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Methodology of development of an intelligent energy-efficient system of control of temperature and humidity regime in industrial greenhouse

Abstract. The cost of energy carriers affects the cost of products that are grown in industrial greenhouses. The purpose of the study is to develop a methodology for creating an intelligent system for energy-efficient microclimate management in industrial greenhouses operating under conditions of uncertainty, based on a combination of methods for predicting energy consumption and minimising them through the use of artificial neural networks. Methodology – the input parameters of the neural network prediction model are: the value of external and internal greenhouse air temperatures, the value of relative humidity, solar radiation absorbed by the greenhouse, and the level of carbon dioxide in the greenhouse. The outputs of the forecasting model are the values of natural gas and electricity costs. Based on the use of fuzzy logic methods and a genetic algorithm, models for finding and using optimal parameters of PI controller settings adapted to changes in the operating conditions of the automation system are developed and investigated. Methods of improving the quality of regulation of technological parameters by combining various intelligent control algorithms in one automation system are analysed, which helps to reduce energy costs by 10-13%. It is established that for closed-ground structures, heating and ventilation systems have the highest energy consumption (on average, more than 4,000 m³ of natural gas and almost 1,000 kWh of electricity are consumed per day for heating and ventilation in an industrial greenhouse. Correlation analysis of the relationships between external disturbances and energy costs that ensure compliance with a given technology for growing plant products, confirmed the hypothesis about the presence of conditions of uncertainty in the functioning of an industrial greenhouse formed by random disturbances, incomplete information about the biological component; while the linear correlation coefficients do not exceed $r < 0.35$. This creates conditions for the use of neural networks both for predicting energy costs and for forming energy-efficient management strategies. This provides better regulation in conditions of uncertainty, the adjustment time and overshoot are reduced by two to three times. To create an energy-efficient microclimate management system in industrial greenhouses that operates in conditions of uncertainty, a neural network model for predicting the energy costs of natural gas and electricity has been developed. The authors of the study have improved the structural and functional scheme of the automation system for controlling the temperature and humidity regime in industrial greenhouses by combining intelligent algorithms for stabilising the operation of technological equipment at the lower level of control and optimising energy costs by predicting them at the upper level. The introduction of such a system allows to saving natural gas for heating up to 13% and electricity – up to 10%. The study proved that the development of an intelligent energy-efficient system for automatic control of microclimate parameters in closed-ground structures should be based on a combination of methods for intelligent adjustment of PI controller parameters and forecasting energy consumption

Keywords: energy efficiency indicators, resource efficiency, microclimate parameters, indoor structures, industrial greenhouse, intelligent control system

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INTRODUCTION

The main problem of modern cultivation of products in industrial greenhouses is the cost of energy carriers, which significantly affects the cost of grown products. Thus, the share of energy in the structure of product prices is 60-90%. Therefore, the task of developing new methods and approaches to minimise energy losses is urgent. It is important to take into consideration that the volume of energy consumption in industrial greenhouses is affected by poorly predicted natural factors, such as cloud cover, wind strength and direction, and other factors that create the main features of the functioning of modern industrial greenhouses: non-stationarity, uncertainty. This is explained by the influence of natural disturbances, which are random in nature and incompleteness of information about the states of the biological component. At the same time, agrotechnical standards require high accuracy of temperature stabilisation (+/-1°C), its timely change depending on the level of photosynthetic active radiation, the phase of plant development and the time of day. This increases the requirements for existing automation systems and their provision by using modern intelligent algorithms for processing information coming from the control object, and applying the results obtained to form appropriate management strategies in order to maximise production profits.

Modern economic conditions require the creation of such a greenhouse for growing vegetable crops, which would allow implementing energy-saving technology for their production by minimising energy costs, while ensuring the appropriate quality of products and their volumes. Well-known strategies include regulating temperature and humidity conditions, supply of CO₂ depending on the plant growth phase and time of day, and dynamic control of additional growth factors based on solar radiation values.

Nowadays, several types of algorithms for controlling microclimate parameters have become widespread, such as: traditional, nonlinear, p-system, based on fuzzy logic and the use of neural networks, and hybrid algorithms [1-5]. Traditional control algorithms include: proportional-integral (PI) and proportional-integral-differential (PID), which are most often used in regulating the microclimate in industrial greenhouses due to their flexibility, simplicity, and good control indicators [6]. M. Azaza [2] used an intelligent system based on fuzzy logic to control the temperature and humidity in the greenhouse, with ventilation and maintenance of plant feeding standards. They achieved 22% and 33% energy and water savings, respectively. M. Vera [7] in their study used a fuzzy model that allows adjusting the internal temperature inside the greenhouse, using a proportional servo valve to activate the heating of the coolant at night, and another drive to control the ventilation rate during the day. K. Li [8] used a multilayer perceptron to predict the temperature in the greenhouse. However, the disadvantage of such a system is the need for a large set of input data to achieve appropriate accuracy in the operation of a fuzzy system. In addition, since the algorithm takes into account the experience of experts in formulating the model,

comprehensive knowledge of the functioning of the system is required.

Thus, there is a need to create and use new intelligent control systems based on a combination of modern control methods, which would ensure the implementation of optimal control according to the energy efficiency criterion.

The purpose of the study is to develop a methodology for creating an intelligent system for energy-efficient microclimate management in industrial greenhouses operating under conditions of uncertainty, based on a combination of methods for predicting energy costs and minimising them through the use of artificial neural networks.

RESULTS AND DISCUSSION

The conducted systematic analysis of the process of growing products in industrial greenhouses determined the main features of the greenhouse as a complex control object:

- the object identifies a structural set of subsystems that interact with each other;
- each of the systems can be included as a subsystem in a more complex one;
- complex systems interact with the external environment as a whole;
- management processes are implemented both using feedbacks and on the basis of forming a set of goals, each of which is solved by its own method;
- complex management systems have their own characteristics at each stage (information collection, analysis, development of control actions, implementation) [9].

As already noted, an industrial greenhouse has all the features of a complex system with the possibility of separating separate subsystems. Since each of these subsystems has its own local goals, conflict situations may arise during the functioning of the system as a whole. Thus, there is a need for coordination of control subsystems, the solution of which is to determine the interaction of subsystems, in which control actions that are optimal according to the efficiency criteria for each of the subsystems are also optimal according to the general criterion for the process in general.

The conducted studies in the greenhouse complex confirm the non-linearity and non-stationarity of processes occurring in an industrial greenhouse when growing vegetable products. The hypothesis that there are conditions of uncertainty in the functioning of an industrial greenhouse is confirmed, the linear correlation coefficients between the inputs and outputs of the control object do not exceed $r < 0.35$. This creates conditions for the use of neural networks that can function effectively in conditions of uncertainty to predict energy consumption. A graphical representation of the correlations is shown in Figure 1.

The correlation relationship is described by regression equations of the form:

- for gas consumption:

$$y_1 = -0.2608x + 6.5303,$$

- for electricity consumption:

$$y_2 = -0.2904x + 1.2493.$$

The greenhouse, as a control object, is multidimensional with complex internal connections, which affects the stationarity of dynamic characteristics. This leads to a deterioration in the quality of control, since in typical automation systems it depends on the dynamic properties of the object. In turn, the analysis of the operation of the temperature and humidity control system in a greenhouse with a PI controller,

as it is most common in closed-ground structures, showed that in order to maintain the progenitors of regulation at a given level and the quality of the transition process, the parameters of the regulator are variable. Therefore, the problem arises of continuously determining the controller settings that adapt to changes in the dynamic properties of the control object, while ensuring the appropriate quality of transients [10; 11].

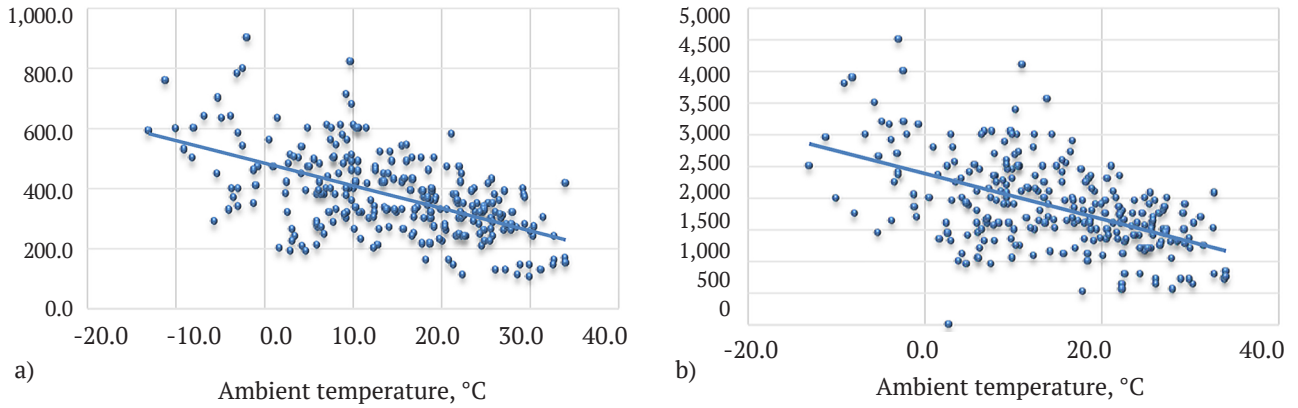


Figure 1. Correlation between gas (a) and electricity (b) consumption and external temperature

The use of various methods for controlling microclimate parameters allows choosing the best algorithm for achieving energy-efficient regulation indicators. Figure 2 shows the use of regulators that implement PI-algorithm, but the calculation of parameters of their settings is carried out based on the results of using fuzzy logic, a genetic algorithm, and a typical engineering technique (for comparison).

The proposed approach provides the necessary opportunities for practical use of the results for predicting the further behaviour of the object and forming energy-efficient strategies for managing the greenhouse complex in the future [6].

The genetic algorithm method was used to find the optimal PI controller settings [12]. The comparison block constantly compares the coordinates of the object's state

with their specified value. If there is a difference between a given signal value and a valid one in the control object $\varepsilon = X_{pv} - x \neq 0$, then the signal is sent to the optimisation unit, the functional purpose of which is to find the optimal settings of the regulator based on the genetic algorithm.

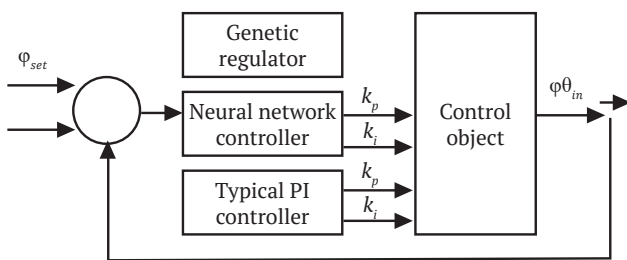


Figure 2. Structural and functional diagram of the automatic control system using various methods for determining the optimal parameters of the PI controller settings for the temperature and humidity regime in the greenhouse: $\theta_{set}, \varphi_{set}$ – set temperature and humidity values, k_p, k_i – transmission coefficient and isodrome time of the PI controller, $\theta_{in}, \varphi_{in}$ – output values of internal temperature and humidity

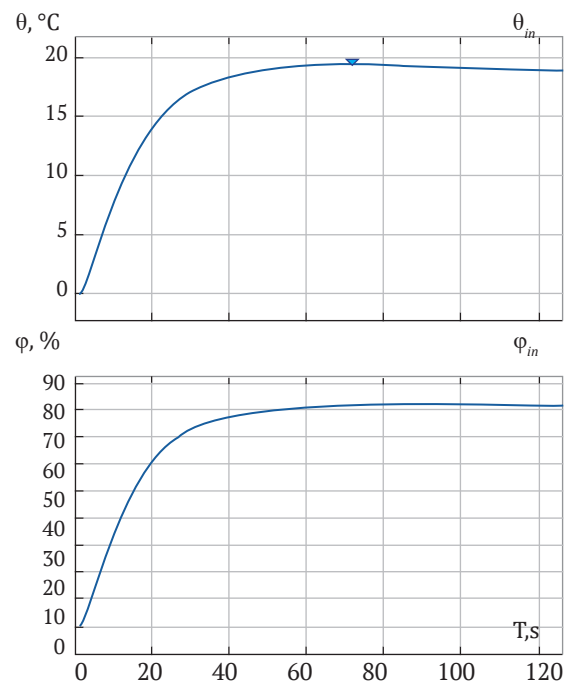


Figure 3. Transient characteristic of the automatic control system for the temperature change channel (θ_{in}) and humidity (φ_{in}) with settings parameters determined based on the use of a genetic algorithm for the PI controller

At the first stage, the training parameters are selected that are set by the optimisation function, which includes the equations of the control object, regulator, and perturbation. Next, the process of obtaining a solution for fixed parameter values and comparing them with the input values takes place based on training, and the optimal parameters of the controller are selected. The use of a genetic algorithm has yielded the following results (Fig. 3): optimal settings for the temperature control channel $k_p=74.8$ proportional component, $k_i=1.8$ integral component; for humidity control channel $k_p=72.7$ proportional component, $k_i=2.1$ integral component for the specified values of temperature and humidity in the greenhouse: $\theta_{in\ set}=18^\circ\text{C}$ and $\varphi_{in\ set}=80\%$.

A fuzzy expert system was also used to optimise the settings of the local control system with a PI controller. The rules of the fuzzy expert system are based on ensuring a minimum area between the transition process and the time axis (1):

$$I = \int_{t_0}^t (x_{pv} - x) dt \rightarrow \min, \quad k_p, k_i \quad (1)$$

where: x_{pv} , x – respectively, the set value of the parameter and its value at the output of the object; $k_p, k_i \in [k_{min}, k_{max}]$ – transmission coefficient and isodrome time of the PI controller.

Production rules for a fuzzy knowledge base are developed based on the expert knowledge and have the form: if $E=vid$, If $E=dod$, then $K_p=zero$, $I T_i=zero$, where vid – negative values, dod – positive values, ser – average values, vel – large values, and $zero$ – zero values (Fig. 4).

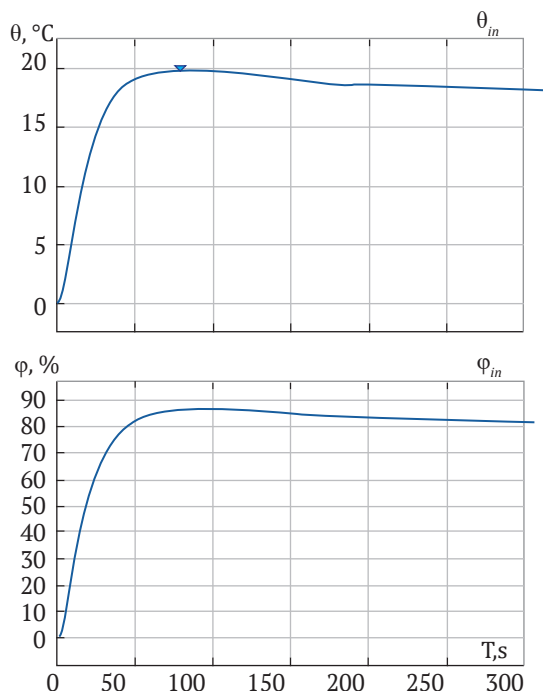


Figure 4. Transient characteristic of the automatic control system for the temperature change channel (θ_{in}) and humidity (φ_{in}) with the parameters of the PI controller settings determined based on the use of a neural network expert system

The algorithm for setting up a neural network controller includes the following steps:

- collection of information about an object’s behaviour when it is affected by perturbations;
- development of production rules, considering technological data;
- phasification of input and output parameters;
- development of a neural network structure;
- training of a neural network expert system;
- testing of results based on modelling.

For the specified values of temperature and humidity in the greenhouse: $\theta_{in\ set}=18^\circ\text{C}$ and $\varphi_{in\ set}=80\%$ of the PI controller settings for the output temperature control channel of the fuzzy expert system were (Fig. 4): $k_p=73.1$ proportional component, $k_i=3.3$ integral component; for humidity control channel $k_p=71.2$ proportional component; $k_i=3.6$ integral component.

As a reference model for comparing the obtained modelling results, the traditional method of searching for the parameters of the PI controller is used.

Using the traditional method of calculating the optimal parameters of regulator settings, namely the Ziegler Nichols method [13], the following values of the parameters of the PI controller settings were obtained under constant initial conditions (Fig. 5): transmission coefficient for the temperature control channel $k_p=75.2$ proportional component, and isodrome time $k_i=3.1$ integral component.

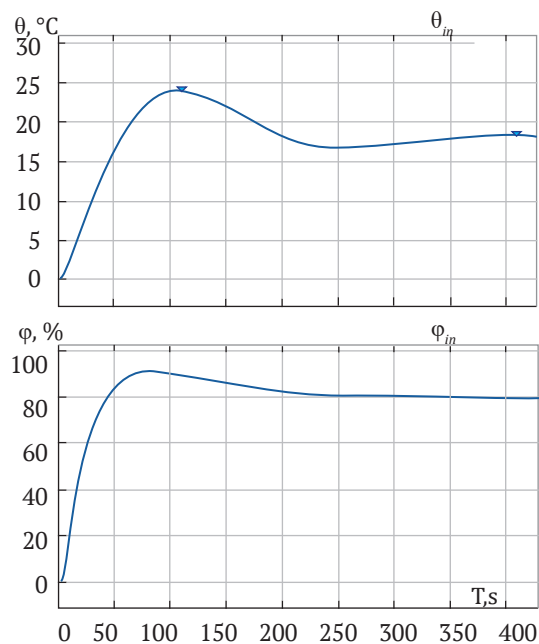


Figure 5. Transient characteristics of an automatic control system with a PI controller, the settings of which are determined according to the standard method, for the temperature change channel (θ_{in}) and air humidity (φ_{in})

To solve the problem of improving the energy efficiency of greenhouse enterprises, it is advisable to apply forecasting of energy costs, namely, gas and electricity, at

the upper level of management [14]. This allows developing energy-efficient strategies for managing microclimate parameters in industrial greenhouses. To do this, it is advisable to use artificial neural networks. The structure of such an automation system is shown in Figure 6.

The neural time series software package was used to synthesise and study the corresponding artificial neural networks. Minimisation the relative root-mean-square learning

error was chosen as a criterion for stopping learning. The Bayesian linear regression method was chosen for training artificial neural networks, since this results in the smallest root-mean-square error with respect to deviation [15]. The number of hidden layers of artificial neural networks – 50.

The learning process is illustrated by a graph of the dependence of the functioning assessment on the number of the learning cycle (Fig. 7).

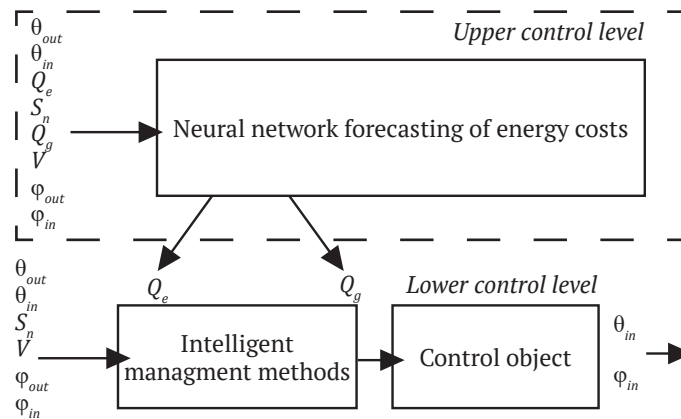


Figure 6. Structural and logical diagram of energy-efficient microclimate management (where $\theta_{in}, \theta_{out}$ – air temperature inside and outside the greenhouse; S_{abs} – solar radiation absorbed by the greenhouse; Q_e, Q_g – gas and electricity consumption in the greenhouse; v – power of the ventilation system; ϕ_{in}, ϕ_{out} – relative humidity of the air inside and outside the greenhouse)

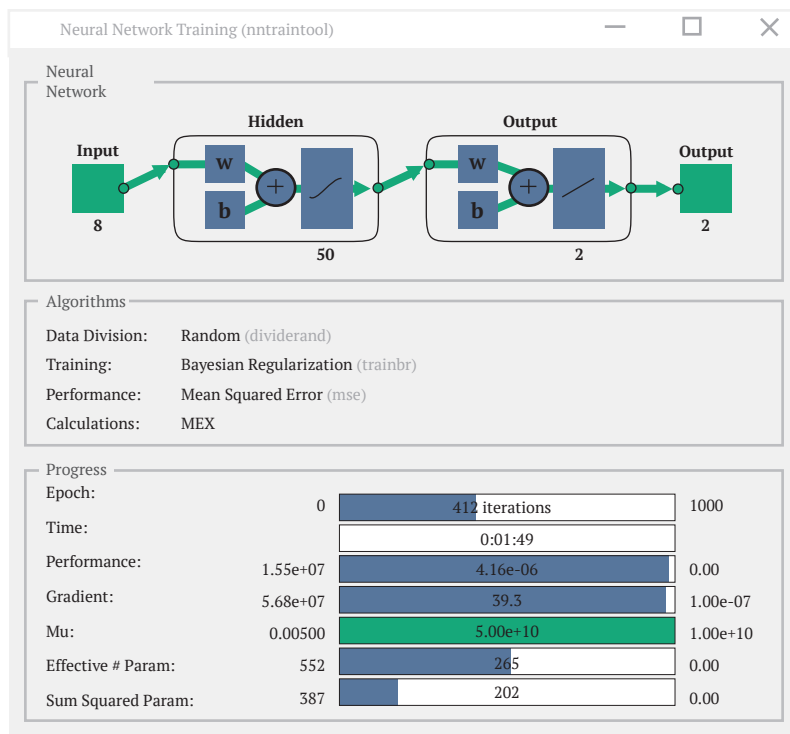


Figure 7. Block diagram of neural network training

A test data array was used to determine the degree of reliability of the results. It was checked whether the pre-dicted values coincided with the actual data of microclimate parameters taken directly at the production site. Regression

analysis methods [16-18] obtained by comparing reference values with values at the network output were used to assess the reliability of the results of artificial neural networks. Evaluation of the developed model for forecasting energy

costs was carried out based on the following criteria: determination R^2 , root-mean-square error σ , Fischer F and Student's t (Table 1).

According to the materials presented in the table, the correlation and determination coefficients are within 90%,

which indicates a close relationship between the inputs and outputs of the model. The measurement error is insignificant – 0.0013. The Student's t indicates the significance of correlation coefficients, which signifies the adequacy of the neural network model for predicting energy consumption.

Table 1. Criteria for the adequacy of a mathematical model

Sample	Criteria			
	R^2	σ	F	t
Gas consumption, m ³	0.99	0.0013	9.39	0.98
Electricity consumption, W/h	0.99	0.0013	9.39	0.97

The methodology for developing an intelligent energy-efficient system for automatic control of microclimate parameters in closed-ground structures is based on a combination of methods: intelligent adjustment of PI controller parameters and forecasting of energy consumption.

The practical implementation of the algorithm for developing an energy-efficient control system takes place according to the following sequence.

1. Conducting experimental studies.
2. Creating a database of microclimate parameters inside and outside the greenhouse.
3. Creating a fuzzy expert system for managing groups of greenhouse coolant supply and ventilation equipment.
4. Development of rules by experts based on the requirements for ensuring the quality of grown products.
5. Processing of information on projected energy consumption values.
6. Select an equipment management strategy to minimise energy consumption by adjusting the regulator settings.

7. Determination of PI controller parameters and simulation.

8. Synthesis of an energy-efficient control system for microclimate parameters in a greenhouse.

To assess economic efficiency, the indicators of minimising energy resources and the payback period of the implemented methods were used. In the course of the study, the following was calculated: distribution, capital expenditures, operating costs, profit from system implementation, and payback periods.

Criteria for evaluating economic efficiency:

$$\begin{cases} \text{Natural gas consumption} \rightarrow \min \\ \text{Electricity consumption} \rightarrow \min \\ \text{Enterprise profit} \rightarrow \max \end{cases} \quad (2)$$

The functions of belonging to the input parameters of the automatic temperature and humidity control system, which are used for technical regulation of microclimate parameters in greenhouses, are synthesised. The following terms are used for all input parameters: “minor impact on energy efficiency”, “average impact on energy efficiency”, and “significant impact on energy efficiency” (Fig. 8).

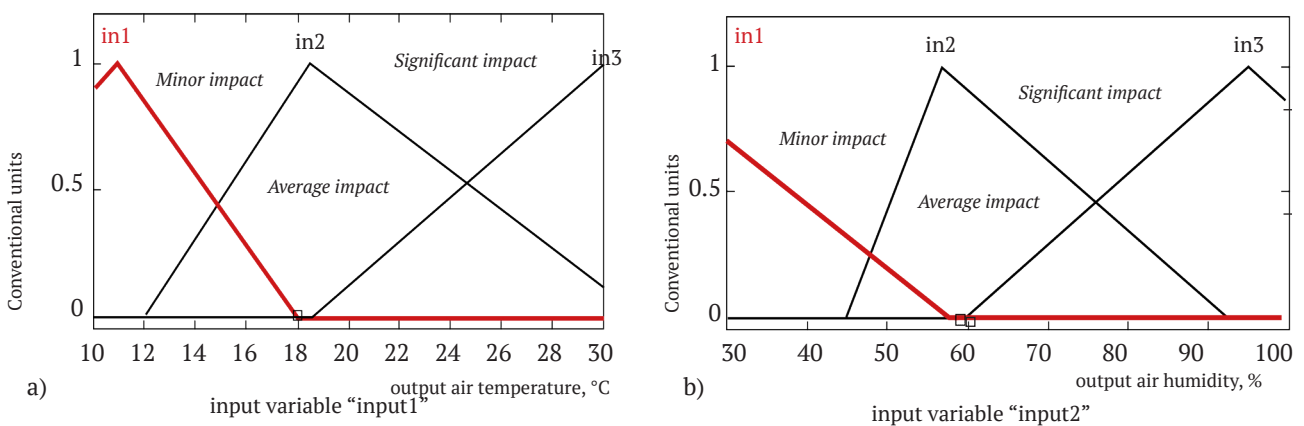


Figure 8. Functions of belonging to energy-efficient parameters of quality control
a) temperature; b) humidity in closed-ground structures

The obtained membership functions allow: predicting the potential effect of the developed methods of controlling technological processes in the greenhouse, taking into account current disturbances, and tracking the qualitative zones of input parameters that affect the energy consumption of the process of growing vegetable products in closed-ground structures

CONCLUSIONS

1. Analysis of the quality of transients as a response to disturbances in automatic systems with a PI controller and an improved model of the object regarding the temperature and humidity regime showed that the parameters of the regulator settings are variable. This proves the relevance of developing methods for finding regulator settings that adapt to changes in the operating conditions of the automation system.

2. Based on the use of fuzzy logic methods and a genetic algorithm, models for finding optimal parameters of the PI controller's settings that adapt to changes in the operating conditions of the automation system are developed and studied. According to the linear integral quality indicator, the best quality of the transition process is demonstrated by a system whose PI controller is configured based on using a genetic algorithm for the following indicators: $k_p=74.8$, $k_i=1.8$ to comply with the microclimate parameters: $\theta_{in\ set}=18^\circ\text{C}$ and $\varphi_{in\ set}=80\%$.

3. A system of intelligent automated energy-efficient control of microclimate parameters in protected ground structures and its algorithmic support has been developed, containing: a block of neural network forecasting of energy costs, a block of decision support, where prices for energy resources are considered, a block of optimisation of regulator parameters based on the use of fuzzy logic and genetic algorithms. The introduction of such a system allows saving natural gas for heating and electric energy – up to 10%.

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Методологія розроблення інтелектуальної енергоефективної системи керування температурно-вологістним режимом в промисловій теплиці

Анотація. Вартість енергоносіїв впливає на собівартість продукції, яку вирощують в промислових теплицях. Мета дослідження – формування методології розроблення інтелектуальної системи енергоефективного керування мікрокліматом у промислових теплицях, що функціонують в умовах невизначеності, на основі поєднання методів прогнозування енерговитрат та їх мінімізації через використання штучних нейронних мереж. Методологія – вхідними параметрами нейромережевої моделі прогнозування є: значення зовнішньої та внутрішньої температур повітря теплиці, значення відносної вологості повітря, поглинуте теплицею сонячне випромінювання та рівень вуглекислоти в теплиці. Виходами моделі прогнозування є значення витрат природного газу та електроенергії. На основі використання методів нечіткої логіки та генетичного алгоритму розроблено та досліджено моделі пошуку та використання оптимальних параметрів налаштувань ПІ-регулятора, адаптованих до зміни умов функціонування системи автоматизації. Проаналізовані методи покращення якості регулювання технологічних параметрів шляхом поєднання в одній системі автоматизації різноманітних інтелектуальних алгоритмів керування, що сприяє зменшенню енергетичних витрат на 10–13 %. Встановлено, що для споруд закритого ґрунту системи опалення й вентиляції мають найбільшу енергозатратність (в середньому за добу на обігрів та вентиляцію в промисловій теплиці витрачається понад 4000 м³ природного газу та майже 1000 кВт·год електроенергії. Кореляційний аналіз зв'язків між зовнішніми збуреннями та енергетичними витратами, що забезпечують дотримання заданої технології вирощування рослинної продукції, підтвердив гіпотезу щодо наявності умов невизначеності функціонування промислової теплиці формуються випадковими збуреннями, неповною інформацією про біологічну складову; при цьому коефіцієнти лінійної кореляції не перевищують $r < 0.35$. Зазначене створює умови для використання нейронних мереж як для прогнозування енергетичних витрат, так і для формування енергоефективних стратегій керування. Зазначене забезпечує більш якісне регулювання в умовах невизначеності час регулювання, перерегулювання зменшуються в два-три рази. Для створення енергоефективної системи керування мікрокліматом в промислових теплицях, що функціонує в умовах невизначеності, розроблено нейромережеву модель прогнозування енергетичних витрат природного газу та електроенергії. В статті автори удосконалили структурно-функціональну схему системи автоматизації керування температуровологістним режимом в промислових теплицях шляхом поєднання інтелектуальних алгоритмів стабілізації роботи технологічного обладнання на нижньому рівні керування та оптимізації енергетичних витрат, шляхом їх прогнозування на верхньому рівні. Упровадження такої системи дозволяє заощадити природний газ на опалення до 13 % та електричну енергію – до 10 %. Авторами доведено, що розроблення інтелектуальної енергоефективної системи автоматичного керування параметрами мікроклімату в спорудах закритого ґрунту має базуватись на поєднанні методів інтелектуального налаштування параметрів ПІ-регулятора та прогнозування енерговитрат

Ключові слова: енергоефективність показників, ресурсоефективність, параметри мікроклімату, споруди закритого ґрунту, промислова теплиця, інтелектуальна система керування