

OPTIMIZATION OF THE OPERATION OF AN AIR-CONDITIONING SYSTEM BY MEANS OF A DISTRIBUTED CONTROL SYSTEM

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ABSTRACT

A control scheme for an air conditioning system is proposed, based on the continuous monitoring of the thermal, electric and climate variables. The dynamic behavior of the relevant variables is determined and expressed in terms of a compact model (the system transfer function). In this study, the indoor temperature control loop has been implemented using a conventional PI algorithm. The controller varies the speed of the compressor motor by means of a frequency inverter, which, in its turn, controls the refrigeration load. It has been observed that the PI controller reduced the variation of the indoor temperature, with significant improvement in the comfort conditions and reduction in the energy consumption. The derived model proved to be suitable for this type of application. Other dynamic important characteristics of the building and of the air-conditioning equipment have been highlighted. The information contained in this model could also be useful for new design and retrofitting.

KEYWORDS

Direct Expansion AC Simulation, Modeling and Control; Environmental Comfort; Energy Saving..

INTRODUCTION

The operation of the vapor compression cycles in air conditioning units of small size (and in the majority of the unitary equipments) is frequently accomplished with the aid of On/Off temperature control of the return air (Lin and Yeh 2007). In such equipments, this kind of control presents unsatisfactory performance, being disadvantageous in relation to the thermal comfort and the energy efficiency (Kulkarni and Hong 2004).

The most common causes of thermal discomfort comes from anti-symmetrical temperature conditions, for instance (Weller and Youle 1981): temperature differences (between the head and the foot) greater than the maximum acceptable (3 °C); the local air movement with temperatures well below the environmental average temperature; and the excessive

local heating, occurrences which are frequently observed in these installations.

In Brazil, data gathered in 2002 (Fabrini et al. 2005) shows that public/commercial buildings are responsible for a significant part of the total energy consumption in the country, being the air conditioning systems responsible for up to 48% of the final energy usage in climatized buildings.

For these equipments, it is expected that the use of new control strategies and new design tools may reduce the energy consumption up to 70% (Ellis and Mathews 2002). Due to this great potential of energy savings in such installations, different ways of increasing the energy efficiency are sought, both from the architectural point of view and from the inherent processes and equipments used in the buildings. The effective operation cost of an air conditioning unit can also be reduced (without compromising the inner air quality) by means of the use of new control strategies and effective tuning of the loops (Canbay et al. 2004).

The complexity of the air conditioning control comes from the non-linear nature of the process, the strong correlation between the two most important controlled variables (the air humidity and temperature) and the restrictions imposed in the control strategy for the external and internal desired conditions (Jota and Dexter 1986).

This paper considers the operation optimization of the air conditioner by means of the use of a control strategy that aims at fulfilling the thermal comfort and the energy efficiency of the process. For this purpose, a semi-empirical model has been developed, being it capable of mathematically describing the relations among the variables which have more influence over the air conditioning behavior. In order to obtain the model parameters, it is used a continuous monitoring system of the data, which are transmitted on line, via Internet.

This system measures, uninterruptedly (twenty four hours per day) the external and internal environmental conditions of a building, the consumption of electric energy, as well as the variables related to the air conditioning operation. The data are collected in intervals of 15 s. A control system has been designed

and implemented in a unitary air conditioner of direct expansion, equipped with conventional techniques of control. The platform used for monitoring is the same used to implement the control strategy.

The aspects related to the practical implementation of the distributed control for monitoring and control via the Internet are described in the paper and some results are presented to show that an improvement in the comfort, as well as the increase of the energy efficiency, has been obtained.

METHODOLOGY

In order to perform the measuring and the control functions, it has been used a platform called CMUF (Portuguese acronym which means “End-Use Monitoring System”). This platform has a distributed architecture in which the stations are connected by a computer communication network for data transmission. In the current setup, the data acquisition is gathered every 15 s, and made available via Internet, practically, in real time.

With the continuous data acquisition for a long time, it is possible to know the dynamic behavior of the variables involved and the existent correlations among them. From the system dominant characteristics so as determined, alternative ways of optimizing the operation of the air conditioner are considered and possible control strategies are devised. Finally, the design of the controllers is made.

It has been, already, possible to verify that, due the variety of the use and environments conditions, it is very important to take into account long term measurements (some months or even years). Thus, the importance of gathering large amount of data is proposed here.

THE TEST SYSTEM DESCRIPTION

The platform (CMUF), used for the tests presented in the paper, can be seen as a low cost tool, especially developed to give support to the energy management personnel, aiming at overcoming the difficulties of getting a continuous and close verification of the building performance in terms of energy and thermo-luminous characteristics. With the aid of CMUF platform, these tasks are accomplished by sub-dividing the loads in groups composed of similar energy consumption end use (Jota et al. 2005). The CMUF platform turns it possible to make a detailed evaluation of the energy consumption in the building, with a more realistic assessment of the critical points, thus allowing the energy manager to act of punctual form. An important characteristic of the use of the CMUF system is the integration of the data acquisition, storing, processing and transmission technologies (Jota et al. 2005).

In the CMUF platform, the microcontroller stations (measuring, actuating or controlling) are connected to each other by a Controller Area Network (CAN), a communication bus, as can be seen in Figure 1. For the Internet connection, a “Web Server” has been used. This web server periodically requires data from the measurement stations to which the sensors are connected. The collected data are sent, via the Internet, to the CMUF data-base. After being stored in this data-base, the data are made available, on-line, for the registered users by means of remote access. This access is accomplished through a proper web-page.

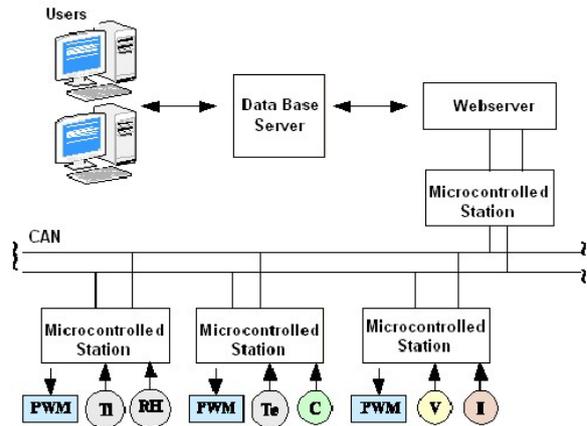


Figure 1 Architecture of CMUF platform

For control applications, there is a special web-page from which registered users can remotely modify the control parameters of the controller and even the control strategy. In the control system presented in this paper, the loop is closed over a data communication network, in which all the elements (sensors, actuators and controller) exchange information by means of the message flow in the network. A block diagram of the control system is shown in Figure 2.

The development of control techniques using the CMUF platform is very promising, because the platform can make available a wide range of information and resource, such as: a report in real time of events and status (fault detection); online identification of the models parameters of the environment conditioning system; the use of inter-blockage (for instance, an open window in the environment conditioning control); and for every significant change detected in the environmental conditions by control system, it is possible to use the data base information for environment condition analysis nearby the building, and compare to measurements of others buildings in the same local area (Castro et al. 2005).

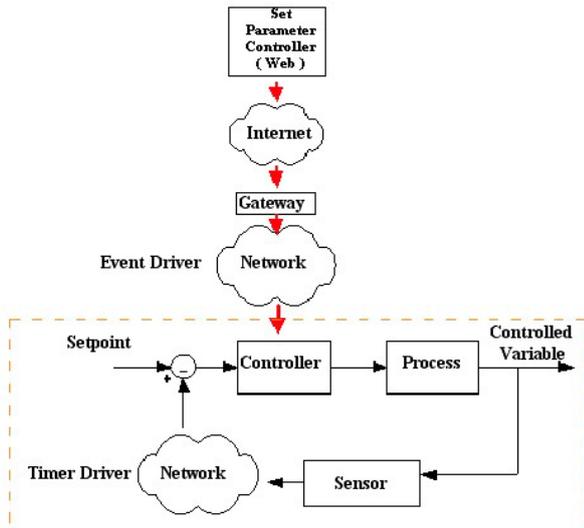


Figure 2 Block diagram of the control system

The building, where the air conditioning system is installed, is located in Belo Horizonte city, MG-Brazil, at the 20° of south latitude; it has been built using bioclimatic architecture elements, aiming at decreasing the heat gain of the conditioned environment, thus increasing its thermal and luminous performance. The room chosen as conditioned zone can be occupied by 42 people; it is located the top floor of the building with four walls in contact with the external environment. The room's illumination is composed of a set of 12 fluorescent lamps of 28 W each.

The air conditioning equipment is a direct expansion system, split type and cassette line. The system is composed of an external condenser unit of 17.4 kW (60,000 Btu/h). The compressor is a scroll type one, with a three-phase motor (4.4 kW, 220 V, 60 Hz). The used cooling fluid is the R-22. The condenser unit is connected to an internal evaporating unit (Figure 3) installed at the roof in a central position. The conditioned air distribution is made by means of four adjustable diffusers. The return air grille is placed at the center of the internal unit. The air conditioning unit has reverse cycle (hot/cold), though, in the control application presented in this work, only the cooling cycle has been studied.

The integrated controller, which comes with this air conditioning unit, imposes cycles on/off on the compressor (working at nominal frequency). After the first test, it became clear that the original control of the air conditioning system would not be capable of fulfilling the necessities in terms of comfort and energy performance. In the control system implemented in this work, it was decided to improve the control system, adding a frequency inverter, thus making it possible to have a better continuous control. Higher efficiency (in energy and quality control terms) can be obtained varying the motor speed of the compressor, thus the refrigeration load is controlled.



Figure 3 Internal unit of the air conditioning system used in the experiments

In order to make possible a detailed analysis of the system, new instruments of measurement have been specified and installed in the air conditioning unit and in the environment. In the air conditioning system the electrical and thermal variables are monitored. The following thermal variables have been chosen to obtain the energy balance: the temperature in the compressor output; the temperature in the compressor input; the temperature in the suction accumulator output; the temperature in the suction accumulator input; the temperature in the condenser output; the temperature in the condenser input; the temperature in the evaporator output. Similarly, the following electrical variables have been considered for energy consumption analysis: the total current of air conditioning equipment; the current in the compressor motor; the current in the evaporator fan.

In the environment, air temperatures and humidity, pressure and luminosity are monitored. Inside the room it is being monitored: air temperature near to the north, south, east, west walls; air temperature at the roof and at the ground; air temperature and humidity in the center of the room (near to the return air grille); air temperature in the supply outlet and pressure. The following environment external variables are being monitored: air temperature and humidity at the south and east walls; air humidity at condenser output and luminosity.

In Figure 4, it is presented an instrumentation diagram of the installed system, with details of the measured variables and their distribution in the environment and in the air conditioning system.

In Figure 5, it is presented a monitoring system screen, illustrating the external temperature (in this case, at day 09/17/2006) during the whole day.

With the monitoring system implemented, a sensible evaluation of the building performance can be elaborated and the subsidies to the energy management

can be supplied, integrating the climatic conditions with air conditioning system and its use.

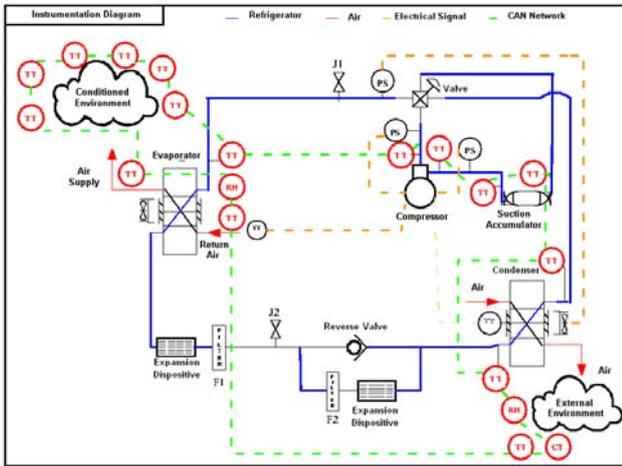


Figure 4 Piping and Instrumentation Diagram

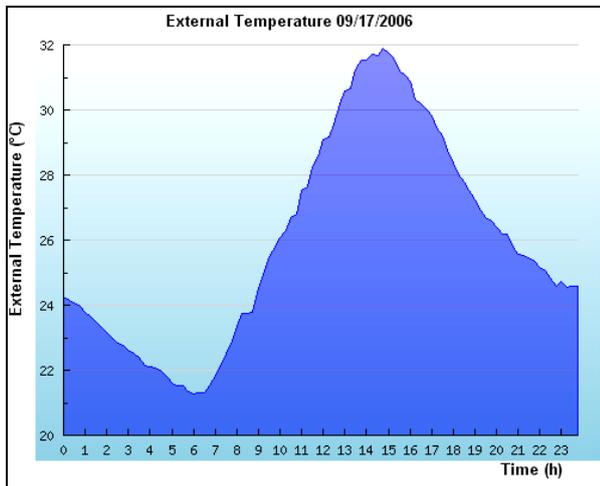


Figure 5 Profile of the external temperature at day 09/17/2006, as presented in the CMUF screen.

The continuous monitoring of the variables allows a wide range of analysis concerning the building and the air conditioning system. Among them, it is worth to cite:

- Evaluation of the energy performance of the building in terms of thermal, electrical and luminous aspects;
- Evaluation of the correlation between the environmental variables (for instance: correlation between the outside and inside temperature, internal temperature and external luminosity, etc);
- Evaluation of the thermal comfort;
- Evaluation of the air quality and its distribution in the environment;

- Evaluation of the thermal influence of the people in the environment (calculation of the occupation load);
- Fault analysis of the air conditioning system;
- Analysis of the heat transfer rates and the power involved in the air conditioning system;
- Evaluation of performance coefficient of compressor vapor cycle of the air conditioning system;

With the analyses proceeding from the great number of the environment and of the system variables monitoring, and with the new actuation system incorporated, corrective measures and control strategies can be used to obtain a better energy performance of the building, obtaining energy profits and comfort.

MODELING, SIMULATION AND DEFINITION OF THE CONTROL STRATEGIES

The objective of the control system implemented in this work is the thermal comfort in the conditioned environment and the energy consumption reduction. In such a way, the control system must keep the internal temperature as close as possible to the established level and thus optimize the energy consumption, besides it must guarantee the security system operation. The stages of the control system design followed the sequence: process modeling, simulation and validation of the models, design of the controller, simulation and performance evaluation of the controller and implementation in the real process.

The controlled variable in this first study is the internal temperature of the room in the central point (return air temperature) and the manipulated variable is the compressor motor speed. In this control system, the compressor motor works on a frequency band between 30 Hz and 60 Hz. The reference value of the frequency generated by the controller is made available to the frequency inverter by means of a Pulse Width Modulation (PWM) output of the microcontroller station.

In the modeling of the process (which can be understood as an efficient form of knowledge compacting), it was decided to make the identification of the model coefficients based on a structure previously defined by means of experimental data, a transfer-function, which can be seen as a way of expressing the dependence of the zone temperature with the speed of the compressor (inferred from the measured electric current).

For the generation of the data set, tests are accomplished with the room empty (with no occupants) and the light bulbs on. The frequency variations had been applied (to the inverter), as step form, and the data of the internal temperature and the electric current were gathered. The data has been sampled in intervals of 15 s with CMUF platform. The method used to obtain the model was the “Complementary Response Method” (Doebelin 1990). The identified model in the refrigeration cycle was of first order without time delay (Equation 1) (Batista 2006)

$$G(s) = \frac{K}{\tau s + 1} \quad (1)$$

where $\tau = 300$ seconds is the time constant, and $K = -0.634$ represents the gain of the internal temperature for a variation of the 0 to 100% in the current of the compressor. The negative signal indicates that a reduction in the internal temperature implies an increase in the compressor speed (increase in the energy consumption).

This transfer-function shows, for example, that the zone temperature may take up to 20 minutes (four time constants) to stabilize after a change in the compressor speed. Together with the transfer-function relating external temperature variations to the zone temperature (which is derived in the sequel), this model gives the designer an important insight to predict the effect of both air-conditioning and disturbance variables.

The control strategy used in the experiments is composed of a conventional PI (Proportional + Integral) controller with “anti-windup” compensator. Using the “Direct Synthesis Method” (Seborg et al. 1989) with the closed-loop time constant chosen to be one tenth of the open-loop time constant, the resulting controller parameters are: $K_c = -15,8$ (Proportional Gain) and $T_i = 300$ s (Integral Time), (Batista 2006).

In order to quantify the obtained energy save due the implementation of the new control strategy, it is necessary to quantify the involved thermal load. Since, the external climatic conditions directly affect the thermal load inside the room, the energy save quantification is not a simple task. It necessary to create models which describe the external variables influence on the internal temperature.

It is known that the external temperature is the variable that has great influence in the internal thermal load, and that this does not affect the internal temperature in the same instant, due the long time lags associated with heat transfer over the building envelope. With the analysis of the data monitored a model, that reflects influences of the external temperature on the internal temperature, was obtained using an auto regressive structure, yielding (Equation 2)

$$y(k) = a y(k - 1) + b u(k - 377) \quad (2)$$

where $y(k)$ represents the internal temperature at the k -th sampling instant, $u(k-377)$ the external temperature with a delay of 377 samplings of 15 s (or 94 minutes and 15 s), $a = 0.98$ and $b = 0.005$ (Freitas 2007). The delay was evaluated using the cross correlation coefficients between the external and the internal temperatures.

An efficient control, such air quality as energy saving, is obtained with use of advanced control strategies, which require a complete dynamic analysis of an air conditioning system. A model has been developed by Freitas (Freitas 2007). It involves the modeling of the subsystems: the external environment, the internal environment and the air conditioner equipment. To develop these sub-models, each one of these parts is subdivided and interrelated. For instance, the dynamic models of the refrigeration machine components – compressor, condenser, capillary tube, evaporator and suction accumulator – are developed individually and thus they are integrated. Therefore, the model represents the set of all factors that significantly describes the plant dynamic behavior.

Due to the complexity of this system, it is necessary the simulation of all air conditioner including the building, the indoor and outdoor environments. To do this special simulation tools are required to deal with the great range of time constants involved (few seconds to hours). This more detailed study has been made with the aid of VisualSPARK tool (LBNL 2003) (Sowell et al. 2004), using the data collected with the CMUF platform. Dynamic semi-empirical models have been developed for the referred building (Freitas 2007).

With the aid of this integrated model, the cause-effect relationships between the more significant variables of the air conditioning system can be easily obtained. Thus, actuation and control strategies can be simulated, evaluated and implemented for the global optimization of the process.

EXPERIMENTAL RESULTS

In order to analyze the performance of the plant with the implementation of the PI controller, several tests have been accomplished in the system. These tests were performed with the system operating in the following conditions: empty room; all the light bulbs on; closed curtains; with the air conditioning system operating in the cooling; evaporator fan operating in high speed; with the air supply diffusers in a fixed position; and the air external damper was closed.

The first test made was in the closed loop using the original On/Off Controller of the plant, in which the set point was adjusted for 18 °C. This test was made too in the plant with the implemented PI controller,

aiming to provide a comparative performance analysis of the two controllers in terms of energy and comfort.

The Figure 6 presents the response of the internal temperature and the air conditioner electric current as a function of time, with the system operating with On/Off controller. The great temperature oscillations that occur between On/Off cycles (3.52 °C around set point) compromise the condition of user thermal comfort.

The system response, with PI Controller, it is presented in Figure 7. The internal temperature presents variations of 0.93 °C around set point. The air conditioner current keeps an average value of 8.59 A, without switching the compressor. The significant reduction in the variations of the internal temperature reflects the performance improvement of the system in comfort terms, with the use of the PI controller in respect to On/Off controller.

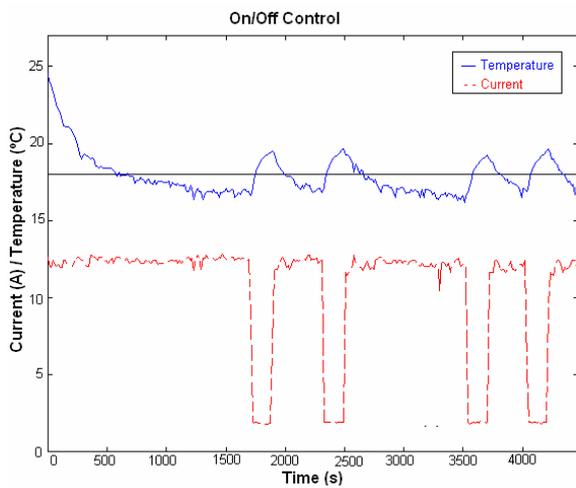


Figure 6 Variations in the temperature of the return air (and corresponding On/Off control signal) with set point fixed at 18 °C.

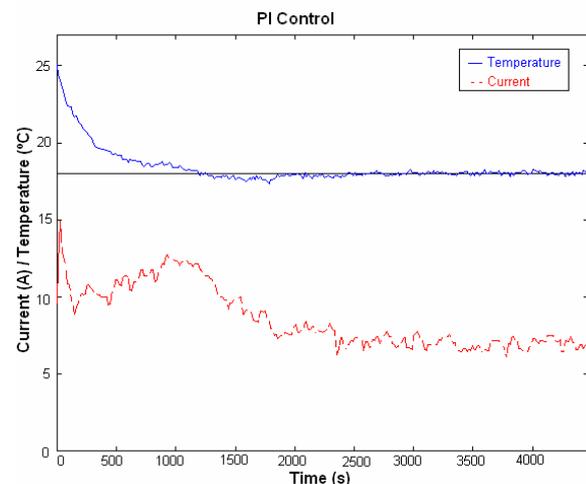


Figure 7 Variations in the temperature of the air (and corresponding PI controller output signal) with set point fixed at 18 °C.

In order to assess the potential energy saving obtained with the implementation of the new control strategy, two experiments have been analyzed: firstly, the influence of the external variable in the internal temperature was not considered, and, in the second case, the influence of the external temperature is explicitly taken into account. These two results emphasize the importance of developing a detailed and realistic evaluation of the ambient and the system variables to provide an analysis of the obtained profits. The importance of the construction of a theoretical-experimental model lies in the fact that these two variable types have to be considered separately. To make a fair comparison between both control strategies, the experiment has to be accomplished under the same ambient conditions, both internal and external, which, of course, can easily be done with process simulation. However, in the exclusively experimental tests, while the internal system variables can be kept the fairly constant, it is quite unlikely that the same external climate conditions be obtained. In other words, without the models (of the building and of the air-conditioning), it is impossible to reach definite conclusions about the effects of the many variables that affect the system, and its cause-effect relationship.

To evaluate the potential of the energy economy it was calculated the relations enters the amount of consumed electrical energy and amount of heat removed of the environment, by means of calculus of the involved electrical power and the processed thermal load for the air conditioner.

In order to determine the electric power involved (Equation 3)

$$P = \int v i \cos \varphi dt \quad (3)$$

it was calculated accumulated electric load (Coulombs) with the integration electric current it in the time, this current is been measured in an only phase (in the input bar of the air conditioning equipment). Considering that the voltage of the concessionaire (v) and the power factor (cos φ) is the same for both the test conditions, these tests have been carried on the same time period (with the same number of samples), thus , the integral of the electric current can be used to express fairly well the electric power.

Concerning to the calculation of the thermal load to be processed for the air conditioner, it was considered (Equation 4)

$$Q = \frac{dm}{dt} c \Delta T \quad (4)$$

where the outflow (dm/dt) and the specific heat of air (c) constants in the two tests conditions. The difference of external and internal temperature (ΔT) can to indicate the relation of the involved thermal power.

In the first case, for the system operating with PI controller, an energy saving of 2.89% has been obtained if compared with the system operating with On/Off controller. This is a significant economy; however, this is not a realistic evaluation of these profits, since, for in such a way, the models that represent the influence of the external variable were not considerate.

In the second case, it is using the auto-regressive model obtained with a delay of 377 samples (of 15 s) between the external and the internal temperature, a saving of 20.16% has been obtained with the use of the PI controller. This is a substantial economy, from both energy saving and financial point of view.

It is worth of note that these two results (with and without the delay) emphasize the importance of the continuous (long-term) monitoring and of the detailed analysis of the involved variable in the air conditioning system. The developed models proved to be suitable for controller design. Other dynamic important characteristics of the building and of the air-conditioning equipment have been highlighted. The authors believe that the information contained in these simple, compact, models can help designers in the dimensioning of new and retrofitted air-conditioning equipments.

CONCLUSIONS

The CMUF system proved to be a powerful tool for analysis and support the management of buildings energy, making available diagnostic and historic energy consumption of the equipment. This information helps the energy manager in choosing possible decisions and making punctual actuations, involving, also, adequate control strategies to the systems.

With the stored data in the CMUF system (months of observation of the building behavior and with several tests carried out in the air conditioning system), it was possible to detect the problems with the On/Off controllers applied to the air conditioning system: waste of energy and precarious thermal comfort. It is shown that the implementation of a PI control with frequency inverter reduced the temperature variations in the interior of the room, making possible one better conditioning of the environment with minor expense of electric energy. The air-conditioning system, in particular, is a process with potential for improvement of energy performance. Only from a continuous and systematic assessment of several variables, it is possible to make, with security, one evaluation as this. With implementation of the PI control strategic, it was verified a reduction of about 20% in the consumption, that it represents a significant improvement.

The implemented monitoring structure is the great center of studies. Dynamical semi-empirical models

have been developed and it will apply for the studies of the cause and effect relations between the variables that affect the air conditioning system. Thus determining the parameters of control that are will use in advances control strategies, such as: feed-forward, Smith predictor, multivariate and multi loops control.

Thus, better conditions of comfort and energy efficiency can be obtained with the introduction of the external air flux control, aiming at a more efficient control of the temperature and the internal humidity.

ACKNOWLEDGEMENTS

The authors acknowledge the technical and financial support provided by the Energy Company of Minas Gerais - CEMIG (Research and Development Project Nr.016), by FINEP (CT-ENERG) and by CNPq. We are also thankful to the members of the "Centre for Intelligent Energy Research" (CPEI / CEFET-MG) for fruitful discussions.

NOMENCLATURE

AC – Air Conditioner
 CAN – Controller Area Network
 CMUF – End-Use Monitoring System (portuguese acronym)
 G(s) – Transfer Function (in the Laplace domain)
 PWM – Pulse Width Modulation
 PI – Proportional plus Integral
 SPARK – Simulation Problem Analysis and Research Kernel
 a – polynomial coefficient (AR model) [-];
 b – polynomial coefficient (AR model) [-];
 c – air specific heat [J/kg K];
 cosφ – power factor [-];
 I – electric current [A];
 k – sampling [-];
 K – process gain [°C/A];
 K_c – proportional gain [-];
 m – air mass [kg];
 P – power [W];
 Q – thermal load [W];
 s – Laplace (complex) variable [σ+jω];
 T – air temperature [°C];
 t – time [s];
 T_i – integral time [s];
 τ – process time constant [s];
 u – input variable [%];
 v – voltage [V];
 y – output variable [-].

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