CONTROL STRATEGIES FOR ENERGY CONSERVATION IN ROOM AIR CONDITIONING UNITS

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ABSTRACT
Demand Side Management (DSM) considers room air conditioner load as one of the most suitable loads to implement direct customer load control in order to exercise peak demand control as well as energy consumption control in supply systems. In DSM, the room A/C units located at customer premises are directed to enter energy/demand saving control modes by means of control signals issued from sub stations either via remote radio link or via power line carrier communication link at distribution level when the utility wants to exercise demand control during periods of power shortage. A prior contractual arrangement with the customer is of course implicit. Two popular control techniques employed in room A/C units in order to limit their energy consumption and their average power demand are examined in this paper using SIMULINK simulation as the study tool.

KEYWORDS: Energy Conservation, Air Conditioner,

1. Introduction

The room A/C unit contains two a.c single phase motors-one for the compressor and one for the air fan. The air fan runs continuously whereas the compressor motor is on an ON/OFF cycle mode operation. The thermostat and its setting will decide the state of the compressor motor. The bimetallic type thermostat trips the compressor motor when the inside temperature exceeds the thermostat setting by a small value (due to thermostat hysteresis) and the compressor motor is switched on when the inside temperature goes below the setting by the same small value. In a 1.5T room A/C unit, the compressor motor is rated for 2kW and the fan motor is rated for 149W.It has been found from the experimental observations that the daily duty factor (defined as the ratio of total compressor motor ON time to the total time for which the A/C unit was operational) usually varies from 0.4 to 0.5 in the case of an A/C unit selected properly. Also the duty factor for operation between 9:00AM to 6:00PM has been found to have a range of 0.5-0.6.This implies that if the unit is powered for 24hours a day, an 1.5T unit is likely to consume 20 to 25 units of electrical energy every day. Considerable energy saving opportunity exists in the case of room A/C units at the expense of slight/negligible discomfort to the occupants. The conventional bimetallic thermostat based controller will have to be replaced by electronic sensor based controller in order to exercise the kind of control covered in this paper [1].

The basic components of a room A/C unit are the compressor; air cooled condenser, expansion valve, evaporator, two motors and air filter. The refrigerant absorbs heat from the evaporator and rejects it to the condenser. The fan draws in air from outside and circulates it over the condenser to cool it. The fan also draws in outside air through the compressor compartment for ventilation of the conditioned space. The amount of ventilating air is controlled by a damper position in its path. The room air enters the evaporator chamber, goes over the cooling coils and comes back into the room through the air filter.

The expansion valve used room A/C units is of capillary tube type. The capillary tube holds back the refrigerant gas while releasing the liquid only into the cooling coil. The length of the tube and its diameter are the controlling factors in its performance. Once the compressor stops, the capillary tube will equalize pressures in the system in about half a minute. This is a distinct advantage, for the compressor is free to start on no load when it is switched on next time. Hence it is very vital that the controller ensures that at least half a minute is allowed before the compressor is switched on again after being switched off. Usually more than this minimum time will be available due to the large time constants in the thermal system, delays involved in the temperature sensing and the hysteresis band available in the thermostat. But when the temperature sensing is done electronically and the bimetallic thermostat is replaced by an electronic thermostat it may be necessary to build in electronic logic to ensure that the compressor motor remains off for at least a minute after it is stopped once [2, 3].

2. Heat Load Components [1]

Cooling load calculations room A/C units deal with heat gains of two kinds:

1. Sensible heat, which, as it flows into or is produced in a space, will tend to cause a temperature rise in space.
2. Latent heat, in the form of moisture, which, although it does not cause a temperature rise, does change the condition of air in the space, resulting in higher humidity.

Sensible Heat gains to the space include:

1. Heat transmission through the building structure as a result of conduction, convection and radiation.
2. Heat entering the space as a result of solar radiation through windows or other transparent or translucent components.
3. Sensible heat brought in as a result of ventilation and infiltration of outside air.
4. Sensible heat produced by occupants.
5. Sensible heat produced in the space by the lights, appliances, motors, UPS units and other equipment.
6. Sensible heat to be extracted from materials or products brought into the space.

Latent heat gains may be classified as:

1. Latent heat from outside air (both introduced for ventilation and infiltrates into the space).
2. Latent heat from occupants.
3. Latent heat from cooling, hot baths or moisture producing equipment in the space.
4. Latent heat from products or materials brought into the space.

A further load classification that is frequently used is based on the sources of heat. Loads are:

1. External, if they come from without the conditioned space. These are either sensible or latent.
2. Internal, if they are produced within the conditioned space. These may be either sensible or latent heat.

3. Electrical Analogue Model for an Air Conditioned Room [1-4]

The dynamic behavior of the air-conditioned room has been modeled from fundamental physical principles. The model thus obtained is a lumped parameter electrical analog model where each parameter represents a physical quantity. However, accurate measurement of these quantities would be difficult, because in reality they are distributed parameters.

Several variables, such as: temperature, solar radiation, humidity, wind speed, air infiltration etc influence the flow and storage of heat in a room in a very complex manner. Representation of every component and process in detail will make modeling very difficult and the model becomes intractable. Therefore, assumptions are made to obtain a simple, yet fairly accurate model.

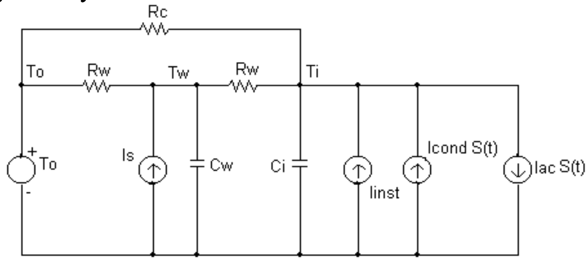

Fig.1 Electrical Analogue Model of an Air Conditioned Room

The effect of only major variables like temperature, solar radiation, air infiltration, humidity and internal heat is taken into account while developing the model. The lumped parameter model thereby is shown in Fig.1.

The walls, base and roof of the room are represented by a T network formed by R_w and C_w, where R_w represents the equivalent thermal conduction resistance and C_w represents the thermal storage capacity of the room (walls, base and roof). The average air infiltration is represented by an equivalent resistance R_c. C_i represents the thermal capacitance of the air inside the room. T_o is the outside temperature, T_w is the wall temperature and T_i is the inside temperature.

The heat removed by the air conditioner is represented by a current source I_{ac} in fig.1. The value of this source is I_{ac} multiplied by a switching function S(t). Switching function S(t) is 1 when the compressor motor is ON and 0 when compressor motor is OFF.

Normally the temperature of air at the fan outlet in a room A/C unit is kept within a small band around a set temperature by thermostatic control. When the air conditioning unit compressor is switched off all the refrigerant return to a liquid state in a short time and when thermostat switches the compressor motor on it takes a little time for the vapor system to come to the steady state. However, this time is small and once the vapor system comes to steady state the heat removal rate and the compressor load remains essentially constant since the outlet air temperature is maintained more or less constant. Thus, neglecting the load and heat removal rate variations during switching on transients, it may be safely assumed that, whenever the compressor is ON the heat removal rate and compressor load are at a fixed level. Hence, the representation of the air conditioner heat removal rate by a constant current source is justifiable. Also the energy consumption by the compressor motor is, proportional to the total ON period of the motor over a day or equivalently to the average duty factor over the day.

Most of the solar radiation and part of the internal heat do not heat the inside air directly; rather their energy is first absorbed by the walls, roof and other mass inside the room and then it is delivered to the inside air. Therefore, these two components (solar radiation and the portion of internal heat sources involved in this indirect heating of air) are combined to give the source I_s represented by a current source in the electrical analogue. This current source is connected across C_w to represent the heat storage effect.

I_{inst} is the current source to represent the instantaneous component of internal heat sources such as bulbs, fans etc., which heat up air inside directly. I_{cond} is the current source used to represent the heat addition due to the condensation of water vapor in the room A/C unit evaporator tubes. This condensation takes place only when the unit is ON. This usually represents only a small addition to the heat load and hence is neglected in the simulation study reported here.

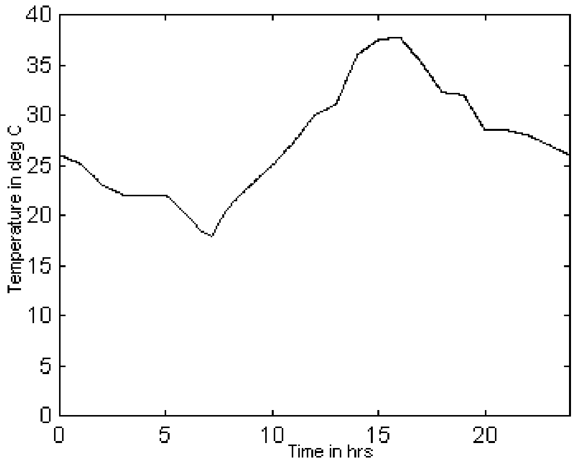

Fig.2 Daily Variation in the Outside Air Temperature

There is an unavoidable delay between the air temperature and the actuating temperature of a thermostat due to thermal time lags in the sensing unit. This delay serves the useful function of avoiding too frequent switching of the unit under heavy load conditions and also avoids the compressor motor starting on loaded condition. The sensing system is not shown in Fig.1. However, it was modeled by a first order transfer function in the simulation model.

The model parameters for a typical room of 6mx6mx4m have been calculated/estimated using standard calculation practices used in air conditioning calculations. These values are listed below.

$R_w = 0.004\ ^0C/W$
$R_c = 0.01\ ^0C/W$
$C_w = 6{,}000{,}000\ J/^0C$
$C_i = 175{,}000\ J/^0C$
$I_{ac} = 7500W$ (for a 2T unit)

The source functions T_0, I_s and I_{inst} are available in the form of table of hourly values.T_0 is arrived at by temperature records in ref. [4] studies and the solar radiation heat gain is calculated by using standard solar radiation curves. The roof area was taken as the solar radiation incidence area and the solar radiation on side walls were ignored.

The source I_{inst} was estimated through knowledge of electrical equipment used inside the room and their use pattern.

The plots of these source functions T_0, Is and I_{inst}, obtained by interpolating between the hourly values, are shown in Fig.2, Fig3 and Fig.4 respectively.

In an electrical analogue for a thermal system temperature difference is analogous to potential difference, heat flow is analogous to current, thermal resistance is analogous to electrical resistance and thermal capacity or thermal storage is analogous to electrical capacitance.

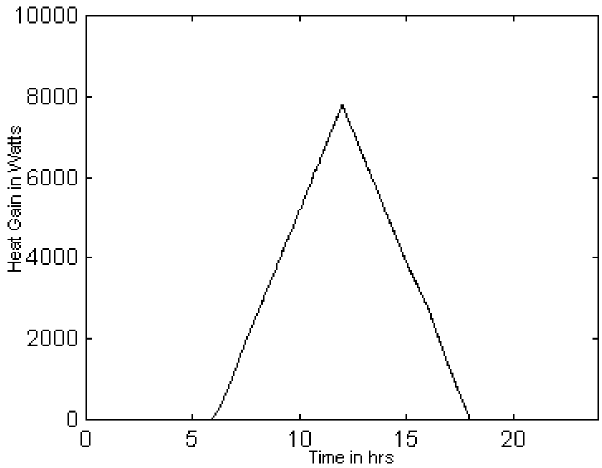

Fig.3 Daily Variation of Heat Gain Due to Solar Insulation

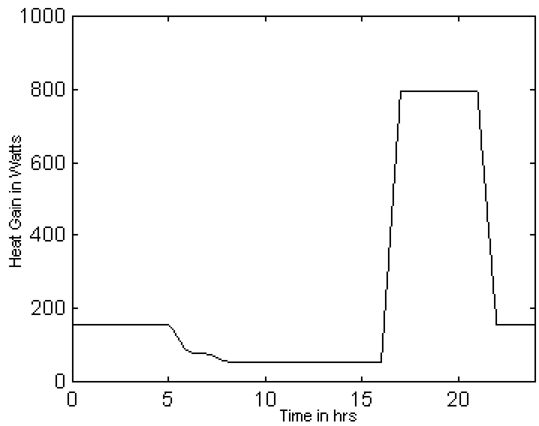

Fig.4 Daily Variation of Heat Gain Due to Internal Sources

The governing equations of the system can be obtained by writing Kirchoff's current law at the two nodes where the unknowns are T_w and T_i.

The system equations after simplifying are cast into the form of two first order differential equations with coupling. This form is suitable for solution by numerical methods.

$$\frac{dT_w}{dt} = \frac{I_S}{C_W} + \frac{T_i}{R_W C_W} + \frac{T_O}{R_W C_W} - \frac{2T_W}{R_W C_W} \tag{1}$$

$$\frac{dT_i}{dt} = \frac{I_{inst}}{C_i} + \frac{(I_{cond} - I_{ac})S(t)}{R_W C_W} + \frac{T_O}{R_C C_i} + \frac{T_W}{R_W C_W} - \frac{T_i}{C_i}\left(\frac{1}{R_W} + \frac{1}{R_c}\right) \tag{2}$$

4. Control Strategies for Energy Conservation [5-7]

Three control modes are implemented in an electronic thermostat. They are 'NORMAL', 'HOLD' and 'RAMP'.

In the NORMAL mode the electronic thermostat behaves as a normal thermostat with the only difference that since the temperature is sensed electronically and the setting is done electronically much more flexibility will be available in the electronic thermostat. In a bimetallic strip based thermostat the range of set temperature available is limited and even if the user wants to save energy by increasing the set temperature, the range available is limited. Also, the hysteresis band in such a thermostat can not be adjusted. These shortcomings are solved in an electronic thermostat.

When HOLD mode is chosen in an electronic thermostat, the duty ratio of the room A/C unit is kept constant from that time instant onwards. Normally, the duty ratio, i.e. the ratio of ON Time to total duration of a switching cycle, goes on varying as the outside temperature and solar radiation increase. The peak in the heat load on the unit takes place after the peak in the outside temperature and solar incidence. This is due to the thermal time lag introduced by the large heat capacity of walls, base and roof. Usually, the room A/C unit faces maximum load after 90 to 120 minutes of outside temperature and solar radiation reaching a peak. The duty ratio will reach a peak at this time if the unit is on NORMAL mode. It could be as high as 0.8 in a properly sized unit and it could approach unity if the sizing is not proper. If the unit is undersized the unit will remain ON continuously for hours together during this period and yet the room temperature may increase. Not allowing the compressor motor to go off periodically affects the heating in compressor motor and is detrimental to its life. In the HOLD mode the duty ratio, the ON time and the OFF time of the room A/C unit is kept constant disregarding the set temperature and allowed band around it. The price paid is the increasing temperature inside. Usually a supplementary control that overrides this mode will have to be built in to avoid the inside temperature becoming too high for the comfort of users. But it is possible to arrange the HOLD mode duration in such a way that the discomfort to the user is marginal and unnoticeable. Considerable energy saving will be possible by using this mode. Moreover the compressor motor life will be extended.

But what is the value of ON time and OFF time that will be used to decide the condition of compressor motor in the HOLD mode? Two possibilities exist and both are used in actual implementations. In the first case the average duty factor in the last hour immediately prior to the HOLD command is calculated and a fixed time interval, usually 15min,is divided as per this duty factor For e.g. let the room A/C unit be running with an average duty factor of 0.4 at the time of receiving HOLD command. Then the room A/C unit will be cycled at the rate of 6 minutes ON and 9 minutes OFF till the HOLD command is removed. In the second method the ON duration and OFF duration of the last cycle of ON/OFF is used as the held value of ON duration and OFF duration. The values used for the last ON/OFF cycle completed and does not refer to the ongoing cycle of switching at the time of incidence of HOLD command. The HOLD logic has to see one complete cycle of switching has taken place before the room A/C unit is put on HOLD. In fact it is better that the HOLD logic ensures that at least two switch-offs have taken place before HOLD is obeyed. This is to ensure that the unit does not go into HOLD mode with a large ON time. This will happen at starting of the unit. The first cycle ON time of a room A/C unit will be large since the heat load will be high at the time of powering the unit. If the unit is asked to go into HOLD during or immediately after the first cycle the held ON time will be large and instead of energy conservation it will result in more consumption. Thus, the HOLD logic must wait for a steady state cycle i.e. it must record at least two switches-offs of compressor motor before it puts the unit on HOLD. This logic is used in the simulated system.

The HOLD command on a unit should be removed and it should be allowed to go back into NORMAL mode only after the heat load has gone down well below the peak level. When the hold mode is terminated the normal set temperature value comes back into effect and the unit remains in ON condition for a long time before settling down to a cyclic operation. Many room A/C units released from HOLD mode simultaneously can put a large peak demand on the distribution system – the very thing the utility was trying to avoid by asking all the room A/C units in the distribution area to go into HOLD mode by remote radio control. The duration of this large ON period will depend on the set temperature value and the heat load at the time of releasing the HOLD command. Hence, if the unit is put on HOLD it should be released only after the day has cooled down. The optimum HOLD period would be from 12:00 noon to 8:00PM or so in our climate.

The HOLD mode suffers from virtual loss of control on the inside temperature and the consequent possibility of noticeable user discomfort. The RAMP mode offers a solution to this. In this mode the thermostatic action remains i.e., the thermostat tripping controls the ON/OFF cycle. But, the set temperature is no more a constant. In the RAMP mode, the set temperature is ramped up first from its NORMAL mode value at 1^0C/hr or 2^0C/hr till the set value reaches about 28^0C or 29^0C and after that it is ramped down at the same rate till it reaches the NORMAL mode setting. There is an effective control on the inside temperature and at the same time considerable energy saving is possible. This mode has been by far more popular than HOLD mode.

5. Description of the SIMULINK Model of the System

The room A/C unit system, with the parameter values and source function given earlier, was simulated in MATLAB-SIMULINK in order to estimate the possible energy savings under different modes of control. The simulation model developed is shown in Fig.5.

A 'hierarchical block' approach was used in the development of the model. Fig.5 shows the top layer model. The major parts of the system are embedded in the subsystem blocks.

There are five subsystem models at this level. They are the input sources model, the A/C Room Model, the ON/OFF Control Model, the Hold Mode Control Block and the Ramp Mode Model. The remaining components at the top-level model are for signal outputting and signal observation.

The Input Source Model contains three look up table elements needed for the three source functions, the outside temperature, the solar radiation heat gain and the instantaneous component of internal heat gain. The tabular values are entered against time in minutes and the look up table elements do interpolation if needed. A clock element through a gain block of gain 1/3600 convert the simulation time in seconds into minutes and provides the time information into the look up tables.

The Hold Mode Control Block contains two step function elements and a summer. The first step function outputs a unit step with transition at an instant which is a parameter that can be set by opening that element. Similarly the second one outputs a negative unit step at a designated time point later. Addition of these two gives the HOLD mode control signal.

The Ramp Mode Block is an enabled model and it is executed only when the '*Ramp Mode ON'* step source element at top level goes high. This block has a look up table inside which outputs the linearly increasing and decreasing temperature reference in force while RAMP mode lasts. A threshold switch element at the top level directs the correct set temperature value for NORMAL and RAMP modes into the subsequent blocks.

6. Selected Simulation Results

Various simulation runs using the developed model were carried out using SIMULINK in MATLAB 6.5. Some representative outputs are discussed in this section. The aim of this research was to illustrate how a reasonably complex system can be simulated in SIMULINK by developing a suitable simulation model. Many runs with variations in system parameters and source functions will be needed to evaluate completely the efficiency of the control strategies under varying conditions and at various locations.

The system was simulated in the NORMAL mode to study the effect of thermostat setting on the daily energy consumption. The effect of sensing delay was examined by running the simulation with various sensing delays. Also the effect of changing the hysteresis in the thermostat was investigated.Fig.6 shows the growth of ON time of the unit over a day and indicates clearly that most of the energy consumption takes place during the 10:00AM to 6:00PM period. Also the daily duty factor is seen to be about 0.35.Fig.7 shows similar information for hysteresis band of ± 4^0C.The total hours of energy consumption has come down and there is a long period for which the unit remained OFF continuously (the flat portion in the curve).

Fig.8 shows the variation of total daily operation hours against the set temperature in the NORMAL mode. The delay in sensing the inside temperature is seen to result in longer operation hours at all settings. Doubling the hysteresis band value has the effect of decreasing the total time of operation. But, the most significant point is the extent of possible energy savings by setting the thermostat to higher levels. For example, revising the thermostat setting from 21^0C to 24 ^{0}C results in 1.85 hours less of operation and it amounts to about 25% energy savings on 21^0C setting basis. The duration of unit operation seems to be almost proportional to the thermostat setting for any band value and sensing delay.

Fig.9 shows the effect of HOLD mode between 12:00noon to 8:00PM on energy consumption at various thermostat settings. It can be seen that the energy consumption has come down by a factor of about 0.87 at all settings. This represents 13% energy savings at all setting. But, this saving came at a price. The inside temperature goes above set value during the HOLD mode.Fig.10 shows the maximum inside temperature for various cases and it can be seen clearly that HOLD mode with high temperature setting in the thermostat is as good as switching off the unit!

Fig.11 shows the variation of ON duration in switching cycles and clearly shows that the ON duration is held constant during the HOLD mode. It also shows that there is a large period of operation immediately after the HOLD mode is released.

The total number of switching operations for various cases is shown in Fig.12.The simulation results verify the expected relation between the number of switching operations and the relevant variables like the set temperature, hysteresis band and sensing delay. The lower the set temperature the higher the frequency of the switching. The higher the hysteresis bands the lower the number of switching operations.

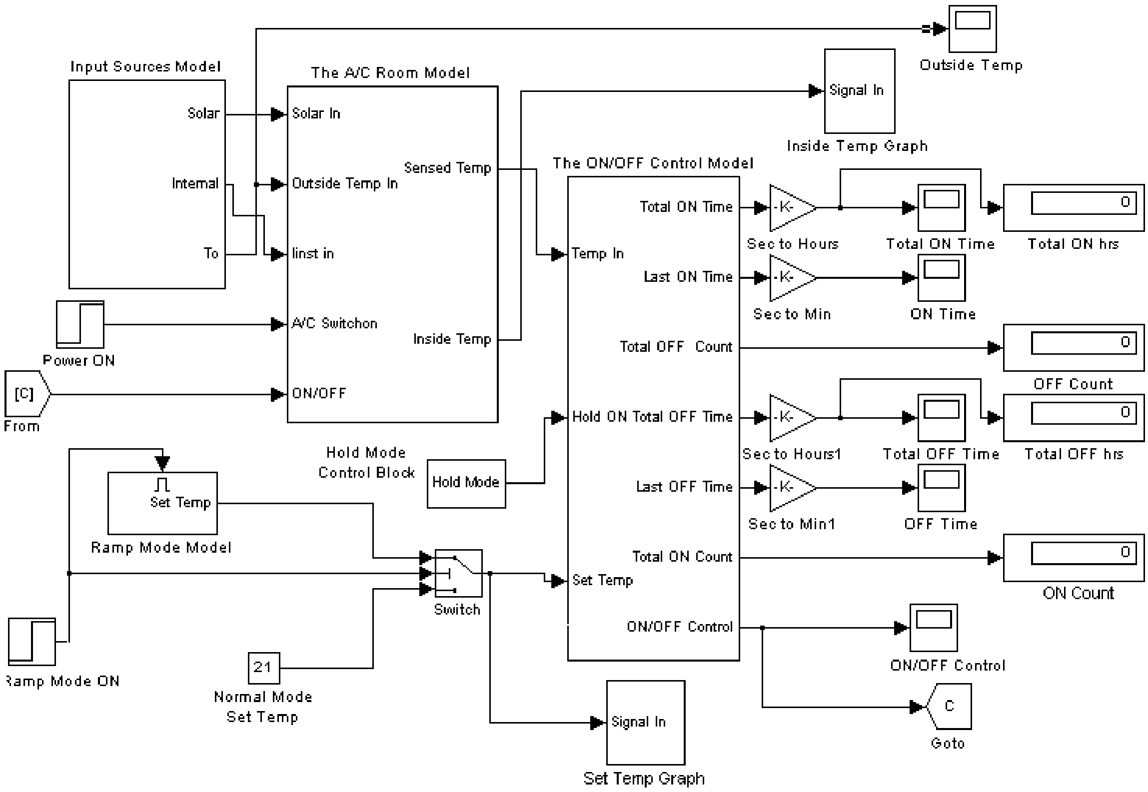

Fig.5 SIMULINK Model of a Room Air Conditioning System

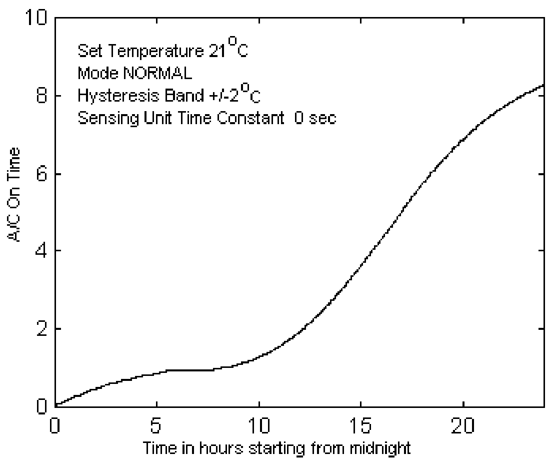

Fig .6 Growth of ON time of the Room A/C Unit

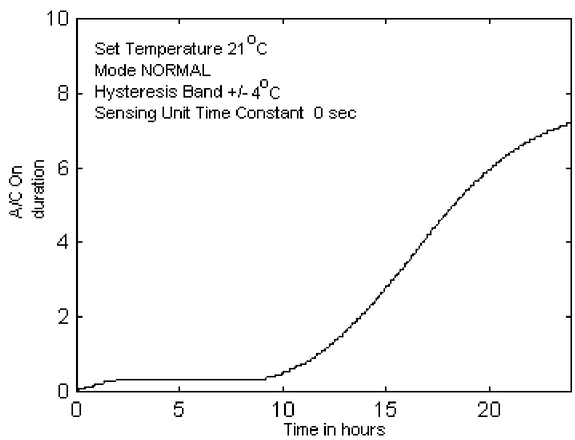

Fig .7 Growth of Total ON duration the A/C Unit

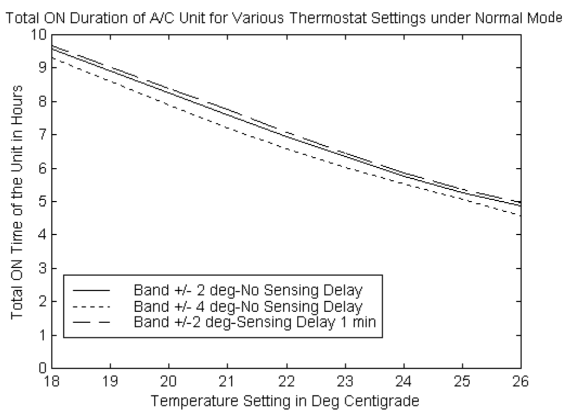

Fig .8 Variation of total ON time with set temperature

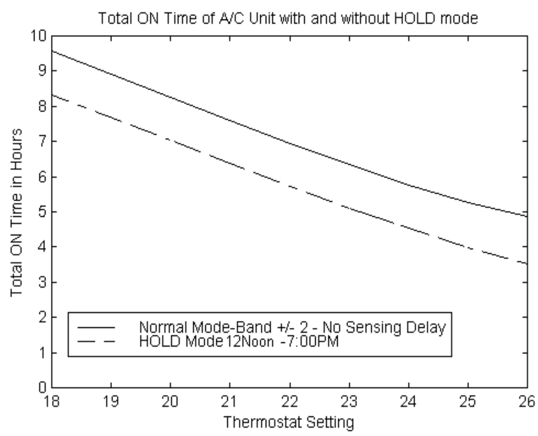

Fig .9 Effect of HOLD mode operations on total hours of operation

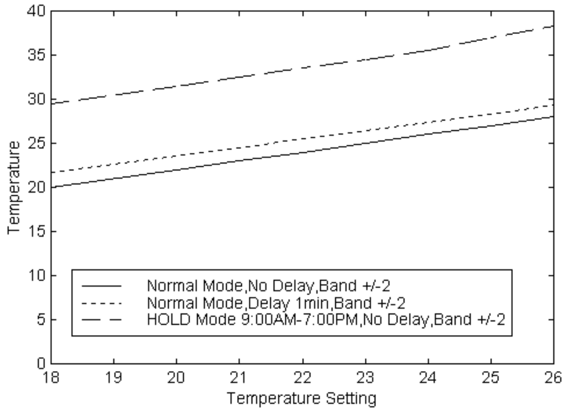

Fig .10 Maximum inside temperature Vs set temperature

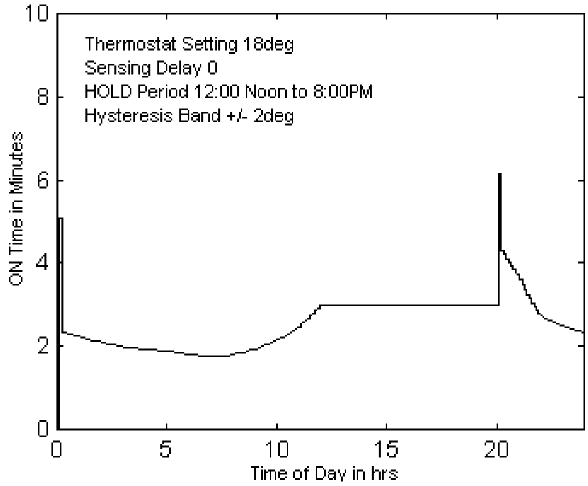

Fig.11 Variation of ON duration in switching cycles

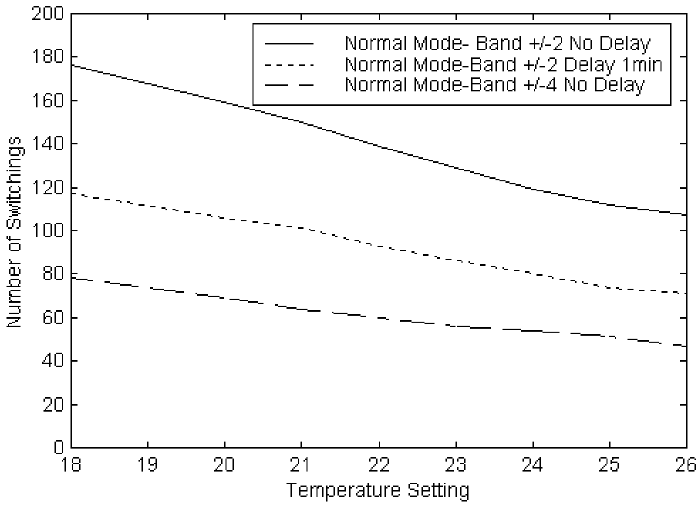

Fig .12 Number of switching in the A/C unit in 24 hrs Vs set temperature

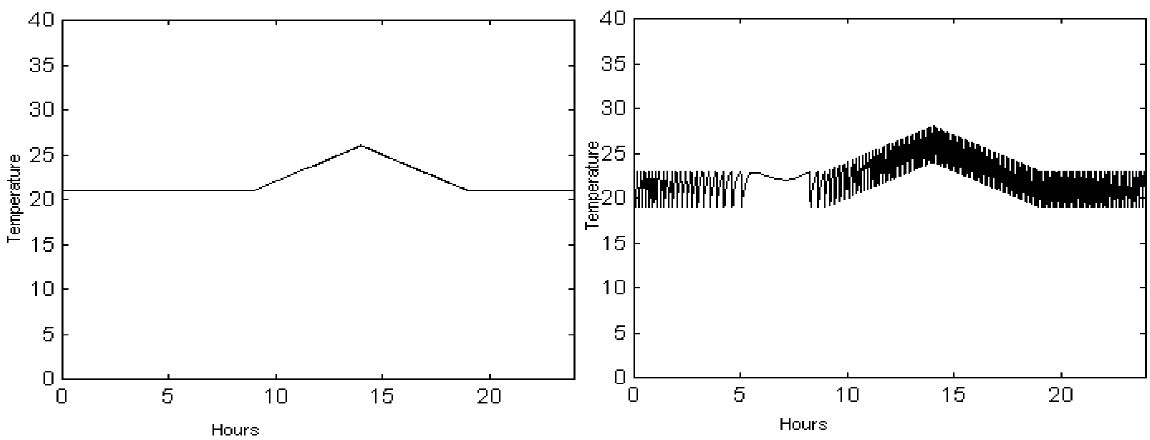

Fig .13 Set temperature and inside Temperature in RAMP mode of control

The total number of switching operations for various cases is shown in Fig.12.The simulation results verify the expected relation between the number of switching operations and the relevant variables like the set temperature, hysteresis band and sensing delay. The lower the set temperature the higher the frequency of the switching. The higher the hysteresis bands the lower the number of switching operations.

Higher sensing delay lowers the number of switching. Fig.13 shows the set temperature and the inside temperature in the case the unit operated in the RAMP mode from 9:00AM to 7:00PM.The thermostat setting before enabling the RAMP mode was 210C and after the RAMP mode operation is over the set temperature comes back to the same value. The ramp rate was 10C/hr, going up to 260C at 2PM and then coming back 210C at 7PM.The total ON period without RAMP mode was 7.6 hours and with RAMP mode it was 7 hrs. This represents energy savings of about 10%.

7. CONCLUSION

In this paper, two popular control techniques employed in room A/C units in order to manage their energy consumption and power demand has been studied. Various simulation runs using the developed model were carried out using SIMULINK in MATLAB 6.5. Many runs with variations in system parameters and source functions will be needed to evaluate completely the efficiency of the control strategies under varying conditions and at various locations.

The system has been simulated in the NORMAL mode to study the effect of thermostat setting on the daily energy consumption. The results indicate that 13% energy saving has been occurred. For RAMP mode this study shows 10% energy saving has been occurred.

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OTAQ HAVASININ KONDENSELLƏŞDİRİLMƏSİ QURĞUSUNDA ENERJİYƏ QƏNAƏTƏ NƏZARƏTİN STRATEQİYASI

ŞƏYANFƏR H.A., KƏRƏMİ M., AĞAYEİ D.

SIMULINK/MATLAB 6.5 modelləşdirmə proqramı vasitəsilə otaq havasının kondenselləşdirilməsi qurğusuna nəzarətin iki üsulu tədqiq edilmişdir. Tədqiqatın əsas məqsədi enerji tələbatına və enerjiyə qənaətin tənzimlənməsinə yönəldilmişdir.

СТРАТЕГИИ КОНТРОЛЯ ЭНЕРГОСБЕРЕЖЕНИЯ В УСТРОЙСТВАХ КОМНАТНОГО КОНДИЦИОНИРОВАНИЯ ВОЗДУХА

ШАЯНФАР Г.А., КАРАМИ М., АГАЕИ Д.

С помощью программы моделирования SIMULINK / MATLAB 6.5. исследованы два метода контроля работы устройств комнатного кондиционирования воздуха с целю регулирования спроса, потребления энергии, а также ее сбережения.