A review of control systems for energy and comfort management in buildings

Soufiane Merabti, Belkacem Draoui  
Department of mechanic engineering  
Arids zones energetic laboratory – (ENERGARID)  
University of Tahri Mohamed  
Bechar, Algeria  
merabit.soufiane1@gamil.com, bdraoui@yahoo.com

Fatah Bounaama  
Department of electrical engineering  
Arids zones energetic laboratory – (ENERGARID)  
University of Tahri Mohamed  
Bechar, Algeria  
fbounaama2002@yahoo.fr

Abstract—Building management system has ability to control buildings electrical and mechanical equipment namely heating, cooling and ventilating. Building management system can also provide indoor thermal comfort within residential buildings including institutional, commercial and industrial buildings and able to reduce energy consumption. However most of heating, ventilating, and air conditioning (HVAC) systems are controlled by using conventional controllers whose functions are based on proportional integral derivative controllers. This controller is not the ultimate solution to save energy because the operations of HVAC systems are nonlinear. Thus, the implementation of fuzzy logic, neuro-fuzzy, fuzzy PID, neural network and genetic algorithm controllers within smart buildings will be more efficient which consequently will save more energy. This paper reviews different methods of control systems for energy and comfort in buildings. Additionally, it highlights the recent developments in building management system controllers including its conceptual basis, limitations and capabilities.

Keywords—energy saving, building management system, PID controller, fuzzy controller, genetic algorithm, neural network.

I. INTRODUCTION: PROBLEM STATEMENT

A. Energy

Algeria’s total final consumption has been steadily increasing in recent years. The country has seen an increase of 22% in just three years.

Taking a closer look at various sectors, the residential sector is the one which consumes the most energy 43%, followed by the transport sector 36% and the industry sector 21%. More detailed figures are outlined in the table below.

TABLE I: FINAL ENERGY CONSUMPTION IN ALGERIA 2012 AND 2013 BY SECTOR

<table>
<thead>
<tr>
<th>sector</th>
<th>Change in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>+9.0</td>
</tr>
<tr>
<td>Transport</td>
<td>+3.9</td>
</tr>
<tr>
<td>Industry</td>
<td>+3.7</td>
</tr>
</tbody>
</table>

In electricity consumption the residential sector is the biggest consumer in Algeria, representing 38.1% of the nationally consumed energy. Other important sectors are the tertiary sector 20.93% and the manufacturing industry 17.83% [1].

B. Comfort conditions

The comfort of a person is mainly dependent upon the following factors temperature, humidity, clothing, air flow and work rate. An evaporative cooler decreases temperature and increases air flow but increases humidity. The effect of the temperature reduction far outweighs the increase in humidity. Any additional air flow further improves the comfort level.

In the nineties, the buildings lacked natural ventilation and smart architecture etc. when the buildings needs for energy saving, because people spend the most time in buildings. The environmental comfort in a work place is strongly related to the occupant’s satisfaction and productivity. On the other hand, as well known, energy consumption is also strongly and directly related to the operation cost of a building.

In the recent days, special emphasis has been given to the bioclimatic architecture of buildings. Bioclimatic architecture is geared towards energy savings and comfort by using shadowing and glazing systems, natural ventilation, solar spaces thermal mass, Trombe walls, cooling systems with radiation and evaporation, etc.

The quality of comfort in buildings is determined by three basic factors: Thermal comfort, indoor air quality and visual comfort [2]. When discussing thermal comfort, there are two main different models that can be used: the static model PMV (Predictive Mean Vote) PPD (Predicted Percentage Dissatisfied) and the adaptive model. The PMV/PPD model was developed by P.O. Fanger using heat balance equations and empirical studies about skin temperature to define comfort. PMV predicts the mean thermal sensation vote on a standard scale for a large group of persons. The American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE) developed the thermal comfort index by using coding -3 for cold, -2 for cool, -1 for slightly cool, 0 for natural, +1 for slightly warm, +2 for warm, and +3 for hot.
Indoor Air Quality (IAQ) refers to the air quality within and around buildings and structures, especially as it relates to the health and comfort of building occupants. Understanding and controlling common pollutants indoors can help reduce your risk of indoor health concerns. Indoor air quality can be affected by gases (including carbon monoxide, radon, volatile organic compounds) [2]. IAQ is part of Indoor Environmental Quality (IEQ), which includes IAQ as well as other physical and psychological aspects of life indoors (lighting, visual quality, acoustics, and thermal comfort).

At present, there are two modes of outdoor air supply for controlling occupant micro-environment, including the constant quantity outdoor air supply and Demand Control Ventilation (DCV). As for the constant quantity outdoor air supply, it cannot meet the indoor air needs induced by pollutant source and supply outdoor air quality. Meanwhile, its energy saving potential is very limited. On the contrary, the DCV has advantages in these two aspects.


According to the small review above, we have many studies about thermal comfort and indoor air quality but is still lacking. In fact, the occupant micro-environment demand air supply is a complex system, which covers the aspects of the demand target, the conservation relations, and the influence of different factors. Meanwhile, the air supply characteristics change dynamically over time. In particular, the air diffusion difference will lead to the variations of effective supply outdoor airflow reaching occupant micro-environment. Therefore, it is necessary to determine reasonable outdoor air supply to solve this problem.

C. Control Strategy

In the building climate regulation is a multivariate problems having no unique solution, the goals of an intelligent management system for energy and comfort are as follows:

- To satisfy the user’s preferences that are inserted into the system through a smart card unit and to maintain thermal, visual and indoor air quality comfort based on guidelines.
- To minimize the building’s energy consumption levels for heating/cooling and lighting.
- To supervise the whole operation of the system.

The above objectives are achieved by the use of a fuzzy controller at each zone level of the building, supervised by a suitable cost function. The detailed description of the control strategy follows. Control systems engineering in buildings [10] is a prediction of future errors $K_p$, $K_i$, and $K_d$, all non-negative, denote the coefficients for the proportional, integral, and derivative terms, respectively (sometimes denoted P, I, and D).

$$G_{PID} = K_p + \frac{K_i}{s} + sK_d$$  \(1\)

Where $P$ controls the present error, $I$ depends on the accumulation of past errors and $D$ is a prediction of future errors $K_p$, $K_i$, and $K_d$. The control systems in buildings [10] is a classification of conventional controllers are two classes: classical controllers and optimal, predictive, and adaptive controllers.

A. Classical controllers

a. I controller

Usually the control systems are using integral $I$ controller. In this control design method, the control systems act in such a way that the control effort is proportional to the integral of the error. If the input goes to zero, then the integral stops changing and whatever value it had just before the input became zero. The integral value may change in either direction as the signal goes positive and negative. Negative area may be subtracted from positive area which, ultimately, lowers the value of an integral gain [12].

b. PI controller

The combination of proportional $P$ and $I$ controller is important to increase the speed of the response and also to eliminate the steady state error $E_s$. Without derivative action, PI-control system is less responsive to real (non-noise) and relatively fast alterations in state. So the system will be slower to reach set point and slower to respond to perturbations than a well-tuned PID controller [12].

c. PID controller

A $P$ controller has the effect of reducing the rise time and makes the system response fast but never be capable of reducing the steady state error to zero. An integral controller has the effect of reducing the steady state error to zero but distort the dynamic response. A derivative controller increases the stability, reduces the overshoot and improves the dynamic response but increases the noise and sensitivity. The purpose of installing PID controller is to improve the performance of the model in a coordinated manner. These values may be interpreted in terms of time based on current rate of change. The weighted sum of parameter values is used to adjust the process via a control element such as the position of a damper, a control valve, or the power supplied to a heating element etc. As used in this paper, the transfer function of PID controller may be given by (1) [13].
The control signal $u$ from the controller to the plant is equal to the proportional gain $K_p$ times the magnitude of the error plus the integral gain $K_i$ times the integral of the error plus the derivative gain $K_d$ times the derivative of the error [14].

$$u = K_p e + K_i \int e \, dt + K_d \frac{de}{dt}$$  \hspace{1cm} (2)

Fig. 1. PID-controlled system [12].

**B. Optimal, predictive and adaptive controllers.**

A most of time we find Predictive optimal control used in industry where a large-scale supervisory system is employed [15]. Predictive control function is based up on the assumption of future reference point, which can lead into optimal control law to provide improved tracking characteristics and smaller actuator changes [16]. In [17-19] have considered predictive control to be very important due its characteristics which include a model for future cooling load. It also improves thermal comfort mainly by reducing overheating but especially through using passive cooling techniques. However, mathematical analysis of building’s thermal situation generally yields nonlinear models taking into account these models differ from a building to another. Adaptive controllers have the ability to adapt to the climate conditions and regulate a self in the various buildings. More than this ability, adaptive fuzzy controllers are regarded as the most promising adaptive control systems for buildings [20].

Because this optimal solutions are not always feasible, such techniques suffer from various drawbacks, some of which are [11]:

- The need for a model of the building.
- The use of elements of bioclimatic architecture complicates the process of minimization of the cost function and if such a minimization is obtained, the results are not applicable in practice.
- The need to make parameter estimation in real time with the algorithms being used sensitive to noise. Thus, under real conditions, such techniques may give erroneous results.
- Such techniques do not deal with the problem of comfort. Nonlinear features that could determine some difficulties when monitoring and controlling HVAC equipment characterize the PMV index.
- The resulting control systems are not user friendly, since the user does not participate in the configuration of the climate of his environment.
- These control methods are not use learning methods.
- The classical control maximizes the energy conservation without giving priority to passive techniques.

**III. APPLICATION OF INTELLIGENT COMPUTATIONAL IN BUILDINGS**

Application of smart methods to the control systems in buildings essentially started in the nineties. Boman et al, [21] they proposed a multi-agent system for controlling of buildings, but their approach didn’t pay much attention to learning. Mozen et al, [22] they used neural networks for the intelligent control of lighting in residential building. Minar, [23] based on machine learning they proposed the design of multi-agent systems for the real time control of a building. Angelov et al, [24] they used evolutionary algorithms to develop heating, ventilation and air Conditioned (HVAC) models with control purposes. A kind of artificial neural network controller, based on a back-propagation algorithm, has been designed in hydronic heating systems [25].

Neural networks have been frequently used in Japan [26] where they have been applied to air conditioners such as commercial products etc. A system of two neural networks has been incorporated in an air conditioner to further fine-tune the equipment to the user’s preferences. One of the two neural networks estimates the value of the PMV index by using sensor just inputs. However, this is not always optimal for a user. The other neural network further corrects this output. The user can train this neural network.

**A. High level program controllers (fuzzy logic controllers)**

Fuzzy logic is a mathematical tool that was introduced by Lotfi Zadeh in the1965, to deal with uncertainty [16]. The combine of the neural networks technology, with fuzzy logic, and the algorithms used in computational intelligence is the basic concept behind the most of smart buildings. PMV calculating results is nonlinear and to overcome this kind of results time delay, system uncertainty, some advanced control algorithms have been incorporated with fuzzy adaptive control [27]. Some describes of the fuzzy logic control are mentioned below.

**a. Fuzzy systems and evolutionary computation**

Scientific research have been motivated to develop intelligent management system in buildings by energy savings, gas emission reduction and maintaining a comfort conditions for occupant. The combine of the neural networks technology, with fuzzy logic, and the algorithms used in computational intelligence is the basic concept behind the most of smart buildings. PMV calculating results is nonlinear and to overcome this kind of results time delay, system uncertainty, some advanced control algorithms have been incorporated with fuzzy adaptive control [27]. Some describes of the fuzzy logic control are mentioned below.

Genetic algorithms and methods coming from the theory of adaptive control are used to optimize fuzzy controllers. Fuzzy logic control has been used in a new generation of furnace controllers that apply adaptive heating control in order to maximize both energy efficiency and comfort in a private home heating system [31]. The development of fuzzy controllers to control thermal comfort, visual comfort, and natural ventilation, with the combined control of these subsystems has led to remarkable results [27, 29, 32-40].

b. Combine neuro-fuzzy techniques

Neuro-fuzzy systems originated when neural networks were used in fuzzy technology. Hybrid systems like adaptive neuro-fuzzy inference system [41]. Wu and Cai, [42] developed an adaptive fuzzy-neuro method for the supply air pressure control loop of HVAC system. R.Al-Jarrah and A.Al-Jarrah, developed artificial intelligence technique adaptive neuro-fuzzy controller for air conditioning systems in [43]. Naji et al, have been used for estimating building energy consumption [38].

The technology of neural networks has found important applications not only to the control systems of buildings [44-49]. This technology has been used in several applications in the control of energy consumption and renewable energy sources.

c. Adaptive fuzzy PD and fuzzy PID controller

The structure of the adaptive fuzzy PD controller is the same as for the fuzzy PD controller. The difference between the two is that the adaptive fuzzy PD controller uses a second-order system as a reference model for determining the scaling factors of the controller. The objective is to design an adaptive fuzzy PD controller such that the behavior of the controlled building remains close to the behavior of a desired model.

The fuzzy PID controller successfully demonstrated better performance than the conventional PID and fuzzy PD controllers for many cases. The fuzzy PID controller is also able to tolerate many poor selections or inadequate implementations of the controller gains which would make most conventional controllers unstable [50]. The fuzzy PID and fuzzy PI had found some important applications [51-54].

\[ \text{Fig. 2. Structure of fuzzy PID controller [16].} \]

B. Neural network controllers

The neural network has been investigated for its applicability in building energy predictions over the past ten years. Various neural network architectures have been applied in energy predictions. They include back propagation, recurrent neural networks, auto associative neural networks and general regression neural network demonstrating relatively successful results having coefficient of variations in the range of 2–40%. These variations in the accuracy of the predictions depend mostly on the neural network architecture used, the regularity of the building operation and the accuracy of data measurement devices, Kumar et al, reviewed application of neural network for analysis energy of building in [55]. Table below has summary of applications of neural networks in energy consumption and conservation.

<table>
<thead>
<tr>
<th>System</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy demand controller</td>
<td>[56]</td>
</tr>
<tr>
<td>Energy consumption of residential buildings</td>
<td>[57]</td>
</tr>
<tr>
<td>Energy conservation in buildings through</td>
<td></td>
</tr>
<tr>
<td>efficient air-conditioning control</td>
<td>[44]</td>
</tr>
<tr>
<td>Modeling of the space and hot-water</td>
<td>[58]</td>
</tr>
<tr>
<td>heating energy consumption in the</td>
<td></td>
</tr>
<tr>
<td>residential sector</td>
<td></td>
</tr>
<tr>
<td>Prediction of the indoor air temperature</td>
<td>[59]</td>
</tr>
<tr>
<td>of a building</td>
<td></td>
</tr>
<tr>
<td>Cooling load prediction in buildings</td>
<td>[60]</td>
</tr>
<tr>
<td>Prediction of heating energy consumption</td>
<td>[61]</td>
</tr>
<tr>
<td>Evaluating energy performance certificates of residential buildings</td>
<td>[62]</td>
</tr>
</tbody>
</table>

C. Genetic algorithm controllers

Genetic algorithm has been applied for energy management in many ways, for example Huang and Lam are proposed solutions for HVAC control problems [63]. This technique is also applied to the control problems of energy systems consisting of fuel cells, heat pumps and thermal storage [64]. Wright et al, [65] applied genetic algorithm to analyses occupant thermal discomfort and energy cost in building. Hongwei et al, [66] applied genetic algorithm to mixed nonlinear programming problems and integer in an energy plant, and made a comprehensive economic analysis by changing the environmental legislative contexts and economic.

Azadeh and Tarverdian proposed an integrated algorithm based on genetic algorithm, simulated-on genetic algorithm, DOE and time series to forecast electricity energy consumption [67]. Yu presented a technique which demonstrated the application of genetic programming to learn occupancy
behavioral rules that predict the absence and presence of an occupant in a single-person office [68]. An optimum scheduling approach of a cold water supply system in smart building has been presented by [69]. Osman et al, presented a combined between genetic algorithm and fuzzy logic controller technique for constrained nonlinear programming problems so that the search region is able to adapt toward the promising area [70]. Tang, Quck and Ng have used a genetic algorithm based fuzzy neural network to tune the parameters in Kang fuzzy neural network [71]. Muni et al, proposed genetic programming methodology simultaneously selects a good subset of features and constructs a classifier using the selected features [72].

The combination of genetic algorithm and artificial neural network to estimate and predict electricity demand using stochastic procedures has been presented by Azadeh et al, [73]. Mossolly et al, proposed optimal control approaches of variable air-volume and air-conditioning systems [74]. The control approaches included a base control approach of a fixed temperature set point and two advanced approaches for ensuring indoor air quality and comfort. The optimization problem for each control approach was formulated based on the cost of energy consumption and constrained by system and thermal space transient models. They used genetic algorithm to solve the problem of optimization. Supervisory control for hybrid solar vehicles proposed by Sorrentino et al, [75] and some initial tests have been performed on the road. An optimal design method for the energy system of a single building has been implemented for the first time by establishing an optimal design technique for a distributed energy system [76]. Ali et al, proposed a power control model for comfort and energy saving, using a fuzzy controller and genetic programming genetic programing [77].

IV. COMPARISON OF CONTROL SYSTEMS

The table below has a comparison of control systems (PID, fuzzy controller, fuzzy PID controller, adaptive fuzzy PD, neural network controller, neuro-fuzzy, genetic algorithm controller) that we collected previously.

<table>
<thead>
<tr>
<th>Control systems</th>
<th>DCV ventilation control</th>
<th>Temperature control</th>
<th>Energy consumption</th>
<th>Thermal comfort control (PMV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PID</td>
<td>✓</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fuzzy systems</td>
<td>✓</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fuzzy PID control</td>
<td>✓</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Adaptive fuzzy PD</td>
<td>✓</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Neural network control</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
</tr>
<tr>
<td>Neuro-fuzzy control</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
</tr>
<tr>
<td>Genetic algorithm control</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
</tr>
</tbody>
</table>

TABLE III: COMPARISON OF CONTROL SYSTEMS

References

- [13]
- [37]
- [40]
- [27, 40]
- [25, 46, 56, 78]
- [41-45]
- [63-67, 73-75]
V. CONCLUSION

In Algeria, demand on HVAC is rising which leads to more electricity consumption. Building's intelligent control systems have the ability to save energy by applying a set of rules which are based on real life events such as occupant’s density, weather data, sun radiation and etc. Accordingly we presented in this article a partial review of control systems for energy management and comfort in buildings. The paper firstly defined the problem statement, where energy and controller the conditions of operation. Then we presented current and conventional control systems and their disadvantages. As well it highlighted the development of intelligent control systems to improve the efficiency of control systems in buildings. Finally we compared between the methods of control systems that we reviewed in this paper. The upgrading of control systems now a day is a necessity to save energy and to minimize its negative impact on environment and this can be enhanced by development and applying intelligent control systems.

ACKNOWLEDGMENT

This work was supported by university of Tahri Mohamed Bechar-Algeria in laboratory ENERGARID. We like to thanks M. Tamali and B. Chellali for their helps in the preparing of this paper.

REFERENCES


