Development and simulation of the pulsed fuzzy controller with low control costs

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Abstract. The article deals with the development and simulation of the control system of water level in the tank as a typical automation object. The level automatic control system (ACS) based on traditional pulse controllers is presented. The system is proposed as well that performs fuzzy logical inference to generate pulsed control action and at the same time implements low-cost control. Comparative analysis of these control systems simulated with MATLAB / Simulink / Fuzzy Logic Toolbox was made. It is shown that the developed fuzzy ACS is more effective than a traditional ACS.

1. Introduction

The introduction of the Industry 4.0 concept in the practice of industrial enterprises allows to increase the efficiency of controlled technological processes, as well as to reduce production costs. Therefore, enterprises (to use new principles) must implement appropriate technical decisions, including those that involve the implementation of optimal technological processes, the integration of computer systems featured with artificial intelligence, and the increase in the efficiency of equipment use.

The task of the designed system is the automatic control of the water level in the drainage tank (DT) of the power unit as a typical control object [1, 2] with parameters that can change during operation under the influence of disturbances. In order to carry out an automatic control of an object in an uncertain environment, we apply control based on the fuzzy sets theory [3, 4].

For the fuzzy control system design, a traditional automatic control system (ACS) was used as a basis (implemented using the VLR-2 controllers). This system is made according to the traditional scheme of controlling objects without self-levelling (an example of such an object is the channel controlling the liquid level in a tank) [1, 2]. The controller forms a proportional (P) control law in common with a constant speed actuating mechanism (AM) and a proportional feedback signal of the control valve (CV) position. The development of both the traditional control system (on the means of VLR-2 controllers) and the proposed fuzzy control system was carried out on the basis of the technical characteristics of the control object provided by Kol’skaya Nuclear Power Plant experts:

- the characteristics of the control valve 6s-9-2 (for the controller 3RT20S03);
- the characteristics of the actuator (MEO-250.25-0.25);
- the transition function of the control object through the channel “the CV position change – the level change”, that was obtained under disturbance by the control valve;
- the characteristics of the level sensor (DMEU-MI).

The article presents the results of the development of the liquid level ACS based on the fuzzy controller and shows its capabilities and advantages compared with the classical pulse controller. Dynamic system models were created by the MATLAB/Simulink/ Fuzzy Logic Toolbox (that are intended to performe scientific and engineering calculations) [5, 6].
2. Model of the traditional pulse control system

We consider the liquid level pulsed ACS (for an object without self-levelling) that implements the automatic control method widely used in practice [1, 2]. This method consists in the formation by the controller of a proportional-integral (PI) law together with the constant speed AM. In this case, the VLR-2 controller executes the algorithm of a pulse proportional-differential (PD) converter (two relays with hysteresis looped by general feedback). The duty cycle of the controller output pulses is PD-dependent on the error signal change.

The simulation scheme of the ACS developed using MATLAB / Simulink is shown at Figure 1a. The control is carried out according to the so-called single-pulse scheme (pulse by level) without inputting a feedback signal on the material balance (there are no pulses for the inflow and outflow in the DT).

![Figure 1. Diagram of the ACSs models in MATLAB / Simulink Fuzzy Logic Toolbox:](image)

a) model of the traditional ACS; b) model of the fuzzy ACS.

The controller changes the flow rate from the DT outflow by actuating the drain valve: as the level rises, the valve opens. The change in the inflow into the tank is not controlled and we consider it as a disturbance to the control object. To provide stability, the feedback on the position of the control valve is introduced into the system, and thus the P-control law is implemented.

A serious disadvantage of the existing system is the presence of a static error caused by the fact that in the adopted structure proportional pulse control is carried out using proportional feedback. In the steady state, each value of the level corresponds to a certain value of the opening of the valve. The required level is provided by regulating the material balance between inflow and outflow. Since the ability to control the disturbing effect (inflow into the tank) is absent, this is the cause of the static error, the so-called “irregularity” caused by the disturbance, in the steady state.

3. Model of the fuzzy pulse control system

To design a fuzzy pulse control system, we replaced the conventional relay-pulse controller with the fuzzy controller in the ACS scheme. The output of the fuzzy controller is subjected to pulse-width modulation (PWM), and there is no feedback on the valve position in the scheme. The simulation scheme of fuzzy ACS created using the MATLAB / Simulink / Fuzzy Logic Toolbox is shown at Figure 1b. In the developed ACS, two signals are received in the inputs of the fuzzy controller: the first signal is the control error (the difference between the measured level value and its setpoint). For a fuzzy controller, this is the linguistic variable "error e". The second input signal is the rate of the control error change (linguistic variable “the error change rate de/dt”).
In the fuzzy controller output, the speed of change in valve position is generated (linguistic variable “the speed of the valve position change \( V_{out} \)). It determines the pulse width value. In accordance with the pulse width value, the PWM module outputs the signal to the actuator.

Design of the fuzzy ACS is made on the basis of a simple logical scheme for the formation of a nonlinear (relay) law that ensures simplicity of control and reduction of energy costs for its implementation [7].

The idea of control logic is as follows. With small deviations of the level from its setpoint (the absolute error \(|e|\) is less than the threshold \(\varepsilon\)), control is not performed. Control is not performed even with large deviations as well, if there is a sufficiently high rate of the deviation change (the absolute rate \(|de/dt|\) exceeds the threshold \(\varepsilon\)' ), but this speed has the sign opposite to the sign of the deviation. In this case, the deviation is reduced by itself, even if the actuator does not work. It turns on (opening or closing the valve) only when there is a high deviation, and its rate of change has the same sign as the deviation itself (the deviation increases in magnitude). Also, the actuator turns on when the speed \(de/dt\) has the opposite sign, but is small. In accordance with the described control logic, the value of the width of the control pulse to the actuator (that moves the valve) is generated in the controller output.

Figure 2 explains the idea of control logic. It shows what the valve displacement areas look like (and the rate of the controller output change \( V_{out} \)) depending on the error \( e \) and the speed of its change \( de/dt \). Figure 2a shows the projection of the controller output signal \( V_{out} \), which determines the formed pulse width, onto the plane of the input parameters. The dependence of the formed pulse width on the error and the rate of its change for the adopted fuzzy knowledge base (in the form of the corresponding surface) is shown at Figure 2b.

Figures 2a and 2b circumscribe the area of inactivity of the actuator. In addition, at Figure 2b, it can be seen that the pulse width is variable for the fuzzy system (depending on the input signals), that improves the control accuracy.

![diagram](image-url)

**Figure 2.** The logic of the control algorithm (a) and the response surface of the fuzzy controller (b).

The base of the production rules for the fuzzy controller (to determine the speed \( V_{out} \) of control valve movement for the pulse width formation) is shown in Table 1.

| de/dt | The actuator inaction area | Fast CV opening | Slow CV opening | Slow CV closing | Fast CV closing |
|-------|---------------------------|----------------|----------------|----------------|----------------|
| \(\varepsilon\) | \(\varepsilon\)' | \(\varepsilon\)' | \(\varepsilon\) | \(\varepsilon\)', \(\varepsilon\)' | \(\varepsilon\)' |

A control system implemented on the basis of fuzzy inference usually operates according to the following principle [4, 8]. Instrumentation indications (meterage) are translated into a fuzzy form, processed, defuzzified, and then fed to the actuating device as crisp signals.
Table 1. Base of fuzzy rules for determining the speed of the control valve movement ($V_{out}$) for the pulse width formation.

| Rate of control error change $de/dt$ | Control error $e$ |
|------------------------------------|------------------|
| negative ($n_2$)                   | fast negative ($n_f$) zero ($z$) zero ($z_1$) |
| zero ($z_2$)                       | small negative ($n_s$) zero ($z$) small positive ($p_s$) |
| positive ($p_2$)                   | zero ($z$) zero ($z$) fast positive ($p_f$) |

To implement the described algorithm, the input signals $e$ and $de/dt$ are converted to the values of fuzzy linguistic variables. That is, the procedure for presenting real numbers to fuzzy numbers is performed. The obtained fuzzy variables are used in the implementation of fuzzy inference: operations are carried out on these variables, which are formulated as fuzzy rules.

To perform fuzzification, the variable ranges are divided into linguistic sets (terms), and each of the sets corresponds with the membership function $\mu(x)$ of the variable $x$ ($e$ or $de/dt$).

For three terms of the input variable $e$, the following notation is used: $n_1$ (negative), $z_1$ (allowable), $p_1$ (positive). The three terms of the input variable $de/dt$ we denoted as: $n_2$ (negative), $z_2$ (small), $p_2$ (positive).

We divide the range of the output variable $V_{out}$ into five sets: $n_f$ is negative fast, $n_s$ is negative small, $z$ is zero, $p_s$ is positive small, $p_f$ is positive fast. Based on the value of the linguistic variable $V_{out}$ (the rate of change of the controller output variable), the width of the generated pulse is determined. Variables for terms $p_s$, $n_s$ correspond to slow valve movement, and the variables for terms $p_f$, $n_f$ correspond to fast valve movement.

We used triangular membership functions for specifying the internal linguistic terms of the variables ($z$, $z_1$, $z_2$, $n_s$, $p_s$). To define the marginal terms ($n_f$, $n_1$, $n_2$) and ($p_f$, $p_1$, $p_2$), trapezoidal membership functions are used (Figure 3).

Figure 3. The implementation of fuzzy inference.

In accordance with the algorithm, the knowledge base of the fuzzy ACS includes seven fuzzy production rules:

- if $e = z_1$, then $V_{out} = z$;
- if $e = n_1$ and $de/dt = p_2$, then $V_{out} = z$;
- if $e = p_1$ and $de/dt = n_2$, then $V_{out} = z$;
- if $e = n_1$ and $de/dt = z_2$, then $V_{out} = n_1$;
- if $e = n_1$ and $de/dt = n_2$, then $V_{out} = n_f$;
- if $e = p_1$ and $de/dt = z_2$, then $V_{out} = p_1$;
- if $e = p_1$ and $de/dt = p_2$, then $V_{out} = p_f$.

To implement the production rules and to obtain a fuzzy set of the output variable, implication and aggregation operations were performed. For each knowledge base rule, the implication was performed...
using the minimum operation. The result of the inference over the entire knowledge base is found by aggregating fuzzy sets using the maximum operation. For the inverse transformation of fuzzy variables into crisp variables (defuzzification procedures), a crisp conclusion is made using the method of the center of gravity.

Thus, a set of fuzzy rules and fuzzy variables is used to implement fuzzy inference (Mamdani fuzzy inference [4] is used), that results in a crisp value of the output variable change rate \( V_{out} \) (Figure 3).

The variable \( V_{out} \) effects the value of the formed pulse width at the controller output.

4. Results of experimental studies

Figure 4 shows the simulation results of processes in control systems with the classic pulse controller and the fuzzy pulse controller (under the action of perturbation by the influx into the DT), obtained using MATLAB / Simulink / Fuzzy Logic Toolbox.

Using the designed models, the graphs of transient processes in systems based on traditional automatic control systems and fuzzy automatic control systems are obtained. Processes were considered at an initial level deviation of 100 mm; setpoint was adopted 800 mm; the required control accuracy is not worse than ± 10 mm.

Figure 4a shows the processes when both systems were pre-configured to work in the desired mode. It is seen that both systems have approximately the same time to reach the specified mode and provide the controlled variable within the desired range. However, fuzzy ACS has the advantage of significantly reducing control costs. The number of generated pulses to actuate the CV (in the case of fuzzy control) is significantly less than when using traditional ACS. More economical use of a control valve has an effect on increasing its lifetime and saving energy.

In addition, another positive feature of the fuzzy ACS is demonstrated by the graphs of Figure 4b. The operation of the controllers is shown in the mode when the inflow is disturbed by \( \Delta G = 4 \) kg/s. One can see a clear advantage of the developed fuzzy controller: there is the static error in the system with the traditional controller (due to presence of proportional feedback on valve position). Meanwhile, the fuzzy system provides the required level value. In this case, the number of generated pulses on the actuator in the case of using fuzzy control is also significantly less than when using traditional control.
Figure 4. Transients in traditional ACS and fuzzy ACS in nominal mode (a) and under disturbance by inflow into the tank (at $\Delta G = 4$ kg/s) (b).

It should be noted that in practice (using traditional ACS), the initial setting of the setpoint correction factor, depending on the control “irregularity” (Figure 1a), is made in order to compensate for it. However, when the inflow into the tank changes (uncontrolled perturbation), the control error will cause the valve to move to a new steady state corresponding to a new control irregularity. Therefore, if it is necessary to provide high control accuracy, the system has to be complicated by introducing an additional perturbation signal.

5. The discussion of the results
The proposed fuzzy ACS has advantages that are important both for developers of automation systems and for their users. These advantages allow you to:
• reduce the cost of designing ACS by reducing the complexity of the software;
• improve the efficiency of the control loops due to the functionality;
• improve the reliability of automation systems by reducing their sensitivity to disturbances, as well as reducing the wear of actuators.

It should be noted that the designed fuzzy controller is more efficient compared to both its relay prototype and fuzzy controllers made according to the traditional scheme [8-12]: with uniform membership functions throughout the whole range and forming the output signal for any ratios of control error and its rate of change, in the sense of ease of implementation and efficiency in operation.

6. Conclusion
We presented the results of development of the controller based on fuzzy inference (when forming a pulse control action), that provides the effective operation of the control loop by reducing its sensitivity to disturbance. In addition, the low-cost control logic implemented in the controller allows reducing the wear of actuators.

The proposed approach to the design of a fuzzy ACS can be used to create single control loops, as well as developing an automated process control system with a complex hierarchical structure (both at the top and at the bottom of the hierarchy) used for large technological systems.

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