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MODELING AND SIMULATION OF BUILDING ENERGY CONSUMPTION

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ABSTRACT

Building energy consumption represents much of the total energy consumed in advanced countries. For this reason, the aim of this paper is to study the energy consumption profile by day for each domestic appliance: controllable appliances (heating, ventilation and air conditioning, electric water heater, dishwasher, washing machine) and non-controllable appliances (oven, TV, PC, iron, refrigerator and freezer) where the modeling and the simulation based on MATLAB/Simulink software are presented.

***Keywords**: Building, energy consumption, controllable appliances, non-controllable appliances*

1. INTRODUCTION

The domains of Smart Grid are working together to achieve the satisfaction of the customer. They are arranged to provide the amount of electricity required every second with a very high quality.

In fact, a large number of consumers and the large number of electric appliances installed at home. This paper has the same goal of several works presented in the literature

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which is the decrease of power demand. To achieve the objective, this paper proposes the modeling and simulation of domestic appliances based on Matlab/Simulink software.

Domestic appliances classify in two categories based on their energy consumption characteristics: controllable and non-controllable (Fanti et al., 2018; Ahmed et al., 2016; Mirakhorli & Dong, 2018).

The controllable appliances can be totally or partially switched off by a controller: Heating, Ventilation and Air Conditioning (HVAC) system, Electric Water Heater (EWH), dishwasher, washing machine.

The non-controllable appliances are passive loads that cannot be switched off or partialized. Examples of non-controllable loads are: oven, TV, PC, iron, refrigerator and freezer.

2. MODELING AND SIMULATION OF CONTROLLABLE APPLIANCES

To analyze the households load profile, we need information about the appliances. In this section, we are modeling the domestic appliances in Matlab/Simulink software.

2.1. Electric Water Heater model (EWH)

The EWH is mainly composed of a set of electric coils that heat up the water staled in a tank. The water temperature set-point can be manually set up, and a thermostat controls (on/off) the power source to keep the desired temperature (Fanti et al., 2018; Mirakhorli & Dong, 2018).

The parameters of the EWH are divided into three categories:

- Electric water heater characteristics,
- The use of hot water
- Temperatures set points.

The heat dynamics can be modelled by the following differential equation:

$$C\frac{dT_{hw}(t)}{dt}=G(T_{air}-T_{hw}(t))+HW_d(t)(T_{cw}-T_{hw}(t))+P_t(t)) \quad (1)$$

T_{hw} is the hot water temperature in the tank; Tcw is the inlet cold water temperature; T_{air} is the air temperature outside tank; Wd(t) is the average hot water draw per time and the rest of the parameters.

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A domestic EWH has a thermostat that based on the measured water temperature switches on/off to heat the water. The difference between the set point upper and lower limits of the tank temperature is called the dead band ΔT. If the water tank temperature drops below the set point lower limit minus the dead band, the EWH coils are turned ON (1). However, if the water tank temperature rises to its set point upper limit plus the dead band temperature, the heating coils of EWH are turned OFF (0).

The operation of the EWH depends on the status of the device, which is expressed mathematically as follows:

$$P(t) = \begin{cases} P_0 & T_{hw}(t) < T_{hw,set} - \Delta T \\ 0 & T_{hw}(t) > T_{hw,set} + \Delta T \\ P(t - \Delta t) & T_{hw,set} - \Delta T \leq T_{hw}(t) \\ & \leq T_{hw,set} + \Delta T \end{cases}$$

If the EWH is Off, then P(t) = 0, so the water temperature drops whether there is water usage or not. And if the EWH is ON, P(t) = P0, and if the water usage, Wd, is zero or sufficiently low then the water temperature increases. If water usage is too high, then the temperature drops.

A domestic EWH has a thermostat which is controlled by the difference between temperatures Thw-set and Thw, switching on/off the heater. The difference between the set point upper and lower limits of the tank temperature is called the dead band. If the water tank temperature drops below the set point lower limit minus the dead band temperature range, the EWH coils is turned on. However, if the water tank temperature is raised to its set point upper limit plus the dead band temperature, the eating coils of EWH is turned off (Ahmed et al., 2016; Glaa et al., 2017).

The water heater usage Wd(t) is presented in figure 1 has three peaks: early morning, evening and late evening.

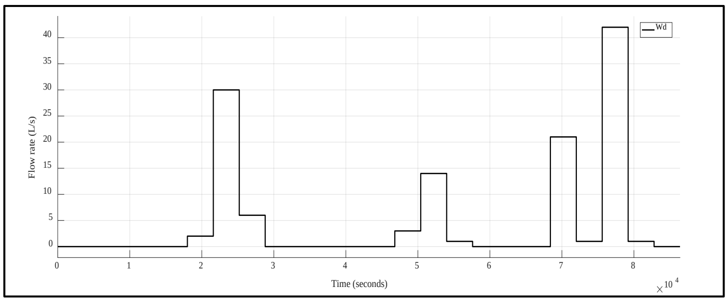

Figure 1: Simulation of flow rate (24h).

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Besides these consumption peaks, water heaters regulate the temperature around the set-point most of the time. Hence, it is important and necessary to consider such behavior in control design to maximize the consumption shifting capability while providing enough hot water (Mirakhorli & Dong, 2018 ; Shad et al., 2012).

A simulated evolution of the water temperature is presented in figure 3: first the water temperature in the tank is similar to the outside temperature, so the thermostat switches on the EWH to heat the water. When the temperature reaches 52 ºC, the thermostat switches off the EWH.

The maximum and minimum temperature of water heater varies between 52ºC and the cold water temperature 15ºC, depending on Wd. For each rise in water use, the temperature decreases and the EWH remain in operation until reaching the desired temperature. Figure 2 shows that when the hot water is used at 7 am and between 19 pm and 22 pm, the water temperature reaches its minimum allowable set point, the EWH will turn on to maintain the water temperature at its comfortable range.

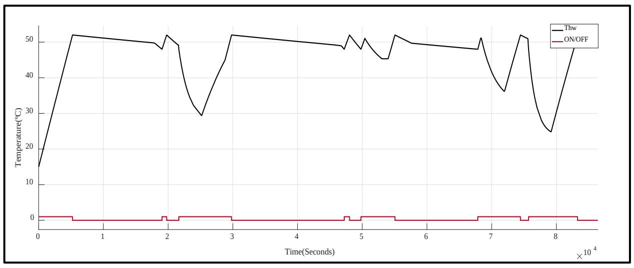

Figure 2: Hot water temperature and operation of the EWH (24h).

The energy consumed by EWH without control presented in figure 3, is proportional to the operation of its thermostat. When the thermostat switches ON the system, the power is at the maximum 1500 W, and when it is off the power is at the minimum 0W (Shad et al., 2017; Glaa et al., 2016).

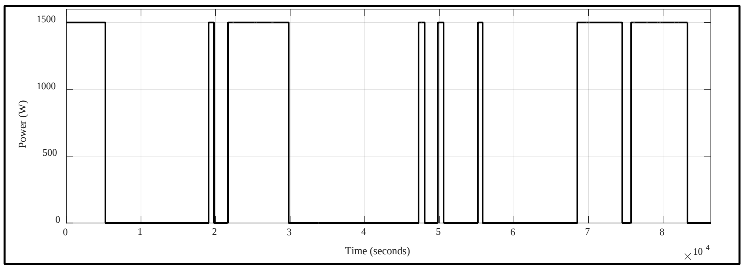

Figure 3: Energy demand without control (24h)

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2.2. Washing machine model

In this work, we use the three essential washing programs which are cotton, cotton eco and synthetics. The simulation of the synthetics program in MATLAB is presented in figure 4 (Demetgul et al., 2014; Hatagar & Halase, 2015; Ahmed et al., 2016).

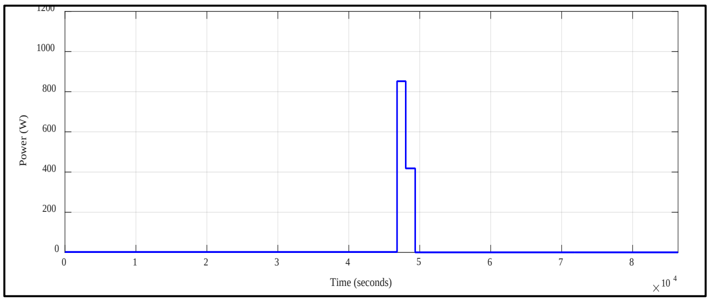

Figure 4: Washing machine model.

According to the proposed model, there is a simple action that can reduce the power of washing machine. We should decrease the degree of the desired temperature for the first fuzzy, decrease the mass of clothes, the rotation speeds and choose the most economic program for the seconds fuzzy (Thinzar & Soe, 2016).

2.3. Heating, ventilation and air conditioning system (HVAC) model

Modeling of heating, ventilation and air conditioning (HVAC) systems is necessary for studying and regulation of energy consumption and quality of indoor environment (Zuñiga et al., 2014; Dejvises & Tanthanuch, 2016; Issi et al., 2018).

An HVAC system in a typical commercial building is usually comprised of three subsystems:

- An air handling unit (AHU);
- An air cooling unit (Chiller);
- An air heating unit (Boiler).

For the simulation of HVAC system, the model includes a relationship between thermal characteristic of a room, thermal characteristic of a heater and a thermostat to control the heater. This model can be mathematically modeled by these following equations:

$$\frac{dT_{in}}{dt} = \frac{1}{C*M_{air}}(Q_t(t) - Q_{Loss}(t)) \qquad (5)$$

$$Q_t(t) = (T_{in} - T_{aircon}) * M_{dot} * C \qquad (6)$$

$$Q_{Loss} = \frac{T_{in} - T_{out}}{R_{eq}} \qquad (7)$$

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Where: Tin is the temperature of the room; Qgain is the thermal energy transferred from the heater; Qloss is the thermal energy transferred from the room to the outdoor environment.

The HVAC system is modeled both in heating and cooling mode. This device tries to keep the room temperature between 23°C and 21°C for the cooling model and between 25°C and 23°C for the heating model, but these values can be changed in the physical model according to the customer's desire and to the exteriors effects.

To satisfy the selected criterion, the constant value must be 1 and the switcher passes through the cooling mode. If not, the constant value is 0 and the switcher passes through the heating mode.

The electric power of the HVAC system is calculated according to the following equation:

$$\mathrm{Pe(t)} = \frac{\mathrm{Pt(t)}}{\gamma} \qquad (8)$$

Where γ = COP "Coefficient of performance" for the heating is obtained by equation 9, and γ = EER "Energy efficiency ratio" for the cooling is obtained by equation 10.

$$\mathrm{COP} = \frac{\mathrm{Th}}{\mathrm{Th-Tc}} \qquad (9)$$

$$\mathrm{EER} = \frac{\mathrm{Tc}}{\mathrm{Th-Tc}} \qquad (10)$$

In the heating mode, the temperature increase from 15°C to desired one presented in figure 5. If the temperature reaches its maximum set point temperature 25°C, the HVAC system is turned OFF and the energy consumed reaches its minimum 0°C.

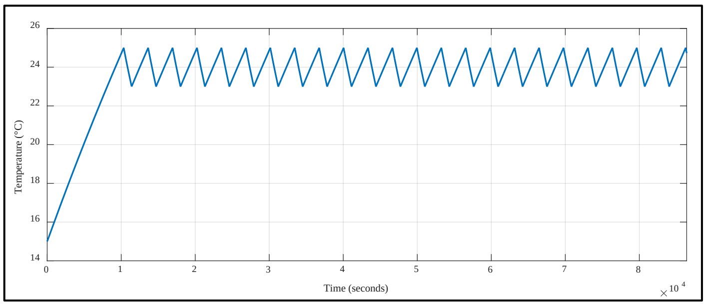

Figure 5: Temperature of heating mode.

In the cooling mode, the temperature decreases from 30°C to desired level 22°C, then stay in the comfortable range ±Δ (figure 6). If the temperature reaches its maximum set point

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temperature 23°C, the HVAC system is turned ON and the energy consumed reaches its maximum which is specified in figure 7.

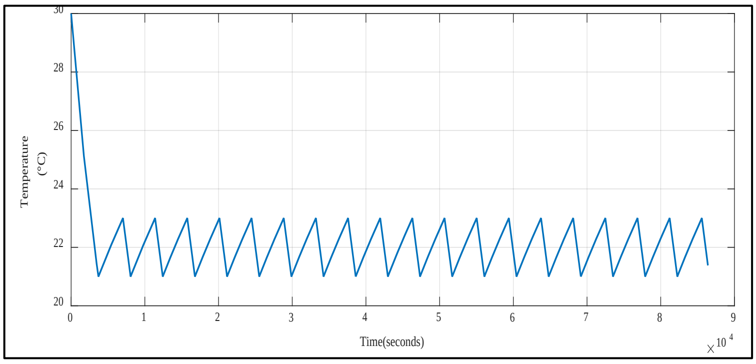

Figure 6: Temperature of cooling mode.

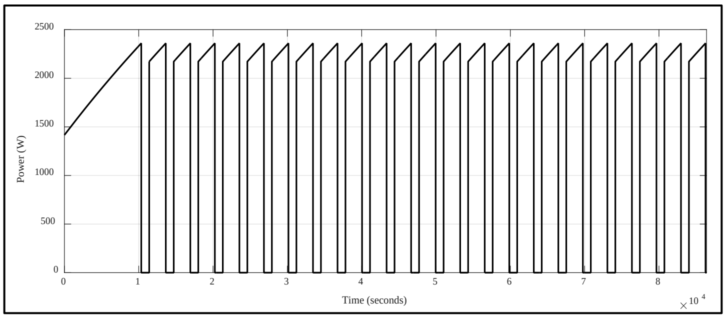

Figure 7: Power of HVAC system without control (24h).

Generally the HVAC cooling mode is used in the summer when the temperature is very hot. In this work the model is simulated from 13h to 15h (figure 9) and the figure 9 is the energy used in this tree hours (Zhang et al., 2016 ; Pouresmaeil et al., 2013; Saleh et al., 2016; El Khaldi et al., 2021).

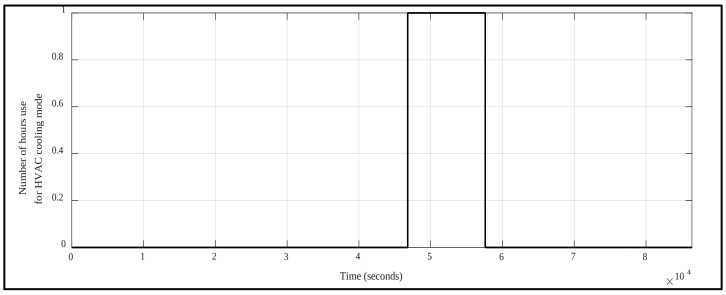

Figure 8: HVAC cooling mode use in 24h.

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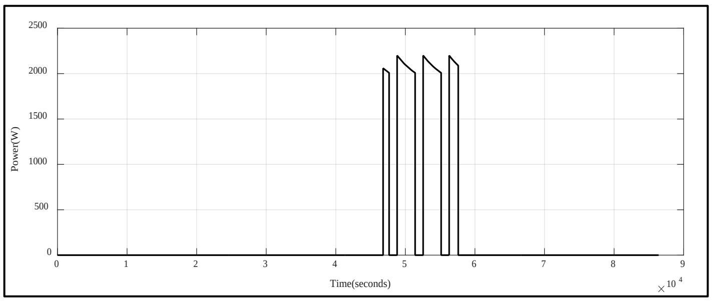

Figure 9: Energy consumed in 24h.

The HVAC heating mode is used in the winter when the temperature is very cold. In this work the model is simulated from 19h to 23h (figure 10) and the figure 11 is the energy used in this four hours at the night.

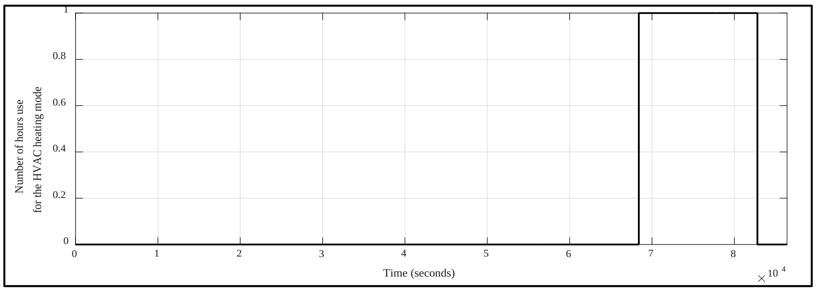

Figure 10: HVAC heating mode use in 24h.

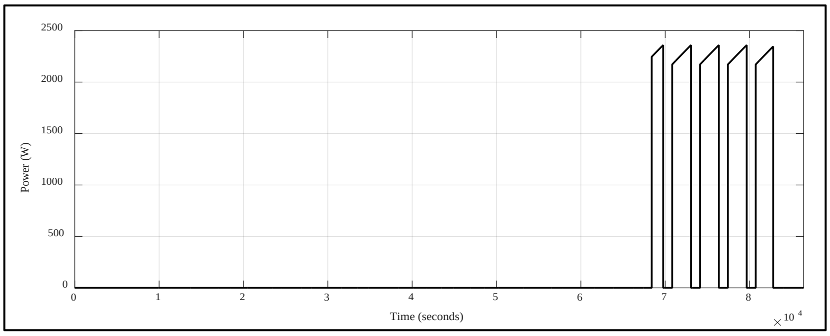

Figure 11: Energy consumed in 24h.

3. MODELING AND SIMULATION OF NON-CONTROLLABLE APPLIANCES

3.1. Refrigerator model

The household refrigerator is normally a thermally insulated cabinet with two compartments. The main objective of the existing control for refrigeration systems is to maintain the foodstuff temperatures within the desired limits imposed by the legislative requirements. The compartment for the production of ice requires a temperature between 0ºC and 5ºC and the compartment for fresh food requires a lower temperature than 0ºC.

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The electric refrigerator model presented in figure 12 is modeled mathematically by equation 1 and 2 with the hypotheses of: homogenous materials, linear cooling cycle with constant COP and neglect of the freezer compartment (Costanzo et al., 2013: Glaa et al., 2016; Sossan, 2016).

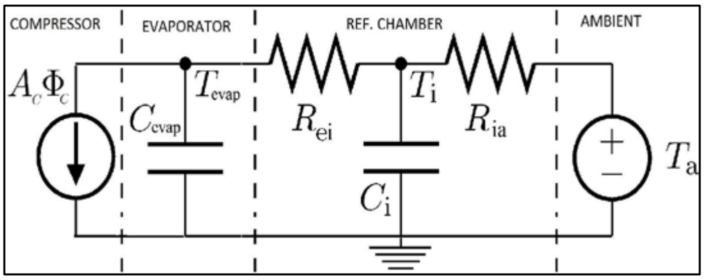

Figure 12: Refrigerator electrical model.

$$\frac{dTi}{dt} = \frac{1}{CiRia}(Ta - Ti) + \frac{1}{CiRei}(Te - Ti) + \sigma1dw1 \qquad (11)$$

$$\frac{dTe}{dt} = \frac{1}{CevapRei}(Ti - Te) - \frac{1}{Cevap}Ac\phi c + \sigma2dw2 \qquad (12)$$

With: Ac= COP, the overall coefficient of performance.

The refrigeration chamber temperature presented in figure 13 can increase due to several factors, mainly at meal times such as opening and closing the door several times, the outside temperature of the kitchen...

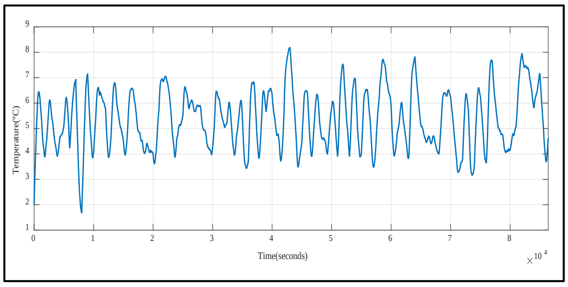

Figure 13: Variation of refrigeration room temperature (24h).

Since the desired temperature is 5ºC, we note that the power (figure 14) has the maximum value 400W for a temperature lower than 5ºC and the minimum value 0W for a temperature higher than the desired temperature.

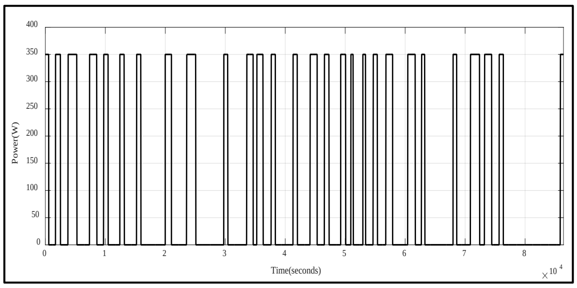

Figure 14: Variation of power (24h).

3.2. Cooker model

The cooker model is:

$$MC\frac{dT}{dt} = hS\big(Text(t) - T(t)\big) + P \qquad (13)$$

Where T is the temperature of electric plate, Text is the temperature around the cooker, M is the electric plate mass, C is the electric plate specific heat, S is the heat exchange surface, H is the heat transfer coefficient, and P is the heat power produced by the electric plate (Harmin et al., 2012; Le, 2018; Wertani et al., 2021).

The operation of the cooker starts with the maximum power for 15min to reach the set temperature 220 (°C), after that, the operation becomes alternative and regulated by a thermostat until the end of the operation of the device. The temperature variation and the power are represented in the figure 15 and 16.

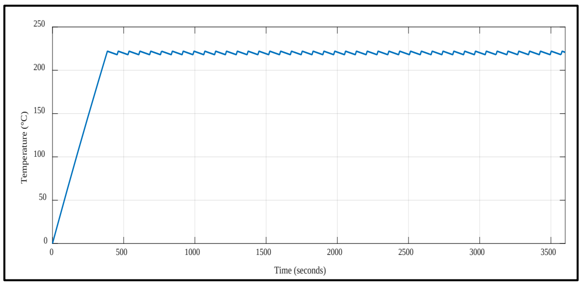

Figure 15: Variation of cooker temperature (24h).

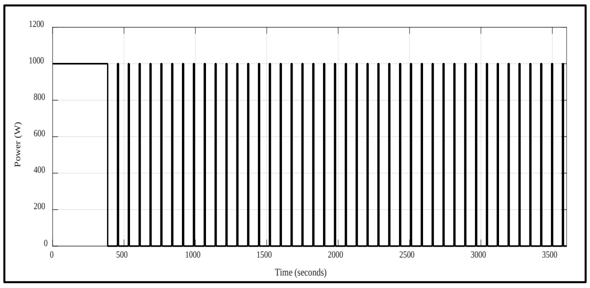

Figure 16: Variation of cooker power (24h).

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Figure 17 shows three times of use the cooker that is connected with the lunch time, a half hour in the morning at 7h:30, another half hour of the midday at 12h and an hour in the afternoon at 19h.

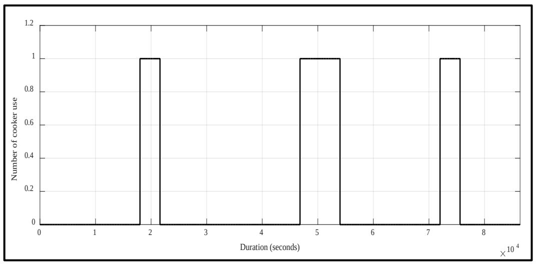

Figure 17. Cooker use in 24h.

Figure 18 shows the energy consumed used for 24h.

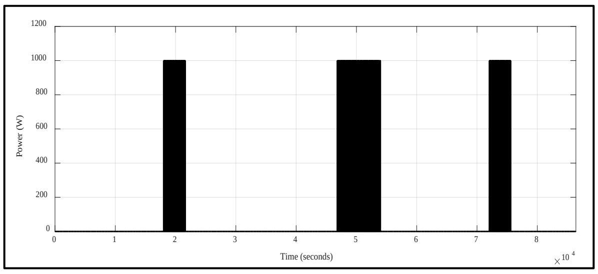

Figure 18: Energy consumed in 24h.

3.3. Low power device

The lighting, the computer and the TV energy consumption are modeled as a constant amount of electricity used during a given time period (Ciabattoni et al., 2014; Bissey et al., 2017; Glaa et al., 2017).

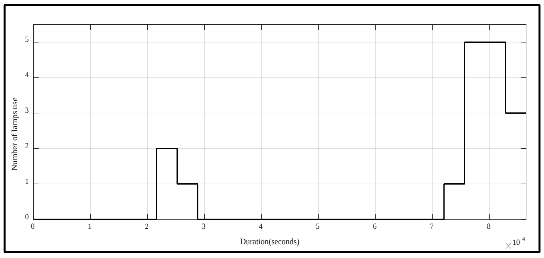

Figure 19: Lighting use for 24h

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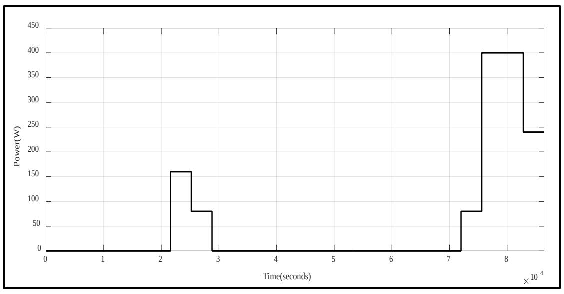

Figure 20: Energy consumed for 24h for Lighting.

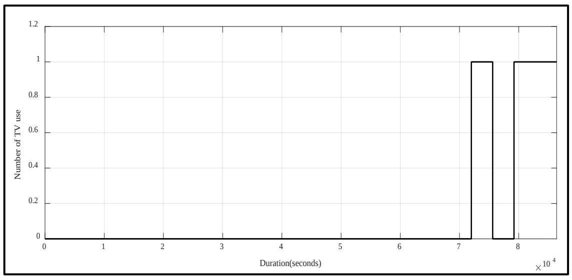

Figure 21: TV use for 24h

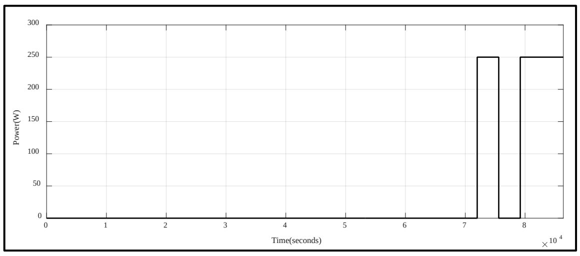

Figure 22: Energy consumed for 24h for TV.

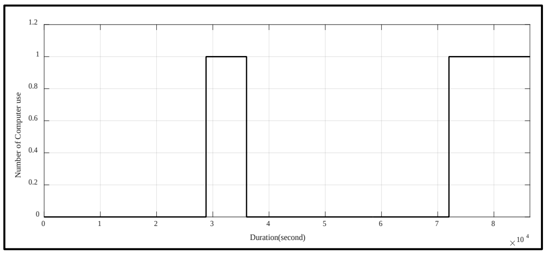

Figure 23: PC use for 24h

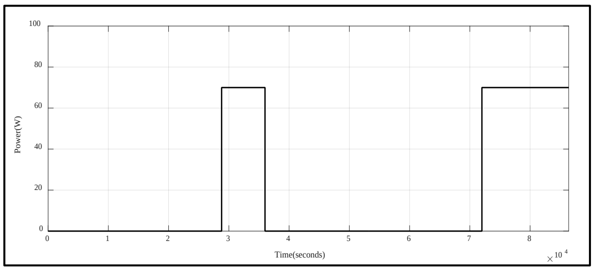

Figure 24: Energy consumed for 24h for PC.

4. CONCLUSIONS

Smart Grids are the expression of the digital revolution in our energy grids and it is certain that they have started and will continue to change the entire value chain. They are not intended to replace the existing electrical network, but to improve it. The Smart Grid must reconcile internal emergence and self-organization by external factors in order to find the most optimal balance of energy distribution in real time.

The major areas of energy consumption in buildings are heating, ventilation, and air conditioning. We proposed in this paper a modeling and simulation of the domestic appliances: controllable appliances and non-controllable appliances because of the large number of consumers and the large number of electric appliances installed at home.

Starting from this study of modeling and simulation of building energy consumption presented in this paper, we will study the development of the fuzzy logic control strategy of domestic appliance. The obtained simulation results will demonstrate the effectiveness of the adopted control technique to decrease the power consumption and the cost of electricity.

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