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ABSTRACT

The article deals with the synthesis of effective algorithms for controlling a chemical reactor and developed a fuzzy synergistic controller for a class of indefinite nonlinear dynamic systems. A synergetic control scheme is proposed for solving the control problem for nonlinear systems. Non-linear systems with configurations and parameters that change over time require a completely non-linear model and adaptive control scheme for a practical operating environment. The synthesis of control laws is performed by the method of analytical design of aggregated controllers (ACAR). Fuzzy logic systems are used to evaluate the unknown nonlinear behavior of the system, and a new adaptive fuzzy controller is developed on the basis of synergetic control theory. It consists of a fuzzy system for approximating unknown system dynamics using adaptive synergic control to archive the desired characteristics. The simulation results are given on a real example to show the effectiveness of the proposed method.

Key words: synergistic synthesis, fuzzy synergetic controller, fuzzy logic system, synergetic control theory, ADAR method.

Introduction

One of the main apparatuses of chemical industry is a chemical reactor, the purpose of which is to ensure at its output a predetermined optimal concentration value provided for in the technological regulations of the target product. It is known that a chemical reactor is an energy-consuming object. In this regard, the economic efficiency of the entire production largely depends on ensuring the normal functioning of the chemical reactor and its performance. The main feature of chemical reactors as control objects is their multidimensionality, as well as the uncertainty of the concentration of the initial mixture. Currently, there are a sufficient number of publications related to the automation and control of chemical reactors, the problem of the synthesis of control systems that ensure the maintenance of optimal operating conditions, which has not been solved, is related to the complexity of the processes occurring in the reactors. Modern complex systems of diverse nature constitute a complex of various subsystems that perform certain technological functions and are interconnected by processes of intense dynamic interaction and energy exchange of matter and information. The indicated super systems are nonlinear, multidimensional, and multiply connected, in which complex transient processes occur and critical and chaotic regimes arise. The control problems of such dynamic systems are very relevant, difficult and practically inaccessible to the existing control theory [1].

A huge number of various chemical processes are implemented in the chemical industry and related industries, differing in the type of chemical reaction, thermodynamic parameters, kinetic characteristics (conversion scheme, kinetic model), phase composition of the starting reagents and reaction mixture, as well as the design and type of reactors [2]. In many cases, the reactor subsystem is central in the general scheme for converting the starting reagents into target products and to a large extent determines the resources and energy saving, the economic efficiency of the production process as a whole, and the degree of satisfaction of consumer demand for certain products. In the class of linear systems, to ensure robustness, adaptive automatic control systems with parameter adjustment, inertialess state controllers, robust systems based on typical PID controllers, and fuzzy control systems are used. However, these approaches are ineffective in the synthesis of control systems for essentially nonlinear objects. The ADAR method, developed in the framework of the synergetic theory of control, seems to be promising in this regard [3]. Fuzzy synergetic methods based on nonlinear dynamics and nonequilibrium thermodynamics allow both successful research of various chemical-technological processes and efficient control of them [4].

Research Methods and the Received Results

A chemical reactor is a volume-type apparatus equipped with a mechanical stirrer and cooling jacket (Fig. 1). The device operates in isothermal mode. The multistep series-parallel reaction is carried out in the reactor as follows:

$$A+B \rightarrow C_1, \quad A+C_1 \rightarrow C_2, \quad A+C_2 \rightarrow C_3 \qquad (1)$$

The kinetics of the reaction is described by a system of equations

$$\frac{dx_1}{dt} = -k_1 x_1 x_2 - k_2 x_1 x_3 - k_3 x_1 x_4; \quad \frac{dx_2}{dt} = -k_1 x_1 x_2; \quad \frac{dx_3}{dt} = k_1 x_1 x_2 - k_2 x_1 x_3; \quad \frac{dx_4}{dt} = k_2 x_1 x_3 - k_3 x_1 x_4 \qquad (2)$$

where x_1, x_2 - are the concentrations of reagents *A* and *B;* x_3, x_4, x_5 - concentration of reaction products; k_1, k_2, k_3 – stage speed constants [5].

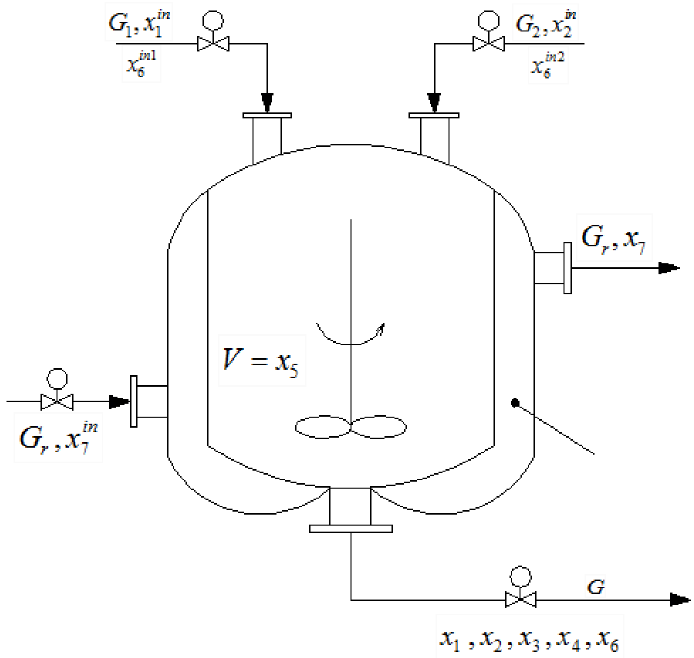

Fig. 1. Flow scheme of chemical reactor.

The apparatus implements a three-stage series-parallel exothermic reaction:

$$A+B\vec{k_1}C_1\ ,\quad A+C_1\vec{k_2}C_2\ ,\quad A+C_2\vec{k_3}C_3 \tag{3}$$

where *A* and *B* are inital reagents; C_1, C_2, C_3- reaction products; k_1, k_2, k_3 - stage speed constants. The target component is the substance C_2. Starting reagents *A* and *B* with concentrations $x_1^{in}, x_2^{in}-$ served in the device in separate streams with costs G_1, G_2- and temperatures $x_6^{in1}, x_6^{in2}-$ respectively. $G_{sv}-$ refrigerant consumption at the inlet and outlet of the apparatus; x_7^{in}, x_7- refrigerant temperature at the inlet and outlet of the apparatus; $G-$ mixture consumption at the outlet of the apparatus; x_1, x_2, x_3, x_4- component concentrations A, B, C_1, C_2 in the reactor; x_6- the temperature of the reaction mixture in the apparatus; $V=x_5-$ apparatus volume; $G_{sv}-$ shirt refrigerant volume [6].

The mixture from the reactor is taken by the pump. Since an exothermic reaction proceeds in the apparatus, a coolant is fed into the reactor jacket to cool the reaction mass [7].

A mathematical model of the dynamics of a chemical reactor consists of material balance equations for each component in the reactor, heat balance equations of the reaction mixture and the coolant in the shirt [8-9]:

$$\frac{dx_1}{dt}=R_1+\frac{G_1\cdot x_1^{in}}{V}-\frac{G\cdot x_1}{V},\quad \frac{dx_2}{dt}=R_2+\frac{G_2\cdot x_2^{in}}{V}-\frac{G\cdot x_2}{V},\quad \frac{dx_3}{dt}=R_3-\frac{G\cdot x_3}{V},\quad \frac{dx_4}{dt}=R_4-\frac{G\cdot x_4}{V},\quad \frac{dx_6}{dt}=\frac{G_1\cdot x_6^{in1}}{V}+\frac{G_2\cdot x_6^{in2}}{V}-\frac{G\cdot x_6}{V}+\frac{\Delta H_1\cdot k_1\cdot x_1\cdot x_2+\Delta H_2\cdot k_2\cdot x_1\cdot x_3+\Delta H_3\cdot k_3\cdot x_1\cdot x_4}{\rho\cdot C}-\frac{K_T\cdot F_T\cdot (x_6-x_7)}{V\cdot\rho\cdot C}$$

(4)

where $R_1=-k_1\cdot x_1\cdot x_2-k_2\cdot x_1\cdot x_3-k_3\cdot x_1\cdot x_4$, $R_2=-k_2\cdot x_1\cdot x_2$, $R_3=k_1\cdot x_1\cdot x_2-k_2\cdot x_1\cdot x_3\cdot x_4$, $R_4=k_2\cdot x_1\cdot x_3-k_3\cdot x_1\cdot x_4-$ is the rate of reaction on components. $\Delta H_i, i=1,\dots,3-$ thermal effect of the corresponding reaction stage; K_T, F_T- heat transfer coefficient through the wall and heat transfer surface of the apparatus; $\rho, C-$ density and heat capacity of the reaction mixture; ρ_r, C_r- density and heat capacity of the refrigerant.

Analysis of the ODE system (4), which describes the dynamics, shows that the object is multidimensional, nonlinear, and multiply connected. Suppose that, based on the conditions of physical feasibility, the flow rate of the input stream of reagent B and the flow rate of the refrigerant, i.e. $u_1=G_2$, $u_2=G_r$.

The system of equations of the model will take the form:

$$\frac{dx_1}{dt}=R_1+\frac{G_1\cdot x_1^{in}}{V}-\frac{G\cdot x_1}{V},\quad \frac{dx_2}{dt}=R_2-\frac{G\cdot x_2}{V}+\frac{x_2^{in}}{V}u_1,\quad \frac{dx_3}{dt}=R_3-\frac{G\cdot x_3}{V},\quad \frac{dx_4}{dt}=R_4-\frac{G\cdot x_4}{V},\quad \frac{dx_6}{dt}=\frac{G_1\cdot x_6^{in1}}{V}-\frac{G\cdot x_6}{V}+\frac{\Delta H_1\cdot k_1\cdot x_1\cdot x_2+\Delta H_2\cdot k_2\cdot x_1\cdot x_3+\Delta H_3\cdot k_3\cdot x_1\cdot x_4}{\rho\cdot C}-\frac{K_T\cdot F_T\cdot (x_6-x_7)}{V\cdot\rho\cdot C}+\frac{x_6^{in2}}{V}u_1$$

(5)

The flow of the initial reagent G_1- at the input to the device is suggested as the control effect for the volume regulation. In addition, one should also choose the control for stabilizing the concentration x_4 at the given degree under the action of disturbances. The analysis of the structure of equations of mathematical model of reactor [8] shows that variables x_1 and x_3 may act as the internal controls and the direct external effect can be performed only on x_1 by the change of the consumption of initial reagent G_1 at the input to reactor. Thus, the control channels of the concentration of the target component and volume of the mixture in the device are represented as follows: $u_1 \to x_1 \to x_4, u_2 \to x_5,$ where $u_1 = x_1,$ $u_2 = x_2$ [9].

In general, the problem of synergetic synthesis of the control system is formulated as follows: the control principle, $u = (u_1, \ldots u_m)^T$, should be determined as the function of state variables of object $u_1 = (u_1, \ldots u_n),$ ..., $u_m = (u_1, \ldots u_n),$ which transforms the representative point of system in phase space from the random initial state to the environment of the given invariant manifolds $\psi_s(x_1, \ldots, x_n) = 0,$ *S = 1,..., m* and subsequent motion along the intersection of manifolds to somewhat stationary point or to somewhat dynamic mode [10].

Macro variables $\psi_s(x_1, \ldots, x_n)$ must satisfy the functional equation $T_1 \dot{\psi}_1(t) + \psi_1(t) = 0$, (10) which at $\phi(\psi)\psi > 0$ and $T > 0$. Because the mathematical model of object (8) contains two external controlling effects $u_1 = G_2$ and $u_2 = G_r$, we use the ADAR method on the basis of parallel-series combination of invariant manifolds [11].

Let us introduce aggregate macrovariables to consideration, the first of which determines the relationship of x with controlled variable x and the second reflects the technological requirement to the volume of reaction system as follows

$$\psi_1 = x_4 - \overline{x_4}, \qquad \psi_2 = x_7 + v \cdot (x_6) \tag{11}$$

where $v(x_6)$ is somewhat function, which should be determined at subsequent procedure of synthesis [15]. Macrovariables (11) should follow the solution of principal functional equation of ADAR method (10).

Let us introduce the macrovariables and of equation (11) to functional equation (10) for the synthersis of control principle, $u = (u_1, \ldots u_m)^T$. As result, we obtain the following equations [12]:

$$T_1 \frac{dx_4}{d\tau} + x_4 - \overline{x_4} = 0, \quad \text{and} \quad T_2 \left[\frac{dx_7}{d\tau} + \frac{\partial v_1}{\partial x_6} \cdot \frac{dv_1}{d\tau} \right] + ¿ x_7 + v_7 = 0 . ¿ \tag{12}$$

We obtain the following relationships for the control principle from equations (12):

$$u_1 = \frac{(x_4 - \overline{x_4})}{T_1} + \overline{G} - u_1,$$

(13)

$$u_2 = \frac{(x_7 + v_1) x_4}{T_2 ¿ x_7^{in}} - \frac{R_1 \cdot x_4}{x_7^{in}} - \frac{\overline{G} \cdot ¿ x_1}{x_7^{in}} \cdot \frac{\partial v_1}{\partial x_6} \cdot \frac{(R_5 \cdot x_4 - x_5 \cdot \overline{G})}{x_1^{in}} ¿$$

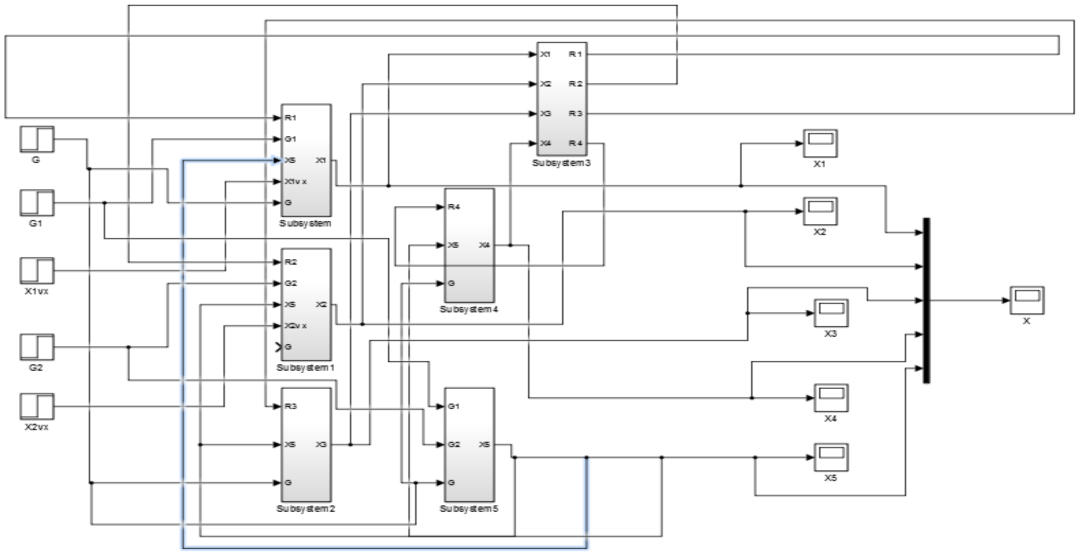

Fig. 2. Simulation model of the control system.

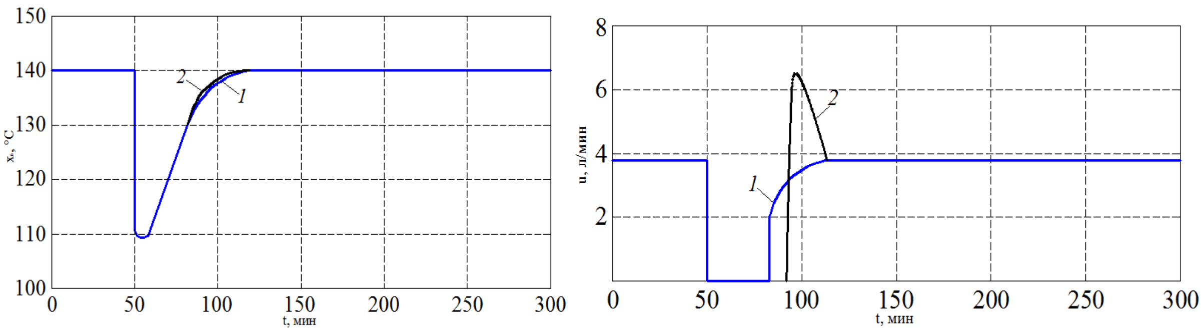

Fig. 3. Transients of the output variable and control at the initial deviation of state variables from statics:

1 - the first embodiment of the control algorithm, 2 - the second option.

As a result of simulation it was found that the closed-loop control system does not have a static control error when uncontrolled parametric and signal disturbances act on the object, changes in the set actions and the initial conditions deviate from static values when implementing the version of the control law that provides only for partial measurement of the object state variables. Fault detection schemes which are based on residualgeneration between the measured and some estimated process states require the investigation of mathematical models of the process [13]. Figure 1 shows examples of transients in a closed system “chemical reactor - non-linear robust controller” with an initial deviation of the state variables of the object, which corresponds to a disturbance in the region of large deviations from the equilibrium state. The deviation of the state variables of the object from the values in statics can be caused by any parametric or signal disturbance, which leads to the exit of the object from the desired equilibrium state [14]. In this case, the control system must ensure the transfer of the object to a given final state, determined by the required temperature.

A fuzzy system is a collection of IF-THEN rules in the form:
$R^{(l)}$: *IF* x_1 *is* F_1^l *and* … *and* x_n *is* F_n^l *THEN* y *is* G^l

where $x=(x_1,\ldots,x_n)^T$ - is the input of the fuzzy systems

The chemical rector model has input linguistic variables:

- "T" - process temperature;

- "F" - the flow rate of the process (carbonated-ammonized brine; gas; suspension);

- "Q" is the concentration of the process (carbonized-ammoniated brine; gas; suspension);

- "P" - process pressure;

The outputs of the column model are linguistic variables:

- "F" - suspension flow rate;

- "Q" - suspension concentration;

Linguistic variables are characterized by the membership functions of physical quantities to their terms. The enlarged structure of the model is shown in Figure 4.

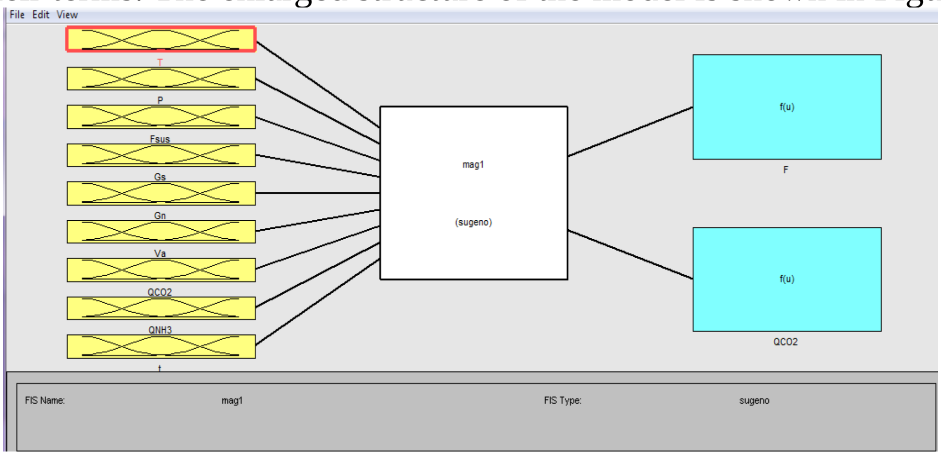

Fig. 4. Model of a chemical reactor in the Fuzzy Logic Toolbox package

To implement the rule base, 28 rules were drawn up (Fig. 5.).

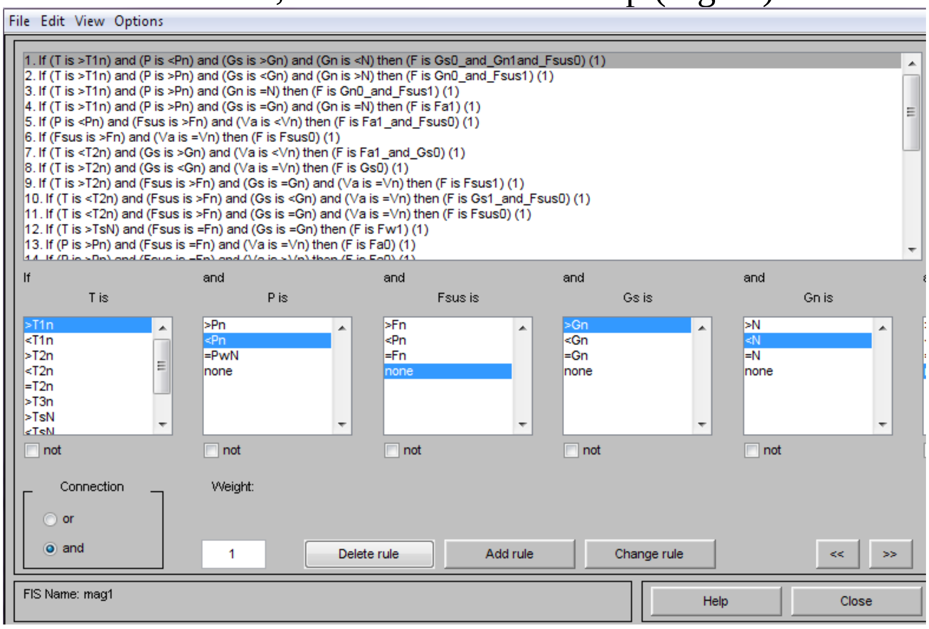

Fig. 3. Setting the rule base of the fuzzy controller model

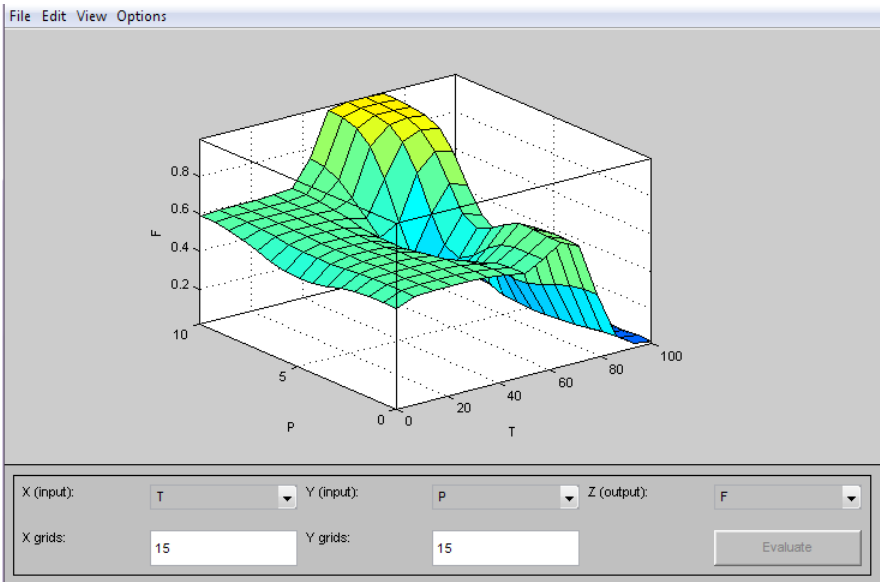

Fig. 4. Fuzzy inference algorithm results output window

In the fuzzy inference system algorithm for the And method parameters, "Or method", "Implication", "Aggregation" the following are used values:

- "And method" - (operator "AND") "MIN";
- "Or method" - (operator "OR") "MAX";
- "Implication" - (activation of the rules) "MIN";
- "Aggregation" - (accumulation of conclusions) "MAX".

As a defuzzification method, the centroid method was used, which in this particular case (unit membership functions of the output parameters of a fuzzy controller) [16] works similarly to the singleton sets method.

Conclusion

In this paper, we have developed a fuzzy synergetic controller for regulating and tracking control of a class of nonlinear systems. The control law has been introduced by using methods of synergetic theory and fuzzy logic control which can handle the nonlinear systems with system uncertainties and external disturbances. The problem of analytical synthesis of nonlinear control laws, which stabilizes the temperature and concentration of the process in the chemical reactor by means of synergistic control methods, is solved. Computer simulation of the object-regulator isolated system confirmed these properties of synthesized control system as the ability to switch chemical reactor from one mode of work to another, disturbance invariance, covariance to the given actions, and asymptotic stability. These facts make synergetic control theory very promising applied to such complex, manifold, and nonlinear objects of chemical engineering as chemical reactors. The results of studying the generalized system properties of the object allow solving the synthesis of the control system in various fields.

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