Optimization of structure of control system with fuzzy controller

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Abstract. The article gives a brief description of the three-phase separator of the "Heather-Triter" type. A three-phase separator of the "Heather-Triter" type is used to obtain commercial oil from well products, and to separate well products for gas, oil, and water. To regulate the oil level and phase separation, the separator is equipped with direct-acting mechanical control valves on the oil outlet line and on the water outlet lines. The issues of modeling the level control system in a three-phase separator of the "Heather-Triter" type, and criteria for the quality of production management are considered. The description of the model of a three-phase separator of the "Heather-Triter" type is given. It works with various methods of fuzzy controllers. A method for improving the quality of level control in the Troika is described by the Heather-Triter phase separator using a fuzzy controller. The issues of optimizing the structure of a control system with a fuzzy controller are considered. A method for improving the quality of level control in a three-phase Heather-Triter separator is described.

1. Introduction

Development and introduction of automated process control systems is mostly trendy in the development of up-to-date industrial production. In this regard, optimization of industrial processes is becoming more widely used. Of great importance in the optimization is a properly developed and most realistic mathematical model of the process control system [8]. The mathematical model allows simulating the processes occurring within the system. By studying the simulation model, it is possible to obtain the data and information that can be used to control a real object [5].

Fuzzy sets are a tool enabling to develop models for controlling complex objects which do not always make it possible to develop precise mathematical models using integro-differential equations[7]. In this article, we will describe mathematical model of a three-phase separator "Hiter-Triter" type, we will consider methods for optimization of the control system structure using the fuzzy controller.

2. Brief characteristics of the three-phase separator of "Hiter-Triter" type

A three-phase separator of the Heather-Triter type is used to produce marketable oil from well products, to separate well products into gas, oil and water.

The Heater-Triter separator (hereinafter referred to as the "separator") is a horizontal cylindrical apparatus containing an emulsion input unit, an emulsion heating unit by a flame tube, a coalescence unit, a water, oil and gas separation unit. To improve the separation of water and oil, it is possible to wash the emulsion with hot water and add a demulsifier. On the cylindrical part of the body and on the
bottoms of the devices are technological fittings, a fitting for the installation of instrumentation and automation equipment and hatches. On the bottom (from the inlet side of the mixture), a flange connection of the heater’s flame tubes to the housing is provided.

To regulate the oil level and phase separation, the separator is equipped with direct-acting mechanical control valves on the oil exit line and on the water exit lines. The problems of separator control are as follows:

1. There are cases when mechanical control valves do not cope with their task, because of which the phase separation level is not maintained at a given value, and water begins to flow to the oil outlet line.
2. Systems of regulation of oil and water levels are interconnected, which negatively affects the quality of transients. The consequence of this is water pollution with oil and high water cut after the separator.

It seems advisable to combine the control of the separator taking into account its state in all of the above parameters on the basis of fuzzy logic methods.

3. The level control system modeling in a three-phase separator «Hiter-Triter» type

3.1. Production control quality criteria
The quality of the products of this process is determined by the water content of the oil, which should be less than 10%. This parameter is constantly monitored at the exit of the BCS. This parameter should not exceed the established norm. Oil quality is monitored at the top level of PCS. This division employs specialists responsible for monitoring the output parameters of production as a whole. They receive product data automatically.

The quality of an automated control system is determined by a combination of properties that ensure the effective functioning of both the control object itself and the control device, i.e. the entire management system as a whole.

The properties that make up this set and have quantitative meters are called quality criteria of the control system.

The quality of an automated system can be assessed by criteria such as the complexity of the synthesis of the system and the required computing power (processor time and memory). The complexity of the synthesis of the system in our case implies a waste of time on the development of a fuzzy controller.

To reduce the complexity, it is proposed to use the following methods to optimize the structure of the control system with a fuzzy controller:

1. Transition from one fuzzy controller to series-connected fuzzy controllers;
2. Transition from one fuzzy controller to parallel fuzzy controllers;
3. Feedback elimination method.

The use of these methods leads to a decrease in the number of rules drawn up during the synthesis of a fuzzy controller, which reduces the time required to develop a fuzzy controller. Also, by reducing the number of rules, the requirement for computing power is reduced, that is, less processor time and memory are required for data processing.

3.2. Description of the three-phase separator model of "Hiter-Triter" type
We will create a Heather-Triter separator model, which will consider the dependence of the liquid level and water level on the flow rate of the emulsion, its emulsion and the degree of opening of the valves for oil and water output. The conceptual model of the Heather-Triter separator is shown in Figure 1.
Designation of model parameters:

\( F_e \) - water-gas-oil emulsion flow rate, m\(^3\)/h;

\( \gamma_o \) – volume fraction of oil in the emulsion, %;

\( \gamma_w \) – volume fraction of water in the emulsion, %;

\( \gamma_g \) – volume fraction of gas in the emulsion, %;

\( \alpha_o \) – oil outlet valve opening degree, %;

\( \alpha_w \) – the degree of opening of the valve at the outlet of water, %;

\( LG_1 \) – fluid level, m;

\( LG_2 \) – water level, m.

The productivity of the oil and gas separator with direct heating (Heather-Tritter) in terms of liquid by technological parameters is 6848 m\(^3\)/day, and the maximum allowable 11810 m\(^3\)/day.

We assume that in the water-gas-oil emulsion of gas there will be 5%, after the first stage of separation, the volume fraction of water in relation to the liquid can be from 60 to 98%, therefore, the volume fraction of oil from 2 to 40%. The inflow of water-gas-oil emulsion will be equal to 7208.4 m\(^3\)/day (300.35 m\(^3\)/h), and the maximum allowable inflow of 12431.6 m\(^3\)/day (517.98 m\(^3\)/h).

The liquid level in the apparatus should be maintained within 0.4-0.8 m, and the water level in the range of 0.6-0.8 m.

Create a level management model:

\[
\begin{align*}
\frac{dLG_2}{dt} &= k_1 \times (F_{w1} - F_{w2}), \\
\frac{dLG_1}{dt} &= k_2 \times (F_{o1} - F_{o2} + F_{w1} - F_{w2})
\end{align*}
\]

where, \( \frac{dLG_2}{dt} \) – water level change, %/h;

\( \frac{dLG_1}{dt} \) – fluid level change, %/h;

\( k_1, k_2 \) – scaling factors, %/m\(^3\);

\( F_{w1} \) – inlet water flow, m\(^3\)/h;

\( F_{w2} \) – outlet water flow, m\(^3\)/h;

\( F_{o1} \) – input oil consumption, m\(^3\)/h;

\( F_{o2} \) – output oil consumption, m\(^3\)/h.

Calculation of scaling factors.
The volume of the three-phase Heather-Triter device is 80 m$^3$. The volume occupied by the liquid level in the range of 0.4-0.8 m will be considered equal to 10 m$^3$. Therefore

$$k_1 = \frac{100}{10} = 10\% / m^3$$

(2)

The volume occupied by the phase separation level in the range of 0.6-0.8 m will be considered equal to 20 m$^3$. Therefore

$$k_2 = \frac{100}{20} = 5\% / m^3$$

(3)

The inlet water flow rate is calculated by the formula:

$$F_{w1} = F_2 \times \gamma_w,$$

(4)

Inlet oil consumption is calculated by the formula:

$$F_{o1} = F_2 \times \gamma_o,$$

(5)

The flow rate of water and oil at the outlet depends on the degree of opening of the valves. Therefore, we obtain the functions:

$$F_{w2} = f(\alpha_w)$$

(6)

$$F_{o2} = f(\alpha_o)$$

(7)

The synthesis of this fuzzy controller is complicated by the fact that it is necessary to draw up a large number of rules for it, namely $54 = 625$ rules.

4. Optimization of the control system structure using the fuzzy controller

In control theory, special attention has always been paid to the synthesis of mathematical models and control algorithms with insufficient information about the control object and the useful signals acting on it, and interference.

Over time, it became clear that the use of classical methods of control theory is no longer sufficient to control such systems, and new methods and approaches need to be developed. One of these approaches is based on fuzzy sets and fuzzy logic. Initially, this approach was applied and proved to be effective in creating expert systems. Somewhat later, it began to be used to create expert management systems and more recently, for the synthesis of regulators and control systems for technological systems.

In this article, we consider methods for optimizing the structure of a control system with a fuzzy controller:

1. Transition from one fuzzy controller to series-connected fuzzy controllers;
2. Transition from one fuzzy controller to parallel fuzzy controllers;
3. Feedback elimination method.

Optimization criteria will be:

The complexity of the synthesis;
required computing power (processor time and memory).

4.1. Method of consecutively connected fuzzy controllers

This method is perfect in cases where the system is better divided into blocks (links). The scheme of this method is presented in Figure 3.
The application of this method allows reducing the complexity of the synthesis process of a fuzzy controller, in the event that it is easier to calculate small blocks and conduct experiments with them than to calculate large blocks and conduct experiments with it.

A fuzzy controller is a static link, therefore, a series connection of fuzzy regulators will also be a static link. This statement reduces the computational process, because the internal connections of the fuzzy controller are necessary only at the stage of its synthesis and are not calculated during its operation.

Another advantage of this method is the ability to replace one of the blocks when changing the system, i.e. there is no need to make calculations for the entire controller, but it is enough to calculate a new block.

Consider an example of calculating the number of rules. For the structure shown in Figure 3, suppose that \( n_1 = 5 \) terms are described for input \( x_1 \), \( n_2 = 6 \) terms for \( x_2 \), \( n_3 = 7 \) terms for \( x_3 \), and \( n_4 = 8 \) terms for \( y_1 \).

Then the number of rules for HT (Figure 3) will be equal to where - the number of rules; \( \times \) rules.

Upon transition to the series connection of fuzzy regulators (HT1 and HT2), the number of rules will be equal where - the number of rules; \( \times \) rules.

This method should be used when the condition is met.

This method is applicable in cases where the output parameter of the fuzzy controller is independent of all input parameters. The scheme of this method is presented in Figure 4.

The transition from one fuzzy controller to two parallel fuzzy controllers can help reduce the number of rules in the synthesis, which, in turn, can reduce the complexity of developing a fuzzy controller.

The requirement for a microprocessor that implements a fuzzy controller is also reduced, namely, less processor time and memory are required for data processing.

Consider an example of calculating the number of rules. For the structure shown in Figure 4, suppose that \( n_1 = 5 \) terms are described for input \( x_1 \), \( n_2 = 6 \) terms for \( x_2 \), \( n_3 = 7 \) terms for \( x_3 \), and \( n_4 = 5 \) terms for \( x_4 \).

Then the number of rules for HT (Figure 4) will be equal

\[
M = n_1 \times n_2 \times n_3 \times n_4 = 5 \times 6 \times 7 \times 5 = 1075 \text{ rules.}
\]

In the case when two parallel fuzzy controllers are used (HT1 and HT2)

\[
M' = n_1 \times n_2 + n_3 \times n_4 = 5 \times 6 + 7 \times 5 = 65 \text{ rules.}
\]

This method should be used when the condition \( M' \rangle M \) is met.
4.2. Method of the fuzzy controllers parallel connection

The essence of this method is to switch from a fuzzy controller with feedback to a fuzzy controller without feedback, which reduces the number of input parameters, as a result of which the number of rules drawn up during the synthesis and operation of the fuzzy controller is reduced.

In practice, to compensate for the disturbance, it is necessary to control the current control action, i.e. to reduce the disturbance one must either increase or decrease the control action. Therefore, it is necessary to apply a control action to the input of the fuzzy controller.

4.3. Method of feedback exception

If the change in the control action does not depend on the current value, you can reduce the number of inputs, which will lead to a decrease in the rules. In our case, the control action will be a change in the degree of valve opening, which does not depend on the current value.

Let us consider an example of calculating the number of rules. For the structures shown in Figure 5, suppose that \( n_1 = 6 \) terms are described for input \( x_1 \), \( n_2 = 5 \) terms for \( x_2 \), and \( n_3 = 7 \) terms for \( y \).

We calculate the number of rules for a fuzzy controller with feedback in the Figure 5 rules.

Then for the fuzzy controller shown in Figure 5, the number of rules will be equal to: rules.

5. Optimization of the fuzzy controller for control of the separator

To implement optimal control, we divide the conceptual model of HT presented in Figure 2 into two parallel ones (Figure 6).

Optimization is carried out by two methods:

1. Division of one fuzzy controller into two parallel fuzzy controllers. As a result, the number of rules is reduced, \( 52 + 52 = 50 \) rules, which reduces the time to develop a fuzzy controller, reduces the requirement for a fuzzy controller system (requires less CPU time and memory to process data).

2. Obtaining at the output of HT2 the change in valve opening (\( \Delta \alpha_w \)), instead of the new value of the degree of opening of the valve of the water flow at the outlet (\( \alpha_w \)). This is implemented to reduce the input parameters for HT2, and therefore, to reduce the rules drawn up.

Designations for model with parallel HT (Figure 6):

\[ \Sigma F \] – total oil and water consumption at the outlet, \( \text{m}^3/\text{h} \);  
\[ \Delta \alpha_w \] – change in the opening of the outlet water flow valve, \( \% \);  
\( 1/p \) – an integrating unit in which the calculation of a new values \( \alpha_w \):

\[ \alpha_w = \alpha'_w + \Delta \alpha_w \]  

where, \( \alpha'_w \) – the degree of opening of the outlet water flow valve until the water level changes;  
\( f(\alpha_w) \) – structural unit in which the discharge water flow is calculated, depending on the degree of valve opening.

\[ F_w = f(\alpha_w) \]  

where, \( F_w \) – outlet water flow, \( \text{m}^3/\text{h} \);  
\( F_o \) – output oil consumption, \( \text{m}^3/\text{h} \);  

Oil consumption at the outlet is calculated by the formula:

\[ F_o = \Sigma F - F_w \]  

where, \( F_w \) – output oil consumption, \( \text{m}^3/\text{h} \);  
\( f(F_o) \) – a structural unit in which the degree of opening of the valve at the oil outlet is calculated, depending on the oil consumption at the outlet.

\[ \alpha_o = f(F_o) \]
The calculation of a fuzzy controller consists of the following steps: fuzzification; aggregation; activation; accumulation; defuzzification.

Initially, expert information was collected. As a result of the collection of expert information, reference point tables for HT1, HT2 are derived. The reference point tables describe the entire area of definition of inputs and outputs of HT [1-3].
Table 1. Table of reference points for HT1

| LG1, m | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 |
|--------|-----|-----|-----|-----|-----|
| Fe, m³/hour | 100 | 70  | 90  | 100 | 110 |
|          | 150 | 120 | 140 | 150 | 160 |
|          | 200 | 170 | 190 | 200 | 210 |
|          | 250 | 220 | 240 | 250 | 260 |
|          | 300 | 270 | 290 | 300 | 310 |

Next, linguistic variables were developed for the input and output parameters of the fuzzy controller. Fuzzification is considered completed if correspondence is established between the numerical values of the input variables of the fuzzy inference system and the values of the membership function of the corresponding terms of the linguistic variables $\mu(Fe), \mu(LG1), \mu(LG2), \mu(dLG2)$.

For example, when $Fe = 160$ m³/h, the second and third terms are used, the membership function $\mu(Fe_2)$ is 0.8, and $\mu(Fe_3)$ is 0.2.

At the stage of aggregation, we calculate the degree of truth of the conditions for some rules of the fuzzy inference system. If $Fe = Fe_2 (\mu(Fe_2) = 0.8)$ and $LG1 = LG1_2 (\mu(LG1_2) = 0.55)$ then $z$, where, $z$ – truth conditions for rules.

At the activation stage, we calculate the degree of truth of additional consequents. For HT1 we will use production rules of the form:

If $LG1 = LG1_1$ and $Fe = Fe_1$, then $\sum F = \sum F_1 \cap \sum F = \sum F_j C$
where $C$ – degree of belonging of a variable to a term $\sum F$ [1-3].

If $LG1 = LG1_1$ and $Fe = Fe_1$, then $\sum F = \sum F_1$, for this consequent, the degree of truth will be equal to 1, since the rule corresponds to the extreme reference point ($C=1$). There is no additional consequent. Similarly, we calculate the degrees of truth of other consequents.

Production rules for HT1, HT2 were drawn up. For example, see Table II shows the production rules for HT1.

Table 2. The system of production rules for HT1 in tabular form.

| LG1 Fe | LG11 | LG12 | LG13 | LG14 | LG15 |
|--------|------|------|------|------|------|
| Fe1    | $\sum F_1$ | $\sum F_1, \sum F_2^{0.46}$ | $\sum F_1^{0.46}, \sum F_2$ | $\sum F_1^{0.18}, \sum F_2$ | $\sum F_2, \sum F_3^{0.18}$ |
| Fe2    | $\sum F_2$ | $\sum F_2, \sum F_3^{0.46}$ | $\sum F_2^{0.46}, \sum F_3$ | $\sum F_2^{0.18}, \sum F_3$ | $\sum F_3, \sum F_4^{0.18}$ |
| Fe3    | $\sum F_3$ | $\sum F_3, \sum F_4^{0.41}$ | $\sum F_3^{0.46}, \sum F_4$ | $\sum F_3^{0.18}, \sum F_4$ | $\sum F_4, \sum F_5^{0.18}$ |
| Fe4    | $\sum F_4$ | $\sum F_4, \sum F_5^{0.46}$ | $\sum F_4^{0.46}, \sum F_5$ | $\sum F_4^{0.18}, \sum F_5$ | $\sum F_5, \sum F_6^{0.12}$ |
| Fe5    | $\sum F_5$ | $\sum F_5, \sum F_6^{0.34}$ | $\sum F_5, \sum F_6$ | $\sum F_5^{0.34}, \sum F_6$ | $\sum F_6$ |

We calculate the accumulation for $Fe = 160$ m³/h, $LG1 = 0.54$ m, these values correspond to the subclauses $\mu(\sum F_2) = 0.44$ and $\mu(\sum F_3) = 0.2024$. We apply the method of finding the maximum value from the corresponding subclauses, therefore $\mu_{max} = 0.44$.

Defuzzification is carried out by the method of center of gravity:
\[
\sum F = \frac{\int_{F_{\text{max}}}^{F_{\text{max}}} F \cdot \mu(\sum F) \cdot d \sum F}{\int_{F_{\text{min}}}^{F_{\text{max}}} \mu(\sum F) \cdot d \sum F}
\]  \hspace{1cm} (12)

where, \( \sum F \) – total oil and water consumption at the outlet, m\(^3\)/h;
\( \sum F_{\text{max}} \) – maximum total oil and water consumption at the outlet;
\( \sum F_{\text{min}} \) – minimum total oil and water consumption at the outlet.

6. Conclusion
The article describes a way to improve the quality of level control in a three-phase Heather-Triter separator through the use of a fuzzy controller and its further optimization. Application of optimization to HT will allow obtaining greater accuracy of regulation, as well as leading to a decrease in computing capacity. In turn, increasing the accuracy of the regulation of technological parameters will make it possible to improve the quality of the produced marketable oil.

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