Specific problems on the operation of the automatic control system of temperature into an individual dwelling

DANIEL POPESCU

Department of Electrical Engineering for Civil Engineering and Building Services
Technical University of Civil Engineering Bucharest
Bd. Pache Protopopescu nr.66, 021414 Bucuresti Sector 2
ROMANIA
dpopescu@instal.utcb.ro

Abstract: The article makes an analysis of the functioning for the heating automation system with hot air blown into an individual dwelling. The structure of the automatic control system for indoor temperature in the dwelling is determined, in which the controller is a thermostat having feature type relay with hysteresis, the conditions related to the evolution of automatic control of the process are specified and the oscillation period of the control system is calculated.
The automatic temperature control system model in individual dwelling is established using Simulink and its functioning by simulation in different representative situations is checked. The results of the simulation are compared with those obtained by calculation or they are used to determine the performance of the automatic control system

Key-words: nonlinear automatic system, changeover controller, thermostat, relay with hysteresis, oscillation period of the control system, precision of the control, comfort in buildings, automation of heating installations.

1 Introduction

This article deals with ensuring indoor comfort in individual dwellings by using nonlinear automatic control systems of the type changeover [1,2,3,4,5].
Indoor temperature regulation is done by using a thermostat, placed in a room chosen as being representative. Heating is assured with blowing hot air at a constant temperature [6,7,8,9].
By comparison to the complex automatic control systems, using the thermostat temperature control device in individual dwellings [10] is a cheap and reliable solution, and automatic control system performance may be acceptable, if the right information about hysteresis loop that characterize bimetallic lamella of the thermostat, the function mode of the command cycle for the heating and thermal inertia of the house is used [11].
The changeover adjusting of the temperature with thermostat is the most used solution for individual dwellings.
Indoor thermal comfort is ensured in large buildings by implementing control structures with feed-forward loop, which controls the water temperature depending on the outside temperature (main disturbance which acts on the process of building heating) [12,13]. The adjusting structure may be used for individual dwellings if an automation device called "ambient probe" is used; the device is placed in the reference room where the indoor temperature is measured and allows correction with $\pm$ 2.5^{0}C of the reference indoor temperature value set by the control cabinet of the heating plant.
Recent research on indoor temperature control in large buildings use control methods of heating taking into account the heat loss through the building envelope [14,15,16,17]. A perimetral monitoring system of the temperatures of the external surfaces of building provides infrared thermal map of these areas. The thermal map is processed in order to obtain an electrical signal used for driving the heating installation. The indoor temperature is maintained constant by regulating the temperature of the outer surface of the building.

2 Objectives of the paper

The paper presents the time domain analysis of the control system for the indoor temperature using differential equations. Using basic concepts from the theory of nonlinear automatic systems [18,19,20,21,22,23,24] the mathematical inequalities that must be satisfied between the outdoors temperature, hot air temperature, desired indoor temperature and the size of insensitivity domain of the hysteresis are specified, so that the

cycle of control of the heating process can evolve over time. It calculates the oscillation period of the automatic control system.
Using the mathematical model made in Simulink for automatic adjustment of the indoor temperature, it is analyzed its behavior in time, for different representative situations. Through analysis, it is checked:
- the precision for automatic control of the indoor temperature through stationary error evaluation;
- the oscillation domain of the controlled variable;
- the conditions for the cyclic operation of heating process;
- the coincidence between the values of oscillation periods obtained by calculation with those determined by computer simulation;
- the determination of a minimum acceptable value for the temperature interval Δ of the hysteresis of the thermostat.

3 Automatic indoor temperature control structure into individual dwelling

The room chosen as representative for individual dwelling is heated with hot air blowing at 40^0C. The indoor temperature is adjusted by successive actions start / stop for introducing hot air in the room, until they get to values as close as the temperature θ_{ref} set at 18^0C or 20^0C. Control of duty cycles is assured by a changeover controller (thermostat), appropriate located on a wall of the room, which has feature type relay with hysteresis (Figure 1).

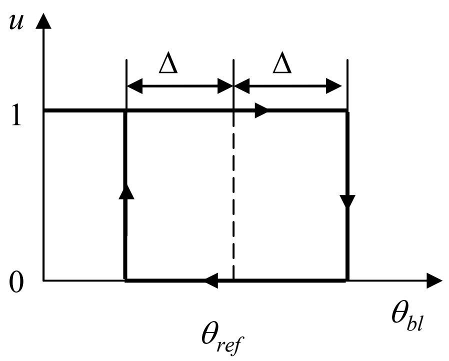

Fig. 1. Feature type relay with hysteresis.

Bimetallic lamella of the thermostat is deformed by heating / cooling and operates an electric switch used to control the introduction of hot air in the house. The values of the temperatures at which is actioned the electrical contact are established as shown in figure 1, in which is highlight the cycle with hysteresis of the command u according to the temperature θ_{bl} of bimetallic lamella. The temperature interval corresponding to the hysteresis of the bimetallic lamella is denoted by Δ.
Bimetallic lamella temperature θ_{bl} depends on ambient temperature θ_{room} according to the relation

$$\theta_{bl}(s) = \left[\frac{1}{1+\tau_{bl}\cdot s}\right]\cdot \theta_{room}(s), \quad (1)$$

where τ_{bl} is the thermal inertia of bimetallic lamella.
Heated room behaves like a first-order inertial element with transfer function

$$H_2(s) = \frac{1}{1+\tau_2 s}. \quad (2)$$

The structure of the automatic adjustment system of indoor temperature is presented in figure 2.

4 Imposed conditions for the functioning of automatic control structure

It is noted in figure 2 that the command $u = 1$ the room temperature θ_{room} and bimetallic lamella temperature θ_{bl} is moving towards the value given by $\theta_{out} + K_1$; if the command $u = 0$, then the temperatures θ_{room} and θ_{bl} decrease toward the temperature θ_{out}. The operation of automatic adjustment structure is only possible if the limits within which varies the temperature of bimetallic lamella θ_{bl} are located outside the cycle with hysteresis; therefore, the relations of inequality that need to be fulfilled to generate the periodical commands that produce the heating of the room are:

$$\theta_{out} + K_1 > \theta_{ref} + \Delta, \quad \theta_{out} < \theta_{ref} - \Delta. \quad (3)$$

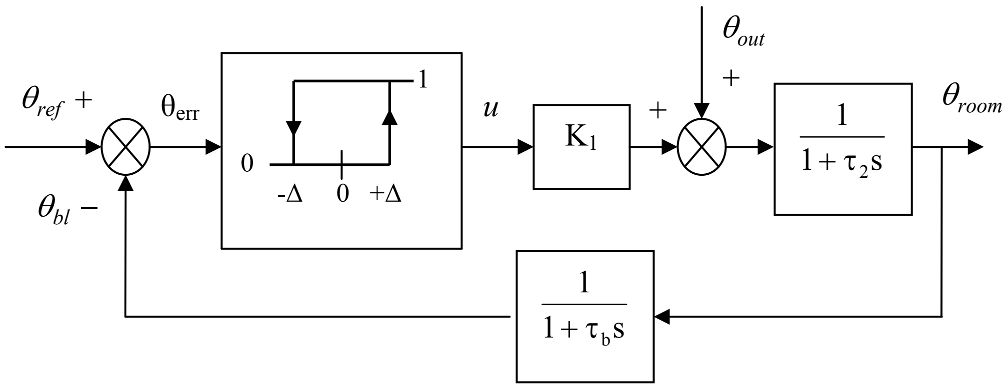

Fig. 2. The structure of the automatic adjustment system of indoor temperature.

5 Determination of the oscillation period of the automatic control system

Starting from the structure of the automatic control system shown in figure 2, the following differential equations can be written:

$$\tau_2 \frac{d\theta_{room}}{dt} + \theta_{room} = \theta_{out} + K_1 \cdot u \qquad (4)$$

$$\tau_{bl} \frac{d\theta_{bl}}{dt} + \theta_{bl} = \theta_{room}. \qquad (5)$$

Substituting θ_{room} from equation (5) into equation (4) it obtain

$$\tau_2 \tau_{bl} \frac{d^2\theta_{bl}}{dt^2} + (\tau_2 + \tau_{bl})\frac{d\theta_{bl}}{dt} + \theta_{bl} = \\ = \theta_{out} + K_1 \cdot u \quad . \qquad (6)$$

Since the time constant τ_2 is much bigger than τ_{bl}, then equation (6) is reduced to an equation of the first order

$$\tau_c \frac{d\theta_{bl}}{dt} + \theta_{bl} = \theta_{out} + K_1 \cdot u, \qquad (7)$$

having the time constant $\tau_c = \tau_2 + \tau_{bl} = 480s$.

For performing calculations and simulation of system model the following numerical values are selected: $K_1 = 40^0 C$, $\tau_2 = 450s$, $\tau_{bl} = 30s$, $\Delta = 1{,}5^0 C$; the simplifying hypothesis is used, in which the outside temperature has a constant value $\theta_{out} = 5^0 C$.

The oscillation period T is composed by two time intervals: first interval $[0, t_0]$, when $u = 1$ and the second interval $(T - t_0)$, when $u = 0$. These time intervals are calculated by solving the equation (7), taking into account the characteristic of the bimetallic lamella shown in figure 1.

$$[0, t_0], \quad \theta_{bl}(0) = \theta_{ref} - \Delta :$$

$$\tau_c \frac{d\theta_{bl}}{dt} + \theta_{bl} = \theta_{out} + K_1 \qquad (8)$$

$$[t_0, T], \quad \theta_{bl}(t_0) = \theta_{ref} + \Delta :$$

$$\tau_c \frac{d\theta_{bl}}{dt} + \theta_{bl} = \theta_{out} \qquad (9)$$

The differential equation (7), in the time interval $[0, t_0]$, has the solution

$$\theta_{bl} = \theta_{out} + K_1 + [\theta_{ref} - \Delta - \theta_{out} - K_1] \cdot e^{-\frac{t}{\tau_c}} \qquad (10)$$

which for $t = t_0$, moment in which $\theta_{bl}(t_0) = \theta_{ref} + \Delta$, allow the calculation of the value t_0 thus:

$$t_0 = \tau_c \cdot \ln\left[\frac{\theta_{out} + K_1 + \Delta - \theta_{ref}}{\theta_{out} + K_1 - \Delta - \theta_{ref}}\right] = 53{,}4s. \qquad (11)$$

For the time interval $[t_0, T]$ the solution of differential equation (7) is

$$\theta_{bl} = \theta_{out} + [\theta_{ref} + \Delta - \theta_{out}] \cdot e^{-(t-t_0)/\tau_c}, \qquad (12)$$

which for $t = T$ (moment in which $\theta_{bl}(T) = \theta_{ref} - \Delta$), we can calculate the oscillation period T as follows:

$$T = t_0 + \tau_c \cdot \ln\left(\frac{\theta_{ref} + \Delta - \theta_{out}}{\theta_{ref} - \Delta - \theta_{out}}\right) = 164{,}6s. \quad (13)$$

If it calculates t_0 and T for θ_{ref} = 20^{0}C, θ_{out} = -10^{0}C, $\Delta = 1^0 C$, $K_1 = 40^0 C$, $\tau_2 = 450s$, $\tau_{bl} = 30s$, $\tau_c = \tau_2 + \tau_{bl} = 480s$, then we obtain:

$$t_0 = \tau_c \cdot \ln\left[\frac{\theta_{out} + K_1 + \Delta - \theta_{ref}}{\theta_{out} + K_1 - \Delta - \theta_{ref}}\right] = \quad (14)$$

$$= 450 \cdot \ln\left[\frac{-10 + 40 + 1 - 20}{-10 + 40 - 1 - 20}\right] = 90{,}3s$$

$$T = t_0 + \tau_c \cdot \ln\left(\frac{\theta_{ref} + \Delta - \theta_{out}}{\theta_{ref} - \Delta - \theta_{out}}\right) = \quad (15)$$

$$= 90{,}3 + 450 \cdot \ln\left[\frac{20 + 1 + 10}{20 - 1 + 10}\right] = 120{,}31s$$

6 The model of automatic temperature control system in individual housing

The model of automatic temperature control system is done using Simulink, in two variants, which differ by the way they act the main disturbance (outdoor temperature):

- variant 1, in which outdoor temperature has a constant value, that temperature is the average diurnal (figure 3);
- variant 2, in which the outdoor temperature varies sinusoidal form day to night, with a given amplitude to an average diurnal value (figure 4).

7 Analysis of the functioning of automatic heating system model of individual housing

A. Shall be checked by simulation using the model developed in variant 1 (figure 3), the fact that the command u is launched periodically for heating of the house and evaluate the precision of the temperature adjustment in the house with θ_{room} and θ_{bl} (figure 5).

The simulation is done for θ_{ref} = 18^{0}C, θ_{out} = 5^{0}C, $\Delta = 1{,}5^0 C$, $K_1 = 40^0 C$, $\tau_2 = 450s$, $\tau_{bl} = 30s$, $\tau_c = \tau_2 + \tau_{bl} = 480s$, identical to the values entered in the relations (11) for t_0 and (13) for T.

Analyzing the graphs obtained by simulation, it is found that the room temperature is regulated around average value of 18^{0}C, equal to that required by θ_{ref} and the periodical evolution of commands applied to the automated heating process for which shall be determined from graphs $t_0 \cong 55s$ and $T \cong 160s$. The size of oscillation domain for adjusted parameter θ_{room}, determined by graph, has the approximate value of 3^{0}C, that which was expected because $\Delta = 1{,}5^0 C$.

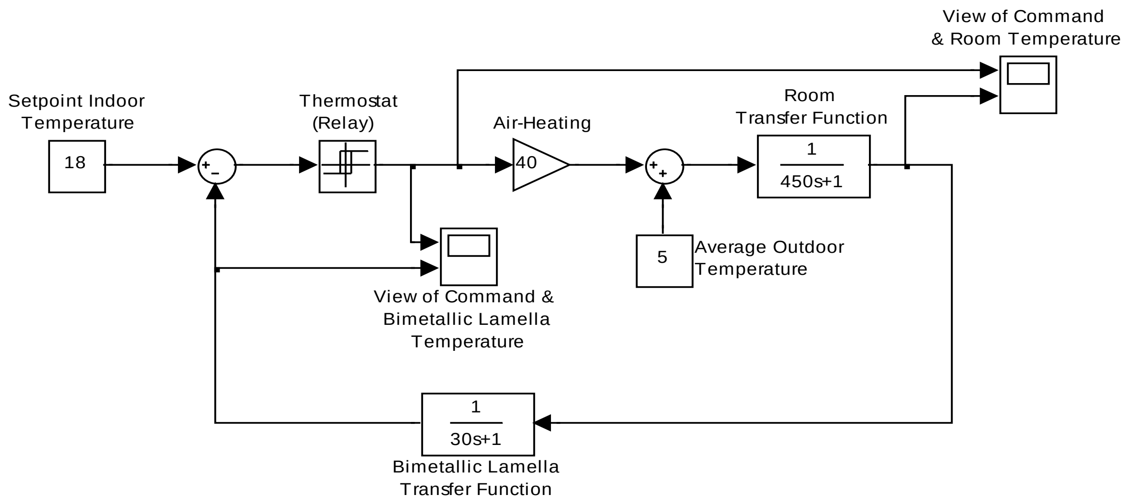

Fig. 3. The model of automatic temperature control system in which outdoor temperature has a constant value.

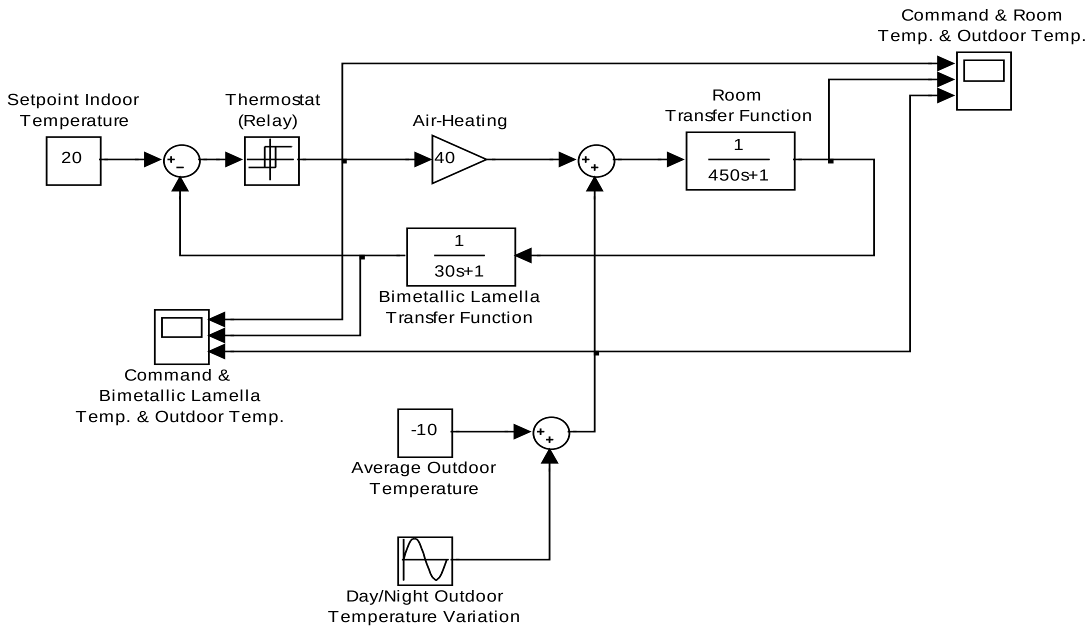

Fig. 4. The model of automatic temperature control system in which the outdoor temperature varies sinusoidally.

B. The simulation is done for θ_{ref} = 20^{0}C, θ_{out} = -10^{0}C, $\Delta = 1^0 C$, $K_1 = 40^0 C$, $\tau_2 = 450s$, $\tau_{bl} = 30s$, $\tau_c = \tau_2 + \tau_{bl} = 480s$, identical to the values entered in the relations (14) for t_0 and (15) for T. The simulation results are presented in figure 6.

It is found through simulation that the regulation of room temperature is around average value of 20^{0}C, equal to that imposed by θ_{ref} and that is taking place the periodically evolution of commands applied at the automated heating process; using the graphs it determine $t_0 \cong 88s$ and $T \cong 122s$. The size of oscillation domain for adjusted parameter θ_{room}, determined by graph, has the approximate value of 2^{0}C, that which was expected because $\Delta = 1^0 C$.

C. Simulation is done using the model developed in Simulink, version 2 from figure 4, in which numerical values entered are the following: θ_{ref} = 20^{0}C, $\Delta = 1^0 C$, $K_1 = 40^0 C$, $\tau_2 = 450s$, $\tau_{bl} = 30s$; the outdoor temperature has the average value θ_{out} = -10^{0}C, over which are overlapping variations from day to night with sinusoidal form and amplitude 8^{0}C.

The graph obtained for the indoor temperature θ_{room} during the day when the outside temperature achieve the highest value θ_{out} = -2^{0}C, is shown in figure 7, and the graph obtained for θ_{room} during the night, when the outside temperature achieves the lowest value θ_{out} = -18^{0}C, is shown in figure 8.

It is noted the evolution of the temperature adjustment cycles in the room by repeating the command u for heating and, as expected, the time interval [0, t_0] when the command $u = 1$, is higher in the case when θ_{out} = -18^{0}C than if θ_{out} = -2^{0}C.

The value $\Delta = 1^0 C$ chosen for the characteristic of the thermostat ensure the adequate precision for the indoor temperature in the house. A decrease of the value Δ at thermostat would enhance the precision of the adjustment, but it would force too much the actuator of the control system by decreasing the oscillation period T.

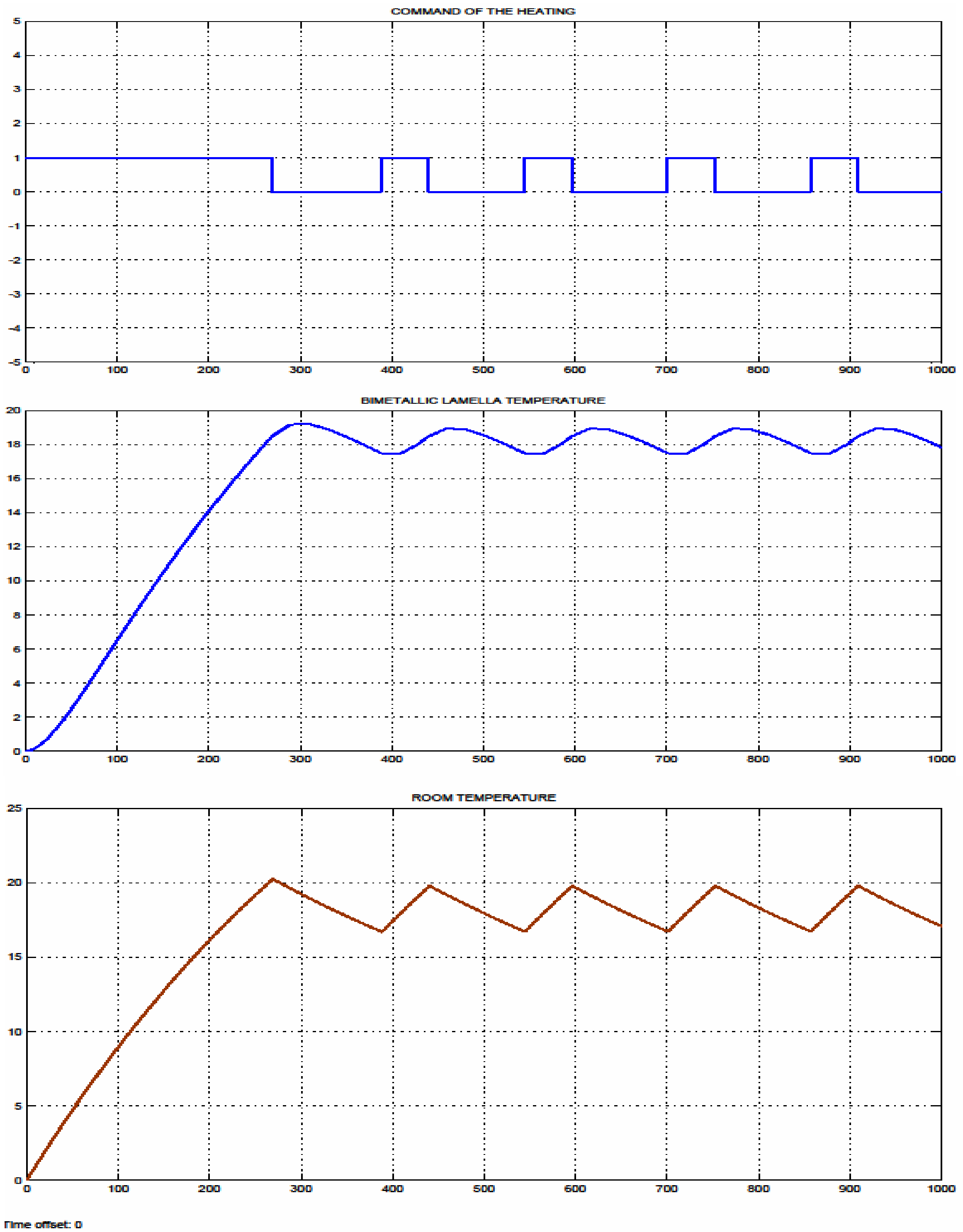

Fig. 5. Model simulation results in which outdoor temperature has a constant value.

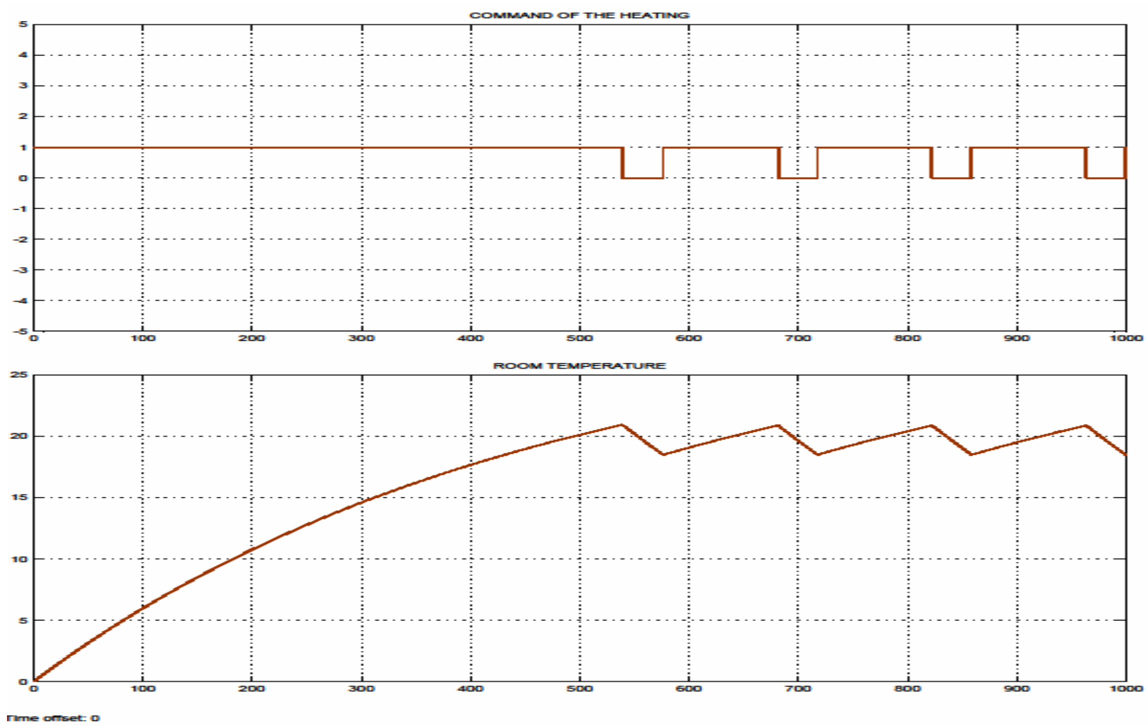

Fig. 6. Model simulation results in which the outdoor temperature varies sinusoidally.

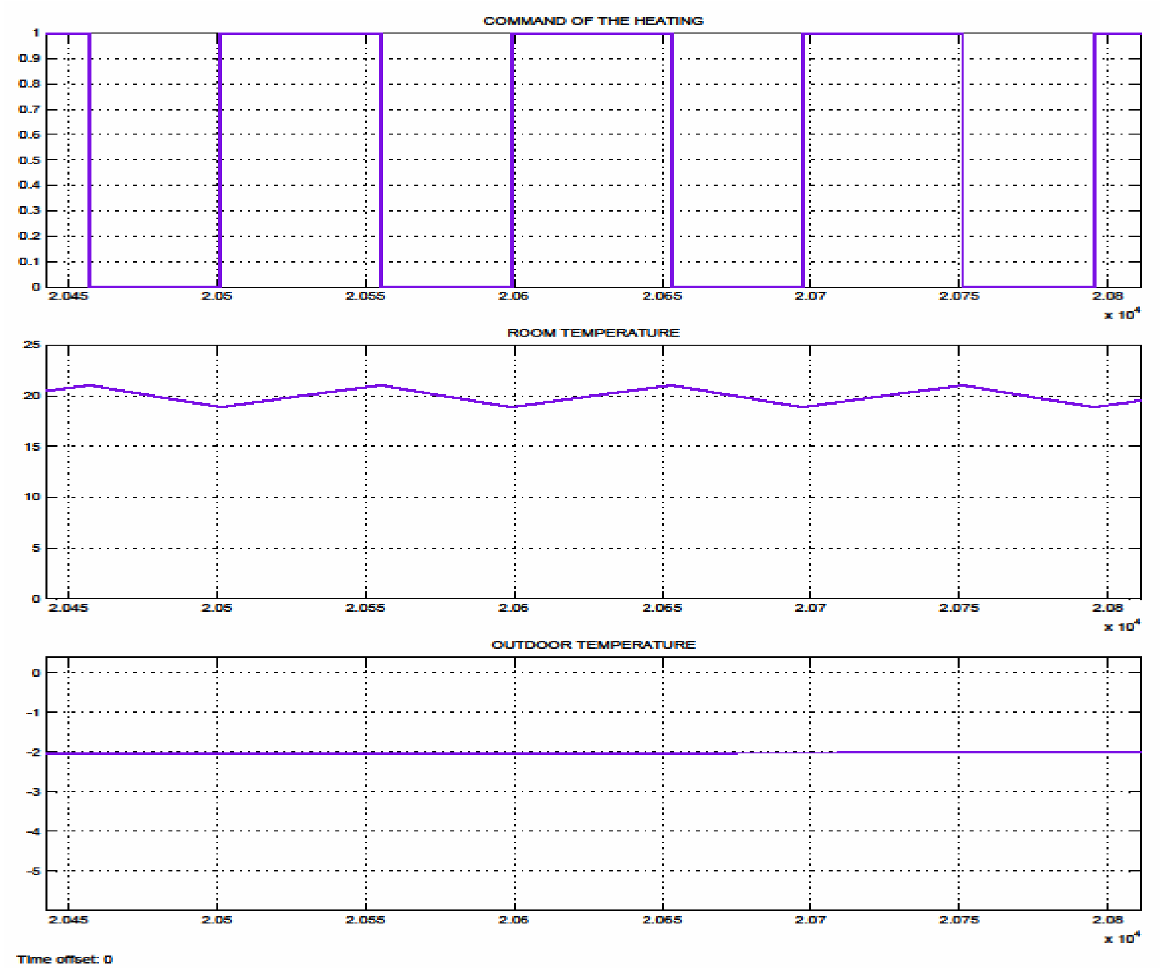

Fig. 7. The graph obtained for the indoor temperature when the outside temperature achieve the highest value.

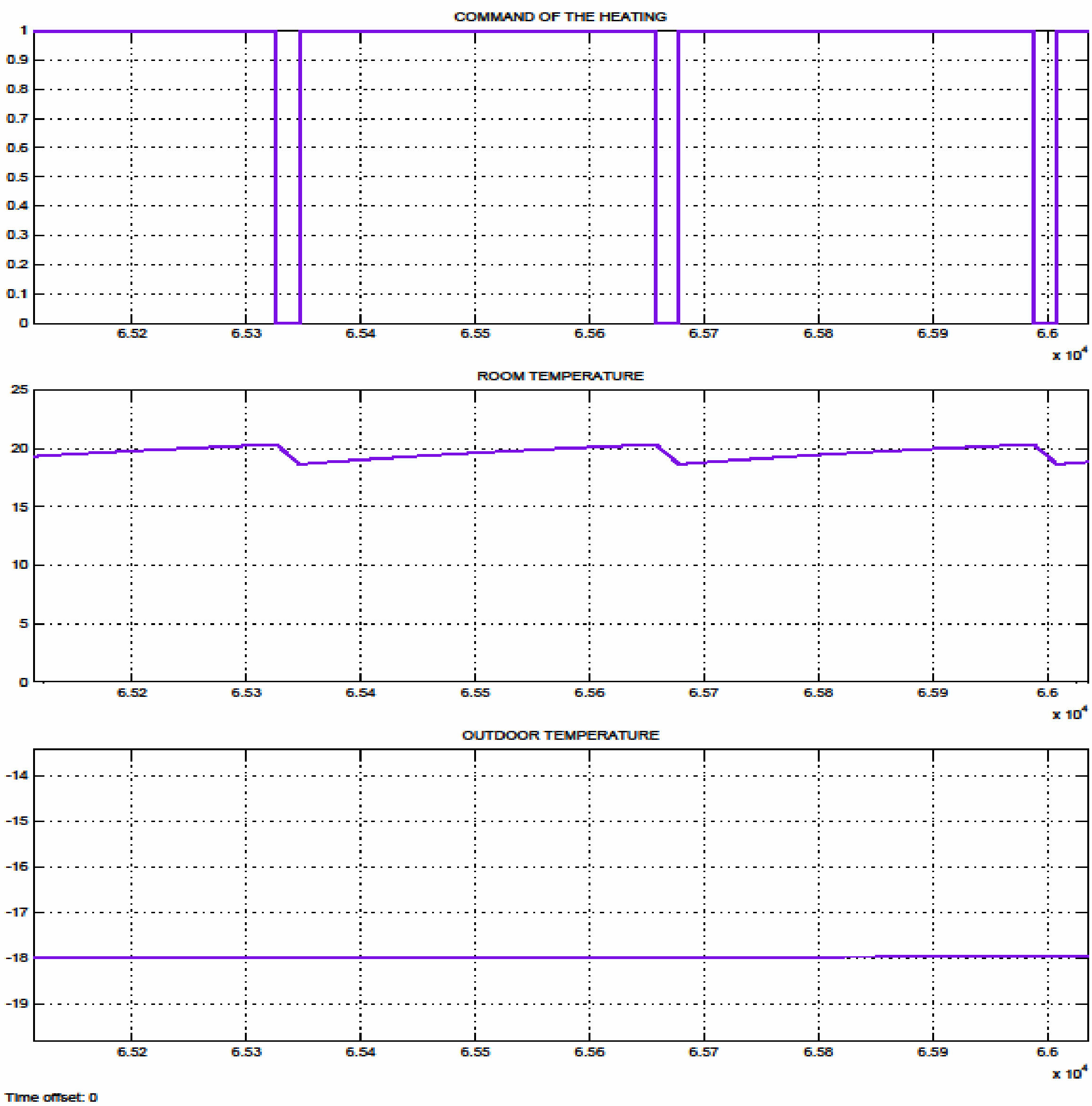

Fig. 8. The graph obtained for the indoor temperature when the outside temperature achieves the lowest value.

8 Conclusions

It is found that are satisfied the conditions (3) for the automatic control system, in all situations analyzed by simulation.

The approaching between numerical values obtained for t_0 and T by calculation in paragraph 5 and by simulation in paragraph 7 variants A and B, validates the correctness of the two approaches in this paper.

The analysis perform in paragraph 7, in the variants of point C, corresponds quite well the real situation of a cold winter day in Romania.

The decreasing values chosen for the temperature domain Δ, corresponding to the hysteresis of thermostat (figure 1), increase the control precision of indoor temperature, but would extra force the actuator that controls the introduction of warm air in the home, by increasing the switching frequency.

The way in which was made the analyze of the automatic control system for indoor temperature into an individual housing when using the hot air heating, can be applied in the case when using a similar structure of the automatic control, for heating with radiators through which circulate heat transfer medium heated to a constant temperature.

The automation solution with changeover regulator (thermostat) placed in a room chosen as reference, can not be applied for automatic control of the indoor temperature in the great buildings.

References:

[1] Belea, C., (1983) *Automatică neliniară*, Editura Tehnică, Bucureşti.

[2] Doroshin, A. V., Neri, F. (2014) *Open research issues on Nonlinear Dynamics, Dynamical Systems and Processes*. WSEAS Transactions on Systems, 13, in press.

[3] Ciufudean, C., Neri, F. (2014) *Open research issues on Multi-Models for Complex Technological Systems.* WSEAS Transactions on Systems, 13, in press.

[4] Neri, F. (2014) *Open research issues on Advanced Control Methods: Theory and Application.* WSEAS Transactions on Systems, 13, in press.

[5] Pekař, L., Neri, F. (2013) *An introduction to the special issue on advanced control methods: Theory and application* (2013) WSEAS Transactions on Systems, 12 (6), pp. 301-303.

[6] Mira, N., (coordinator) (2010) *Enciclopedia tehnică de instalații,* vol. 1, Instalații de încălzire, ISBN 978-973-85936-5-7, Editura ARTECNO Bucureşti.

[7] Karthikeyan, P., Neri, F. (2014) *Open research issues on Deregulated Electricity Market: Investigation and Solution Methodologies*. WSEAS Transactions on Systems, 13, in press.

[8] Panoiu, M., Neri, F. (2014) *Open research issues on Modeling, Simulation and Optimization in Electrical Systems.* WSEAS Transactions on Systems, 13, in press.

[9] Azzouzi, M., Neri, F. (2013) *An introduction to the special issue on advanced control of energy systems* (2013) WSEAS Transactions on Power Systems, 8 (3), p. 103.

[10] Iordache, F., Popescu, D. (2005) *Aspecte privind automatizarea funcționării unor instalații de încălzire centrală de tip individual*, Instalatorul, No. 6, pp. 10-15, ISSN 1223-7418, Editura ARTECNO Bucureşti.

[11] Pekař, L., Neri, F. (2012) *An introduction to the special issue on time delay systems: Modelling, identification, stability, control and applications* WSEAS Transactions on Systems, 11 (10), pp. 539-540.

[12] Popescu, D., Ionescu, D., Iliescu, M. (2009) *Conducerea automată a instalațiilor de încălzire din clădirile mari – aspecte privind realizarea practică*. Instalatorul, No. 4, pp. 24-26, ISSN 1223-7418, Editura ARTECNO Bucureşti.

[13] Popescu, D., Ionescu, D., Iliescu, M. (2008) *Aspecte privind comportarea părții fixate a sistemelor de automatizare din instalațiile de încălzire ale clădirilor mari*, A 43-a Conferință Națională de Instalații, pp. 31-36, ISBN 978-973-755-406-2, Sinaia, October 15-18, 2008.

[14] Popescu, D., Ciufudean, C. (2008) *Automatic Control System for Heating Systems in Buildings Based on Measuring the Heat Exchange through Outer Surfaces,* Proceedings of the 8th WSEAS International Conference on Simulation, Modelling and Optimization (SMO'08), pp. 117-121, ISBN 978-960-474-007-9, ISSN 1790-2769, Santander, Cantabria, Spain, September 23-25, 2008.

[15] Popescu, D., (2008) *A New Solution for Automatic Control of Heating Systems in Buildings Based on Measuring Heat Transfer Through Outer Surfaces*, Proceedings of the 10th WSEAS International Conference on Automatic Control, Modeling and Simulation (ACMOS'08), pp. 206-209, ISBN 978-960-6766-63-3, ISSN 1790-5117, Istanbul, Turkey, May 27-30, 2008.

[16] Popescu, D., Ciufudean, C., Ghiauş, A. (2009) *Specific Aspects of Design of the Automated System for Heating Control that Accounts for Heat Losses Through the Building's Envelope.* Proceedings of the 13th WSEAS International Conference on Systems (part of the 13th WSEAS CSCC Multiconference –CSCC'09- Circuits, Systems, Communications and Computers), pp. 352 – 356, ISSN 1790-2768, ISBN 978-960-474-097-0, Rodos, Greece, July 22-24, 2009.

[17] Popescu, D., Ciufudean, C., Ionescu, D. (2009) *Experimental Analysis of the Automated System for Heating Control based on Heat Losses through Building's Envelope*. 9th WSEAS International Conference on Simulation, Modelling and Optimization (SMO'09), pp. 160 – 166, ISSN 1790-2769, ISBN 978-960-474-113-7, Budapest Tech University, Hungary, September 3-5, 2009.

[18] Neri, F. (2014) *Open research issues on Computational Techniques for Financial Applications.* WSEAS Transactions on Systems, 13, in press.

[19] Hájek, P., Neri, F. (2013) *An introduction to the special issue on computational techniques for trading systems, time series forecasting, stock market modeling, financial assets modeling* WSEAS Transactions on Business and Economics, 10 (4), pp. 201-292.

[20] Bojkovic, Z., Neri, F. (2013) *An introduction to the special issue on advances on interactive multimedia systems* WSEAS Transactions on Systems, 12 (7), pp. 337-338.

[21] Guarnaccia, C., Neri, F. (2013) *An introduction to the special issue on recent methods on physical polluting agents and environment modeling and simulation* WSEAS Transactions on Systems, 12 (2), pp. 53-54.

[22] Neri, F. (2012) *An introduction to the special issue on computational techniques for trading systems, time series forecasting, stock market modeling, and financial assets modeling* WSEAS Transactions on Systems, 11 (12), pp. 659-660.
[23] Muntean, M., Neri, F. (2012) *Foreword to the special issue on collaborative systems* WSEAS Transactions on Systems, 11 (11), p. 617.
[24] Volos, C., Neri, F. (2012) *An introduction to the special issue: Recent advances in defense systems: Applications, methodology, technology* WSEAS Transactions on Systems, 11 (9), pp. 477-478.