2019 6th International Conference on Control, Decision and
Information Technologies (CoDIT'19) | Paris, France / April 23-26, 2019

A Fuzzy Logic-Based Approach for HVAC Systems Control

A. Berouine[1,2], E. Akssas[1], Y. Naitmalek[1,2], F. Lachhab[3], M. Bakhouya[1], R. Ouladsine[1], M. Essaaidi[2]
[1]International University of Rabat
Faculty of Computing and Logistics, ECINE, LERMA
Sala El Jadida, Morocco
{anass.berouine, radouane.ouladsine, mohamed.bakhouya, youssef.nait-malek}@uir.ac.ma
[2]ENSIAS, Madinat Al Irfane, BP 713, Agdal Rabat, Morocco
essaaidi@ieee.org
[3]International University of Agadir, Bab Al Madina
Qr Tilila, B.P. 8143, Agadir, Morocco
fadwa.lachhab@e-polytechnique.ma

***Abstract*— In this paper, an approach for HVAC (Heating, Ventilation and Air-Conditioning systems) control has been designed and evaluated in real sitting scenarios against conventional logical methods (e.g. On/Off, PID, state feedback) in terms of energy consumption and occupants' thermal comfort. The proposed approach uses fuzzy logic as a soft control method in order to maintain the ambient temperature at required set points by controlling the speed of the HVAC evaporator fan. We have first used MATLAB fuzzy toolbox where the control system is designed using Fuzzy logic technique. The system's control is based on two inputs, the set point temperatures and temperature difference, while the control output is the speed's variation of the evaporator fan. Energy consumption was analyzed at various set point temperatures for the considered control methods. Experimental results show that the potential of controlling the evaporator fan speed with a Fuzzy Logic controller allows sustaining an ambient temperature with significant reduction in energy consumption.**

Keywords—Fuzzy Logic, HVAC control, Energy efficiency in building, Thermal comfort.

I. INTRODUCTION

Building equipment and especially the Heating Ventilation and Air-Conditioning (HVAC) systems account for almost 40% of the total energy usage in residential and commercial buildings [1][2][3]. Recent researches showed that energy consumption can be reduced by 20 to 30% when using advanced control systems. In fact, controlling the power of the evaporator fan motor, which is originally running at a frequent constant speed, can reduce its rotational speed according to the needed load (i.e., cooling or heating process). In fact, applying less power to the system could save considerably the energy consumption while maintaining best thermal conditions.

Various automatic controllers were used in controlling HVAC systems in order to drive speed control to the desired set point values. These control techniques can be categorized into three main types. Firstly, the well-known ON/OFF control is a simple control approach in which the control output is full ON if there is a variation from set point, or completely OFF otherwise. However, there is a bit of subtlety applied in practical on-off systems when repeatedly switch ON and OFF at very high frequency. This could introduce continuous oscillations in the value of the controlled variable. These oscillations could be also propagated right through the system in a connected process. Secondly, the Proportional Integral Derivative (PID) control technique is used in a wide range of applications for industrial process control because of its flexibility and reliability. Approximately 95% of the closed loop operations of industrial automation sector use PID [4]. Basically, the PID continuously calculates an error value as the difference between a desired set point and a measured process variable and applies corrections based on proportional, integral, and derivative terms [5]. Despite its feasibility and easier implementation, the PID control relies on the mathematical formulations [6], in which the PID gains and tuning methodology cannot be well estimated, especially when complex processes are required to collectively performing a control task. The third control method is the State Feedback controller (SFC), which takes into consideration a model of the controlled system [7]. It calculates the inputs to be applied to the system in order to maintain the output of that system at a particular set point (e.g., temperature control, speed control). However, despite its simplicity, defining a model for a given system can be a little tricky, which makes its operation and deployment slightly more complex.

Fuzzy Logic control (FLC) technique has been proposed to alleviate the dependency on the mathematical model. It has been confirmed that the Fuzzy logic is very closer to the human reasoning and thinking than the conventional logical systems [8]. More precisely, the FLC method handles the abstraction of classical or crisp data that may only be the integer values 0 or 1 (i.e., completely True (1) or completely False (0)). This could be performed by taking a form of many-valued logic that can be any real number between 0 and 1 [9] and by converting this data from crisp input and output variables to linguistic variables with fuzzy components. For example, to control an air conditioner system, the crisp input of temperature and the controlled output variable should be converted to the corresponding linguistic variables, such as Very Cold, Cold, Medium, and Very Fast, Fast, Slow. In fact, the main purpose of fuzzy logic is to convert the linguistic control strategy based on expert knowledge into an automatic control strategy [10][11]. This means that human operators can understand the system's operations and their experience can be then used in the design of controllers, especially for complex systems like the HVAC.

Compared to traditional control techniques, which require a formal modeling of the physical reality, FLC is the best technique in which the precision control can be achieved for time-optimal control applications and provides more space for further improvements. FLC is more stable against external disturbance, minimal overshoot and undershoot, and provides fast response [12]. In fact, it was presented not as a control methodology, but as a method for processing data by allowing partial set membership instead of non-membership. The fundamentals of FLC have been elaborated by Lotfi A. Zedeh, a professor at the University of California at Berkley and the Father of Fuzzy Logic [13]. The present paper aims to integrate the occupants' preferences as a dynamic element of the Fuzzy control approach without taking into account any characteristics of the building envelope, which could make the developed system operative and applicable in different buildings. The remainder of this paper is structured as follows. Section 2 presents an overview of FL and the design of the proposed system. In Section 3, the prototype Hw/Sw components are described. Preliminary results are presented in Section 4. In Section 5, conclusions and future work are given.

II. FL SYSTEM DESIGN OVERVIEW

The Fuzzy Logic Controller consists of four main parts: fuzzification, inference engine, fuzzy rule base and deffuzification [14]. These components and the general architecture of a FLC are depicted in Fig. 1. Each component affects the effectiveness and the behavior of the controller [15][16]. For instance, in the fuzzification process, a measurement of crisp input data gets translated with the fuzzy component, which converts those data into fuzzy data or Membership functions (MFs) called linguistic variables, similar to human decision [17][18]. In the second step, the fuzzy inference process combines the MFs with the control rules (i.e. Rule base) to derive the control output. The rule base is the core of fuzzy inference engine process and those rules are directly related to a human being's intuition and feeling. It mainly provides necessary information for linguistic control rules for the fuzzification and defuzzification. During an actual application, a control output is obtained from the results of fuzzy inference engine [19]. That control output should be converted from the linguistic variable back to the crisp output. This process is called defuzzification.

In the design process of the FL controller for HVAC, we have used MATLAB Fuzzy logic Toolbox, which provides tools to create and edit fuzzy inference systems. Fig. 2 describes the overall flow process of the designed system using FLC. There are two types of Fuzzy Logic Controller: Mamdani based controller and Takagi-Sugenos besed controller [20][21][22]. We applied the Mamdani-type FIS technique as a fuzzy inference method because it allows working with Membership Functions as output whereas Sugeno FIS has no output membership functions. The system consists of two input parameters: user desired temperature and calculated temperature error. The former is gathered from the user using a mobile application and the latter is computed via the difference between actual indoor temperature and the user desired set point (i.e., how close is the measured temperature of the controlled space to the desired temperature by occupants). The system has one output parameter that controls the evaporator fan speed of the HVAC system as shown in Fig. 2.

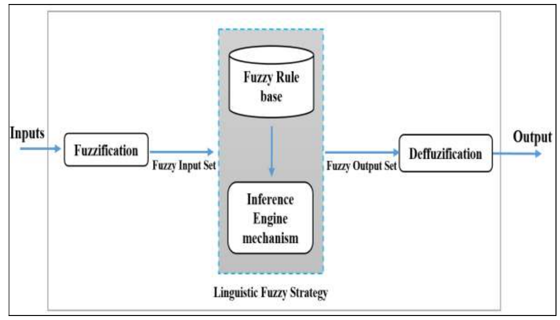

Figure 1. The general fuzzy logic architecture

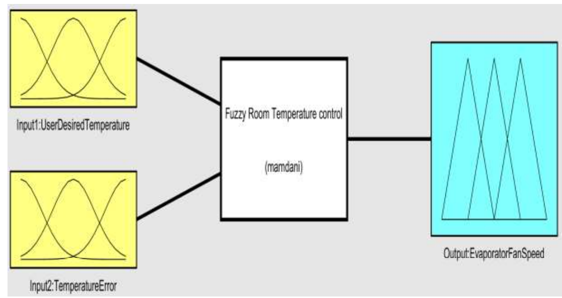

Figure 2. Fuzzy controller's inputs and output

Regarding the first input, we have the occupants' desired temperature parameter, which is divided into five MFs: Very Cold (VF), Cold (C), Medium (M), Hot (H), and Very Hot (VH) as shown in Fig. 3. We used three types of MFs to control the system: Polynomial based curves, such as the functions (zmf, smf) and Triangular membership function (trimf) of the overall range of the user's set point temperature, which is between 16 °C and 30°C as shown in Table1.

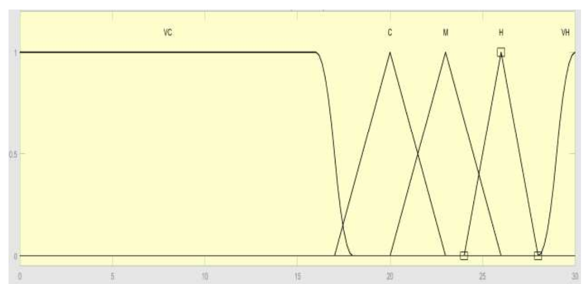

Figure 3. Occupants' desired temperature membership functions

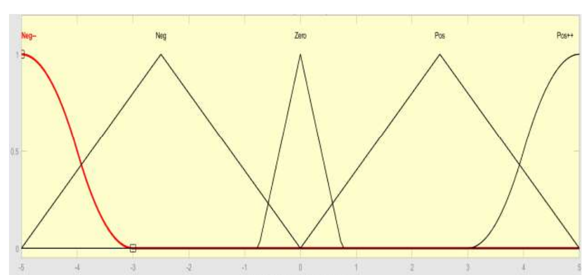

Figure 4. Error membership functions

The second input is the Error parameter, which represents the difference between the actual space (e.g., room) temperature and the desired one as shown in Fig. 4. It provides information about change rate of error and how fast is the measured temperature approaching to the user desired temperature, which is also divided into five MFs with a limited range of error, between -5 and 5 as shown in

Table 1. The system's output represents the speed variation of the evaporator's fan, which varies according to the change rate of error. This parameter is classified into six MFs as shown in Fig. 5. The range of this parameter is between 0 ms to 18 ms, which represents the speed delay of the evaporator's fan as also described in Table 1.

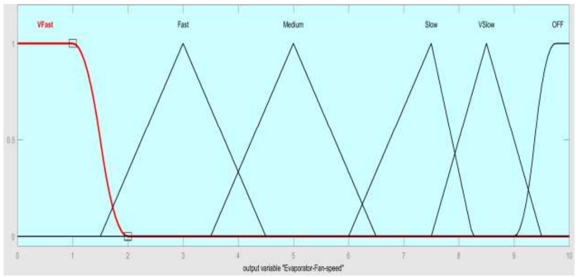

Figure 5. Evaporator's fan speed delay membership functions

TABLE 1 : TYPES OF MFs USED

MFs used for each category range of occupants' preferences			
	MF	Range (°C)	Type of MF
MF1	Very Cold	[16 18]	zmf
MF2	Cold	[17 20 23]	trimf
MF3	Medium	[20 23 26]	trimf
MF4	Hot	[24 26 28]	trimf
MF5	Very Hot	[28 30]	smf
MFs used for each range of error			
	MF	Range (e)	Type of MF
MF1	Extra negative	[-5 -3]	zmf
MF2	Negative	[-5 -2.5 0]	trimf
MF3	Zero error	[-0.75 0 0.75]	trimf
MF4	Positive	[0 2.5 5]	trimf
MF5	Extra positive	[3 5]	smf
MFs used for each range of the evaporator's fan speed delay			
	MF	Range (°C)	Type of MF
MF1	Very Fast	[1 2]	Zmf
MF2	Fast	[1.5 3 4.5]	trimf
MF3	Medium	[3.5 5 6.5]	trimf
MF4	Slow	[6 7.5 8.25]	trimf
MF5	Very Slow	[7.5 8.5 9.5]	smf
MF6	Off	[9 9.75]	zmf

III. EXPERIMENTAL SETUP

This section presents the experiments and results aiming at evaluating and studying the efficiency of the proposed FLC technique of the HVAC system deployed in our EEBLab. This later was built essentially for implementing and testing different scenarios related to related to eHealth [24], Energy efficiency in buildings [26][28], ICT [23][25], and renewable energies [27]. As shown in Fig. 6, the experimental prototype is composed of two main components: hardware and software components. The hardware component includes an Intelligent Control Card (ICC) and a Smart Meter (SM). The ICC allows interfacing with the HVAC system and includes the control approaches, which regulate the temperature based on the desired schedules. The SM component was developed for measuring the power consumption of the HVAC, which is integrated into the ICC. Regarding the software component, we developed a holistic platform based on IoT and Big data technologies. The platform includes all communication interfaces between embedded systems (i.e. sensing and actuation nodes). It is also used for real-time data acquisition, processing, visualization, and storage. Moreover, we have also developed a control mobile application for a full remote feedback control of the HVAC system. The rest of this section describes each of these components.

A. The ICC Component

A new intelligent electronic card, as depicted in Fig. 7, has been developed and deployed into the HVAC system [26]. In fact, the classic one which comes with the deployed HVAC system, was replaced with the ICC and includes same functionalities and blocks: (A) the stabilized power supply circuit 12V, which includes mainly the LM7812 component to decrease the voltage from the AC/DC transformer and stabilize it at 12V in order to power the on-off control relays for (C) the compressor, (D) the valve and (F) the external/internal fan. The block (B) is the stabilized power supply 5V, which uses the LM7805 component to reduce the voltage from 12V to 5V in order to power the micro-controller (i.e., NodeMCU) and embedded temperature sensors. The block (G) is composed of TRIAC and OPTO TRIAC MOC3021 components, which are used for controlling and varying the speed of the evaporator fan. The block (E) is the zero-crossing detector circuit that shows the zero-crossing transition of the voltage signal. More precisely, the block circuit contains a comparator and a rectifier. It is used to implement the speed variation of the fan by acting on the priming delay of the TRIAC, which must be less than 10ms. It is worth noting, that the frequency of the network voltage in Morocco is 50Hz, so the period is 20ms, and the signal passes by zero 2 times each period, which means 10 ms between each pulse of detecting the zero cross points. If the delay increases, the speed decreases, and the reverse is correct. For example, in order to have a maximum speed, the delay must be zero, and to have half of the speed the delay must be equal to 5ms.

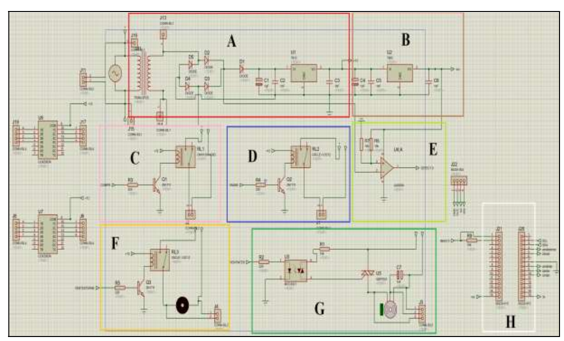

Figure 7: The control card circuit

The last block (H) is a NodeMCU v2, a low cost development board equipped with tiny Wi-Fi module ESP8266. The board has the capability to connect to a Wi-Fi network and run programs to control Input/Output (I/O) pins. The board works on 5v and its consumption is nearly negligible compared to the other equipment. NodeMCU can be programed either using the Arduino Core or the Lua scripting language. However, Arduino core is used in this study to implement the Fuzzy Logic controller and embed it into the board. While it boots up, the board connects to the Wi-Fi network and authenticate itself to the Message Queue Telemetry Transport (MQTT) broker. This IoT protocol is an extremely lightweight publish/subscribe messaging transport. It is mostly used for connections with remote locations where a small code footprint is required and/or network bandwidth is at a premium. The program is designed to acquire data from wired sensors, receive user desired temperature, real-time control of the I/O pins and send data to the deployed IoT and Big data platform. This communication is ensured by the use of MQTT where the NodeMCU can send (publish) and read (subscribe) using topics. A topic is a category name used to exchange information between two endpoints. As an example, the NodeMCU micro-controller gathers the indoor/outdoor temperatures from the wired sensors and uses them for calculating the error and then sending them to be stored in the database for visualization and further analysis. Furthermore, the user could remotely control the board using the developed Android application, as depicted in Fig. 6.

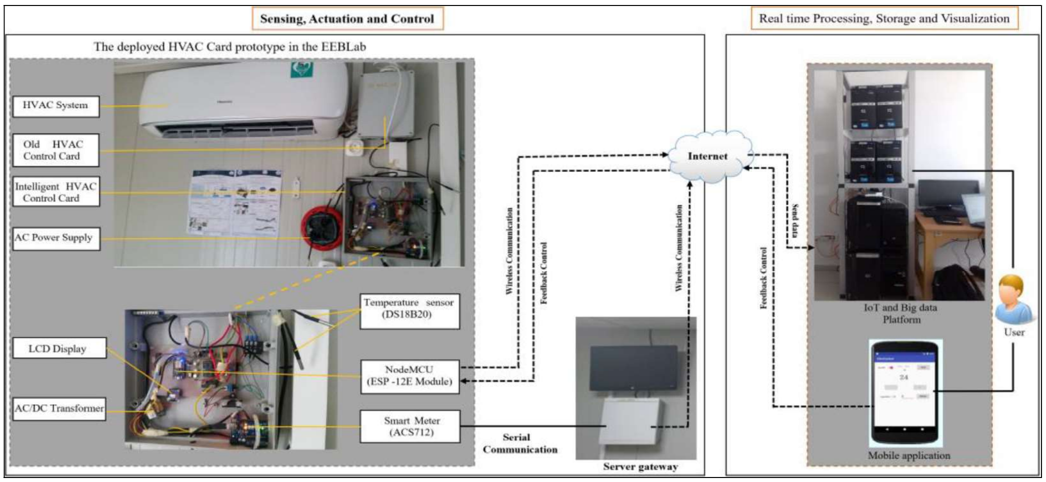

Figure 6: The general architecture of the experiment setup

B. The SM component

As shown in Fig. 6, we used an electricity sensor for measuring electricity consumption of the HVAC system. Mainly, the ACS712 current sensor is connected between supply loads to measure the current flowing through the load using Arduino board, and based on the current values the power consumed by the system is then computed. The smart meter is connected with the raspberry pi gateway, which is a low power tiny computer that integrates a Wi-Fi module. It also uses the MQTT protocol to send instantaneously the measurements to our server [29].

C. IoT and Big data Platform

The platform is fully based on open source technologies and integrates mainly Kaa IoT platform, MongoDB database, apache Storm, Flume and MQTT (Message Queue Telemetry Transport) protocol. Kaa is a free, open-source IoT platform for building, managing, and integrating connected devices within the Internet [23][30]. Apache storm is an open source distributed real-time computation system, which reliably processes unbounded streams of data. Moreover, apache Flume is allowing Kaa platform to move large amounts of log data to the Storm system. However the platform is composed of the following three services. The data acquisition, represented by the Kaa application, is used to get the measurements from our sensors using MQTT. The data processing and storage is composed of Spouts and Bolts services. The spouts receive the data from the Kaa application, and then transmit it to the first Bolts in which the data is pre-processed. The data is then transmitted to the Bolts dedicated for recording data into MongoDB database for further analysis. The data visualization is a web application, in which the data is represented in a format of charts. These charts are updated in real time, and the data can be exported for further applications and services.

We have also developed in a previous work [26], a remote mobile application for real-time feedback control. There are four main functionalities: an ON/OFF switch button to activate/deactivate the HVAC system, a button to change the cycle mode (heating or cooling), a real-time display of inside and outside temperature values, and a temperature variation control to fix the desired set point value. The control application sends and receives data from the real-time platform that allows exchanging data with the control card under the global platform. In fact, the application is based also on MQTT protocol to send data to the board. Afterward, data sent by the occupant (i.e., desired temperature, mode operation (Heating/Air conditioning), state of the HVAC (On/Off)) are received and can be used for controlling and regulating the speed of the evaporator fan of the system.

IV. Results and Discussions

The experiments have been conducted and two main metrics are evaluated: *i)* the indoor air temperature response at various temperature set points (Fig. 8), and *ii)* the electricity consumption of the HVAC system (Fig. 9), calculated by our Smart meter, which is in Watt/h. The temperature set points of the experimented space were in the range from 24 to 27 °C. The measurements were taken between 23.00 PM and 07.00 AM and at a time interval of two hours for on/off (*23h00-01h00*), PID (*01h00-03h00*), State feedback (*03h00-05h00*), and FLC (*05h00-07h00*) respectively. The metrics have been evaluated under heating operation mode and respectively cooling mode of the HVAC system according to the current ambient temperature and preferences temperature set by the occupants.

As illustrated in Fig. 8, the indoor temperature curve follows correctly the desired set point values for all control methods; however, we have noticed the following. FLC and SFC appear more stable than ON/OFF and PID controllers during the experiment, especially in the highest temperature set point (i.e., 27 °C), both of controllers reach and maintain the desired set points values. Furthermore, all controllers present a less error on all desired set points area except in the highest temperature set points, the ON/OFF and PID have a remarkable error. However, FLC and SFC have a slight overheat and overcool for all set points in comparison with PID, as expected especially in the highest temperature set point. This is due to this type of controller, which delivers too much heat before the temperature reached the OFF point. As a result, the temperature will overshoot, and then there is a warm up times period, which explain the undershooting of temperature because of the on/off thermostat control. In fact, it needs for about 5 to 10 minutes to cycle the air and in this time the heating unit blows the cold air, which explains the overcooling. Compared to ON/OFF, PID, SF controllers, the FLC showed almost the same transient response behavior for both settling and rise time for all temperature set points. This behavior could be enhanced if adequate types of MFs, such as trapezoidal waveform, Gaussian waveform are used. This could improve the performance of the controlled system, which requires significant dynamic variation in a short interval of time. In parallel, the deployed smart meter has gathered 26242 electrical power values, which we have used to measure the electricity consumption of the HVAC system according to the deployed controller. As it can be observed from the curve depicted in Fig. 9, FLC shows a considerable reduction in energy consumption in comparison to other control methods. The total hourly electrical power average consumed by the system during the experiment for all temperature set points is estimated at 2250 W/h, but 644.6 W/h for On/Off, 561.9 W/h for PID, 534.2 W/h for SFC and 509.3 W/h for FLC. These results show an energy saving for the FLC against ON/OFF, PID and SF: 10.99% for ON/OFF, 9.37% for PID, 4.37% for SFC. It's worth noting that the normal On/OFF control mechanism used in conventional HVAC system can deliver between 755 and 1000 W/h in the heating mode and between 855 and 1000 W/h in the cooling operation mode. The Fuzzy logic control can save more than 33.55% of energy.

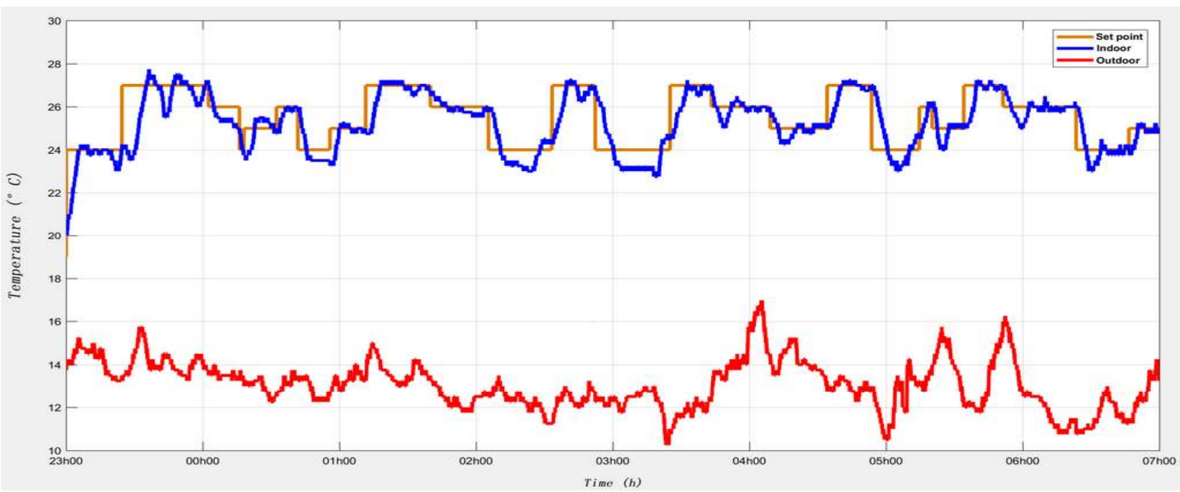

Figure 8: The indoor air temperature response at various temperature set points

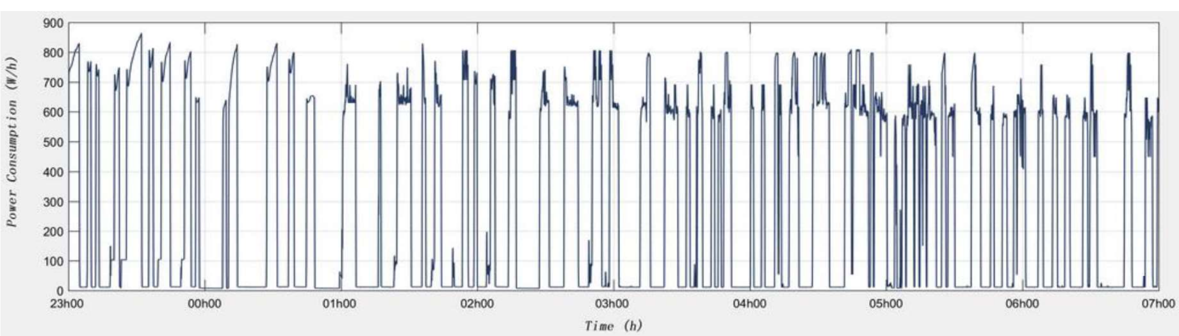

Figure 9: The hourly electricity consumption of the HVAC system

V. Conclusions and Perspectives

Most recent studies have shown that advanced control systems are required to further reduce energy consumption of HVAC systems while maintaining a good thermal comfort. In this work, a FLC approach was designed and deployed for HVAC control. The proposed FLC was compared against the ON/OFF, PID and SF controllers using two main metrics, comfort and energy consumption. The experimental results showed that FLC and SFC perform better in terms of thermal comfort than ON/OFF and PID. In fact, FLC and SFC showed a better stability and less error for all temperature set points. Both of FLC and SFC neglect overshoot and undershoot values compared to ON/OFF and PID. This work showed also that controlling the HVAC system with FLC enabled better control of the space air temperature with significant energy saving compared to ON/OFF, PID and SFC. In fact, the FLC showed a reduction in energy consumption against these controllers, about 11% for On/Off, 9% for PID, and 4% for SFC. In addition, the results demonstrated that the conversion of crisp variables into fuzzy variables with triangular and polynomial MFs limits the performance of FLC in terms of transient response time. Therefore, our ongoing work will investigate, using simulations and experimentations, membership functions with further comparison against ON/OFF, PID and SF controllers. Future work focuses on further enhancing our work by investigating predictive control for HVAC systems using recent machine learning techniques. A platform is under development for deploying real-time machine learning techniques for forecasting internal and external data (e.g., temperature, occupancy), which are required for the deploying predictive control approaches [31]. Preliminary results obtained from experiments conducted on a standalone ventilation system show the performance of the predictive control against the PID and SF controllers for improving both energy conservation and indoor air quality [32].

ACKNOWLEDGMENT

This work is performed under CASANET (Context-Aware Sensor-Actuator Networks for Energy-Efficient Buildings) project (2016-2019), which is funded by « le Ministere de l'Enseignement Superior, de la Recherche Scientifique et de la Formation des Cadres (MESRSFC) » and « le Centre National pour la Recherche Scientifique et Technique (CNRST) ». A part of this work is also supported by MIGRID (Grant 5-398), which is funded by USAID under the PEER program (2017-2019).

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