academicJournals

Vol. 12(1), pp. 13-23, 16 January, 2017
DOI: 10.5897/IJPS11.822
Article Number: A44FE2062333
ISSN 1992-1950

http://www.academicjournals.org/IJPS

International Journal of Physical Sciences

Full Length Research Paper

Energy saving by applying the fuzzy cognitive map control in controlling the temperature and humidity of room

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Received 2 June, 2011; Accepted 15 July 2011

This paper investigated the implementing of soft computing methodology of fuzzy cognitive map on controlling parameters of heating, ventilating and air-conditioning systems. In the past few years, many researches have been done on application of different controllers on heating, ventilating and air-conditioning system as a more energy consuming part of the building automation system. Unlike the conventional control methods which are used more in this area like PID controller, the fuzzy cognitive maps method was chosen to control of the temperature and humidity of the room in winter operation season and summer operation season. By applying the fuzzy cognitive map controller, more energy efficiency and also more energy saving has obtained. The advantages of using fuzzy cognitive maps indicated as a controller on the typical heating, ventilating and air-conditioning system in this paper. The algorithm of FCM control reached to the goals of comfort, robustness and energy saving.

Key words: Fuzzy cognitive map, heating ventilating and air-conditioning system, energy saving, energy efficiency, robustness.

INTRODUCTION

The heating, ventilating and air-conditioning (HVAC) system is the more energy consuming part of the building automation systems (BAS) in the intelligent buildings. Due to the limited sources of energy in the world and also fuel crisis, designing the better controllers to saving energy and energy efficiency is more important challenging for control engineers (Tachwali et al., 2007). Due to the great impact of HVACs systems on power and energy consumption, knowing the structure and operation of HVAC systems are possessing importance (Tashtoush

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Abbreviations: HVAC, Heating, ventilating and air-conditioning; **BAS**, building automation system; **FCM**, fuzzy cognitive map, **FL**, fuzzy logic, **ANN**, artificial neural network.

et al., 2005). According to Tashtoush et al. (2005) energy efficiency and indoor climate conditions are most important goals of designing HVAC systems. As a result of complicated quality of an HVAC system, obtaining to the mathematical model of HVAC is very difficult (Tashtoush et al., 2005) and also designing the proper controller become a big challenge (Lei et al., 2006; Wang et al., 2006). Designing the suitable controller could be saved a considerable amount of energy (Huang et al., 2006).

Research contributions and motivations

Fuzzy cognitive maps (FCMs) are utilized to model the complex dynamical systems and control plants. Most of the previous works on FCMs discuss about implementation of this method on modeling the complex systems. According to Stylios and Groumpos (2004), applying FCMs as a control system make efforts toward more intelligence on control systems. In spite of the accuracy of the conventional control methods (Stein et al., 2000), intelligent control methods could modify some negative points of the conventional methods.

Applying the PID controller on HVAC systems based on Tashtoush et al. (2005) work, shows the consuming more energy due to the overshoot and undershoot which are observed, but by applying intelligent control methods overshoot and undershoot cancelling are reached. Fuzzy logic (FL) and artificial neural network (ANN) beyond the others are more usable but in FL method to obtain more accuracy, a large number of rules block required which is more time consuming and also in ANN method the volume of the mathematical calculation needs more time. Obtaining to the more accuracy and also decrease the calculation time the FCM method is chosen. The FCMs is combination of the FL method and ANN method and contain the robust characteristics of both methods (Aguilar, 2005; Stylios and Groumpos, 2000). Finally, applying the combination of control techniques of fuzzy logic and neural networks are recommended to control of buildings. The hybrid method of fuzzy logic and neural networks contain the robust characteristics of both methods. In addition, the shortcomings of both methods are omitted in this method. The robustness of FCMs is another important reason of choosing this method. Regarding to definition, characteristics and simplicity of mathematical model of FCMs, implementing the FCMs as a direct control is recommended in control the parameters in building automation systems to achieve more intelligence in building and as well more energy saving. As a result of structure of FCMs, the run time of control process is declined. Due to the ability of FCMs in having learning strategy, the consumption of energy could be decreased. Due to the fact that, the energy sources are limited and energy crisis, saving more energy is important goal of using building automation systems. Therefore, The FCMs as a direct control system are proposed to reach the objectives of decreasing run time of control process and saving energy. Decreasing the consuming energy by HVAC system due to the eliminating of overshoots and undershoots on the supply temperature and supply humidity. On the other words, saving energy is the highlight contribution of this research.

Research objectives

Applying the FCM controller as a direct control on HVAC systems to obtain a nonlinear, robust controller and also achieving to a closed-loop, real-time and on-line learning ability controller with simple control algorithm and also fast convergence by using supervised learning are the objective of this paper. On the other words, the main objectives of this research are designing a nonlinear robust controller using Fuzzy Cognitive Map (FCM) to control the temperature and humidity of the room, to optimize and improve thermal comfort issue and Energy efficiency by obtaining the balance between thermal comfort and energy usage and designing a Closed-loop real-time on-line learning ability controller with simple control algorithm.

Description of HVAC system

As a result of increasing the population and global warming and many other serious reasons, demanding for energy saving is feasible (Tachwali et al., 2007). Due to the much consumption of energy by HVAC systems, is almost around 50% of total of generated electrical energy in the world, designing the appropriate controller for declining the consumption of energy is considerable (Tachwali et al., 2007).

A heating, ventilating and air conditioning system or on the other words HVAC system consist of number of subsystems as indoor air loop, chilled water loop, refrigerant loop, condenser water loop and outdoor air loop (Lei et al., 2006; Wang et al., 2006). HVAC systems consist of a number of nonlinear and time-varying subsystems (Wang et al., 2006). So the HVAC systems are known as typical non-linear time-variable multivariable systems with disturbances and uncertainties (Lei et al., 2006). The typical HVAC systems include of a room, humidifier, heater, cooler, fan and duct (Tashtoush et al., 2005). According to Tashtoush et al. (2005), winter operation seasons' components are the zone, duct, mixing box, heating coil and humidifier but heating coil and humidifier are replaced by cooling coil and dehumidification coil in summer operation season. Assuming the homogeneous temperature distributing in the zone, the equal effect of walls and roofs in the zone in every respect and no effect of ground, the constant air's density, disregarding the pressure losses of interzone and the external heat sources like the number of persons and appliances as an uncontrolled inputs are considered.

Referring to Tachwali et al. (2007) and Tashtoush et al. (2005), the mathematical model of typical HVAC systems based on many studies on dynamical model of HVAC consists of the zone model, mixing box model, duct model, fan model, heating coil model, humidifier model, cooling coil model and dehumidification coil model as follows:

The rate of thermal energy change in the zone is described by Equation (1) and through the walls and roof by Equations (2 to 4) and the humidity ratio of the zone by Equation (5).

$$dT_z/dt=(\beta/c_z)(T_{sup}-T)+(2\gamma/c_z)(T_{w1}-T)+(\lambda/c_z)(T_R-T)+(2\delta/c_z)(T_{w2}-T)+(1/c_z)q(t) \quad (1)$$

$$dT_{w1}/dt=(\gamma/c_{w1})(T_z-T_{w1})+(\gamma/c_{w1})(T_o-T_{w1}) \quad (2)$$

$$dT_{w2}/dt=(\delta/c_{w2})(T_z-T_{w2})+(\delta/c_{w2})(T_o-T_{w2}) \quad (3)$$

$$dT_R/dt=(\lambda/c_R)(T_z-T_R)+(\lambda/c_R)(T_o-T_R) \quad (4)$$

$$dW_z/dt=(f_{sa}/V_z)(W_s-W_z)+(1/\rho_w V_z)P(t) \quad (5)$$

Where:

$\beta= f_{sa}\rho_a C_{Pa}$, $\gamma=U_{w1}A_{w1}$, $\lambda= U_R A_R$, $\delta=U_{w2}A_{w2}$

The Equations (6) and (7) illustrate the energy and mass balance of mixing box, which outside temperature is (T_o), return temperature from the zone is (T_r), outside humidity ratio is (W_o), return humidity ratio from the zone is (W_r), mass flow rate of the outdoor air(m_o)and mass flow rate of the recalculated air(m_r).

$$T_m=(m_rT_r+m_oT_o)/(m_r+m_o) \quad (6)$$

$$W_m=(m_rW_r+m_oW_o)/(m_r+m_o) \quad (7)$$

According to the Tashtoush et al. (2005) and Clark et al. (1985) expanded the transient model for duct unit. The Equation 8 shows the rate change of air temperature of duct model. T_i is inlet air temperature and T_{out} is the exit air temperature. The h_i is heat transfer coefficient inside the duct and h_o is the heat transfer coefficient in the ambient. M_d is mass of the duct model; C_d is specific heat of the duct material; Mass flow rate of the air stream is m_a; specific heat of air is c_{pa}.

$$dT_{out}/dt=(((h_i+h_o)\ m_a c_{pa})/(h_i M_d C_d))(T_{in}-T_{out}) \quad (8)$$

Referring to the Tashtoush et al. (2005) passing the air from the fan, increasing the temperature around 1-2°C. Heating coil exchange the heat from water to air to provide prepared ventilating air in building. T_{wi} is the temperature of supplied heating water to the heating coil. T_{wo} is the exit water temperature of heating coil. The assumptions in the heating coil part are the constant mass flow rate of the water inside coil, neglecting the thermal resistance due to the considering of high conductivity of the coil material and T_{wo} is considered to be constant and is equal to 10°C. Equation (9) shows the energy balance between hot water and cold air which rate of exchanging energy in the air passes from the coil is equal to energy which is added by the flow rate of water in the heating coil and the transferred energy by return air to the surrounding. Equation (10) indicates the mass balance.

$$C_{ah}\ (dT_h/dt) = f_{sw}\rho_w C_{Pw}\ (T_{wi}-T_{wo})+(\ UA)_a(T_o-T_{co})+ f_{sa}\rho_a C_{Pa}(T_m-T_{co}) \quad (9)$$

$$V_{ah}(\sigma W_{co}/\sigma t) = f_{sa}(W_m-W_{co}) \quad (10)$$

The mass transfer of water vapor to the atmospheric air to increase the water vapor in the mixture is humidification. Due to the undesirable impacts of very low moisture content on the human body, measuring and controlling of the moisture in the air are considerable phase of air conditioning. According to Tashtoush et al. (2005), developing the energy and mass balance equations of the humidifier model by Kasahara et al. (2000) are as follows:

$$C_h(dT_h/dt)= f_{sa}C_{Pa}(T_{si}-T_h)+\alpha_h\ (T_o-T_h) \quad (11)$$

$$V_h(dW_h/dt)= f_{sa}(W_{si}-W_h)+(h(t)/\ \rho_a) \quad (12)$$

The rate of humid air, producing by humidifier and also function of humidity ratio in Equation (12), indicates by h (t). Set point values of the system for winter operation season are considered as outside temperature of 5°C, outside humidity of 0.00377 kg/kg (dry air), supply temperature of 25°C, constant value of the volume flow rate of the supply air and is equal to f_{sa}=0.192 m^3/s, two lamps with load 0.5 kW and also two persons with 0.15 kW load are considered as uncontrolled inputs in the zone and the initial values of the zone temperature and zone humidity ratio when t=0 are equal to $T_z(0)=T_o$ and $W_z(0)=W_o$. The desired values are 22°C for zone temperature and 0.008 kg/kg for the zone humidity ratio.

The important component of air conditioning unit and also the important interface between the primary plant and the secondary air distribution system is cooling coil. Passing air through the coil in contact with the cold fin surfaces causes heat transfer from air to the water by flowing inside the tubes. Due to the significance of the cooling coil, study of the cooling coil transient behavior and its response characteristics were developed by several models. In Tashtoush et al. (2005) work, developing transient model of a chilled-water coil by Elmahdy and Mitalas (1977) is adopted. In Equations (14)

Table 1. Parameters of PID controllers in summer operation season.

Cooling mode	Cooling coil	Dehumidifier
Gain	2	5
Integrator	0.0015	0.0035
Differentiator	0.1	0.1

Table 2. Parameters of PID controllers in winter operation season.

Heating mode	Heating coil	Humidifier
Gain	3	0.65
Integrator	0.011	0.008
Differentiator	25	10

and (15), T_a is air temperature and W_a is humidity ratio which are used as a function of water temperatures T_{w1} and T_{w2} respectively.

$$T_a\,(T_{w1}) = -0.0587(T_{w1})^2 + 1.773\,(T_{w1}) + 1.1816 \quad (13)$$

$$W_a\,(T_{w2}) = 3.2434\times10^{-5}(T_{w2})^2 - 1.7972\times10^{-5}\,(T_{w2}) + 6.223\times10^{-3} \quad (14)$$

Validity range for Equations (13) and (14) is T_w=5-50°C. Set point values of the system for summer operation season are considered as outside temperature of 32°C, outside humidity of 0.01251 kg/kg (dry air), supply temperature of 13°C, constant value of the volume flow rate of the supply air and is equal to f_{sa}=0.192 m^3/s, two lamps with load 0.5 kW and also two persons with 0.15 kW load are considered as uncontrolled inputs in the zone and the initial values of the zone temperature and zone humidity ratio when t=0 are equal to $T_z(0) = T_o$ and $W_z(0) = W_o$. The desired values are 22°C for zone temperature and 0.008 kg/kg for the zone humidity ratio.

LITERATURE REVIEW

Here, the controller designed by Tashtoush et al. (2005) is reviewed and the PID controller was used. The values of the parameters of The PID controllers, obtained from Ziegler-Nichols method. The PID controller transfer function which was used consists of three different elements which can be described as $G_c(s) = K_p + K_I/s + K_D s$.

Based on previous discussions about HVAC systems, the operation of the system are categorized on two different operation seasons as summer and winter. It is clear that each operation season requires two separate controllers to control temperature and humidity respectively. The Table 1 shows the parameters of the PID controller for cooling mode of summer operation season. The other two controllers related to the heating mode of winter operation season which are related to control of temperature and humidity respectively. The Table 2 indicates the parameters of these two mentioned controllers. At the result section, the responses of the HVAC system under control of mentioned PID controller have been got and finally the results of PID controller and FCM one are compared. Figures 1 and 2 shows the results of applying PID controller based on Tashtoush et al. (2005) work.

Overview of FCM

At first time, the cognitive maps are introduced by Robert Axelord in 1976 in social and political sciences. The application of cognitive maps at first was a way to represent social scientific knowledge and model decision making in social and political systems. The applications of cognitive maps are not also in political and social sciences but also in many areas like analysis of electrical circuits, medicine, supervisory systems, organization and strategy planning, analysis of business performance indicators, software project management, information retrievals, modeling of plant control, system dynamics and complex systems and modeling virtual world, etc (Aguilar, 2005; Bertolini, 2007; Ghazanfari et al., 2007). Finally in 1986 the idea of cognitive maps were extended by Bart Kosko to fuzzy cognitive maps by replacing the numeric value of concepts with fuzzy values or on the other hands with lying the value of concepts in interval [0, 1] or [-1, 1] (Bertolini, 2007). Also the relationships between concepts take a value in interval [0, 1] or [-1, 1] (Bertolini, 2007). FCMs indicates the behavior of the system in terms of concepts which each concept stand for a situation or feature of the system (Aguilar, 2003, 2005). The whole system is shown by FCMs as a directed graph with concepts and their causal relationships in a given scenario (Khor and Khan, 2003).

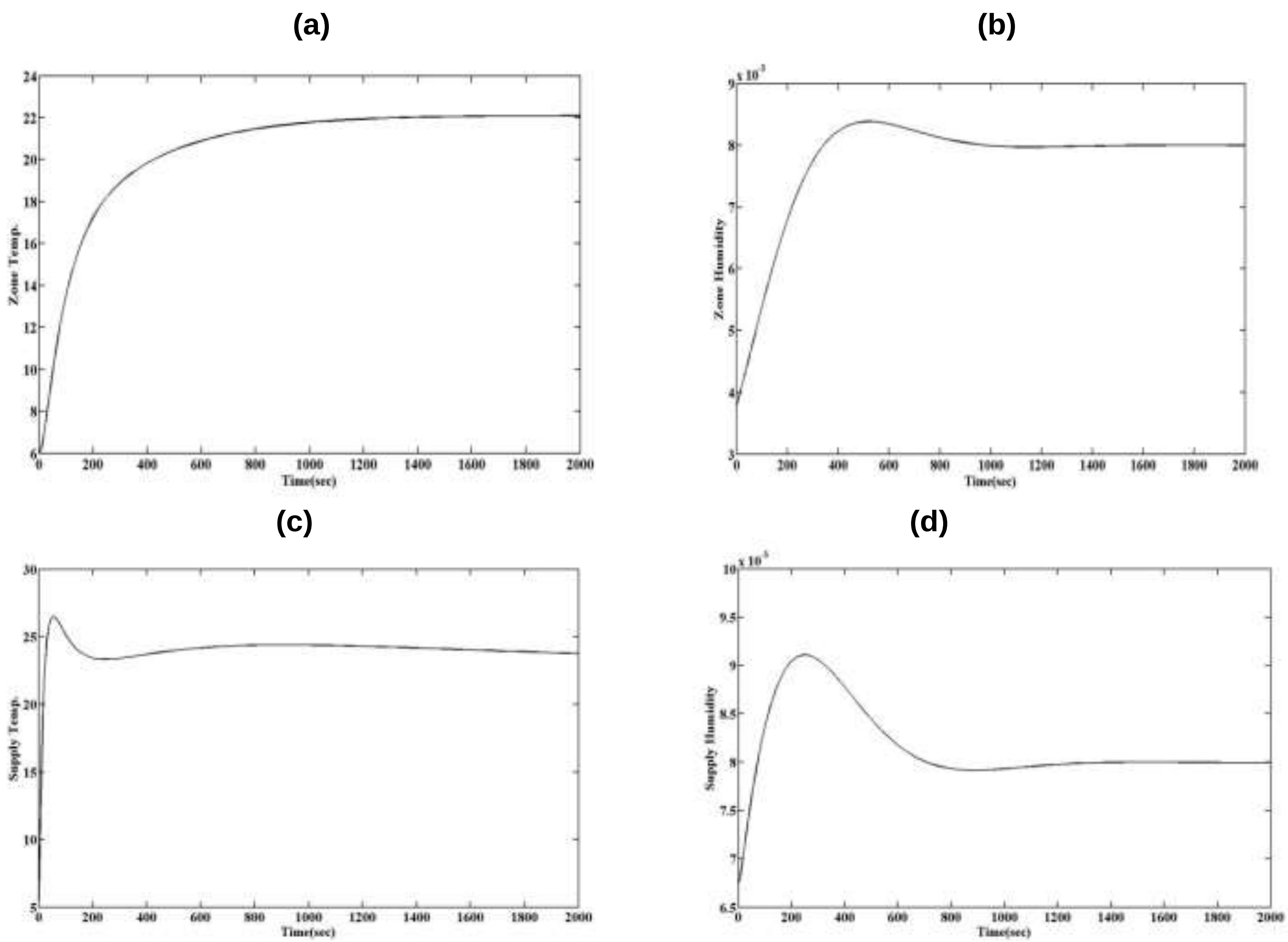


Figure 1. (a) Temperature of the controlled zone in winter operation season by PID controller. (b) Humidity ratio of the controlled zone in winter operation season by PID controller. (c) Supply air temperature of the controlled zone in winter operation season by PID controller. (d) Supply humidity ratio of the controlled zone in winter operation season by PID controller.

The nodes in a directed graph are representative of concepts and also the causal relationships between concepts are illustrated by graph's edges (Aguilar, 2005). The value of each concept shows the degree of activation of each concept at particular time (Aguilar, 2005). According to above mentioned the value of causal relationships between concepts should be taken values in interval [-1, 1].The value of -1 indicates the strongly negative effect, +1 shows strongly positive effect and 0 has no effect. Referring to the values of edges, the causalities or relations are categorized into three types as if the relation of concepts takes positive value, express positive causality, if the relation of concepts takes negative value, express negative causality and if the relation of concepts takes zero value, express no relationship.

For one thing FCMs are hybrid model between fuzzy logic and neural networks (Aguilar, 2005). In other words, FCMs are defined as a fuzzy-graph structure with existence of systematic causal propagation, in particular forward and backward chaining (Stylios and Groumpos, 2000). In comparison of fuzzy rule based method by FCMs many of knowledge-extraction problems which are related to fuzzy rule based method could be prevented (Aguilar, 2005). The other advantages of FCMs in comparison by expert system or neural networks are its simplicity to use for representing structured knowledge, and also computation of inference by numeric matrix operation (Papageorgiou and Groumpos, 2005).

MATERIALS AND METHODS

Mathematical model of fuzzy cognitive map

Besides the graphical structure, FCM follows its mathematical model which consists of a 1×n state vector A which contains the

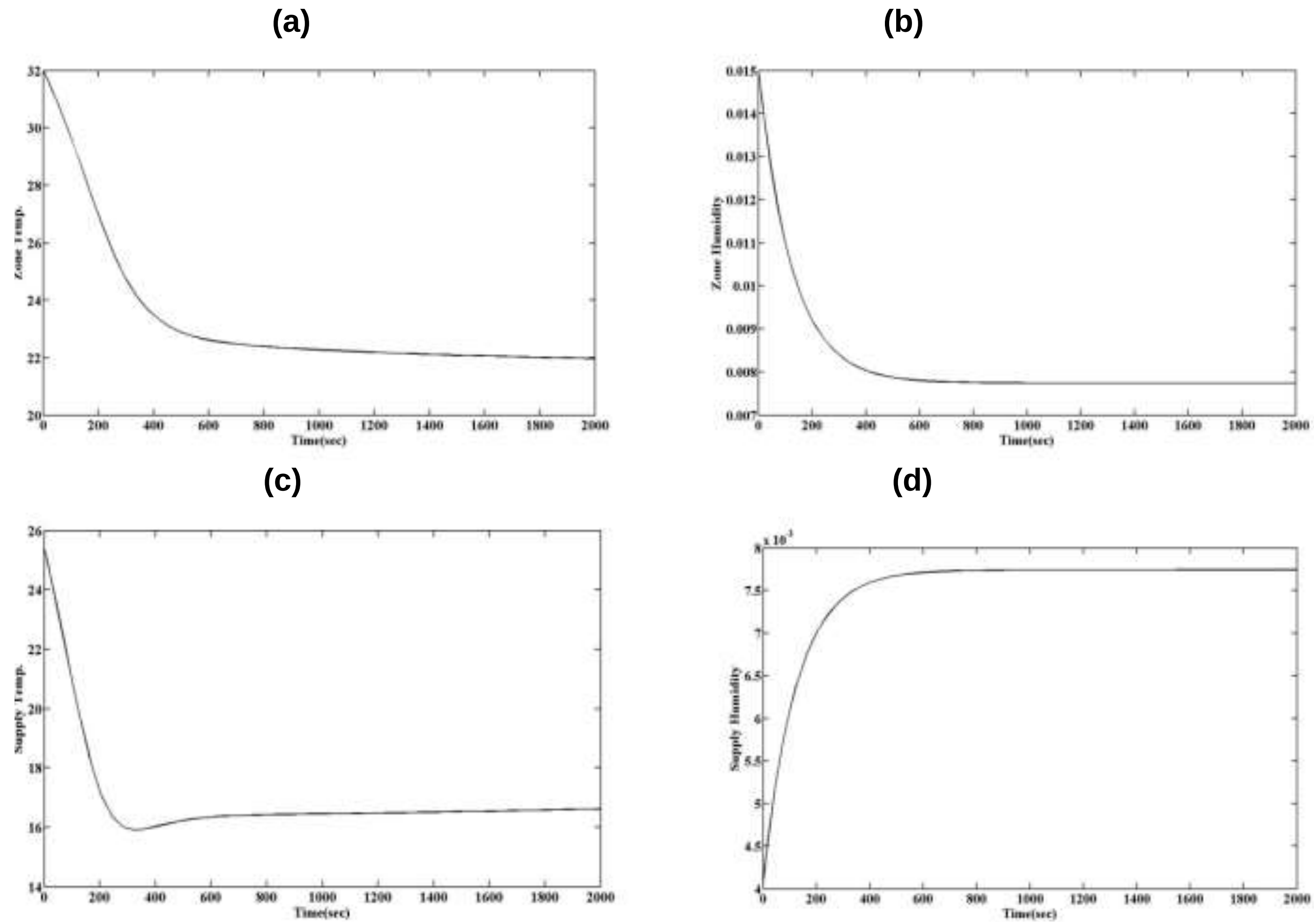


Figure 2. (a) Temperature of the controlled zone in summer operation season by PID controller. (b) Humidity ratio of the controlled zone in summer operation season by PID controller. (c) Supply air temperature of the controlled zone in summer operation season by PID controller. (d) Supply humidity ratio of the controlled zone in summer operation season by PID controller.

values of the n concepts and also an n×n weight matrix which includes the weights W_{ij} of the causality between concepts. The number of concepts is indicated by n. The value of each concept depends on linked concepts with proper weights and also the previous value of concept. After transferring the fuzzy values to the concepts, the $A_i^{new}=f\,(\Sigma A_j^{old}\times W_{ij})+A_i^{old}$ (13) rule is used to calculate the activation level of A_i for each concept. A_i^{new} indicates the activation value of concept *i* at time t+1, A_j^{old} shows the activation value of concept *j* at time t and also *f* is a threshold function. There are two types of threshold functions which are applied in FCMs structure. The first one which is the unipolar sigmoid function to squash the content to the interval [0, 1] is $f\,(x)=1/(1+e^{-\lambda x})$ (14) and the second one which has been utilized to transform the content in the interval [-1, 1] is $f\,(x)=\tanh(x)$ (15). The threshold function is chosen based on the used method to describe the concepts (Stylios and Groumpos, 2004).

Applying the FCM controller on HVAC system

Based on construction of FCM, describing the concepts according to the goals, activities or state and characteristic of the system are needed. Referring to the HVAC system, inputs and outputs of the system and the affecting parameters on inputs and outputs and also the system, two controllers are required one for heating model and the other for humidifier model in winter operation season and also two controllers for cooling coil and dehumidification coil in summer operation season. The concepts for heating model should be described as follows:

Concept 1: The temperature of the zone T_z, which is the output of the model.
Concept 2: The T_{wi} is temperature of the supplied water to the heating coil, which is the manipulated variable.
Concept 3: The temperature out from the duct T_{out}, which is the output of the duct model.

The concepts for humidifier model should be described as follows:

Concept 1: The humidity of the zone W_z, which is the output of the model.
Concept 2: The W_{si} is humidity ratio of the supply air to the humidifier in, which is the manipulated variable.
Concept 3: The humidity ratio out from the humidifier W_h, which is the output of the humidifier model.

The concepts for cooling model should be described as follows:

Concept 1: The temperature of the zone T_z, which is the output of the model.
Concept 2: The T_{w1} is temperature of water in cooling coil, which is the manipulated variable.

The concepts for dehumidifying model should be described as follows:
Concept 1: The humidity ratio of the zone W_z, which is the output of the model.
Concept 2: The T_{w2} is temperature of water in dehumidifying coil, which is the manipulated variable.

The impacts of the concepts are shown by weight matrix. The weight matrix is a n×n matrix which n is the number of concepts and impact of each concept on the others is a number in an interval [-1, +1]. The connection between concepts for heating model controller is as follows:

Linkage 1: It connects concept 1 (zone temperature T_z) with concept 2 (supply temperature of water T_{wi}). When the value of T_z increases, the value of T_{wi} increases and vice versa.
Linkage 2: It connects concept 1 (zone temperature T_z) with concept 3 (temperature out from the duct T_{out}). When the value of T_z increases, the value of T_{out} increases and vice versa.
Linkage 3: It connects concept 2 (supply temperature of water T_{wi}) with concept 1 (zone temperature T_z). When the value of T_{wi} increases, the value of T_z increases and vice versa.
Linkage 4: It connects concept 2 (supply temperature of water T_{wi}) with concept 2 (supply temperature of water T_{wi}). When the value of T_{wi} increases, the value of T_{wi} increases and vice versa.
Linkage 5: It connects concept 3 (temperature out from the duct T_{out}) with concept 1 (zone temperature T_z). When the value of T_{out} increases, the value of T_z increases and vice versa.
Linkage 6: It connects concept 3 (temperature out from the duct T_{out}) with concept 2 (supply temperature of water T_{wi}). When the value of T_{out} increases, the value of T_{wi} increases and vice versa.

The connection between concepts for humidifier model controller is as follows:

Linkage 1: It connects concept 1 (zone humidity W_z) with concept 2 (supply humidity ratio to humidifier W_{si}). When the value of W_z increases, the value of W_{si} increases and vice versa.
Linkage 2: It connects concept 1 (zone humidity W_z) with concept 3 (humidity ratio out from the humidifier W_h). When the value of W_z increases, the value of W_h increases and vice versa.
Linkage 3: It connects concept 2 (supply humidity ratio to humidifier W_{si}) with concept 1 (zone humidity W_z). When the value of W_{si} increases, the value of W_z increases and vice versa.
Linkage 4: It connects concept 2 (supply humidity ratio to humidifier W_{si}) with concept 2 (supply humidity ratio to humidifier W_{si}). When the value of W_{si} increases, the value of W_{si} decreases and vice versa.
Linkage 5: It connects concept 3 (humidity ratio out from the humidifier W_h) with concept 1 (zone humidity W_z). When the value of W_h increases, the value of W_z increases and vice versa.
Linkage 6: It connects concept 3 (humidity ratio out from the humidifier W_h) with concept 2 (supply humidity ratio to humidifier W_{si}). When the value of W_h increases, the value of W_{si} decreases and vice versa.
Linkage 7: It connects concept 3 (humidity ratio out from the humidifier W_h) with concept 3 (humidity ratio out from the humidifier W_h). When the value of W_h increases, the value of W_h decreases and vice versa.

The connection between concepts for cooling model controller is as follows:

Linkage 1: It connects concept 1 (zone temperature T_z) with concept 1 (zone temperature T_z). When the value of T_z increases, the value of T_z increases and vice versa.
Linkage 2: It connects concept 1 (zone temperature T_z) with concept 2 (temperature of water in cooling coil T_{w1}). When the value of T_z increases, the value of T_{w1} increases and vice versa.
Linkage 3: It connects concept 2 (temperature of water in cooling coil T_{w1}) with concept 1 (zone temperature T_z).When the value of T_{w1} increases, the value of T_z decreases and vice versa.
Linkage 4: It connects concept 2 (temperature of water in cooling coil T_{w1}) with concept 2 (temperature of water in cooling coil T_{w1}). When the value of T_{w1} increases, the value of T_{w1} decreases and vice versa.

The connection between concepts for dehumidifier model controller is as follows:

Linkage 1: It connects concept 1 (zone humidity W_z) with concept 1 (zone humidity W_z). When the value of W_z increases, the value of W_z increases and vice versa.
Linkage 2: It connects concept 1 (zone humidity W_z) with concept 2 (water temperature of the dehumidifying coil T_{w2}). When the value of W_z increases, the value of T_{w2} increases and vice versa.
Linkage 3: It connects concept 2 (water temperature of the dehumidifying coil T_{w2}) with concept 1 (zone humidity W_z). When the value of T_{w2} increases, the value of W_z decreases and vice versa.
Linkage 4: It connects concept 2 (water temperature of the dehumidifying coil T_{w2}) with concept 2 (water temperature of the dehumidifying coil T_{w2}). When the value of T_{w2} increases, the value of T_{w2} decreases and vice versa.

According to the structure of FCMs, the values of the concepts correspond to the real measurements values that have been transformed in the interval [0, 1]. The measurement values are transferred by the transformation mechanism to their representative values of concepts. The chosen transformation mechanism (Kim et al., 2008) is:

$$g(s_i^t) = \begin{cases} 0, & \text{if } s_i^t < a_i \\ (s_i^t - a_i)/(2(m_i - a_i)), & \text{if } a_i \le s_i^t \le m_i \\ 0.5 + (s_i^t - m_i)/(2(b_i - m_i)), & \text{if } m_i < s_i^t \le b_i \\ 1, & \text{if } s_i^t > b_i \end{cases}$$

Where:
s_i^t=observed value of the *i*th state at time t; $a_i = \min_{t \in T}\{s_i^t\}$; $b_i = \max_{t \in T}\{s_i^t\}$; $m_i = \text{average}_{t \in T}\{s_i^t\}$.

The initial vector of FCM is structured by transformation of initial measurement values of HVAC system. Then FCM starts to simulate the behavior of the process by equations (13) and (14). On the other words, the values of concepts are calculated at each running step of the FCM by considering that each running step at FCM is defined as time step. After few simulation steps, the values of concepts do not change. When the FCM reaches to this mentioned step, the final values of the concepts should be transformed to the real values and applied to the actuators. In spite of the advantageous of FCMs in designing to control the complicated and complex nonlinear systems, the most considerable weak point of FCMs are their potential to convergence to the undesired steady state is obvious (Papageorgiou and Groumpos, 2004). Learning ability of the FCMs is the best way to solve the mentioned problem.

By updating the strengths of causal links the values of concepts approach to the desired steady states (Lu et al., 2010).

Applying learning method on fuzzy cognitive map

Here, implementing the learning method is considered. Whereas the weakness of FCM are discussed in last section, adding learning method is an appropriate solution to convergence the results to the desired steady state. Among the different learning strategies which are used to train the weight matrix, the δ learning method is preferred. Referring to Lu et al. (2010), the δ learning method is a sort of supervised learning. According to Lu et al. (2010), reason for choosing this learning method are avoiding from low convergence speed, large iterative number and complexity of algorithm. On the other words, the other learning methods like genetic algorithm (GA), particle swarm optimization (PSO) or unsupervised learning's are disadvantageous due to the invariant weights, low learning speed, complexity of calculation and large number of iteration steps. Therefore, applying supervised learning on FCM due to the fast convergence make more suitable the control procedure to the online real-time controlling (Lu et al., 2010). Chosen learning method, the supervised δ learning rule (Lu et al., 2010) is $W_{ij}(K+1)=W_{ij}(K)+\Delta W_{ij}(K)$ which is $\Delta W_{ij}(K)=\eta\, A_i(K)\, A_j(K)(1-A_j(K))(d_j-A_j(K))$.

Where:
d_j = The expected value of input node j ; A_i =The state value of nodes connecting with this input node ; A_j = The state value of input node j ; η = η ϵ [0,1] is learning rate; K= The iteration step.

RESULTS AND DISCUSSION

In this research, the FCM method is utilized as a controller to control the parameters of zone temperature and zone humidity. The simulation results by MATLAB software show the comparison of the PID controller which is used in Tashtoush et al. (2005) with FCM controller for controlled variables of zone temperature and zone humidity respectively and for control variables supply air temperature and supply humidity ratio respectively. The comparison of the results of simulation by applying FCM controller and also PID controller in winter operation season got the below results. Figures 1 and 3 shows the responses of the HVAC system by implementing PID controllers and FCM controllers respectively in winter operation season.

Figure 3a shows the zone air temperature (T_z) which is controlled by discussed FCM controller in winter operation season. The air temperature increases slowly and exponentially in approximately 1000s to obtain to the 22°C which is set point value with small error. Figure 3(b) demonstrates the humidity ratio of the zone (W_z). It is clear that from the figure that the humidity ratio of the zone increases from 0.0039 to 0.0081 kg/kg and stabilizes in approximately 700 s with small error. Figure 3(c) shows the supplied air temperature (T_s) in winter operation season. The supplied air temperature increases softly from 5 to 24°C and stabilizes to 24°C in about 700 s. Figure 3(d) illustrates the supplied humidity ratio of the zone (W_s). It is clear that from the figure that the humidity ratio of the zone rises rapidly from 0.0068 to 0.0081 kg/kg to reach and stabilizes to the steady state value of 0.008 kg/kg in about approximately 300 s with a very small error.

Figure 1(a) illustrates the zone air temperature (T_z) which is controlled by mentioned PID controller in winter operation season. The air temperature increases slowly and exponentially in approximately 1200 s to obtain to the 22°C which is set point value with small error. Figure 1(b) demonstrates the humidity ratio of the zone (W_z). It is clear that from the figure that the humidity ratio of the zone increases to 0.0085 kg/kg then decreases until stabilizes to obtain to the 0.008 kg/kg which is set point value in approximately 1000 s without almost any error. Figure 1(c) shows the supplied air temperature (T_s). The supplied air temperature increases to 27°C at the beginning and then decreases until stabilizes to 24°C. Figure 1(d) illustrates the supplied humidity ratio of the zone (W_s). It is clear that from the figure that the humidity ratio of the zone rises rapidly to 0.0093 kg/kg then declines smoothly to reach and stabilizes to the steady state value of 0.008 kg/kg in about approximately 1400 s.

In winter operation seasons results; the important improvement by FCM controllers is the cancellation of overshoots and undershoots which have seen on the Tashtoush et al. (2005) work. Referring to the achieved outcomes or outputs of the system, clearly the author designed control systems which is FCM one are smoother than the PID one. On the other words, in spite of the fact that the PID controllers are more advantageous and practical controllers, the outputs of the FCM controllers are smooth, but in Tashtoush et al. (2005) work, the outputs of some parts of the system have overshoot or undershoot before achieving to the desired set point value. It is clear that, by cancelling overshoot and undershoot, a part of energy which is consumed to produce them is saved and in addition using FCM controllers which are saved the energy by setting the suitable initial values for the system. The total consuming energy by PID controller is 15.295 × 10^4 in 2000s and 14.82× 10^4 in same time for FCM one. The difference between two controllers shows 4.75% saving energy by FCM one. Comparison the results by PID and FCM controllers shows the FCM controllers are faster than PID one. The steady state is occurred sooner in FCM controller versus PID one. Comparison the results of the robustness of the PID and FCM controllers shows the FCM controllers are more robust than PID one. The steady state is occurred with negligible value in FCM controller versus PID one with small settling time in compare with PID one.

Moreover, the comparison of the results of applying FCM controller and PID one for summer operation season got the below results. Figures 2 and 4 shows the responses of the HVAC system by implementing PID controllers and FCM controllers respectively in summer operation season.

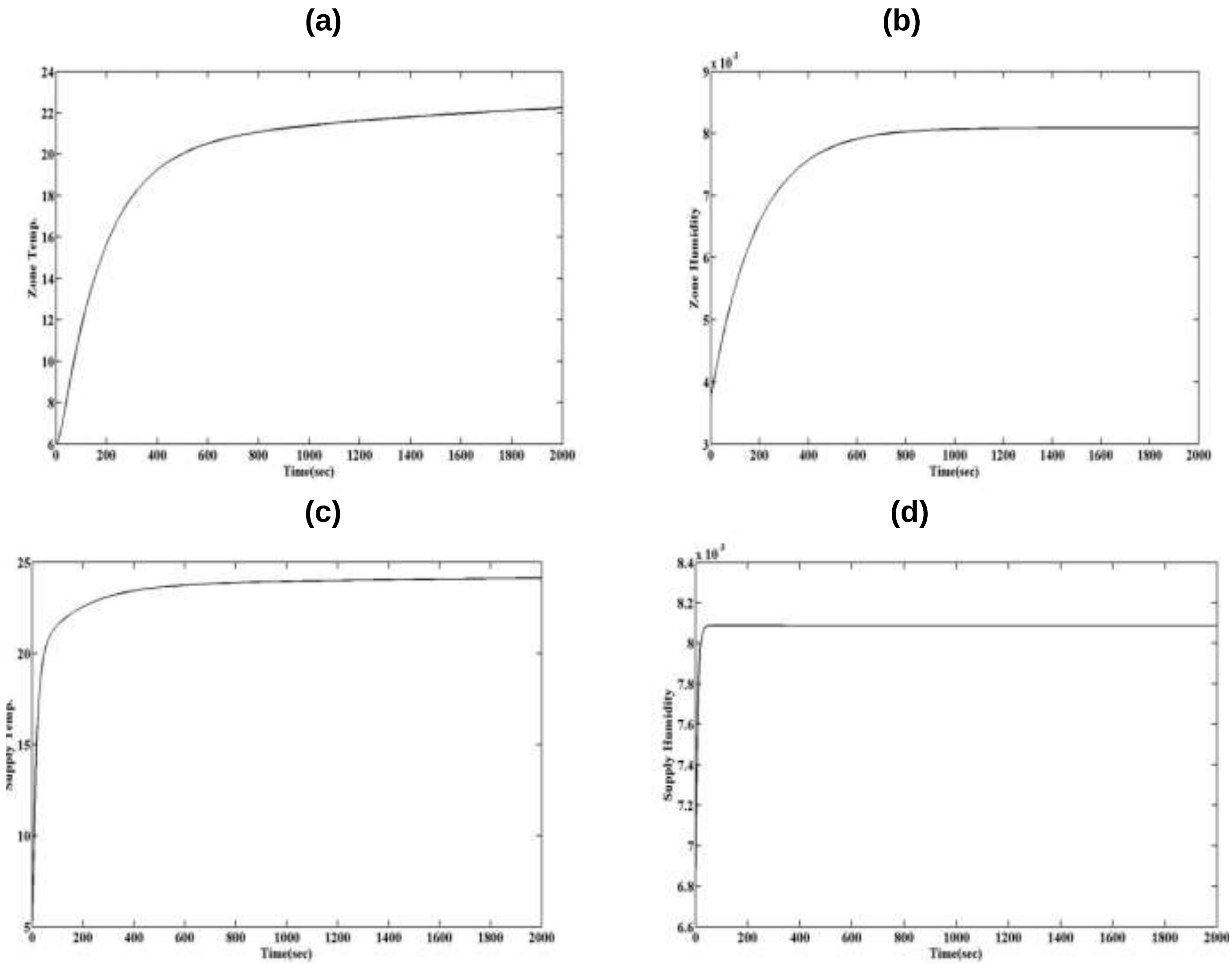
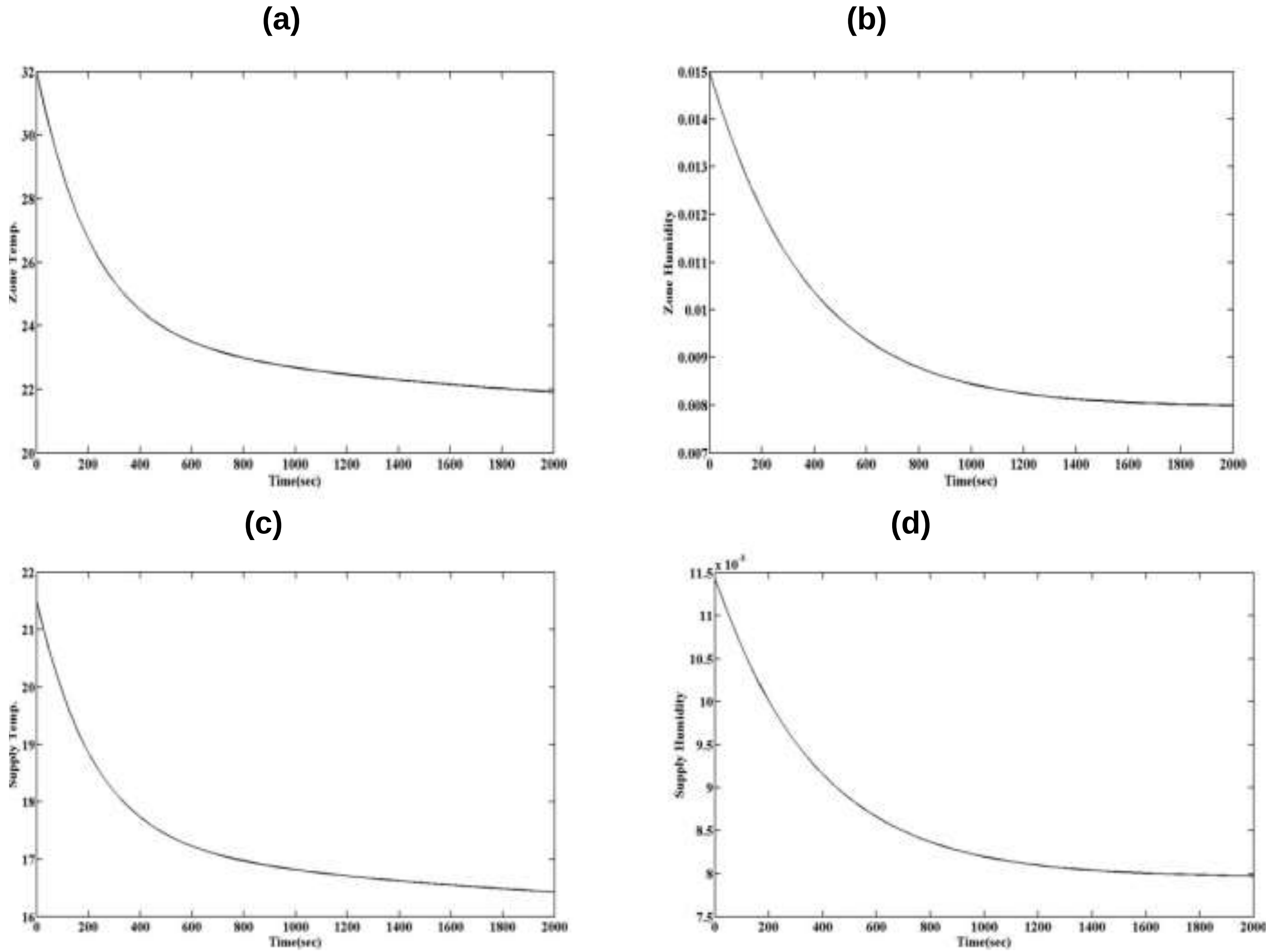


Figure 3. (a) Temperature of the controlled zone in winter operation season by FCM controller. (b) Humidity ratio of the controlled zone in winter operation season by FCM controller. (c) Supply air temperature of the controlled zone in winter operation season by FCM controller. (d) Supply humidity ratio of the controlled zone in winter operation season by FCM controller.

Figure 4a shows the zone air temperature (T_z) which is controlled by mentioned FCM controller in summer operation season. The air temperature declines smoothly and exponentially to obtain to the 22°C which is set point value in about 1200 s with a small error. Figure 4b illustrates the humidity ratio of the zone (W_z). The humidity ratio of the zone decreases smoothly to obtain to the 0.008 kg/kg which is set point value in approximately 1000 s with negligible error. Figure 4c demonstrates the supplied air temperature (T_s) in summer operation season. The supplied air temperature decreases smoothly and stabilizes to 16.4°C. Figure 4(d) shows the supplied humidity ratio of the zone (W_s). It is obvious that from the figure that the humidity ratio of the zone declines slowly from 0.0115 to 0.008 kg/kg and stabilizes in about approximately 950 s.

Figure 2a shows the zone air temperature (T_z) which is controlled by mentioned PID controller in summer operation season. The air temperature decreases slowly and exponentially to obtain to the 22°C which is set point value in approximately 1700 s with a small error. Figure 2(b) illustrates the humidity ratio of the zone (W_z). It is obvious that from the figure that the humidity ratio of the zone declines smoothly to obtain to the 0.008 kg/kg which is set point value in approximately 1000 s with a small error. Figure 2c demonstrates the supplied air temperature (T_s). The supplied air temperature decreases from 25.5 to 16°C at the beginning until 350 s and then increases to 17°C. Figure 2d illustrates the supplied humidity ratio of the zone (W_s). It is obvious that from the figure that the humidity ratio of the zone rises smoothly from 0.0044 to 0.0078 Kg/Kg and stabilizes to

Figure 4. (a) Temperature of the controlled zone in summer operation season by FCM controller. (b) Humidity ratio of the controlled zone in summer operation season by FCM controller. (c) Supply air temperature of the controlled zone in summer operation season by FCM controller. (d) Supply humidity ratio of the controlled zone in summer operation season by FCM controller.



0.0078 kg/kg in about approximately 1200 s.

In summer operation season; the remarkable point is the cancellation of overshoots and undershoots which have seen on the Tashtoush et al. (2005) work. Based on the obtained results or outputs of the system, obviously the FCM designed control systems are smoother than the PID one. On the other words, despite the fact that the PID controllers are more useable controllers, the outputs of the FCM controllers are smooth, but in the Tashtoush et al. (2005) work, the outputs of some parts of the system have overshoot or undershoot before reaching to the desired value. It is obvious that, by cancelling overshoot and undershoot; a part of energy which is used to produce them is saved and also using FCM controllers which is saved the energy by decreasing the initial values. The total consuming energy by PID controller is 8.618 × 10^4 in 2000 s and 6.4× 10^4 in same time for FCM one. The difference between two controllers shows 22.18% saving energy by FCM one. Comparison the results of the robustness for the PID and FCM controllers depicts the FCM controllers are more robust than PID one. The steady state is happened with negligible value in FCM controller versus PID one with small settling time in compare with PID one.

The comparison of the results of simulation by applying FCM controller, it is obvious that, in contrast with PID controller (Tashtoush et al., 2005), the FCM one has no overshoot or undershoot. Obtaining to cancel the overshoot and undershoot decrease the pressure to the system and also decline the energy consumption.

The results of the simulation shows that, this method has the features like simple algorithm, small number of iteration steps and good robustness and it will be suitable for real time control of complex industrial process.

The learning method is implemented to updates the weight matrix to get better results and decrease the cycles. Through using a δ learning rule, FCM has a reason process which is similar to human does, and then an online real-time control is achieved.

Conclusions

In this work, the comparisons of the Fuzzy Cognitive Maps method to control versus PID controller have been done. As mentioned previously, decreasing the consuming energy by HVAC system due to the eliminating of overshoot and undershoot on the supply temperature and supply humidity is obtained and also decreasing on the supply temperature in fewer runtime is achieved. Good robustness is another advantage of using this method and also the simple mathematic model of the controller which does not involve with the mathematical model of the system according to the characteristics of FCMs. It is clear that, this method is more efficient in saving energy and optimizing the balance between thermal comfort and energy usage to improve thermal comfort issue and Energy efficiency. The simulation results shows, for designing a nonlinear robust Closed-loop real-time on-line learning ability controller with simple control algorithm, the FCMs could be a better choice among the others.

Conflict of Interests

The authors have not declared any conflict of interests.

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