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Design of A hierarchical Sugeno Fuzzy Controller for HVAC in Large Buildings

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Abstract— In this paper Fuzzy controller is used to control Heating, Ventilating and Air Conditioning (HVAC) System, which is time varying nonlinear system. This controller consists of two fuzzy levels. The first fuzzy level controls two varying feedback parameters (Air temperature and Air quality) and to make the controller adequate with these changes. While the second level controls the Error and Change of Error that comes from first fuzzy control level. In this research, a hierarchical Sugeno fuzzy controller type will be designed .The proposed structure is used to reduce the number of rules and the computational time required for the simulation processes, so it is suitable for nonlinear temperature control for low energy large buildings with features such as large capacity and longtime delay. The controller is developed using a computer simulation of a virtual building contains most parameters of a real building. Fuzzy rules are learned from experts and system performance observations. The proposed controller is tested using Matlab/Simulink environment, the results show that the Sugeno controller has a good response. Achieving these purposes will increase the thermal comfort and reduce energy consumption.

Index Terms— Thermal Comfort, HVAC, Sugeno Fuzzy Control, Large Buildings.

I. INTRODUCTION

After the energy crisis in the 1970s, energy conservation has been considered as a major parameter in all buildings. The greatest energy consumption in buildings occurs during their operation rather than during their construction, there are many types of construction buildings, some of these buildings called low energy buildings. Low energy buildings are any type of buildings that from design, technologies and building products use less energy, from any source than a traditional or average contemporary building. In the practice of sustainable design, sustainable architecture, low-energy building, energy-efficient landscaping low-energy houses often use active solar and passive solar building design techniques and components to reduce their energy expenditure. Based on surveys, the energy consumption in the HVAC equipment in all residential, commercial, and industrial buildings constitutes about 40% to 50% of the world's energy consumption [1]-[4] as shown in Figure 1. Thus, in recent years, many techniques have been considered for reducing the energy consumption in HVAC systems. The implementation of different control methodologies for controlling parameters of heating, ventilating and air-conditioning (HVAC) systems as a part of building automation systems and other energy consumption factors and energy sources were investigated [1].

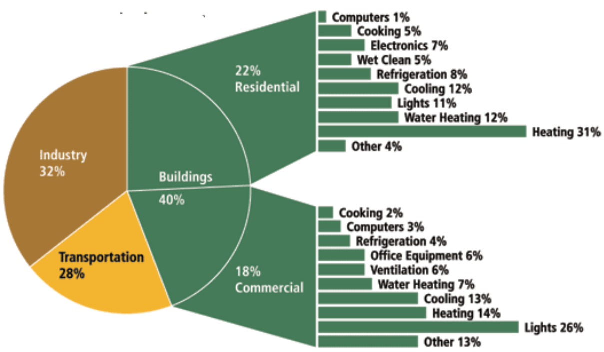

Figure 1 Energy Consumption by Sector [5]

Classical HVAC control techniques such as the ON/OFF controllers (thermostats) and the proportional-integral-derivative (PID) controllers are still very popular because of their low cost. However, in the end, these controllers are expensive because they operate at a very low-energy efficiency. Proper control of low energy buildings [2], which is more difficult than in conventional buildings due to their complexity and sensitivity to operating conditions, is essential for better performance. This paper presents hierarchical fuzzy controller the HVAC system capable of maintaining comfort conditions within a thermal space with time varying thermal loads acting upon the system with high air quality. To achieve this objective, we carry out the design of an HVAC control system that counteracts the effect of thermal loads on the space comfort conditions. The controller achieves this objective by adapting the varying parameters of thermal loads acting upon the system and using the hierarchical fuzzy with two levels to take the appropriate control actions to maintain space comfort conditions. First fuzzy level is adaptive level for varying parameters. It controls the deference temperature just after entering the room and the real temperature in the room. This variation in temperature is due to slow spread nature of heating the air in an open large spaces and it is due to changes happened in this space as large windows opened or any external disturbances [3]. The second varying parameter is the quality of air inside this space cause if people are crowded in this space CO2 concentration will change and the need of new air is essential, so a new cold air must enter the space. These varying parameters are nonlinear and cannot be expected, when it will be changed such as adaptive controller is needed, also an intelligent controller as fuzzy control method is very useful and flexible with unknown systems [4].

II. Sugeno Type Fuzzy Inference

In this section the Sugeno method of deductive inference for fuzzy systems based on linguistic rules is introduced. The Sugeno procedure was proposed in an endeavor to expand a systematic method for producing fuzzy rules from a certain input-output data collection. A generic rule in a Sugeno model, which has two—inputs x and y, and output z, is as follows [6]:
IF x is A and y is B, THEN z is z = f (x; y)
Where z = f (x; y) is a crisp function. Usually f (x; y) is a polynomial function of the inputs x and y. However, in general it can be any public function characterizing the output of the system inside the fuzzy area. When f (x; y) is a constant the inference system is known as a zero-order Sugeno model. It is a particular case of the Mamdani system in which each rule's resultant is determined as a fuzzy singleton. When f (x; y) is a linear function of x and y, the inference system is known as a first order Sugeno model.
In a Sugeno model each rule has a crisp output presented by a function; for this reason the total output is gained via a weighted average defuzzification (Eq. 1) [7].
The weighted average method is one of the most popular methods used in fuzzy applications as it is a very effective method in terms of calculation. The algebraic expression is as follows:

$$Z^* = \sum \frac{\mu c(z).z}{\mu c(z)} \qquad (1)$$

Where $\sum$ represents the algebraic sum while z is the centroid of each symmetric membership function. In the design procedure of such a controller two input linguistic variables are used, namely error (e) as X and its rate of change ($\dot{e}$) as Y. Increasing or decreasing the control signal is assumed as output linguistic variable (U). In order to form fuzzy If - Then Rules Gaussian membership functions are considered for input linguistic variables (X) and (Y), respectively. The general shape of input membership functions are as follows:

$$\mu(z) = \exp\left(\frac{(z.c)^2}{2\alpha}\right) \qquad (2)$$

Where c is the mean and α is the variance of each membership function. The parameter z is the crisp input amount which has to be fuzzified and z is its membership function degree with a numerical value in the interval [0, 1]. Also 25 output polynomial functions are defined for first-order Sugeno type fuzzy inference.
Applying inputs' membership functions and output polynomial functions will result in a rule-base which is composed of 25 rules as the table 1:

R1: IF X is Zero and Y is Zero THEN,
U1 = p1x + q1y + r1

TABLE 1: FUZZY CONTROL RULE BASE

Er	*Ch-Er*	*Zero*	*Small*	*medium*	*Large*	*Very large*
Zero		Z	S	M	L	VL
Small		S	M	L	VL	VL
Medium		M	L	VL	VL	VL
Large		L	VL	VL	VL	VL
Very large		VL	VL	VL	VL	VL

As shown in Figure 2, the above 25 IF-THEN rules are combined together in the form of first-order Sugeno model.

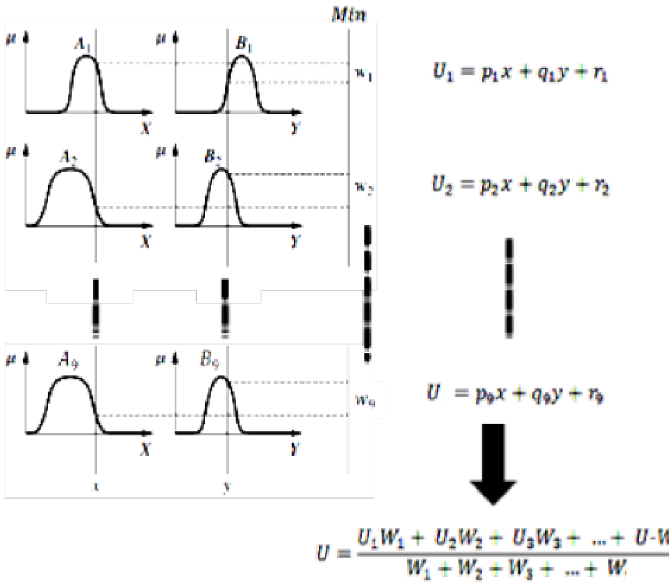

Figure.2 Sugeno Fuzzy Model

III. Hierarchical Fuzzy Control

For designing a fuzzy system with a good amount of accuracy, an increase in the number of input variables to the fuzzy system results in an exponential increase in the number of rules required. If there are n input variables and m fuzzy sets are defined for each of these, then the number of rules in the fuzzy system is m^n, this can be shown with the help of a small example. Suppose there are 5 input variables and for each variable 3 fuzzy sets are defined, then the total number of rules is 243. Now, suppose number of fuzzy sets is increased to 5 (to increase the accuracy of the system), then the new number of the rules would be 3120. Thus resulting a huge increase in the number of the rules. The idea behind the construction of a two-level hierarchical scheme is to make a layered structure of control where each layer takes into account a certain number of variables and gives a single variable as the output. Hence the complexity of the system reduces, and along with it, the number of rules to be framed [8].

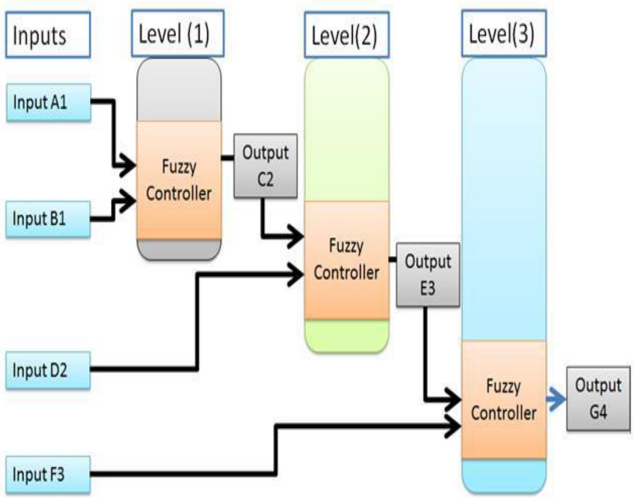

Figure 3 A three Level Hierarchical Fuzzy Control

A hierarchical fuzzy rule based control strategy is proposed for the optimum control of the heating system. Fuzzy rule based controllers are widely used on systems with high uncertainties and can be interpreted linguistically Figure 3.

Fuzzy rules are generated from optimization results calculated for values of the inputs at the centers of the fuzzy sets. Even if it is assumed that each of the fuzzy input variables is described by 5 fuzzy sets, the total number of rules would be very large (625). Therefore, it would take many years to generate the rules and they would be very difficult to understand. A hierarchical approach is adopted to reduce the number of fuzzy rules to 25 rules each level only which mean (75) rules for whole system with reduction of (550) rules with conventional method.

IV. HVAC System

A single-zone HVAC system is shown in Figure 4. It consists of the following components: a heat exchanger (air conditioner), a circulating air fan, the thermal space [9], the chiller providing chilled water to the heat exchanger, connecting ductwork, dampers, and mixing air components. In our discussion, we assume the system is operating on the cooling mode (air conditioning). The basic operation of the system in the cooling mode is as follows
First, 25% of fresh air is allowed into the system and it gets mixed with 75% of the recirculated air (position 5) at the flow mixer. Second, air mixed at the flow mixer (position 1) enters the heat exchanger where it gets conditioned. Third, the air coming out of the heat exchanger already is conditioned to enter the thermal space, and it is called supply air (position 2). Fourth, the supply air enters the thermal space to offset the sensible (actual heat) and latent (humidity) heat thermal loads acting upon the system. Finally, the air in the thermal space is drawn through a fan (position 4), 75% of this air is recirculated and the rest is exhausted from the system.

The control inputs for the system are the pumping rate of cold water from the chiller to the heat exchanger and the circulating airflow rate using the variable speed fan. These set of control actions characterize the HVAC system as:

- A variable-air-volume system (VAV) that results in the lowest energy consumption.
- A variable chilled water flow rate system that allows a reduction of pump energy at light loads [10].

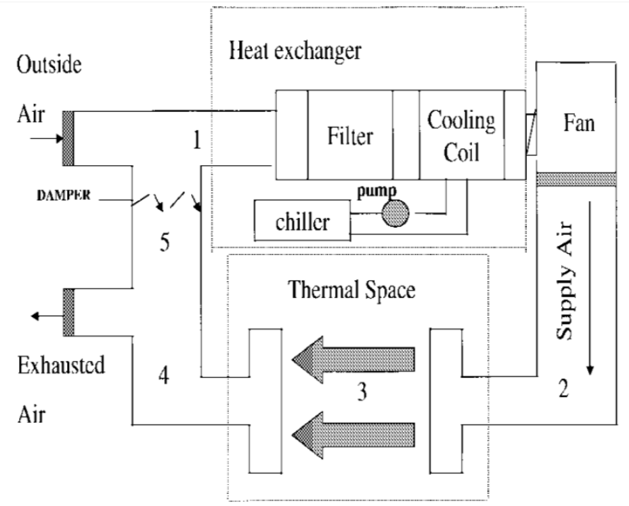

Figure 4: Model of the HVAC System

The System consists of:
System: Air temperature inside the room or hall.
Fuzzy Level 1: Control the error of varying parameters to adjust main controller.
Fuzzy Level 2: The main temperature controller.
Disturbances: As opening windows or doors and CO2 concentration.
Temperature T0: The reference Air Temperature.
Temperature T1: Air Temperature after disturbances.
Temperature T2: Air Temperature after being heated from heating system (AHU).
Temperature T3: Air Temperature inside the room as shown in Figure 5.

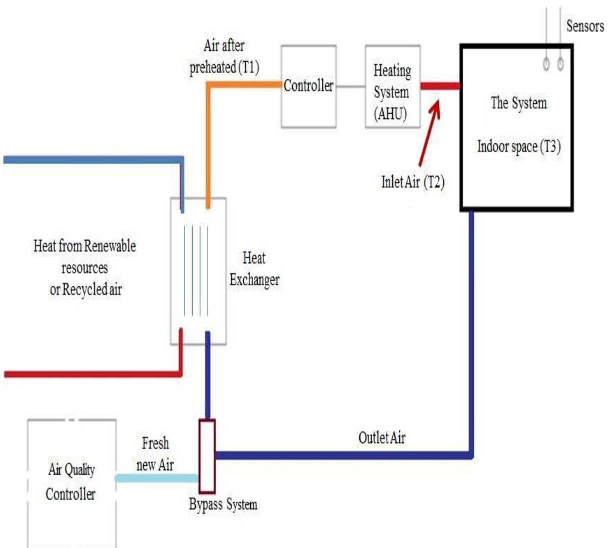

Figure 5: HVAC System

V. Sugeno Fuzzy Controller Design

To design a fuzzy control with a good amount of accuracy, an increase in the number of input variables to the fuzzy system results in an exponential increase in the number of rules required. Therefore, we use hierarchical fuzzy logic control (Sugeno method) to be implemented in large buildings as malls, hypermarkets, or large centers. It is extremely hard to get mathematical model for the system, therefor we have to adapt the varying parameters and the essential varying parameters are:

- Occupants Crowded and the amount of heat needed.
- Air quality degradation and need of fresh air.
- Doors and windows opening make disturbance of the system.

Therefore, it is hard to expect these varying parameters offline or online. Applying the principle of fuzzy control to HVAC system. The proposed fuzzy control system structure is shown in Figure 6

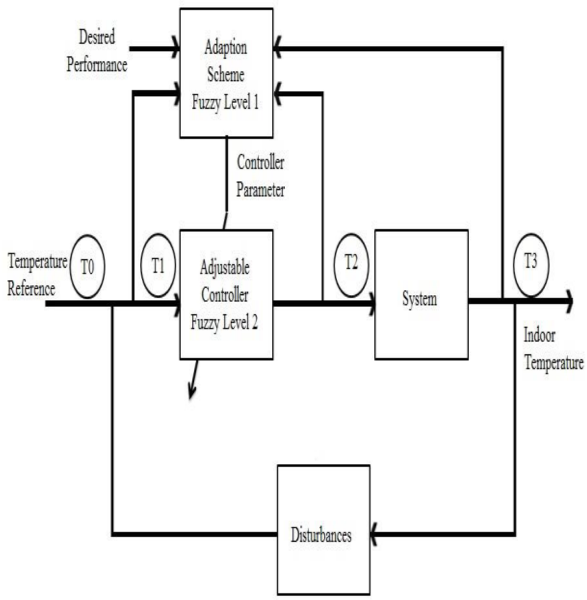

Figure 6: Fuzzy Controller Scheme

We suppose that the initial air temperature values for both T1 and T3 will be -20 C º. Both T1 and T3 temperature will have the same value of temperture until they reach 20 Cº then T1 and T3 will have different value of temperature. The change of T1 and T3 happen because in the beginning of the day we predict that no new air is needed then a variation in temperature between T1 and T3 is due to disturbances we previously talked about. Controller's performance in the period between -20 Cº and 30 Cº as shown in Figure 7, is needed to stabilize the system and give the desired design requirments performance.

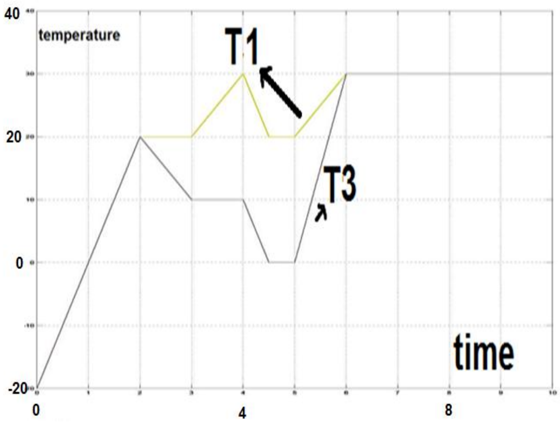

Figure .7: Air Temperature T1 and T3

By using the fuzzy logic graphical user interface, the fuzzy inference system (FIS) for Sugeno type based controller and each input variable has five membership functions as shown in Figure 8 and Figure 9 respectively.

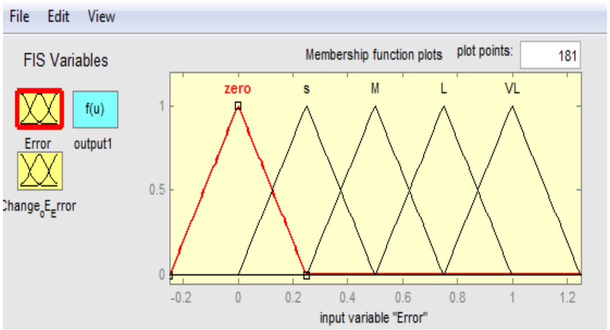

Figure 8: Membership Function of Input Error e

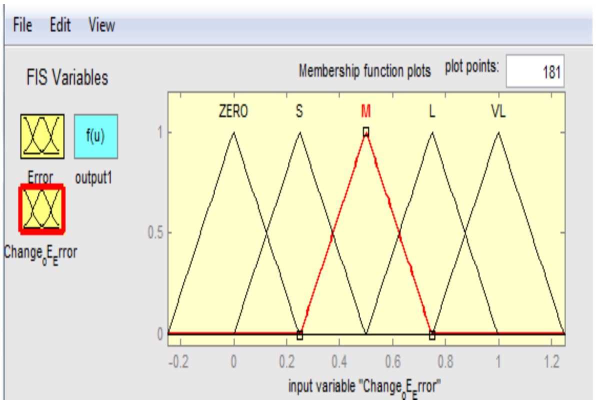

Figure 9: Membership Function of Input Change of Error Δe

The Error membership functions are; zero, small, medium ,large , very large while the change of error membership functions are zero, small , medium ,large , very large.
The output variable also has five membership functions namely; zero, small, medium, large, and very large as shown in Figure 10 below:

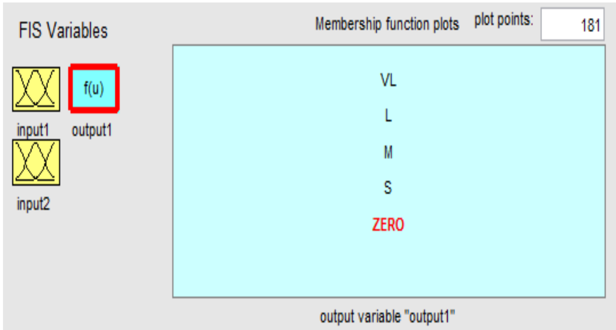

Figure 10 Fuzzy Control Output

These rules in table 1 were applied to the inputs and the output of the Sugeno-type fuzzy inference system based controller as shown in Figure 11.

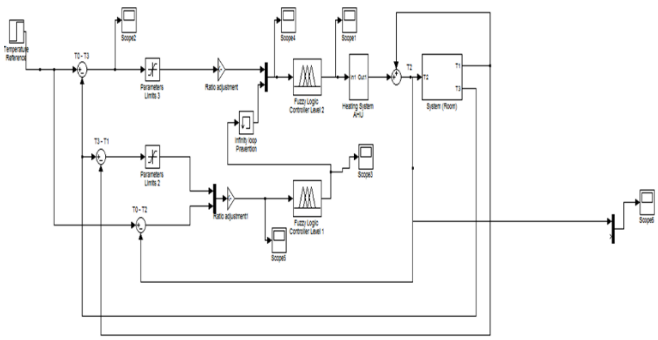

Figure 11: HVAC Fuzzy Controller Simulink Block Diagram

The system is time varying and we need an intelligent control as fuzzy control approach. The control method is depending on two control level; In first fuzzy level the inputs are the change of error .In second fuzzy level inputs are the error and the result of fuzzy control level 1(Change of Error). Error is the difference between reference air temperatures (T0) and the air temperature inside the room (T3) - as any traditional close loop control - and fuzzy control level 1(Change of Error) correct control operation of fuzzy level 2 because of these reasons:

1. If a new fresh air enters the system there is no feedback for this change and based on that no change in the error T0. T3.
2. The nature of heat spread is slow so we cannot know what air temperature is just after heating system .If we don't take it in to consideration it never mind that heating system works as On / Off method (Open loop control for heating system) Therefore, these

problems make fuzzy control level 1 is very important to correct this control loop. Sugeno Fuzzy-Controller will control the first level of its adapted to the varying parameters. These parameters may caused by disturbances or unexpected system performance.

Results of Sugeno fuzzy controller with a desired reference temperature of 30 C is shown in Figure 12. These results show good results.

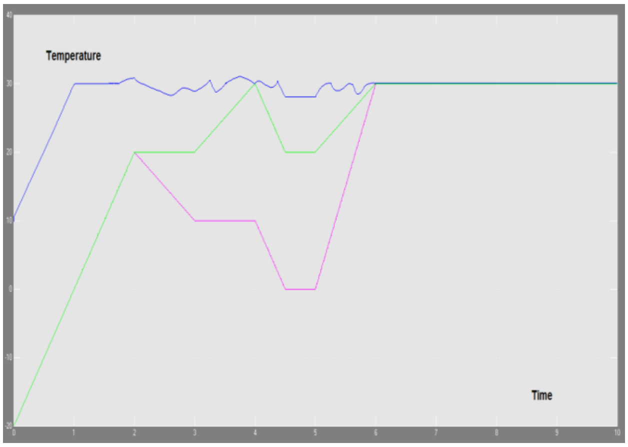

Figure12. Sugeno Method Result Blue Line is T2, Red Line is T1 and Green Line is T3

IV. CONCLUSION

A hierarchical fuzzy control approach (Sugeno method) is introduced to control a HVAC system for large buildings. This approach reduces the fuzzy rule numbers but still maintains the linguistic meaning of fuzzy variables and adapt to changes and disturbances that may be happened to the system in any time. Hierarchical fuzzy method help to reduce the number of rules used in this controller and make it easy to understand rules evaluation and make it possible to increase the number of inputs without fearful of rules increase. Hierarchical fuzzy make it easy to partition the controller and this approach gives a better understand of controller running. The proposed controller tested using Matlab/Simulink program.

The results show that the heat ventilation air condition (HVAC) systems by Sugeno fuzzy logic controller has good results.

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