OPTIMAL CONTROL OF AIR CONDITIONING SYSTEM

Asma **REBAI**, Salim **HADDAD**, Ridha **KELAIAIA**
LGMM Laboratory, Université 20 Août 1955 - Skikda, Algeria
{a.rebai, s.haddad, r.kelaiaia}@univ-skikda.dz

Keywords: Air conditioning, Optimization, Thermal comfort, Optimal control strategy.

Abstract*:* *This paper presents an optimal method for control the functioning time of an air condi- tioning system that allows reducing the electrical consumption by maintaining thermal comforts. In this work, the minimizing of the electrical consumption of a house is adop- ted as objective function, and thermal comfort is taken as a primary constraint, thus the mathematical model of air conditioning is formulated. Then an optimal control method based on reducing the electrical consumption of a house equipped with air conditioning system by optimizing the operating time of the air conditioner is proposed. Subsequently, the simulation results show a significant reduction of the total consumption at the same time maintaining thermal comfort. The proposed optimal control strategy of air condi-tioning system is carried out in MATLAB/Simulink with satisfactory results for a house. The rest of the load (washing-machine, refrigerator, freezer, etc.) is assumed as a constant complementary charge. Simulation results show a significant reduction of the electrical consumption.*

1. INTRODUCTION

The sharp rise in the electricity demand is a direct consequence of the change in consumption habits, especially because of the use of more and more prevalent of air conditioning. This is evident to create peak consumption in the summer. Peak energy demand refers to the time of day when loads on the electricity distribution infrastructure reach a maximum. During the summer months this tends to happen between 16:00 and 20:00 when high outdoor temperatures coincide with people returning home from work, resulting in high residential air-conditioner use. Reducing these loads is becoming increasingly important, because of an emerging shortage of electricity as a result of rapid population growth.

The air conditioning process is a controllable load which takes an important part in the tertiary and residential buildings. Therefore its management has an important potential to reduce the peaks of consumption.

In the literature, many control methods have been developed or proposed for air conditioning systems [1], this work focuses on a study of control methods for heating, ventilation and air-conditioning (HVAC) systems and the emphasis is on the predictive control approach model. Other studies have shown that pre-cooling thermal mass can reduce the cooling load of commercial buildings or shift the cooling load away from peak demand periods [1–9].

However, reductions in peak cooling demand have been demonstrated in theory and through field tests by either increasing the amount of thermal insulation used within a wall [10], or by increasing the thermal mass of the wall [11–13]. Automatic control for air conditioning systems On/Off control, PID control, time control (On/Off switch, fixed time, boosted start and optimum start and stop) were reviewed in [14].Al-Sanea and Zedan [15] showed that peak cooling loads in Riyadh could be reduced by up to 26% by optimizing summertime thermostat temperatures. [16] In this project we addresses the problem of designing a new control algorithm for HVAC systems that improves the comfort level of the occupants in buildings and at the same time consumes less energy to reach this goal. Callaway [17] considered the manipulation of 60,000 air conditioner thermostat set points to follow the dynamic output of a wind farm at a resolution of one minute. The air conditioning models were based on resistance-capacitance (RC) models. Callaway and others [18–21] have considered the dynamics associated with controlling a large number of thermostatically controlled loads or electric vehicles to achieve short-term grid benefits. Because they consider shorter-term periods, weather is held constant for the simulations and on this model [22], a discrete-time inverse optimal control strategy was developed and implemented to an experimental air conditioning system for simultaneously controlling indoor air temperature and humidity.To meet the energy demands while maintaining human thermal comfort,this paper [23] established a comfortable space air conditioning system of environmental parameters on extent of comfort index through the simulation analysis of the air conditioning thermal comfort equation.

However, this section analyzes the main references on optimization methods applied to the load management.

The first group [24] optimal load management in a building includes the methods of cost minimization. This cost is a combination of electricity and the cost penalty expressed as human comfort. The principle of these methods is to identify the key strategies of shedding and issue recommendations for building operators to offoad the load properly.

The second group consists of the realization of extensive simulations with different combinations of parameters; comparison means between these simulations the optimal point, which is a sub-optimal solution. For example, [25] developed a simulation environment to study a range of key parameters that influence the cost of operating the system. The optimal control strategy which consists in minimizing all costs of electricity has been validated by simulations.

The objective of this research is to minimize the electrical consumption of a house without sacrifice human comfort by control functioning time of the air conditioning system.

The paper is organized as follows: Section 2 presents case study for our air conditioning system where its presents a brief presentation of the loads in the house and illustrate a mathematical model for the air conditioning and the modal implemented in matlab/Simulink and Section 3 describes the optimization problem with the objectives function and constrains and the problem formulation after the results and discussion of optimization.

2. CASE STUDY

In this research, we used the data from Nevada, USA, in July 6, 2016 (*Figure 2*) for a house (300 m^2) with required temperature inside the rooms given by the limits: T^{min} = 20°C and T^{max} = 22°*C*.

The appliances considered are:

- 5.5 kW Air Conditioning Unit (varies with compressor power demand)
- 3.5 kW Air Conditioning Unit (varies with compressor power demand)
- Refrigerator (700 W) - variable
- Pool pump (1 kW) - works 8 hours/day in summer (morning and afternoon)
- One electric oven (3 kW) used occasionally
- Dishwasher (500 W) used occasionally
- Cloth-washer (750 W) used occasionally
- Cloth-dryer (2.5 kW) used occasionally
- Numerous light fixtures (used mainly at night)
- Two flat screen TV sets (usually one the two is used in the afternoon and evening hours)
- 4 ceiling fans (100 W each usually 2 out of 4 are used on a continuous basis.
- Electronic loads (laptops, clocks, alarm system, etc.)

The differential equation system is obtained [26]:

$$\frac{dT_m}{dt} = \frac{I_s}{C_m} + \frac{T_{int}}{R_m C_m} + \frac{T_{ext}}{R_m C_m} - \frac{2T_m}{R_m C_m} \tag{1}$$

$$\frac{dT_{inst}}{dt} = \frac{I_{inst}}{C_0} - \frac{I_{ac}S(t)}{C_0} + \frac{T_{ext}}{R_f C_0} + \frac{T_m}{R_m C_0} - \frac{T_{int}}{C_0}\left(\frac{1}{R_m} + \frac{1}{R_f}\right) \tag{2}$$

where:

E: The electrical consumption of the air conditioner [*KW h*]

X (*t*): The switching function (1 when the compressor motor is ON and 0 when is OFF)

T^{min}: Minimum temperature inside the room [°*C*]

T^{max}: Maximum temperature inside the room [°*C*]

T_m: The wall temperature [°*C*]

T_{ext}: Exterior temperature [°*C*]

R_m, C_m: The equivalent thermal conduction resistance [°*C/W]* and thermal storage capacity of the room (wall, base and roof) [J/°C]

R_F, C_0: The equivalent thermal conduction resistance of the average air infiltration [°C/W] and thermal capacity the air inside the room [*J/°C*]

I_s: The current source of two components (solar radiation and the portion of in- ternal heat sources involved in this indirect heating of air) [*W]*

I_{inst}: The current source of heat source produced by lamp, computer, nobody, etc. [W]

I_{ac}: The heat removed by the air conditioner [*W]*

The values of model parameters are listed:

C_m	6000000 J/°C
C_0	118235.4 J/K°
R_f	0.01 °C/W
R_m	0.004 °C/W

Figure 1 shows the conditioning room model in MATLAB/Simulink that is built from this differential equation system.

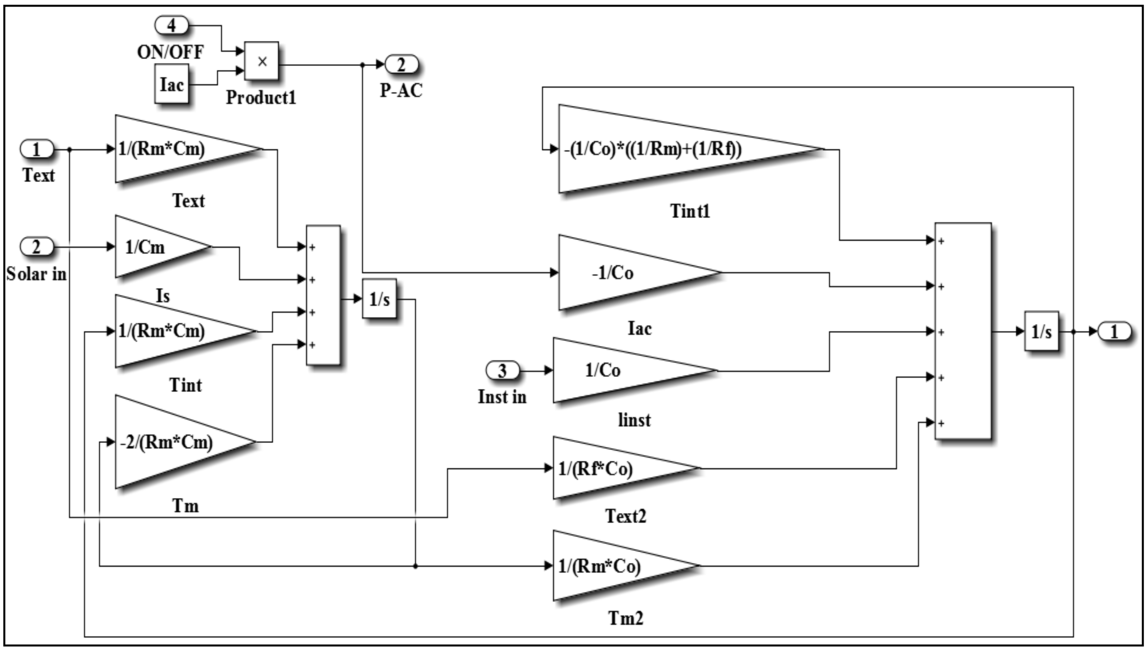

Fig.1. Air conditioning room model

Table 1. Exterior temperature of 6 July 2016

Time	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00
T_{ext} **(°C)**	28	27	26	25	25	24	25	28	29	31	32	34

Time	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
T_{ext} **(°C)**	35	36	37	37	37	37	35	34	32	31	30	29

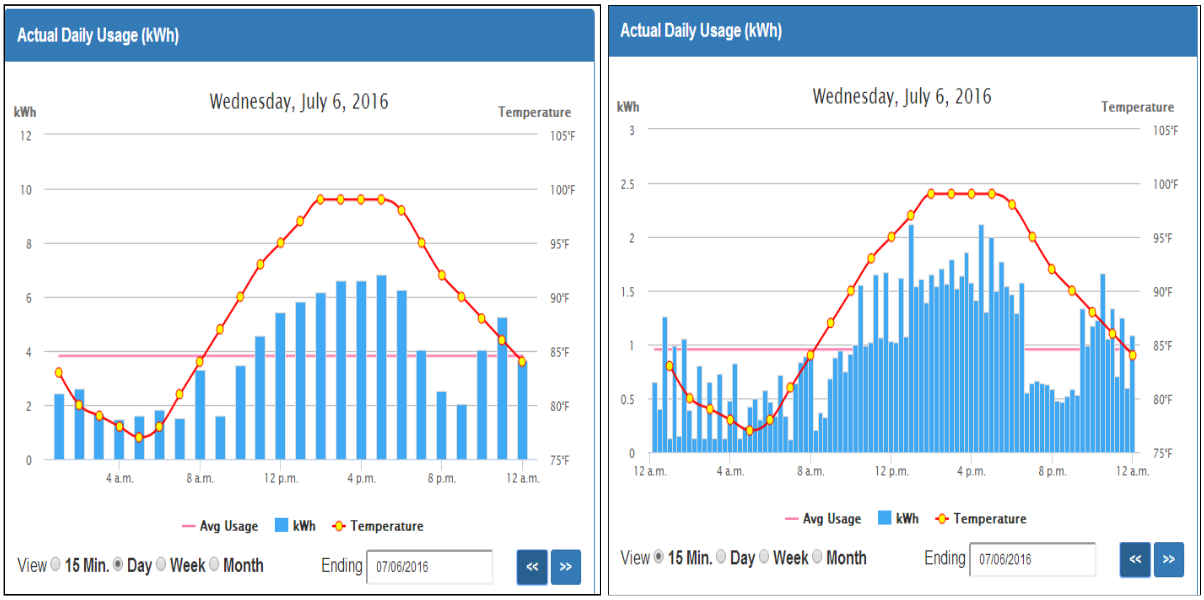

Fig.2. Exterior temperature and the power demand curve for July 6, 2016

3. OPTIMIZATION PROBLEM

The objective of the problem is to reduce the electrical consumption of a house equipped with air conditioner of 5.5 kW by optimizing the operating time of the air conditioner.

3.1. Definition of the objective function

The objective of the problem is to reduce the electrical consumption of a house equipped with air conditioner of 5.5 kW by optimizing the operating time of the air conditioner. Consequently, the objective function can be summarized, as follows:

$$\underbrace{Min}_{x_i \in \{0,1\}} \; [E] = \sum_{i=1}^{D} E x_i \text{ , } i = 1 \ldots D \tag{3}$$

D being the simulation time.

3.2. Definition of the constraints

In the following, our interest is focused on the comfort*:*

Since human thermal comfort is strongly related to the building, the requirement of thermal comfort is generally considered as a primary constraint of the optimization of the building problem

$$T^{min} \leq T^{int} = f(E\, x_i) \leq T^{max} \tag{4}$$

$T^{int} = f(Ex_i)$ *:* Interior temperature of the room, it can be obtained from resolution of the following differential equations [26]:

$$\frac{dT_m}{dt} = \frac{I_s}{C_m} + \frac{T_{int}}{R_m C_m} + \frac{T_{ext}}{R_m C_m} - \frac{2T_m}{R_m C_m} \tag{5}$$

$$\frac{dT_{inst}}{dt} = \frac{I_{inst}}{C_0} - \frac{I_{ac}S(t)}{C_0} + \frac{T_{ext}}{R_f C_0} + \frac{T_m}{R_m C_0} - \frac{T_{int}}{C_0}\left(\frac{1}{R_m} + \frac{1}{R_f}\right) \tag{6}$$

3.3. Problem formulation

Mathematically, the problem of the optimization is formulated as follows:

$$\underbrace{Min}_{x_i \in \{0,1\}} \ [E] = \sum_{i=1}^{D} E\, x_i \ , \ \text{i=1...D} \tag{7}$$

Such that the constraint:

$$20°C \leq T_{int} \leq 22°C \tag{8}$$

is satisfied.

3.4. Optimization results

The dsolve matlab function was used to solve the differential equations system (constraint of comfort).

3.4.1. Before Optimization

Total consumption of the house in the day of July 6, 2016 reaches to 94.11 KWh.

3.4.1. After Optimization

The operating time of the air conditioner: 2 h and 17 mn.

The electrical consumption of other loads: 55.611 KWh

The electrical consumption of the air conditioner: 11.935 KWh Total consumption of the house: 67.546 KWh

By this optimization, we were able to reduce the energy consumed from 94.11KWh to 67.546 KWh by saving 28% of the energy consumed during 24h.

4. CONCLUSION

From the discussion above, it can be concluded that the optimal control method for the air conditioning system can reduce the total electrical consumption

The presented method is based on efficiently reducing the total electrical consumption without sacrificing the thermal comfort of occupants.

Optimal control method to minimize functioning time of air conditioning was planned using optimization method .From the results, it was concluded that it is possible to save around 28 % from the total consumption in 24 hours.

The results of simulation show that air conditioning system can substantially save energy and also maintain thermal comfort. This method can adapted for all the house or building.

REFERENCES

[1] A. Abdul, J. S. Farrokh, *Theory and applications of HVAC control systems- A review of model predictive control*, Building and Environment, vol. 72, 343-355, 2014.

[2] A.Rabi, L.K. Norfod, *Peak load reduction by preconditioning buildings at night*, International Journal Energy Ressource, 15:781-798, 1991.

[3] J.E. Braun, *Load control using building thermal mass,* J Sol Energy Eng, 125:292, 2003.

[4] P. Xu, P. Haves, M. Piette, J.E Braun, *Peak demand reduction from pre-cooling with zone temperature reset in an office building,* (LBNL-55800), 2004.

[5] K. Le, J.E. Braun, *Model-based demand-limiting control of building thermal mass,* Build Environ, j.buildenv, 43:1633-1646, 2008.

[6] R. Yin, P. Xu, M.A. Piette, S. Kiliccote, *Study on auto-DR and pre-cooling of commercial buildings with thermal mass in California*, Energy Build, 42: 967-975, 2010.

[7] S.P. Corgnati, A. Kindinis, Thermal *mass activation by hollow core slab coupled with night ventilation to reduce summer cooling loads,* Build Environ, 42:3285-3297, 2007.

[8] D.O. Rijksen, C.J. Wisse, AWM. Van Schijndel, *Reducing peak requirements for cooling by using thermally activated building systems, Energy* Build, 42: 298-304, 2010.

[9] SA. Al-Sanea, M. Zedan, *Improving thermal performance of building walls by optimizing insulation layer distribution and thickness for same thermal mass,* Appl Energy, 88: 3113-3124, 2011.

[10] M.E. Dexter, *Energy conservation design guidelines: including mass and insulation in building*

walls, ASHRAE J, 22:35-48, 1980.

[11] D.M. Burch, W.E. Remmert, D.F. Krintz, C.S. Barnes, Laboaratory ORN, *Field study of the effect of wall mass on the heating and cooling loads of residential buildings*. (Log home report.). Build Therm Mass Semin, 265-312, 1982.

[12] SA. Al-Sanea, M. Zedan, SN. Al-Hussain, *Effect of thermal mass on performance of insulated building walls and the concept of energy savings potential*. Appl Energy, 89:430442, 2012.

[13] M.V. Harrold, D.M. Lush, *Automatic controls in building services*. IEE Proc B Electr Power Appl, 135:105-133, 1988.

[14] SA. Al-Sanea, M. Zedan, *Optimized monthly-fixed thermostat-setting scheme for maximum energy-savings and thermal comfort in air-conditioned spaces*. Appl Energy, 85:326-346, 2008.

[15] P. Prahlad, *Modeling and optimal control algorithm design for HVAC systems in energy efficient buildings*. International Research journal for engineering science, Technology Innovation (IRJEST), ISSN-2315-5663 vol2 (2), pp.29-39, Feb2013.

[16] D.S. Callaway, *Tapping the energy storage potential in electric loads to deliver load following and regulation with application to wind energy*. Energy Convers Manage, 50(5):1389–1400, 2009.

[17] S. Bashash, H.K. Fathy, *Modeling and control of aggregate air conditioning loads for robust renewable power management*. IEEE Trans Control Syst Technol, 21(4):1318–1327, 2013.

[18] N.A. Sinitsyn, S. Kundu, S. Backhaus. *Safe protocols for generating power pulses with heterogeneous populations of thermostatically controlled loads*. Energy Convers Manage, 67:297–308, 2013.

[19] N. Lu. *An evaluation of the HVAC loads potential for providing load balancing service.* IEEE Trans Smart Grid, 3(3):1263–1270, 2012.

[20] C.Y. Chang, W. Zhang, J. Lian, K. Kalsi . *Modeling and control of aggregated air conditioning loads under realistic conditions*. Innovative smart grid technologies (ISGT), IEEE PES, 2013.

[21] C. Perfumo, E. Kofman, J.H. Braslavsky, J.K. Ward. *Load management: model-based control of aggregate power for populations of thermostatically controlled loads*. Energy Convers Manage, 55:36–48, 2012.

[22] T. Broeer, J. Fuller, F. Tuffner, D. Chassin, N. Djilali. *Modeling framework and validation of a smart grid and demand response system for wind power integration*. Appl Energy, 113:199–207, 2014.

[23] M. Flavio, N.S. Edgar, X. Yudong, D. Shiming. *Real time neural inverse optimal control for indoor air temperature and humidity in a direct expansion air conditioning system*. International journal of refrigeration.S0140-7007(17)30147, 2017.

[24] K. Keenery, J. Braun. *Simplified method for determining optimal cooling control strategies for thermal storage in building mass*, *Intl. J. of HVAC&R Research*, Vol.2, No.1, 59-78, 1996.

[25] G. Henze, R. Dodier, M.Krarti. *Development of a predictive optimal controller for thermal energy storage systems*, Intl. J. of HVAC&R Research, Vol.3, No.3, 233-264, 1997.

[26] K. Le, T. Tran-Quoc, Jean-Claude Sabonnadière, and Ch. Kieny, and N. Hadjsaid, *Peak load reduction by using air-conditioning regulators*. Electrotechnical Conference. MELECON, The 14th IEEE Mediterranean, pp. 713-718, 2008.