USING THE FUZZY CONTROLLER TO CONTROL PROCESS PARAMETERS

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Abstract: *In the course of writing this article, the goal was to develop the algorithm for setting up an adaptive fuzzy controller with a double rule base. To achieve this goal, a fuzzy controller designed to control the temperature of the steam leaving the boiler. As the boiler was considered the model of boiler BKZ-75-39GMA. In the course of writing, the fuzzy controller was synthesized and adapted. On the basis of the work done, the algorithm for adaption the fuzzy controller was determined.*

1. Introduction

Fuzzy controllers generate control signals based on the application of the fuzzy logic [1-6]. 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, whose value is chosen for controlling of the valve opening gap, the boiler unit outlet steam temperature is selected. Since this parameter could be influenced by parametric interferences such as steam-generating capacity variation of the boiler unit hence steam temperature variation downstream the superheater first stage as well as the condensate temperature variation, it is then presumed as necessary for the fuzzy controller to be capable, unattended, to automatically compensate for the above 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.

2. The fuzzy control adaptation

The steam temperature toutlet steam is controlled by varying the injection flow rate of steam spray attemperator the internal condensate located between the first and second stages of the superheater.

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.

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 downstream the first superheater stage t_{sIst},

X_2 − the condensate temperature t_c;

X_3 – the valve opening gap α;

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

The model has been obtained on the basis of 45 design points, which will determine the valve opening gap.

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.

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. This table describes the entire scope of the fuzzy controller inputs and outputs. This table is constructed based on experimental data.

Table 1. *Table of reference points*

Input		Output
t_{sIst}	t_C	α
360	50	20
360	55	40
360	60	60
360	65	80
360	70	100
370	60	20
370	65	40
370	70	60
370	75	80
370	80	100
380	70	20
380	75	40
380	80	60
380	85	80
380	90	100
390	80	20
390	85	40
390	90	60
390	95	80
390	100	100
400	90	20
400	95	40
400	100	60
400	105	80

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. A 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 [6]. Terms applied are triangular shape because they help to obtain smooth static characteristics.

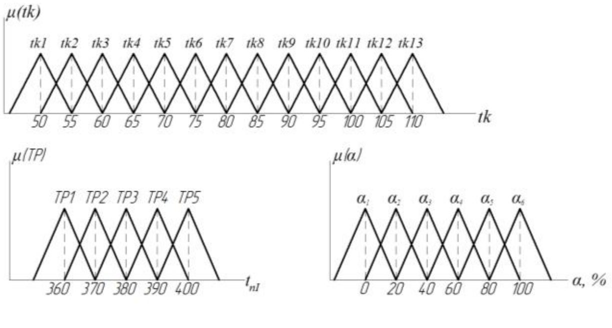

Fig 1. Linguistic variables inputs and outputs

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

Table 2. *The desired values of the valve opening gap α*

№	t_{sIst}	t_C	α
	TP_1	tk_1	23
	TP_1	tk_2	36
	TP_1	tk_3	58
	TP_1	tk_4	82
	TP_1	tk_5	98
	TP_1	tk_6	93
	TP_1	tk_7	96
	TP_1	tk_8	99
	TP_1	tk_9	97
	TP_1	tk_{10}	94
	TP_1	tk_{11}	93
	TP_1	tk_{12}	91
	TP_1	tk_{13}	92
	TP_2	tk_1	22
	TP_2	tk_2	21
….	…	…	…
64	TP_5	tk_{12}	77
65	TP_5	tk_{13}	97

Production rules were constructed from table 2 (table 3). 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 downstream the attemperator first stage f t_{sIst} (360, 370, 380, 390, 400°C), 13 value 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 [1].

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

№ 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* $\alpha= \alpha_6$

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 of this rule consequent (then $\alpha=\alpha_2$ 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 isolatedly, the matrix (1) is derived, compiled by the truth degrees of 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 term the valve opening gap α.

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 we denote as the integer N the "left" of the terms which are used in the production rule consequents, then the "right" term will have a number (N+1) [6]. The left term is a term with a lower number, that is, that in figure 1 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's introduce the designation:

$$W = N + v, \qquad (2)$$

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:

$$v=\frac{C+r}{2}, \qquad (3)$$

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.

Consider the determination of the production rule characteristics using the first rule: If tv= tV1 and tc=tc1 then α=α2 and $\alpha=\alpha_3^{0.12}$.

The left term number is 2. The additional consequent truth degree 0.12, r=0, because it's the left term which is basic. Therefore, we get the production rule characteristics: W_1= 2.06.

Using the formula (2) we now get the characteristics of rest production rules from table 3: W_2=2.585; …; W_{65}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]. In determining the additional consequents truth degree the reference point were take as basic (table 1) which represent the maxmums of the input linguistic variables terms (figures 1) [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. The model as developed is conducive to the fuzzy controller synthesis, 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 downstream the superheater first stage t_{sIst} in the range from 360° to 400°C, the condensate temperature t_c from 50° to 110°C, will be used the outlet steam temperature 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 4).

Table 4. *Values calculated by means of the model*

t_{sIst}	t_C	t_{sII}	α
363	54	362	18
365	56	345	40
368	58	310	86
372	63	327	68
378	59	315	93
376	82	340	46
374	84	270	128
376	92	334	47

371	83	352	24
373	104	300	78
372	102	325	47
377	98	350	25
374	106	322	51
379	108	306	76
373	87	290	100
382	52	343	68
384	59	376	26
387	63	356	52
383	57	335	76
386	67	313	101
392	78	324	89
389	84	370	25
393	88	352	50
394	92	331	75
397	102	309	100
388	108	359	23
396	104	368	25
387	104	337	51
398	107	328	75
392	98	358	36
392	53	369	49
398	61	394	22
391	72	357	51
393	56	347	75
394	78	317	101
396	82	321	96
398	94	375	25
392	87	351	51
397	98	331	76
391	107	364	22
396	108	366	25
394	102	340	58
392	99	325	76
399	109	368	26

Let's introduce the designation:

$$W^* = W - \Delta W \cdot \mu(C_p) \cdot \mu(C_k), \qquad (4)$$

where W* – new production rules characteristics as derived from table 7;

W – production rules characteristics from table 3;

$\mu(C_p) \cdot \mu(C_k)$ – the input variables degree membership, where Cp is the membership degree of the steam temperature downstream the superheater first stage 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 the table 4, 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 3) we find the rules, in which terms of the steam temperature t_{sI} and of the condensate temperature t_c coincide with those from table 4. We change over to the next production rule using the characteristics of the selected rule and using the formula (2), where W is substituted by W*.

Thus, in obtaining the production rule characteristics, we 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 4, we determine that the steam temperature downstream the superheater first stage t_{sIst} lies between the TS1 and TS2 terms (figure 1), the condensate temperature of t_c too lies between the TC1 and TC2 terms (figure 1). Further on we find a rule from table 3, where the temperatures occur lying among the same terms numbers. The first production rule from table 3 is now to be selected.

2. At first, we have to determine a new production rule characteristics W_1*=2.06 – 0.15·0.7·0.1=2.0495.

3. Using the formula (6) we now may calculate it to change over to a new production rule: If t_v= T_{v1} and t_c=T_{c1} then α= α_2 and α= $\alpha_3^{0.099}$. Similarly, the remaining 44 production rules (table 5) are calculated.

Table 5. *New production rules and their characteristics W**

№	W*	New production rules
1	1,0495	*If t_n= T_{n1} and t_k=$T\kappa_1$ then α= α_1 and α= $\alpha_2^{0,099}$*
2	2,5175	*If t_n= T_{n1} and t_k=$T\kappa_2$ then α= $\alpha_2^{0,035}$ and α= α_3*
3	3,042	*If t_n= T_{n1} and t_k=$T\kappa_3$ then α= α_3 and α= $\alpha_4^{0,084}$*
4	4,992	*If t_n= T_{n2} and t_k=$T\kappa_3$ then α= $\alpha_4^{0,984}$ and α= α_5*
5	5,013	*If t_n= T_{n2} and t_k=$T\kappa_3$ then α= α_5 and α= $\alpha_6^{0,026}$*
6	5,561	*If t_n= T_{n2} and t_k=$T\kappa_7$ then α= $\alpha_5^{0,122}$ and α= α_6*
7	4,488	*If t_n= T_{n2} and t_k=$T\kappa_7$ then α= α_4 and α= $\alpha_5^{0,976}$*
8	5,591	*If t_n= T_{n3} and t_k=$T\kappa_9$ then α= $\alpha_5^{0,182}$ and α= α_6*
9	4,639	*If t_n= T_{n3} and t_k=$T\kappa_8$ then α= $\alpha_4^{0,278}$ and α= α_5*
10	4,6315	*If t_n= T_{n3} and t_k=$T\kappa_8$ then α= $\alpha_4^{0,263}$ and α= α_5*
11	5,573	*If t_n= T_{n3} and t_k=$T\kappa_9$ then α= $\alpha_5^{0,146}$ and α= α_6*
12	5,627	*If t_n= T_{n3} and t_k=$T\kappa_9$ then α= $\alpha_5^{0,254}$ and α= α_6*
13	2,004	*If t_n= T_{n3} and t_k=$T\kappa_5$ then α= α_2 and α= $\alpha_3^{0,008}$*
14	1,973	*If t_n= T_{n3} and t_k=$T\kappa_6$ then α= $\alpha_1^{0,946}$ and α= α_2*
15	4,627	*If t_n= T_{n3} and t_k=$T\kappa_8$ then α= $\alpha_4^{0,254}$ and α= α_5*
16	1,944	*If t_n= T_{n3} and t_k=$T\kappa_5$ then α= $\alpha_1^{0,888}$ and α= α_2*
17	1,504	*If t_n= T_{n4} and t_k=$T\kappa_7$ then α= $\alpha_1^{0,008}$ and α= α_2*
18	2,045	*If t_n= T_{n3} and t_k=$T\kappa_6$ then α= α_2 and*

		$\alpha = \alpha_3^{0,09}$
19	4,636	*If* $t_n = T_{n3}$ *and* $t_k = T\kappa_8$ *then* $\alpha = \alpha_4^{0,272}$ *and* $\alpha = \alpha_5$
20	3,049	*If* $t_n = T_{n4}$ *and* $t_k = T\kappa_8$ *then* $\alpha = \alpha_3$ *and* $\alpha = \alpha_4^{0,098}$
21	1,513	*If* $t_n = T_{n4}$ *and* $t_k = T\kappa_7$ *then* $\alpha = \alpha_1^{0,026}$ *and* $\alpha = \alpha_2$
22	3,004	*If* $t_n = T_{n4}$ *and* $t_k = T\kappa_8$ *then* $\alpha = \alpha_3$ *and* $\alpha = \alpha_4^{0,008}$
23	4,022;	*If* $t_n = T_{n4}$ *and* $t_k = T\kappa_9$ *then* $\alpha = \alpha_4^{0,044}$ *and* $\alpha = \alpha_5$
24	2,074	*If* $t_n = T_{n5}$ *and* $t_k = T\kappa_9$ *then* $\alpha = \alpha_2$ *and* $\alpha = \alpha_3^{0,148}$
25	5,583	*If* $t_n = T_{n4}$ *and* $t_k = T\kappa_{11}$ *then* $\alpha = \alpha_5^{0,166}$ *and* $\alpha = \alpha_6$
26	5,562	*If* $t_n = T_{n4}$ *and* $t_k = T\kappa_{11}$ *then* $\alpha = \alpha_5^{0,124}$ *and* $\alpha = \alpha_6$
27	4,022	*If* $t_n = T_{n5}$ *and* $t_k = T\kappa_{11}$ *then* $\alpha = \alpha_4$ *and* $\alpha = \alpha_5^{0,044}$
28	5,589	*If* $t_n = T_{n4}$ *and* $t_k = T\kappa_{11}$ *then* $\alpha = \alpha_5^{0,178}$ *and* $\alpha = \alpha_6$
29	4,488	*If* $t_n = T_{n5}$ *and* $t_k = T\kappa_{12}$ *then* $\alpha = \alpha_4$ *and* $\alpha = \alpha_5^{0,976}$
30	5,062	*If* $t_n = T_{n4}$ *and* $t_k = T\kappa_{10}$ *then* $\alpha = \alpha_5$ *and* $\alpha = \alpha_6^{0,124}$
31	1,561	*If* $t_n = T_{n4}$ *and* $t_k = T\kappa_7$ *then* $\alpha = \alpha_1^{0,122}$ *and* $\alpha = \alpha_2$
32	1,567	*If* $t_n = T_{n4}$ *and* $t_k = T\kappa_7$ *then* $\alpha = \alpha_1^{0,134}$ *and* $\alpha = \alpha_2$
33	2,977	*If* $t_n = T_{n4}$ *and* $t_k = T\kappa_8$ *then* $\alpha = \alpha_2^{0,954}$ *and* $\alpha = \alpha_3$
34	2,074	*If* $t_n = T_{n5}$ *and* $t_k = T\kappa_9$ *then* $\alpha = \alpha_2$ *and* $\alpha = \alpha_3^{0,148}$
35	3,03	*If* $t_n = T_{n5}$ *and* $t_k = T\kappa_{10}$ *then* $\alpha = \alpha_3$ *and* $\alpha = \alpha_4^{0,06}$
36	3,061	*If* $t_n = T_{n4}$ *and* $t_k = T\kappa_8$ *then* $\alpha = \alpha_3$ *and* $\alpha = \alpha_4^{0,122}$
37	2,964	*If* $t_n = T_{n5}$ *and* $t_k = T\kappa_{10}$ *then* $\alpha = \alpha_2^{0,928}$ *and* $\alpha = \alpha_3$
38	2,098	*If* $t_n = T_{n5}$ *and* $t_k = T\kappa_9$ *then* $\alpha = \alpha_2$ *and* $\alpha = \alpha_3^{0,196}$
39	3,977	*If* $t_n = T_{n5}$ *and* $t_k = T\kappa_{11}$ *then* $\alpha = \alpha_3^{0,954}$ *and* $\alpha = \alpha_4$
40	4,533	*If* $t_n = T_{n5}$ *and* $t_k = T\kappa_{12}$ *then* $\alpha = \alpha_4^{0,066}$ *and* $\alpha = \alpha_5$
41	4,548	*If* $t_n = T_{n5}$ *and* $t_k = T\kappa_{12}$ *then* $\alpha = \alpha_4^{0,096}$ *and* $\alpha = \alpha_5$
42	5,506	*If* $t_n = T_{n5}$ *and* $t_k = T\kappa_{13}$ *then* $\alpha = \alpha_5^{0,012}$ *and* $\alpha = \alpha_6$
43	4,524	*If* $t_n = T_{n5}$ *and* $t_k = T\kappa_{12}$ *then* $\alpha = \alpha_4^{0,048}$ *and* $\alpha = \alpha_5$
44	4,016	*If* $t_n = T_{n5}$ *and* $t_k = T\kappa_{11}$ *then* $\alpha = \alpha_4$ *and* $\alpha = \alpha_5^{0,032}$
45	5,548	*If* $t_n = T_{n5}$ *and* $t_k = T\kappa_{13}$ *then* $\alpha = \alpha_5^{0,096}$ *and* $\alpha = \alpha_6$

The program to control the outlet steam temperature tsII and as well as for the fuzzy controller adaptation is developed in the software Unity Pro XL using ST language based on PLC Modicon M340.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 that consequent in production rules with a double consequent, which is optimal for the current values of the boiler unit parameters.

3. Conclusion

Algorithm of adaptation fuzzy controller is developed, which includes the following steps:

1. The definition of a conceptual model of a fuzzy controller.

2. Development of a model that characterizes the flow of the process.

3. Synthesis of fuzzy controller. Synthesis includes: collection of expert information, construction of the table of reference points, definition of linguistic variables, construction of the table of desirable values, synthesis of the received production rules.

4. The fuzzy controller adaptation: obtaining characteristics obtained at the stage of synthesis of production rules, the use of a model characterizing the flow of the process to obtain new characteristics and new production rules.

5. Develop program code that implements the adaptation of a fuzzy controller.

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