Development of the automatic supervisory control system based on fuzzy inference

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Abstract. The development of the supervisory control system designed to ensure the automatic stabilization of the petroleum processing parameters in a multi-flow furnace is considered. The structure of the subsystem that generates the setpoints of the local flow controllers in order to optimize technological processes is proposed. The supervisory subsystem is designed to minimize two criteria of the controlled values. The genetic algorithm is used to tune the parameters of the fuzzy inference based supervisory subsystem. The description of the system implementation based on intelligent controllers is suggested as well as the results of system simulation in MATLAB.

1. Introduction

In order to improve the efficiency of the oil refining process, high-tech industrial automation solutions are being widely implemented to increase the productivity of process units. The article considers the technological process of a multi-flow furnace of an oil refining plant as an object of automation. The automatic control of the furnace in the existing control system is carried out according to one main parameter: the temperature of the oil product at the output of the furnace. The furnace flow control is performed manually by the operator by setting a setpoint for each of the furnace flows. Thus obtaining heat energy from each furnace coil is uneven, since it depends on the internal design of the furnace. In addition, a disadvantage of the existing control system is the high requirements for the process unit operator. It is necessary for the operator to provide constant attention and perform many actions in monitoring and controlling the furnace load. At the same time, due to the irregular manual temperature equalization of the flows, which is carried out by the operator, a decrease in the furnace performance is observed.

In order to control a multi-flow furnace, a multi-connected control system (MCS) has been developed. It allows reducing the number of control parameters (formed manually by the operator) and ensuring automatic stabilization of the output parameters.

The proposed MCS implements the function of supervisory control: it generates setpoints for local flow controllers (based on information about controlled output parameters), ensuring optimization of technological processes of a multi-flow furnace. At the same time, the continuous automatic maintenance of the minimum difference between the temperatures in the furnace flows makes it possible to ensure a significant increase in the heat transfer efficiency of the burners to the flows of the oil product.

It should be noted that multi-flow furnaces of oil refining plants are characterized by a complex technological process. The state of such a process is determined by a large number of controlled variables having a different physical nature, constantly changing under the influence of random uncontrolled factors. Change in the dynamic characteristics of the control object reduces the
effectiveness of using traditional methods of automatic control, as it leads to a deterioration of the work quality even of initially optimally tuned controllers. For control systems operating under conditions of uncertainty and the effects of perturbations, the apparatus of fuzzy logic that operates with the theory of fuzzy sets is turned out to be the most promising [1 – 3].

The fuzzy supervisory control problem can be solved with an approach to high-level controller design [4]. For example, the fuzzy supervisor has been designed to correct the gain of the controller’s output signal [5]. The genetic algorithms and the system simulation were used to optimize the parameters of the supervisory fuzzy controller [6]. The supervisory hierarchical control scheme with supervisory fuzzy controller affecting the direct controller input [7] is more preferable in our case.

To solve the problem of controlling a multi-flow furnace, MCS has been developed and investigated as a supervisory control system, which adjusts setpoints for flow controllers. The supervisory system is implemented on the intelligent fuzzy controllers.

2. Methodology

The multi-flow furnaces of oil refining plants have a relatively large number of controlled variables and control actions, i.e. they are multi-dimensional control objects. The process of choosing method of control is determined by the nature of the connections between the controlled variables that exist inside the controlled object [8, 9]. If the controlled variable of one control channel is affected by an additional disturbance from the input variables of another channel, then the performance of the first channel may deteriorate. In this case, it is advisable to compensate this disturbance by introducing additional connections between the respective controllers.

We have analyzed need for a system with disturbance compensation for controlling a multi-flow furnace. Control of the furnace as a multi-dimensional object is interacting, that is, each controller, acting on the actuator of its control channel (flow temperature deviations), also acts on the actuators of other controlled variables. Each output variable is affected by an additional disturbance from input variables (flowrates on other flows) through channels with the corresponding transfer functions. However, as the analysis of the initial data (characteristics of the control object) showed, these additional disturbances do not significantly impair the quality of operation of each control channel, due to the lower transmission coefficients compared to the main input. Therefore, it does not seem appropriate to implement compensating connections between controllers in order to isolate the controlled values of each channel from processes in other furnace flows, i.e. control processes in furnace flows are autonomous. Thus, in the design and practical implementation of the automatic control system of the furnace as a multi-dimensional object, we will use the same methods as for one-dimensional systems. For technical implementation, we take the structure of the system, in which each output variable (deviation of the flow temperature) is controlled only one one-dimensional controller.

It should be noted in this case, for a multi-connected control system, monitoring of the temperature equalization controllers of the flows should be carried associatively. This necessity is arisen from the fact that among the intersecting closed contours of a multi-dimensional object there are contours with positive feedback (additional disturbance from processes in other flows). The temperature equalization of the flows is controlled by varying the flow rates (furnace loading). At the same time, the change in flow rates affects both the flow temperatures and the overall consumption of oil product through the furnace. It should be noted that the total (summary) flow control channel implemented in the MCS is fast-acting in comparison with flow temperature equalization control channels. This circumstance allows to design systems for controlling flowrate and temperature of flows as standalone systems.

Consider the development of process control systems on the example of a 6-flow furnace. The overall structure of the supervisory control system is presented in Figure 1. In the designed system, it is necessary to control the flows by the adjusting setpoints for each of the flow controllers $F_{sp_1} - F_{sp_6}$. The generated setpoints (instead of the settings entered by the operator) will be used by the existing control circuits of the system (based on traditional PID-controllers), which ensure the flow control of the $F_1 - F_6$. The differences (deviations) between the flow temperatures of each of the furnace coils and the average flow temperature (indicated $\Delta T_1 - \Delta T_6$) are used as output parameters of the object.
Figure 1. The general structure of the fuzzy supervisory control system for a multi-flow furnace.

Structurally, a multi-flow furnace model consists of multi-dimensional links. Linear multi-dimensional link corresponding to the control channels “flow rate – flow temperature deviation” is described in the matrix form as the ratio

\[ \Delta T(s) = W(s)F(s), \quad F(s) = [F_1(s), F_2(s), \ldots, F_6(s)]^T; \quad \Delta T(s) = [\Delta T_1(s), \Delta T_2(s), \ldots, \Delta T_6(s)]^T, \]  

where \( F(s), \Delta T(s) \) are vectors (columns) of Laplace transform of input and output values, the upper index "T" denotes the transposition operation; \( s \) is the Laplace operator. In addition, in expression (1) there is a matrix transfer function, i.e. matrix of elements that are the transfer functions of the individual channels (the channels “flow rate – flow temperature deviation”):

\[ W(s) = \left[ W_{ij}(s) \right], \quad \text{where} \quad W_{ij}(s) = \frac{T_i^{\text{ji}}}{s^2 + T_i^{\text{ji}} s + 1}; \quad i, j = 1, 6. \]  

Here \( K_{ij} \) is the transmission coefficient and \( T_i^{\text{ji}}, T_i^{\text{yu}}, T_i^{\text{yu}} \) are time constants, \( \tau_{ij} \) is the lag time for each control channel “flow of the \( i \)-th channel \( F_i \) – partial deviation of temperature of the \( j \)-th flow \( \Delta T_j \).”

The output of the object is the deviation of the temperature of the \( j \)-th flow (the sum of deviations due to changes in \( F_i \)) \( \Delta T_j = \sum_{i=1}^{6} \Delta T_{ij} \); \( j = 1, 6 \). In addition, it was taken into account that the total furnace flow control loop that operates based on the deviation of the total flow \( F_\Sigma \) from the value \( F_{\text{sp} \Sigma} \) (formed as the sum of the settings for each flow entered by the operator) also is involved in setpoint generation for each of the furnace flows.

Thus, the settings for each of the furnace flows \( F_{\text{sp}1} - F_{\text{sp}6} \) are formed depending both on the deviation of the total furnace flow and the deviations of the flow temperatures from their specified values. The following requirements are put forward for designing a system. It is necessary to minimize the deviations of the flow temperatures for each of the furnace coils from the average value.
Based on these requirements, the supervisory control system for a multi-threaded furnace has been created that generates setpoints for local flow controllers. The system automatically provides the minimum difference between flow temperatures, while keeping the specified total furnace flow. As it can be seen in Fig. 1, the supervisory control system designed on the basis of fuzzy inference is a “superstructure” above the existing furnace loading control system. The supervisory control system receives from the operator the values of the settings for each flow controller, as well as information about the state of the control object (total flow rate and flow temperature deviations). Based on these data, the system generates setpoints for flow controllers, allowing automatic equalization of flow temperatures while keeping the specified total flow rate.

3. Supervisory control subsystem model

In accordance with this structure the mathematical model of the system for a 6-flow furnace has been created in the MATLAB / Simulink [10]. Let us consider in detail the subsystems that implement the function of supervisory control based on fuzzy inference. As part of the mathematical model of the system, there is a fuzzy supervisory control subsystem FUZZY MC, the structure of which is shown in Figure 2.

The FUZZY F subsystem is used to control the total consumption of oil product. In the FUZZY MC subsystem, signal processing of the measured flow rates is provided for suppressing the effect of noise during the formation of settings. The external inputs of the subsystems are the tuning parameters of the membership functions of the variables used by the fuzzy inference procedure. The input of each of the subsystems FUZZY F, FUZZY T1 (T2-T6) receives an error \( e \) (the deviation of the controlled parameter from the specified value). For the FUZZY F subsystem, the error \( e \) is determined by the deviation of the total flow rate from the specified value; for each FUZZY T1 (T2-T6) subsystem, the error is the deviation of the flow temperature from the average value of the furnace temperature. In each subsystem, the rate of the error change \( (de/dt) \) used to form the output value is determined. The
subsystems output is the generated (on the basis of fuzzy inference) change value of a given flow rate for the controller of the corresponding flow of the basic control system. Thus, the setpoint for each flow controller is formed on the basis of the operator’s setpoint $F^o_{spi}$, taking into account two generated output values: the output of the total flow controller $F_{sf}$ and the output of the flow temperature deviation controller $F_{sTi}$, as algebraic the sum of these components $F_{spi} = F^o_{spi} + F_{sf} + F_{sTi}; \ i = 1,6$. The fuzzy control for each controller is implemented by the REG FIS subsystem (Figure 3), which has the following operation logic. If there is a large deviation of the process parameter from the set value $e$, the output variable (change in the set flow rate or $F_{sf}$) is performed at high speed.

![Figure 3. Model of the fuzzy control subsystem REG FIS.](image)

When $e$ is small, the control is not performed if the rate of change of the error ($de/dt$) is low. When the rate of error change $de/dt$ is high, even for small $e$, the output signal changes with medium speed.

To implement the described algorithm, the input signals $e$ and $de/dt$ in the FIS REG subsystem are converted to the values of fuzzy linguistic variables (fuzzification process is performed). Under fuzzification we mean the procedure for representing a number belonging to a set of real numbers as a fuzzy number. The obtained fuzzy variables are used in the implementation of fuzzy inference: on fuzzy variables, operations formulated as fuzzy rules are performed. During the fuzzification process, the ranges of variables are divided into linguistic terms (sets), within each of which the membership function $\mu(x)$ of the variable $x$ ($e$ or $de/dt$) is built for each of the sets. The range of the error $e$ consists of three sets: $NL1$ (negative high), $Z1$ (zero), $PL1$ (positive high). Also, the range of the error change rate $de/dt$ is divided into the same number of terms with similar designations: $NL2$ (negative high), $Z2$ (low), $PL2$ (positive high). The knowledge base is suggested to realize the fuzzy inference. Five fuzzy production rules are executed by the subsystem FIS REG:

1) if $e$ is $PL1$ then $V_{out}$ is $PL$;
2) if $e$ is $NL1$ then $V_{out}$ is $NL$;
3) if $e$ is $Z1$ and $de/dt$ is $Z2$ then $V_{out}$ is $Z$;
4) if $e$ is $Z1$ and $de/dt$ is $NL2$ then $V_{out}$ is $PM$.
5) if $e$ is $Z1$ and $de/dt$ is $PL2$ then $V_{out}$ is $NM$.

Defuzzification procedure includes weighted averaging method to calculate the output value speed:

$$V_{out} = \sum_{i=1}^{m} \mu(V_{out}) \frac{1}{\sum_{i=1}^{m} \mu(V_{out})}.$$

Then the variable $V_{out}$ is used for calculation of the controller output values $F_{sf}$ (for the flow controller) and $F_{stI}$ (for the flow temperature controller).

### 4. The controller parametric synthesis

The genetic algorithm (GA) \cite{12, 13} is used to adjust the membership functions parameters in the REG FIS subsystem. The preliminary optimization is performed with MATLAB \cite{11} for a single-loop control system. The terms of membership functions for the of the input and output variables of fuzzy controllers are shown at Figure 4.

We have defined the parameters of the membership functions that minimize the selected quality criterion. The criterion is $J(X) = \int_0^T (e^2(t) + (\lambda u(t))^2) dt$. The first term in the integrand characterizes the control accuracy and the second term determines the total cost of control \cite{14-16}. A factor $\lambda$ is selected experimentally.

![Membership functions of the fuzzy control loop.](image)

We use GA to optimize the parameters of membership functions as follows. We form the vector $X$ of eight parameters of the membership functions for the input and output variables. GA operates with $X$ as an “individual” to select the best values in accordance with criterion $J$. Figure 5 illustrates the process of the control system optimizing (for one of the implementations).
Figure 5. The synthesis of the MCS using the genetic algorithm.

Considering the complex of the GA populations, we see (Figure 5a) how the criterion values change (for the best individuals, as well as for the average value of the criterion). 15 generations were analyzed before optimal parameters were obtained. Figure 5b shows column plots of elements of the vector of optimal parameters $X_{opt}$. The transition process (with optimal parameters) is shown in Figure 5c.

A calculation is presented for the setpoint disturbance by 7% of the nominal value. We see that the controller performs a disturbance in 50 s and the controlled variable is maintained at the required level.

5. The results of simulation

The results of the model studies of the developed system of fuzzy supervisory control are presented in Figure 6.

Figure 6. Transients in the supervisory control system when two channels
are disconnected from the control.

For clarity, two of the six flows are disconnected from the control, i.e., the supervisory subsystem does not generate a setpoint for them (the oil consumption in the streams is set manually by the operator). Transient graphs (obtained when disturbed by given flow rates at the 250th, 300th, and 350th seconds, Figure 6a) demonstrates good control quality (rapid temperature equalization) for flows.

All disturbances are eliminated: temperature deviations do not exceed 1 degree, and eliminated within 50 s (Figure 6b). For comparison: the deviation of the disconnected streams exceeds 2 degrees. The graphs show that the maintenance of the specified total flow rate is carried out with good accuracy (deviation less than 1 m³/h, Figure 6c).

It should be noted that the system implemented on the basis of intelligent fuzzy controllers with low sensitivity to changes in the parameters of technological processes, will allow increasing the efficiency of the objects of automation of oil refineries, in case to random uncontrolled factors. The calculation was made, at which the time constant (for expression (2)) changed by 10%.

The studies were performed for two cases: when the system is implemented on PID controllers and on fuzzy controllers. In the first case, temperature error was about 6 degrees; in the second case it was not greater than 4 degrees.

Thus we have demonstrated that the use of fuzzy supervisory control is appropriate for designing an effective system.

6. Conclusion

We have developed the multiply-connected fuzzy supervisory control system which is the software add-on for the existing system. The system stabilizes the controlled values and reduces the burden on an operator and the number of parameters he have to control. The main advantage of supervisory control consists in continuous monitoring and control of the process in a mode close to the optimal one. Note that in case of manual settings (e.g. when an automatic unit fails) the supervisory control in advisor mode allows an operator to make informed decisions for effective control.

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