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Advanced Control Structure for Energy Management in Ground Coupled Heat Pump HVAC System

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Abstract: Over the last 15 years, computerized controls have become more and more common in our homes**.** The smart home looks at expanding the use of the computers into the difference parts of the home, creating a network that can be easily and conveniently controlled. The use of computer controls removes the need to actually flick a switch and allows elements of the home to respond automatically to the people living in it. Successful control and heating ventilating and air-conditioning (HVAC) systems is a primary concern in building project: in order to achieve the required comfort and energy efficiency goals, a lot of variables must be coordinated and kept at particular pre-designed operation points. The management control systems can be applied to try to achieve optimum settings for different operations in the complicated systems. To optimal settings must balance three aspects: (1) comfort, (2) energy efficiency, and (3) performance margins on order to be able to quickly adapt to unexpected disturbances. This work has used TRNSYS software package to model a HVAC system composed by a geothermal heat pump (GHP) and several fan-coils (FC) for a typical distribution of offices in the area of the Mediterranean Sea. In this model, a control structure has been designed using various configurations of cascade control to incorporate extra sensors and actuators in order to achieve PMV specifications and save energy.

Keywords: smart house, distribute and applied control, heating ventilation and air conditioning systems

1. INTRODUCTION

Nowadays, the problems with energy and the environment are one of the most important in the world. The possibility too use the computers system of the smart house to improve the energy efficiency at home is a new way that is open. Building energy running costs are high, and buildings also contribute, in developed countries, approximately 50% of all carbon emissions into the atmosphere. Unless the energy comes from renewable sources then excessive mechanical heating or cooling of buildings leads to unnecessary additional carbon emissions (Urchueguía *et al.*; 2006). Around the 68% of this energy is consumed by HVAC systems. In this situation, it is necessary to develop and advanced control structures for these systems with the purpose of improving its energy efficiency while keeping comfort requirements (Rohles, 1974) of the different building areas.

Conventional control of a fan-coil in a HVAC system usually uses on-off strategies affecting the fan but, to the authors' knowledge, use of the two actuators (fan and coil) as well as a downward heatpump control is not used in current installations.

Changes in control structure must be justified by energy savings as such changes do involve a cost of extra sensors or actuators. The aim of this work is to evaluate the energy savings that an advanced control structure can produce for a particular HVAC system. This evaluation is performed with a TRNSYS Simulation Studio, which is new generation software for modelling a multi-zone area and the equipments for the calculus of its thermal conditions in buildings. It have modelled a HVAC system based on a Geothermal Heat Pump supplying heating or cooling to an office building in typical conditions of the Mediterranean area. The advantages of geothermal heat pumps over air-cooled setups are discussed in (Hepbasli, 2003; Sanner, 2003; Urchueguía *et al.*; 2006).

This new control structure is based on a two-level cascade control system. Cascade control is, indeed, well known (Albertos and Sala, 2003; Skogestad and Postlethwaite, 2005); the contribution of this paper relates to the particular application domain of HVAC in buildings. The first level the located in the fan coils and it regulates the comfort state in the different offices, this comfort is estimated by the PMV. The second level tries to regulate the set point of the water to water heat pump in function of the water flow that is needed by the fan coils. Its stability and its capacity to adapt to unexpected disturbances will be studied.

This new control has been compared with a conventional control system based in On/Off actuators. The power

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consumption of the heat pump, the two circulation pumps and the electric motor of the fan coil will be calculated to know the total power consumption for both systems. These consumptions will allow knowing the total energy saved by the new control structure and quantity saved in each month.

In the authors' opinion, the use of well-crafted control structures with linear regulators might get comparable or better performance than other more involved or heuristic options (Calvino *et al.,* 2003; Underwood, 2000) with better maintainability in practice (using standard PID regulators).

2. ELEMENTS AND MODELS OF AN HVAC SYSTEM

This section describes the HVAC system and the building used for simulation of the later proposed control structures.

The system which has been modelled is an office area in the Mediterranean coast, located in Valencia, Spain. A Ground Coupled Heat Pump (GCHP) with three boreholes of fifty meters depth and a water-to-water heat pump constitute its HVAC system. All this system is connected with a net of seven fan coils that will heat and cool the office area, see Figure 1. The elements that consume energy are the circulation pumps, the water-to-water heat pump and the electric motor of the fan coil; all their consumptions are assumed measurable. The Predicted Mean Vote (PMV) is the variable that has been used to measure the comfort in the different offices; its definition is in the standard ISO7730, see (ISO, 1994) in the references, later summarised in Section 3.

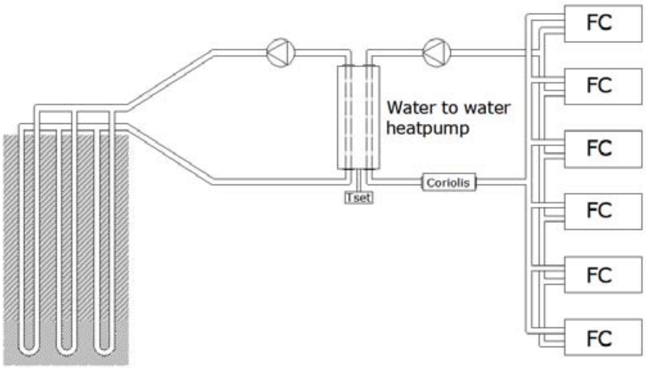

Fig. 1. HVAC system model

The ground heat exchanger is most commonly used in ground source heat pump applications. The model is a U-tube ground heat exchanger. A heat carrier fluid is circulated through the ground heat exchanger and either rejects heat to, or absorbs heat from the ground depending on the temperatures of the heat carrier fluid and the ground.

In typical U-tube ground heat exchanger applications, a vertical borehole is drilled into the ground. A U-tube heat exchanger is then pushed into the borehole. The top of the ground heat exchanger is typically several feet below the surface of the ground. Finally, the borehole is filled with a fill material; either virgin soil or a grout of some type.

The program assumes that the boreholes are placed uniformly within a cylindrical storage volume of ground. There is convective heat transfer within the pipes, and conductive heat transfer to the storage volume. The total effect injected to the volume is:

$$q = \frac{C_f Q_f}{V_f}\cdot(1-\beta)\cdot(T_{fin} - T_a) \tag{1}$$

where:

q	Heat per unit of volume
C_f	Volumetric heat capacity of the fluid
Q_f	Total fluid flow rate
V_f	Storage volume
β	Damping factor
T_{fin}	Inlet fluid temperature
T_a	Ground temperature

The temperature in the ground is calculated from three parts; a global temperature, a local solution, and a steady-flux solution. The global and local problems are solved with the use of an explicit finite difference method. The steady flux solution is obtained analytically. The temperature is then calculated using superposition methods (Hellstrom, 2005).

To model de water-to-water heat pump is as follows, the amount of energy rejected by the source fluid stream in cooling is given by equation, (Mitchell and Braun, 1997):

$$\dot{Q}_{rejected} = Cap_{cooliing} + P_{cooling} \tag{2}$$

The outlet temperatures of the two liquid streams can then be calculated using equations (3) and (4):

$$T_{source,out} = T_{source,in} + \frac{\dot{Q}_{rejected}}{m_{source} Cp_{source}} \tag{3}$$

$$T_{load,out} = T_{load,in} + \frac{Cap_{cooling}}{m_{load} Cp_{laod}} \tag{4}$$

where:

$\dot{Q}_{rejected}$	Energy rejected by the heat pump
$Cap_{cooliing}$	Heat pump cooling capacity at current conditions
$P_{cooling}$	Power drawn
$T_{source,in}$	Temperature of liquid entering the source side
$T_{source,out}$	Temperature of liquid exiting the source side
m_{source}	Mass flow rate of the liquid on the source side
Cp_{source}	Specific heat of the liquid on the source side
$T_{load,in}$	Temperature of liquid entering the load side
$T_{load,out}$	Temperature of liquid exiting the load side
m_{load}	Mass flow rate of the liquid on the load
Cp_{laod}	Ground temperature

For the fan-coils the energy transferred from the air stream to the fluid stream is then given by:

$$\dot{Q}_{fluid} = \dot{m}_{air}\left(h_{air,in} - h_{air,out}\right) - \dot{m}_{cond} h_{cond} \tag{5}$$

and the outlet fluid temperature can then be calculated using the equation (6):

$$T_{fkuid,out} = T_{fluid,in} + \frac{\dot{Q}_{fluid}}{\dot{m}_{fluid} Cp_{fluid}} \qquad (6)$$

where:

$\dot{Q}_{fluid}$	Energy transferred from the air to the fluid
$\dot{m}_{air}$	Total flow rate of air through the coil
$h_{air,in}$	Enthalpy of air entering the coil.
$h_{air,out}$	Enthalpy of air exiting the coil
$\dot{m}_{cond}$	Flow rate of condensate draining from the coil
h_{cond}	Enthalpy of condensate draining from the coil
$T_{fkuid,out}$	Temperature of fluid exiting the coil
$T_{fluid,in}$	Temperature of fluid entering the coil
$\dot{m}_{fluid}$	Total flow rate of fluid through the coil
Cp_{fluid}	Specific heat of coil fluid

The implementation of a cascade control system is aimed to make a quantitative assessment of profits, from the energy efficiency point of view, with respect to a conventional control system. Furthermore, as two actuators are available in each room (fan and coil), two reference signals can be tracked. On is, of course, PMV; the other one has been chosen to be the flow of air in steady-state. An On/Off control was chosen as a reference system for comparison. In order to compare the systems we have established the same operating conditions on both, i.e., the same heating and cooling load conditions. Both systems will be switched on from 9:00 to 18:00. Such time span may be considered the standard work period for an office.

The measurement and analysis has been simulated along one year of operation. In order to simulate the year-round the weather conditions of the area of Valencia, a data base from TRNSYS software has been used.

3. BUILDING MODEL

Both control systems have been simulated in a typical office distribution in the area of Valencia, this area is located in front of the Mediterranean cost in Spain. The total air-conditioned area is 108 m² and it is distributed among a corridor, four offices and a meeting room, see Figure 2.

The parameters and building characteristics of the office area has been implemented in the specific software of TRNSYS called TRNBuild. All offices are equipped with one fan coil except the meeting room that has two. Loads were calculated with standard software taking into account the load profile variations during the whole season in heating and cooling mode. Load peak values in heating and cooling modes were sized at 6 kW and 7 kW, respectively.

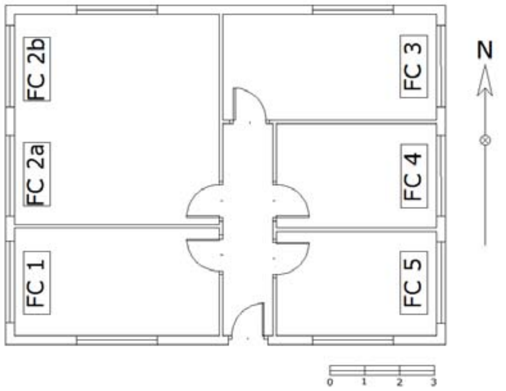

Fig. 2. Distribution of the offices and the fan coil*s*

The building model is a non-geometrical balance model with one air node per zone, representing the thermal capacity of the zone air volume and capacities which are closely connected with the air node. Thus the node capacity is a separate input in addition to the zone volume. For example, the convective heat flux to the air node is calculus as follows:

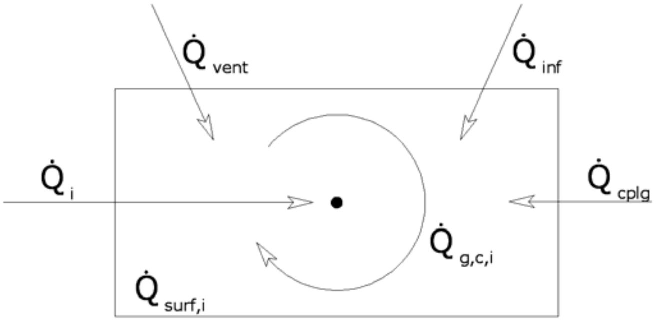

Fig. 3. Scheme for convective heat flux to the air node

$$\dot{Q}_i = \dot{Q}_{surf,i} + \dot{Q}_{\inf,i} + \dot{Q}_{vent} + \dot{Q}_{g,c,i} + \dot{Q}_{cpjg,i} \qquad (7)$$

where:

$\dot{Q}_i$	Convective heat flux to the air node
$\dot{Q}_{surf,i}$	Convective heat flow from all inside surfaces
$\dot{Q}_{\inf,i}$	Infiltrations gains
$\dot{Q}_{vent}$	Ventilation gains
$\dot{Q}_{g,c,i}$	Internal convective gains
$\dot{Q}_{cpjg,i}$	Gains due to flow air in zone i or boundary conditions

To know more about the mathematical model, see Mitchell and Braun, 1997.

4. PERFORMANCE CRITERIA FOR CONFORT: PMV

There are different alternatives in measuring thermal confort (Rohles, 1974; Calvino *et al.*, 2003). The PMV is an index used in the ISO 7733-1994 (see references) that predicts the mean value of the votes of a large group of persons on the following 7-Point thermal Sensation scale, Table 1:

Table 1. Thermal Sensation scale

-3	-2	-1	0	1	2	3
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

The PMV index can be determined when the the activity and the thermal resistance of the cloth are estimated, and the following environmental parameters are measured: air temperature, mean radiant temperature, relative air velocity and partial water vapour pressure.

The PMV index is based on heat balance of the human body. Man is in thermal balance when the internal heat production in the body is equal to the loss of heat to the environment. Its expression is:

$$\begin{aligned} PMV = & \left(0.303 \cdot e^{-(0.036 \cdot M)} + 0.028\right) \cdot \{M - 3.05 \cdot 10^{-3} \cdot \\ & \cdot (5733 - 6.99 \cdot M - P_D) - 0.42 \cdot (M - 58.15) - 1.7 \cdot 10^{-5} \cdot \\ & \cdot M \cdot (5867 - P_D) - 0.0014 \cdot M \cdot (34 - T) - 3.984 \cdot f_{cl} \cdot \\ & \cdot (T_{cl} - T_{rad}) - f_{cl} \cdot \alpha_k \cdot (T_{cl} - T_{rad})\} \end{aligned} \tag{8}$$

where:

PMV	Predicted Mean Vote
M	Metabolic rate, W/m^2
P_D	partial water vapour pressure, Pa
f_{cl}	Ratio of clothing and nude surface
T	Air temperature, ºC
T_{rad}	Mean radiant temperature, ºC
T_{cl}	Surface temperature of clothing, ºC
α_k	Convective heat transfer, W/m^{2}ºC

Note, however, that there are many variables whose precise measurement is difficult. This is the main weak point of fully-automated HVAC system. However, if user interaction is enabled, as the dynamics of such systems and buildings is usually slow, the humans usually try to act as controllers introducing excessively high or low setpoints in order to accelerate the overall response. When that is done in multiple rooms, couplings, oscillations and energy waste occur. Comfort estimation is, hence, a key part of a successful automation strategy in smart buildings.

5. CONTROL STRUCTURE

5.1. Cascade Control Structure

The cascade control system has two levels; the first one is located in all fan-coils, Figure 4, and the second one in the water-to-water heat pump, Figure 5.

The first level has two regulators the PIDa, which controls the electric motor of the fan, and the PIDw, which controls the opening of the circulation valve of the water in the coil. The objective of this first level is to regulate the comfort state in the different office of the area; the Predicted Mean Vote (PMV) will estimate this comfort state. The existence of two actuators allows the user to control a secondary variable, in this case the airflow.

The cascade control structure works as follows: If the external loop, which is controlled by PIDa, detects some variation of the PMV with respect to its reference, Ref$_a$, it will connect the electric motor of the fan and will increase progressively the power to it, as needed, in order to try to compensate the deviation of the PMV, without taking into account the possibility of water flow changes. This loop will be the main master loop in the cascade structure.

The slave loop is the one concerning the water actuator. If the power to the fan motor is bigger than a prefixed reference value, the PIDa will manage the water flow according in order to bring the fan flow to the desired steady state. For instance, in the refrigeration mode, requirements of the fan power above the set point value indicate that the flow of cold water in the coil should be increased. In this way, the fan flow can vary during the transient to optimize operations, but it will reach desired value once the overall system reaches steady state.

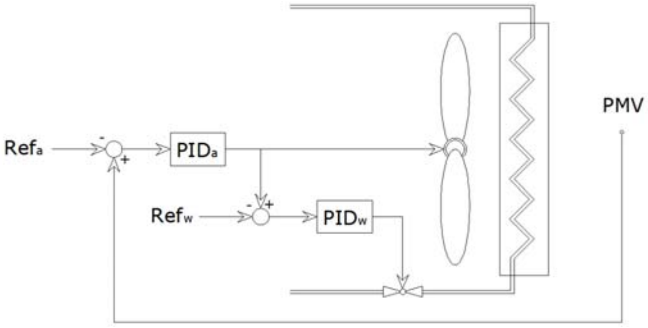

Fig. 4. Cascade controls for the fan-coils

A good control of the temperature set-points can help saving energy.

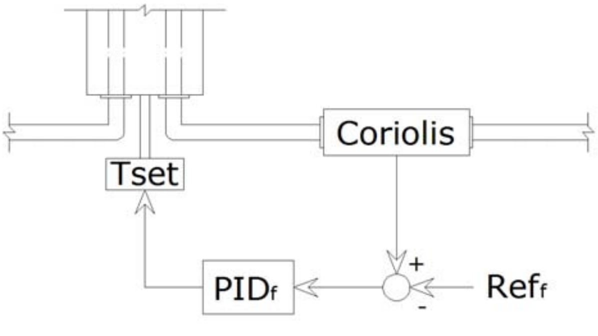

Fig. 5. Control for the heat pump

The second cascade control level will be a slave loop regulated by the water flow that trough the fan coil, Figure 4. This loop will use as controlled variable the water flow that reaches the heat pump, which is the sum of the individual flows of all fan coils. The manipulated variable will be the heat pump set point temperature. The control goal is that, at least in steady state, the water flow is equal to a prefixed value, Ref$_f$. For instance, if the flow is bigger than the reference, the regulator will increase the set point temperature when the heat pump is heating and will decrease it when the heat pump is cooling. The regulation loop, combined to the first control level at each fan coil has the effect of adapting the temperature set point to the actual needs of the conditioned spaces. This idea, in the author's opinion, enables some energy savings with respect to fixed heat-pump setpoints common in practice (see below).

5.2. Standard Control

The presented control structure will be compared in performance and energy savings against a standard control configuration, to be described below.

The standard regulation system will be an On/Off control; this control will either connect or disconnect the fan-coil. If it is connected the water valve will be totally open and the electric motor of the fan will give the maximum air flow, on the other hand, if it is disconnected the water valve will be closed and the electric motor of the fan will be switched off. The control variable will be the PMV, its set point will be zero and it will have a small hysteresis interval between -0.5 and 0.5 units, in order to try to avoid an excessive number of connections and disconnections of the system. Such switching, in a real situation, could damage the actuators of the fan coil subsystem.

Also, in the basics scheme, the water-to-water heat pump will not have any regulation; its set point temperatures will be 8ºC in cooling and 45ºC in heating

6. SIMULATION RESULTS

6.1 Behaviour of the cascade control

The optimal settings for the cascade control system have to adapt to the unexpected disturbances and to reach the comfort condition quickly. The regulator settings have been obtained by trial and error, as usual in practical PID's. Model-based tuning is under research.

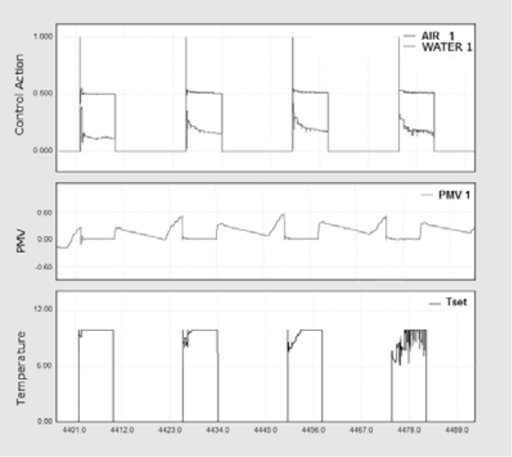

Fig. 6. Output values for the office 1

Figure 6 shows the output in the office number one data for the second, third and fourth of July, during this days the heat pump is cooling the offices area, we have chosen this days because are the warmest in the year and they can be considered the most representative, as a consequence, these are the days when the office area need more energy for cooling. The first graph shows the control action for the PIDa, which controls the electric motor of the coil, and PIDw, which controls the water valve in the coil. During this period the Ref_w is limited to the 50% of the control action of the PIDa. The graph shows that the control structure developed works correctly. In the first instance the electric motor start to increase it power to try to compensate the deviation of its reference, which is the PMV, when the power of electric motor is bigger than its 50%, the water valve starts to open to avoid that the electric motor gives more that the fixed value. The second graph shows the comfort condition that we evaluate with the PMV. We are interested in the neutral thermal sensation and this value in the Fanger`s scale is zero. We can see that the control system reaches its reference quickly during the control periods. So, the first and second graphs prove that the two PIDs of the cascade control in the fan coil can reach their references and compensate their deviations quickly. The third graphs shows the temperature set point of the heat pump controlled by PIDf, during the most part of the period control it has its maximum value that is ten degrees but it is possible to see some moments where is necessary to decrease the set point temperature, in order to improve transient performance. This result is very important; the most of the HVAC system during its design are overestimated, in this context, for this reason it produces much more energy that it is necessary in the office area. This kind of control system can compensate these kind overestimations of design.

6.2 Comparison between the control system structures.

Figure 7 compares the consumption power per month when it is used the cascade control system and the standard control system. It shows that in the most of the months the cascade control system consumes less energy than the standard systems.

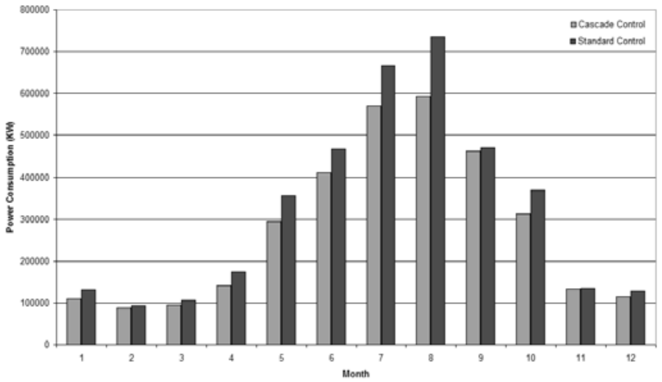

Fig. 7. Power consumption for the cascade and standard control systems

These differences are bigger during the summer months and smaller during the winter months. The reason is that in the area of Valencia the summers are very warm, so it is necessary a high cooling power to have a comfort state in the offices; in these moments it is when the cascade control have more chance to save more energy and where the new control structure is more efficiency, for this reason, July and August are the months where the consumptions between the start control and cascade control are bigger.

On the other hand, the temperature in winter in Valencia is quite warm. In this situation, we have to add that the control is active during only from 9:00 to 18:00; this period is in the daytime as a consequence the offices have gains per solar radiation during all working time. In this situation, the offices do not need to too much power in heating to search the whish comfort conditions as a consequence during this period the cascade control does not have too many opportunities to be active, for this reason, the saved energy is much more less than in summer. How ever the consumptions are smaller than in the standard control.

7. CONCLUSIONS

This work has presented an advanced control structure for a HVAC with a geothermal heat pump applied to a standard distribution office area in the city of Valencia, located in the Spanish Mediterranean coast. Simulations have been implemented in TRNSYS software, which is new generation software for modelling a multi-zone area and the equipments for the calculus of its thermal conditions in buildings. This new control system is based in a cascade control system with two levels. The first level is located in the fan coils and it regulates the comfort state in the different offices, this comfort is estimated by the PMV. The availability of two actuators allows setting a steady-state set point for airflow. The second level manipulates the set point of the water to water heat pump, taking the water flow that is needed by the fan coils as controlled variable; this regulation is oriented to basically save energy. This new system has been compared with a conventional control system, the fan coils it has been use an On/Off actuator with a set point based also in the PMV and the heat pump has a fix set point temperature for the different seasons.

Along the whole year, the systems have been connected from 9:00 to 18:00 that it can be consider the standard work period for an office. During these periods, the power consumption of the electric motor of the fan coil, the heat pump and the circulation pump have been computed in order to obtain the global consumption of the two control systems.

The simulation has showed that the new control structure can keep the comfort level in the offices and it can adapt easily to unexpected disturbances. On the other hand, this new system could save energy during all the months of the year and the total save energy was a 15% respect the conventional system. The biggest difference was during the summer: July and August were the months where the new control system could save more energy in all the year. The difference of the saved energy was not too much in the winter season; the reason was that the area of Valencia has a warm temperature during these months and during the all working period the offices have a solar gains, so, the requirements for heating are less than for cooling in this situation the new control structure could not have the possibility to save too much energy. The control structure tries to coordinate the elements that configure the HVAC system. The effectiveness of this simulation has demonstrated that this kind of control systems gives the possibility to keep the HVAC in the whished state, as well as ensuring, in the steady state, that some of the actuators come back to a pre-specified operating point. Research is under way in order to use such structure after establishing a list of optimum set points for different periods of the year, in the different rooms, as well as the use of natural ventilation, in order to get further energy savings. Nevertheless, the capacity of adapting the heat pump set-point to the office demand provided significant savings and allows us compensate the overestimate design of the different elements of the HVAC.

8. ACKNOWLEDGEMENT

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