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Thermoelectric climate control systems for agro-industrial facilities with non-linear control of Peltier modules

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Abstract. A promising direction in solving the problem of energy saving at agribusiness facilities is the use of an integrated approach - the principle of trigeneration, in which thermal energy is generated based on the thermoelectric method, which involves the use of special modules from thermoelements based on the Peltier effect. On the basis of this method, a climate control system for agro-industrial complex objects has been developed, represented by a block diagram and an equivalent functional model. To assess its compliance with a certain quality of the control process during the transition of the system to a new operating mode, a comparative analysis of the use of linear and nonlinear control algorithms for thermoelectric modules was carried out. In this case, the nonlinearities were set by two saturation links corresponding to the Saturation blocks in the MatLAB Simulink environment. With the help of the developed models, a study was made of the operation of the proposed climate control system in the time domain for the studied control modes of thermoelectric modules at different values of saturation blocks, according to the results of which it was found that the use of nonlinear control can reduce the time of transients, dynamic control error and oscillation, which unattainable using traditional linear algorithms.

1 Introduction

Every year, due to the global shortage of energy resources and a sharp increase in their cost, the problems of energy conservation become more and more urgent [1-6]. They are especially acute in the sectors of the agro-industrial complex (AIC) [7], where for a number of objects it is mandatory to create a special microclimate for production, which requires significant energy costs [8].

The solution to this problem in many countries of the world at the moment is reduced to the installation of special energy-saving equipment at agricultural facilities and / or technical re-equipment of the energy supply systems used. In addition, a number of authors note the prospects of using an integrated approach to solving the problem of energy saving based on the principle of trigeneration [9–11], which implies the simultaneous production of electrical

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and thermal energy, which makes it possible to reduce the energy intensity of production and the cost of agricultural products.

As one of the main components for building multifunctional trigenerative systems, it is proposed to use the thermoelectric method [12-17], which is characterized by a number of key advantages (environmental friendliness, exceptional reliability of components, the possibility of extremely fast cooling, high accuracy of temperature control, independence of module parameters from gravity and orientation in space, low sensitivity to high mechanical loads, no need for maintenance). This method is based on the use of the Peltier effect [18-21] (absorption or release of heat during the flow of direct electric current through dissimilar conductors), implemented using thermoelectric modules (TEM).

2 Thermoelectric climate control system for agro-industrial facilities

The use of the thermoelectric method of obtaining heat and cold makes it possible to implement on its basis a climate control system for agro-industrial facilities [12, 13]. The microclimate control with its help is carried out under the action of control variables in the form of control currents I_C, which are functionals of the desired temperature values of the T_D and the results of temperature measurements using sensors T_S

$$I_C = f(T_D, T_S) \tag{1}$$

The use of a hybrid ventilation system for agricultural facilities based on the convection principle of cooling makes it possible to carry out heat and cold removal from the junctions of thermoelectric modules to create a non-stationary temperature field in the premises of the form $T = f(x, y, z, t)$, where x, y, z - spatial coordinates, t - time.

This field is three-dimensional and non-stationary and is formed using point sources of heat or cold, each of which is described by the Fourier differential equation for heat conduction in the presence of internal heat sources of the form [22]

$$\frac{\partial T}{\partial t} = a\nabla^2 T + \frac{q_V}{c\rho} \tag{2}$$

where $a = \dfrac{\lambda}{c\rho}$ - the coefficient of thermal diffusivity,

λ - coefficient of thermal conductivity,

c - specific heat capacity,

ρ - density,

$\nabla^2 T = \dfrac{\partial^2 T}{\partial x^2} + \dfrac{\partial^2 T}{\partial y^2} + \dfrac{\partial^2 T}{\partial z^2}$ - the Laplace operator,

q_V - the amount of heat released per unit volume of the medium per unit time.

A special case of this equation is convective heat transfer [22], in which the processes of convection and heat conduction proceed jointly

$$\frac{\partial T}{\partial t} + w_x \frac{\partial T}{\partial x} + w_y \frac{\partial T}{\partial y} + w_z \frac{\partial T}{\partial z} = a\nabla^2 T \tag{3}$$

where w_x, w_y, w_z - the projections of the velocity vector on the X, Y, Z axes.

On the basis of the considered principle, a structural diagram of a thermoelectric climate control system for agro-industrial complex facilities has been developed, shown in Figure 1. This circuit is the simplest and includes a single Peltier thermoelectric module (TEM), its temperature controller (TC), a ventilation system (VS) with a single point source of heat/cold, a single temperature sensor (TS) and an inertia compensator (IC) for this sensor. The following designations are adopted on the scheme: T_d - desired temperature; I_c - control current for Peltier thermoelectric module; T_{PS} is the temperature of the point source of heat/cold; T_S - temperature at the outlet of the temperature sensor; T_{Scomp} - temperature at the outlet of the temperature sensor after passing through the inertia compensator.

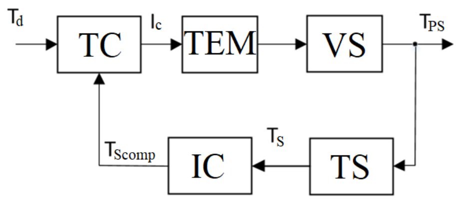


Fig. 1. Structural diagram of thermoelectric climate control system for AIC.

On the basis of this scheme, its equivalent functional model has been developed - Figure 2, where the following designations are adopted: T_{int}(p) - interference effect simulating the processes of heat exchange between the environment and the external sides of the TEM; H_{TC}(p) - transfer function of the temperature controller; H_{AZ}(p) - transfer function of the aperiodic link of the temperature controller (used to reduce the inertia of the Peltier thermoelectric module); H_{TEM}(p) - transfer function of the Peltier thermoelectric module; H_{VC}(p) - ventilation system transfer function; H_{S}(p) - temperature sensor transfer function; H_{IC}(p) - transfer function of the inertia compensator; *p* is the Laplace operator; k_{I} and k_{P} are the transfer coefficients of the integral and proportional components of the temperature controller.

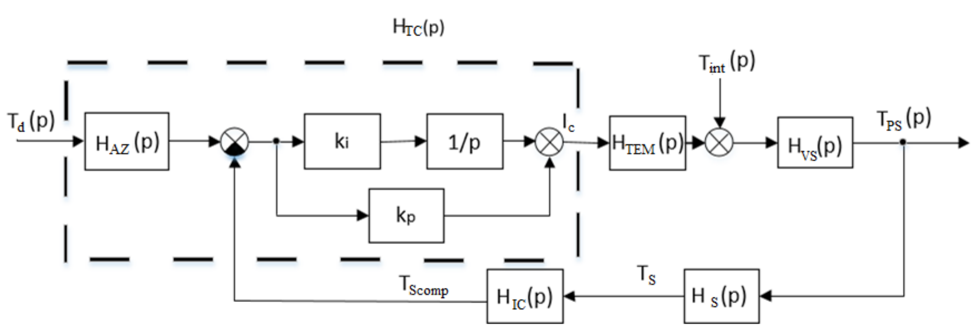


Fig.2. Equivalent functional model of a thermoelectric climate control system for AIC.

The transfer functions of the main structural links, as well as the entire system as a whole for useful and interference effects are presented in detail in [23-25].

3 Linear and non-linear control by Peltier thermoelectric module in climate control systems for AIC

The developed climate control system for agribusiness facilities must correspond to a certain quality of the control process, which is determined by the behavior of the system during the transition to a new mode of operation [26-28].

In this article, for comparative analysis, two types of climate control systems are used: linear and non-linear, the functional models of which in the MatLAB Simulink environment with weight coefficients and transfer functions are shown in Figure 3.
The nonlinearities in Figure 3b are introduced by two Saturation blocks (signal clipping) in order to compensate for undesirable effects from the natural TEM nonlinearities, as well as to give the control system improved quality indicators. The static characteristic of this piecewise linear single-valued (each value of the input quantity x corresponds to one specific value of the output quantity z) continuous nonlinearity is shown in Figure 4 and the analytical one is given as

$$Z = \begin{cases} B \; at \; X > b; \\ kX \; at \left| X \right| \le b; \\ -B \; at \; X < -b. \end{cases} \tag{4}$$

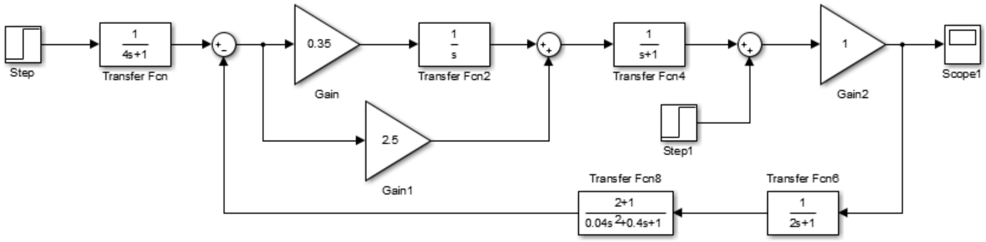
In the case when the linear part of the system is equivalent to a low-pass filter, for these links it is possible to use the method of harmonic linearization, the idea of which is based on the use of an equation obtained by discarding higher harmonics in the expansion of a nonlinear function in a Fourier series. In operator form, this expression has the form

$$z = q(A)x + q'(A)\frac{px}{\omega} \tag{5}$$

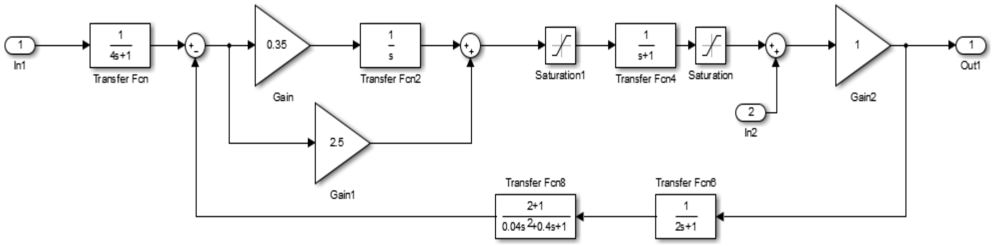
where $q(A) = \frac{B_1}{A}; q'(A) = \frac{A_1}{A}$. - the harmonic linearization coefficients, determined for the selected type of nonlinearity as

$$q(A) = \frac{2B}{\pi b}\left[\arcsin\frac{b}{A} + \frac{b}{A^2}\sqrt{A^2 - b^2}\right]; q'(A) = 0 \, at \; A \ge b. \tag{6}$$

Using the developed models, a study was made of the operation of the proposed climate control system in the time domain for linear (blue color) and non-linear (brown color) TEM control modes for various saturation block values - Figures 5-7.



a)



b)

Fig.3. Linear (a) and nonlinear (b) functional models of a thermoelectric climate control system for AIC in the MatLAB Simulink environment.

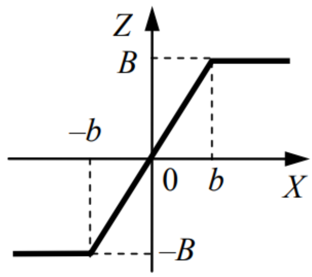


Fig.4. Static characteristic of the nonlinearity of saturation (limitation) of signals.

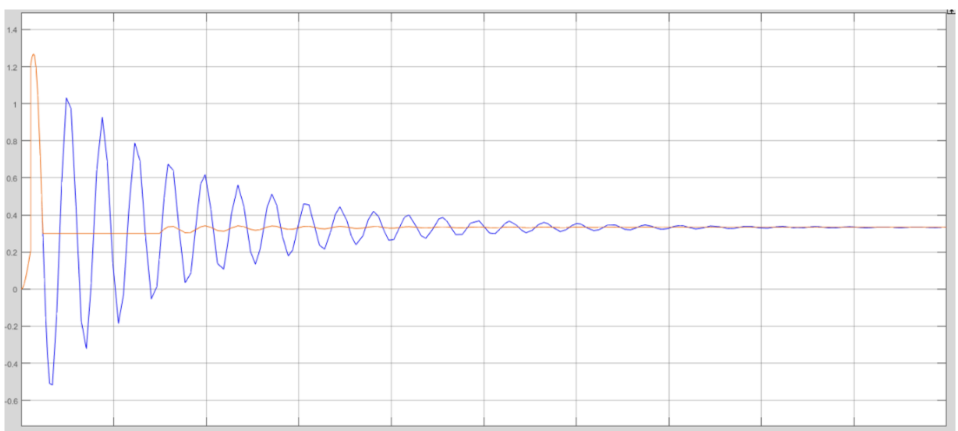


Fig.5. Transient process of the thermoelectric climate control system for AIC with coefficients of the first saturation block (2; -2) and the second (0.7; -0.7).

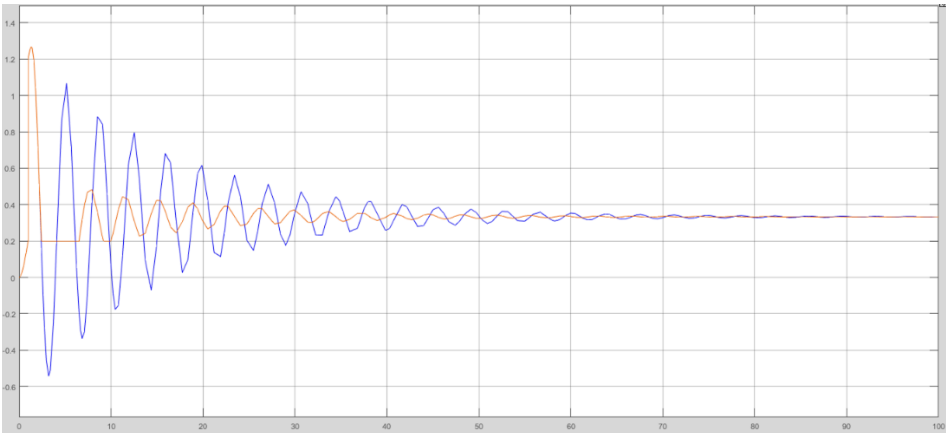


Fig.6. Transient process of the thermoelectric climate control system for agricultural facilities with coefficients of the first saturation block (2; -2) and the second (0.8; -0.8).

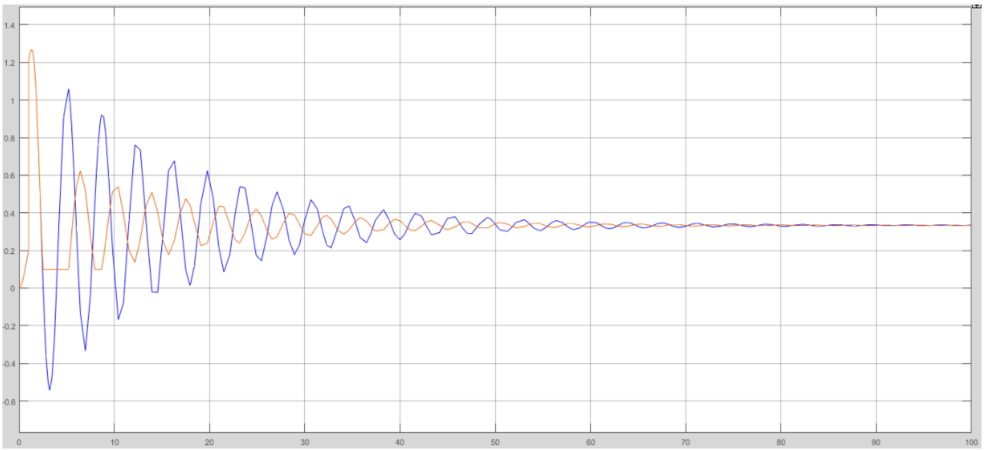


Fig.7. Transient process of the thermoelectric climate control system for agricultural facilities with coefficients of the first saturation block (2; -2) and the second (0.9; -0.9).

4 Conclusion

From the graphs obtained, it can be concluded that the use of a nonlinear TEM control algorithm makes it possible to impart properties to the climate control system that are fundamentally unattainable by traditional linear means. This is manifested in providing extremely high speed during transients (decreased by 2–20 times), as well as reducing the dynamic control error and oscillation in the presence of the same structural elements, their coefficients and natural restrictions on the levels of control and interference effects.

Thus, the proposed approach to nonlinear control in climate control systems for agro-industrial complex can serve as an effective variant of TEM control, which allows solving the problems of optimization and synthesis of this class of devices with improved characteristics and quality indicators.

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