря у локальній зоні приміщення. У рамках створення методу класифікації умов опалення у приміщеннях будинків проведено дослідження залежностей параметрів динамічних моделей локальних зон опалення у приміщенні від характеристик локальних зон опалення. Також визначені закономірності процесу керування обігрівачами, що забезпечують точну ідентифікацію моделей локальних зон опалення без суттєвої зміни заданого температурного режиму. За допомогою обчислювальних експериментів оцінена точність визначення інформаційних ознак для класифікації умов опалення при відтворенні реальних характеристик теплообмінних процесів у приміщенні.

Результати. У ході досліджень розроблено метод ідентифікації динамічних властивостей теплових зон у приміщенні для випадку використання некерованих електричних обігрівачів із двома станами.

Наукова новизна. Уперше визначені закономірності процесу керування потужністю електричних обігрівачів із двома станами та процесу вимірювання температури в локальних зонах опалення у приміщеннях будівель, що дозволили визначати параметри динамічних моделей теплообмінних процесів у приміщенні з високою точністю й без суттєвої зміни заданого температурного режиму, та використовувати ці параметри як інформаційні ознаки при класифікації умов опалення.

Практична значимість. Отримані у роботі закономірності процесів керування обігрівачами й вимірювання температури дозволили створити метод ідентифікації динамічних властивостей локальних теплових зон у приміщеннях будівель, що складає основу для процедури класифікації умов опалення.

Ключові слова: *енергоефективне опалення будівель, інтелектуальне керування, класифікація умов опалення*

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