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MODIFIED ALGORITHM OF AUTOMATIC TEMPERATURE CONTROL IN AN ELECTRIC RESISTANCE FURNACE FOR METAL HEAT TREATMENT

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МОДИФІКОВАНИЙ АЛГОРИТМ АВТОМАТИЧНОГО КЕРУВАННЯ ТЕМПЕРАТУРОЮ В ЕЛЕКТРИЧНІЙ ПЕЧІ ОПОРУ ДЛЯ ТЕРМООБРОБКИ МЕТАЛУ

The purpose. The purpose is to improve the quality of heat treatment of metal in electric resistance furnaces by improving automatic temperature control in the furnace. The main quality criteria of the automatic control system is the minimization of the metal heating time without exceeding the permissible over-regulation of the transient process at the output of the control system.

Research methodology. Provided that the research tasks are solved, the method of computational experiments using specialized computer programs for modeling transient processes in automatic control systems is taken as a basis. When calculating the temperature regulator in the furnace, methods of modern automatic control theory were used. The requirements for the control process and the specifics of the operation of the control object are taken into account. Theoretical research methods (systems analysis and synthesis) were used to study the automatic control system. The research was conducted on the basis of computational experiments using analytical and computerized methods of synthesis of automatic control systems. Evaluation of the effectiveness of the automatic control process was carried out using the methods of mathematical statistics.

Research results. A simulated model of the automatic temperature control system in an electric resistance furnace for heat treatment of metal was created. The method of synthesis of the automatic control system was justified taking into account the requirements for the control process and the features of the control object, and based on it, the calculation of the temperature regulator in the furnace was carried out. Studies of the dependence of the parameters of the transient process at the output of the control system on the parameters of the regulator have been carried out, based on which the regulator settings are determined, which provide rational values of the quality criteria of the control system.

Scientific novelty. For the first time, it was established that an automatic control system with a computerized method configured for maximum speed by a PID regulator and a shaper of a linearly changing temperature set point in the furnace successfully works out the given parameters of the transient process at its output, but only on the condition that the time for heating the metal significantly (more than 1.5 times) exceeds the time of the transient process of the furnace as a control object. Otherwise, an unacceptable temperature overshoot occurs in the furnace. It was determined that the dependence between the maximum level of the control signal at the first switching interval of the speed-optimal regulator and the duration of the transient process at the system output is inverse and exponential in nature. At the same time, this dependence is approximated with high accuracy (the maximum relative error does not exceed

2.5%) by a power of eighth order polynomial. It was found that the accuracy of the proposed modified regulator, optimal in terms of speed, is a variable value in different sections of the graph of the control signal level dependence on the duration of the transient process.

Practical value. The method of synthesis of the automatic temperature control system in the resistance electric furnace for heat treatment of metal is proposed. At the same time, the parameters of the optimal control algorithm are substantiated according to the criterion of minimizing the metal heating time without exceeding the permissible over-regulation of the transient process at the output of the control system.

Keywords: *control system synthesis, temperature, resistance electric furnace for metal heat treatment.*

Introduction. For Ukraine, mechanical engineering is a complex and very important branch of the processing industry, which specializes in the design, production and operation of machines and tools, and includes 27 types of economic activity [1, 2]. Some types of mechanical engineering (production of excavators, equipment for metallurgy, etc.) require a large amount of metal; they are classified as metal-intensive industries of the complex. Machine-building enterprises in Ukraine consume a third of manufactured rolled products, as well as 40% of cast iron and 2/3 of steel castings. Most branches of the machine-building complex are labor-intensive. This is especially characteristic of tool engineering and electronic engineering, where little metal is consumed, but a lot of labor must be spent to produce products. These enterprises employ a large number of qualified labor resources.

Currently, there is an urgent need in Ukraine to update and modernize most sectors of the economy, and it would be appropriate if the domestic machine-building complex provided these processes with a material base. However, the analysis of the state of the machine-building industry of Ukraine shows alarming trends in its development. Over the last decade, the share of large and medium-sized machine-building enterprises has significantly decreased, while the share of small ones, on the contrary, has increased [2]. Such structural changes lead to a significant loss of gross domestic product.

Under such conditions, any innovative scientific and technical solutions leading to an increase in the efficiency of technological processes in the field of mechanical engineering are becoming relevant.

Formulation of the aim of the article. The aim of the work is to improve the quality of heat treatment of metal in electric resistance furnaces through the improvement of automatic temperature control in the furnace.

Main part.

On the basis of structural and parametric identification, based on the experimental acceleration curve, there is obtained the dynamic model of the resistance furnace for heat treatment of metal as an object of automatic control according to the temperature regulation channel in the furnace. Based on the result of this procedure, there is developed a simplified dynamic model of the furnace, shown in Fig. 1.

The analysis of the static characteristic by the temperature control channel in the furnace showed that in the working range of the change of the controlled value, this characteristic can be considered as linear (Pearson's coefficient of linear correlation between the controlled and control values is more than 0.9).

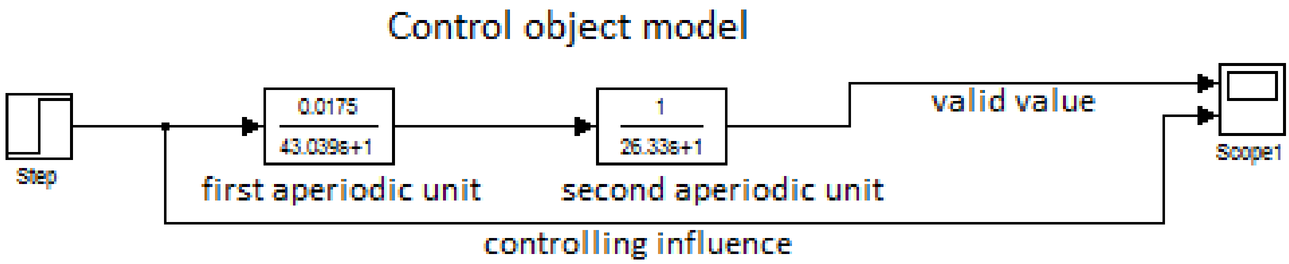


Fig. 1. Dynamic model of the control object

The technology of heat treatment involves the selection of operations and modes of heat treatment in accordance with the conditions of processing and operation of machine parts, constructions, tools, as well as requirements related to the structure and properties of materials, taking into account technical conditions [3, 4]. Technological processes of heat treatment are based on the theory of phase transformations during heating and cooling process. Processing modes for specific parts are determined according to reference books.

One of the main tasks when choosing modes is the acceleration of heat treatment processes, which can be achieved by reducing the heating time. The total heating time consists of the time of heating to a given temperature and the time of exposure to it, which is determined by structural transformations in the alloy, and does not depend on other factors.

Taking into account the described requirements, from the point of view of the features of the technological process, the following requirements for the quality of the system operation in time come first, primarily the requirements for the transition process at the output of the automatic control system, when the temperature in the furnace is transferred from one level (the initial one, which is taken as zero, taking into account the normalization of the initial value of the temperature) to another (the specified value of the temperature at which the metal is hardened):

− the time of the transition process (must be equal to the value specified by the operator with a minimum error);

− the amount of overregulation (should not exceed 2.5%);

− established (steady-state) error of the system (must be zero).

Taking into account the requirements for the automatic control process, the synthesis of the automatic control system was carried out on the basis of a computerized method using a setpoint generator in the form of a linear time-varying signal with the simultaneous use of a PID controller in the furnace temperature control circuit (Fig. 2) [5]. Thus, the specified steel heating time will be implemented through the setting of the corresponding rate of change in time of the temperature setting.

In order for the actual temperature in the furnace to reproduce as accurately as possible a linear change in the temperature setting time, the PID controller is set to the highest speed of the control system.

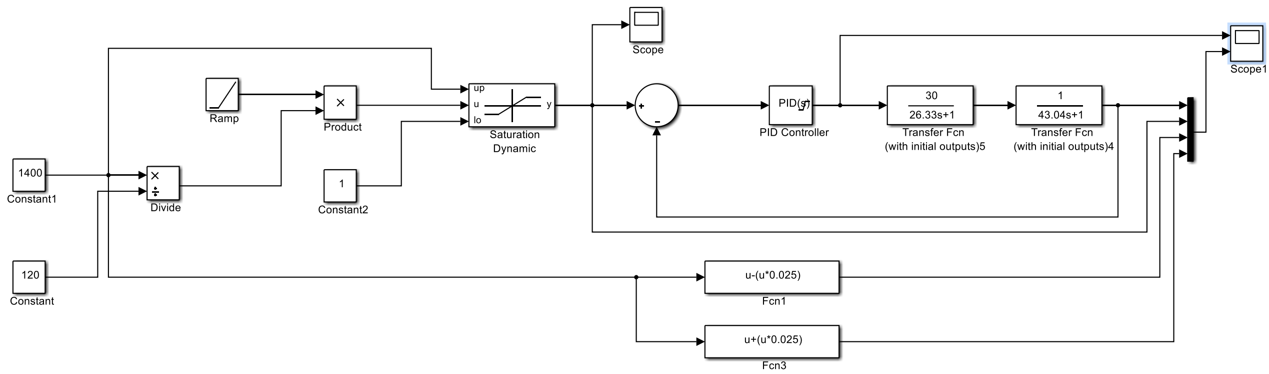
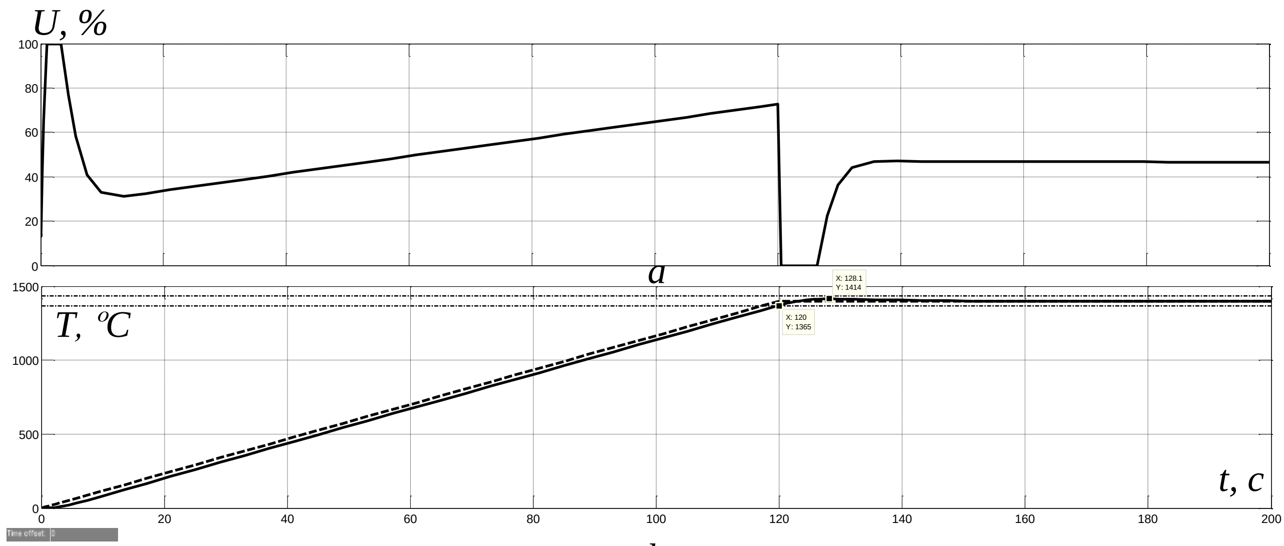


Fig. 2. Structure of a simulation model of an automatic control system with a PID controller and a setpoint shaper in the form of a linear time-varying signal

The results of simulation of the control system are presented in Fig. 3. At the same time, there is considered the case of setting the metal heating time that is significantly longer than the time of the transient process at the output of the control system (the metal heating time is set to 120 s., and the temperature level to which the metal is heated is 1400 °C, i.e. 46.67% of the control effect) .



b

Fig. 3. Change in time: a – control signal (relative capacity of furnace heaters); b – controlled value (temperature in the furnace)

From the analysis of the simulation results in Fig. 3, it can be concluded that the automatic control system with a computerized method set to maximum speed by a PID controller and a shaper with a linear time-varying temperature setting in the furnace successfully gives out the given parameters of the transient process at its output. From Fig. 3b, we see that the actual temperature, changing linearly in time, reaches a value of 1400 °C in exactly 120 seconds, that is, without error. Then there is an overregulation of 14 °C (1% in relative units), but it does not exceed the permissible level of 2.5%.

From the analysis of Fig. 3, we see that the control signal at the beginning of the transient process reaches its maximum value, which ensures a minimum lag of the graph of the change in time over time of the actual temperature from the graph of the set point, then the control signal changes linearly in time according to the change of the set point, and at the end "braking" occurs – it sharply decreases to zero with a successive transition to the level corresponding to 1400 °C.

Now we examine the operation of the control system with a PID controller set to maximum speed and a molder with a linearly time-varying temperature setting in the furnace under the condition of setting a metal heating time that is commensurate with the time of the transient process at the system output (the metal heating time is set to 60 s).

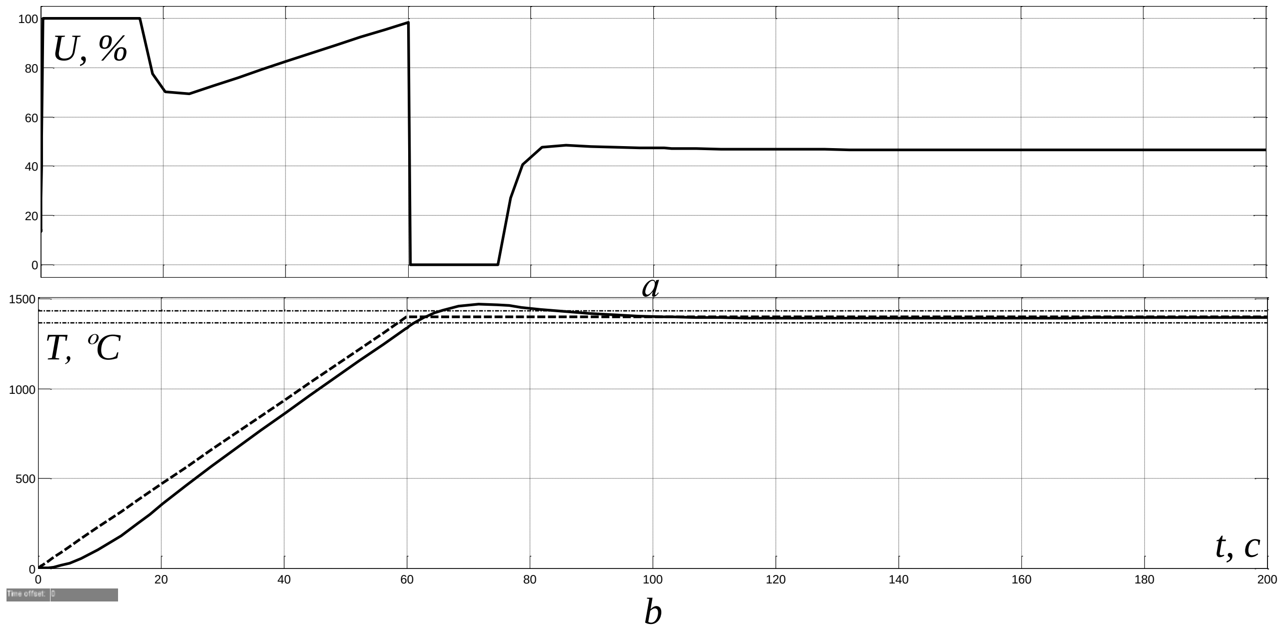


Fig. 4. Change in time: a – control signal (relative capacity of furnace heaters); b – controlled value (temperature in the furnace)

From the analysis of the simulation results of the control system in Fig. 4, we can see that due to the significant dynamics of the change in the set point, the PID controller does not have time to "brake" and an unacceptable overregulation appears, much higher than the level of 2.5% (in Fig. 4, the horizontal lower dash-dotted line).

An attempt to reconfigure the PID regulator to a lower speed resulted in failure to meet the condition for ensuring the specified duration of the transition process (Fig. 5).

From the results of the simulation of the automatic control system with a reconfigured PID controller in Fig. 5, we can see that, under the condition of a metal heating time of 60 s, due to a decrease in the speed of the control system, it was possible to keep the overregulation within the permissible range of ±2.5% of the temperature setpoint (the range is marked in horizontal dash-dotted lines in Fig. 5), but at the same time it produces significantly worse heating time – instead of 60 s, it is 93.81 s (relative error 56.3%), which is unacceptable.

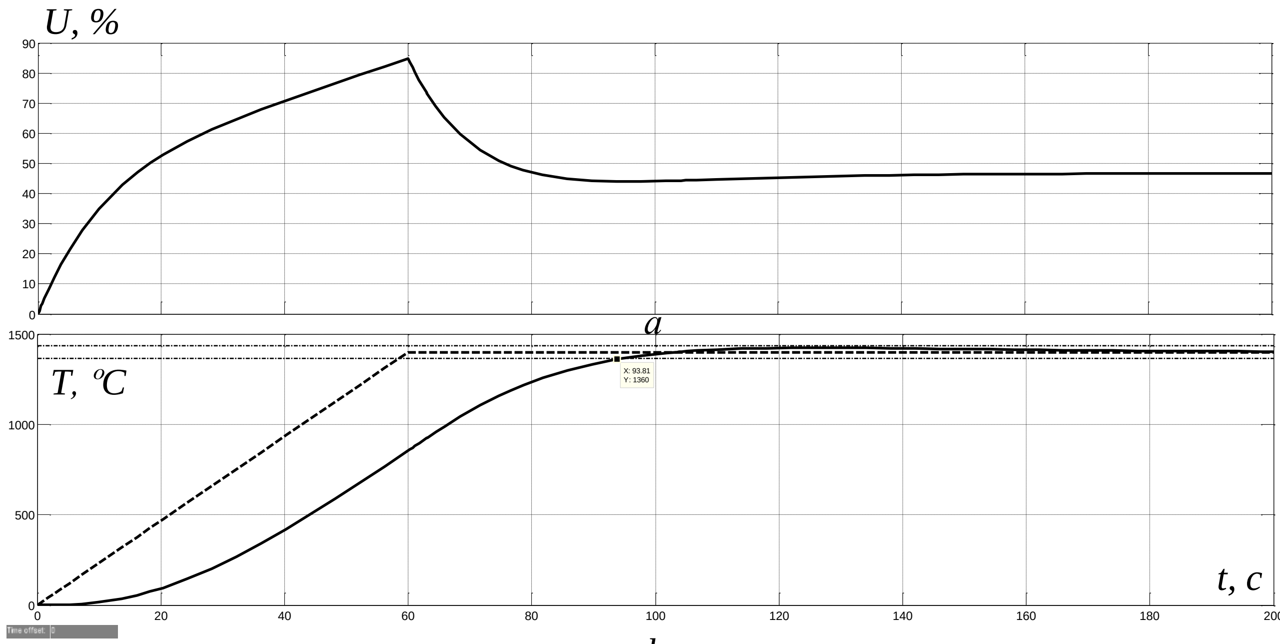


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Fig. 5. Change in time: a – control signal (relative capacity of furnace heaters); b – controlled value (temperature in the furnace)

Taking into account this shortcoming, a method of automatic temperature control in the furnace based on the use of a speed-optimized regulator is proposed. At the same time, the input data for the calculation of the regulator are adjusted in such a way that the transition to the specified level of temperature in the furnace is carried out in a certain specified period of time. This can be achieved by artificially limiting the maximum value of the control signal.

For this, through a series of computational experiments on a simulation model of an automatic control system with a speed-optimal regulator, there was established the dependence between the maximum level of the control signal at the first switching interval of the speed-optimal regulator and the duration of the transient process at the output of the system (after the transient process, we take the time when the temperature reaches the level –2.5% of the set point). The analysis of this dependence showed that it is inverse and has an exponential character. Taking this into account, its approximation was carried out by a power polynomial (Fig. 6).

From the analysis of Fig. 6, it can be concluded that the dependence between the maximum level of the control signal at the first switching interval of the optimal regulator in terms of speed and the duration of the transition process at the output of the system with high accuracy (the maximum relative error does not exceed 2.5%) is approximated by a power polynomial of the eighth order.

Taking into account the established regularity, a simulation model of the automatic control system was implemented using a modified speed-optimal regulator capable of ensuring the specified duration of the transition process at the output of the control system (Fig. 7).

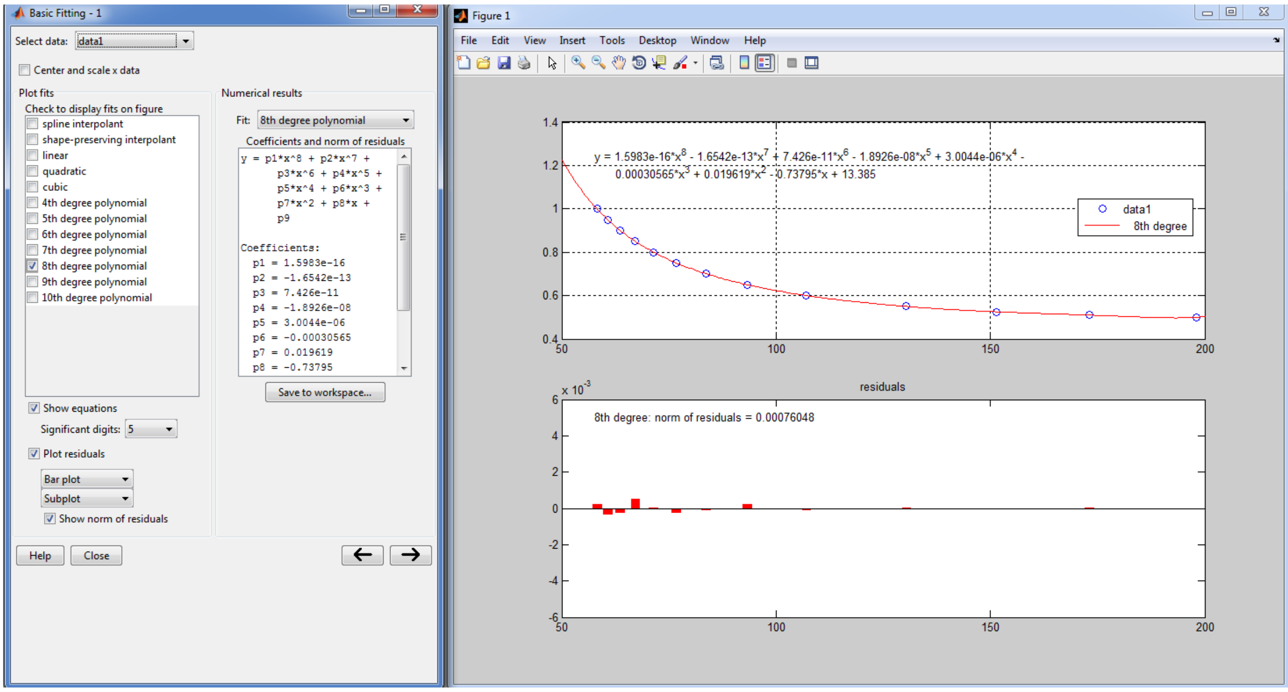


Fig. 6. Results of the approximation of the experimental dependence of the control signal level on the duration of the transition process

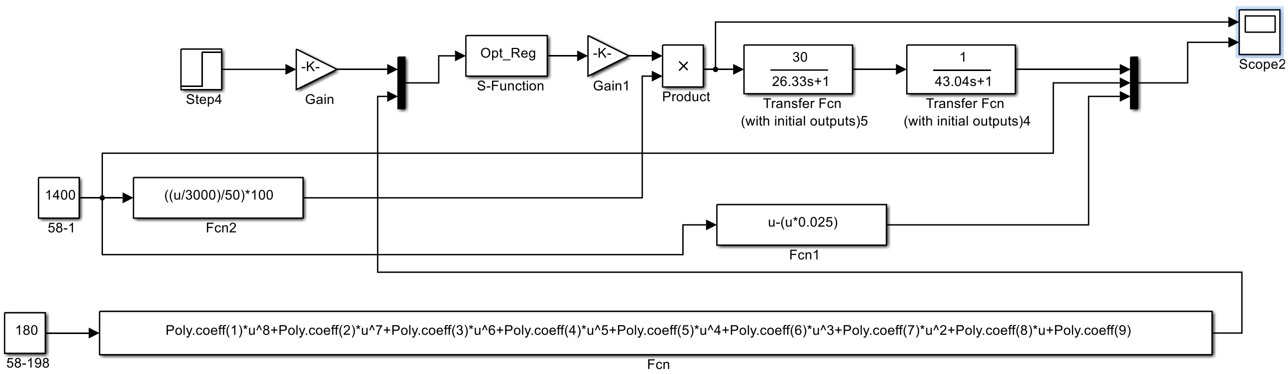


Fig. 7. Structure of the simulation model of the automatic temperature control system in the furnace with a modified speed-optimal regulator

In Fig. 7, the approximating function obtained above, which determines the maximum level of the control signal at the first switching interval of the speed-optimal regulator, is implemented using the “Fcn” function block. And with the help of the S-Function block, the method of calculating the optimal speed of the regulator is implemented.

In order to study the quality of the automatic control system under the condition of its synthesis in various ways, combined models of systems with a PID controller and a speed-optimized controller were developed in the Simulink application of the MATLAB program (Fig. 8).

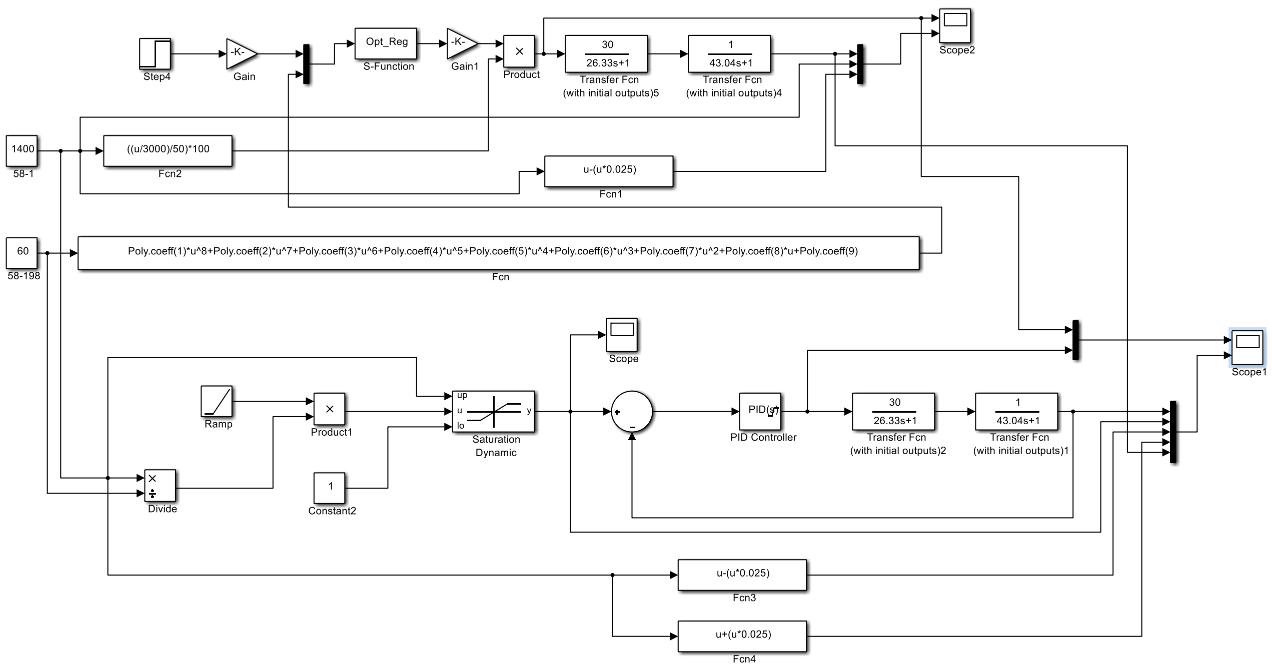


Fig. 8. Structure of simulation models of control systems synthesized in different ways

The results of simulation of the operation of the control system under the condition of the metal heating time setting close to the time of the transient process of the furnace, are shown in Fig. 9.

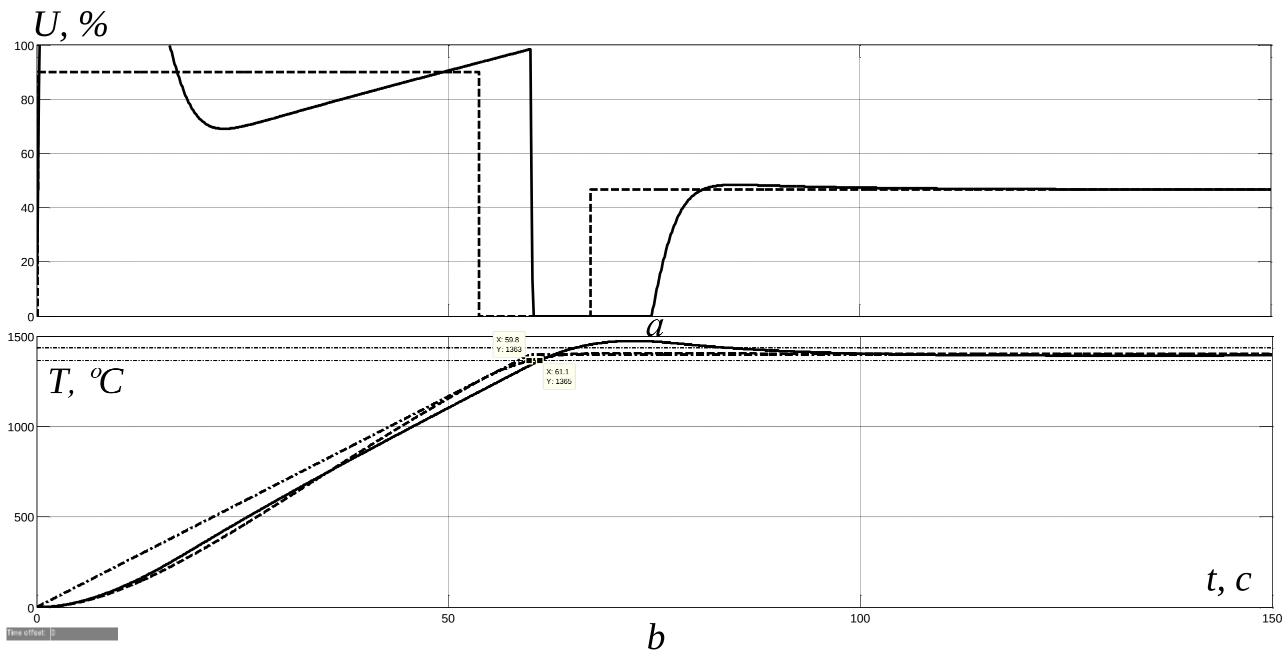
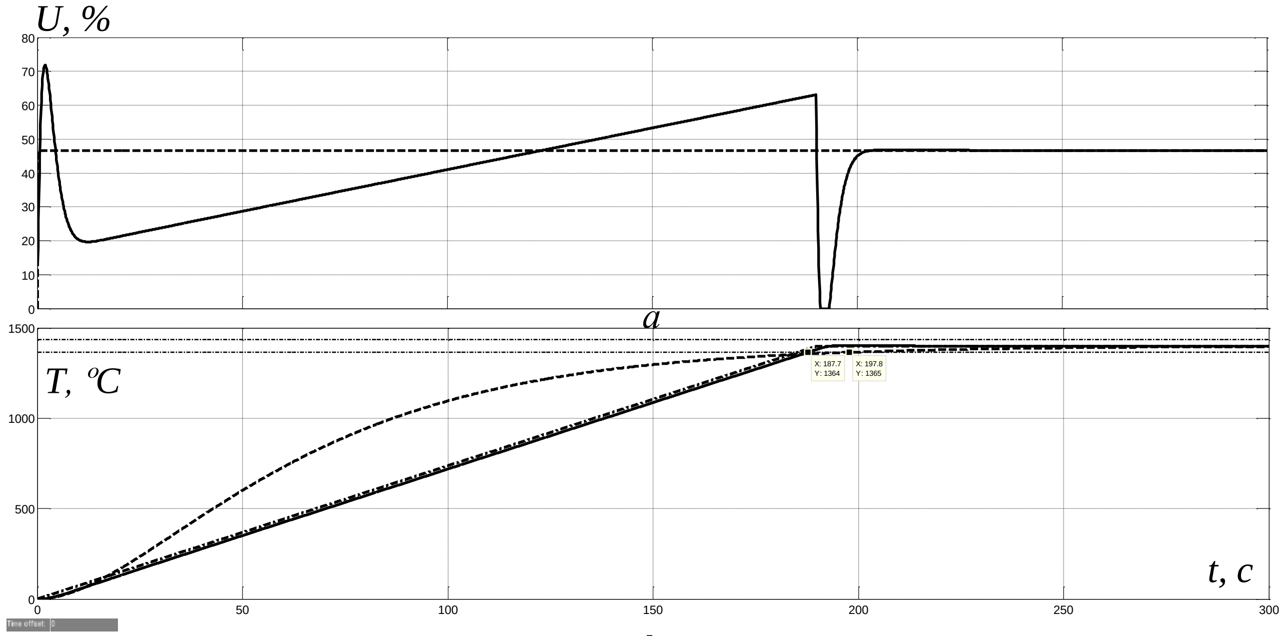


Fig. 9. Change in time: a – control signal (relative capacity of furnace heaters); b – controlled value (temperature in the furnace): solid line – control system with a PID controller; dashed line – control system with the proposed modified speed-optimal regulator; dash-dotted line – temperature setpoint

From Fig. 9b, it can be seen that under the condition of a heating time of 60 s, the automatic control system with a modified speed-optimal regulator ensures the duration of the transient process (time to reach the level – 2.5% of the set point) in 59.8 s (the relative error is 0.3%) with a slight over-regulation of less than 0.5%. And under the condition of using a PID controller with a shaper of a linearly changing temperature setpoint in time, we have a duration of the transient process of 61.1 s, but at the same time the overregulation exceeds the permissible overregulation of 2.5%.

Simulation of the operation of control systems synthesized in different ways was also carried out, under the condition of the metal heating time setting, which is much longer than the time of the transient process of the furnace (Fig. 10) - 190 s.



b

Fig. 10. Change in time: a – control signal (relative capacity of furnace heaters); b – controlled value (temperature in the furnace): solid line – control system with a PID controller; dashed line – control system with the proposed modified speed-optimal regulator; dash-dotted line – temperature setpoint

From Fig. 10b, it can be seen that, under the condition of a metal heating time of 190 s, the automatic control system with a modified speed-optimal regulator ensures the duration of the transient process in 197.8 s (the relative error is 4.1%) with no over-regulation. And under the condition of using a PID controller with a shaper of a linearly changing temperature setpoint in time, we have a duration of the transient process of 187.7 s (the relative error is 1.2%), while the overregulation is less than the permissible level of overregulation of 2.5%, and is less than 0 .2%.

Thus, given the setting of metal heating time, which significantly exceeds the time of the transient process of the control object, both automatic control systems, synthesized in different ways, provide qualitative indicators of the transient process by the temperature in the furnace. However, from Fig. 10b, we can see that under the condition of using the regulator that is optimal in terms of speed, we have a much lower degree of uniformity of heating parts in comparison with the operation of a PID regulator with a shaper of a linearly changing temperature setpoint over time, which speaks in favor of the latter option.

Also, based on the analysis of Fig. 9 and Fig. 10, the following conclusion can be drawn. The accuracy of the proposed modified regulator, optimal in terms of speed, depends on which part of the graph of the dependence of the control signal level on the duration of the transition process we are (Fig. 6). If it's a section with dynamic change, under the condition that the first switching interval of the optimal regulator is not very long (Fig. 9, a), and the transient process at the output of the system does not reach the relative level of 0.606 from the set value of the controlled value (the time differential of the controlled value near the maximum value), then the error is up to 0.2-1 s in absolute values and up to 1% in relative values. And it's a flat section, under the condition that the first switching interval of the optimal regulator is long (Fig. 10, a), and the transient process at the output of the system exceeds the relative level of 0.606 from the set value of the controlled value (the time differential of the controlled value begins to tend to zero), then the error is up to 5-8 s in absolute values and up to 5% in relative values.

Conclusions.

1. The automatic control system with a computerized method configured for maximum speed by a PID regulator and a shaper of a linearly changing time temperature set point in the furnace successfully produces the given parameters of the transient process at its output, but only under the condition that the time for heating the metal significantly (more than 1.5 times) exceeds the time of the transient process of the furnace as a control object. Otherwise, an unacceptable temperature overregulation occurs in the furnace.

2. The dependence between the maximum level of the control signal at the first switching interval of the speed-optimal regulator and the duration of the transient process at the system output is inverse and exponential in nature. At the same time, this dependence is approximated with high accuracy (the maximum relative error does not exceed 2.5%) by a power polynomial of the eighth order.

3. The accuracy of the proposed modified regulator, optimal in terms of speed, depends on which part of the graph of the control signal level dependence on the duration of the transition process we are. If it's a section with dynamic change, under the condition that the first switching interval of the optimal controller is not very long, and the transient process at the output of the system does not reach a relative level of 0.606 from the set value of the controlled value (time differential of the controlled value near the maximum value), then the error is up to 0 ,2-1 s in absolute values and up to 1% in relative values. And if it's a flat area, under the condition that the first switching interval of the optimal controller is long, and the transient process at the output of the system exceeds the relative level of 0.606 from the set value of the controlled value (the time differential of the controlled value begins to tend to zero), then the error is up to 5-8 s in absolute values and up to 5% in relative terms. In addition, with an increase in the given time of metal heating, under the condition of

using an optimal regulator, the non-uniformity of the temperature change over time increases quite significantly.

4. Thus, when setting a time for metal heating that significantly exceeds the time of the transient process of the furnace as a control object (by more than 1.5 times), it is advisable to use a control system with a PID controller set to maximum speed and a shaper of linearly changing times of temperature setting in the furnace. Otherwise, it is better to use a control system with the proposed modified speed-optimal furnace temperature controller.

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АНОТАЦІЯ

Мета. Метою є підвищенні якості термообробки металу в електричних печах опору за рахунок вдосконалення автоматичного керування температурою у печі. Головними критеріями якості роботи системи автоматичного керування є мінімізація часу нагрівання металу без перевищення допустимого перерегулювання перехідного процесу на виході системи керування.

Методика досліджень. За умови вирішення завдань дослідження за основу взятий метод обчислювальних експериментів з використанням спеціалізованих комп’ютерних програм для моделювання перехідних процесів в системах автоматичного керування. При розрахунку регулятора температури у печі використані методи сучасної теорії автоматичного керування. При цьому враховані вимоги до процесу керування й особливості роботи об’єкта керування. Для дослідження системи автоматичного керування використані теоретичні методи дослідження (аналіз й синтез системи). Дослідження проведені на основі обчислювальних експериментів з використанням аналітичних та комп’ютеризованих методів синтезу систем автоматичного керування. Оцінювання ефективності процесу автоматичного керування здійснене з використанням методів математичної статистики.

Результати дослідження. Створена імітаційна модель системи автоматичного керування температурою в електричній печі опору для термообробки металу. Обґрунтований метод синтезу системи автоматичного керування з урахуванням вимог до процесу керування й особливостей роботи об’єкта керування, та на основі нього проведений розрахунок регулятора температури у печі. Проведені дослідження залежності параметрів перехідного процесу на виході системи керування від параметрів регулятора, на основі яких визначені настройки регулятора, при яких забезпечуються раціональні значення критеріїв якості роботи системи керування.

Наукова новизна. Уперше встановлено, що система автоматичного керування з настроєним комп’ютеризованим способом на максимальну швидкодію ПІД-регулятором та формувачем лінійно змінюваної у часі уставки температури у печі успішно відпрацьовує задані параметри перехідного процесу на її виході, але тільки за умови, якщо час нагріванню металу суттєво

(більш ніж у 1,5 рази) перевищує час перехідного процесу печі як об'єкта керування. У противному випадку з'являється недопустиме перерегулювання за температурою у печі. Визначено, що залежність між максимальним рівнем керуючого сигналу на першому інтервалі перемикання оптимального за швидкодією регулятора та тривалістю перехідного процесу на виході системи є зворотною й має експоненціальний характер. При цьому ця залежність з високою точністю (максимальна відносна похибка не перевищує 2,5%) апроксимується ступеневим поліномом восьмого порядку. Виявлено, що точність роботи запропонованого модифікованого регулятора, оптимального за швидкодією, є змінною величиною на різних ділянках графіку залежності рівня керуючого сигналу від тривалості перехідного процесу.

Практичне значення. Запропонована методика синтезу системи автоматичного керування температурою в електричній печі опору для термообробки металу. При цьому обґрунтовано параметри оптимального алгоритму керування за критерієм мінімізації часу нагрівання металу без перевищення допустимого перерегулювання перехідного процесу на виході системи керування.

Ключові слова: *синтез системи керування, температура, електрична піч опору для термообробки металу.*