Modelling of Fuzzy Control Modes for the Automated Pumping Station of the Oil and Gas Transportation System

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Abstract. An attempt has been made to explain to the scientific and technical establishment the fact that the fuzzy controllers with input/output parameters represented by the set of precise terms of automate control objects, which operative algorithm is verbally presented as a unique experience of experts in the domain, in simpler way, with higher speed, slighter error and less costs as compared with the standard fuzzy controllers.

1. Introduction

Pumps and pumping plants of collection systems, seam pressure maintenance, transportation and preconditioning of oil are important for the oil and gas sector as they provide:

- - collection and primary preconditioning of wells at the booster pumping plant (BPP), in close proximity to the automated group measuring units (AGMU);
- - preconditioning of process water on the initial water separation installation (IWSI) and its further pumping to cluster pumping plants (CPP);
- - metrological indicators of measuring units of product quantity and quality of wells at each stage;
- - transportation of commercial oil from the oil preconditioning unit (OPU) into the main pipelines by means of oil-pumping plants (OPP) located at distances up to 15 km.
- Consequently, the problem of energy saving and higher efficiency of pumping plants of collection system, seam pressure maintenance, transportation and preconditioning is topical. The solution of the problem is possible through the development and application of new automation systems for the above mentioned processes, because the analysis of traditional schemes of process control at the refining and petrochemical enterprises based on proportional-integral-differential (PID) controllers showed that the traditional PID controllers are not sufficiently effective for most of the complicated control objects owing to a number of features of the process progress [1–8].

2. Conceptual model of booster pumping station

The process diagram of the said pumping plant incorporates two asynchronous electric motors (AM), frequency converter, microprocessor controller, centrifugal pumps (main P–1 and standby P–2), pipe fittings and tank (E–3).

The programmable logic controller is the basis of BPP automation system and it performs both mathematical and logical operations which are necessary to either control the oil transport process or to perform control (PID controller) depending on the progress dynamics of the plant operation processes. However, PID controllers, which are the basis of automated electric drive systems with frequency converters, cannot provide high quality control by nonlinear technological processes which include BPP objects. Consequently, energy consumption increases and energy-saving effect is greatly reduced due to the introduction of VFD. Figure 1 shows a conceptual model of booster pumping plant.

Input variables are Q_6 is flow rate through valve 6 (figure 1) of the incoming emulsion to the tank from BPP-1s, Q_{17} is flow rate through valve 17 of the incoming emulsion to the tank from POGP-1, Q_{18} is flow rate through valve 18 of the incoming emulsion to the tank from tank VST-1, ω_{out1} is angular velocity at the outlet of the main pump, ω_{out2} is angular velocity of the output standby pump, Q_Σ is total flow rate of the oil emulsion incoming to the BPP.
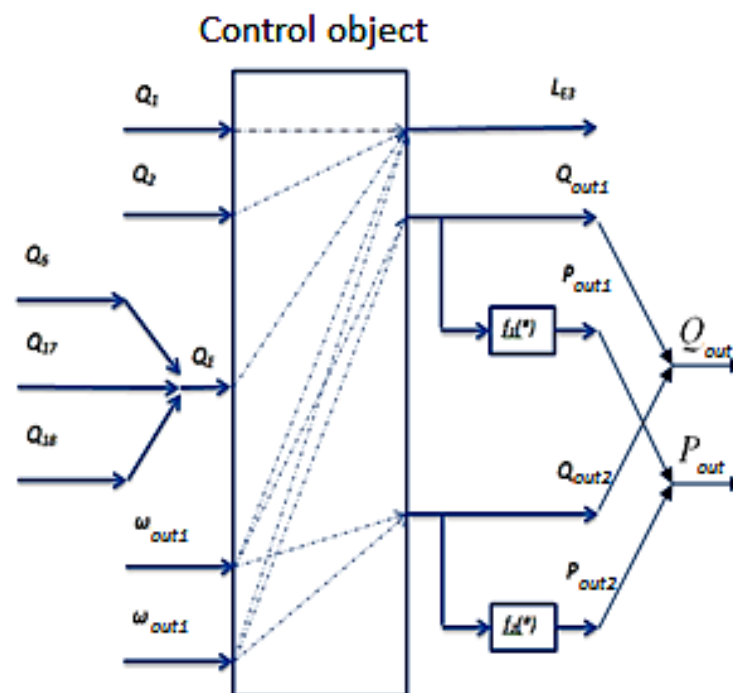

Figure 1. Conceptual model of a booster pumping station, where: Q_{out}, P_{out} – flow rate and pressure at the BPP outlet made up of individual flow rates Q_1, Q_2 and pressure values P_1, P_2 – on pumps P-1 and P-2 outlets.

BPP output variables are: the liquid level in the tank L_{E3}; Q_{out1}, P_{out1} is the flow rate and pressure respectively on the outlet of the main pump P-1; Q_{out2}, P_{out2} are the flow rate and pressure respectively on the outlet of the standby pump P-2; $f_1(*)$ and $f_2(*)$ are the conversion function P_{out1} and P_{out2} depending on Q_{out1} and Q_{out2}, Q_1, Q_2 are feedback channels, composed of separate flow rate values Q_{out1} and Q_{out2} on pump P–1 and P–2 outlets.

The dependence of the pump pressure head and flow rate on the angular velocity of the motor is described by the following nonlinear expression:

$$ H = \frac{H_F}{\omega_N^2}\omega^2 - S_F Q^2 , \tag{1} $$

where H_F is hypothetical static pressure head, m; S_F is hypothetical hydraulic pump resistance, s^2/m^5; Q is pump feed (amount of fluid pumped by the pump per unit of time), m^3/s; ω and ω_N are current and nominal rotational speed of the pump shaft, respectively. Figure 1 shows that output function L_{E3} = f (Q_6, Q_{17}, Q_{18}, Q_1, Q_2, ω_{out1}, ω_{out2}) is the function of seven arguments whereas functions P_{out1} =

$f_1(\omega_{out1}, \omega_{out2})$, $P_{out2} = f_2(\omega_{out1}, \omega_{out2})$, $Q_{out1} = f_3(\omega_{out1}, \omega_{out2})$ and $Q_{out2} = f_4(\omega_{out1}, \omega_{out2})$ are those of two arguments. Therefore, the pumping plant in question can be characterized as a multilinked nonlinear control object with the dimension equal to three.

It follows that the booster pumping plant controlled parameters are: level in the tank L_{E3}, pressure (P_{out1}, P_{out2}) and flow rate (Q_{out1}, Q_{out2}) in the output pipelines. The level in the BPP tank should be maintained at 2.5 meters (tank height is 5 m, length is 10.2 m, and capacity is 200 m^3).

3. Logical diagram of pumping station process control

The prerequisites to improve the control quality of pumping plant are the fast response of the electric motor speed and controlled valves displacement to external interferences and assurance of certain preset values of the controlled parameters (flow rate, pressure head and level).

The continuous variation of the oil supply to the pumping plant leads to oscillations in oil pressure and flow rate in the pipeline, which reduces the control quality. Consequently, PID controllers require periodic and time-taking adjustment causing the increase in operating costs of the control system. To boost the energy efficiency and control quality, it is proposed to use a multi-dimensional discrete logic controller, which input and output variables are represented by the set of terms of rectangular shape of the membership function, i.e. discrete terms [9–12].

Electric motors and valve K-33 are controlled by the signals from microprocessor controller (MPC), which receives information from the sensors: motor angular speed, position of the valve K-33 actuator (valve closing position as percentage), pressure and liquid level in the tank L_{E3}. The level in the PP tank should be maintained at 2.5 meters (tank height is 5 m, length is 10.2 m, and capacity is 200 m^3). Logical diagram of the process control algorithm is shown in figure 2. As a result, controllers w_1, w_2, and K-33 are come in action when the transition condition are true ($L_{E3}> 2.5$ m) and ($L_{E3} \gg 2.5$ m).

As can be seen from figure 3, in such a program for each control loop, along with controlling ($PRContS_{Q20}$, $PRContS_{Q21}$, $PRContS_{Q-33}$), there are also compensation ($PRCS_{Q20}$, $PRCS_{Q21}$, $PRCS_{Q-33}$) production rule systems. Thereby, the interference of multidimensional discrete logic controller loops is minimized and the control quality of liquid level in the tank is increased.
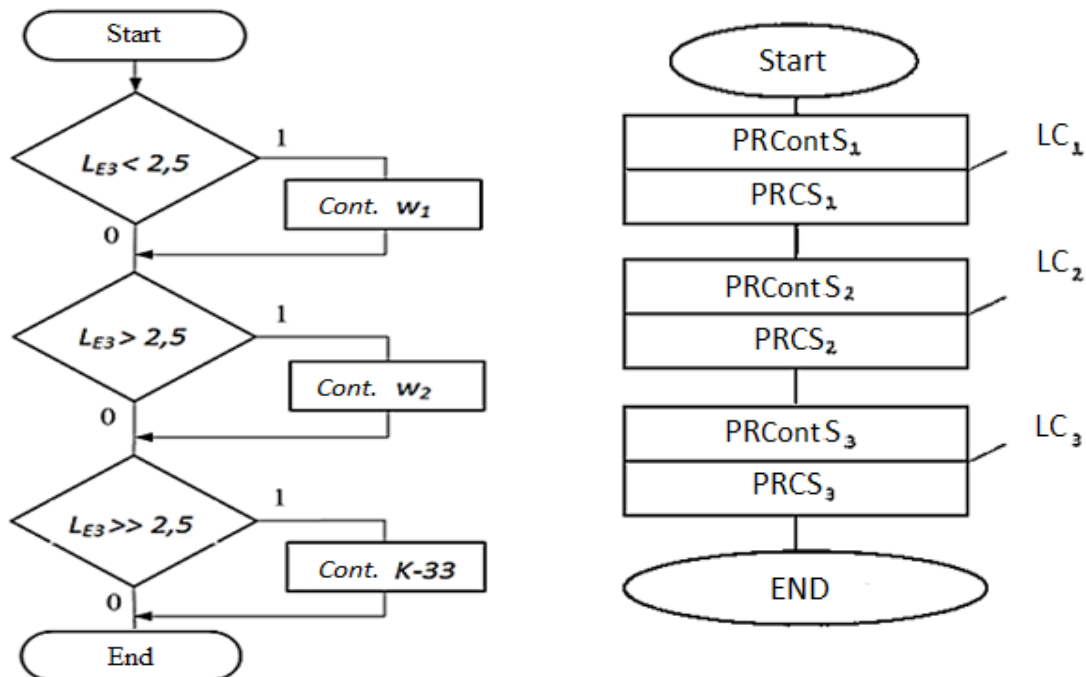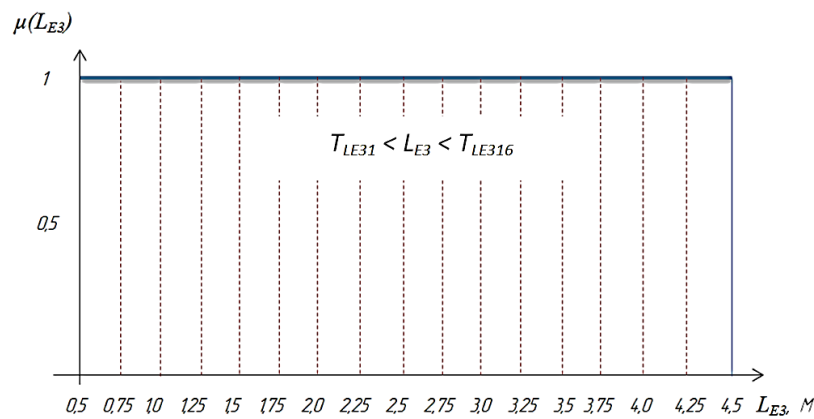
Figure 2. Logical diagram of pump station control process.

Figure 3. Logical structure of the software-based 3-dimensional discrete logic controller of the pumping station.

Figure 4 shows the interpretation of the controlled parameter L_{E3} by the set of 16 discrete terms L_{E31}, L_{E32}, …, L_{E315}, L_{E316} (e.g., $T_{LE31} < T_{LE3} < T_{LE316}$ etc.). Interpretation of the other adjustable controlled parameters Q_{out} and P_{out} is similar.

The analytical expression for the term set for L_{E3} variable is as follows:

$$T(L_{E3}) = \sum_{i=1}^{16} L_{E3} \cdot ((i-1) \cdot 0{,}25 \leq L_{E3} < i \cdot 0{,}25. \tag{2}$$

where i is the number of discrete term.

Figure 4. Location of discrete terms of the oil emulsion level in the tank along the universal numerical axis.

4. Interpretation of the compensation function by set of discrete terms

Figure 5 shows compensation function TLE3к, which analytical expression of the universal term sets corresponds to:

$$T = \sum_{i=1}^{16} T_{LE3кi} \cdot ((i-1) \cdot 6 \leq t_{TLE3к} < i \cdot 6 \tag{3}$$

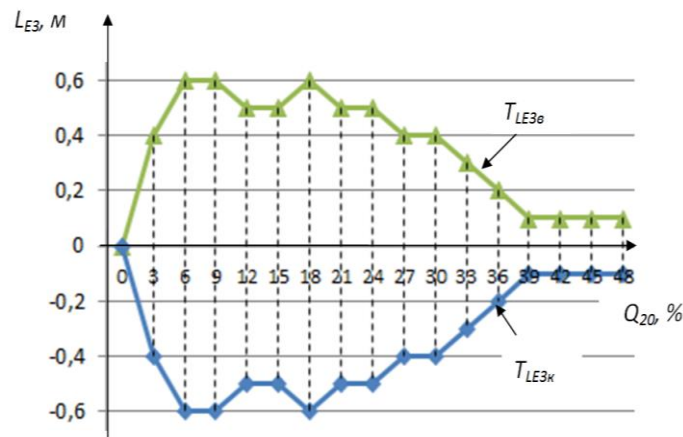Introduction of compensation functions changed the structure of the program of pumping plant MPLC.

Figure 5. Interpretation of the compensation function $T_{LE3к}$ by the set of discrete terms $T_{LE3к1} \div T_{LE3к16}$.

Replacement of the control (ω_1, ω_1, Q_{33}) and controlled (Q_{20}, Q_{21}, L_{E3}, Q_{33}, H_{out}) parameters of the pumping plant by the set of discrete terms allows us to construct a production rule system for the three-loop discrete fuzzy controller. For a loop with the controlled parameter L_{E3}, the system has the following structure:

$$\begin{cases} If \ L_{E3} = L_{E312}vL_{E313}v...vL_{E315}vL_{E316}, \ then \ Q_{20} = 0; \\ \quad If \ L_{E3} = L_{E311}, \ then \quad Q_{20} = T_{Q201}vT_{Q20k1}; \\ \qquad\qquad\qquad ... \\ \qquad\qquad\qquad ... \\ \qquad\qquad\qquad ... \\ \quad If \ L_{E3} = L_{E32}, \ then \quad Q_{20} = T_{Q2015}vT_{Q20k15}; \\ \quad If \ L_{E3} = L_{E311}, \ then \quad Q_{20} = T_{Q2016}vT_{Q20k16}. \end{cases} \qquad (4)$$

According to this expression, the parameter value L_{E3} is maintained at the level of 2.5 m with the error of $\pm$ 0.25 m, and certain discrete terms $L_{E3к1} \div L_{E3к16}$ are introduced into production rule consequents to compensate the other control loops for parameter L_{E3}. The production rule system relating to controlled parameters L_{E3}, Q_{out}, P_{out} is built using the similar structure.

5. Conclusion
In this paper, the electric pumping station control system has been proposed based on the three-dimensional fuzzy logic controller, which input and output variables are represented by the set of terms of rectangular shape of the membership function. This system enables us to stabilize the oil level at 2.5 m with the absolute error of $\pm$ 0.2 m, as well as to improve the preconditioning quality of oil emulsion at the oil preconditioning plant.

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