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Intelligent and Adaptive Fuzzy Control System for Energy Efficient Homes

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***Abstract.** "Smart houses" have widely established their position as a research field during the last decade. Nowadays the technical solutions related to energy resource management are being rapidly developed and integrated into the daily lives of people. The energy resource management systems use sensor networks for receiving and processing information during the realia time. Smart house adaptive and intelligent solutions has advanced towards common environment, which can take care of the inhabitants' well-being in numerous ways. This paper propose to use a context sensitive and proactive fuzzy control system for controlling the automation processes in smart house environment. The designed monitoring system has adaptive and intelligent options, and it can operate using real time information received from sensors. The system is designed to operate fully in the background and can be installed to any exiting working system. This paper describes a central heating boiler control system implemented using the fuzzy control system designed. Author concentrates on the basic operation of such systems and present findings from the design process and initial tests.*

***Keywords:** Energy Efficiency, Fuzzy logic, Sensow network.*

I. INTRODUCTION

The number of studies related to intellectual and adaptive system use in the smart home context is increasing daily. Nowadays it is not difficult to imagine a situation when a person could live in a house where all processes are managed by artificial intelligence. Most of the time the smart system of house management system will be able to react correctly to the actions of the human or take proper proactive actions, both based on predesigned model and measured variables. However, at some point the system might make a mistake or a wrong decision which then will have to be modified or customized by the user. The adaptive control system may result in a decision-making structure which might change dynamically adding a new decision or changing the priorities of a decision. Such activities indicate some topical problems:

- how to change the decision-making and model operating scenarios;
- how the system can identify the required scenario which meets the user's needs.

Recieved data recognition is an effective method for providing existing rules and activating context linked actions [1, 5, 11]. Nowadays this is used regarding an intellectually developed environment creation and by using machine learning algorithms it can be utilized in building proactive systems [7]. Some smart home technologies have been built using content recognition technology [4] and neural networks for decision-making [9]. By using context-based smart home technology flexible and adaptive process management can be provided. Context recognition deals with fuzzy quantities of environment, like brightness, temperature, humidity, level, etc.. A person in this system acts as an expert and may affect the performance of the system by using fuzzy variables. Nowadays a lot of neural networks algorithms, which have already been utilized for decision making, can be converted to fuzzy systems to improve its implementation in smart house context. Moreover, by integrating fuzzy systems into smart home management and decision-making processes a more genuine and natural environment can be established.

This article describes the fuzzy control method for heating circuit management, which can adapt to the user's needs by acquiring new operating requirements. In order to use the system, prior training is not required; it can add or remove requirements or modify the existing ones by using the information received from the environment in real time.

II. RELATED WORKS

Today, the main studies which are related to the introduction of Smart environment into people's daily lives are associated with the device, network, software security and user interface development, that will allow the automation of the management processes and the reduction of the energy consumption in systems. Nowadays the discovery of energy consumption is ongoing and most of the producers unfortunately do not define it as main

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priority [2]. The competitiveness of European technologies could strengthen the European position in the global market for energy effective solutions. The EU is making rapid progress towards establishing Europe-wide energy consumption standards; however, most European countries have established and follow their own set of regulations.

Although smart environment system energy consumption effective solutions are currently not available, none represent a complete solution with low cost-performance parameters. The intelligent smart environment systems will raise the level of convenience for the user and reduce working system total energy consumption as result it will reduce system running costs while increasing its quality, thereby increasing competitiveness and profitability of consortium SMEs [10].

When designing automation systems more and more attention has been paid to the Fuzzy system [8] because these systems are well suited for the environment where the dynamic values can change unexpectedly and the next step cannot be predicted or calculated mathematically. Many articles have proven that Fuzzy systems are quite easy to understand and design because they are based on natural language. Control systems that use fuzzy logic in the automation process are generally fast, user friendly and cheap because they do not need much memory and resources to operate. [6]

III. FUNDAMENTALS OF THEORY OF FUZZY LOGIC

Fuzzy set theory provides a major newer paradigm in modeling and reasoning with uncertainty. Though there were several forerunners in science and philosophy, in particular in the areas of multivalued logics and vague concepts, Lotfi A. Zadeh, a professor at University of California at Berkeley was the first to propose a theory of fuzzy sets and an associated logic, namely fuzzy logic [12]. Essentially, a fuzzy set is a set whose members may have degrees of membership between 0 and 1, as opposed to classical sets where each element must have either 0 or 1 as the membership degree—if 0, the element is completely outside the set; if 1, the element is completely in the set. As classical logic is based on classical set theory, fuzzy logic is based on fuzzy set theory.

Major industrial application areas

The first industrial studies related to fuzzy logic using fuzzy control systems were initiated in the 1980s when two Danish engineers L.P. Holmblad and J.J. Østergaard developed a fuzzy controller for automated cement kilns with the option to control the specific burning temperature during the production process. The results were first published in 1982 [3]. The results did not obtain a great interest in Europe, but gained a lot of popularity in Japan where the developed methodology was improved and fuzzy logic was applied in the automation process of the Sendai City subway train management. The developed product gained a lot of support and the technology that was applied was adapted for other similar management systems which were based on the classic On – Off operating principle [5]. This success contributed to the great interest by the industry representatives regarding the feasibility of introducing the Fuzzy logic into the control system automation processes and as a result they were used in industrial control systems as well as in facility heating/ventilation systems.

In the 1990s, the Japanese started to integrate the fuzzy controller in everyday products like washing machines, camcorders, vacuum cleaners as well as transport; as a result, in 1992, a successful technology implementation experience in Japan increased the interest of Europe and the US regarding the fuzzy controller technology and this lead to the fuzzy logic implementation in Europe, in 1993 in the area of information systems.

Fuzzy and linguistic variables.

The fuzzy logic-based decision-making systems use fuzzy sets and fuzzy values. Fuzzy sets and fuzzy size definitions are based on the concept of affiliation functions. In the classical approach, the sets can be defined by using the affiliation functions with two values: value 1 is the affiliation of the object while 0 — the object's irrelevance to the set. While working in the context of fuzzy logic, intermediate values of the affiliation function are permitted, which shows the level of affiliation of an element.

As a result, the fuzzy values can be defined by using a variable set $\langle a, Q, X \rangle$ where $\boldsymbol{a}$ is the description of the value, $\boldsymbol{Q}$ is a universal set which is the definition area of value $\boldsymbol{a}$ and $\boldsymbol{X}$ is the fuzzy set that describes the value limits of the variable $\boldsymbol{a}$.

The most important task in relation to the development of the Fuzzy logic automation system is associated with the processing of the received information and its classification within databases. Profiling allows the identification of the data regularities within a system to enable decision-making. In order to increase the speed of a working system, the database performance features are provided through the individual sub-systems in which the existing knowledge is classified by using three categories – the situation, the action and the result, which reflect the system interaction with the environment.

The fuzzy logic-based decision-making system is based on the variables with fuzzy linguistic values which are effectively used in practice for two reasons:

- When the resource management tasks related to quality assurance are dealt with in the state of uncertainty, it is often crucial to interpret the quality conditions using a certain measure or a degree by which the given condition is executed or not rather than according to the principle of "completed" / "failed" by checking the strict form of inequality as a means of quality indicator. For example, if the quality indicator must be no less than 0,6, then in the case of the value being 0,568999 the wrong decision could be made, classifying the case as an unsatisfactory result of *quality*.

- Linguistic values are a very good tool for strategic decision-making related to system building. The decision-making procedures are much easier to set and use with the help of the linguistic values of the input variables and the decision-making indicator. For instance, the use of the linguistic variable Water may result in the fuzzy values or set of values: cold, warm, hot.

IV. CONTROLLER MODEL IDENTIFICATION

The article describes the heating boiler control system, which uses three linguistic values relating to space: low, adequate, high and two linguistic values relating to water temperature: hot, cold. Let us look at a set of requirements that uses the input data of the linguistic variables. As a result, the management conditions of the distribution valve by using water temperature and the room temperature are as follows.

IF (room temperature = "high" && water temperature = "hot") THEN close control valve.
IF (room temperature = "low" && water temperature = "hot") THEN open control valve.
IF (room temperature = "adequate") THEN do nothing.
IF (room temperature = "high" && water temperature = "cold") THEN close control valve.
IF (room temperature = "low" && water temperature = "cold") THEN close control valve.

Referring to an expert opinion, the affiliation of the physical values of the temperature will be defined to the set of fuzzy values: "low" = 0,1; "adequate" = 0,5; "high" = 0,9; "cold" = 0,1; "hot" = 0,9.

Using the defined values, the conditional terms will be transformed:

Close control valve min(0,9;0,9);
Open control valve min(0,1;0,9);
Do nothing: 0,5 = 0,5;
Close control valve min(0,9;0,1);
Close control valve min(0,1;0,1);

A valve servo motor ESBE ARA 600 was used in the experiment that ensured the maximum turning step which is equal to 90 degrees. For the actuator to work, 120 seconds are required in order to execute a full cycle. As a result, the procedure "close control valve" means rotating the valve by 90 degrees and the procedure "open control valve" means rotating the valve by -90 degrees. Using the industrially defined analogue management system during the experiments has proven that the system provides inconsistent temperature changes which do not allow stabilizing the temperature of the heating system. (Fig. 1). This is based on the engine performance time (120 sec.) and the time of thermal inertia in the heating system.

To avoid wide temperature variations, the optimal valve rotation angle for every system iteration should be determined by using the formula 1.

$$\alpha = \frac{average\ value * \max value + 0.1 * range_n}{average\ value + \min value} \quad (1)$$

As a result, the data of the experiment have determined that the first rotation step of the iteration = 15,75 degrees. During the experiment, the control system can operate only with integers; this results in the first iteration rotation step being equal to 16 degrees and it is necessary for the execution of the iteration for 22 seconds. Consequently, the remaining operating range of the valve = 74 degrees and the time required for an action is 98 sec.

By completing each iteration cycle, standby time t_{wait} is required and it provides accurate reading of the information by taking into account the inertia change of the heating system temperature using formula 2.

$$t_{wait} = \frac{t_1 + t_2 + \cdots + t_n}{n}, where\ t_{wait} > t_n - t_{n-1} \quad (2)$$

where t_1 is the time between the temperature changes.

In an operating system new physical values of the temperature are defined for the fuzzy variables. Table 1 shows the operating principle of the current method which chooses the optimal valve operating range using the pre-defined conditions by reducing the temperature fluctuations.

Table1.
Valve calibration steps.

Cold	Hot	Adequate	Operating range	Operating step
0,1	0,9	0,5	90	16
0,1	0,75	0,425	75	15
0,15	0,75	0,45	60	11
0,15	0,75	0,45	60	11
0,3	0,75	0,525	45	6
0,3	0,65	0,475	35	5
0,38	0,65	0,515	27	4
0,38	0,59	0,485	21	3
0,42	0,59	0,505	17	3
0,42	0,55	0,485	13	2
0,5	0,55	0,525	5	1
0,5	0,55	0,525	5	1
0,5	0,55	0,525	5	1
0,5	0,55	0,525	5	1

It is known [5] that the thermometric temperature sensors are not able to instantly intercept the temperature changes of the particular environment as the heat exchange between the environment, the thermometric surface happens with finite rate and it takes time for the temperature sensor to read the correct temperature value. Suppose that the temperature sensor with the temperature T0 is placed in a new environment with a temperature of Θ. As a result, the sensor temperature will change by using the formula 3:

$$T - \theta = (T_0 - \theta)e^{-\frac{\tau}{\lambda}} \qquad (3)$$

where Θ – the real temperature of the environment, τ – time, λ – temperature sensor thermal inertia factor.

In order to determine the temperature sensor inertia factor, the activation time of the system is (t = 0). A certain temperature difference has been determined, if the initial temperature difference T_0 and θ is known. Consequently, the adaptive system is able to determine the inertia changes of the temperature by using the Formula 4.

$$n = \frac{T_0 - \theta}{T - \theta} = e^{\frac{\tau}{\lambda}} \qquad (4)$$

As a result, using the method for determining the operational temperature range as well as the inertia factor of the temperature sensor, the article describes the algorithm of the adaptive heating valve control system (Fig. 1.):

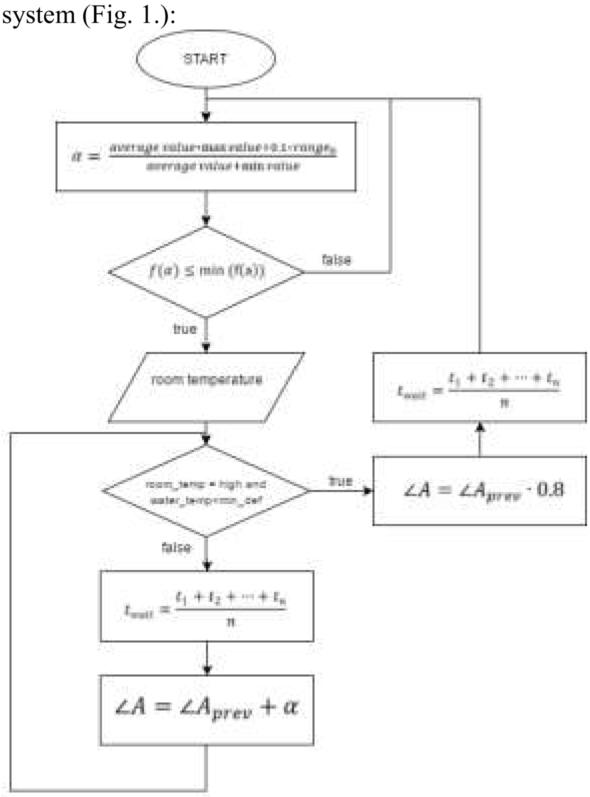

Fig. 1. Algorithm of the adaptive heating valve control system

V. ADAPTIVE SUBSYSTEM EXPLOITATION IN AUTONOMOUS ADAPTIVE CONTROL SYSTEMS.

For an adaptive control system to function, the training cycle and the operational calibration of the starting system for certain tasks and the environment – it is necessary to define a set of requirements and values of the starting system which contains general knowledge of the object and the operating environment. During the initial stage a system is able to meet the basic management principles at the beginning of the life cycle of a system or in case of emergency by using the sensor nodes. It is known that the management of a system is not effective when using only the predefined constant values in comparison with a system that works with the help of the empirical knowledge basis.

In order to create the control system of the initial phase, the article describes a situation where poorly formalized management objects are used. The main task of the system is to provide minimum object management possibilities at the early stage of the system life cycle; as a result, a control system which uses fuzzy logic principles was applied.

The system input data are the peak operating angle is l of the management engine and the maximum full time of the rotation cycle is t_{max}.

The basis of the control module consists of the fuzzy variables F1 .. Fn, dF1..dF2 described in this article characterizing the boiler temperature, room temperature and the linguistic values of the valve position:

$$\text{FN \& dFM} \rightarrow \text{AN*M} \qquad (5)$$

where N and M are unclear sets that contain information about the certain room temperature and boiler temperature value range.

In order to select an executable requirement *A* from the requirement sets the following formula is used:

$$A = \frac{\Sigma(A_k \cdot P_k)}{\Sigma P_k}. \qquad (6)$$

where A_k – the number of an executable requirement, P_k – the output values of the current requirement.

In cases when the system expert wants to limit the range of decision, the system is assigned with the requirement having the maximum value which will result in the completion of the task that matches the requirement.

VI. CONTROLLER PRACTICAL VALIDATION

Using the Climate change financial instrument as a means of co-financing in the project “The use of renewable energy sources in the household sector”, in cooperation with LLC “Chelsea Trade”, a private house had been connected to the heating system with a total capacity of 90kW which uses alternative and renewable resources for energy production.

The autonomous heating and hot water preparation system that was installed works, by using a series of temperature, water flow and pressure sensors for central boiler and pump node. The adaptive management of the circuit valve of the heating system was carried out with the aim of reducing the fuel and the electricity consumption during system operation.

To test the methodology described in this article a boiler control module is developed in which the control algorithm was implemented by using the Arduino language. In order to implement all the requirements of the algorithm ArduinoUno microcontroller and the analogue temperature sensor LM335 were used; to visualize the operational processes LCD displays (1602B) were used. The actuator was implemented by using ESBO ARA 600 servomotor which was used to regulate the heating valve.

The time of the experiment

- The first stage – September 2016, with the average outdoor air temperature + 13,2 C°. The heating system was in the standby mode most of the time and the highest consumption of the fuel was used to maintain the boiler combustion process (Fig 2.)

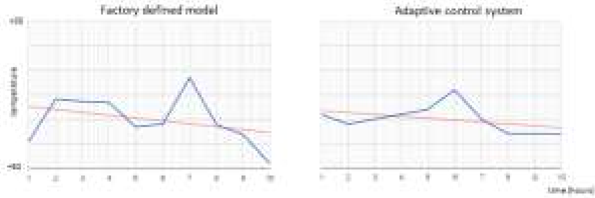

Fig. 2. The first phase of the temperature variation in the heating system.

- The second stage – November 2016, with the average outdoor air temperature + 0,6 C°. The heating system operates using 50% of its nominal capacity (Fig.3).

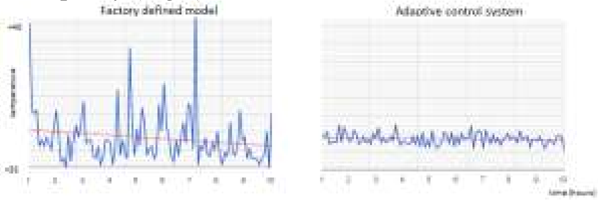

Fig.3. The second phase of the temperature variation in the heating system.

- The third stage – 7th January, 2017. The average daily air temperature –18,2 C°. The heating system operates using 90% of the nominal capacity (Fig.4).

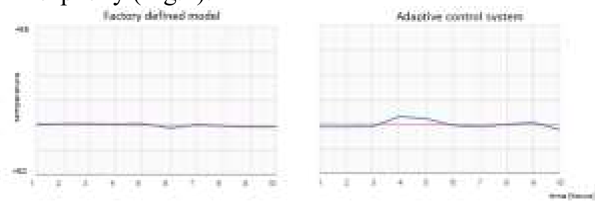

Fig. 4. The third phase of the temperature variation in the heating system

Benchmark value determination

The time t_{et} (min) will be assumed as the reference value – how long the heating system can operate using the Q quantity of fuel. Let us assume that the heating system operates via industrially defined ON-OFF valve control algorithm and the system can be considered as active as long as the room temperature stays within the given border.

As a result, each stage has certain benchmark values of the system performance, which are also taken from the boiler output temperature fluctuations.

Table 2.
Burning boiler fuel consumption

$T_{et1\ (min)}$	$Q_{1\ (kg)}$	kg/min	$T_{et2\ (min)}$	$Q_{2\ (kg)}$	kg/min	$T_{et3\ (min)}$	$Q_{3\ (kg)}$	kg/min
260	16	0,06	133	16	0,12	82	16	0,20
502	32	0,06	250	32	0,13	158	32	0,20
758	48	0,06	378	48	0,13	228	48	0,21
958	64	0,07	508	64	0,13	300	64	0,21
1218	80	0,07	592	80	0,14	398	80	0,20
1470	96	0,07	718	96	0,13	462	96	0,21
1712	112	0,07	873	112	0,13	515	112	0,22

The summary of the experiment results

During the experiment the results confirmed that:

By using the control algorithm of the adaptive heating system mixer described in this article, the overall increase in the system performance expectancy in relation to the benchmark model (Table 2) can be seen, but there are cases when the heating system is operating at a nominal capacity and the mixer valve is opened to 90%; then by using the adaptive valve control algorithm with the calibration tasks the excess energy is consumed (Fig. 5).

Table 2.
Adaptive management system application results.

$Q_{(kg)}$	$t_{et1\ (min)}$	$t_{fuzzy1\ (min)}$	$t_{et2\ (min)}$	$t_{fuzzy2\ (min)}$	$t_{et3\ (min)}$	$t_{fuzzy3\ (min)}$
16	260	↑ 264	133	↑ 148	82	↑ 83
32	502	↑ 510	250	↑ 268	158	↓ 142
48	758	↑ 762	378	↑ 392	228	↓ 219
64	958	↑ 962	508	↑ 535	300	↓ 298
80	1218	↑ 1224	592	↑ 618	398	↓ 390
96	1470	↑ 1478	718	↑ 738	462	↓ 462
112	1712	↑ 1722	873	↑ 896	515	↓ 505

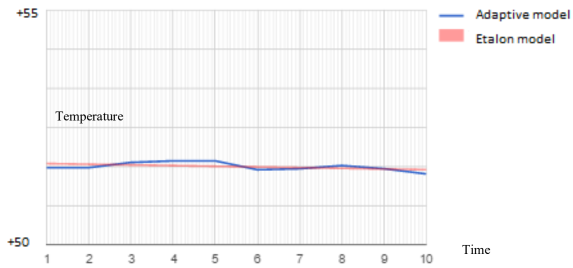

Fig.5. The heating system is operating at a nominal capacity.

VII. CONCLUSIONS

This article has described and practically tested the fuzzy control algorithm for the management of the heating system mixer module for adaptive management that can be adapted to the user's needs while acquiring new operating rules. In order to use the system, it does not need prior training, the training process takes place during the operation of the system by modifying the pre-defined requirements using the information received real-time via the sensors. The article proves that the effectiveness of the control algorithm depends on the boiler operating temperature and the outside air temperature. In cases when the boiler operates using nominal energy, the control of the operational process increases the consumption of fuel resources wasting the heat energy through heating temperature calibration.

The long-term use of the adaptive control module of a heating system, in systems operating on 40 to 60% of the rated power is obtained by decreasing the consumption of the heating fuel by 8% (~1920 kg/year) by using a 50 kW heating system.

The data obtained will be used for further research by developing intellectual management methodology of the universal heating system.

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