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Fuzzy Logic-Based Direct Load Control Scheme for Air Conditioning Load to Reduce Energy Consumption

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ABSTRACT A huge body of research is concentrated on developing advance load control strategies for reducing energy consumption and ensuring smooth operation of power system. Air conditioning loads are considered major energy consuming electrical loads in residential and business buildings, and that may cause significant rise in energy consumption. This paper presents an implementation of fuzzy controller with different number and shapes of membership functions for smoothing energy consumption of an air conditioning load while dealing with thermal disturbances. Simulations are conducted in MATLAB Simulink and the results demonstrate that the fuzzy controller with triangular membership function gives the desired performance with an error of less than 1% and saves 25% energy consumption. The obtained results are found effective in terms of smoothing energy consumption pattern of an air conditioning load without compromising consumer' s comfort. Performance of the designed controller is also compared with different controllers including self-tuning adaptive fuzzy controller, linear quadratic regulator (LQR) and nonlinear controllers. The presented fuzzy controller stands-out in terms of desired performance, simplicity and implementation.

INDEX TERMS Fuzzy controller, air conditioning load, energy consumption, temperature control.

NOMENCLATURE

T_3	Room temperature
W_3	Room humidity ratio
T_2	Temperature of supply air
W_s	Supply air humidity ratio
T_o	Outdoor air temperature
W_o	Humidity ratio of outdoor air
V_{he}	Heat-exchanger volume
C_p	Air specific heat
Q_o	Sensible heat load
V_s	Thermal space volume
f	Cubic feet per minute
gpm	Gallons per minute
h_w	Liquid water enthalpy
h_{fg}	Water vapor enthalpy
ρ	Air mass density
MFs	Membership functions
HVAC	Heating, ventilation and air conditioning

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I. INTRODUCTION

Fundamental objective of power system operation is to ensure reliability through maintaining a rigorous balance between generation and demand [1], [2]. A system operator (SO) is responsible to supply the load demand through generation scheduling. However, sometimes, this technique causes uncertainties in power generation and the operation may become expensive with increased cost of power generation. In the literature, numerous techniques are presented to reduce power consumption [3]–[9] of major electrical loads. In the recent years, control of electrical loads for demand side management (DSM) has gained more attention due to penetration of intermittent renewable power generation sources. Demand-side management (DSM) is a technique for managing a customer' s load either by peak and off-peak pricing factor or through direct control of electrical loads, called as direct load control (DLC) [10]–[14]. DSM is widely used for load management to ensure reliable operation of power system, reduced spinning reserves and smooth response to load changes.

Air conditioning loads are one of the major electrical energy consuming devices and are considered as the most suitable appliances for DLC implementation. Importantly, in a domestic load profile, air conditioning loads are quite dominant over the overall shape or pattern of the electrical load curve [15], [16]. Thus, controlling air conditioning loads can help in an effective normalization of the aggregated load profile of a residential or commercial building. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), defines air conditioning loads to exhibit four characteristics including control of air temperature, air humidity, air quality and air circulation. Former two are considered of prime importance from the user' s perspective. It implies that, an air conditioning load must meet the desired level of above-mentioned characteristics [17].

Various researchers have attempted to develop direct load control (DLC) for improving energy consumption of major energy consuming loads such as air conditioners and HVAC etc. In this regard, there are many control methods reported in the literature including proportional−integral−derivative (PID), proportional−integral (PI), proportional−derivative (PD), adaptive, linear quadratic regulator (LQR) controller, nonlinear or fuzzy controllers [18]–[24]. In nonlinear feedback controller, a nonlinear mathematical model is linearized first, then a feedback controller is designed for that linearized model. An estimator is implemented to estimate the thermal noises. A noise rejection controller is then designed to reject these thermal noises, which impacts the performance of an air conditioning load [22], [23]. Complex mathematical calculations are involved in the design process of a nonlinear feedback controller. This controlling method is expensive due to controller, estimator and noise rejection feature. The controller achieves the desired values without considering human thermal comfort, which is one of the major disadvantage of a nonlinear feedback controller [22], [23]. In a linear quadratic regulator (LQR), complex mathematical model is designed first to implement LQR on an air conditioning load. An important and difficult problem while designing this controller is the pole placement. However, human comfort is not considered in that controller [21]. In adaptive controllers, gain factors and different parameters are updated again and again to get optimized solution for the problem [24]. These controllers require more time to achieve the desire results in terms of room temperature and humidity but sometimes human thermal comfort gets disturbed due to requirement of an ambitious performance from controller. Thus, there is a room for developing a controller with the capability to optimize load management without compromising human comfort. Many authors suggested that fuzzy logic based controller may be more effective to control power consumption of a load in a desired manner i.e. energy consumption is improved without compromising the consumer' s comfort [25]–[27].

A fuzzy logic system (FLS) is described as a nonlinear representation of an input value sets to a scalar output values. It works on IF-THEN or IF-OR rules [28] by imitating the ways of making decisions by human, involving all the intermediate possibilities between digital values 0 and 1 (Yes or No) [29]. Fuzzifier takes the crisp inputs. Inference engine generates inference based on fuzzy rules and then defuzzifier converts back that inference to crisp output [30]. A typical fuzzy logic system is shown in fig. 1. FLS predicts approximate results by converting linguistics rules based on expert' s choice when the data is vague. No mathematical model is required to implement FLS and it may be implemented easily.

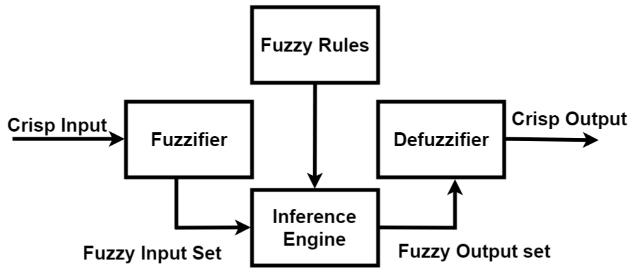


FIGURE 1. Fuzzy logic system (FLS) block diagram.

In the literature, many authors have proposed fuzzy controller technique for an air conditioning load. Majority of the proposed techniques are based on only fuzzy rule formation [31]–[44]. Generally, fuzzy controllers are implemented without considering external parameters and thermal noises affecting the performance of an air conditioning load [38]–[40]. As far as power consumption is concerned, most of the papers are based on implementation of fuzzy controller only. In a few papers, energy consumption is calculated using mathematical equation or measured after practical implementation with limited features of their controller [36], [45]–[47].

Objective of this paper is to design a fuzzy logic controller (FLC) and implement it on a mathematical model of an individual air conditioning load. The designed fuzzy controller effectively deals with the load consisting of indoor and outdoor parameters in the presence of thermal disturbance, which has not been reported in the literature. Fuzzy rules are based on user's choice and comfort. FLC is implemented with different number and shapes of membership functions (MFs). Performance of the controller is compared with other techniques including nonlinear, optimal, self tuning fuzzy controllers etc. Simulation results show that presented fuzzy controller with five triangular MFs achieves the required thermal conditions with an error of less than 1% and saves 25% of total energy consumption without compromising human comfort.

Key contributions of this research paper are as follows:

1) Most of the work presented in the past is based only on fuzzy rule formation. In this paper, fuzzy controller is implemented on an air conditioning load while considering indoor as well as outdoor thermal conditions.
2) The developed controller achieves the desired temperature and humidity ratio simultaneously without

TABLE 1. Literature review with identification of research gaps.

Sr. No.	Technique	Research Gaps	Ref.
1	Fuzzy controller	Fuzzy rule formulation to find fuzzy comfort index. Only sensors are used to get output. Only two parameters are considered.	[48]
2	Fuzzy controller	Only fuzzy rule formation. No implementation of fuzzy rules on load.	[31]–[44]
3	Fuzzy controller	Controller uses error and error rate to control temperature only.	[55]
4	Fuzzy controller	Two parameters are used in controller design. No simulations for energy consumption.	[56]
5	Fuzzy controller	Simulations given for defuzzification only. No implementation of fuzzy rules on load.	[57]
6	Fuzzy-PD controller	Error and error rate are used to control valve opening. A simple transfer function is supposed and step response is obtained through simulation.	[18]
7	Self-tuning fuzzy PID controller	Controller is applied to control temperature of two different zones.	[19]
8	Hybrid fuzzy PID controller	Only temperature is controlled. Gains are updated again and again until desirable results achieved.	[20]
9	Linear-quadratic regulator (LQR)	Controller is applied on augmented HVAC model. Complex in designing mathematical model. Pole placement is difficult while implementation of this controller.	[21]
10	Nonlinear feedback controller	Estimator is designed first to estimate thermal loads and then controller is implemented. A disturbance rejection controller is applied to reject those thermal loads. Controller will be expensive when implemented.	[22], [23]
11	Decentralized Nonlinear Adaptive Controller	Two different types of controller are applied in this control scheme. Require extensive mathematical computations. The controller is complex in implementation.	[24]

disturbing human comfort and without disturbance rejection controller.

3) The presented controller exhibits error of approximately less than 1% in achieving the desired temperature and 6% in the humidity ratio.
4) The designed fuzzy controller is implemented using a number of MFs with their different shapes.
5) To ensure effectiveness of the developed controller, energy consumption is computed for different cases.
6) This paper carries a rigorous comparison of the developed controller with self-tuning adaptive fuzzy controller, linear quadratic controller, and nonlinear controllers.
7) Implementation of the developed fuzzy controller exhibits 25% energy saving of the air conditioning load.

The paper is organized as follows; introduction is given in section-I. Section-II consists of literature review. Mathematical model of an air conditioning load is explained in section-III. In section-IV, methodology is proposed. Section-V contains simulation results. Results are discussed and analyzed in section-VI and the paper is concluded in section-VII.

II. LITERATURE REVIEW

The literature review is divided into two subsections; first section consists of fuzzy controller implemented separately and second sub-section consists of fuzzy controller integrated with other techniques. Literature review with identified research gaps is presented in Table-1.

A. FUZZY LOGIC CONTROLLERS

Traditional air conditioning loads work on constant speed thus they have limited choices in controlling room temperature without disturbing human thermal comfort. Fuzzy rules based models are explained in [31]–[35], [48]–[52] to control air conditioning loads at variable speed for saving energy. A new technique of load scheduling and curtailment is proposed in [53]. Load scheduling is applied to daily used loads while load curtailment is implemented on seasonal load i.e air conditioning systems, using fuzzy logic. Fanger's model and predictive mean vote are used in [54] to design air conditioning load to control temperature through fuzzy rules.

Fuzzy controller is used in micro-controllers to compare and validate results with simulation results in [36], [37], [45]. Islam *et al.* [38] designs a controller in which fuzzy rules are implemented on the very-large-scale integration (VLSI) chip using very high speed integrated circuit hardware description language (VHDL) from electronic design automation (EDA) tool to obtain desired temperature and humidity. [39] proposes a fuzzy controller to control the compressor and fan. Cooling and heating valves are controlled through fuzzy controller whose inputs are temperature and humidity [40], [41], [58]. A new concept of using two fuzzy logic controllers is explained in [42]. In this technique, output of first fuzzifier serves as an input to second fuzzifier for controlling fan speed. The proposed controllers reduce the use of remote control and human endeavor. In [43], [44], [56], indoor as well as outdoor climate conditions have been considered for implementing fuzzy logic controller to maintain required room thermal conditions. In [55], interfacing devices are utilized to process data collected from sensors and to transfer this data to experimental setup. Two different methods of defuzzification are discussed [57] for air-conditioning systems. Heating, ventilation, and air conditioning (HVAC) model is proposed in [46] where microprocessor is used for interfacing fuzzy controller to obtain desired temperature and humidity. A fuzzy model is discussed to control temperature and humidity in different rooms of building [59], [60].

A multivariable optimization technique is introduced in [61], in which, a slide switch is used to select weighting factors for cost and comfort criteria which optimize the operation of heating and ventilation controller. Fuzzy rules are defined in [62], [63], to maintain indoor air quality and thermal comfort in operating rooms according to set standards.

An old fuzzy controller is simplified with predictive mean vote to regulate the controller which in result saves 6% energy [64]. Exhaust, cooler and ventilator fan speed are controlled through fuzzy using MATLAB Simulink [65]. Ventilation is also controlled while maintaining room temperature and humidity [66]–[68]. Fuzzy controller is implemented in pharmaceutical industry to control indoor thermal conditions with an additional feature of controlling microorganism in air [69]. Air conditioning load is tested in [70] with and without fuzzy logic controller. A comparison between ON/OFF and fuzzy controller shows the superiority of fuzzy controller in terms of performance [71]. Wang *et al.* [72] proves that fuzzy is 1.3 times more effective than traditional controller in controlling speed of fan and compressor.

B. FUZZY INTEGRATED WITH OTHER TECHNIQUES

In [18], a practical expert fuzzy based controller is merged with proportional−derivative (PD) controller. A multiple model predictive controller has been designed through fuzzy logic in [73] while considering energy efficiency factor. Fuzzy logic integrates with proportional−integral (PI) controller to maintain room temperature in [47], [74]. Control area network is implemented to control vehicle air conditioning load using fuzzy rules [75]. A fuzzy genetic algorithm is presented in [76] which improves large time requirements and accuracy. A fuzzy controller is suggested [77], which is implemented on experimental setup and results are compared with simulation results. Similarly, a self-tuned fuzzy control algorithm is explained in [78]. A fuzzy proportional−integral−derivative (PID) controller is applied through internet-of-things (IOTs) to control temperature [79], [80]. IOTs when used with fuzzy controller produce better results than working alone. A predictive mamdani control strategy integrated with fuzzy linearization model is implemented on HVAC and its performance is compared with traditional controllers [81].

Fuzzy neural network is suggested in [82]–[84]. Fuzzy logic controller produces more accurate results when used with adaptive controller [85]–[89]. Fuzzy logic is integrated with other traditional controllers like PD, PI, PID, adaptive and optimal controllers explained in [19], [20], [90]–[92]. Results are compared with each other and it is proved that fuzzy works better than other traditional controllers.

III. SYSTEM MODEL

A mathematical model of an air conditioning load is given below [21]–[23] in the form of differential equations

$$\dot{T_3} = \frac{f}{V_s}(T_2 - T_3) - \frac{h_{fg}f}{C_pV_s}(W_s - W_3) + \frac{1}{0.25C_pV_s}(Q_o - h_{fg}M_o) \tag{1}$$

$$\dot{W_3} = \frac{f}{V_s}(W_s - W_3) + \frac{Mo}{\rho V_s} \tag{2}$$

$$\dot{T_2} = \frac{f}{V_{he}}(T_3 - T_2) + \frac{0.25f}{V_{he}}(T_o - T_3) - \frac{fh_w}{C_pV_{he}}((0.25W_o + 0.75W_3) - W_s)) - 6000\frac{gpm}{\rho C_pV_{he}} \tag{3}$$

Eqs. 1-3 represent room temperature, room humidity ratio and air supply temperature, respectively. Q_o and M_o represent thermal loads called as sensible heat load and moisture load, respectively. The thermal loads are disturbances, that are affecting room thermal conditions through sun light falling on window panes, heat emitting from the persons in the room or when door is opened for people entering or leaving the room. F and gpm, volumetric flow rate of air and chilled water flow rate, respectively, are controlling inputs. In this model, outdoor temperature and humidity ratio are also considered, T_o and W_o, respectively.

Equations are converted in state space format for control purposes. Let,

$u_1 = \text{cfm} = \text{f}$; $u_2 = \text{gpm}$;
$x_1 = \text{Room Temperature} = T_3$;
$x_2 = \text{Room Humidity ratio} = W_3$;
$x_3 = \text{Supply air temperature} = T_2$
$y_1 = T_3$; $y_2 = W_3$
and by defining parameters,

$$\alpha_1 = \frac{1}{V_s};\quad \alpha_2 = \frac{h_{fg}}{C_pV_s};\quad \alpha_3 = \frac{1}{\rho C_pV_s};\quad \alpha_4 = \frac{1}{\rho V_s}$$

$$\beta_1 = \frac{1}{V_{he}};\quad \beta_2 = \frac{1}{\rho C_pV_{he}};\quad \beta_3 = \frac{h_w}{C_pV_{he}}$$

the new equations take the form,

$$\dot{x_1} = u_1\alpha_1 60(x_3 - x_1) - u_1\alpha_2 60(W_s - x_2) + \alpha_3(Q_o - h_{fg}M_o) \tag{4}$$

$$x_2^{\cdot} = u_1\alpha_1 60(W_s - x_2) + \alpha_4 M_o \tag{5}$$

$$\begin{aligned} x_3^{\cdot} &= u_1\beta_1 60(x_1 - x_3) + u_1\beta_1 15(T_o - x_1) \\ &\quad - u_1\beta_3 60((0.25W_o + 0.75x_2) - W_s) \\ &\quad - 6000u_2\beta_2 \end{aligned} \tag{6}$$

IV. PROPOSED METHODOLOGY

A mathematical model of an air conditioning load eqs. 4-6 is explained in previous section. All internal and external parameters are used in model of the system. Data used for implementing the model is taken from previous literature. Fuzzy rules are formed on the basis of user's choice of thermal comfort with temperature and humidity error as inputs.

$$e_1 = T_3 - T_{3,req}$$
$$e_2 = W_3 - W_{3,req}$$

There are two controlling inputs, air flow rate f and flow rate of chilled water gpm. Room temperature and humidity are the outputs of the air conditioning load while power is considered at output to analyze its behavior when systems dynamics change. MATLAB Fuzzy Logic Toolbox is used to form fuzzy rules and Simulink is used to implement the presented controller. The proposed scheme is shown in the fig. 2.

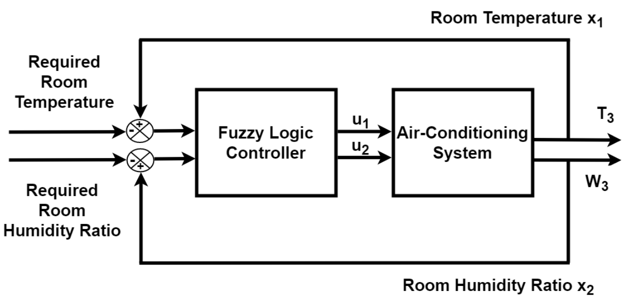


FIGURE 2. Block diagram of proposed methodology.

First mathematical model of the load is implemented in Simulink. Then, fuzzy controller is implemented with three triangular MFs, with increased number of triangular MFs, pi-shaped MFs and gaussian MFs on the load. Fuzzy controller is implemented on the load with some initial and desired conditions. Thermal and humidity loads are used in simulation to test performance of the controller designed. The thermal loads, moisture and sensible heat load, are taken in the form of sinusoidal curve to observe their effect on the system dynamics. The reason for choosing sine wave instead of constant is to imagine room thermal conditions in real scenario where thermal loads are continuously changing. Centroid method of defuzzification is used for each fuzzy controller.

V. SIMULATIONS

Fuzzy logic controller is implemented using the data given in Table-2 [22]. This section is comprised of two sub-sections; first sub-section consists of simulations for controller and the results for energy consumption are given in the next sub-section.

TABLE 2. Numerical values and equilibrium conditions.

Parameter	Value	Parameter	Value
T_{2ref}	$(13^oC)\ 55^oF$	W_s	$0.007\frac{lb}{lb}$
T_o^e	$(29^oC)\ 85^oF$	W_o^e	$0.018\frac{lb}{lb}$
V_{he}	$60.75ft^3$	C_p	$0.24\frac{Btu}{lb.^oF}$
M_o^e	$166.06\frac{lb}{hr}$	Q_o^e	289897.52
V_s	$58464ft^3$	f^e	17000 cfm
ρ	$0.074\frac{lb}{ft^3}$	gpm^e	58 gpm
h_w	$23\frac{Btu}{lb}$	h_{fg}	$1087.1\frac{Btu}{lb}$

A. SIMULATIONS FOR CONTROLLER

To implement fuzzy controller, rules are designed based on user's own thermal comfort. Controller is implemented for different cases as follows;

1) Case-I: Fuzzy controller with three membership functions
2) Case-II: Fuzzy controller with increased number of membership functions
3) Case-III: Fuzzy controller with different shapes of membership functions

The numerical values of various parameters with initial and final conditions for different seasons (summer and winter) are given below in Table- 2, Table-3 and Table-4, respectively.

TABLE 3. Initial and required values for summer season.

$T_{3,initial}$	25°C (77°F)	$W_{3,initial}$	$0.016\frac{lb}{lb}$
$T_{3,required}$	22°C (71.6°F)	$W_{3,required}$	$0.01\frac{lb}{lb}$

TABLE 4. Initial and required values for winter season.

$T_{3,initial}$	14°C (57.2°F)	$W_{3,initial}$	$0.002\frac{lb}{lb}$
$T_{3,required}$	27°C (80.6°F)	$W_{3,required}$	$0.009\frac{lb}{lb}$

1) SIMULATIONS FOR FUZZY CONTROLLER WITH THREE TRIANGULAR MFs

In this case, only three triangular MFs are used for input and output. Two inputs are temperature and humidity ratio errors. Nine fuzzy rules are designed given in Table-5. Fuzzy controller is implemented for summer condition with same parameters given in Table-2 and Table-3. Membership functions are divided into following;

Negative = N,
Zero = Z
Positive = P

Membership functions for temperature error and humidity ratio error are given in figures below in fig. 3 and fig. 4 respectively.

TABLE 5. Fuzzy rules with three MFs.

Temperature Error	Humidity Error	Fan Speed	Chilled water flow rate	Power
P	P	H	H	H
	Z	H	H	H
	N	M	M	M
Z	P	M	M	M
	Z	M	M	M
	N	M	L	L
N	P	M	M	M
	Z	M	L	L
	N	L	L	L

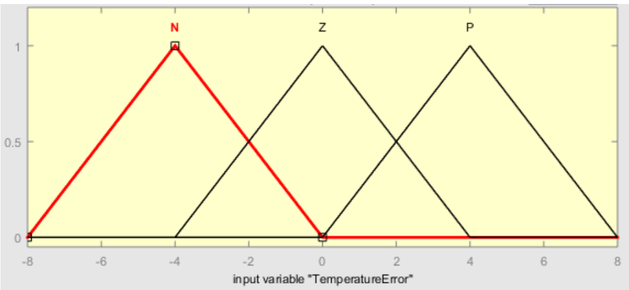


FIGURE 3. Three MFs for temperature error.

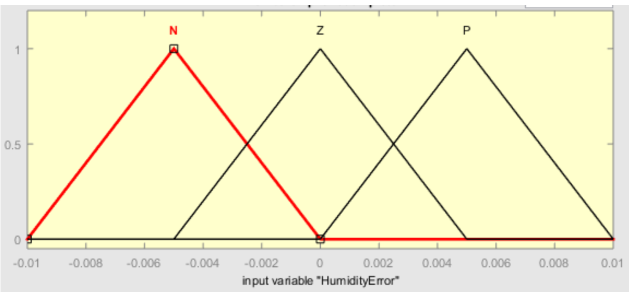


FIGURE 4. Three MFs for humidity ratio error.

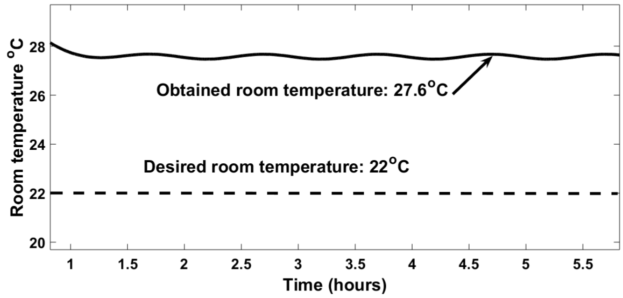


FIGURE 5. Room temperature response in summer with three MFs.

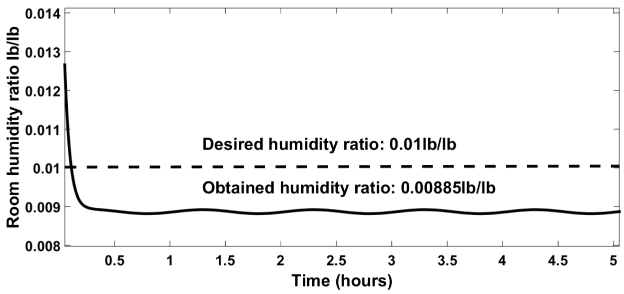


FIGURE 6. Room humidity ratio response in summer with three MFs.

The required room temperature and humidity ratio are 22^oC and $0.01\frac{lb}{lb}$, respectively. The room temperature achieved through this controller illustrated in fig. 5 and it depicts that the controller achieves 27.6^oC temperature. Humidity ratio obtained is shown in fig. 6 and it depicts that controller achieves $0.00885\frac{lb}{lb}$ humidity ratio. The controller shows huge deviation from the required values showing 25% error in achieving required temperature and 11% humidity ratio. It is seen that the performance of controller in this case is slow.

2) SIMULATIONS FOR FUZZY CONTROLLER WITH INCREASED NUMBER OF TRIANGULAR MFs

For this case, fuzzy rules are given in Table-6. Membership functions are divided as

Positive big = PB
Positive = P
Positive small = PS
Zero = Z
Negative = N
Negative big = NB

Triangular membership function is used for fuzzification and centroid method of defuzzification is used by trial and error method. Membership functions for both are given in fig. 7 and fig. 8.

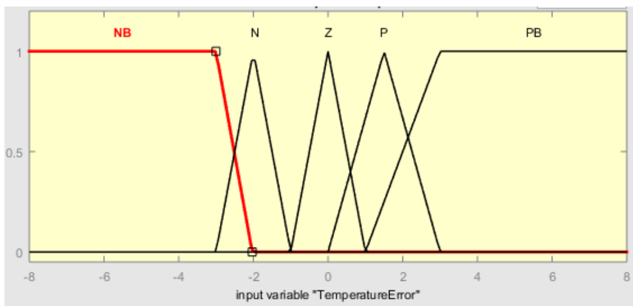


FIGURE 7. Membership functions for temperature error for case-II.

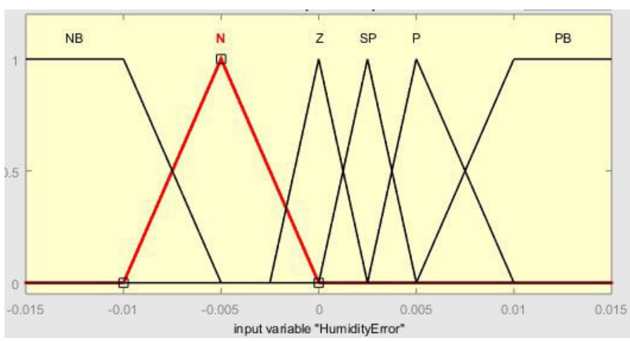
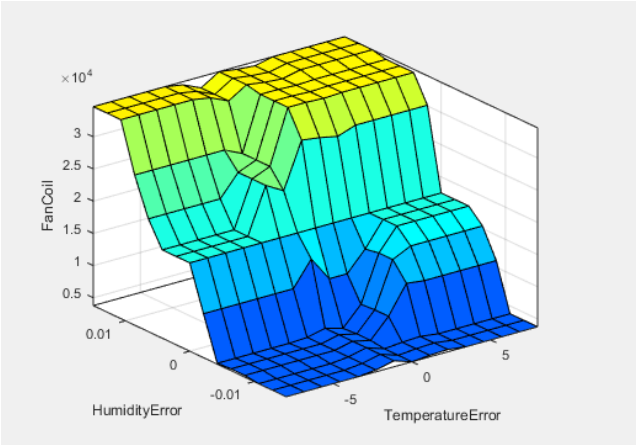
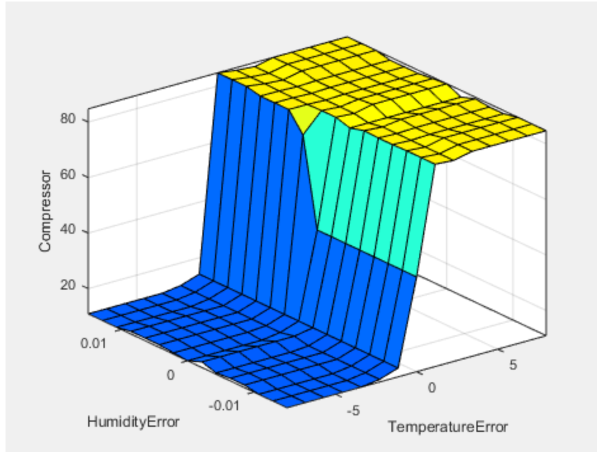


FIGURE 8. Membership functions for humidity error for case-II.

3-D graphs for cfm and gpm are shown in fig. 9a and fig. 9b, respectively. Fan speed is compared with temperature



(a) 3D Fuzzy graph for fan coil speed for controller with increased number of MFs



(b) 3D Fuzzy graph for chilled water flow for controller with increased number of MFs

FIGURE 9. 3D fuzzy graphs for case-II.

TABLE 6. Fuzzy rules for controller with increased number of MFs.

Temperature Error	Humidity Error	Fan Speed	Chilled water flow rate	Power
PB	PB	H	H	VH
	P	H	H	VH
	SP	H	H	H
	Z	M	H	H
	N	M	H	N
	NB	L	H	N
P	PB	H	H	VH
	P	H	H	H
	SP	H	H	H
	Z	M	H	N
	N	L	H	N
	NB	L	H	N
Z	PB	H	H	H
	P	H	H	H
	SP	H	H	N
	Z	M	M	N
	N	L	M	N
	NB	L	M	L
N	PB	H	L	H
	P	H	L	N
	SP	H	L	N
	Z	M	L	L
	N	L	L	L
	NB	L	L	VL
NB	PB	H	L	N
	P	M	L	L
	SP	M	L	L
	Z	M	L	L
	N	L	L	VL
	NB	L	L	VL

and humidity error, shown in fig. 9a which depicts that when temperature and humidity ratio errors are small, then there is a small change in fan speed. In summer, when temperature error is large, an air conditioning load uses maximum potential to maintain desired temperature that is why air speed and chilled water flow rate are high. In winter, when temperature error is large negative NL, the heating capability increases to maintain room temperature at desired values. Similarly, when both errors are positive big, there is an increase in gpm as shown in fig. 9b. At very low negative errors, the speed of both air flow and gpm are low. Controller acts for two seasons, summer and winter. In summer, the required room temperature and humidity ratio are $71.6^oF(22^oC)$ and $0.01\frac{lb}{lb}$, respectively, as shown in Table-3. Response of controller in maintaining room temperature and humidity ratio are shown in fig. 10 and 11. It is observed from the obtained results that controller achieves room temperature of 22.2^o and humidity ratio of $0.0094\frac{lb}{lb}$. It is observed that fuzzy controller in this case maintains room thermal conditions close to required conditions.

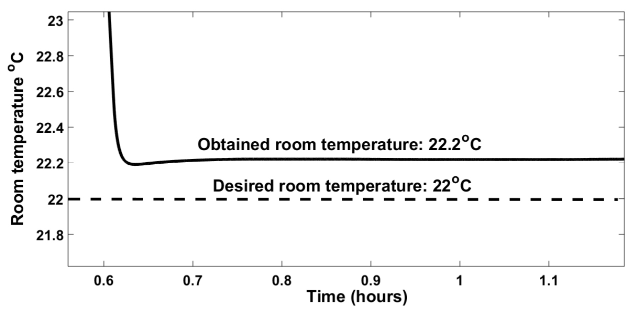


FIGURE 10. Room temperature response in summer for controller with increased number of MFs.

For winter conditions, heater fan turns ON to maintain room temperature. The required room temperature is 27^oC and the humidity ratio is $0.009\frac{lb}{lb}$ given in Table-4. It may be observed that the controller tracks the desired values in a suitable manner as depicted in fig. 12 and fig. 13 i.e. controller is capable to obtain 27.1^oC temperature and $0.0091\frac{lb}{lb}$ humidity ratio. It is evident that the percentage error between desired and achieved temperature and humidity ratio is less than 1% and 6% respectively.

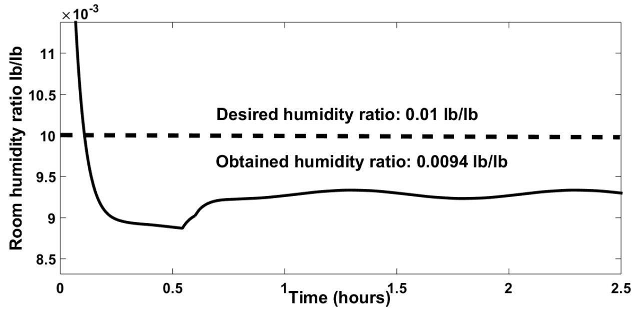


FIGURE 11. Room humidity ratio response in summer for controller with increased number of MFs.

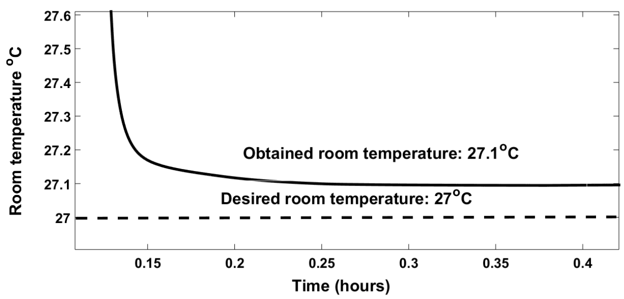


FIGURE 12. Room temperature response in winter for controller with increased number of MFs.

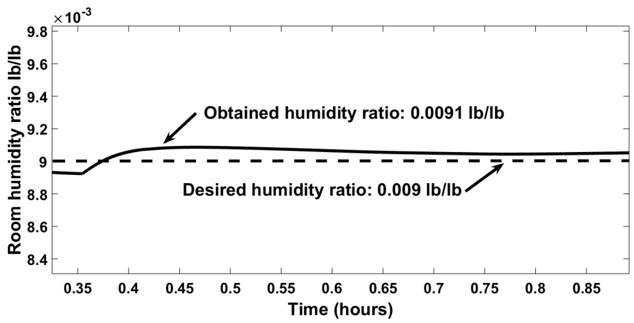


FIGURE 13. Room humidity ratio response in winter for controller with increased number of MFs.

3) SIMULATIONS FOR FUZZY CONTROLLER WITH DIFFERENT MFs

Triangular MFs are used in previous two cases. In this case, different shapes of membership functions are used to test the performance of fuzzy controller. Fuzzy controller is implemented with gaussian and pi-shaped membership functions. Rules and parameters are kept same as that of in case-II i.e. controller with increased number of MFs. Five MFs are chosen for temperature error and for humidity ratio error six MFs are used. The required room temperature and humidity ratio in summer season are 22^{o}C and $0.01\frac{lb}{lb}$.

At first, fuzzy controller is implemented using pi-shaped MF. Simulation results show that the design controller does not achieve desired results. Controller achieves 27.6^{o}C temperature and $0.008875\frac{lb}{lb}$ humidity ratio as shown in fig. 14 and fig. 15. Then, fuzzy controller is implemented with gaussian shaped membership function. It is observed that the controller becomes able to achieve 23.475^{o}C temperature and $0.008875\frac{lb}{lb}$ humidity ratio, illustrated in fig. 14 and fig. 15, respectively.

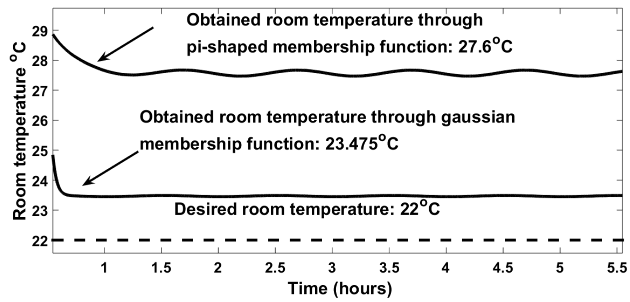


FIGURE 14. Room temperature response for different shapes of MFs.

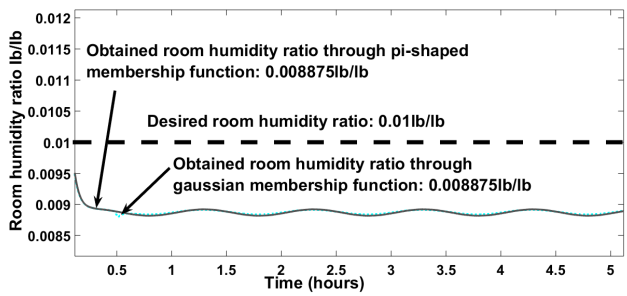


FIGURE 15. Room humidity ratio response for different shapes of MFs.

B. CALCULATIONS FOR ENERGY CONSUMPTION

Energy consumption is calculated for air conditioning load to observe the effect of controller on the load. In case-I and case-III, the controller does not achieve required results. However, in case-II, controller having five MFs for temperature error and six MFs for humidity ratio, achieves desired thermal conditions.

In the case-II, the controller achieves the required temperature in 6 minutes. The total time for the system to remain OFF is 20%.

Following are the air conditioning system's parameters which are used to calculate energy consumption;

Capacity $= 340650.78\frac{Btu}{hr}$

Energy efficiency ratio EER $= 11.4$

Operating time in a year $= 1500$hrs

From the eq. 7 below, energy consumed by a conventional system is

$$Annual\ Energy = \frac{Capacity * Operating\ Time}{EER} \tag{7}$$

The annual energy consumed by conventional load is 4482kWh. The air conditioning load operates for 80% of the total time. The total operating hours of air-conditioning system is $\frac{80}{100}$*1500 = 1200hrs. Upon implementation of the proposed controller annual energy of the air conditioning load is found to be 3585kWh which is 25% less than that of the consumption without controller's action.

Fig. 16 and fig. 17 are 2-D graphs generated from MATLAB Fuzzy Logic Toolbox after fuzzy rule formation. Power consumption is computed with change in room temperature and humidity ratio errors, respectively. In fig. 16, for a very small change in room temperature error, there is a small change in power consumption. When temperature error increases, power consumption starts increasing until consumption becomes constant. When temperature error increases, power consumption does also increase because of increased air flow rate and liquid flow rate to obtain the desired thermal conditions. Thus, the air conditioning load uses its maximum potential to maintain the desired room temperature conditions. In fact, there is an error point where energy consumption becomes constant. Similarly, in fig. 17, there is a small change in power consumption, when humidity ratio error is small. After increase in humidity ratio error upto a certain point, power consumption also increases. Eventually power consumption becomes constant even if humidity ratio error keeps increasing.

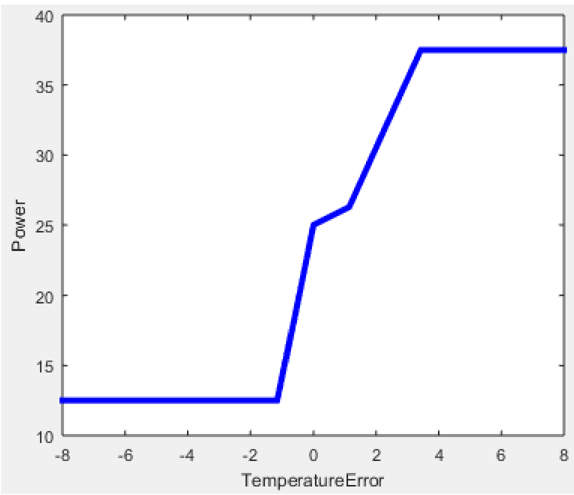


FIGURE 16. Power kW consumed with change in temperature error for controller with increased number of MFs (Case-II).

Annual energy consumption in case-I and case-III is the same as without implementation of the controller on the air conditioning load. This is due to the fact that the controller, in both cases, uses its maximum potential to achieve desired results but could not achieve required thermal conditions. In other words, the controller keeps on consuming energy while achieving desired thermal conditions. A comparison of energy consumption between different cases is given in fig. 18.

VI. DISCUSSION AND ANALYSIS

There have been many techniques reported in the literature to control air conditioning loads in order to save energy consumption, while maintaining indoor thermal comfort for the consumers. Conventional controllers are easy to use and are low-priced but in the long run, they require maintenance which makes them expensive. In this paper, a fuzzy control scheme is presented which maintains indoor thermal conditions while tackling the thermal disturbance. Fuzzy rules are based on human' s choice of comfort.

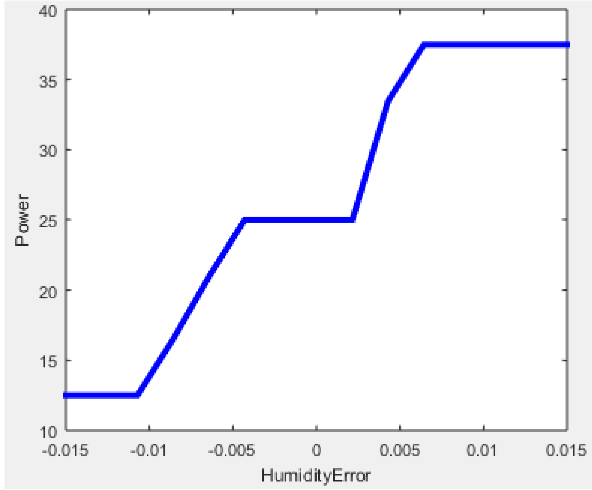


FIGURE 17. Power kW consumed with change in humidity error for controller with increased number of MFs (Case-II).

From the presented results as shown in fig. 5 and fig. 6, it is noticed that the controller remains unable to achieve the desired performance when implemented with three triangular membership functions. There is an error of 25.45% in achieving temperature and 11.5% in humidity ratio. However, with increased number of triangular MFs, controller becomes able to maintain the desired results with an error of approximately less than 1% in the temperature and 6% in humidity ratio. Upon implementation of the developed controller, energy consumption is reduced by 25%. The controller' s performance is tested for different shapes of MFs. First, controller is implemented with pi-shaped MFs and simulation results show that controller gives 25.45% error in temperature and 11.25% error in humidity ratio. However, controller with gaussian MFs performs better than that of controller with pi-shaped MFs. Controller with gaussian MFs gives an error of 6.7% error in temperature and 11.25% in humidity ratio. A detailed comparison of the fuzzy controller for the considered cases is given in Table-7 and Table-8.

From the obtained results, it can be concluded that fuzzy controller with increased number of triangular MFs achieves the desired results when compared with controller having pi-shaped and gaussian shaped MFs. Though, it may not be true for every scenario and system as sometimes triangular MFs do not ensure the desired performance when compared with other MFs.

Performance of the presented fuzzy controller is compared with conventional techniques including LQR and feedback nonlinear controllers. Linear quadratic regulator (LQR) is a linear technique that provides feedback gains, which are optimally controlled to get stable and better results from

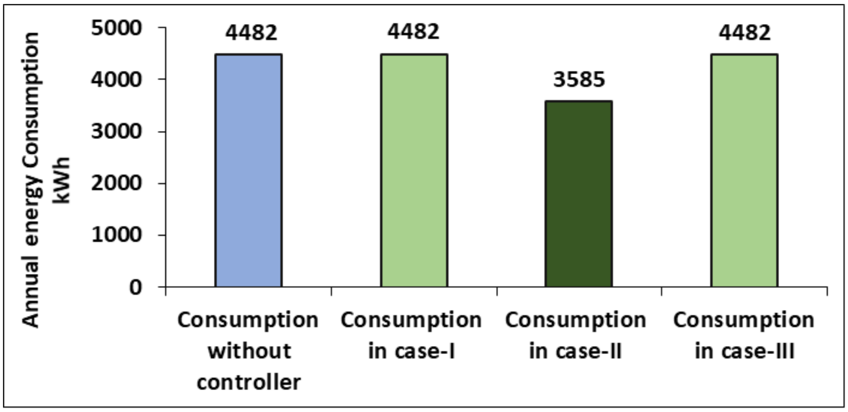


FIGURE 18. Comparison of annual energy consumption in different cases.

TABLE 7. Comparison of controllers in temperature control.

Fuzzy controller	Temperature achieved °C	Percentage error %
with three triangular MF	27.6	25.45
with five triangular MF	22.2	0.91
with pi-shaped MF	27.6	25.45
with gaussian MF	23.475	6.7

TABLE 8. Comparison of controllers for humidity ratio control.

Fuzzy controller	Humidity ratio achieved $\frac{lb}{lb}$	Percentage error %
with three triangular MF	0.00885	11.5
with five triangular MF	0.0094	6
with pi-shaped MF	0.008875	11.25
with gaussian MF	0.008875	11.25

the designed system. This type of control technique is capable to optimally balance error of the system and the control effort based on a cost function specified by a user. In linear quadratic regulator (LQR), first, feedback linearization method is implemented to linearize the mathematical model of the air conditioning load. A LQR controller is then designed to regulate this linearized model of load to obtain desired set points. The objective of LQR is to design a stable controller to minimize the cost function J given below;

$$J = \frac{1}{2}\int_0^{\infty}\left[\int_0^{\infty}\sum_{i=1}^{l} Q_{ii}x^2 + \rho\sum_{j=1}^{m} R_{jj}n^2\right]dt \tag{8}$$

In order to implement LQR method, we need to define two parameters: the state-cost weighted matrix (Q) and the control weighted matrix (R). Q and R are the positive semi-definite state weighting matrix and positive definite control weighting matrix, respectively and are selected to be diagonal matrices. These matrices are chosen from Bryson' s rule as given below,

$$Q_{ii} = \frac{1}{maximum\ acceptaced\ value\ of\ x_i^2} \tag{9}$$

$$R_{jj} = \frac{1}{maximum\ acceptaced\ value\ of\ n_j^2} \tag{10}$$

While, i∈ $\{1, 2, 3, \ldots\ldots, l\}$, j∈ $\{1, 2, 3, \ldots\ldots, m\}$, x is state vector, n is control input and $\rho = (\frac{max\ state\ error}{max\ control\ input})^2$. For this controller, $Q = \begin{bmatrix} 0.00049 & 0 & 0 \\ 0 & 60 & 0 \\ 0 & 0 & 0.00035 \end{bmatrix}$ and $R = \begin{bmatrix} 31 * 10^{-9} & 0 \\ 0 & 2.37 * 10^{-4} \end{bmatrix}$. Upon the simulations, the feedback gain is found to be $K = \begin{bmatrix} 0 & 10.2 & 3 \\ 6 & 100 & 7.5 \end{bmatrix}$.

The LQR achieves infinite gain margin. The greater the gain margin, the better will be the stability of the system. The gain margin refers to the amount of gain, which can be increased or decreased without making the system unstable. Changing the values of the gain matrix beyond a certain point will produce undesirable results. The LQR algorithm minimizes the efforts done by the control systems engineer to improve the performance of the controller. However, user still needs to specify the cost function parameters, and compare the results with the specified goals. Difficulty in finding the right weighting factors limits the application of the LQR based controllers. After simulations, it is seen that LQR controller is able to obtain 23.1^{o}C temperature and 0.0092$\frac{lb}{lb}$ humidity ratio, as seen in fig. 19 and fig. 20, respectively. After calculations, it is concluded that this controller shows 5% error in achieving temperature and 8% error in obtaining humidity ratio.

A nonlinear controller consisting of a regulator is designed using Lyapunov stability theory. A feedback linearization technique is implemented first to linearize the mathematical model of an air conditioning load. An estimator is then designed to estimate the values of unmeasurable states and thermal disturbances. A stabilizing state feedback law is then applied to regulate the load to obtain required thermal conditions. The gain matrix is calculated under the assumptions that the non-designed thermal loads are acting on the system. In this controller, no disturbance rejection controller (DRC) is

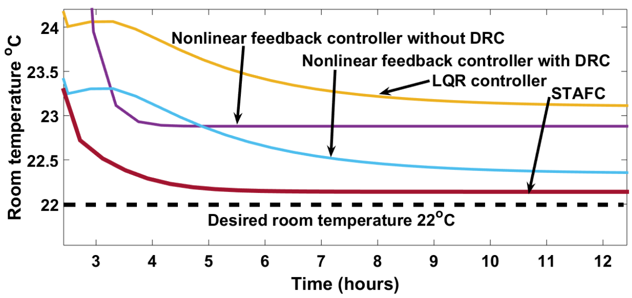


FIGURE 19. Comparison of different controllers for temperature control.

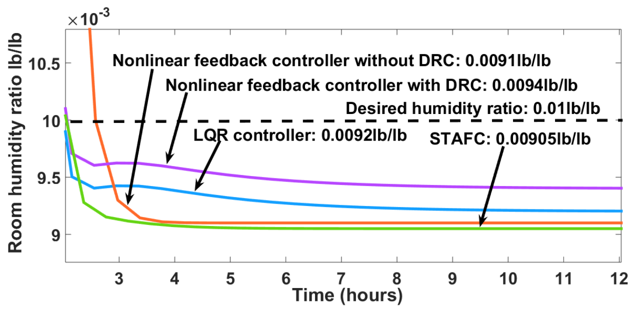


FIGURE 20. Comparison of different controllers for humidity ratio control.

designed to minimize thermal disturbance. For this controller, G is positive definite solution, derived using Lyapunov stability considerations. State feedback law is calculated using $G = \begin{bmatrix} 6.2 & 0 & -7.9 \\ 0 & 0 & 0 \\ -7.9 & 0 & 5593.5 \end{bmatrix}$ and $S = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$. θ, μ and $\in$ are positive scalars and their values are 1, 106, and 14, respectively. T and W are scaling factors and are chosen as identity matrices. The calculated state feedback law for the nonlinear controller is, $K = \begin{bmatrix} 0 & 8.5 & 0 \\ 3 & 5628 & 1.8 \end{bmatrix}$.

It is noted that changing the values of the gain matrix beyond a certain point will produce undesirable results. Simulations results show that nonlinear controller manages to obtain 22.88^{o}C temperature and $0.0091\frac{lb}{lb}$ humidity ratio, as shown in fig. 19 and fig. 20, respectively. After calculations, it is observed that percentage error by this controller is 4% in temperature and 9% in humidity ratio.

In nonlinear controller with DRC, regulator is designed using Lyapunov stability theory. An observer is implemented to estimate the unmeasurable states and thermal loads affecting the system. Thermal loads are used as constant but unknown disturbances. Thermal disturbances cause an increase in the room temperature and humidity ratio. A stabilizing state feedback law is calculated using Lyapunov stability considerations. The gain matrix is calculated under the assumptions that the non-designed thermal loads are impacting the system. Then a disturbance rejection controller is designed and implemented to optimize the operation of an air conditioning load. The disturbance rejection controller (DRC) decreases the effect of thermal loads on the air conditioning load. In nonlinear controller with disturbance rejection controller, state feedback law consists of regulator feedback gain K_R and disturbance rejection controller gain K_D. For this controller, G is positive definite solution, derived using Lyapunov stability considerations. θ, μ and $\in$ are positive scalars and their values are 1, 106, and 14, respectively. T and W are scaling factors and are chosen as identity matrices. State feedback law is calculated using $G = \begin{bmatrix} 6.2 & 0 & -7.9 \\ 0 & 0 & 0 \\ -7.9 & 0 & 5593.5 \end{bmatrix}$ and $S = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$. The calculated state feedback law for nonlinear controller is, $K_R = \begin{bmatrix} 0 & 8.5 & 0 \\ 3 & 5628 & 1.8 \end{bmatrix}$ and for disturbance rejection controller, $K_D = \begin{bmatrix} 0 & 0.0005 \\ 0.0001 & 0.0708 \end{bmatrix}$.

The gain matrices in this controller affect the performance of the air conditioning load. It is noted that changing the values of the gain matrix for the disturbance rejection beyond a certain point will produce undesirable results. The results produced by the controller with disturbance rejection are better than that of produced by the controller without disturbance rejection. After simulations, it is seen that controller achieves 22.3432^{o}C temperature and $0.0094\frac{lb}{lb}$ humidity ratio, as illustrated in fig. 19 and fig. 20, respectively. The percentage error by this controller in achieving temperature is 1.56% and in obtaining humidity ratio is 6%.

In order to be more comprehensive, performance of the presented fuzzy controller is compared with self-tuning adaptive fuzzy controller (STAFC). An adaptive fuzzy controller is designed using output scaling factor. As, no exact methodology is available for selection of scaling factors, so, trial and error method is used here. In this work, scaling factors are selected, which are continuously tuned as per requirement of the fuzzy controller to obtain the required result. In this technique, controlling input is updated by multiplying controller output with output gain G_o and gain updating factor θ. The gain updating factor is obtained through model free fuzzy controller consisting of air conditioning load' s inputs i.e. temperature error and humidity ratio error. The gain updating factor keeps on adjusting in feedback loop until the output is obtained within the acceptable limits. The gain updating factor is independent of any parameter and depends on current states of air conditioning load. Therefore, self-tuning adaptive fuzzy controller is independent of process being controlled. At first, gain updating factor is kept constant and input gain value is adjusted to make efficient use of the controller. The input gains values are adjusted again and gain by trial and error method until the best possible results are achieved.

The gain updating factor θ is 0.55 and 0.7 for room temperature and humidity ratio, respectively. While output scaling factor G_o is 1.7 and 1.3 for fan speed and liquid flow rate, respectively.

It is evident from the results that self-tuning fuzzy adaptive controller achieves 22.14^{o}C temperature and 0.00905lb/lb humidity ratio, as shown in fig. 19 and fig. 20, respectively. Calculations yield that controller exhibits 0.636% error in temperature while for humidity ratio controller shows 9.5%

error. Whereas the proposed fuzziey controller, in case-II, shows 0.9% error and 6% error in achieving required temperature and humidity ratio, respectively.

Simulation results with comparison of performances of different controllers are given in fig. 19 and fig. 20. It is concluded that self-tuning adaptive fuzzy controller (STFAC) performs better than those of other controlling techniques. Convergence time of STFAC is slower than nonlinear controller but it tracks the reference room temperature with percentage error of 0.636%. Convergence time of nonlinear controller with DRC is slower than that of nonlinear controller without DRC but it shows an error of 1.56% in achieving the desired room temperature. LQR exhibits an error of 5% with slow convergence rate. Overall response of the STAFC is much better; tracking its reference level with percentage error of 0.636% in temperature. For the humidity ratio control, STAFC tracks the required humidity ratio with an error of 6% with fast convergence time. Nonlinear controller with DRC gives better performance in terms of achieving the desired humidity ratio with an error of 6% with slow convergence time when compared with other techniques but exhibits 1.56% error while achieving the room temperature.

It is evident from the comparison given in Table-9 that proposed fuzzy controller produces desired results while maintaining human comfort. In terms of energy consumption, fuzzy controller saves 25% annual energy when implemented.

TABLE 9. Comparison of fuzzy controller' s performance with other techniques.

Controller	Temperature achieved ^oC	Humidity ratio achieved $\frac{lb}{lb}$
Linear quadratic regulator (LQR)	23.1	0.0092
Nonlinear feedback controller without disturbance rejection	22.88	0.0091
Nonlinear feedback controller with disturbance rejection	22.3432	0.0094
Fuzzy adaptive controller	22.14	0.00905
Fuzzy with three MFs	27.6	0.00885
Fuzzy with five MFs	22.2	0.0094
Fuzzy with pi-shaped MFs	27.6	0.008875
Fuzzy with gaussian MFs	23.475	0.008875

So it is concluded that the proposed fuzzy controller stands simple and easy to implement as compared to nonlinear, LQR and adaptive controller. The conventional controllers i.e. PID, PI or optimal controllers are either are expensive or complex in design as compared to fuzzy controller. When compared with fuzzy controller, an adaptive fuzzy controller is difficult to design. It is due to the fact that parameters are tuned again and again until the best possible results are achieved. However, fuzzy controller is easy to design and simulate due to easy to use nature of MATLAB Fuzzy Logic Toolbox.

The proposed fuzzy controller can be implemented practically using field-programmable gate array (FPGA) or arduino through coding. Sensors can be used to detect temperature and humidity. Data collected through sensors are fuzzified through membership functions. Fuzzy rules can be introduced in microcontrollers using coding. The output obtained can be converted to suitable voltage DC or AC to drive motor or any suitable apparatus depending upon the operation and requirement. Hence suitable apparatus can be operated through fuzzy logic.

In future, different controllers including fuzzy controller can be implemented practically to draw a comparison of performances between them.

VII. CONCLUSION

This paper has presented a fuzzy logic controller for an air conditioning load. which is capable of reducing the effect of thermal loads (disturbances) on the thermal space. The developed controller is quite effective in maintaining consumer's comfort while ensuring significant energy saving. The key contribution is to design and implement fuzzy controller with different number and shapes of membership functions on mathematical model of an air conditioning load. The designed controller, with increased number of triangular membership functions achieves temperature with an error of approximately less than 1% and humidity ratio with an error of 6% without compromising human comfort. The effectiveness of the applied control scheme is evident through significant reduction in energy consumption which is 25% per annum. Results are analyzed and compared with other techniques, it is concluded that fuzzy controller produces better results and maintains human's thermal comfort.

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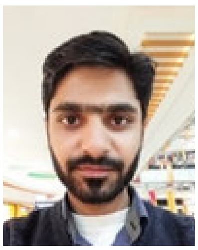

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