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Optimal Reduction of Peak Electricity Demand with Control of Air Conditioning

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Abstract

The significant increase in the electricity demand is a direct consequence of the change in consumption habits, especially because of the use of rising prevalent of air conditioning. Thus, it reveals evident to create peak consumption during summer season. Then, all through the peak periods, the supplementary demand on the grid is satisfied by raising capacity via the exploitation of power plants with a higher marginal cost and greater CO_2. Besides, such a fact increases the cost of producing the kilowatt-hour to the benefit of the business. In addition, the cost is paid back by the consumer via increased utility prices. Therefore, the reduction in these loads is becoming increasingly important as a result of an emerging electricity shortage resulting from rapid population growth.

Through this study, the management and optimization of building's air-conditioning system for efficient energy operation and comfortable environment are studied. Hence, the strategies used in these works depend, firstly, on reducing electrical consumption by optimizing the operation time of the air conditioner; and secondly consist of the development of a regulator control system of air-conditioning units, applied for a house in Nevada (USA), which contains of two thermocouples' sensors, two relays and a battery. The proposed solution reduces peak consumption without loss of thermal comforts.

Subsequently, the proposed air conditioning system is carried out in MATLAB/Simulink with satisfactory results for a house. The rest of the load (washing-machine, refrigerator, freeze, etc.) is assumed as a constant complementary charge. Then, the results confirmed that the optimization method achieved an energy saving of 25 %from total consumption for a day, and even the simulation results show a significant reduction of the total consumption at the same time, maintaining thermal comfort.

Keywords: Air conditioning; optimization; thermal comfort; permissible power; command system; regulator system.

INTRODUCTION

With continuously growing of the world population, energy requirements have rapidly increased, where 85% coming from fossil fuels and about 6% of renewable energy worldwide [1, 2]. Industrialization, urbanization and improving living conditions lead to more demands for comfortable buildings; this increasing directly the energy consumption [3-5]. Likewise, building sector accounts for more than 72% of electricity consumption [6]. In addition, the residential energy consumption is influenced by a lot of factors [7], especially; residential air conditioning has disproportionately large impact on peak electricity demand, which is responsible for 40% of the total energy consumption [8, 9].

The reduction of peak consumption is one of the effective solutions of energy management systems [10]. In addition, this reduction has many interests such as a reduction in underwriting and consumption costs during peak hours for customers, thus avoiding the congestion and the technical problems caused by the DNO (distribution network operators overloads) and limiting the expenses of an expensive energy provider.

Above and beyond, several methods have been proposed in the literature with different degrees of success; the use of renewable energy sources in the house has been a major research topic in recent years, mainly because of the environmental issues, in respect such as pollution [11, 12]. Adem and Cihan [13] present a mountain house in Sakarya-Turkey, which are mainly powered by renewable energy resources; also, the increase of thermal insulation for reducing total electricity, the use of solar shading, adoption of photovoltaic's and load shedding have been demonstrated and field-tested [14]. Al-Sanea and Zedan [15] showed that in Riyadh (Saudia Arabia), cooling of peak loads can be reduced by up to 26% by optimizing thermostat temperature in summer. Besides, thermal insulation reduces as well as peak loads; thus, it reduces energy consumption in buildings as well as the size and capacity of air-conditioning [16, 17]. Braun et al. [18] have used simulations to demonstrate a 40% decrease in total cooling costs from using a thermal mass control strategy. Further, an analysis of the energy manager

"G-homeTech" shows that it allows the reduction of peak demand and savings on the overall energy bill while respecting the technical and regulatory constraints [19]. K.Le [20] worked on techniques that can better control energy in guarantying the comfort levels', the authors proposed two original techniques for the load management in real time: the first one is based on a system of adaptive regulation for heating and air conditioning, and the other one is based on the shedding in function of protection characteristic. On the other side, Y. Riffonneau focuses, in his study, on the PV systems for the residential sector, where at the main objective is to achieve clipping consumption by optimizing the energy photovoltaic and integrating a storage element [21, 22]. Samuel [23] presents a methodology for developing a tree structure to characterize a residential building stock in frame of a bottom approach that aims model and simulate domestic. Balku [24] sees that the aim of his project is to increase the usage of solar and wind capacity of a building by architectural design method in cooperation with architectural and engineering sciences before it is built, and research for maximum energy efficiency. Ben Cheikh [25] work results that old dense buildings with marrow streets built with local material (earth) can save energy and have a good thermal comfort behavior than new built houses. In order to reduce the peak demand and the subsequent cost of electricity, batteries are included in the energy system. In their work [26], Farah has developed four control strategies for charging and discharging the battery, and exporting and importing electricity from the grid.

Having said that, the air conditioning process is a controllable load that plays an important role in tertiary and residential buildings. Therefore, its management has great potential to reduce the peaks of consumption.

In the light of which, the main purpose of this work is to develop the strategy optimizes functioning time of air conditioner in terms of reducing in energy consumption, an adaptive regulator control of air-conditioning units is proposed; thus, the solution is applied for a house to reduce the peak load consumption without sacrifying thermal comfort of occupants.

İn closing, the paper is organized as follows: Section 2 case study introduces the different appliances of the house with the air conditioner model implemented in Matlab/Simulink and the exterior temperature of 06th July 2016; Section 3 shows the optimization and mathematical problem formulation with objective function and constrains after optimization results; whilst Section 4 presents a description of the air conditioning regulator system and finishs with simulation results and discussion. Finally, the last sections conclude this study.

CASE STUDY

In this research, we used for this problem data from a family house in Nevada (western united sates) area (300 m^2); this house consists of 4 bedrooms, a living room, a kitchen and a bathroom. The structure of his walls is a brick material with 0.2 m thicknesses.

The data is for the day of July 6, 2016. Where in the required temperature inside the room is given by T^{min} =20°C, T^{max} =22°C, and the exterior temperature is show in Figure 2.

Here are the appliances it contains:

- Air Conditioning Unit of 5 kW (varies according to compressor power demand)
- Air Conditioning Unit of 3.5 kW (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 Figure 1 shows the conditioning room model in MATLAB/Simulink that is built from this differential equation system.

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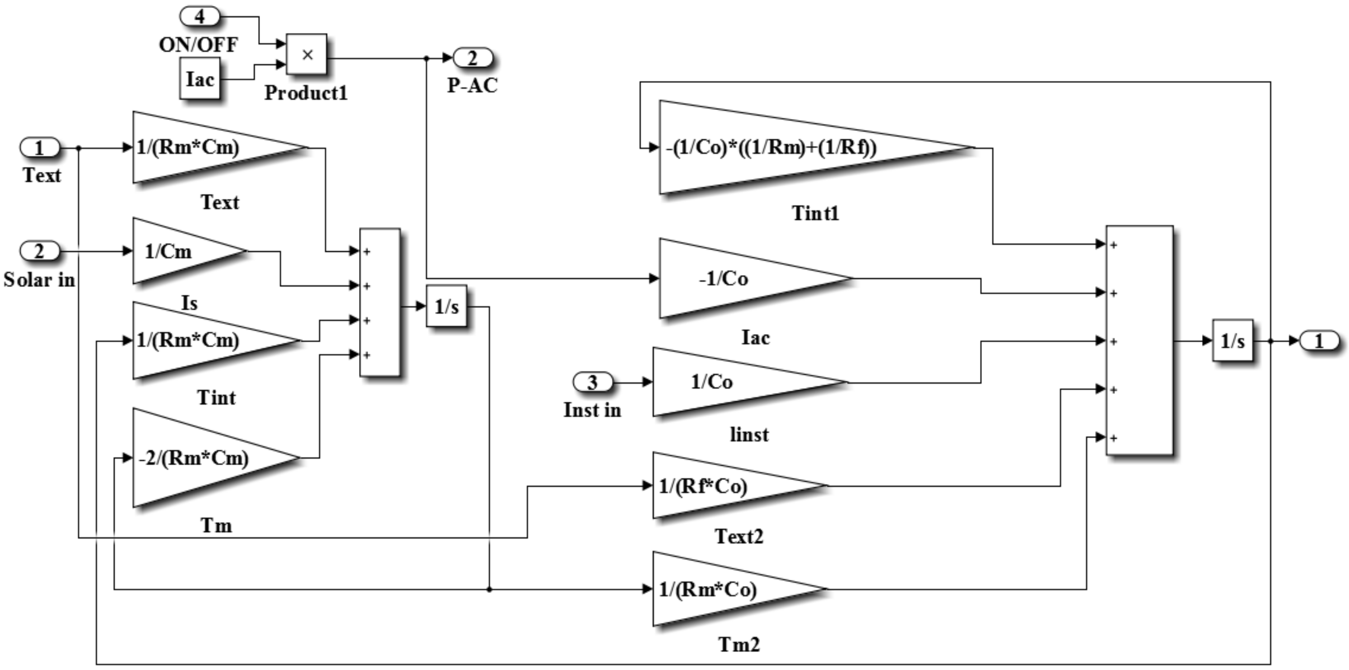

Figure 1. The model of the air conditioning room [20].

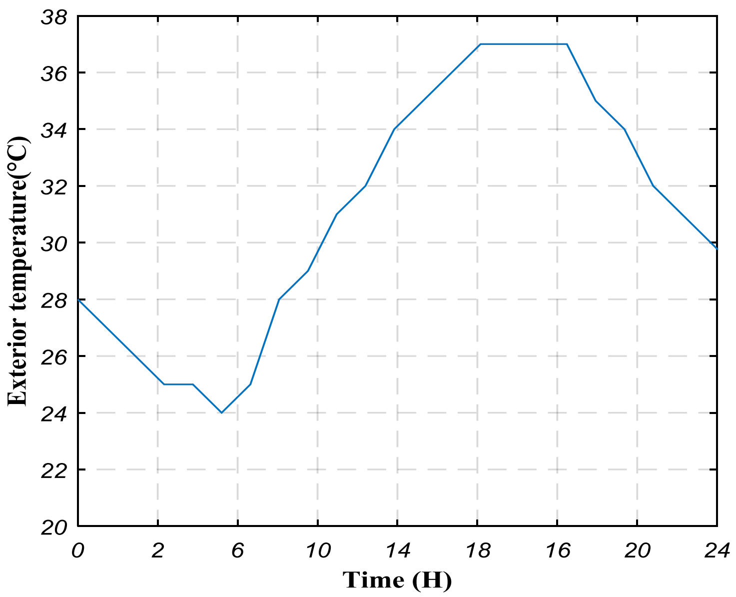

Figure 2. Exterior temperature.

OPTIMIZATION PROBLEM

2.1. Definition of the objective function

The main objective of the problem is to reduce the electrical consumption of a house equipped with air conditioner of 5 kW by optimizing the operating time of the air conditioner. Therefore, the objective function can be summarized, as follows:

$$\underbrace{Min}_{x_i \in \{0,1\}} \left(\sum_{i=1}^{D} E x_i\right), \quad i=1\ldots, D$$

Where

E: The electrical consumption of air conditioning [kWh]

X(t): The switching function (equal 1 if the compressor motor is ON and 0 if it is OFF)

D: Simulation time

Definition of the constraints

Since human thermal comfort is strongly related to the building, the thermal comfort requirement is generally considered as a major constraint of the optimization of the building problem. The constraints of comfort are given by the following equation (1):

$$T^{min} \leq T^{int} = f(E\, x_i) \leq T^{max} \quad (1)$$

$T^{int} = f(Ex_i)$: Interior temperature of the room, which can be obtained by solving the system of differential equations [20] given by equations (2) and (3):

$$\frac{dT_m}{dt} = \frac{I_s}{C_m} + \frac{T_{int}}{R_m C_m} + \frac{T_{ext}}{R_m C_m} - \frac{2T_m}{R_m C_n} \quad (2)$$

$$\frac{dT_{inst}}{dt} = \frac{I_{inst}}{C_0} - \frac{I_{ac}S(t)}{C_0} + \frac{T_{ext}}{R_f C_0} + \frac{T_m}{R_m C_0} - \frac{T_{int}}{C_0}\left(\frac{1}{R_m} + \frac{1}{R_f}\right) \quad (3)$$

Where:

T_m: Wall temperature in [°C]

T_{ext}: Exterior temperature in [°C]

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

R_f : The equivalent thermal resistance of the average air infiltration [°C/W]

C_0: Air thermal capacity inside the room [J/°C].

I_s: The current source of the solar radiation and the portion of internal heat sources involved in this indirect heating of air [W].

I_{inst} : The current source (heat source) produced by computer, lamp, etc. [W].

I_{ac}: Extracted heat by air conditioner in [W].

$x(t)$: The switching function.

The values of model parameters are listed in Table .1

Table 1. The parameters of model [20].

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

Problem formulation

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

$$\underset{x_i \in \{0,1\}}{Min} \left(\sum_{i=1}^{D} E\, x_i\right)$$

Such That the constraint:

$$20°C \leq T^{int} \leq 22°C$$

Is satisfied.

Optimization results

This is a non-linear optimization problem. The matlab **dsolve** function was used to determine the temperature T^{int} by solving the system of differential equations (equation 1 and 2), and then to check the satisfaction of the comfort constraint:

If: $T^{int} \leq 22°C$ then $x_i = 0$ consequently the compressor motor of air conditioning is OFF.

Otherwise $T^{int} > 22°C$, $x_i = 1$ therefore the air conditioning is ON.

This make it possible to considerably minimize the running time of the air conditioner and consequently the electrical energy consumed .Indeed before optimization the total consumption of the house in the day of July 6, 2016 reaches to 94.11 KWh. However, after optimization, the obtained results are summarized in Table 2.

Table 2. Optimized energy consumptions.

The operating time of the air conditioner	3 h
The electrical consumption of other loads	55.111kWh
The electrical consumption of the air conditioner	15 kWh
Total consumption of the house	70.111kWh

By this optimization, we were able to reduce the energy consumed from 94.11 kWh to 70.111 kWh by saving 25.5% of the energy consumed during 24 hours.

AIR CONDITIONING REGULATOR SYSTEM

Description of the air conditioning regulator system

In this paper, the model under study is an air conditioning system (Figure 3) consisting of three parts. First a model of an air conditioned room operated by electric power circuit voltage (220 V). Secondly, a control system contains two thermocouples sensors, fed by a voltage control circuit (12 V).Thirdly an automatic regulation system.

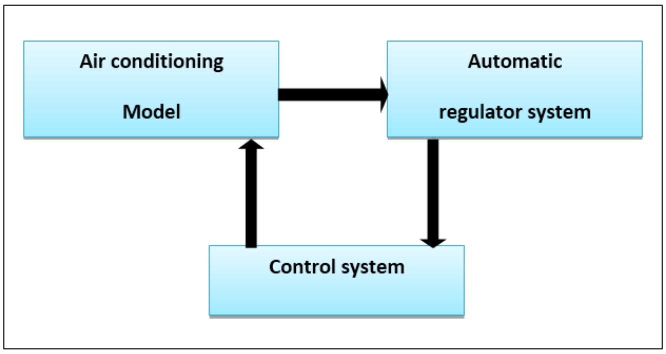

Figure 3. Air conditioning regulator system.

In the first part of the system, the model of an air conditioned room is modeled [20]. It's implemented as blocks in the MATLAB/Simulink environment. The obtained Simulink model is used to provide thermal comfort room and power consumption of the air conditioner; therefore it is necessary to set another command system for controlling the operation of the air conditioner. The command system consists of the set of two thermocouples to maintain the atmosphere of the room around the two temperatures T-set 1 and T-set 2, a 12 V relay to ensure the opening and closing of two thermocouples and a battery with 12 V voltage source to power all of the control part.

The third part of an automatic control system is used to act on the operation of the difference between the total power and the permissible power to ensure comfort while limiting the consumption peak at a preset level.

Implantation of air conditioning regulator system

An air conditioning system schematic's is shown in Figure 5. The air conditioning system is combined of three parts implemented in MATLAB/Simulink environment: air conditioning model, control system and regulation system.

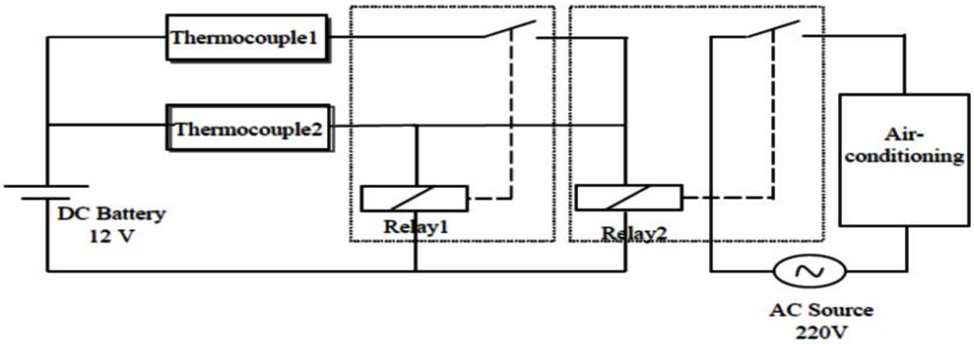

Figure 4. Electrical analogue model for air-conditioned regulator system.

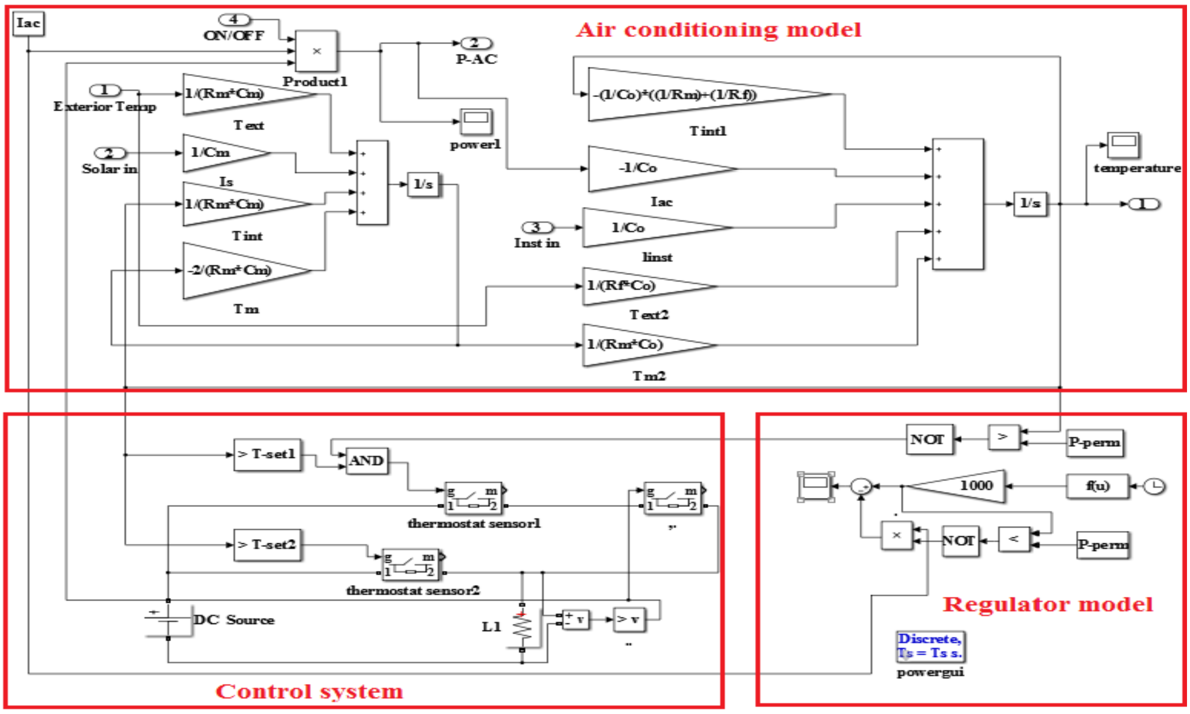

Figure 5. Model of the air conditioning regulator system in MATLAB/ Simulink

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Simulation results

The simulation is done by setting temperature of the room equal to 20 ° C ,the exterior temperature is mentioned in the Figure 5, Simulation is run for 24 hours (from 0 h to 24 h=86400 s).

The permissible power is fixed: 6 kW

From Fig.6 we can see that the electric power consumed in the interval of 14-18 hours is much higher relatively to the other time of day due to the use of air conditioning.

In the normal operation

Figure 7 shows the total power of the house during 24 h. In Figure 8 the temperature of the room using air conditioner, while Figure 9 shows the operation power of the air conditioning. Likewise, we can also observe that in the normal operation, the total consumption of the house reaches 94.11 kWh per day.

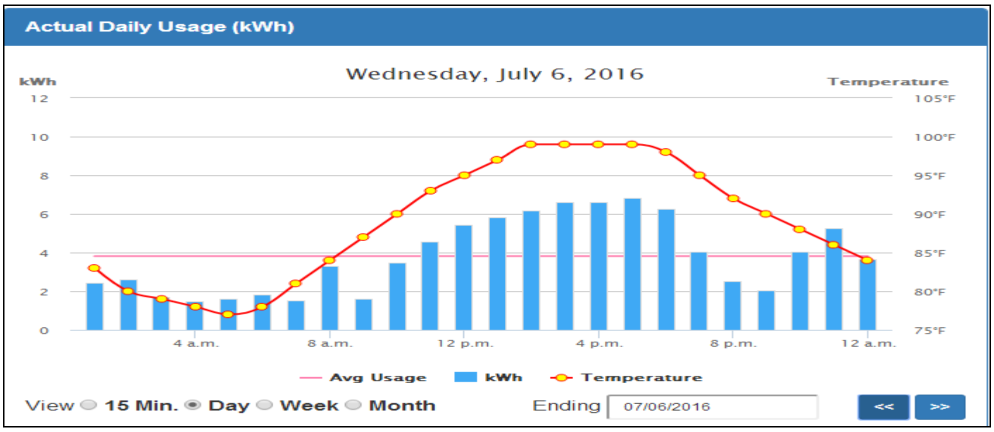

Figure 6. Exterior temperature and the power demand curve for July 6, 2016.

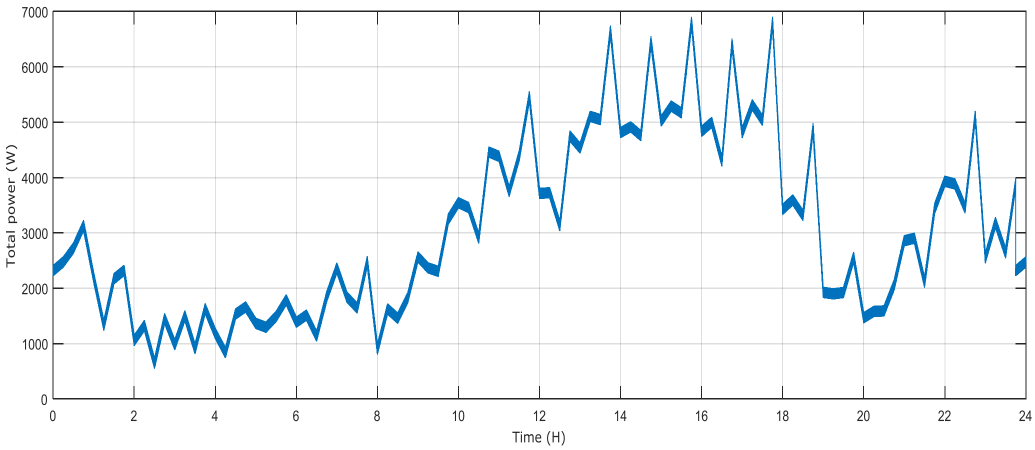

Figure 7. Total power of the house

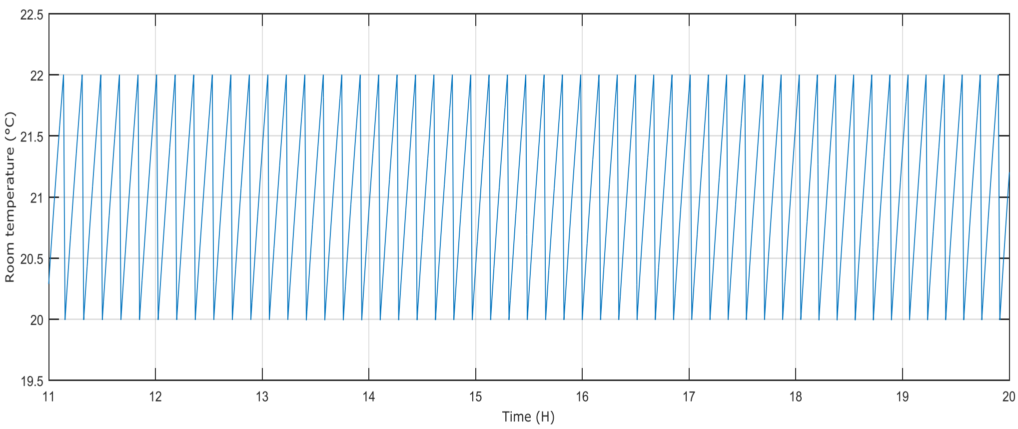

Figure 8. Interior temperature of the room.

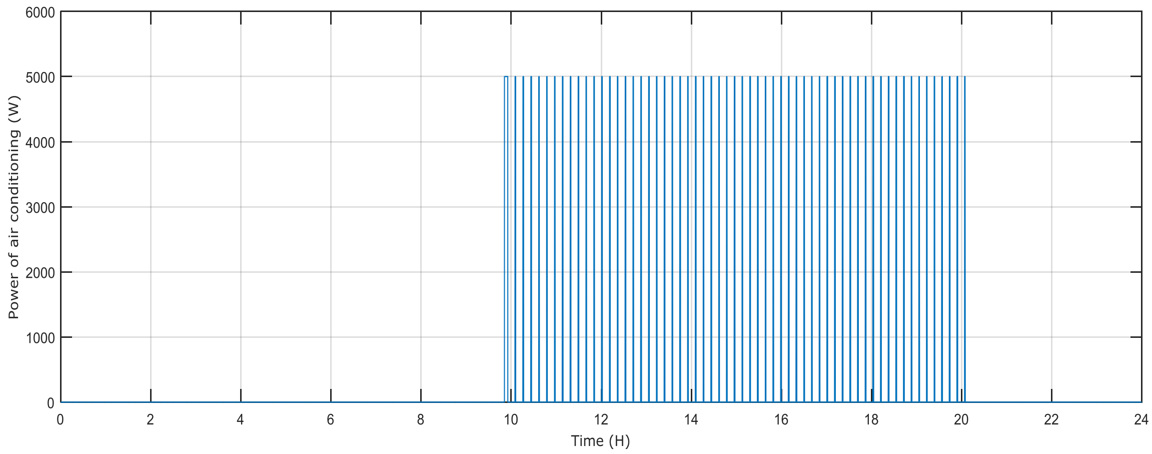

Figure 9. Power of the air conditioning motor.

Figure 7 shows the power consumption the 06th day of July 2016. There are 5 peaks greater than the permissible power that are: 6.65 kW, 6.46 kW, 6.81 kW, 6.41 kW, and 6.81 kW.

For the interior temperature of the room; Figure 8 when the air conditioner is on (from 11am to 9pm) the temperature is always between 20 ° C and 22 ° C so the thermal comfort is maintained.

Figure 9 illustrate that the air conditioning cycle works during the high temperature (11am to 9pm) and it is usually off in the early morning and night hours when the temperature is low.

With use of air conditioning regulator system

Figure 10 shows the total power of the house during 24 h, where as temperature of the room using air conditioner is shown in Figure 11 and Figure 13: the operational power of the air conditioning is represented when the regulator system is functioning.

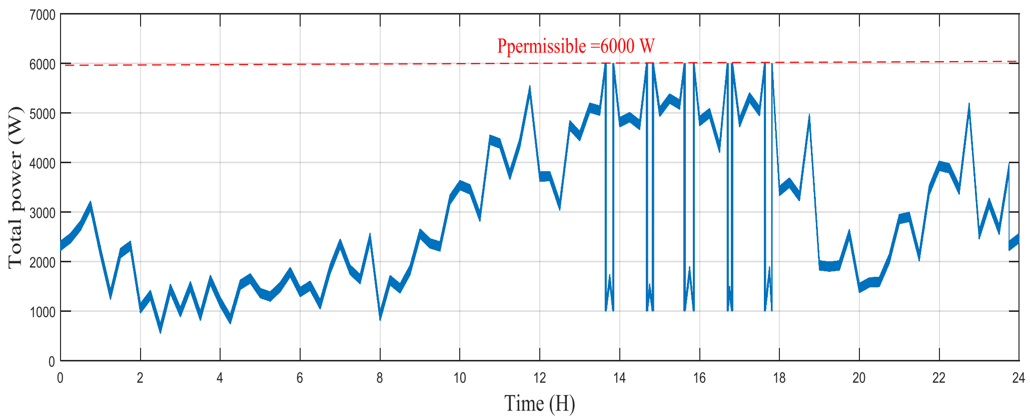

Figure 10. Total power of the house.

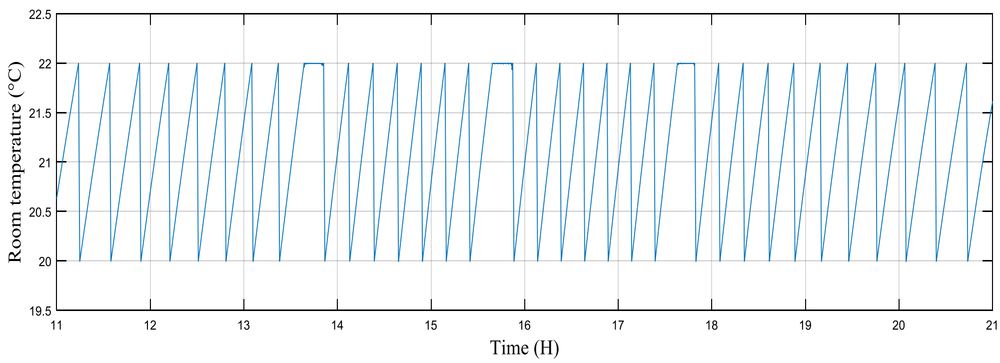

Figure 11. Interior temperature of the room.

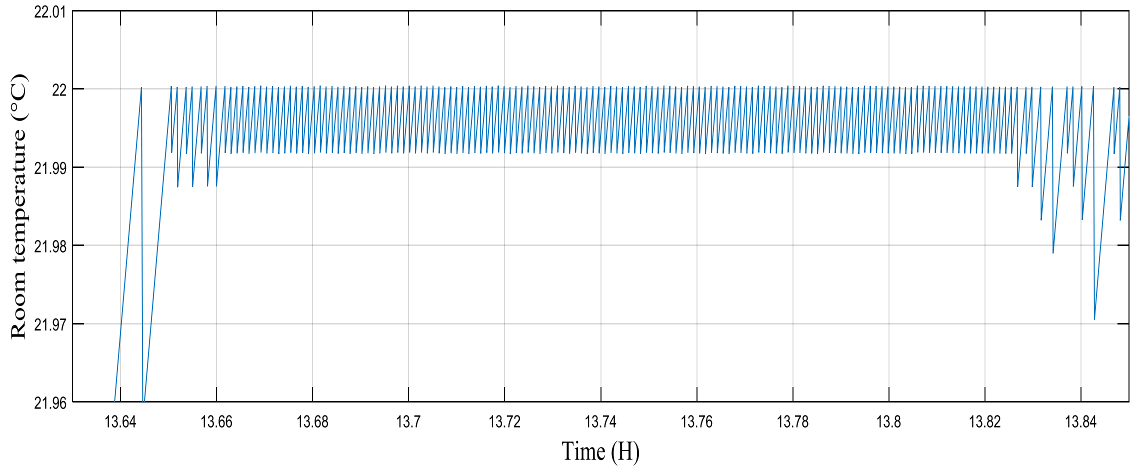

Figure 12. Interior temperature of the room (zoom).

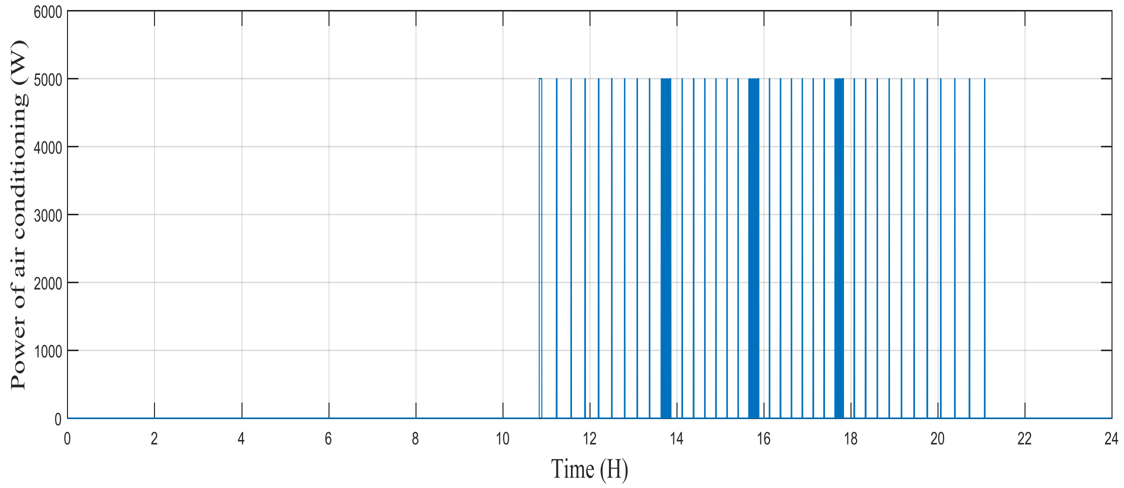

Figure 13. Power of the air conditioning motor.

It can be seen that:

- The peak loads are totally eliminated (Figure 10).
- The temperature (Figure 11) is always less than 22 ° C. therefore the thermal comfort is maintained.

We can say that during the use of our air conditioning:

- The regulator system allows to reducing the total consumption from 94.11kWh to 83.048 kWh (around 9% of the total consumption) and this when we apply air conditioning system for a single room only.
- The peak load is reduced because the power is always inferior to the fixed permissible power 6 kW.
- The thermal comfort is maintained because the temperature varied but always lower than the maximum T=22 ° C.

CONCLUSION

Through this research, two methods have been used, the first one represents an optimization method applied for a house, the decrease of daily consumption is evaluated; the second method represents the development of an air conditioning system. Such system consists of three parts: the first part is the model of the air-conditioned room, the second one is control system based on thermocouples; the third and last part is a regulation system constrained by the value of permissible power. The key idea of the proposed system is based on efficient reduction of the total electrical consumption without sacrificing the thermal comfort of occupants.

The optimal method aims to minimize the functioning time of the air conditioner. According to the results, it is possible to save around 25 % from the total consumption in one day.

The simulation results show that the air conditioning system can significantly save energy and maintain thermal comfort as well. Thus, this method can be adapted for all the houses or buildings.

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