Control of Thermal-Visual Comfort and Air Quality in Indoor Environments Through a Fuzzy Inference-Based Approach

Jean J. Saade and Ali H. Ramadan

***Abstract*—** This study presents a control approach for the adjustment and maintenance of air quality, thermal and visual comfort for buildings’ occupants while minimizing energy consumption. The approach accounts for users’ preferences and is mainly based on the use of fuzzy inference, which lends itself to intelligent system design methods. The control objectives and criteria are described and their models are provided. Then, the fuzzy inference-based controller is designed and made to work in conjunction with the criteria models to satisfy the control objectives. The designed fuzzy controller and criteria models are also simulated using MatLab/Simulink. The simulation results, which are depicted for each control criterion, show that the presented approach is highly efficient in the sense that it is capable of responding in a minimal amount of time to fixed and variable users’ preferences. It is also capable of eliminating overshoots and oscillations in these responses and this has been achieved without the need for any adaptive procedure.

***Keywords*—**Air quality, Energy consumption, Fuzzy inference, Thermal-visual comfort.

I. INTRODUCTION

An important part of today’s technological developments are centered on the design of machines, which are capable of performing tasks that require intelligence. Due to the inability of binary logic and classical mathematics to provide a satisfactory tool for designing such intelligent machines, various technological tools, such as fuzzy logic and inference, artificial neural networks, etc., have been invented for use towards achieving the previously-noted objective. The aim of fuzzy inference is to provide approximate mathematical models expressed using vague and imprecise linguistic terms, which are involved in conditional “if-then” rules [1]-[3].

In situations where disturbances, uncertainty and modifications occur, it would not be feasible to provide precise models using classical mathematics. Approximate models based on fuzzy inference as a smart design or control technique have been shown to be more appropriate [1]-[4]. In this paper, therefore, a fuzzy inference-based control approach for the achievement of indoor thermal-visual comfort and air quality satisfaction while reducing energy consumption is presented.

Efficient management of energy in buildings and maintenance of indoor comfort in acceptable margins, using intelligent design tools, has been the focus of some researchers in recent years [4], [5]. Several alternative solutions have been presented and evaluated in [4] in order to adjust and preserve air quality, thermal and visual comfort for buildings' occupants while reducing energy consumption and taking users’ preferences into account. Among these solutions and according to the presented results, the adaptive fuzzy PD controller ensured the best reduction in overshoots and oscillations and, hence, the lowest energy consumption.

In this study, a fuzzy inference-based control approach for the adjustment of the parameters or criteria, which have a direct influence on the thermal and visual comforts and air quality in indoor environments, is offered. Both fixed and variable user’s preferences, as they relate to temperature affecting thermal comfort, carbon dioxide concentration affecting indoor air quality and illuminance level influencing visual comfort, have been adopted. Whenever a user requests a desired level for any of the mentioned criteria, the fuzzy inference system, in conjunction with the criteria models, responds to his request while eliminating overshoots and oscillations. Hence, a minimization of energy waste has been achieved without the need for adaptivity.

II. CONTROL OBJECTIVES, CRITERIA AND MODELS

The objectives of the control strategy are the following:

- Adjustment and maintenance of thermal-visual comfort and indoor air quality criteria according to users’ preferences [4]-[6].
- Minimizing building energy consumption for heating/cooling, lighting and ventilation processes through the avoidance of overshoots and oscillations [4].

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J. J. Saade, corresponding author, is a professor in the department of Electrical and Computer Engineering, American University of Beirut, P.O. Box: 11-0236, Riad El Solh, 1107-2020, Beirut, Lebanon, phone: 961.1.340 460, fax: 961.1.744 462, e-mail: jsaade@aub.edu.lb

A. H. Ramadan is a graduate student in the department of Electrical and Computer Engineering, American University of Beirut, P.O. Box: 11-0236, Riad El Solh, 1107-2020, Beirut, Lebanon, phone: 961.1.340 460, fax: 961.1.744 462, e-mail: ahr06@aub.edu.lb

These objectives are to be achieved by using a fuzzy logic controller that works in conjunction with furnished criteria models at a certain zone level of the building. The involved criteria and their corresponding models are detailed in what follows.

A. Thermal comfort

Thermal comfort is usually determined by the Predicted Mean Vote (PMV) introduced by Fanger [6]. The PMV depends on temperature, relative humidity, mean radiant temperature, air velocity, activity level, and clothing parameter. However, since temperature is the main contributing factor among those mentioned above, we have chosen it as the main criterion to be controlled for the achievement of thermal comfort. Moreover, users' desired temperature levels have been selected to be between 15°C and 50°C.

We considered that temperature is driven by applied current [3]. Accordingly, the following mathematical transfer function of the thermal model has been considered:

$$\frac{\text{Temp(s)}}{\text{I}_1\text{(s)}} = \frac{1}{\text{s} + 0.0001} \quad (1)$$

Transforming Equation (1) into the time domain, yields

$$\frac{\text{dtemp(t)}}{\text{dt}} = \text{i}_1\text{(t)} - 0.0001\text{temp(t)} \quad (2)$$

Figure 1 shows the representation of the differential equation in (2) in Simulink. In the figure, we have

$$\text{f(u)} = \text{(u [1]-0.0001*u [2])} \quad (3)$$

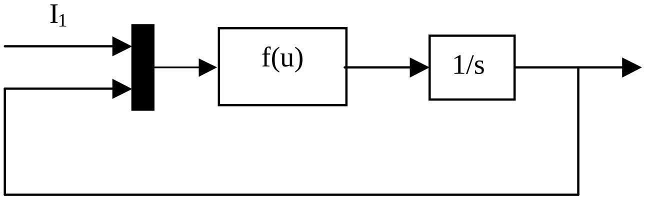


Fig. 1 Thermal model in Simulink

B. Visual comfort

The controlled parameter for achieving visual comfort has been selected as the illuminance level, measured in Lux [4], [7]. The preferred light level in a room depends primarily on the type of activity. Common favourable levels vary between 300 and 1000 Lux [4]. The electric power needed to achieve a specific illuminance level can be expressed as follows:

$$P = \frac{b}{\eta_e \eta_r I_s} \quad (4)$$

where, P is the electric power, b is the illuminance level, η_e is the light source efficiency, η_r is the room lighting efficiency and I_s is the amount of light, expressed in Lumen, that can be emitted by the source per Watt.

The purpose of a lamp is to convert electrical power into light. Different lamps do this with varying efficiencies and the light emitted from a source depends on the type of source. In our project we chose a GLS lamp type with an $I_s = 15$. The light equipment efficiency expresses the percentage of light that goes to the room out of that emitted by the light equipment. The room lightning efficiency expresses how much of the light is absorbed by the room before entering the activity area. Light equipment efficiency and room lighting efficiency influence each other. Common values of the product $\eta_e \eta_r$ are in the range from 0.3 to 0.6. The 0.5 value has been chosen. Replacing $\eta_e \eta_r$ and I_s in Equation (4), yields

$$\text{P} = \text{b} / 7.5 \quad (5)$$

Equation (5) was used to convert the user's desired illuminance levels into power values. The electric power to the light equipment is in the first place caused by an electric current. Based on this fact, we adopted the same mathematical transfer function of the thermal model indicated in section *A* to be implemented in the visual model. After achieving a power level in the controlling process, it can be reconverted to light level using b=7.5P. This has been used to display the controlled power along with the achieved illuminace level.

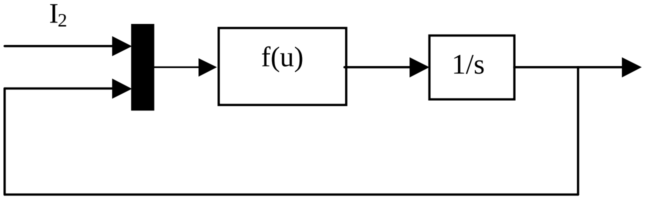
The transfer function of the adopted visual model is given by

$$\frac{\text{P(s)}}{\text{I}_2\text{(s)}} = \frac{1}{\text{s} + 0.0001} \quad (6)$$

Transforming Equation (6) into the time domain, we obtain

$$\frac{\text{dp(t)}}{\text{dt}} = \text{i}_2\text{(t)} - 0.0001\text{p(t)} \quad (7)$$

Figure 2(a) shows the representation of the differential equation in (7) in Simulink, where f(u) is as in Equation (3). Fig. 2(b) and Fig. 2(c) are Simulink representations of the Lux-Watt and Watt-Lux conversions.



(a)

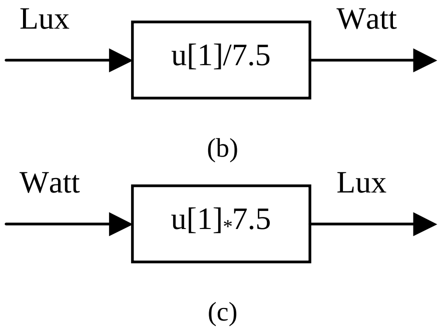


Fig. 2 Simulink representations of: (a) Visual model, (b) Lux-Watt converter and (c) Watt-Lux converter

C. *Indoor air quality*

The quality of air in indoor environments is mainly influenced by the concentration of pollutants. In this context, the CO_2 concentration (measured in ppm) has been chosen because it is a dangerous pollutant that could exist in buildings. Improving the air quality involves the use of a motor, which drives a fan in order to push the polluted air to the outside. The DC motor is driven by applied voltage and its equivalent circuit is shown in Fig. 3.

The characteristic equations of the DC motor are as follows [8]:

$$v(t) = L\frac{di(t)}{dt} + Ri(t) + v_{emf}(t) \tag{8}$$

$$v_{emf}(t) = K_b w(t) \tag{9}$$

$$T(t) = K_t\, i(t) \tag{10}$$

$$T(t) = J\frac{dw(t)}{dt} + D\,w(t) + T_L \tag{11}$$

In the above equations, $v(t)$ is the applied voltage, $i(t)$ is the circuit current, $v_{emf}(t)$ is the back electromotive force, *T(t)* is the torque of the motor and $w(t)$ is the motor angular speed. R, L, K_b, K_t, J, D and T_L are respectively the circuit resistance, circuit inductance, back electromotive force constant, motor torque constant, moment of inertia, viscous coefficient and load torque. The DC motor characteristic equations can be used to obtain the following input-output transfer function:

$$\frac{W(s)}{V(s)} = \frac{K_t}{(sL + R)(sJ + D) + K_t K_b} \tag{12}$$

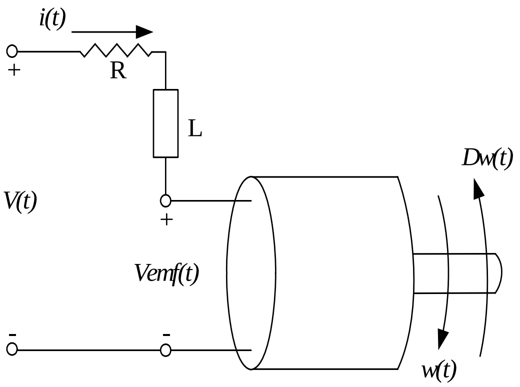


Fig.3 Model of a DC motor

As mentioned earlier in this subsection, the motor is used to drive a fan in order to push existing pollutants (mainly CO_2) to the outside. Usual CO_2 concentrations are found to vary between 600 and 800 ppm [4]. Hence, whenever the CO_2 concentration, denoted by $[CO_2]$, increases (decreases) within this range, the DC motor angular speed, expressed in round per minute (RPM) and being determined by the applied voltage, should be increased (decreased). Moreover, we proposed and used in this study two empirical linear equations which perform $[CO_2]$-to-RPM and RPM-to-$[CO_2]$ conversions, respectively. The first conversion is used in the controlling process, which consists of achieving a suitable angular speed. The second conversion is performed in the post-controlling process to display the controlled RPM along with the achieved $[CO_2]$.

Based on Equation (12), the used transfer function of the DC motor is given by

$$\frac{W(s)}{V(s)} = \frac{2130}{s^2 + 950s + 26} \tag{13}$$

Applying inverse Laplace transform to the above transfer function results in the following differential equation:

$$\frac{d^2 w(t)}{dt} = 2130v(t) - 950\frac{dw(t)}{dt} - 26w(t) \tag{14}$$

The mathematical presentation of the used equations for $[CO_2]$ to RPM conversion and de-conversion are respectively as follows:

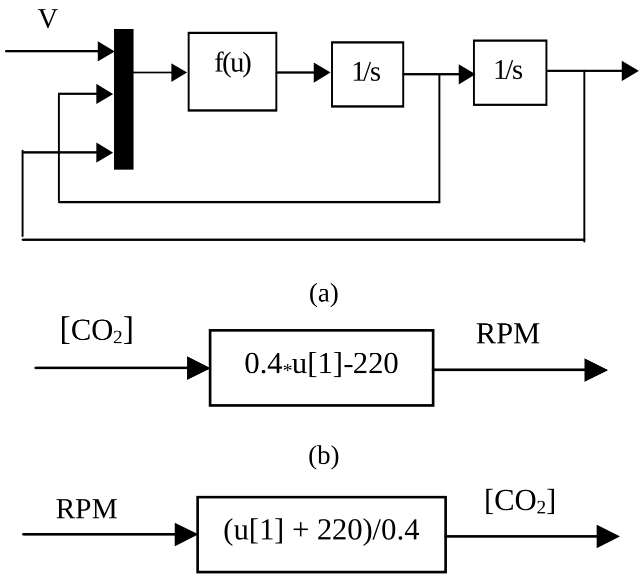
$$\text{RPM} = 0.4*[CO_2]-220 \tag{15}$$

$$[CO_2] = (\text{RPM}+220)/0.4 \tag{16}$$

Figure 4 depicts the representation of the DC motor differential equation in (14) in Simulink, where

$$f(u) = 2130*u\,[1]-950*u\,[2]-26*u\,[3]) \tag{17}$$

The Simulink representation of Equations (15) and (16) are also shown in Fig. 4.



(a)

(b)

(c)

Fig. 4 Simulink representations of: (a) Air quality model, (b) [CO_2]-to-RPM converter and (c) RPM-to-[CO2] converter

III. Fuzzy Inference System

In this section, a fuzzy logic controller for the criteria explained in Section 2 is devised and this is based on the use of fuzzy inference. For each criterion included in the control objectives or its directly linked parameter, the error and error variation have been considered as the input variables of the fuzzy controller. Hence, the error and change in error for the temperature, electric power and RPM are the fuzzy controller input variables. The controller output variables are the currents I_1 and I_2 and voltage V (see Fig. 1, 2, 4 and 5).

The membership functions assigned over the controller inputs and outputs variables are shown in Fig. 6 and 7. The linguistic variables used are *N*, *Z* and *P*, where *N* means negative, *Z* means zero and *P* means positive. The complements of *N*, *Z* and *P* are also used for the change of error in temperature, power and RPM. The membership functions of the fuzzy logic controller include both triangular and trapezoidal forms. The fuzzy inference rules are 27 "if-then" rules. Tables 1, 2 and 3 demonstrate the inference rules for the error and change in error as they relate to the criteria that need to be controlled by controlling their affecting quantities; i.e., I_1 for temperature, I_2 for illuminance-related power and V for [CO_2]-related RPM. The type of fuzzy inference engine is Mamdani and the fuzzy outputs are defuzzified by the center of gravity procedure.

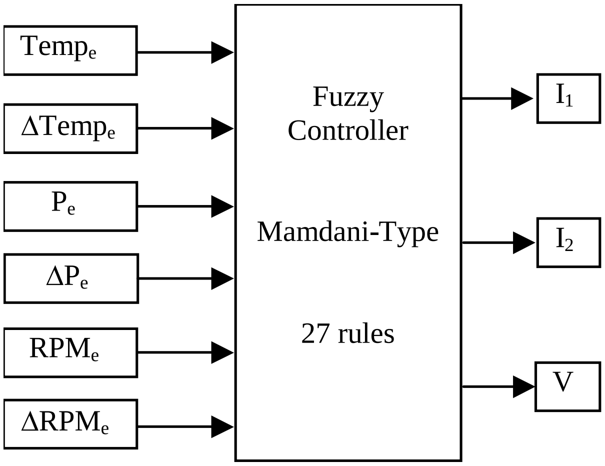
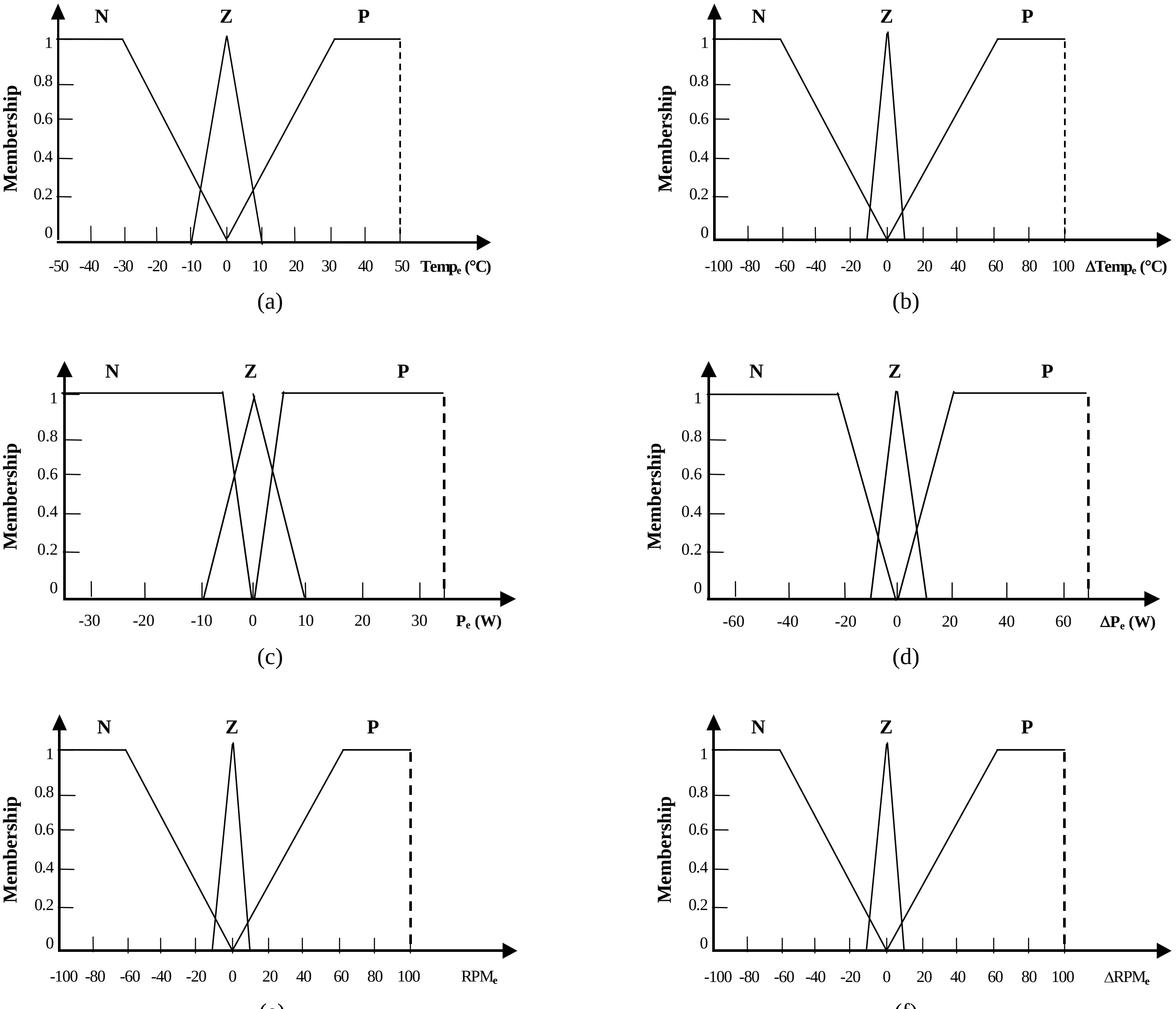


Fig. 5 Implemented fuzzy controller

As has been mentioned earlier in this study, the fuzzy logic controller described above, is supposed to work in conjunction with the models of the criteria introduced in section II in order to satisfy the control objectives. For this to be achieved, the fuzzy controller with some initial, yet reasonable assignment of membership functions and rules and the criteria models with initially assigned constants in their transfer functions were mounted in the Simulink tool available under Matlab. Then a large number of simulation runs were executed for numerous fixed and variable user's preferences related to temperature, illuminance level and carbon dioxide concentration. The performed simulation runs helped a great deal in tuning the membership functions ranges and break points, the constants involved in the transfer functions of the criteria and their models and also in the adjustment of the conversion models so as to arrive at the final fuzzy controller design and models settings. This has led to a near perfect achievement of the control objectives as described in Section II. That is, the final system has been obtained as one that is capable of satisfying desired criteria levels according to users' choices and in a very short time duration. Elimination of overshoots and oscillations has, in addition, been reached. It is worth noting here as well that the achieved smoothness in the control surfaces, shown in Figs. 8-10, of the final fuzzy controller has been observed as one of the contributing factors to the obtained avoidance of overshoots and oscillations in the system responses.

IV. Simulation and Results

This section presents the results of some simulations performed on the fuzzy logic controller and criteria models obtained at the end of the tuning and design stage that has been described in Section III. Fixed and variable users' preferences (or set points), as they relate to the criteria of the control objectives, have been considered.

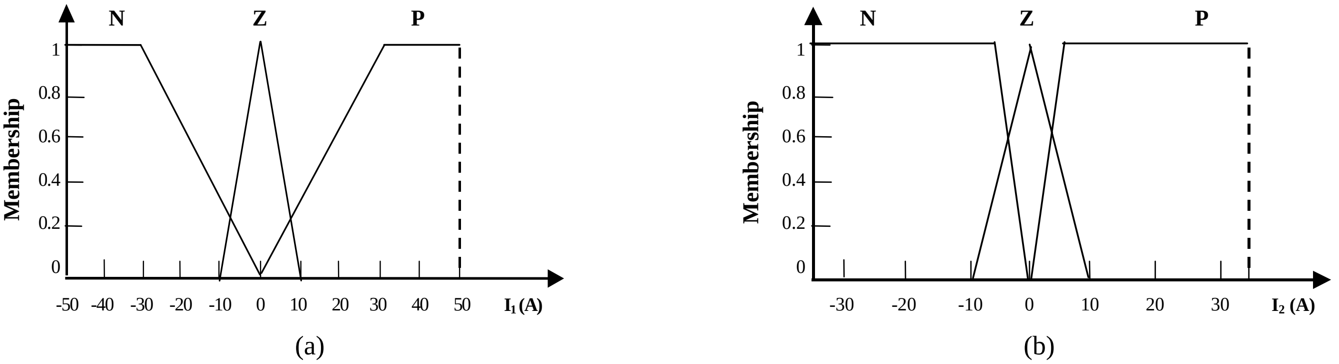


(a) (b)

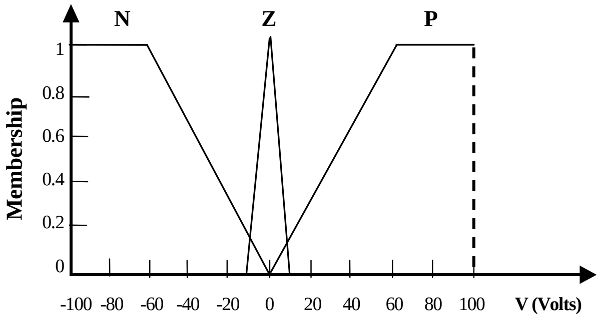
(c) (d)

(e) (f)

Fig. 6 Membership functions for fuzzy controller inputs: (a) temperature error, (b) change in temperature error, (c) power error, (d) change in power error, (e) RPM error and (f) change in RPM error



(a) (b)



(c)

Fig. 7 Membership functions for fuzzy controller outputs: (a) current I_1 (b) current I_2 and (c) voltage

TABLE I
INFERENCE RULES FOR THE THERMAL MODEL

$Temp_e$	$\Delta Temp_e$	I_1
N	N	N
Z	Z	Z
P	P	P
Z	N_c	Z
P	N_c	P
N	Z_c	N
P	Z_c	P
N	P_c	N
Z	P_c	Z

TABLE II
INFERENCE RULES FOR THE VISUAL MODEL

P_e	ΔP_e	I_2
N	N	N
Z	Z	Z
P	P	P
Z	N_c	Z
P	N_c	P
N	Z_c	N
P	Z_c	P
N	P_c	N
Z	P_c	Z

TABLE III
INFERENCE RULES FOR THE FAN MODEL

RPM_e	ΔRPM_e	V
N	N	N
Z	Z	Z
P	P	P
Z	N_c	Z
P	N_c	P
N	Z_c	N
P	Z_c	P
N	P_c	N
Z	P_c	Z

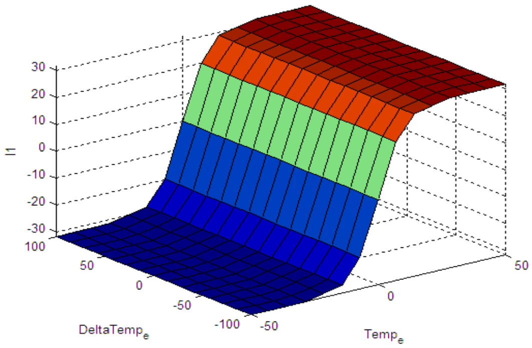


Fig. 8 Control surface for I_1 versus temperature error and change in error

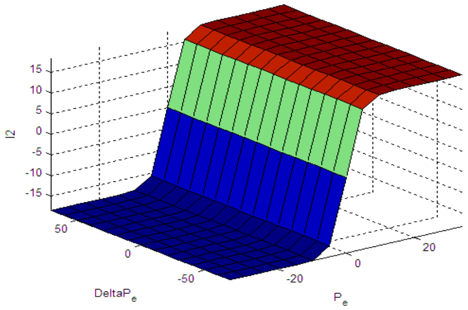


Fig. 9 Control surface for I_2 versus power error and change in power error

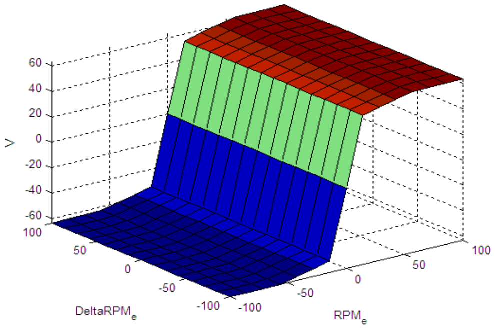


Fig. 10 Control surface for V versus RPM error and change in RPM error

The simulation results shown in Figs. 11-13 are for fixed set points and in Figs. 14-16 are for variable set points. The Simulink implemented system is shown in Fig. 17. For fixed preferences, the following values have been used in the performed simulations: Temperature= 30°C, illuminance level = 650 Lux and [CO2] = 700 ppm. The variable preferences have been modelled using random generators providing various set points at various time intervals for temperature, illuminance level and [CO2] within the limits indicated in Section II of these control criteria.

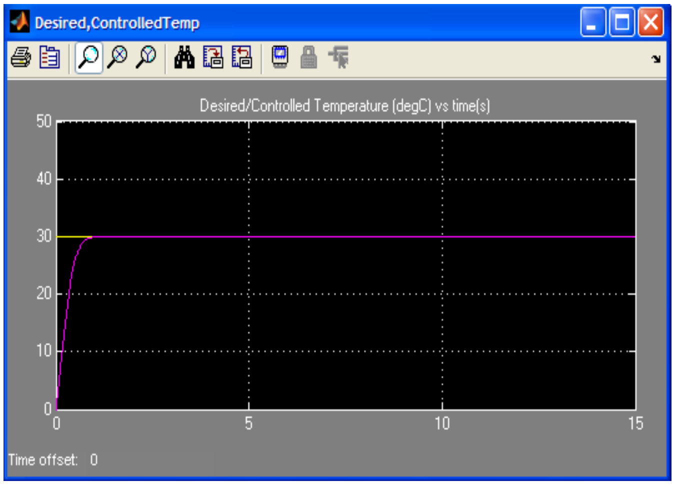


Fig. 11 Controlled temperature level (fixed) versus time (s).

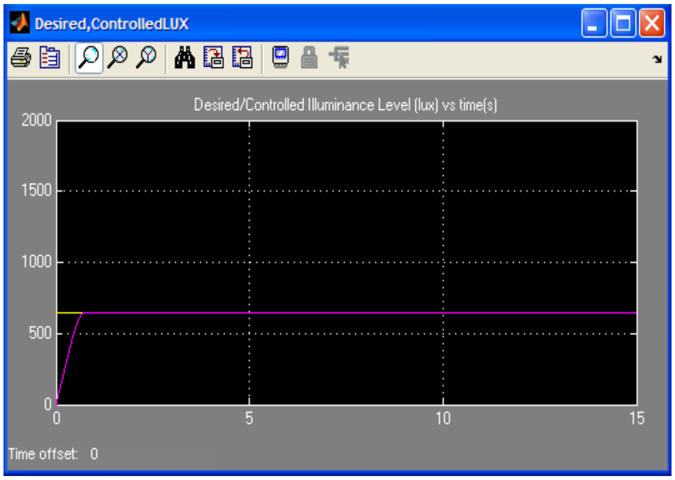


Fig. 12 Controlled illuminance level (fixed) versus time (s).

Figs. 11-13 show that the designed fuzzy system used in conjunction with the criteria models has been capable of achieving the desired criteria levels in about 1 second and this has been done without any noticeable overshoots nor oscillations about the desired set points at the steady state.

The same observations can be made in the variable set points simulations as in Figs. 14-16. Minimization of energy consumption becomes ensured by the virtue of the obtained elimination of overshoots and oscillations. Hence, the presented results show that the control objectives specified in Section II have been satisfied by the presented fuzzy inference-based control approach.

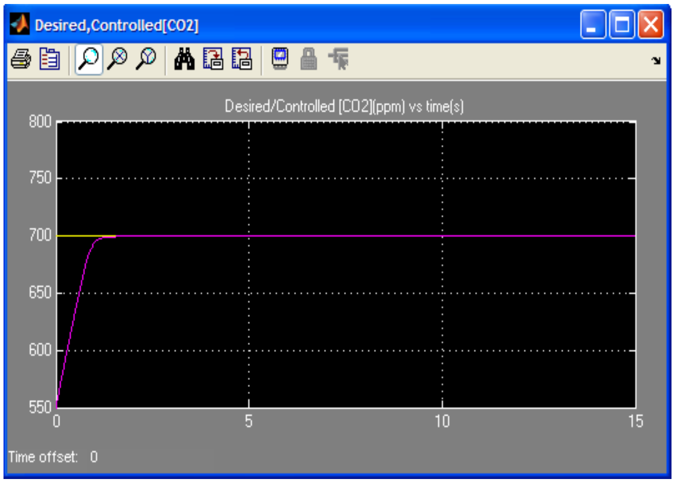


Fig. 13 Controlled [CO_2] (fixed) versus time (s).

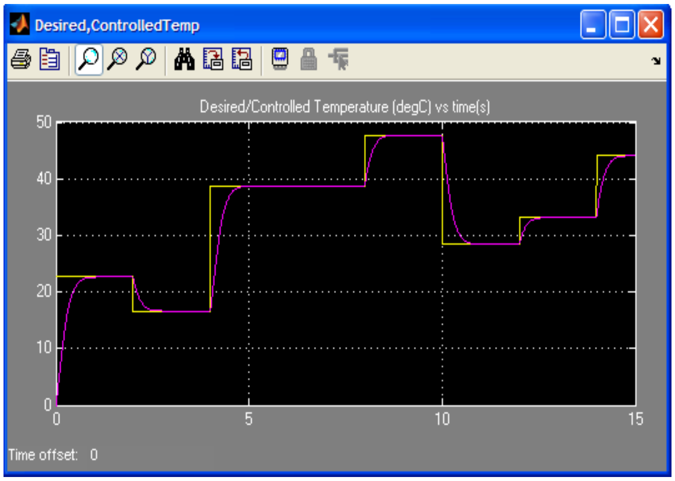


Fig. 14 Controlled temperature level (variable) versus time (s).

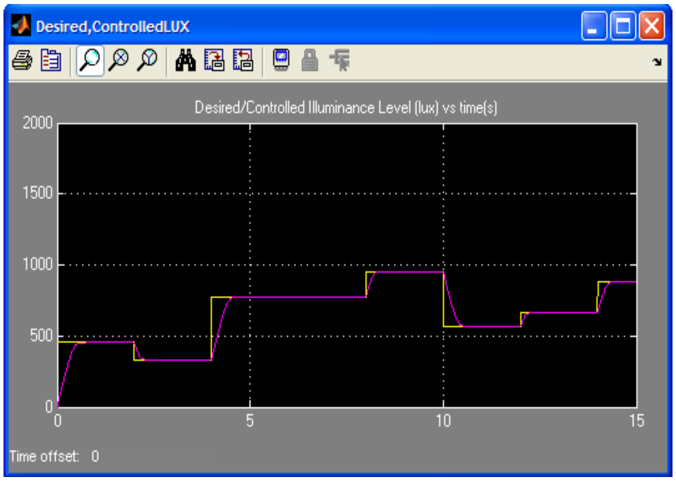


Fig. 15 Controlled illuminance level (variable) versus time (s)

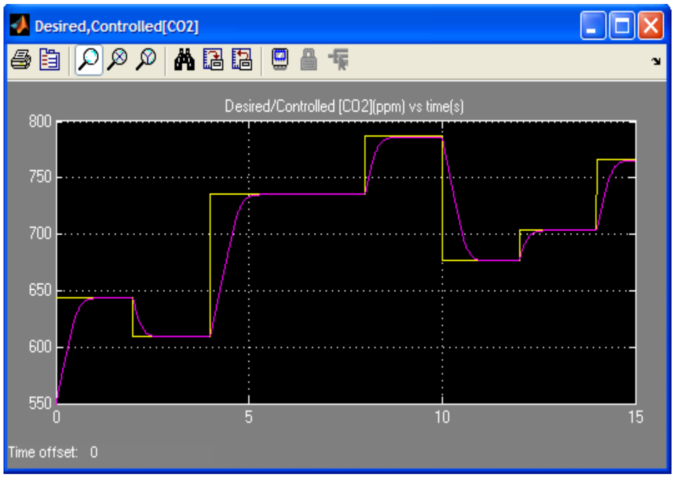


Fig. 16 Controlled [CO_2] (variable) versus time (s).

V. CONCLUSIONS

In this paper, a fuzzy control approach for the adjustment of the criteria, which have a direct influence on the thermal and visual comfort and air quality in indoor environments, has been presented. The criteria involved in the control objectives have been described and their models have been provided. Then, using the fuzzy inference methodology and the offered criteria models a fuzzy logic controller has been designed to work in conjunction with the criteria models so as to achieve the stated objectives of the considered control strategy. Actually, the final design of the fuzzy controller and criteria models has been obtained after a lengthy procedure of simulations, testing and tuning using the Simulink tool available under MatLab.

The end result turned out to be a system that is capable of responding efficiently to users' desired levels, whether fixed

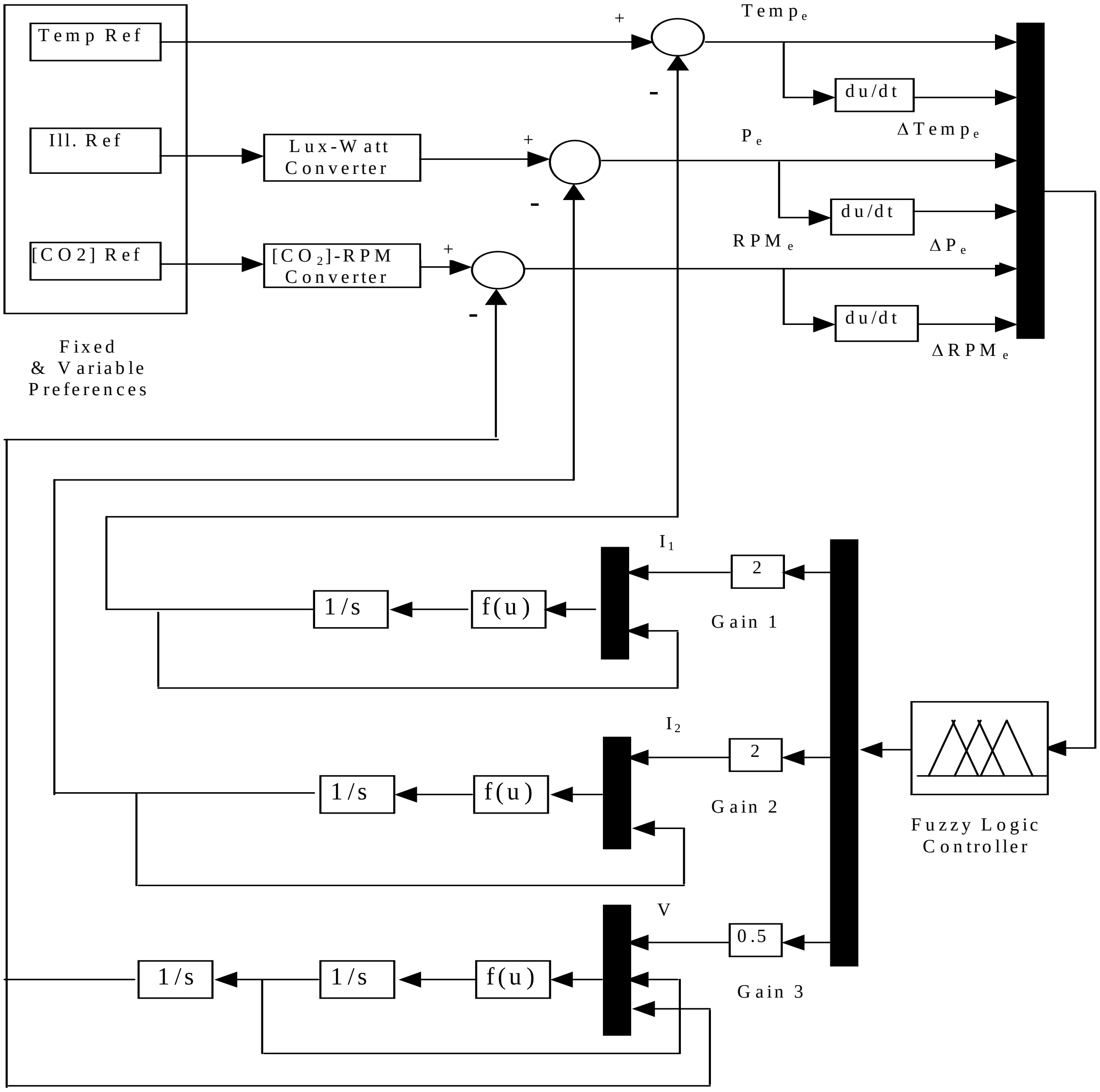


Fig. 17 Entire control system used in Simulink to obtain the simulation results

or variable, of the criteria that determine the thermal and visual comforts and air quality inside buildings. The presented system has, therefore, been shown capable of achieving the user's specified set points for temperature, illuminance level and carbon dioxide concentration in very short time duration while eliminating overshoots and oscillations. Consequently, minimum energy consumption becomes guaranteed.

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Jean J. Saade was born in Lebanon in 1954. He received the B.Sc. degree in Physics from the Lebanese University, Lebanon, in 1979 with a scholarship to pursue graduate studies. He then received the M.Sc. degree in Electrical Engineering in 1982 from Boston University, MA, USA, and a Ph.D. degree, also in Electrical Engineering, from Syracuse University, NY, USA, in 1987.

He taught for four years at Syracuse University during his Ph.D. studies and served for one year as a Visiting Assistant Professor at the same University after graduating. In 1988, he joined the American University of Beirut, Lebanon, and is currently a Professor at the Department of Electrical and Computer Engineering, teaching various analog and digital communication courses, detection and estimation principles, electromagnetic theory, and fuzzy logic. Dr. Saade published a good number of papers in international journals. These publications address the development of essential mathematical aspects of fuzzy sets and logic. He also applied these developments to practical engineering programs related to signal detection, radar, fuzzy control, and robot navigation. His recent publications have been concerned with the development of fuzzy controllers modeling algorithms and learning schemes based on expert data. This is in addition to the development of novel defuzzification methods for fuzzy controllers. In November-December 2006, Dr. Saade's paper on robot navigation published by Elsevier in 2003 has ranked first in the area of computer science according to Science Direct data base and it also ranked between second and fourth in the areas of decision sciences, engineering and mathematics.

Dr. Saade has received special invitations to present his research work at high-level international conferences attended by Nobel prize winners and VIP forums. He has also refereed a good number of papers for international journals including *Fuzzy Sets and Systems* and *IEEE Transactions on Fuzzy Systems*. He is a member of the International Fuzzy Systems Association (IFSA) and the European Society for Fuzzy Logic and Technology (EUSFLAT).

Ali H. Ramadan received the B.E. degree in Computer and Communications with distinction from the University of Lebanon in 2005. He is currently a graduate student at the American University of Beirut with an Electrical and Computer Engineering major. His research interests are fractal antenna engineering, compact UWB antennas design, reconfigurable/smart antennas and design of intelligent systems using fuzzy logic.