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Research paper

An alternative method of hedge algebra-based controller for water level control system in a thermal power plant

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Abstract

The control structure of steam boiler system is one of the most complex systems where required with many control loops and multiple pa-rameters. It is necessary for the controller used for this system to ensure the efficiency of the steam, so the control approaches need to be improved regularly. While some controllers such as PID, Fuzzy logic control have been applied successfully, the Hedge Algebra algo-rithm is a soft-computing tool developed from fuzzy logic that can be applied and calculated effectively with high accuracy in the control aspect. The paper presents an application of the controller based on hedge algebra in the control of the water level for the thermal power plant. Sys-tem quality is assessed through simulation and comparison with the traditional PID controller.

Keywords: *HA; HAC; PID; Steam Boiler; Level Control.*

1. Introduction

For automated systems in the industry, improving the quality of the system with new control methods is attracting many scientists. Hedge Algebra (HA) is a new approach to the fuzzy logic calculations. HA takes benefits of the reasoning ability of the human to deal with uncertainties and inaccurate information of controlled objects. Although HA is based on fuzzy logic, it builds on an algebraic structure and is a tool for ensuring semantic ordering, supporting fuzzy logic in the reasoning and control problems. Besides developing the benefits of the fuzzy system, the HA controllers also promote the advantages of natural language processing and intuitive thinking, and avoid identification problems with complex modeling [1], [2].

The study concentrates on a control problem in the combustion chamber and the steam boiler. The combustion chamber is a multiple outputs and inputs system, in which fuel, wind and water supply are its inputs, and the output consists of saturate steam released from the steam tank, an amount of redundant water, smoke and slag from the combustion process. In this case, water is heated in a boiler until it becomes high-temperature steam. This steam is then channeled through a turbine, which has many fan-blades attached to a shaft. As the steam moves over the blades, it causes the shaft to spin. This spinning shaft is connected to the rotor of a generator, and the generator produces electricity. The steam boiler collects steam then delivers it to the turbine. Water from the steam tank is brought down to the furnace by piping.Hence, the steam boiler control system is a complex system with different control loops that monitor and control hundreds of parameters.

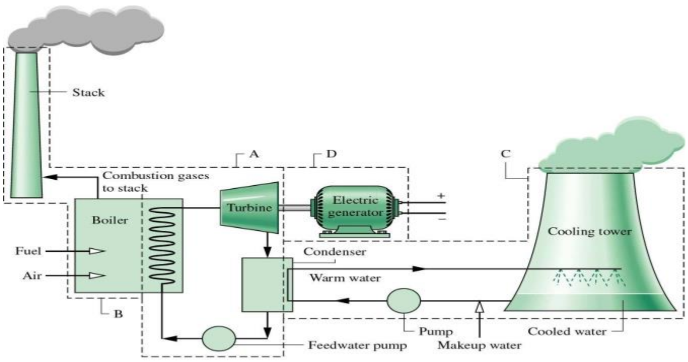

Fig. 1: Steam Turbine Power Plant For Power Generation.

2. Studying the level control system for the thermal power plant

2.1. Experimental system model

The research for the level controller in the laboratory of electrical engineering at Thai Nguyen University of Technology is shown in figures 2, 3, 4 and 5.

Fig. 2: The Experimental Model of the Level Controller.

Fig. 3: The Steam Boiler Controlling Water Level.

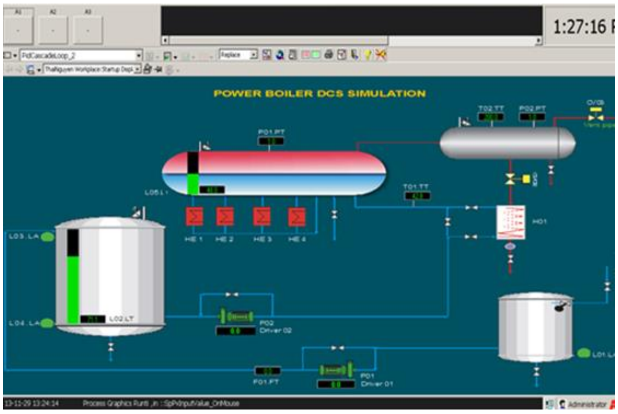

Fig. 4: The Program Interface Controlling Water Level.

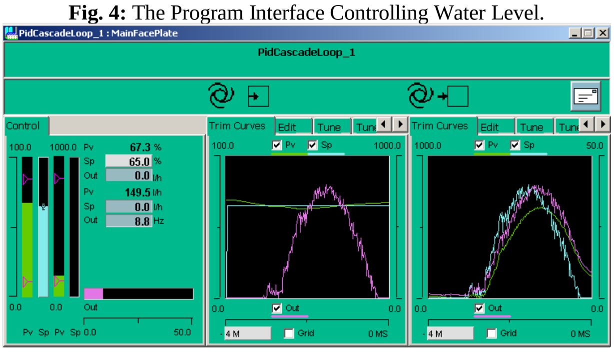

Fig. 5: The Experimental Results with PID Controller.

2.2. Modelling system

The process control system of the thermal power plant including objects such as temperature sensors, pressure sensors, level sensors, flow sensors, motors, etc. As the content above, this process is a multi-input and multi-output system, in which the inputs and outputs are closely related to each other. For example, if the required power of the generator is changed, it will be necessary to control the changing amount of the fuels and supply water, wind. The structure of the steam boiler is described in Fig. 6:

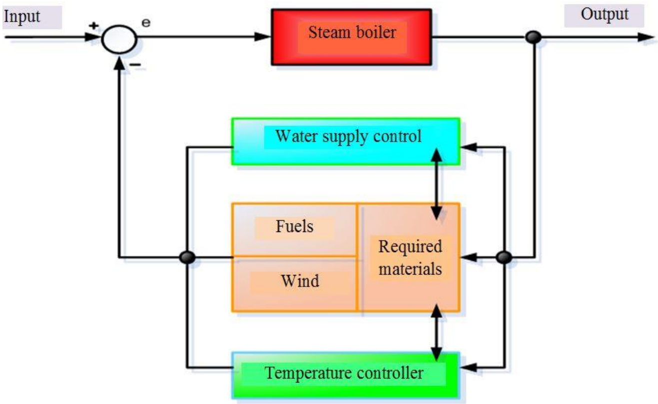

Fig. 6: The Structure Diagram of the Steam Boiler.

Therefore, the schematic diagram of water level controller is formed as Fig. 7.

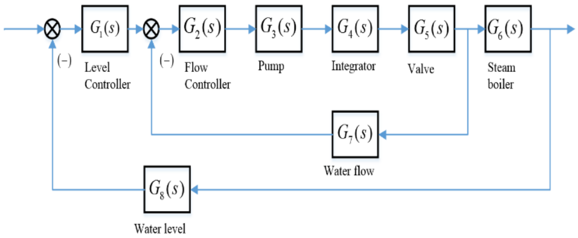

Fig. 7: The Schematic Diagram of Proposed Level Controller.

The transfer functions of elements in the block diagram are written as follows:

W_3 denotes the transfer function of water supply system (Pump in the Fig. 7).

$$G_3(s) = \frac{k_3}{T_1T_2s^2 + T_2s + 1}$$

Because the input signal of the valve is the angular velocity, while the output signal of the power transmission is the speed, an integration block is added with the transfer function W_4:

$$G_4(s) = \frac{k_4}{s}$$

Next, in the valve, the input signal is the angular velocity, whereas water flow plays output role. And, the relationship between the output signal and the input signal of the valve is a first-order inertial equation has the form of W_5:

$$G_5(s) = \frac{k_5}{T_5s + 1}$$

In the steam boiler, the water flow is the input element. The water is transferred into steam. The output signal is the steam flow. The relationship between the output signal and the input signal is a first-order inertial equation with delay is determined by W_6

$$G_6(s) = \frac{k_6}{T_6s + 1}e^{-\tau s}$$

The input signal of the W_7 sensor is the water flow, while the its output signal is the DC current, so the transfer function of the W_7 flow sensor is:

$$G_7(s) = k_7 = \frac{\Delta I_{\max}}{\Delta Q_{\max}}$$

Similarly, the input signal of the W_8 level sensor is the water level, and the output signal is the DC current, so the transfer function of the water level sensor is W_8:

$$G_8(s) = k_8 = \frac{\Delta I_{\max}}{\Delta H_{\max}}$$

The aim of the level and flow control system in the steam boiler is to preserve water level and the water supply flow to the boiler. The paper introduces a control system including two control loops, where an inner flow control loop (with fast response) and an outer level control loop (with slower response) are shown in Fig. 8

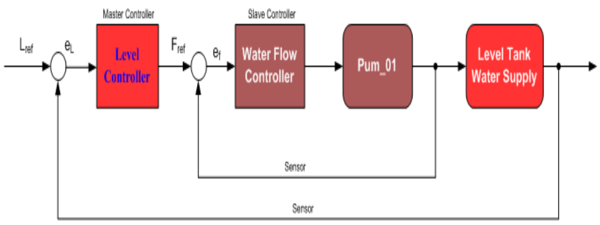

Fig. 8: The Cascade Control Structure Diagram

In order to meet the heating requirement of the steam boiler, the flow of water supply must be kept stable to ensure sufficient water to the heater. To stabilize the water flow, the pump speed named Pum_01 in fig. 8 need to be controlled according to the reference flow. The inner flow control loop is performed as Fig. 9.

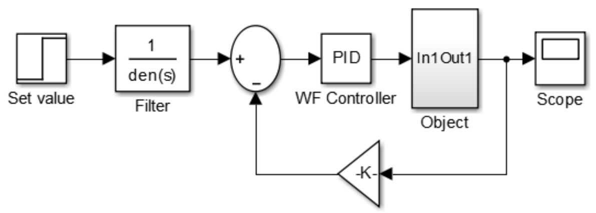

Fig. 9: The Flow Control Loop.

The PID controller applied for the outer level control loop is built in the block diagram as Fig. 10

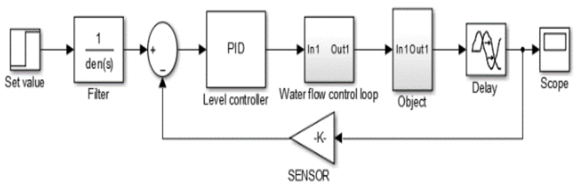

Fig. 10: The Level Control Loop.

3. The alternative study of hedge algebra

3.1. Introduction of hedge algebra

HA is the development basing on the logic perception of linguistics [3], [4]. The input/output relationship in fuzzy logic must define membership functions discontinuously, whereas HA creates an algebraic structure in terms of functions of linguistic input/output variables.

Example: Consider a set of linguistic intervals which is a linguistic domain of TEMPERATURE truth variable including T = dom (TEMPERATURE = {Large, Small, very Large, very Small, more Large, more Small, approximately Large, approximately Small, little Large, little Small, less Large, less Small, very more Large, very more Small, very possible Large, very possible Small, …}.

Then the linguistic domain T = dom(TEMPERATURE) can be considered as an algebraic structure AT = (T, G, H, ≤), where: "T" is the based set of AT; "G" is the set of generators (Large, Small); "H" is the set of linguistic hedges (Very, Little, Less…); "≤" is an semantically ordering relation (Small ≤ Large, more Large ≤ very Large…).

Definition 1: *A given HA: AT = (T, G, H, ≤); f: T→[0,1] is the set of semantic quantifying mapping (SQM) of AT if* $\forall h, k \in H^+$ *or* $\forall h, k \in H^-$ *and* $\forall x, y \in T$*, then:*

$$\left|\frac{f(h_x)-f(x)}{f(k_x)-f(x)}\right| = \left|\frac{f(h_y)-f(y)}{f(k_y)-f(y)}\right| \quad (1)$$

Considering intervals: Large, very Small, and according to the viewpoint of HA, fuzziness can be defined quite clearly basing on the size of the set H(x) shown in Fig.11:

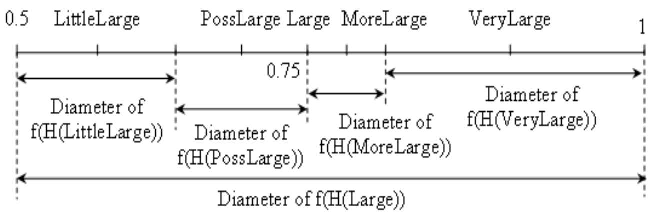

Fig. 11: The Flow Control Loop.

A given semantic quantifying mapping f of X and considering $\forall x \in X$, fuzziness of x can be measured by the diameter of f(H(x)) $\subseteq$ [0, 1].

Definition 2: *Fuzziness measures*

A function f_m: T → [0, 1] is said to be a fuzziness measure if: $f_m(c^-) = \theta > 0$ and $f_m(c^+) = 1-\theta > 0$, whereas c^- and c^+ are negative and positive generating elements. Assume set of hedges $H = H^+ \cup H^-$; $H = \{h_1, h_2 \dots, h_p\}$ with $h_1 > h_2 > \dots > h_p$; $H_+ = \{h_{p+1}, h_{p+2}, \dots, h_{p+q}\}$ with $h_{p+1} < h_{p+2} < \dots < h_{p+q}$. Then: $\forall x,y \in T$, $\forall h \in H$, $\frac{f_m(h_x)}{f_m(x)} = \frac{f_m(h_y)}{f_m(y)}$ this equation does not depend on specific elements and it is called the fuzziness measure of the hedge h and denoted by $\mu(h)$.

a) Propositions of $f_m(x)$ and $\mu(h)$

$$f_m(h_x) = \mu(h) f_m(x), \ \forall x \in T \quad (2)$$

$$\sum_{i=1}^{p+q} f_m(h_i c) = f_m(c) \quad \text{with } c \in \{c^-, c^+\} \quad (3)$$

$$\sum_{i=1}^{p+q} f_m(h_i x) = f_m(x) \quad (4)$$

$$\sum_{i=1}^{p} \mu(h_i) = \alpha$$

$$\sum_{i=p+1}^{q} \mu(h_i) = \beta \quad \text{with } \alpha, \beta > 0 \text{ and } \alpha + \beta = 1 \quad (5)$$

$v(c^+) = \theta + \alpha f_m(c^+)$

$$f_m(x) = f_m(h_{im} \ldots h_{i2} h_{i1} c) = \mu(h_{im}) \ldots \mu(h_{i2}) \mu(h_{i1}) f_m(c) \quad (6)$$

b) Construction of SQM based on the basics of fuzziness measure of hedges

A fuzzy model is considered as follows:

IF $x=A_1$ THEN $y=B_1$

IF $x=A_2$ THEN $y=B_2$ (7)

IF $x=A_n$ THEN $y=B_n$

Assume fuzziness measures of hedges $\mu(h)$ and fuzziness measure intervals of base terms $f_m(c^-)$, $f_m(c^+)$, are given and θ is the neutral terms.

A semantic quantifying mapping v of T is constructed as follows: with $x = h_{im} \ldots h_{i2} h_{i1} c$:

$$v(c^-) = \theta - \alpha f_m(c^-),\ v(c^+) = \theta + \alpha f_m(c^+)$$

$$f_m(x) = f_m(h_{im} \ldots h_{i2} h_{i1} c) = \mu(h_{im}) \ldots \mu(h_{i2}) \mu(h_{i1}) f_m(c) \quad (8)$$

+ If j < p then:

$$v(h_j x) = v(x) + \operatorname{sgn}(h_j x) \times \left[\sum_{i=j}^{p} f_m(h_i x) - \frac{1}{2}(1 - \operatorname{sgn}(h_i x) \operatorname{sgn}(h_1 h_i x)(\beta - \alpha) f_m(h_i x)\right] \quad (9)$$

+ If j > p then:

$$v(h_j x) = v(x) + \operatorname{sgn}(h_j x) \times \left[\sum_{i=p+1}^{j} f_m(h_i x) - \frac{1}{2}(1 - \operatorname{sgn}(h_i x) \operatorname{sgn}(h_1 h_i x)(\beta - \alpha) f_m(h_i x)\right] \quad (10)$$

Visually, each if-then clause is considered as a point, and then n clauses determine linguistic space X×Y named fuzzy curve - C. Then, the approximation problem on the fuzzy set can be transferred to the interpolation problem for the fuzzy curve - C. When f_x and f_y are quantitative semantic functions of X and Y, these functions will convert the fuzzy curve - C to the real curve - C' in space [0,1] × [0,1]. The fuzzy reasoning problem is transferred to the common interpolation problem by the semantic quantitative functions.

3.2. Hedge algebra-based controller

The HAC applied in industrial systems comprises 3 blocks as shown in Fig. 12

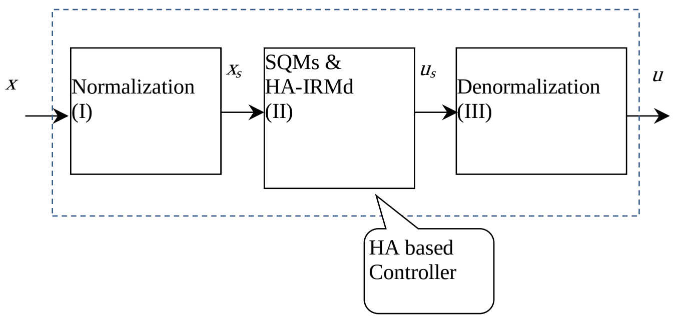

Fig. 12: The Diagram of HAC Controller.

Where:

x is the input value, x_s is the input semantic value.

u is the control value, u_s is the control semantic value.

HAC includes the following blocks:

Block I – Normalization (linear transformation from x to x_s): determining the input variable, state variable, control variables (output variables), and the working range of variables. Identifying calculated conditions (choosing the calculated parameters of HA). Calculating the values of semantic quantifying of input variable, state variable, and control variable (apply hedges on the working range of the variables).

Block II - Semantically quantifying mappings &Hedge Algebra-based Interpolative Reasoning Method (performs semantic interpolation from x_s to us basing on the semantic quantifying mapping and rules): changing fuzzy control rules to control rules with semantic quantifying parameters of HA. Solving the approximated problems based on HA to determine the semantic quantifying of control states. Combining the semantic quantifying values of controls and building semantic quantifying curve.

Block III – Denormalization (linear transformation from u_s into u): basing on the initial conditions of the control problem to solve semantic quantifying curve interpolation and determine the real control value.

3.3. Design of HAC controller replaced for the system

The HAC controller used in this research consists of two inputs and an output. The input variables are the control signals of the HAC, which is the control voltage error (ET) and the derivative of the error (DET); and output variable is the control voltage U. Choosing a set of calculation parameters with:

G = {0, Small, W, Large, 1}

$H^- = \{\text{Little}\} = \{h_{-1}\}$; q = 1

$H^+ = \{\text{Very}\} = \{h_1\}$; p = 1

f_m (Small) = θ = 0.5

μ (Very) = μ (h_1) = 0.5

μ (Little) = μ (h_{-1}) = 0.5

The result is as follows

α = β = 0.5;

f_m (Large) = 1 – f_m (Small) = 1 – 0.5 = 0.5

Calculations of sematic quantifying values for ET, DET and U = {Small, Little Small, Very Small, W, Large, Little Large, Very large} are shown in following equations (11) - (15) and the SAM table (table 1)

υ (Small) = θ – α f_m (Small) = 0.25

υ (Very Small) = υ (Small) + Sign (Very Small) ×

$$\left\{\sum_{i=1}^{1} f_m(h_i Small) - 0.5 f_m\,(h_1 Small)\right\} = 0.125 \quad (11)$$

υ (Little Small) = υ (Small) + Sign (Little Small) ×

$$\left\{\sum_{i=-1}^{-1} f_m(h_i Small) - 0.5 f_m\,(h_{-1} Small)\right\} = 0.375 \quad (12)$$

υ (Large) = θ + α f_m (Large) = 0.75 (13)

υ (Very Large) = υ (Large) + Sign (Very Large) ×

$$\left\{\sum_{i=1}^{1} f_m(h_i \text{Large}) - 0.5 f_m\,(h_1 \text{Large})\right\} = 0.875 \quad (14)$$

υ (Little Large) = υ (Large) + Sign (Little Large) ×

$$\left\{\sum_{i=-1}^{-1} f_m(\mathrm{h_i Large}) - 0.5 f_m\,(h_{-1}\mathrm{Large})\right\} = 0.625 \qquad (15)$$

Table 1: SAM (Semantization Association Memory)

DET \ DE	0.125	0.25	0.375	0.5	0.625	0.75	0.875
0.125	0.125	0.125	0.125	0.125	0.25	0.375	0.5
0.25	0.125	0.125	0.125	0.25	0.375	0.5	0.625
0.375	0.125	0.125	0.25	0.375	0.5	0.625	0.75
0.5	0.125	0.25	0.375	0.5	0.625	0.75	0.875
0.625	0.25	0.375	0.5	0.625	0.75	0.875	0.875
0.75	0.375	0.5	0.625	0.75	0.875	0.875	0.875
0.875	0.5	0.625	0.75	0.875	0.875	0.875	0.875

Simulations of PID and HAC on MATLAB/Simulink are shown in Fig. 13 and the results are displayed in Fig. 14.

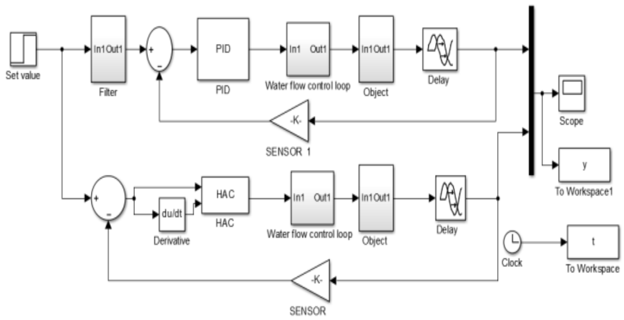

Fig. 13: The Simulation Diagram on Matlab/Simulink.

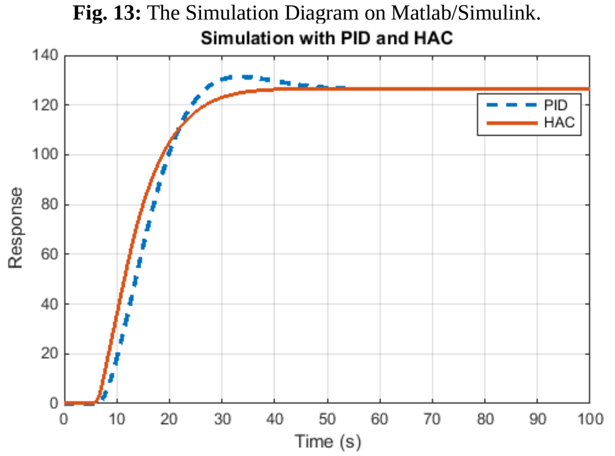

Fig. 14: HAC and PID Simulation Results.

The level control algorithm for the steam boiler in the thermal power plant has been developed and designed by the PID and HAC controller. Simulation results show the stability and accurate tracking of the system. After a certain period of time, the error converges to zero.

It can be seen that HAC performance meets the requirements of the level control problem in the steam boiler.

4. Conclusion

The paper has proposed a new approach to design HAC based controllers for the level control problem in the thermal power plant. The authors have designed and simulated HAC on the MATLAB/Simulink. Simulation and Experimental results show that PID and HAC controllers meet the quality requirements in the level control system and open the possibility of applications in reality.

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