Improvement of Heating System Performance Using Fuzzy Logic

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Abstract – **This paper deals with the possibilities of applying fuzzy controllers in heating systems. The heating plant «Krivi vir» in Niš, is considered as an example. The study involves the possibility of applying fuzzy approach both on higher and lower hierarchy level, as whole plant controller with load management optimization function, and on a boiler load controller, respectively.**

Keywords - **fuzzy controller, boiler, thermal load**

I. Introduction

Complex, nonlinear, multivariable and partially known systems with many disturbing influences, encountered for example in the chemical process industry, biotechnological processes or climate control objects, present great challenges for control engineering. Fuzzy logic controllers have emerged as very useful for control of processes that are complex and ill-defined. The main advantage of fuzzy logic techniques is the ability of control system design without precise mathematical model. Namely, the design approach is based on real or simulation trial and error experiments. It is very important when the mathematical modelling is difficult, or the model-based calculation is not possible in real time.

Numerous examples of fuzzy logic application in heating systems can be found in the literature (the control of drives like valves, pumps and fans, both on/off and frequency regulation, boiler and entire combustion process control, for example) [1]. Very interesting are the efficient studies about fuzzy logic application at miscellaneous climate state variables combining in order to find an optimal working regime of the heating plant [2], [3]. Moreover, in the special fuzzy-neuro control systems, the mutual influences of some variables are treated by fuzzy logic, and previously experience is incorporated by neuro techniques [4]. Our consideration related to the application of fuzzy logic in heating plant “Krivi vir” was inspired by these studies.

Some structures of fuzzy controllers, which are efficiently applied in simulation model, are presented in this paper. The study results are presented as follows. Section II presents a short technology description and some requirements, which must be fulfil during the work with masut. The structure of the fuzzy controller, that assigns the function of boilers during the thermal load management, is completely presented in section III. Section IV is devoted to the fuzzy controller structures for particular boiler load control and some simulation results. The general goals for the further development of heating control system, and odds of fuzzy logic application by that realization are presented, as a conclusion, in section V.

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II. Technology Description

The following requirements must be fulfil to ensure the necessary temperature of supply water and to achieve the maximal efficiency degree of the heating plant.

The necessary supply water temperature is determinate by heating plant-working diagram, which refers to environment temperature. The base for the work of the heating plant is temperature regime of 135/75 ^{o}C and the maximal possible load of boilers (boiler 1 – 35 MW, boiler 2 – 35 MW and boiler 3 – 58 MW).

By working with masut, boilers must be activated according to the most optimal sequence. The requirement is the activation of minimal boiler numbers that work with as large as possible load. The sequence means that there is a concept of leader and following boilers. After achievement of max load with the leader boiler, the next (first following) boiler will be activated and it will supplement the work of former boiler. Notice that the former boiler works at a full load, but the next one has only supplementing task. The same principle is applied on the relation first following - second following boiler.

The selection which boiler will be activated is guided by the criterion of correct function of boilers.

Also, by working with masut, the request is that a boiler unit stays as long as possible, as a substitute, inactivated (it is one criterion for boiler including, after the priorities work diagram and boilers’ correct functions).

III. Load Management Optimization

Based on the simulation model and the equations obtained from mechanical project [7], the following recapitulation can be made: 1. The 35 MW boiler covers from +15°C up to +10°C; 2. The 58 MW boiler covers from +15°C up to 4°C; 3. Two 35 MW boilers cover from +10°C up to +1°C (leading boiler is of 35 MW); 4. The boilers of 35 MW and 58 MW cover from +10°C up to -6°C (leading boiler 35 MW); 5. The boilers of 58 MW and 35 MW cover from +3°C up to -6°C (leading boiler 58 MW); 6. Two boilers of 35 MW and the boiler of 58 MW cover from 0°C up to -15°C (leading boilers 2x35 MW); 7. The boilers of 35 MW, 58 MW and 35 MW cover from -5°C to -15°C (leading boilers 35 and 58 MW).

The question is which combination should be select as optimal one in order to fulfil all mentioned requirements given in section II.

The fuzzy controller, which is successfully used for load management and boilers function assignment tasks, is the Takagi-Sugeno type zero-order controller [5], with characteristics:

The controller has 7 inputs: 1. required thermal load of whole heating plant, 2. boiler 1 serviceability, 3. boiler 2 serviceability, 4. boiler 3 serviceability, 5. boiler 1 previous work, 6. boiler 2 previous work and 7. boiler 3 previous work. Based on working diagram equations, the required thermal load of complete heating plant, range [0 MW – 128 MW], is determined by outside temperature, range [$+15^0$C ÷ -15^0C].

Five membership functions, as shown in Fig. 1, are assigned to the first controller input, which is the required load of complete heating plant. The operational range is [0, 128] MW. Appropriate membership functions are chosen according to maximal boilers load: 1. 0–35 (trapezoidal type), 2. 35–58 (triangular type), 3. 58–70 (triangular type), 4. 70–93 (triangular type) and 5. 93–128 (trapezoidal type).

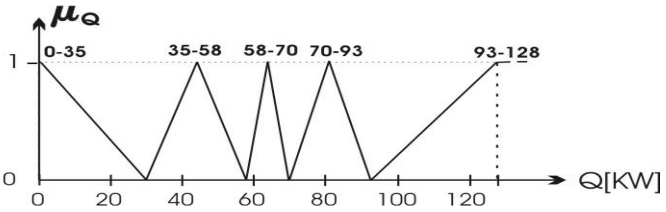


Fig. 1: Membership functions for input 1

The inputs 2-7 can be defined by operator or generated in working process. They are especially important for load ranges, which can be covered by several combinations of boilers working. The operational range is [0, 1]. The same membership functions are assigned to all inputs 2-7: 1. NO (trapezoidal type) and 2. YES (trapezoidal type), Fig 2.

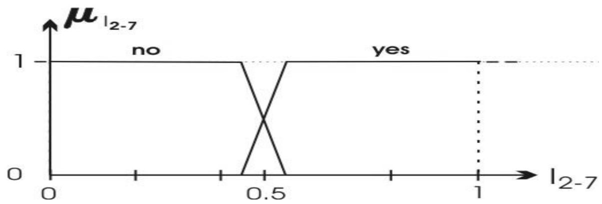


Fig. 2: Membership functions for inputs 2-7

The controller has 3 outputs that are function of load management for boiler 1, boiler 2 and boiler 3, respectively.

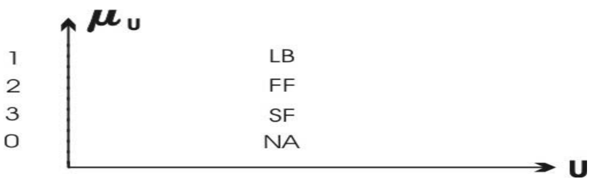


Fig. 3: Membeship functions for outputs 1-3

The same membership functions, singleton type, are assigned to all outputs 1-3, Fig. 3: 1. NA – a boiler will not be activated (constant 0), 2. SF – a boiler will be activated as second following (constant 3) 3. FF – a boiler will be activated as first following (constant 2) and 4. LB – a boiler will be activated as leader (constant 1).

After input/output determination by fuzzy sets, the appropriate rules between inputs and outputs should be defined. The rule base presents set IF-THEN rules that include occasional expert's description how to control the process in an optimal way. A complete list of 44 rules for the applied fuzzy controller is given in Table I.

Beside described membership functions and fuzzy rules, the following methods typical for a fuzzy approach were selected:

- Decision method for fuzzy logic operators AND: PROD
- Decision method for fuzzy logic operators OR: PROBOR
- Implication: MIN
- Aggregation: MAX
- Defuzzyfication: The mean of maxima method

Based on determinate function of boilers and rule – work of boiler with maximal possible load, it is easy to set required thermal load by boilers.

IV. BOILER'S LOAD CONTROL

The control loop is presented in Fig. 4. The control system must track boiler's setup load. Setup point is variable in time, according to conditions, which are treated on higher hierarchy level of control. As example, boiler 1 is considered.

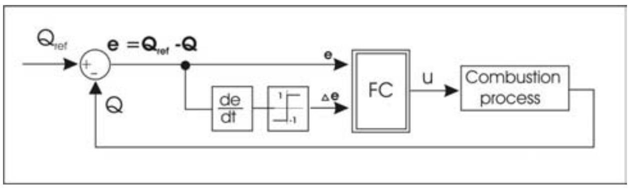


Fig. 4: Boiler's load regulation

The fuzzy controller is Mamdani type with following characteristics [5]:

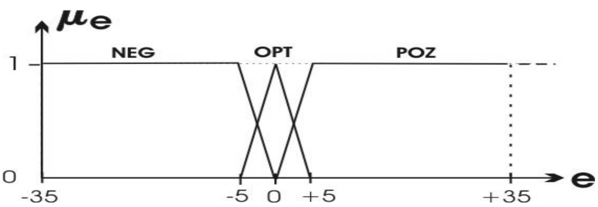


Fig. 5: Membeship functions for input 1

The controller has two inputs, which are important for dynamic characteristics. First input is control error $e = Q_{ref} - Q$, the operational range is [-35, +35] and the membership functions, that are assigned to input 1, are presented on Fig. 5: 1. NEG –negative error (trapezoidal type), 2. OPT–optimal error (triangular type) and 3. POZ – positive error (trapezoidal type).

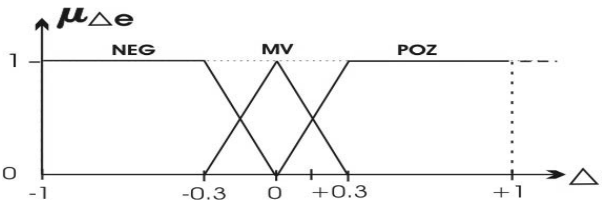


Fig. 6: Membership functions for input 2

The second input is error derivate, Δe. There is limit of this variable so its operational range is [-1 1]. Membership functions that are assigned to input 2 are presented on Fig.6: 1. NEG – negative Δe (trapezoidal type), 2. MV – mean value Δe (triangular type) and 3. POZ – positive Δe (trapezoidal type).

The controller output is signal for increasing / decreasing boiler load, with assigned membership functions, as shown on Fig. 7: 1. FD – fast decreasing (trapezoidal type), 2. SD- slow decreasing (triangular type), 3. NA – no action (triangular type), 4. SI – slow increasing (triangular type) and 5. FI – fast increasing (trapezoidal type).

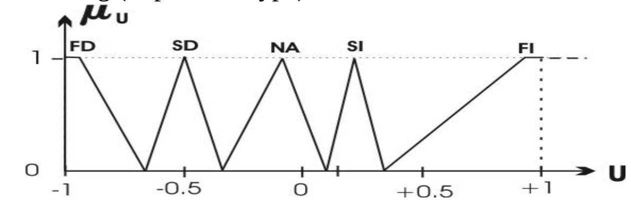


Fig. 7: Membership functions for output

The appropriate rule base is formed and given in Table II.

TABLE II
FUZZY RULE BASE FOR CONTROLLER 2

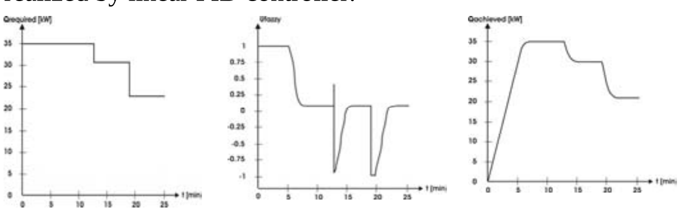
e / Δe	**NEG**	**OPT**	**POZ**
NEG	**FD**	**SI**	**FI**
MV	**FD**	**NA**	**FI**
POZ	**FD**	**SD**	**FI**

The following methods in fuzzy approach were selected:

- Decision method for fuzzy logic operators AND: PROD
- Decision method for fuzzy logic operators OR: PROBOR
- Implication: PROD
- Aggregation: PROBOR
- Defuzzyfication: The centre of gravity method

Two properties of the fuzzy controller can be mentioned.

1. The fist one is local reduction – the reduction effect is blocked if the system error is big, so the system response is fast. The reduction effect increases progressively with approach the error value to zero. This behaviour is similar to time optimal bang-bang control and it is not possible to be realized by linear PID controller.



a) b) c)

Fig. 8: a) Reference value with suddenly changes,
b) Fuzzy control sygnal
c) Boiler load

2. The second property related to different velocities. Namely, the velocities for load decreasing/increasing are sited differently by definition membership functions variously. This property is desired and motivated by technology process of boiler, and cannot be provided by the linear PID control.

To verify the usefulness of suggested fuzzy controller the complete system has been simulated. One of simulation results is presented in Fig. 8. The traces show the satisfactory properties of fuzzy controller in the case of fast changes of reference signal.

V. CONCLUSION

Nowadays, the heating plant “Krivi vir” in Niš is in process of reconstruction and automatization with goal to increase energy efficiency of complete heating systems. Newly installed equipment (Control Systems SIMATIC S7 and SIMATIC WinCC) can be updated by Fuzzy Control++ software, [6]. This software can be used on all automatization levels – from single control loop to optimal control of complete heating plant. In addition, Fuzzy Control++ can be combined with conventional PID control in order to exploit all advantages.

Bearing in mind that any savings at one efficiency level represents more 10,000€ per year, all possible measures must be undertaken. The ultimate level is adaptive control, with ability of adjustment in the case of all environment changes. The master variable will be outside temperature combined with other variables such as wind, solar radiation, relative humidity, etc. After making of a reliable control system infrastructure, the further improvements are possible by software changes only. In that way, the idea of including the artificial intelligence and expert system will be also possible. The proposed adaptive system configuration should be state of the art.

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TABLE I

FUZZY RULE BASE FOR CONTROLLER 1

Ordinal		Qreq (KW)	ST B1	ST B2	ST B3	P.W B1	P.W B2	P.W B3		Func B1	Func B2	Func B3
1.			yes	no	yes/no	yes/no	yes/no	yes/		LB	NA	NA
2.			no	yes	yes/no	yes/no	yes/no	yes/no		NA	LB	NA
3.			yes	yes	yes/no	yes	no	yes/no		LB	NA	NA
4.	**IF**	**≤ 35**	yes	yes	yes/no	no	yes	yes/no	**THEN**	NA	LB	NA
5.			yes	yes	yes/no	yes	yes	yes/no		LB	NA	NA
6.			no	no	yes	yes/no	yes/no	yes/no		NA	NA	LB
7.			no	no	no	yes/no	yes/no	yes/no		NA	NA	NA
8.			yes/no	yes/no	yes	yes/no	yes/no	yes/no		NA	NA	LB
9.			yes	yes	no	yes/no	yes/no	yes/no		LB	FF	NA
10.	**IF**	**> 35 and ≤ 58**	yes	no	no	yes/no	yes/no	yes/no	**THEN**	LB	NA	NA
11.			no	yes	no	yes/no	yes/no	yes/no		NA	LB	NA
12.			no	no	no	yes/no	yes/no	yes/no		NA	NA	NA
13.			yes	yes	no	yes/no	yes/no	yes/no		LB	FF	NA
14.			yes	no	yes	yes/no	yes/no	yes/no		FF	NA	LB
15.			no	yes	yes	yes/no	yes/no	yes/no		NA	FF	LB
16.			no	no	no	yes/no	yes/no	yes/no		NA	NA	NA
17.			no	no	yes	yes/no	yes/no	yes/no		NA	NA	LB
18.			no	yes	no	yes/no	yes/no	yes/no		NA	LB	NA
19.	**IF**	**> 58 and ≤ 70**	yes	no	no	yes/no	yes/no	yes/no	**THEN**	LB	NA	NA
20.			yes	yes	yes	yes	yes	yes/no		LB	FF	NA
21.			yes	yes	yes	no	yes	yes		NA	FF	LB
22.			yes	yes	yes	yes	no	yes		FF	NA	LB
23.			yes	yes	yes	no	no	no		LB	FF	NA
24.			yes	yes	yes	no	no	yes		FF	NA	LB
25.			yes	yes	yes	no	yes	no		LB	FF	NA
26.			yes	yes	yes	yes	no	no		LB	FF	NA
27.			yes	no	yes	yes/no	yes/no	yes/no		FF	NA	LB
28.			no	yes	yes	yes/no	yes/no	yes/no		NA	FF	LB
29.			yes	yes	yes	yes	no	yes/no		FF	NA	LB
30.			yes	yes	yes	no	yes	yes/no		NA	FF	LB
31.	**IF**	**> 70 and ≤ 93**	yes	yes	yes	yes	yes	yes/no	**THEN**	FF	NA	LB
32.			yes	yes	no	yes/no	yes/no	yes/no		LB	FF	NA
33.			yes	no	no	yes/no	yes/no	yes/no		LB	NA	NA
34.			no	yes	no	yes/no	yes/no	yes/no		NA	LB	NA
35.			no	no	no	yes/no	yes/no	yes/no		NA	NA	NA
36.			no	no	yes	yes/no	yes/no	yes/no		NA	NA	LB
37.			yes	yes	yes	yes/no	yes/no	yes/no		FF	SF	LB
38.			yes	no	yes	yes/no	yes/no	yes/no		FF	NA	LB
39.			no	yes	yes	yes/no	yes/no	yes/no		NA	FF	LB
40.	**IF**	**> 93 and ≤ 128**	no	no	no	yes/no	yes/no	yes/no	**THEN**	NA	NA	NA
41.			no	no	yes	yes/no	yes/no	yes/no		NA	NA	LB
42.			no	yes	no	yes/no	yes/no	yes/no		NA	LB	NA
43.			yes	no	no	yes/no	yes/no	yes/no		LB	NA	NA
44.			yes	yes	no	yes/no	yes/no	yes/no		LB	FF	NA