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# Variable Structure Controller for Plastic Injection Moulding System

Oleksandr Veligorskyi
*Chernihiv National University of Technology*
Chernihiv, Ukraine

Maksym Khomenko
*Chernihiv National University of Technology*
Chernihiv, Ukraine

Roustiam Chakirov
*Bonn-Rhein-Sieg University of Applied Sciences*
Sankt Augustin, Germany

Yuriy Vagapov
*Glyndwr University*
Wrexham, UK

***Abstract*—This paper discusses the approach to design of combined ANN and PID temperature controller for a plastic injection moulding system. The proposed method is based on integration of a conventional PID (PI) controller and a multilayer ANN. At the initial stage of operation, the ANN is trained in offline mode to approximately identify the dynamic parameters of the regulator optimised in terms of speed of response and overshoot. Under routine operation mode the ANN control structure is responsible for the fast transients whereas PID (PI) controller provides the high accuracy at the steady state condition. The paper focuses on the structure switching mechanism and the influence on the transient accuracy. In order to verify the proposed approach, the control system having various types of heaters has been modelled and simulated in Matlab/Simulink. The data obtained from the experiment verified the developed model and confirmed the results of simulations.**

***Keywords—plastic industry; melting heater; ANN; PID; temperature controller***

## I. INTRODUCTION

The quality of parts produced using plastic injection moulding method significantly depends on the static and dynamic parameters of temperature control in the melting zone. Deviation of the temperature from desired value impacts injection velocity, cavity pressure, part cooling time and, therefore, decreases the part accuracy fabrication and manufacturing speed. Inappropriate dynamics of temperature control affect on the efficiency of the manufacturing process increasing power consumption and reducing productivity [1]. Therefore, the controllers used in plastic injection industry has to provide accurate control of power applied to the heaters in order to ensure desired temperature in the melting zone.

The major issue in the industrial controller tuning is that the parameters of the heaters in the melting zone are not constant. The parameters can be changed during operational time and depend on the barrel filling level, type of plastics, etc. [2],[3] Various approaches are used to solve this issue. Majority of solutions utilise a combination of classical PID controller and intelligent control such as fuzzy logic [4]-[7], artificial neural networks (ANN) [8]-[12] and combined adaptive neuro fuzzy inference system (ANFIS) control [13],[14]. Recent studies also proposed combination of ANN and model predictive control (MPC) approach [15],[16]. They utilise the ability of MPC algorithm to achieve optimised transient due to implementation of input and output constraints and flexible tuning of cost function. Another way to improve system performance and accuracy that described in [17],[18] is to use switching control strategy when the system switches over between two types of control algorithm depending on the parameters of the transient.

This paper discusses the approach to design of a variable structure ANN and PID temperature controller for plastic moulding system which process dynamics is increased due to fast transient provided by ANN algorithms. The main scope of the article is focused on comparison of different switching strategies between ANN and PID and their influence on the quality of transient. The procedure of the controller design is described in the section II and focused on development of the regulator switching rules. To verify the proposed method, the system having various types of heaters has been modelled and simulated in Matlab/ Simulink software environment.

## II. CONTROLLER DESIGN

### *A. Reinforce Control Algorithm*

The first step in the controller design is the analysis of various control strategies that could provide a desired fast transient response. The variable gain algorithm having variable duration of control steps [19] has been chosen to be implemented in the controller. This algorithm is based on the state space methods to calculate the fastest transient response without overshoot. Fig. 1 shows a typical control

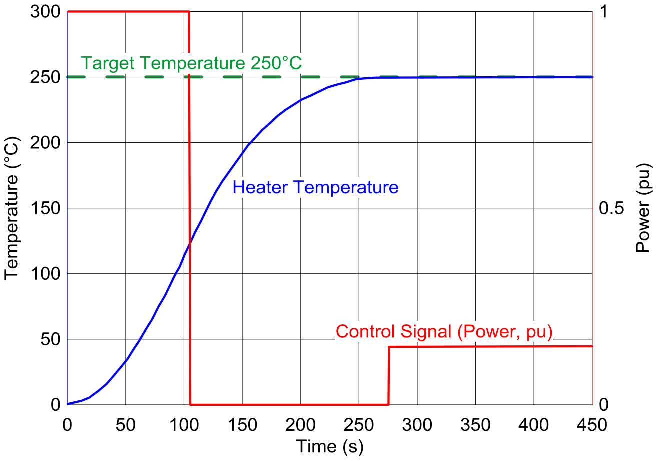


Fig. 1. Transient response of the system represented by second order plant transfer function (2) under different duration of control steps.

signal under generated using the variable gain algorithm and a transient response obtained for the second order plant. It can be seen that at the first control step 100% of power available in the system is applied to the heaters to produce as much heat as possible. At the second control step the power of the heater is turned off (0%) and the desired temperature is reached using the inertia of the plant. Finally, the controller supplies the appropriate amount of power to keep the desired temperature constant. A main drawback of this method is significant sensitivity to the heater parameter deviations. Therefore, it is not an effective method of the temperature control of a plastic injection moulding system, but can be used as a reference controller for the ANN training procedure as proposed in [20].

The heaters commonly used plastic injection moulding industry are usually described by the second order transfer functions [2] that can be represented as following

$$G(s)=\frac{k}{(s+a)(s+b)} \tag{1}$$

where $a$ and $b$ are time constants of the plant second order transfer function.

Plastic manufacturing industry uses a variety of barrel heaters for the melting process. The transfer functions of most common heaters have been investigated and identified in [2] and three of them have been taken as examples for the further investigation and analysis. These are

$$G(s)=\frac{3.166\times10^{-2}}{\left(s+2.384\times10^{-3}\right)\left(s+7.840\times10^{-3}\right)} \tag{2}$$

$$G(s)=\frac{4.316\times10^{-3}}{\left(s+3.565\times10^{-4}\right)\left(s+1.176\times10^{-2}\right)} \tag{3}$$

$$G(s)=\frac{1.499\times10^{-1}}{\left(s+4.008\times10^{-3}\right)\left(s+2.248\times10^{-2}\right)} \tag{4}$$

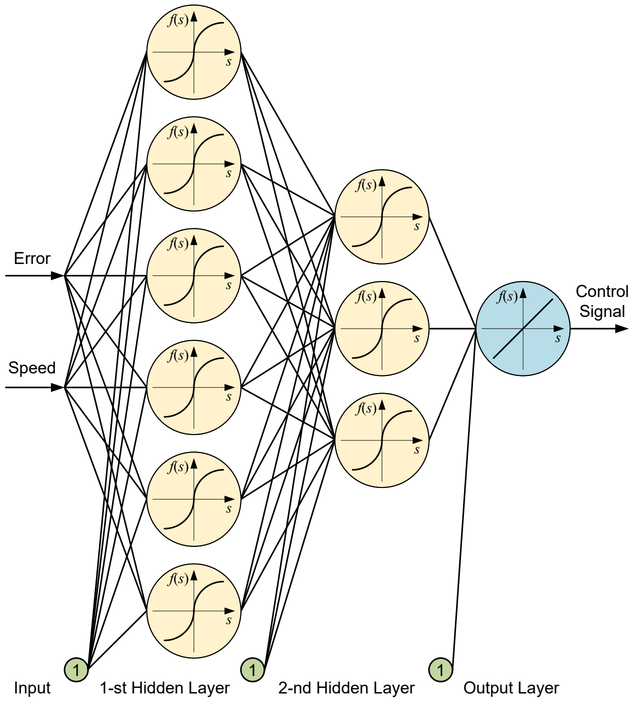


Fig. 2. ANN controller structure.

These transfer functions represent the typical plants (heaters) used in the plastic injection industry, however the actual coefficients in the equations for the real heaters can be slightly varied. One of the three transfer functions (2) - (4) could be chosen to calculate the dynamics of the reference controller for ANN training algorithm. According to the approach described in [19]-[21] the reference controller for the second order transfer function could be represented by the following system of equations:

$$\begin{cases} kA_2P_1m_1+kW_2Q_1m_1+kP_2m_2=T(0) \\ kB_2Q_1m_1+kQ_2m_2=aT(0) \end{cases} \tag{5}$$

where $A_1=\mathrm{e}^{-ah_1}$; $B_1=\mathrm{e}^{-bh_1}$; $W_1=\frac{1}{b-a}\left(A_1-B_1\right)$;

$P_1=\frac{1}{ab}\left[1+\frac{1}{a-b}\left(bA_1-aB_1\right)\right]$; $Q_1=\frac{1}{b}\left(1-B_1\right)$;

$A_2=\mathrm{e}^{-ah_2}$; $B_2=\mathrm{e}^{-bh_2}$; $W_2=\frac{1}{b-a}\left(A_2-B_2\right)$;

$P_2=\frac{1}{ab}\left[1+\frac{1}{a-b}\left(bA_2-aB_2\right)\right]$; $Q_2=\frac{1}{b}\left(1-B_2\right)$;

$h_1$ and $h_2$ are the duration of the first and the second control steps respectively; $m_1$ and $m_2$ are amplitude of the first and the second control steps respectively; $T(0)$ – the desired heater temperature.

Since the amplitude of $m_1$ and $m_2$ are known and equal 100% (1 in pu) and 0% respectively the system of equations (5) could be rewritten as:

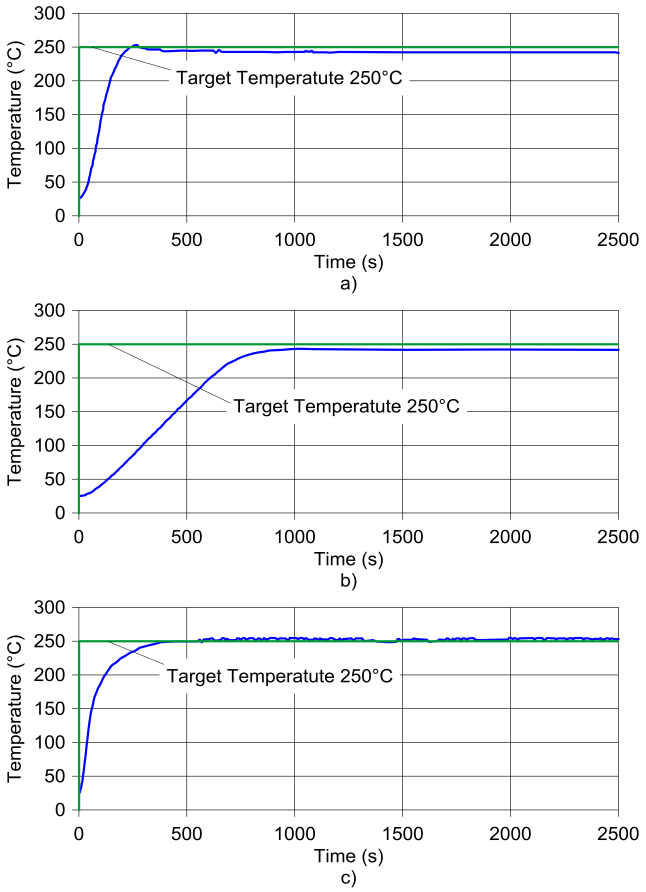


Fig. 3. Transient response of ANN based system for the heater transfer function (a) – equation (2); (b) – equation (3); (c) – equation (4).

$$\begin{cases} 1\times k\left(A_2P_1+W_2Q_1\right)=T\left(0\right) \\ 1\times kB_2Q_1=aT\left(0\right) \end{cases} \tag{6}$$

The heater should be energised upon completion of the second control step by a certain amount of power to maintain the temperature of the melting zone at the desired level. The value of power amplitude during the next control steps could be calculated using the following equation.

$$m_n=T\left(0\right)\frac{ab}{k} \tag{7}$$

where $n = 3, 4, ...$

The system (6) contains two unknown variables – the durations of the first and second control steps $h_1$, $h_2$. Therefore, the solution of the system (6) under different temperatures T(0) provides the time duration for both $h_1$ and $h_2$ control steps. It also allows a reference controller with different duration of control steps be implemented into the control system. However, this problem can not be resolved analytically – it requires implementation of numerical methods. When the control step durations are defined for all desired temperatures then the reference controller is ready to be used in ANN offline training procedure.

### *B. ANN Design*

The multilayer feed forward network (FFN) was selected for design of the controller. FFN has strong ability of function approximation and requires relatively low computational resources. Fig. 2 demonstrates the structure of selected FNN. The temperature error and the speed of the error variation provide a good representation of the dynamic properties of control system and are also used as the ANN inputs. The network comprises of two hidden layers – the 1-st hidden layer has 6 neurons whereas the 2-nd hidden layer has 3 neurons. Two hidden layers were chosen because such structure can provide solution of inverse dynamics problem (the dynamic system control belongs to this type of problems) whereas one hidden layer can not provide it as described in [22]. A hyperbolic tangent function selected due to good learning efficiency plays a role of the activation function for all neurons in hidden layers. The quantity of neurons in each hidden layer was estimated from computational experiment where networks with different number of neurons in hidden layers were examined. The structure showed the lowest approximation error has been chosen for implementation. The output layer has a single neuron having a linear activation function. The output of the output layer should be in the range from 0 (the load is not energised) to 1 (full power is applied to the load).

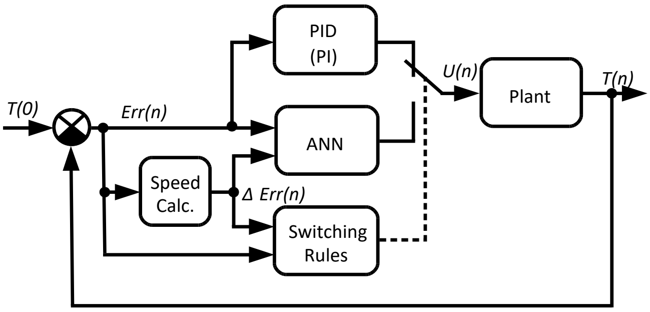


Fig. 4. Simplified diagram of temperature control system having switching structure, where $T(0)$ – set point temperature; $Err(n)$ – temperature error; $\Delta Err(n)$ – speed of temperature error change; $U(n)$ – control signal; $T(n)$ – current temperature.

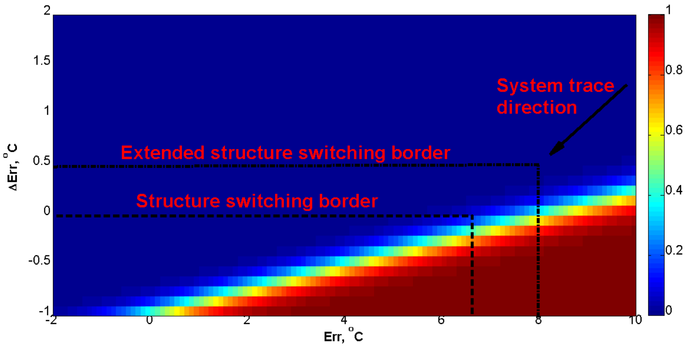


Fig. 5. Fragment of ANN control surface with marked structure switching borders.

The ANN was trained offline on the data set obtained from the reference controller. The data set has been collected at the sampling period of 1.3 s and the gap of 5 samples has been used for calculation of the speed of the error varying. The transient responses of the trained ANN for different heaters are shown in Fig. 3. The target temperature of 250°C has been selected for all curves in Fig. 3. These curves show that the ANN performs satisfactory in transient region, but have a lack of accuracy at steady state condition including tendency to oscillate at the “fast” heater test as can be seen in Fig. 3c.

These drawbacks are derived from the nature of ANN which has no integral component and, therefore, must have a non-zero error in steady state. It is also related to the limitations of finite sample time in combination with sharp control strategy of the reference controller where maximum power initially applied to the heater brings a very short duration of the control step – equal or lower than the sample time.

### *C. Controller Structure Switching Rules*

Comparing to ANN, PID controllers commonly used in industry have opposite drawbacks such as big overshoot and slow response [4], whereas its advantages are negligibly low steady state error and better ability to withstand the disturbances. Therefore, PID or PI (if D component equals to zero) controller could be used at the steady state conditions. The combination of ANN and PID (PI) controllers in the same control system is shown in Fig. 4 where the control structure could be changed depending on the mode of operation. The ANN is in operation at the beginning of a transient when a new setpoint is established. When the temperature reaches the set point zone the switching rules force the system to use a PID or PI algorithm to control the heater. The system remains in that state till installation of the new setpoint value.

Switching rules could be derived from the steady state error and ANN control surface shown in the Fig. 5. The

TABLE I. TRANSIENT RESPONSE PARAMETERS OF THE SYSTEM WITH DIFFERENT STRUCTURE SWITCHING RULES.

| **$T_{set\ point}$, °C** | **200** | | | | | |
|---|---|---|---|---|---|---|
| **Control** | **(I)** | | **(II)** | | **(III)** | |
| **Parameter** | **$t_{set}$, s** | **Overshoot, %** | **$t_{set}$, s** | **Overshoot, %** | **$t_{set}$, s** | **Overshoot, %** |
| Transfer function (2) | 250 | 0.25 | 250 | 0.20 | 251 | 0 |
| Transfer function (3) | 1288 | 1.60 | 989 | 0.75 | 1054 | 0.65 |
| Transfer function (4) | 564 | 5.65 | 342 | 0.45 | 308 | 0 |

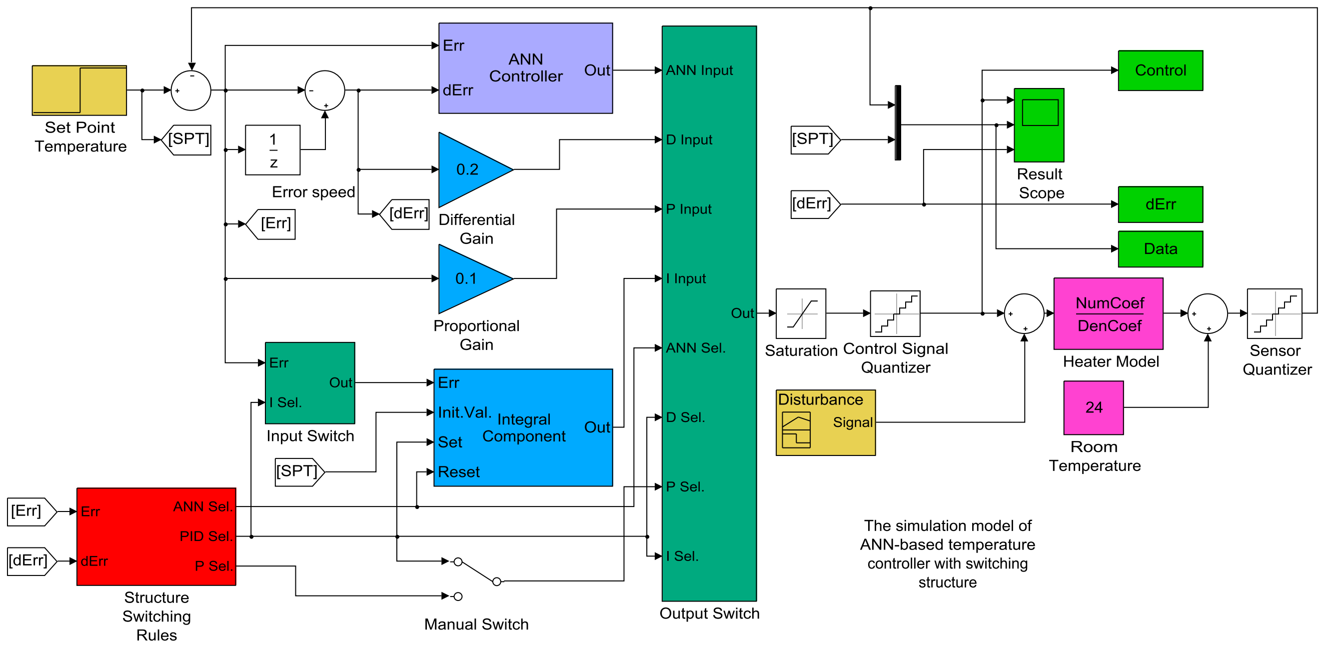


Fig. 6. Simulink block diagram of temperature control system with switching structure.

structure of temperature controller should be changed from ANN to PID when system error reaches ANN steady state error and its speed equal to zero. However, variations of the heater parameters, disturbances and noise immunity should be taken into account for appropriate controller design. Hence, the controller structure switching boundaries should be extended as it sown in Fig. 5. However, such approach still could lead to undesirable level of overshoot that depends on PID parameter tuning. There are two main solutions of this issue. First solution is an increase of the value of PID differential component. However, an excessive increase could made the system unstable [23].

Second solution is to use a separate switching rule for the proportional component. Since the proportional component is responsible for overshoot it is proposed to turn it on and off depending on error changing speed. Such approach guaranties the system to have a low speed when it reaches the setpoint and, therefore, the overshoot could not be high. In this case the switching rule could be formulated as following:

IF ($\Delta Err(n) \le$ *desired* $\Delta Err(n)$)
THEN *turn on proportional gain*
ELSE *turn off proportional gain*.

## III. MATLAB SIMULATION AND EXPERIMENTAL DATA

In order to evaluate the dynamics of switching structure controller for plastic injection moulding system the Simulink model shown in Fig. 6 has been developed and investigated.

Block *Structure Switching Rules* controls the structure of the system and therefore its dynamics. *ANN Controller* is selected at the transient beginning. Simultaneously PID components *Proportional Gain*, *Differential Gain* and *Integral Component* are disconnected from the controller output by the means of *Output Switch*. Block *Input Switch* also disconnects the temperature error signal (*Err*) from the *Integral Component* input to prevent the saturation.

When the temperature error and speed of error changing reach the structure switching boundaries the block *Structure Switching Rules* disconnects *ANN Controller* from the regulator output and connects the components of PID controller to it. This block also establishes the signal (connected to *Set* port of *Integral Component*) to set the initial value of integrator if needed. The block *Manual Switch* could be used to select one of two switching strategies. If the *Manual Switch* is in the top position all PID components are selected simultaneously while controller structure switching takes place. On the other hand, the proportional component of PID is governed independently from the other components by the speed limiting rule as described above.

The simulation of system behaviour was conducted for the heaters having transfer functions (2) - (4). The scope of simulation was investigation of the influence of controller structure switching rules on the system dynamics and accuracy. The results of simulation are shown in Fig. 7,

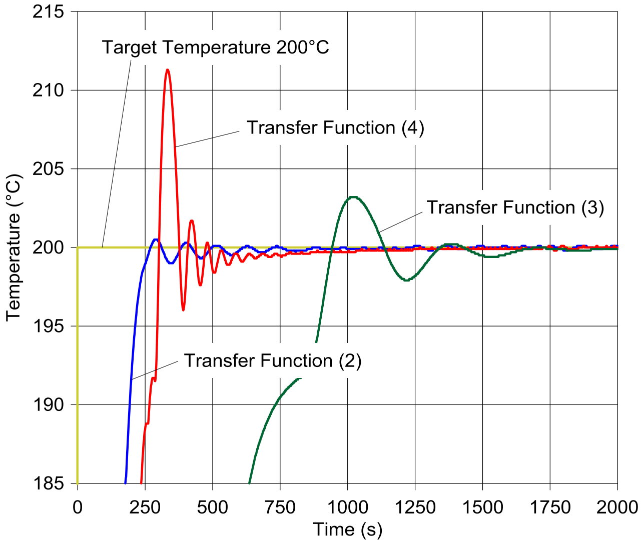


Fig. 7. Simulation results for the system with simultaneous structure switching to PI regulator and heaters with transfer functions (2) - (4).

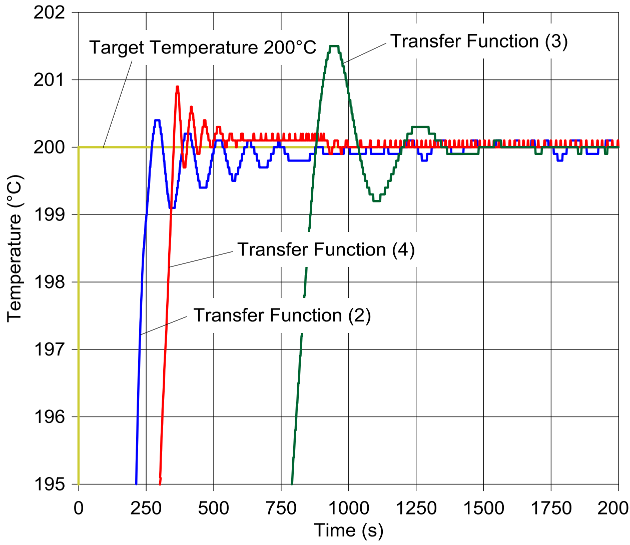


Fig. 8. Simulation results for the system with speed limiting structure switching to PI regulator and heaters with transfer functions (2) - (4).

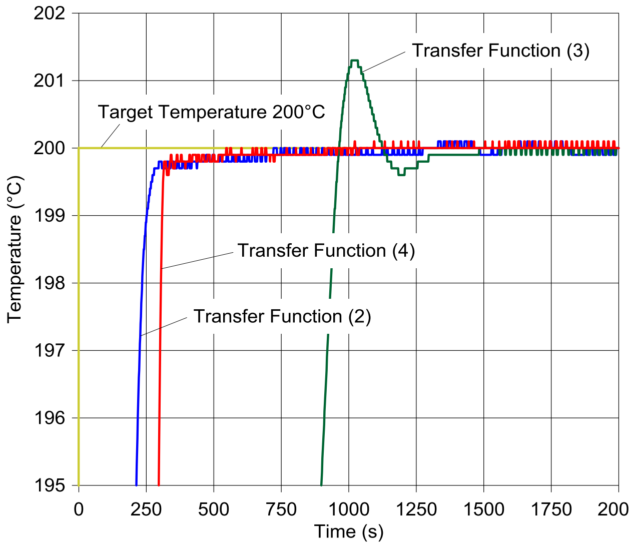
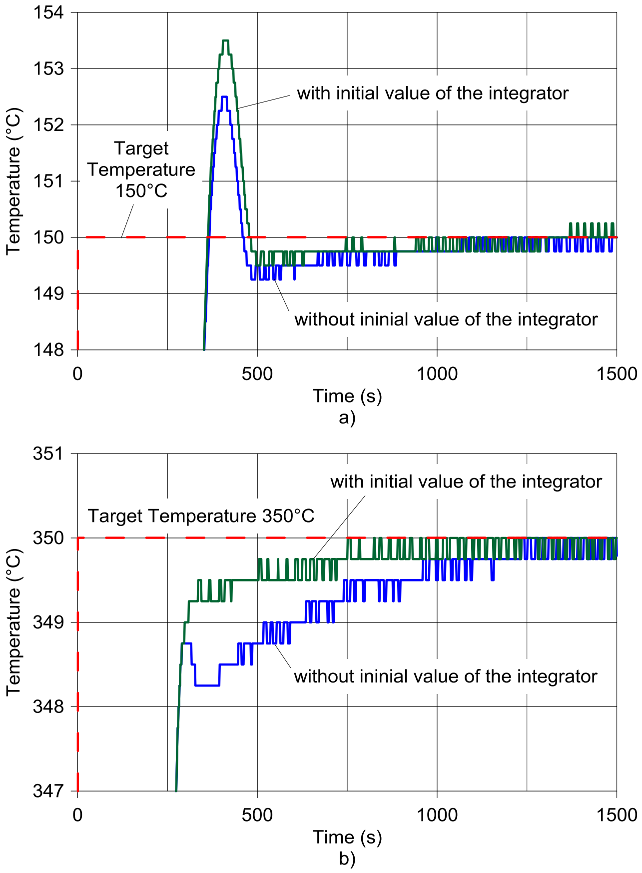


Fig. 9. Simulation results for the system with simultaneous structure switching to PID regulator and heaters with transfer functions (2) - (4).

Fig. 8 and Fig. 9. It can be seen that the switching the simultaneous regulator structure to PID in the end of transient leads to the lowest overshoot. On the other hand, the switching to PI regulator with speed limiting feature provides a good quality of transient and, therefore, can be used in temperature control algorithm. The general parameters of transient responses are presented in Table I where (I) – PI with simultaneous switching ($P = 0.1$, $I = 3\times10^{-4}$); (II) – PI with speed limiting switching ($P = 0.1$, $I = 3\times10^{-4}$); (III) – PID with simultaneous switching ($P = 0.1$, $I = 3\times10^{-4}$, $D = 0.2$); $t_{set}$ – temperature settling time (the time when the temperature reaches the setpoint ±1°C and then never leaves this range). The results of simulation show that the best combination of system response and accuracy could be achieved for the following regulators: (1) PID regulator with simultaneous switching structure rules and well-tuned differential component; (2) PI regulator with separate switching rule for proportional gain that limits speed of error changing in the system.

Block *Integral Component* has an input *Init.Val.* so the initial value of integrator could be loaded at the time when it is connected to the controller output. The initial value of the *Integral Component* could be derived from (7) if parameters of heater are known. However the simulation results show (see Fig. 10) that the initial value of the integrator has a very weak influence on the accuracy of the system when the setpoint temperature is relatively low (up to 200°C). Such results could be explained by the fact that the integral component starts acting while the system has a non zero error and speed. Therefore, the integrator value is changed significantly from the initial low weight. It is observed that the initial value of integrator could be zero for the low



a)

b)

Fig. 10. Simulation results for the heater having transfer function (2) with and without initial value of the integrator, (a) for 150°C setpoint, (b) for 350°C setpoint

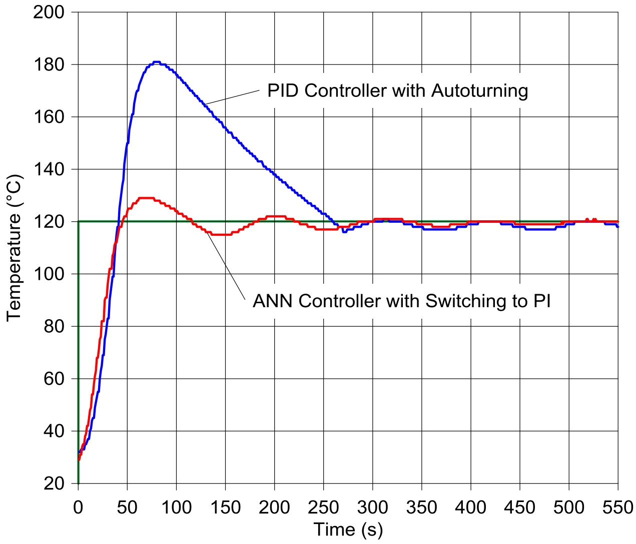


Fig. 11. Experimental transient responses of proposed controller and industrial PID controller with autotuning.

setpoint temperatures. For the higher setpoint temperatures the initial value of integrator decreases the settling time. As it is already mentioned, the exact parameters of the heater are generally unknown. It is suggested that the worst value might be used in (7) to calculate the initial value (the worst value is the highest gain of the heater defined as $k/ab$).

The experimental data has been obtained form the real tests in order to verify the proposed method and confirm the simulation results. The control system used in experiment has the following configuration: ANN controller that switches to PI regulator with separate switching rule for proportional gain limiting the speed of error changing. The heater used in the tests has been described by the transfer function (4). The same experiment was conducted with industrial PID controller that has an embedded autotuning algorithm. Resulting transients are shown in Fig. 11. The diagram highlights the benefits of proposed algorithm: much less overshoot in comparison with PID controller (7.5% to 50%) and better accuracy.

## IV. CONCLUSION

This paper discusses the approach to the temperature controller design for the plastic injection moulding system. The proposed method utilises a conventional PID (PI) controller and a multilayer ANN trained in offline mode to approximately identify the dynamic parameters of the regulator optimised in terms of speed of response. The simulation results and its comparison to currently used in industry PID regulator demonstrate the benefits of the proposed method – faster temperature transients with smaller overshoot.

The main principle of the proposed controller is based on division of the process in to two time duration regions and implementation of different control structures for these regions. The paper focuses on the structure switching mechanism and its influence on the transient accuracy. Two switching strategies of controller structure were derived. It was shown that both of them could be used effectively in combination with PID (PI) regulators. The experimental data obtained from the tests verified the developed model and confirmed the results of simulations.

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