Fuzzy controller adaptation

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Abstract. During writing this work, the fuzzy controller with a double base of rules was studied, which was applied for the synthesis of the automated control system. A method for fuzzy controller adaptation has been developed. The adaptation allows the fuzzy controller to automatically compensate for parametric interferences that occur at the control object. Specifically, the fuzzy controller controlled the outlet steam temperature in the boiler unit BKZ-75-39 GMA. The software code was written in the programming support environment Unity Pro XL designed for fuzzy controller adaptation.

1. Introduction

In today's world it is impossible to find an area where electricity would not be used. All equipment at any enterprise particularly in mechanical engineering operates on electricity obtained from a combined heat and power plant. To produce electricity, a superheated steam produced by boilers is used, which enters turbines where mechanical energy is converted into electrical energy.

Also steam is widely used to control a steam-air hammer. Depending on the nature of the distribution of the operating periods of the energy source, the hammer can operate in several modes: successive automatic blows; single blows with an upper pause; also there is a swing cycle operating automatically.

Thus, one can conclude that for different operating modes of the hammer, steam with different temperatures and different pressures is needed. The steam used in a production process is produced by boiler units. That is why it is important to develop a control system of a boiler unit which allows one to obtain steam of desired temperature and pressure.

Fuzzy controllers generate control signals based on the application of the fuzzy logic [1]. Over the years, fuzzy controllers have been of still greater use in modern automatic control systems [2]. Fuzzy controllers can be used to control all the parameters of complex process objects. In this paper, the fuzzy controller is used to control one of the parameters of process in production of superheated steam in the boiler unit BKZ-75-39 GMA. As a parameter, which value is chosen for controlling the valve opening gap, the boiler unit outlet steam temperature is selected. Since this parameter could be influenced by parametric interferences such as change in boiler steam-generating capacity and, therefore, change in steam temperature behind the first stage of superheater as well as change in condensate temperature, it is then presumed as necessary for the fuzzy controller to be capable, unattended, to automatically compensate for the above-mentioned interferences.

In that way, the main objective in this paper is the synthesis and the fuzzy controller adaptation. The fuzzy controller adaptation is designed so that it could control automatically in a way to match parametric interferences.

The steam temperature $t_{outlet\ steam}$ is controlled by varying the injection flow rate of “internal” condensate into the steam cooler located between the first and second stages of the superheater. The condensate "injection" flow rate is varied with the 6C-13-1control valve. The 6C-13-1 valve opening gap depends on the steam temperature behind the first stage of superheater t_{sI}, on the steam temperature behind the second stage of superheater $t_{outlet\ steam}$, that is to say, on the final steam temperature and on the condensate temperature t_c respectively.

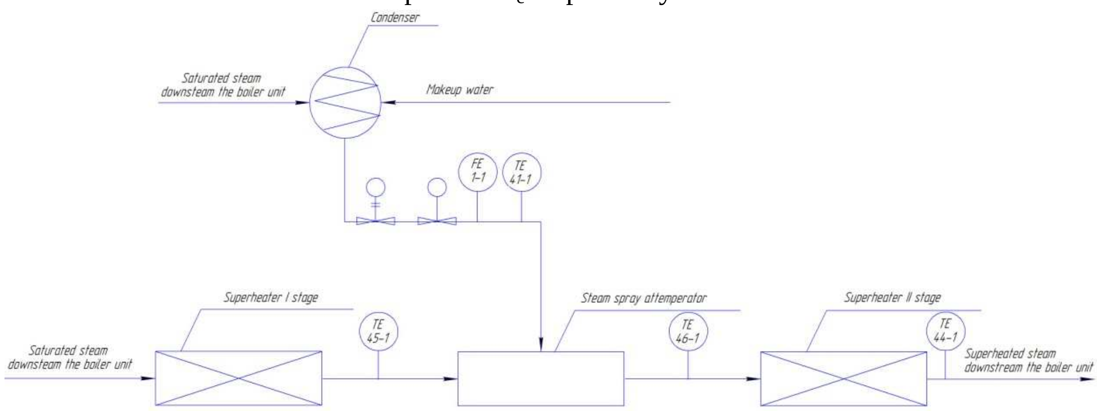

Figure 1. Process diagram

In order to adjust the fuzzy controller adaptation, one must have a clear idea of how the process works, i.e. a model should be built which could characterize the steam spray attemperator operation. The model was constructed using a regression analysis, a statistical method of research. This is the most widely used technique to show the dependence of any of parameter on one or more independent variables. Thus, it is possible to use a regression model to show the impact of three parameters: the steam temperature downstream the attemperator first stage t_{sI}, the condensate temperature t_c and the valve opening gap α(%) on the outlet steam temperature.

Let us build a regression model in MS Excel using data from Table 1 describing the outlet steam temperature variation at the steam temperature t_{sIst} =360, 380, 400°C, at the condensate temperature t_c =50, 80, 110°C, at the valve gap opening α=0...100%.

Table 1. The determination of outlet steam temperature at t_c=50°C

t_{sI},°C \ α, %	0	25	50	75	100
360	360	350	330	315	310
380	380	375	360	350	330
400	400	395	380	370	350

From the regression model, the following equation has been obtained:

$$y=3.33+1.1*x_1-0,48333*x_2-0.81556*x_3, \quad (1)$$

where X_1 – the steam temperature behind the first stage of superheater t_{sIst},

X_2 − the condensate temperature t_c;

X_3 – the valve opening gap α;

y– steam temperature behind the second stage of superheater t_{sII}.

The model has been obtained on the basis of 45 design points, which will determine the valve opening gap. This number has come out as a result of multiplying the number of the fuzzy controller input parameters in a developing model (1), i.e. 3 values of the steam temperature behind the first stage of steam cooler t_{sIst} (360, 380, 400°C), 3 values of the condensate temperature t_c (50, 80, 100°C), 5 values of the valve opening gap α (0, 25, 50, 75, 100).

The condensate temperature t_c, the steam temperature t_{sIst} and the valve opening gap 6C-13-1 are influenced by the boiler unit steam-generating capacity, which can look like 55, 60, 65, 70, 75 tons per hour. This parameter is not going to be considered in calculation as with this value considered 625 (5^4=625) production rules could be obtained. The calculation will be effected with the boiler unit steam-generating capacity of 70 tons per hour, because it is most often occurring steam-generating capacity in the boiler unit of this type. Similarly, it is possible to carry out calculations for other values of the boiler unit steam-generating capacity as well.

The fuzzy controller input will be supplied with the steam temperature t_{sIst} coming from the superheater first stage and the condensate temperature t_c. The valve opening gap α in percentage represents the fuzzy controller output variable by means of which the steam temperature is exactly controlled.

2. The fuzzy controller synthesis

The fuzzy controller conceptual model built determines which parameter values must be put together for the fuzzy controller to function properly in the process of the expert information gathering. As a result of the above process, the reference points table for the fuzzy controller was derived (Table 2). This table describes the entire scope of the fuzzy controller inputs and outputs. This table is constructed based on experimental data.

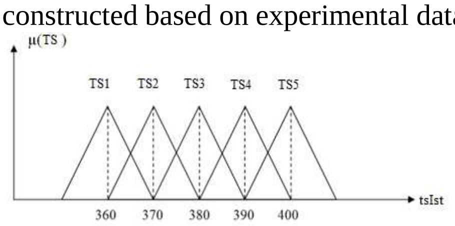

Figure 2. Input linguistic variable t_{sIst}

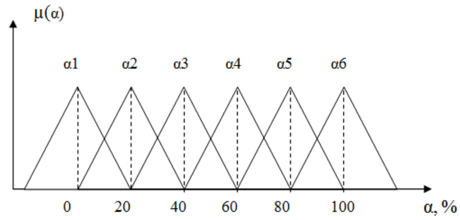

Figure 3. Output linguistic variable for the valve opening gap α

Table 2. Table of reference points

t_{vI} \ t_c	360	370	380	390	400
50	20	20	20	20	20
55	40	20	20	20	20
60	60	20	20	20	20
65	80	40	20	20	20
70	100	60	20	20	20
75	100	80	40	20	20
80	100	100	60	20	20
85	100	100	80	40	20
90	100	100	100	60	20
95	100	100	100	80	40
100	100	100	100	100	60
105	100	100	100	100	80
110	100	100	100	100	100

The next step in the fuzzy controller synthesis is the determination of linguistic variables inputs and outputs, which variables are described by the range of current values and by membership functions for each of the terms. Triangular shape terms are used to describe the input linguistic variables, the vertex of which is located at the reference point, the base is located between the two nearest reference points [2]. Terms applied are triangular shape because they help to obtain smooth static characteristics.

Furthermore, the production rule synthesis must be carried out by means of creating a table of desired values for the fuzzy controller output variable, that is the valve opening gap α, for each value of the steam temperature t_{sIst} and condensate temperature t_C term.

Production rules were constructed from Table 3 (Table 4). 65 production rules were obtained. This number has come out as a result of multiplying the number of the fuzzy controller terms input variables (5*13=65), i.e. 5 values of the steam temperature behind the first stage of steam cooler t_{sIst} (360, 370, 380, 390, 400°C), 13 values of the condensation temperature t_c (50, 55, 60, 65, 70, 75 80, 85, 90, 95, 100, 105, 110°C). These rules determine which of consequents are basic or additional, the truth degree is determined for additional consequent. Both the technique of determining consequents and their truth degrees are described in [3].

Table 3. The desired values of the valve opening gap α

№	$t_{пI}$	$t_к$	α	№	$t_{пI}$	$t_к$	α
1	T_{s1}	T_{c1}	23	10	T_{s1}	T_{c10}	94
2	T_{s1}	T_{c2}	36	11	T_{s1}	T_{c11}	93
3	T_{s1}	T_{c3}	58	12	T_{s1}	T_{c12}	91
4	T_{s1}	T_{c4}	82	13	T_{s1}	T_{c13}	92
5	T_{s1}	T_{c5}	98	14	T_{s2}	T_{c1}	22
6	T_{s1}	T_{c6}	93	15	T_{s2}	T_{c2}	21
7	T_{s1}	T_{c7}	96	…	…	…	…
8	T_{s1}	T_{c8}	99	64	T_{s5}	T_{c12}	77
9	T_{s1}	T_{c9}	97	65	T_{s5}	T_{c13}	97

Table 4. The production rules

№ of rules	Production rules
1	*If* $t_v= T_{v1}$ *and* $t_c=Tc_1$ *then* $\alpha= \alpha_2$ *and* $\alpha= \alpha_3^{0,12}$
2	*If* $t_v= T_{v1}$ *and* $t_c=Tc_2$ *then* $\alpha= \alpha_2^{0,17}$ *and* $\alpha= \alpha_3$
…	…
65	*If* $t_v= T_{v5}$ *and* $t_k=Tc_{13}$ *then* $\alpha= \alpha_5^{0,12}$ *and* $\alpha= \alpha_6$

Let us consider the first rule: *If* $t_v= t_{V1}$ and $tc=t_{c1}$, then $\alpha=\alpha_2$ and $\alpha=\alpha_3^{0,12}$. As can be seen from this rule consequent ($\alpha=\alpha_2$ and $\alpha=\alpha_3^{0,12}$), for α_2 the degree is equal to 1, whereas for α_3 it is equal to 0.12. This means that α_2 is the basic consequent and α_3 is the additional one.

So after looking into each of rules separately, the matrix (2) is derived, compiled by the truth degrees of the basic and additional consequential. The column number of the matrix indicates the number of the rule; the line number is the number of the valve opening gap term α.

$$\left(\begin{array}{ccccccccccccccccccccccc}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.03 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0.17 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0.08 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.12 & 1 & 0.08 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.08 & 0.003 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0.08 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0.08 & 0.37 & 0.17 & 0.003 & 0.12 & 0.29 & 0.22 & 0.6 & 0.47 & 0 & 0 & 0 & 0 & 0.12 & 1 & 0.17 & 0.6 & 0.37 & 0.47 \\
0 & 0 & 0 & 0.08 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1
\end{array}\right.$$

$$\begin{array}{cccccccccccccccccccccc}
0 & 0 & 0 & 0 & 0.08 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.03 & 0 \\
0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0.08 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \\
0 & 0 & 0 & 0.17 & 0 & 0.29 & 0.37 & 0.08 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.003 & 0.12 & 0.17 & 0.29 & 0 & 0.08 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.03 & 0.29 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.29 & 0.17 & 0.003 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0.29 & 0.37 & 0.08 & 0.6 & 0.003 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0
\end{array}$$

$$\left.\begin{array}{cccccccccccccccccccc}
0.17 & 0 & 0 & 0 & 0 & 0 & 0 & 0.08 & 0.17 & 0 & 0 & 0.03 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.003 & 0.12 & 0 & 0.08 & 0.17 & 0.29 & 0.22 & 1 & 0 & 0 & 0 \\
0 & 0.17 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.12 & 1 & 0.12 & 0 \\
0 & 0 & 0.17 & 1 & 0.22 & 0.37 & 0.08 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.08 & 1 & 0.12 \\
0 & 0 & 0 & 0.22 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{array}\right) \tag{2}$$

3. The fuzzy controller adaptation

Adaptation will be produced for the developed fuzzy controller by means of a training algorithm.

As a training algorithm the gradient descent algorithm is selected, in which as an initial point for algorithm, the Mamdani fuzzy controller can be used.

If one denotes he "left" of the terms which are used in the production rule consequents as the integer N t, then the "right" term will have a number (N+1) [5]. The left term is a term with a lower number, that is, that in Figure 3 to the left with respect to the other term of a production rule. Therefore, the right term is a term with a larger number being located with respect to another term of the rule on the right side.

Let us introduce the designation:

$$W = N + v, \tag{3}$$

where W – the production rule characteristic, which are obtained from the truth degree values of the basic and additional consequents, i.e. on the basis of this characteristics one can return to the production rule;

N – the left term number;

v – number as determined by the formula:

$$v = \frac{C + r}{2}, \tag{4}$$

where r = 1, if the consequent "right" term is used, and r = 0 if the "left" term is applied;

C – the additional consequent truth degree.

Let us consider the determination of the production rule characteristics using the first rule: *If* $t_v = t_{V1}$ *and* $tc = t_{c1}$ *then* $\alpha = \alpha_2$ *and* $\alpha = \alpha_3^{0.12}$.

The left term number is 2. The additional consequent truth degree 0.12, r=0, because it is the left term which is basic. Therefore, one gets the production rule characteristics: $W_1 = 2 + \frac{0.12+0}{2} = 2.06$.

Using the formula (3), let us now get the characteristics of rest production rules from Table 4: $W_2 = 2 + \frac{0.17+1}{2} = 2.585$; …; $W_{65} = 5 + \frac{0.12+0}{2} = 5.06$.

In the process of the fuzzy controller synthesis both the basic and additional consequents as well as the additional consequents truth degrees were determined [2, 3]. During determination of the true degree of an additional consequent, the reference points were taken as the base (Table 4) which represent the maxmums of the input linguistic variables terms (Figures 2, 3) [2, 3]. It is to be understood that in practice, the input parameters can take different values, therefore, the fuzzy controller adaptation must be carried out to allow the controller to be automatically adjusted to match parametric interferences. On the basis of experimental data, the model (1) has been developed which characterizes the steam spray attemperator operation. Using the developed model, a synthesis of the fuzzy controller was conducted, the production rules were obtained with their characteristic calculated on the basis of which the fuzzy controller will be adapted. During adaptation, arbitrary values of the steam temperature behind the first stage of superheater t_{sIst} in the range from 360° to 400°C and the condensate temperature t_c from 50° to 110°C will be used. The outlet steam temperature t_{out} may be preset in the range from 270° to 400°C.

Arbitrary values of the steam temperature, condensate temperature t_{sI} and desired outlet steam temperature t_{sII} are entered into the model (1); the controller in its turn autimatically adjusts to match variations and produces the current valve for the valve opening gap α (Table 5).

Table 5. Values calculated by means of the model

№	t_{vI}	t_c	t_{sII}	α
1	363	54	362	18
2	365	56	345	40
3	368	58	310	86
4	372	63	327	68
…	...	...	...	…
45	399	109	340	68

Let us introduce the designation:

$$W^* = W - \Delta W \cdot \mu(C_p) \cdot \mu(C_k), \tag{5}$$

where W* – new production rules characteristics as derived from table 5;

W – production rules characteristics from table 4;

$\mu(C_p) \cdot \mu(C_k)$ – the input variables degree membership, where C_p is the membership degree of the steam temperature behind the first stage of superheater t_{sIst}, C_k is the membership degree of the condensate temperature, i.e. Cp must be multiplied by C_k;

ΔW – adaptation step, which is determined by an expert to specify the controller precision.

To create both new production rules and their characteristics, by selecting in turn the lines from Table 5, it is necessary to determine among which terms lie the steam temperature downstream the superheater first stage t_{sIst} and the condensate temperature t_c. Further, from the previously obtained rules (Table 4) one can find the rules, in which terms of the steam temperature t_{sI} and of the

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condensate temperature t_c coincide with those from Table 5. Let us change over to the next production rule using the characteristics of the selected rule and using the formula (3), where W is substituted by W*.

Thus, in obtaining the production rule characteristics, let us change over to a next rule. New rules are needed to create the fuzzy controller adaptation.

The process of obtaining a new rule:

1. By selecting the 1st line from table 5, one can determine that the steam temperature behind the first stage of superheater t_{sIst} lies between the TS1 and TS2 terms (Figure 2). The condensate temperature of t_c also lies between the TC1 and TC2 terms. Further, let us find a rule from Table 4, where the temperatures occur lying among the same terms numbers. The first production rule from Table 4 is now to be selected.

2. At first, one has to determine a new production rule characteristics $W_1^*=2.06 - 0.15 \cdot 0.7 \cdot 0.1 = 2.0495$.

3. Using the formula (6), one now may calculate it to change over to a new production rule: If $t_v = T_{v1}$ and $t_c = T_{c1}$ then $\alpha = \alpha_2$ and $\alpha = \alpha_3^{0.099}$. Similarly, the remaining 44 production rules (Table 6) are calculated.

Table 6. New production rules and their characteristics

№	New production rules characteristics W*	New production rules
1	2.0495	*If* $t_s = T_{s1}$ *and* $t_c = Tc_1$ *then* $\alpha = \alpha_2$ *and* $\alpha = \alpha_3^{0.09}$
2	2.5175	*If* $t_s = T_{s1}$ *and* $t_c = Tc_2$ *then* $\alpha = \alpha_2^{0.03}$ *and* $\alpha = \alpha_3$
3	3.042	*If* $t_s = T_{s1}$ *and* $t_c = Tc_3$ *then* $\alpha = \alpha_3$ *and* $\alpha = \alpha_4^{0.08}$
…	…	…
6	5.0585	*If* $t_s = T_{s5}$ *and* $t_c = Tc_{13}$ *then* $\alpha = \alpha_5$ *and* $\alpha = \alpha_6^{0.11}$

The program to control the outlet steam temperature t_{sII}, as well as that for the fuzzy controller adaptation, is developed in the software Unity Pro XL using ST language based on PLC Modicon M340. The parameter controlled is the outlet steam temperature of the downstream of the steam spray attemperator.

4. Conclusion

Thus, this paper deals with the fuzzy controller synthesis designed to control the outlet steam temperature t_{sII} in the boiler unit. Besides, the fuzzy controller adaptation has been effected based on the method of selection of such consequent in production rules with a double consequent which is optimal for the current values of the boiler unit parameters.

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