ABSTRACT

LINING DONG, Graphic User Interface Design and Rule-based Home Energy Management Algorithm Development for Home Energy Management Systems. (Under the direction of Dr. Ning Lu)

This research focuses on the development of graphic user interface as well as a rule-based peak-shaving algorithm for the FREEDM smart home energy management (HEM) system. The HEM system consists of a Matlab-based home appliance modules database, an algorithm engine, and a graphical parameter input and output display interface. The designing and implementation of a graphical user interface which considers both technical constraints and customer usability is critical because the parameters inputting process are not intuitive for homeowners and the visualization of home energy use helps to inform the homeowners' energy decisions. It is critical that a user friendly graphical interface is designed and implemented considering both the technical necessity and the customer usability. The contributions of the thesis are three-fold. First, a graphical user interface is designed and implemented to support the algorithm development. Second, a rule-based HEM algorithm is developed for dynamically managing the home energy consumption. Third, a HEM architecture is developed to host the development of future HEM algorithms rather than the one developed in this thesis. The HEM graphical interface and the rule-based HEM algorithm are currently in use to support the FREEDM smart house software and hardware test-bed.

Graphic User Interface Design and Rule-based Home Energy Management Algorithm Development for Home Energy Management Systems

by
Lining Dong

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Electrical Engineering

Raleigh, North Carolina

2015

APPROVED BY:

Dr. Aranya Chakrabortty

Dr. David Lubkeman

Dr. Ning Lu
Chair of Advisory Committee

DEDICATION

To my parents and my future family.

To teachers who nourished me with knowledge.

To all the friends who have given me support and courage.

BIOGRAPHY

Lining Dong was born in Hohhot, Inner Mongolia, China. He received his Bachelor of Engineering degree in Electrical Engineering and Automation from South China University of Technology in May 2013. He started to pursue a Master of Science degree in Electrical Engineering at North Carolina State University in August 2013. His research interests include design and developing home energy management algorithms and modeling residential load behaviors.

ACKNOWLEDGEMENTS

This research was supervised by Dr. Ning Lu at North Carolina State University. I am very grateful for her guidance in defining the research topics, developing the methodologies, and analyzing the results. I am also immensely grateful to Jiahong Yan for his selfless help to work with me implementing and testing control algorithms and developing the interface of the graphical user interface for the FREEDM smart house test system. I want to show my gratitude to Dr. David L. Lunkeman at North Carolina State University for sharing his pearls of wisdom with me during the course of this research. I also want to thank my fellow graduate students: Gonzague Henri, David Mulcahy, Xiangqi Zhu, and Jian Lu for reviewing the thesis and providing me with many valuable comments that greatly improved the manuscript.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 INTRODUCTION

1.1 Background

In recent years, environmental awareness and the limitation in fossil fuel storage greatly encouraged the development of renewable generation resources. In 2020, the renewable penetration in many states in the United States are expect to reach 20% or higher. Rooftop photovoltaics (PVs) are expected to be affordable to many residential home owners, as well as the advanced home-automation devices. In addition, the wide deployment of smart meters has enabled the utilities to implement variable electricity prices at retail level. Thus, the consumers are going to be charged at different rates depending when and how much they use electricity at different time of the day. Therefore, it is important for home owners to have a home energy management system that can track and automatically schedule the energy use and inform the consumer what the options are for different consumption patterns.

At the FREEDM center in North Carolina State University, a smart house test system is developed. The hardware implementation of the smart house includes a number of controllable and non-controllable home appliances supplied by an ac/dc mixed power source. The smart home can be connected to rooftop PVs and energy storage devices (ESD). A HEM system [1] is used to control the operation of the controllable load resources and the distributed energy resources such as the PV and ESD. A software test system is implemented in Matlab. HEM algorithms will first be developed and tested on the software test bed and then implemented in the hardware test bed.

Because the algorithms and the parameter settings are all coded in Matlab, it is hard for the HEM users to understand and change the appliance and control algorithm settings. The output of the HEM has to be processed by Matlab and there is no standardized way to compare results obtained by different algorithms or under different operation conditions. Therefore, the design and implementation of a graphical user interface becomes critical for the further development of the FREEDM smart home test system.

My thesis topic is selected to resolve this critical technical challenge faced by the HEM development team. There are three key components of my thesis work: 1) the development of the software architecture for the smart house HEM, 2) the design and implementation of a graphical user interface (GUI) [2], and 3) the development and implementation of a control algorithm for managing home energy consumption peaks [3].

1.2 Requirements for the HEM GUI Design

This section introduces the design requirements for the HEM GUI.
In recent years, HEM has drawn great attentions from researchers all over the world because of the potential of controlling loads for energy savings and improved efficiency. However, little has been done in the area of graphical interface design. In [37-39], the authors described a few methodologies of graphic user interface design and its functionality but the focus of the GUI is not on home-level energy management and the developed GUI cannot be used as a common platform for algorithm design and testing. Therefore, in my thesis, I focused my effort on design and implement a Matlab-based GUI that can be used by algorithm developers for testing their algorithms and comparing results between algorithms. The general settings of the HEM include the following. The house is a single-family home that powered by a solar PV with an energy storage device and an electric vehicle. Each operation period is 24 hours, starting from the midnight today to the midnight the next day. The time step is 1-minute. There are three rate structures considered: flat rate, time-of-use, and critical-peak-price.

The requirements for the HEM GUI design are:

- Provide a parameter setting interface for HEM controllable appliance modules. The HEM controllable appliance database is categorized into two categories based on the appliance characteristic: thermostatic controllable appliance (TCA) and thermostatic non-controllable appliance (non-TCA). The TCA loads include an air conditioning unit, a space heating unit, a water heater and a refrigerator. The non-TCA loads include cloth washer, dryer, and dishwasher.
- Provide a parameter setting interface for distributed energy resource (DERs) [4] modules. The DEM DER modules include a rooftop PV, a battery, and an electricity vehicle.
- Provide an input module that receives the utility prices, weather information (e.g. outdoor temperatures and humidity), and utility control signals (peak-shaving, etc.)
- Provide output displays that highlight the actual and forecasted house energy consumption, utility rates and payments, the status reports for controllable and observable appliances and distributed generation resources, the healthiness report of the devices.
- Select algorithms and make comparisons for different what if scenarios. For example: when running an EMS algorithm, the user can compare the cost savings with the base case (the no-control case) through a side-by-side chart provided by the GUI.

1.3 Requirements for the HEM Software Architecture

The goal for software architecture design for the FREEDM HEM system is to offer a common simulation platform for HEM algorithm developers to implement and test their control algorithms more conveniently. The architecture for the HEM is shown in Figure 1.1. The information received from the utility (e.g. electricity prices, demand response commands), the weather service provider (e.g. temperature, humidity, wind speed, solar radiation), and the consumer’s input settings (e.g. the appliance settings) will be stored in the HEM database [5]. A house module contains the appliance models and the simulation engine. The parameters of the appliance models can be changed through the GUI and sent back to the HEM database. Algorithms are the engines of the HEM system and algorithm selections are made through the GUI.

Once an algorithm is selected, the user can hit the run button to call the appliance model parameters from the data base, run the algorithm, and generate simulation results, which are saved and sent back to the data base. Next, the GUI will display the results by reading data from the data base. This process allows the algorithm developers to develop and implement their algorithm independently to the HEM system and compare the results generated by their algorithms through monitoring the results displayed by the GUI.

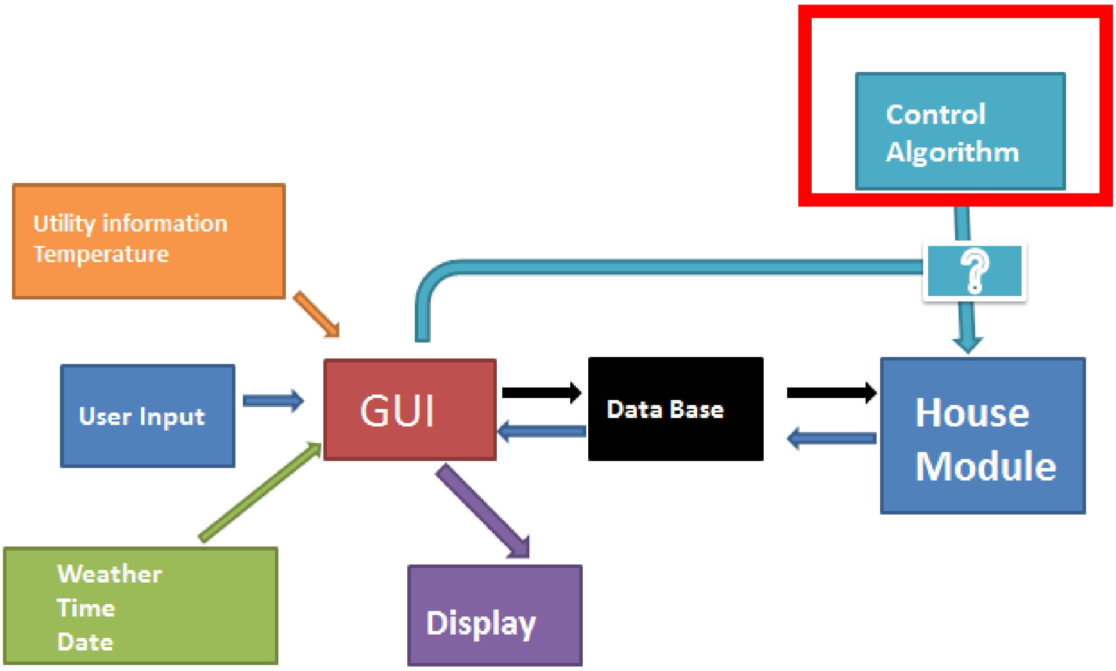


Figure 1.1. The software architecture of the FREEDM HEM GUI

1.4 Requirements for the Rule-Based Control Algorithm

The HEM system could simulate power consumption status of a residential house, however, in daily life the house owner will not pay much attention about how to reduce unnecessary energy use or avoid high electricity use during high electricity market price period. From the simulation results generated by HEM system, the load profile of simulated houses have some spike during the day, which represents that several appliances are operating at that time. These high density energy use will not only cost house owner more money but also make the transformer suffer more stress. Thus an algorithm is developed to reduce the spike for high density electricity use.

The requirements for the rule-based control algorithm [6] are:

- Reduce the spike occurring during the day to a specific power limit.
- Reduce the influence of comfort level for residents in the house.
- Test the robustness of algorithm by implementing it in house load with different characteristics.
- Generate and evaluate the simulation results and find the most optimal scenarios.

1.5 Data Preparation

The HEM system needs specific data inputs to initialize the simulation. The main data Inputs include:

- Utility information including a flat-rate electricity price, hourly time-of-use prices (predefined), real-time critical-peak prices (updated every 5 minutes), and peak power control signals.
- Weather information including hourly temperature profiles, humidity, and solar radiation.
- Predefined appliance power ratings in the current HEM system design
- The appliance operation status such as the minimum run time, minimum down time, probability of use [7], etc. are predefined so that the comparison of algorithms can be carried out on a fair basis.

CHAPTER 2 HEM GUI DESIGN AND IMPLEMENTATION

This chapter presents design considerations and basic functionalities of the HEM GUI. The HEM system processes input information ranging from consumer-determined appliance parameters to utilities pricing and control commands as well as setup parameters of HEM control algorithms. The HEM serves as not only as an energy use dashboard that provides customers cost and billing information but also a situation awareness tool that alerts customers possible malfunctions of home appliances and home-owned distributed energy resources. Different from interfaces used by algorithm developers who understand how the system operates, a customer HEM GUI needs to be visually pleasant, easy to use, and compact so that even users with little knowledge about the HEMS can quick understand how to set up the HEM and interpret HEM results through a limited number of display windows. Because the users of the HEM GUI for the FREEDM smart house are a mixed group of HEM algorithm developers and students who serve as customers for testing the HEM algorithm settings, the HEM GUI needs to accommodate both kinds of users. Therefore, I designed a HEM GUI system that includes three kinds of window: the main window, the input selection windows, and the output display windows.

As shown in Figure 2.1, the main window allows the users to monitor the operation status of the home and navigate through different setting buttons to select and input the appliance parameter settings, HEM algorithms, and compare results [8]. In the following sections, I am going to introduce the functionalities and design considerations of the three types of windows.

Out Door Temperature : 85 °F
In Door Temperature : 72 °F

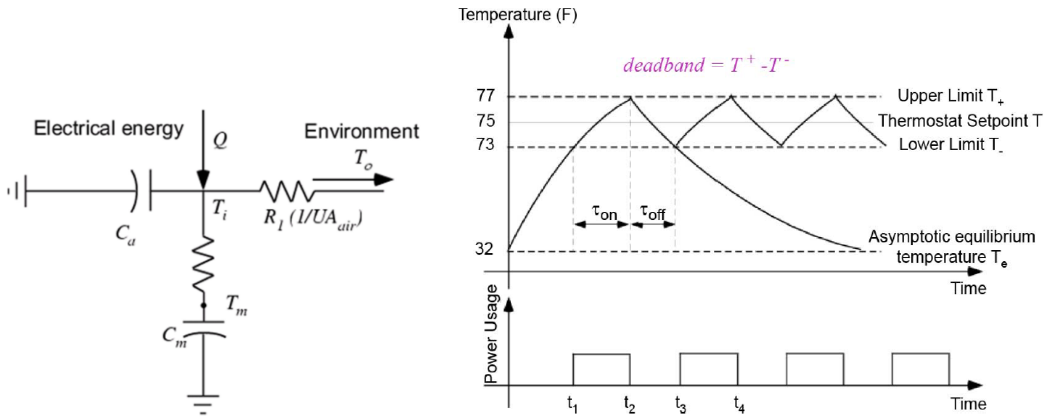
Figure 2.1. The main window of the FREEDM HEM GUI

2.1 Input Parameters

As shown in Figure 2.1, under APPLIANCE SETTING, there are eight appliance parameter setting buttons for the following eight controllable devices: air conditioning unit AC, space heater, water heater, cloth washer, dishwasher, dryer, fridge and electric vehicle.

a) Setup Parameters for the Air Conditioning Unit

The main parameters of the AC models [9] include the set point temperature and acceptable temperature upper and lower limits, as shown in Figure 2.2 [31]. The button labeled with ‘AC’ links to the input interface for setting up the parameters of the air conditioner unit. As shown in Figure 2.3, a user can set three different temperature settings for three different time periods during the day, or a user can set a desired temperature range within which the AC can operate. After finishing setting up the temperature settings, user can select the button labeled as ‘SAVE OPTIONS’ to save the parameters as a default setting in the database. The button labeled with ‘DEFAULT’ gives user an option to use pre-selected parameters. The user also hit the FINISH button to save all settings to the database or select the ‘CANCEL’ button to cancel the action.



C_a = air heat capacity (Btu/°F or J/°C)
C_m = mass (of the building and its content) heat capacity (Btu/°F or J/ °C)
Q = heat rate for HVAC (Btu/h or W)
UA = the gain/heat loss coefficient (Btu/°F·h or W/°C)
R_1 = $1/UA$
R_2 = $1/UA_{mass}$
T_o = ambient temperature (°F or °C)
T_i = air temperature inside the house (°F or °C)
T_m = mass temperature inside the house (°F or °C)

Figure 2.2. Air Conditioner modeling parameters [31]

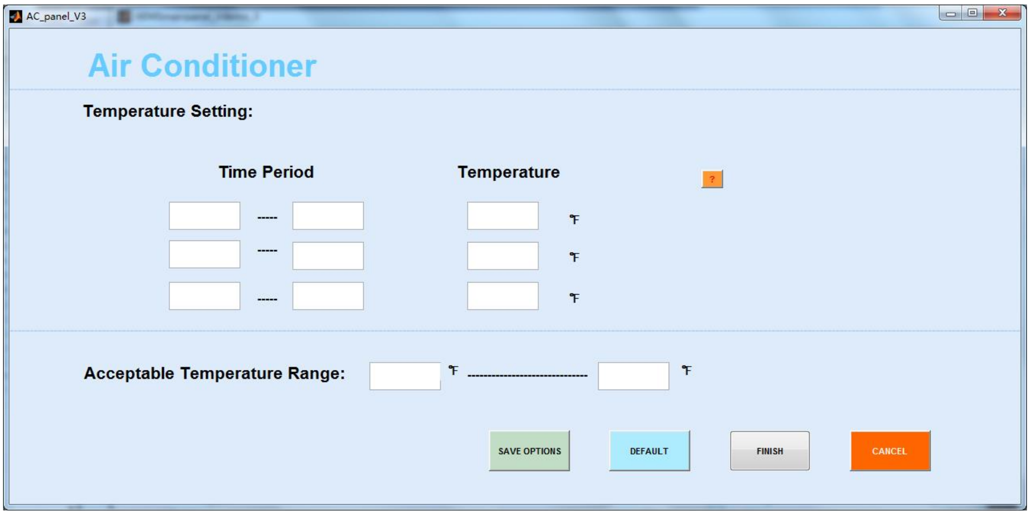


Figure 2.3. Air Conditioner parameters setup interface

b) Setup Parameters for the Space Heating Unit

The main parameters of the space heating models are similar to those of the AC model and also include the set point temperature and acceptable temperature upper and lower limits.

The button labeled with ‘Space Heater’ [10] links to an input interface to set parameters for the space heater. As shown in Figure 2.4, a user can set three different temperature settings for three different time periods during the day. Also, user could set a desired temperature range. After finishing setting these parameters, user could select the button labeled with ‘SAVE OPTIONS’ to save the parameters as default setting into the database. The button labeled with ‘DEFAULT’ gives user an option to use default parameters retrieved from the database. User also could select the button labeled with ‘FINISH’ to save settings to database directly or select the button labeled with ‘CANCEL’ to cancel the action.

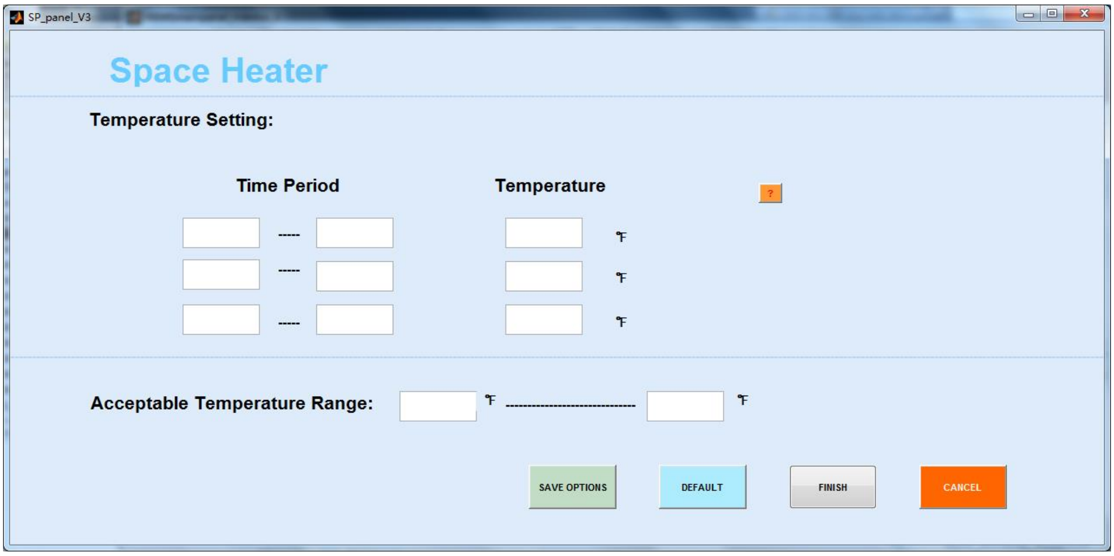


Figure 2.4. Space heater parameters setup interface

c) Setup Parameters for the Water Heater Unit

The button labeled with ‘Water Heater’ links to input interface to set parameters for water heater. As shown in Figure 2.6, user can set three different temperature settings for three different time periods during the day. Also, user could set their desired temperature range. After finishing setting these parameters, user could select the button labeled with ‘SAVE OPTIONS’ to save the parameters as default setting into the database. The button labeled with ‘DEFAULT’ gives user an option to use default parameters. User could also select the button labeled with ‘FINISH’ to save settings to the database or select the button labeled with ‘CANCEL’ to cancel the action.

The difference between the water heater model and the space heating and air conditioner models are the modeling of hot water consumptions. As shown in Figure 2.5 [36], small hot water consumptions will result in small temperature drops and large consumptions such as taking shower and washing clothes or dishes will cause a large temperature drop. The timing and amount of the hot water consumption will be modeled internally so there will be no parameters needed for the consumers to set up from the HEM GUI.

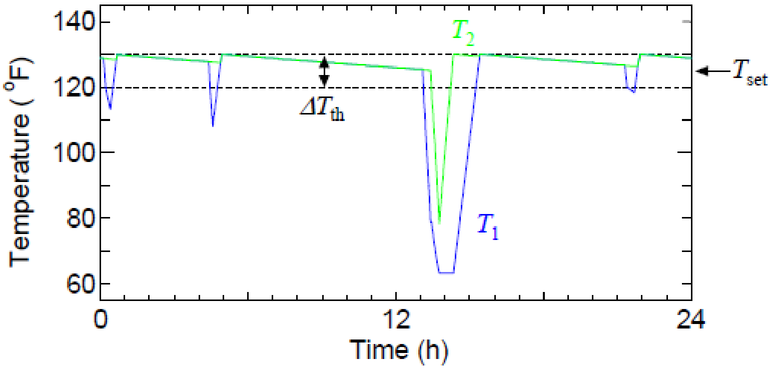


Figure 2.5 The temperature profile of a water heater unit

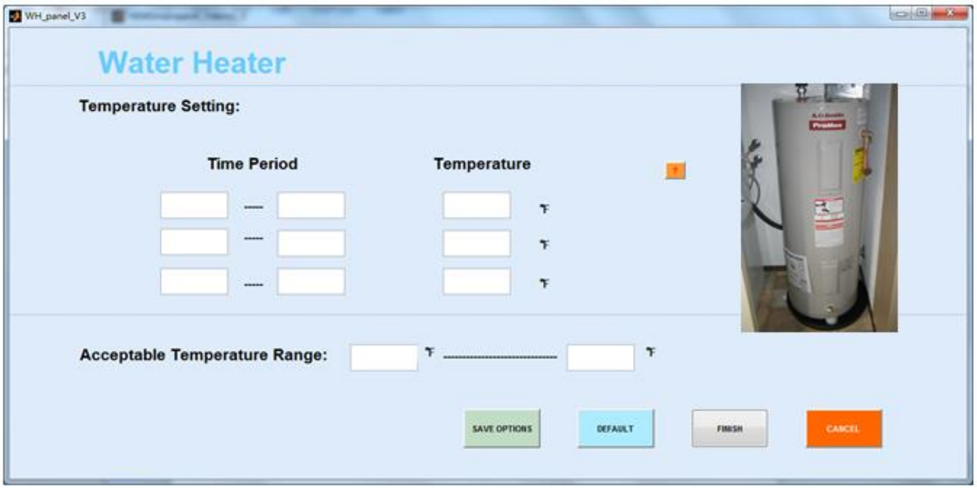


Figure 2.6 Water heater parameters setup interface

d) Setup Parameters for the Refrigerator Unit

The button labeled with ‘Fridge’ [11][12] links to input interface to set parameters for the refrigerator. As shown in Figure 2.7, user could select different operation levels in a drop box. The levels range from level 0 to level 10 with corresponding power rate from 200W to 380W. Here we offer user an option to let refrigerator work in the ‘power saving’ mode, in which the refrigerator consumes less energy. The button labeled with ‘COMPARISION will call for the function that compares the energy consumption between different selected levels or between the power saving modes and the “freeze” mode. The results will be displayed in the monitor window. Users can also select the ‘FINISH’ button save the settings to database or select the ‘CANCEL’ button to cancel the action.

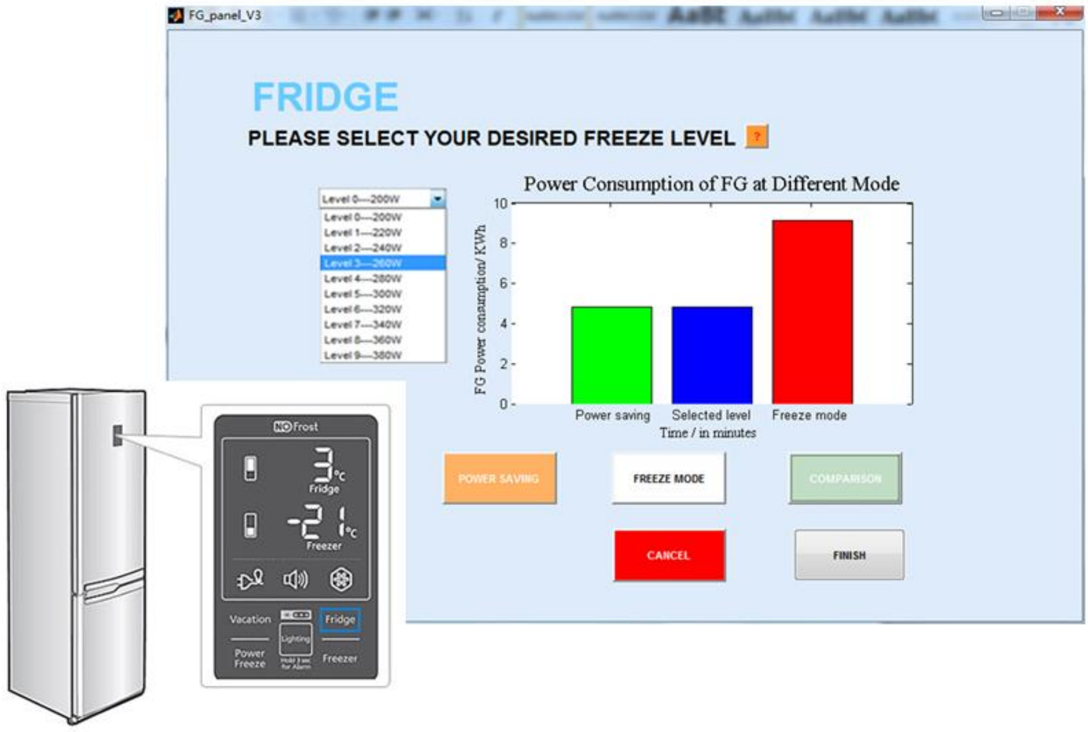


Figure 2.7 Fridge parameters setup interface

e) Setup Parameters for the Electric Vehicles

The button labeled with ‘EV’ [13] [14] links to the input interface to set parameters for the electric vehicle, such as the battery capacity, the charging options, and the preferred starting and ending charging time. The information can be used for the HEM scheduling algorithms to optimize the charging schedules based on the available grid service options and rate structures. The EV interface [15] is shown in Figure 2.8. By clicking the button ‘FINISH’ labeled, the parameters will be saved into the database.

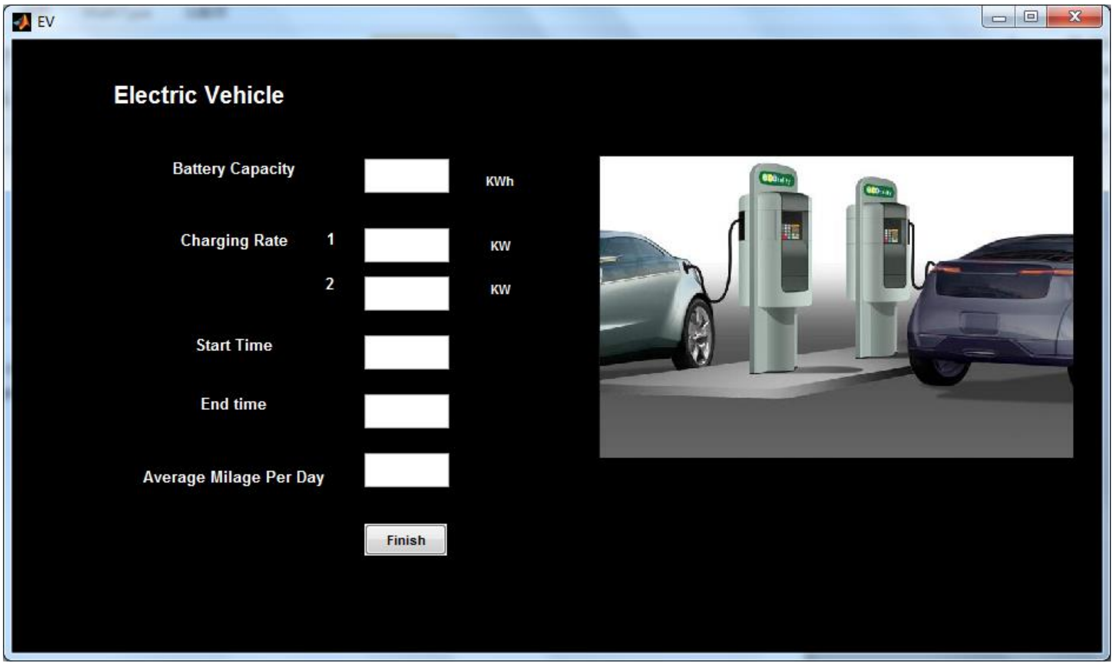


Figure 2.8 Electric vehicle parameters setup interface

f) Adding Appliances to the HEMS GUI

The button labeled with ‘ADD’ links to an empty interface which allows the user to add in other appliances. User could select different types of appliances from drop box in the panel. A thermostatic controllable appliance customized interface is shown in Figure 2.9. The basic function for this panel is the same as TCA appliance like air conditioner introduced before.

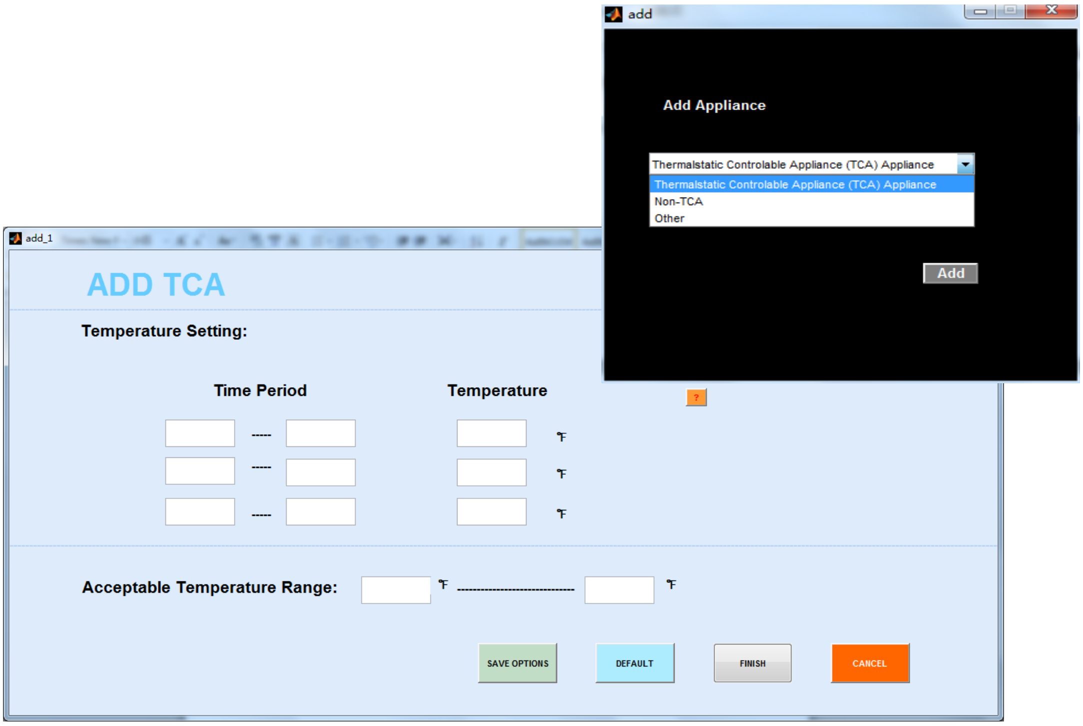


Figure 2.9 Parameters setup interface for adding appliances

g) Set up Operational Periods for Controllable Appliances

The buttons labeled with Cloth Washer, Dishwasher, Dryer link to another type of input interface, the time schedule inputs. It allows the user to schedule the appliance operation time periods. For example, when do they want to wash their cloth washer, when will they wash dishes? As shown in Figure 2.10, the user could save the settings into database by clicking the button labeled with FINISH.

CLOTH WASHER

PLEASE SET THE WORKING DURATION

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐

DRYER

PLEASE SET THE WORKING DURATION

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐

DISH WASHER

PLEASE SET THE WORKING DURATION

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑

Figure 2.10 Time schedule setup interface for controllable loads

h) Control Strategy Selection

Under CONTROL STRATEGY, there are five buttons for five existing control strategies developed for the FREEDM smart home: Price-Cap, Power-Cap, Consensus, No Control, and Customize. The button labeled with ‘Customize’ links to an interface that allows the user to add other control strategies. Once a strategy is selected, the user can hit the ▶ button to run the algorithm based on the selected appliance settings.

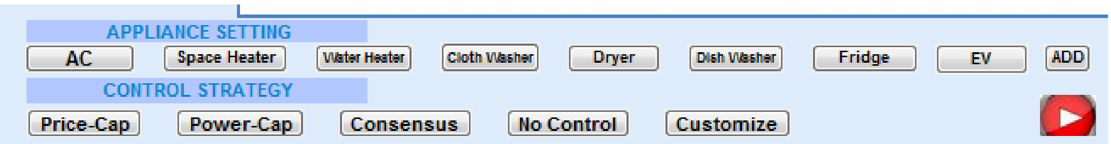


Figure 2.11 **Control strategy selection interface**

2.2 Output and Operation Status Display

There are six screens (labeled from no.1 to no.6) that used as a home energy consumption dashboard [16]. The consumption data are generated by the background simulation module in real-time and accessed through the HEM database by the GUI.

Screen No.1 displays the current location of the house, the weather of the site, the time of the day, indoor and outdoor temperatures. For example, in Figure 2.12, it shows that the smart house located in Raleigh, NC and it is a rainy Thursday at 23:00, and the outdoor temperature is 85$^\circ F$ and the indoor temperature is 72$^\circ F$.

Figure 2.12 General information display

Screen No.2 displays the current working status of each appliance [17] inside the HEMS. By clicking the button attached in the screen to the right-lower corner, a detailed interface will pop out as shown in Figure 2.13. By clicking button labeled with “GO”, the interface will show the current working status of each appliance inside the smart home, there are five different working statuses: ON, OFF, STANDBY, MAINTAINANCE and OFFLINE. STANDBY means the appliance is loaded and is waiting for the HEM “on” command to be turned on. For example, at 3:00 p.m., a user puts his wet clothes into the dry and set the dryer as “standby”. Then, the HEM control algorithms will know that the dryer can be turned on any time after 3.00 pm. MAINTAINANCE means that the appliance consumption is abnormal and it may need to be maintained or replaced. OFFLINE means that the HEMS cannot detect the appliance and the user needs to check the web connection of the appliance. Thus, the operation status of each appliance can be readily accessed through the display.

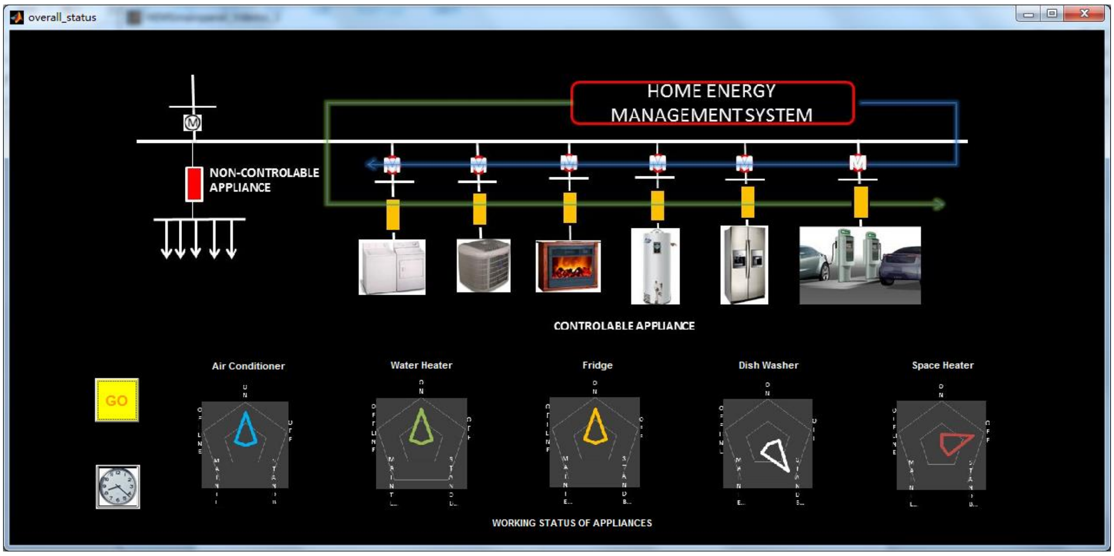


Figure 2.13 Appliance Operation Status

As shown in Figure 2.14, screen No.3 shows the daily cost comparison between two cases: with HEM control (the bar on the left) and without HEM control (the bar on the right).

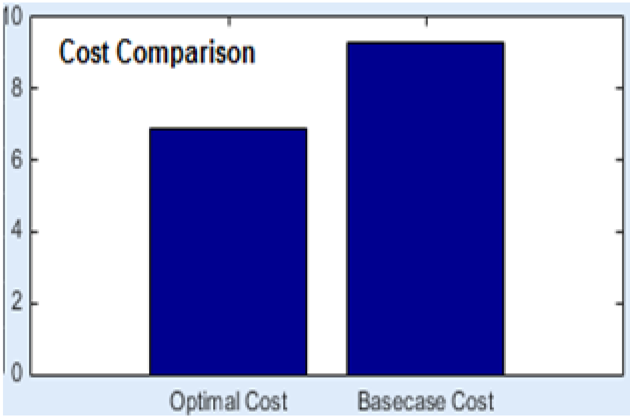


Figure 2.14 Cost comparison window

Screen No.4 shows the daily power consumption of the smart house. In the results shown in Figure 2.15, the power-cap control strategy is selected. The green line shows the forecasted power consumption of the house and the red line shows real time power consumption of the house.

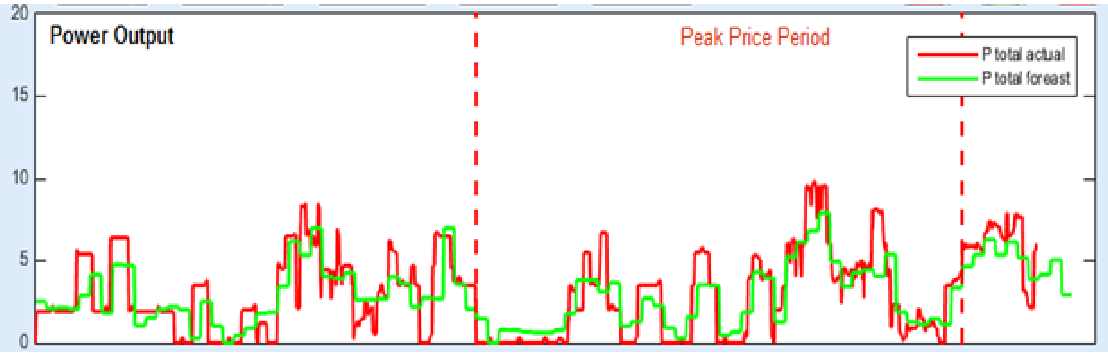


Figure 2.15 Power output monitoring

Screen No.5 displays the status of distributed energy resources such as PVs and energy storage units. As shown in Figure 2.16, the power output of a roof top PV system (red line) and the state of charge for the energy storage unit of the PV system (blue line) can be displayed so that the user can observe the available storage capacity for storing extra PV generation outputs.[18]

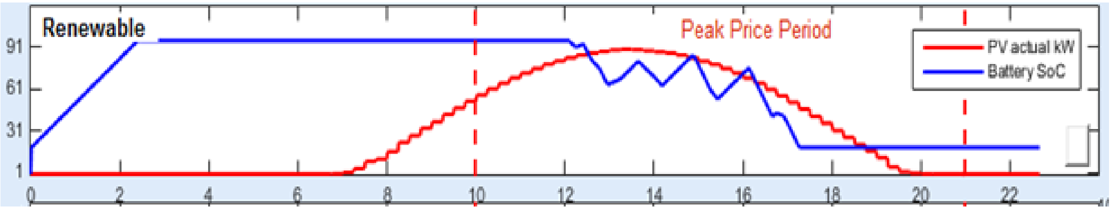


Figure 2.16 Battery output and solar generation output window

Screen No.6 shows the daily working status of six major appliances in the smart. The color bars show the working periods of the appliances. For example, in Figure 2.17, the yellow bars represent the working status of the air conditioner unit, as shown; the air conditioner is on between 0-2am, 3-4am, 6-7am. Noted that for screen No.4, 5, 6, there are two vertical dash lines showing the high price periods in a day.

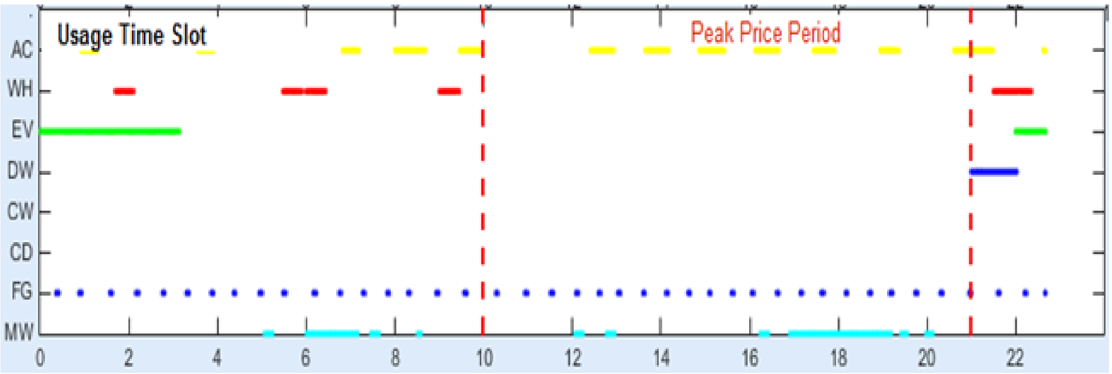


Figure 2.17 Appliance operation status

CHAPTER 3 HEM SOFTWARE ARCHITECTURE

An HEM system is an energy management system that has all or some of the following main functionalities: monitoring energy use, storing and analyzing data, forecasting and scheduling energy use, controlling loads and preparing customer reports. An example of the HEM system is shown in Figure 3.1.

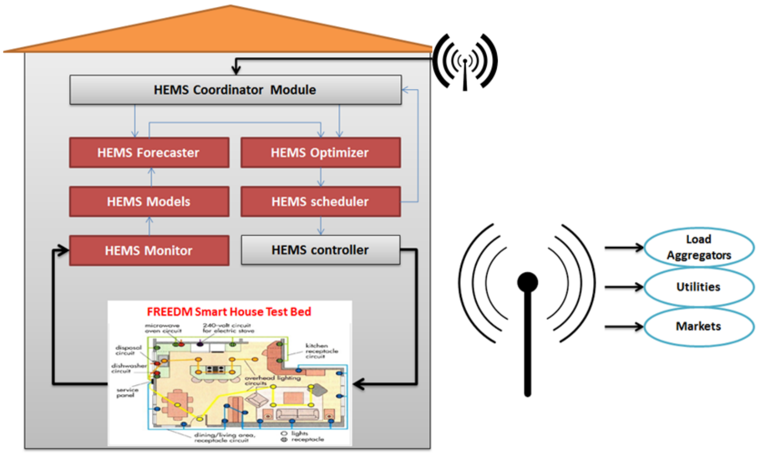


Figure 3.1. Configuration of a HEM system

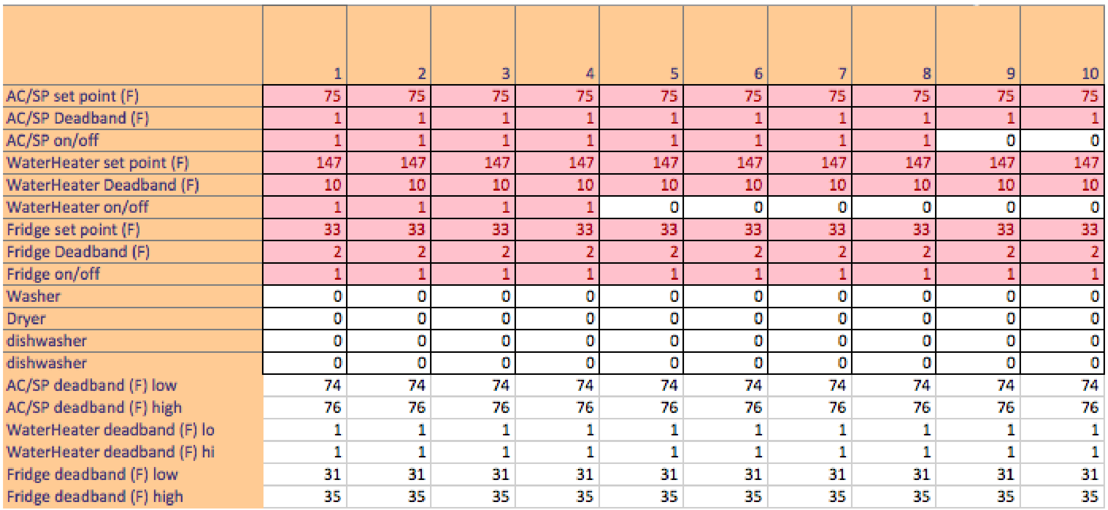
The HEM monitors the status of the energy use for forecasting or fault detection purposes. Sensors installed at major appliances such as stoves, washers, dishwashers, or air conditioning units can help the HEM disaggregate the energy uses and analyze the status of each device. Advanced data analytics can use the acquired data to derive load models that forecast future energy use under different operating conditions. Scheduling algorithms are at the heart of the HEM because they can schedule the operation of controllable appliances and coordinate with home-owned distributed energy resources to minimize cost, integrate more renewable energy and improve system reliability. Note that each HEM will need to communicate energy prices, billing data, and other information through wired or wireless networks to utilities, load aggregators, and retail electricity markets. In this section, the design and implementation of the software architecture [19] of the HEM system will be discussed in detail.

3.1 Database Design of the HEM

The database for HEM system [20] can be categorized into three parts based on the function of GUI and the results generated by simulation program: input, output and preference.

The input data sheet is shown in Figure 3.2, the parameters user set through GUI will be saved automatically in the sheet using the format shown below. Then the data will be used as the input settings by HEM simulation program.

The input parameters are (row by row):
1) Set point for temperature for air conditioner and space heater;
2) Dead band for air conditioner and space heater;
3) Working status of air conditioner and space heater;
4) The temperature set point for water heater;
5) Dead band for water heater;
6) Working status of water heater;
7) Set point for temperature for fridge;
8) Dead band for fridge;
9) Working status of fridge;
10) Working status of cloth washer;
11) Working status of dryer;
12) Working status of dishwasher;
13) The lower temperature setting regards to temperature set point for air conditioner and space heater;
14) The upper temperature setting regards to temperature set point for air conditioner and space heater;
15) The lower temperature setting regards to temperature set point for water heater;
16) The upper temperature setting regards to temperature set point for water heater;
17) The lower temperature setting regards to temperature set point for fridge;
18) The upper temperature setting regards to temperature set point for fridge;



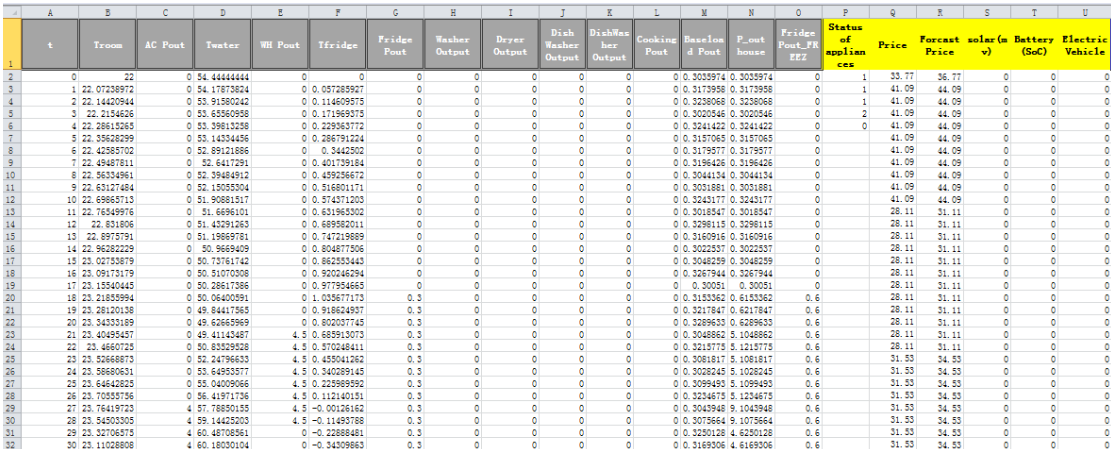
	1	2	3	4	5	6	7	8	9	10
AC/SP set point (F)	75	75	75	75	75	75	75	75	75	75
AC/SP Deadband (F)	1	1	1	1	1	1	1	1	1	1
AC/SP on/off	1	1	1	1	1	1	1	1	0	0
WaterHeater set point (F)	147	147	147	147	147	147	147	147	147	147
WaterHeater Deadband (F)	10	10	10	10	10	10	10	10	10	10
WaterHeater on/off	1	1	1	1	0	0	0	0	0	0
Fridge set point (F)	33	33	33	33	33	33	33	33	33	33
Fridge Deadband (F)	2	2	2	2	2	2	2	2	2	2
Fridge on/off	1	1	1	1	1	1	1	1	1	1
Washer	0	0	0	0	0	0	0	0	0	0
Dryer	0	0	0	0	0	0	0	0	0	0
dishwasher	0	0	0	0	0	0	0	0	0	0
dishwasher	0	0	0	0	0	0	0	0	0	0
AC/SP deadband (F) low	74	74	74	74	74	74	74	74	74	74
AC/SP deadband (F) high	76	76	76	76	76	76	76	76	76	76
WaterHeater deadband (F) lo	1	1	1	1	1	1	1	1	1	1
WaterHeater deadband (F) hi	1	1	1	1	1	1	1	1	1	1
Fridge deadband (F) low	31	31	31	31	31	31	31	31	31	31
Fridge deadband (F) high	35	35	35	35	35	35	35	35	35	35

Figure 3.2. Input database structure for HEM system

The output data sheet is shown in Figure 3.3, the results generated by system simulation modules will be automatically saved into the sheet using the format shown below.

The output results are (column by column):

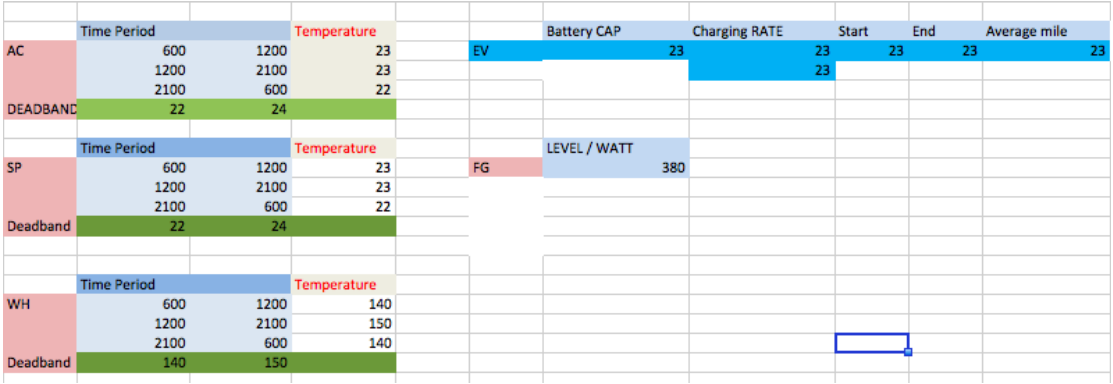
1. Current room temperature;
2. Current power output of air conditioner;
3. Current water temperature for water heater;
4. Current power output for water heater;
5. Current temperature for fridge;
6. Current power output for fridge;
7. The power output for washer;
8. The power output for dryer;
9. The power output for dish washer;
10. The power output for entire house;
11. The working status of appliances;
12. Current marker electricity price;
13. Current power output of solar panel;
14. Energy Storage State of Charge
15. Electric Vehicle charging rate;



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1	t	Troom	AC Pout	Twater	WH Pout	Tfridge	Fridge Pout	Washer Output	Dryer Output	Dish Washer Output	DishWasher Output	Cooking Pout	Baseload Pout	P_out house	Fridge Pout_FREEZ	Status of appliances	Price	Forcast Price	solar(mv)	Battery (SoC)	Electric Vehicle
2	0	22	0	54.44444444	0	0	0	0	0	0	0	0	0.3035974	0.3035974	0	1	33.77	36.77	0	0	0
3	1	22.07238972	0	54.17873824	0	0.057285927	0	0	0	0	0	0	0.3173958	0.3173958	0	1	41.09	44.09	0	0	0
4	2	22.14420944	0	53.91580242	0	0.114609575	0	0	0	0	0	0	0.3238068	0.3238068	0	1	41.09	44.09	0	0	0
5	3	22.2154626	0	53.65560958	0	0.171969375	0	0	0	0	0	0	0.3020546	0.3020546	0	2	41.09	44.09	0	0	0
6	4	22.28615265	0	53.39813258	0	0.229363772	0	0	0	0	0	0	0.3241422	0.3241422	0	0	41.09	44.09	0	0	0
7	5	22.35628299	0	53.14334456	0	0.286791224	0	0	0	0	0	0	0.3157065	0.3157065	0		41.09	44.09	0	0	0
8	6	22.42585702	0	52.89121886	0	0.3442502	0	0	0	0	0	0	0.3179577	0.3179577	0		41.09	44.09	0	0	0
9	7	22.49487811	0	52.6417291	0	0.401739184	0	0	0	0	0	0	0.3196426	0.3196426	0		41.09	44.09	0	0	0
10	8	22.56334961	0	52.39484912	0	0.459256672	0	0	0	0	0	0	0.3044134	0.3044134	0		41.09	44.09	0	0	0
11	9	22.63127484	0	52.15055304	0	0.516801171	0	0	0	0	0	0	0.3031881	0.3031881	0		41.09	44.09	0	0	0
12	10	22.69865713	0	51.90881517	0	0.574371203	0	0	0	0	0	0	0.3243177	0.3243177	0		41.09	44.09	0	0	0
13	11	22.76549976	0	51.6696101	0	0.631965302	0	0	0	0	0	0	0.3018547	0.3018547	0		28.11	31.11	0	0	0
14	12	22.831806	0	51.43291263	0	0.689582011	0	0	0	0	0	0	0.3298115	0.3298115	0		28.11	31.11	0	0	0
15	13	22.8975791	0	51.19869781	0	0.747219889	0	0	0	0	0	0	0.3160916	0.3160916	0		28.11	31.11	0	0	0
16	14	22.96282229	0	50.9669409	0	0.804877506	0	0	0	0	0	0	0.3022537	0.3022537	0		28.11	31.11	0	0	0
17	15	23.02753879	0	50.73761742	0	0.862553443	0	0	0	0	0	0	0.3048259	0.3048259	0		28.11	31.11	0	0	0
18	16	23.09173179	0	50.51070308	0	0.920246294	0	0	0	0	0	0	0.3267944	0.3267944	0		28.11	31.11	0	0	0
19	17	23.15540445	0	50.28617386	0	0.977954665	0	0	0	0	0	0	0.30051	0.30051	0		28.11	31.11	0	0	0
20	18	23.21855994	0	50.06400591	0	1.035677173	0.3	0	0	0	0	0	0.3153362	0.6153362	0.6		28.11	31.11	0	0	0
21	19	23.28120138	0	49.84417565	0	0.918624937	0.3	0	0	0	0	0	0.3217847	0.6217847	0.6		28.11	31.11	0	0	0
22	20	23.34333189	0	49.62665969	0	0.802037745	0.3	0	0	0	0	0	0.3289633	0.6289633	0.6		28.11	31.11	0	0	0
23	21	23.40495457	0	49.41143487	4.5	0.685913073	0.3	0	0	0	0	0	0.3048862	5.1048862	0.6		28.11	31.11	0	0	0
24	22	23.4660725	0	50.83529528	4.5	0.570248411	0.3	0	0	0	0	0	0.3215775	5.1215775	0.6		28.11	31.11	0	0	0
25	23	23.52668873	0	52.24796633	4.5	0.455041262	0.3	0	0	0	0	0	0.3081817	5.1081817	0.6		31.53	34.53	0	0	0
26	24	23.58680631	0	53.64953577	4.5	0.340289145	0.3	0	0	0	0	0	0.3028245	5.1028245	0.6		31.53	34.53	0	0	0
27	25	23.64642825	0	55.04009066	4.5	0.225989592	0.3	0	0	0	0	0	0.3099493	5.1099493	0.6		31.53	34.53	0	0	0
28	26	23.70555756	0	56.41971736	4.5	0.112140151	0.3	0	0	0	0	0	0.3234675	5.1234675	0.6		31.53	34.53	0	0	0
29	27	23.76419723	4	57.78850155	4.5	-0.00126162	0.3	0	0	0	0	0	0.3043948	9.1043948	0.6		31.53	34.53	0	0	0
30	28	23.54503305	4	59.14425203	4.5	-0.11493788	0.3	0	0	0	0	0	0.3075664	9.1075664	0.6		31.53	34.53	0	0	0
31	29	23.32706575	4	60.48708561	0	-0.22888481	0.3	0	0	0	0	0	0.3250128	4.6250128	0.6		31.53	34.53	0	0	0
32	30	23.11028808	4	60.18030104	0	-0.34309863	0.3	0	0	0	0	0	0.3169306	4.6169306	0.6		31.53	34.53	0	0	0

Figure 3.3. Output database structure for HEM system

Figure 3.4 shows the preference setting for air conditioner, space heater, water heater, fridge and electric vehicle. By clicking SAVE OPTIONS in the appliance interfaces, the parameters user set will be saved into database using the format shown below. The button labeled with DEFAULT in the appliance interfaces could for these data as the input settings for simulation modules.



	Time Period		Temperature			Battery CAP	Charging RATE	Start	End	Average mile
AC	600	1200	23		EV	23	23	23	23	23
	1200	2100	23				23			
	2100	600	22							
DEADBAND	22	24								
	Time Period		Temperature			LEVEL / WATT				
SP	600	1200	23		FG	380				
	1200	2100	23							
	2100	600	22							
Deadband	22	24								
	Time Period		Temperature							
WH	600	1200	140							
	1200	2100	150							
	2100	600	140							
Deadband	140	150								

Figure 3.4. Input preference database structure for HEM system

3.2 Information Flows in the HEM System

In this section, an example is given which illustrates the information flow [21] of HEM system to indicate how information transport from the beginning as input to the end as the output that display on the GUI monitors.

The HEM system needs lots of data inputs to initialize the simulation for different appliances modules included in the system. The data input will be gathered and saved into the database through the GUI, then the appliance modules will use the settings from database to carry out a simulation, and the appliance modules will generate the simulation results and save the correlated data into database, finally the GUI will display the results by reading the data from database.

Using the air conditioner simulation as an example, the HEM system gets information (e.g. electricity market price and current environment temperature, current time) from utility and save them into the database, at the same time, user of the HEM system sets appliance settings (e.g. temperature setting, temperature dead band, etc.) for air conditioner through the GUI and save the user settings into the database as well. To start a simulation of air conditioner in the HEM system, the air conditioner module will read data from the database and implement these data as input for program (e.g. electricity market price and current environment temperature, current time, temperature settings and temperature dead band of user). Then the program will generate correlated results (e.g. power output, working period of air conditioner, room temperature of the house, etc.) and save them into the database. At the same time GUI will read the information from database and display the information in correlated monitor in the interface. The information flows among the modules are illustrated in Figure 3.5.

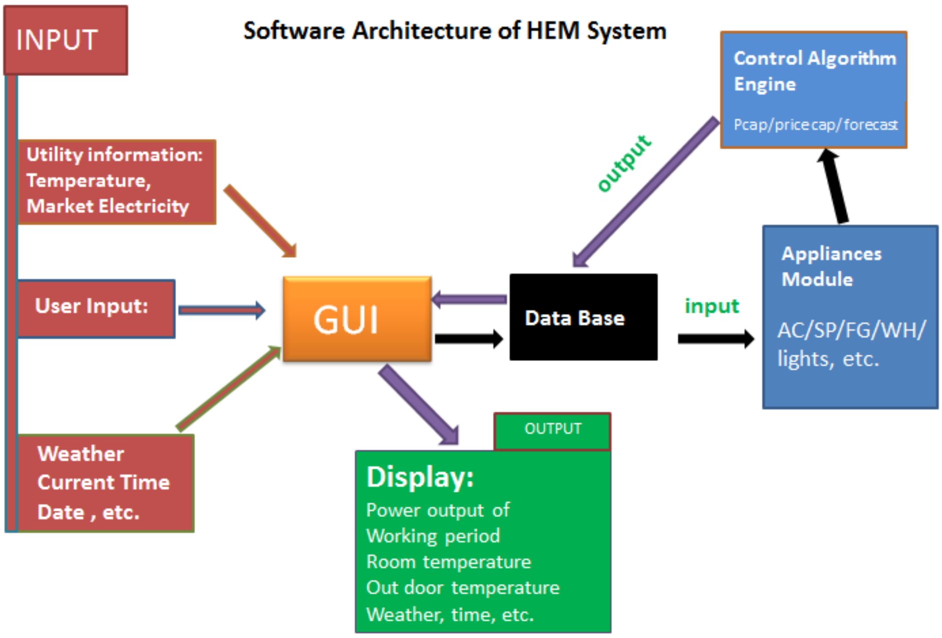


Figure 3.5. Information flow between HEM system and GUI

CHAPTER 4 RULE-BASED CONTROL ALGORITHM

The Matlab-based HEM system can simulate the energy consumption of home appliances considering outside temperature and consumer behavioral factors such as probability-of-use. Those capabilities make the HEM system a suitable test bed for new algorithm development. In this chapter, a rule-based control algorithm for controlling the peak power consumption of a household is developed. Then, a sensitivity analysis is conducted to evaluate the impact of the input parameter changes on the robustness of the algorithm performance for different loading conditions.

4.1 Problem Formulation

Although behaviors of a residential house owner can be hard to predict, they do usually follow a few routines [22-23]. For example, when people get up in the morning, they normally will take a shower, cook some breakfast, make themselves a cup of coffee, and watch some TV or listen to the radio. The electricity consumption can be high during the morning hours, because everything needs to be done in an hour or so. Then, after the breakfast, kids will go to school and adults will go to work. The energy consumption will drop significantly. For those families who will have lunch at home, there will be a short peak at noon for cooking load. Because of the time limit, the period of load peak will be normally tens of minutes. For those families who do not go home for lunch, the consumption will remain low till late afternoon when people return home from work or school. The main loads will be food processing and cooking load that related with preparing dinner. After dinner, the family members may wash dishes, watch TV, use their computers, etc. They may also wash clothes, vacuum the floor, or do some housework. However, those usages are normally not part of their daily routines.

Therefore, residential load consumption follows a time-of-the-day pattern. When people are at home, energy consumptions are high. Peak power of the house can reach 15-20 kW when all the energy consumptions happen in a short period of time [23]. When people are sleeping and resting, not at home, or on vacation, energy consumption can drop below 1 kW most of the time. When the peak load periods of several houses supplied by the same transformer coincide with each other, the aggregation of peak power can cause the equipment to be overloading and causes higher losses. Moreover, if the high energy use period is within a period which the electricity price is high, the energy bill will be high.

How to reduce the peak energy consumption at high prices and high energy use periods is the problem which is going to be solved in the thesis. Therefore, a robust, rule-based priority-list methodology is developed for shaving energy peaks by executing power cap control.

4.2 Modeling Approach and Algorithm Design

In this section, the modeling approach of the HEM system and the algorithm design process as well as simulation results generated by HEM system will be introduced. First, a simulation environment to simulate the base load power consumption of a house without control will be introduced. Then, a rule-based priority-list appliance control algorithm will be introduced. The robustness of the algorithm is validated by Monte Carlo simulation of different operation conditions.

1. HEM System Modules Introduction

The Home Energy Management System (HEMS) testing environment is developed by Dr. Ning Lu’s research group at the FREEDM center at North Carolina State University (NCSU). The system is developed on Matlab platform and consists of different appliances modules; the system simulates the energy consumption of a single-family residential house load. There are 19 appliances included in the system, which can be categorized into two categories: thermostatically controllable appliance and non-thermostatically controllable appliance. For thermostatically controllable appliances, modules for air conditioner, space heater, water heater and fridge are included. For non-thermostatically controllable appliances, modules for dishwasher, cloth washer and dryer, TV, lights, range and micro wave oven are included.

a. Non- Thermostatically Controllable Appliances

The non-thermostatically controllable appliances are modeled using a probability-of-use (POU) method. The working status of an appliance is determined by the likelihood it will be operated based on historical data collected at the home. At each hour, there is a POU associated with small random energy use. The higher the POU, the more frequently the appliance will be turned on at that hour. To make the simulation more realistic, two types of POU were developed based on different consumption routines: POU for weekend and POU for weekday.

As shown in Table 4.1, for example, the possibility for a range to work between 6 a.m. to 8 a.m. is 0.7, which means that the range module will have 70% percent chance to start working during that period. Once the appliance is on, the POU for the operation duration will determine the turn-on time. Likewise, the turn-off time is also determined by the POU. An example of how a range unit is operated between 6:00 a.m. and 7:00 a.m. is illustrated in Figure 4.1.

Table 4.1. Probability of use for appliances for weekend

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
CW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.1	0.7	0.7	0.7	0.1	0.1	0.1	0
DY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.1	0.7	0.7	0.7	0	0
DW	0	0	0	0	0	0	0	0	0.1	0.1	0.1	0.1	0.8	0.8	0	0	0	0	0	0.8	0.8	0.8	0.1	0
TV	0	0	0	0	0	0	0	0	0	0.1	0.1	0.8	0.8	0.5	0.1	0.1	0.1	0.1	0.7	0.8	0.8	0.8	0.8	0.1
RG	0	0	0	0	0	0.7	0.7	0.7	0.1	0	0	0.5	0.5	0	0	0	0	0.8	0.8	0.8	0.1	0	0	0
LT	0	0	0	0	0	0	0.7	0.9	0.1	0	0	0	0	0	0	0	0	0.5	0.6	0.6	0.9	0.9	0.9	0.2
OW	0	0	0	0	0	0	0.7	0.7	0.7	0	0	0	0.6	0.6	0	0	0	0	0.7	0.7	0.7	0.4	0.2	0

CW=cloth washer; DY=dryer; DW=dishwasher; TV=television; RG=range; LT=lights; OW=micro oven

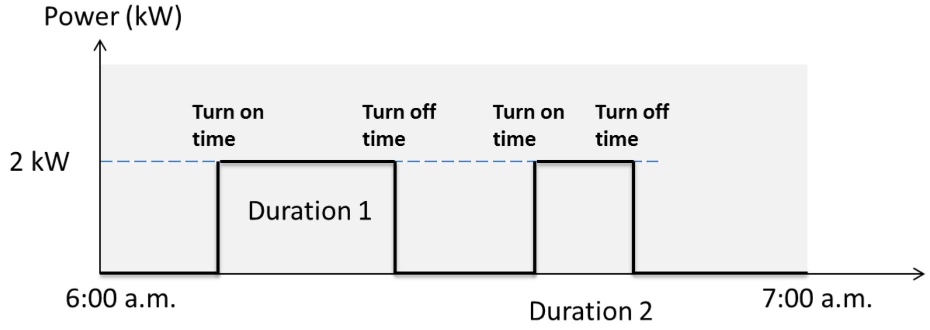


Figure 4.1. The operation of a range surface unit between 6:00 a.m. and 7:00 a.m.

b. Thermostatically Controllable Appliances

The thermostatically controllable appliances include air conditioners, space heaters, water heaters and refrigerators. The operation mechanism of the air conditioner and space heater modules are described in [24][25]. For the space heater unit, its thermal behavior is shown in Figure 4.2. There is a temperature set point, T_{set}, for space heater that represents the user desired room temperature. An upper room temperature limit, T^{+}, and a lower room temperature limit, T^{-}, represent the higher and lower room temperatures a user can tolerate around T_{set}.

Then, we have the following equations illustrate the behavior of a space heating unit:

$$T_{deadband} = T^{+} - T^{-} \tag{4-1}$$

When the space heater is working, the room temperature will rise based on the equation:

$$T_{room}^{t+1} = T_{o}^{t+1} + QR - (T_{o}^{t+1} + QR - T_{room}^{t})\,\mathrm{e}^{-\Delta t/RC} \tag{4-2}$$

When the space heater is not working, the room temperature will drop based on the equation:

$$T_{room}^{t+1} = T_{o}^{t+1} - (T_{o}^{t+1} - T_{room}^{t})\,\mathrm{e}^{-\Delta t/RC} \tag{4-3}$$

Where:

C	equivalent heat capacity $(\mathrm{J}/{}^{o}\mathrm{C})$,
R	equivalent thermal resistant $({}^{o}\mathrm{C}/\mathrm{W})$,
Q	equivalent heat rate (W).
Δt	time step (1 min) and
T_o	ambient temperature.

For time between t_1 and t_2, t_3 and t_4, the space heater unit starts to work and the room temperature starts to rise. At time t_2, the room temperature reaches the upper limit, T^{+}, the heating element stops working and the room temperature starts to drop until room temperature reaches lower limit, T^{-}. Then, the space heater will start to work again.

For air conditioners, the operating theory is similar to space heaters; on the contrary while the air conditioner starts to work, the room temperature will drop and when it stops to work the room temperature will rise.

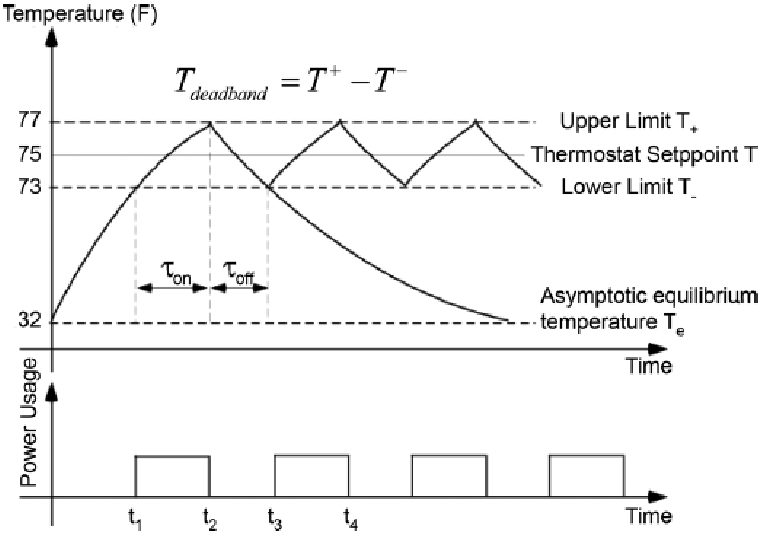


Figure 4.2. Thermal behavior of space heater [34]

For water heater, its thermal behavior is shown in Figure 4.3; there is a temperature set point for water heater that represents for the user desired temperature. When the water heater is working, the water temperature will rise based on the equation:

$$T_{water}^{t+1} = T_o^{t+1} + QR - (T_o^{t+1} + QR - T_{water}^{t})\,\mathrm{e}^{-\Delta t/RC} \tag{4-4}$$

When the water heater is not working, the water temperature will drop based on the equation:

$$T_{water}^{t+1} = T_o^{t+1} - (T_o^{t+1} - T_{water}^{t})\,\mathrm{e}^{-\Delta t/RC} \tag{4-5}$$

Where:

C	equivalent heat capacity $(\mathrm{J}/{}^{o}\mathrm{C})$;
R	equivalent thermal resistant $({}^{o}\mathrm{C}/\mathrm{W})$;
Q	equivalent heat rate (W);
Δt	time step (1 min);
T_o	ambient temperature;

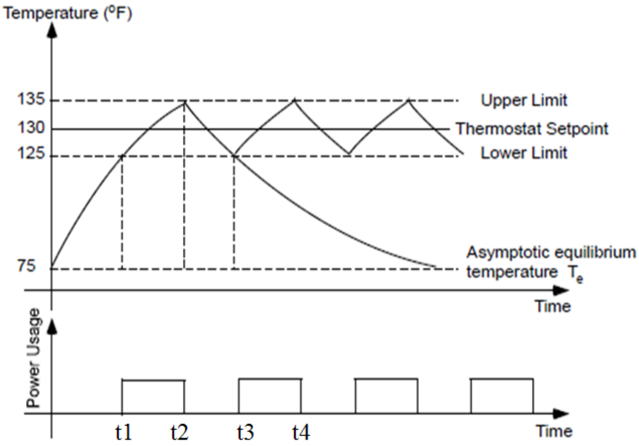
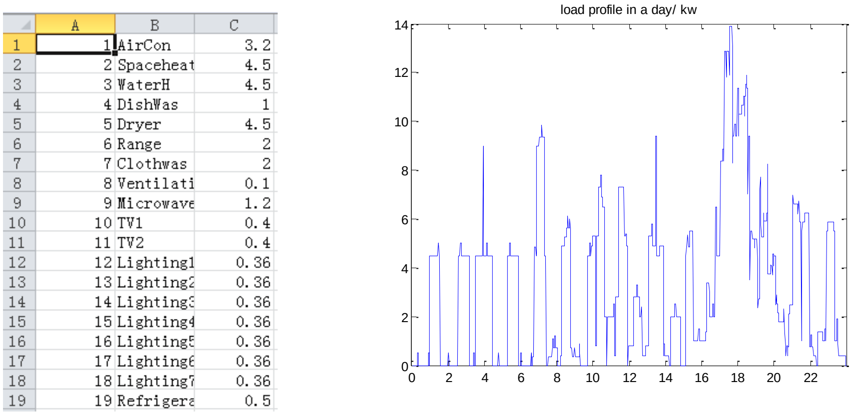


Figure 4.3. Thermal behavior of water heater [33]

For a refrigerator, the working theory is similar to that of an HVAC system introduced before. However, the refrigerator is usually not controlled by a user. Normally, it cannot be switched off, because it needs to maintain a specific temperature dead band to keep the food fresh.

For both the TCA and non-TCA appliances inside a household, we assign a pre-set rated power. Thus, once an appliance is working, the HEM system will consider it is working at the rated power. This allows a load profile be generated based on the appliance working status. We can see from Figure 4.4 (a) that the space heater and water heater are the two TCA appliances that have the highest power rating. As shown in Figure 4.4 (b), the daily load profile of a residential household in winter shows that there are two peak power consumption periods during 17:00-19:00 and 21:00-22:00. Thus, the control objective of the rule-based control algorithm developed in this thesis is to shave the peak by implementing power cap-controls.



	A	B	C
1	1	AirCon	3.2
2	2	Spaceheat	4.5
3	3	WaterH	4.5
4	4	DishWas	1
5	5	Dryer	4.5
6	6	Range	2
7	7	Clothwas	2
8	8	Ventilati	0.1
9	9	Microwave	1.2
10	10	TV1	0.4
11	11	TV2	0.4
12	12	Lighting1	0.36
13	13	Lighting2	0.36
14	14	Lighting3	0.36
15	15	Lighting4	0.36
16	16	Lighting5	0.36
17	17	Lighting6	0.36
18	18	Lighting7	0.36
19	19	Refrigera	0.5

(a) (b)

Figure 4.4. (a) A list of rated powers for different residential household appliances, (b) an example of the daily load profile in winter season

2. Design and Implementation of a Rule-Based Control Algorithm

Demand response (DR) [27] is defined as: “Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized.” Peak shaving is a technique that is used to reduce electrical power consumption during period of maximum demand on the power utility for energy savings. [26]

In this thesis, the goal is to reduce the peak power consumption during peak load periods without compromising the customer’s comfort. To design a control algorithm for controlling the power consumption during the peak hours, we started with analyzing why the peak happens and what choices a consumer has to reduce the consumption without sacrificing his comfort.

As shown in Figure 4.4 (b), there are several power spikes in a day. The first power spike happens between 6:00-8:00 and the second happens between 17:00-19:00. By analyzing the switching status [28] of appliances shown in Figure 4.5, between 6:00-8:00, the fridge, four lights, space heater and water heater have working periods that overlap with each other, causing the first spike. Between 17:00-19:00, the fridge, cloth washer, the range unit, dishwasher, water heater, space heater, four lights, and two TVs are all working heavily, causing a peak load period with higher power and longer duration than those of the morning peak.

As listed in Figure 4.4(a) [29], the rated power for both the space heater and the water heater is 4.5KW. The lights and TVs are only a few hundreds of W. Thus the peak load reduction by those types of load is negligible. Furthermore, keeping the lights on are for both safety and comfort reasons and leaving the TV on is also crucial for entertainment reasons. Thus, only the two TCA appliances are the ones to be controlled for reducing the peak loads.

The range and the cloth washer also have overlap operation periods with other appliances. The power ratings of the two appliances are both at 2KW. So it is worthy of controlling. However, compared with TCA loads, whose consumption can be put off without influencing the user comfort, they should be given less priority on the controllable appliance list. Therefore, we focused our effort on investigating to what extent an individual household load consumption can be reduced using TCAs alone.

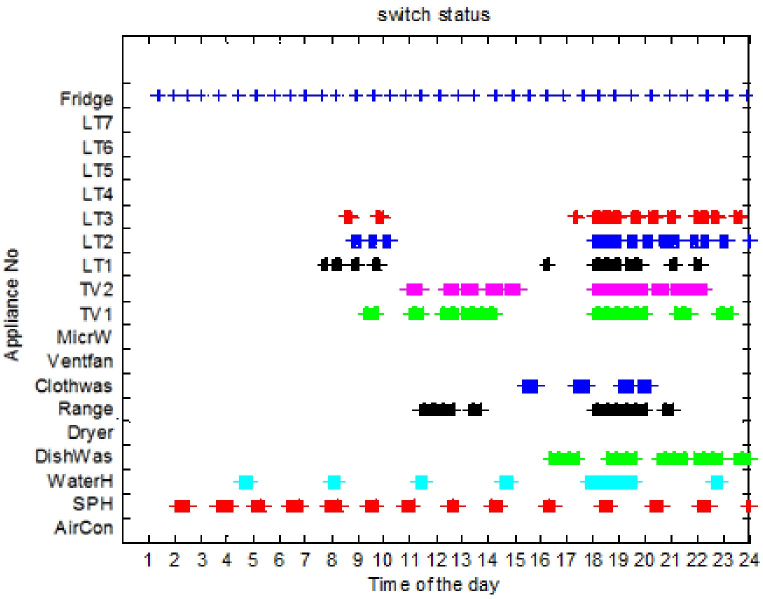


Figure 4.5. Switch status of the appliances in HEM system for 24 hours

(there will be a colored dot if the appliance is ON)

To strictly define the priority of operation, a rule-based control algorithm is developed. Figure 4.6 shows the control logic of the algorithm. The time step of the simulation is 1 minute and the duration is 24 hours.

After initialization, at each time step, we will update the appliances' status and get the current total power consumption of the house. Then, comparison is made to see if the power cap is exceeded. If not, we maintain the same operation status for the space heater and water heater. If the power cap is exceeded, the program will get the current room temperature and water temperature; compare them with the upper and lower limit of temperature settings to decide which of the four scenarios it will go into.

1) Both the room temperature and the water temperature are within the dead band of setting.
2) The room temperature is within the dead band but the water temperature is out of the dead band.
3) The water temperature is within the dead band but the room temperature is out of the dead band.
4) Both water temperature and room temperature are out of dead band.

In Scenario 1, if both room and water temperature is in an acceptable range, then shutting down any of the appliances will not affect the comfortable level of house owner. The program will then shut down the two appliances for a specified period based on the timer setup (e.g. 5-minute, 10-minute, or 15-minute).

In Scenario 2, the water heater will need to work to maintain the water in the acceptable range. Then, the space heater will be shut down.

In Scenario 3, the space heater will need to work to maintain the room temperature in the acceptable range. Then, the space heater will be shut down.

In Scenario 4, both will need to work to maintain the temperature in the acceptable range. Both space heater and water heater will be turned on.

A countdown timer will be triggered once a selection is made to maintain the determined working status of the space heater and the water heater for a specific duration (e.g. 5-minute, 10-minute, or 15-minute). During that period, the program will not compare the total power consumption with the power cap. This will reduce the communication needs between the device and the central controller to save the bandwidth and avoid frequent switching behaviors to prolong the appliance lifetime. When the specified duration is reached, the controller will once again examining the total power to see if it exceeds the threshold. Then, the controller may enter on of the four loops again for capping the energy consumptions in the household.

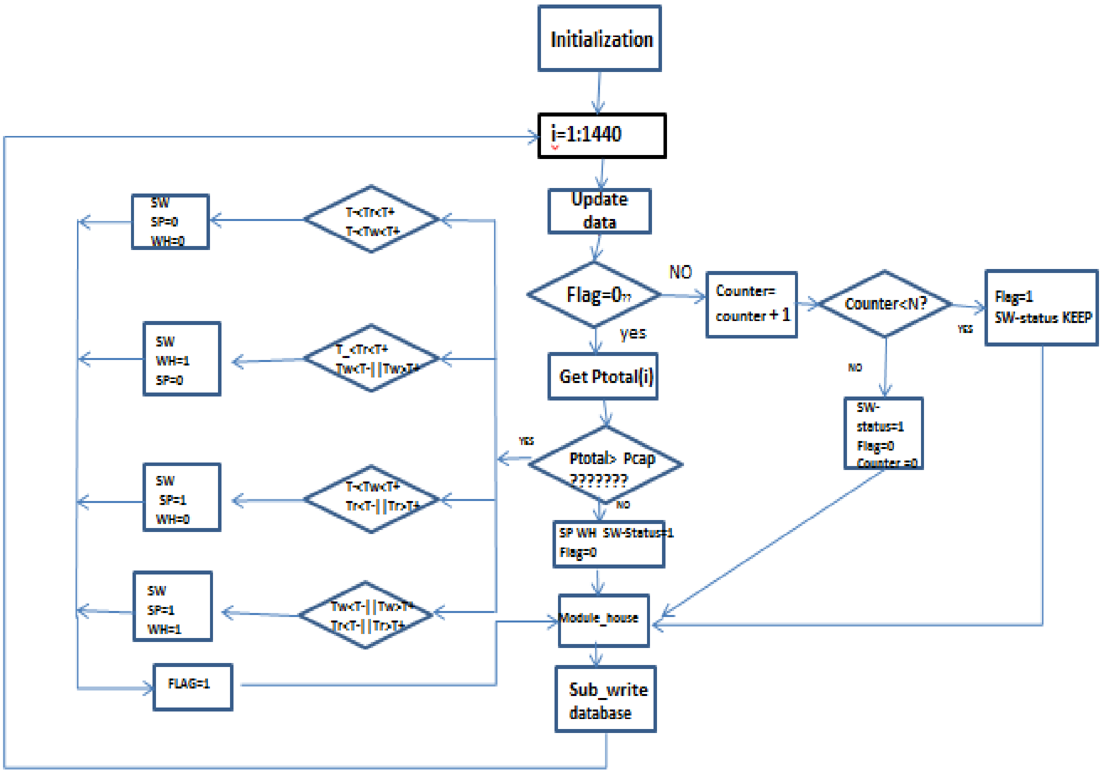


Figure 4.6. Control logic for rule-based control algorithm

There are two key parameters in this control algorithm logic: the power threshold and the timer for maintaining the same working status for a period of time. To test the robustness of the performance of the control algorithm, six operation conditions are designed for sensitivity analysis.

1. Low power threshold and low interference time: power threshold equals to 8KW, counter ceiling equals to 5.
2. Low power threshold and middle interference time: power threshold equals to 8KW, counter ceiling equals to 10.
3. Low power threshold and high interference time: power threshold equals to 8KW, counter ceiling equals to 15.
4. High power threshold and interference time: power threshold equals to 10KW, counter ceiling equals to 5.
5. High power threshold and interference time: power threshold equals to 10KW, counter ceiling equals to 10.
6. High power threshold and interference time: power threshold equals to 10KW, counter ceiling equals to 15.

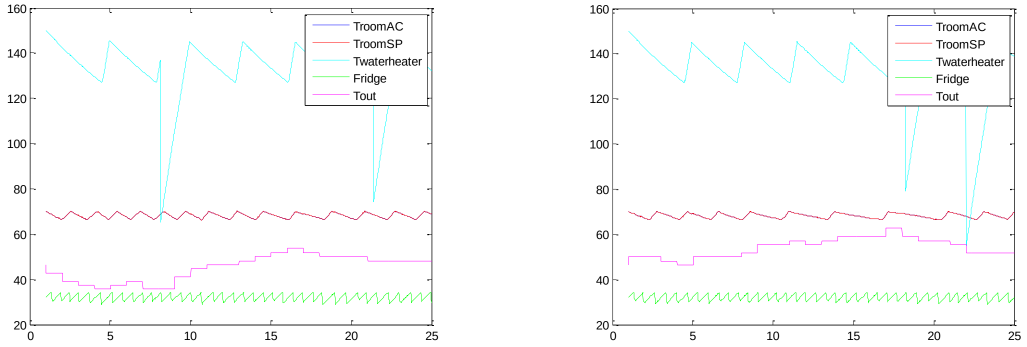
In order to test the robustness of the algorithm, three different temperature (see Figure 4.7) profiles in a winter season were selected. Under each temperature scenarios, there are three set of probability of use table implemented representing the low, medium, and high occupancy days. This setting may also represent for households in three different locations with three different load consumption patterns. We simulated 90 cases for each defined scenarios to generate a statistically stable results for evaluating the performance of the developed rule-based control algorithm.

Thus, we define one simulation run in a scenario as: 1) One of the three temperature profiles (cold, mild, and warm day in winter) is used; 2) one of the three probability of use settings (light use, regular use, and heavy use) is selected. In each scenario, we will run 90 times to represent 90 different load patterns generated for the same weather condition and the same loading pattern. In total, 6480 daily load profiles can be generated including 90 cases for each of the 72 scenarios including 3 day-types (cold, mild, warm), 3 energy consumption patterns (regular-probability1, light-probability2, heavy loading-probability3).

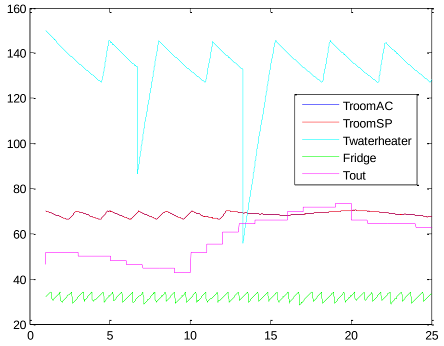
To evaluate the performance of this algorithm, three evaluation criteria were selected.

1. The first criterion is the time for total power consumption of the house to exceed the power threshold.
2. The second criterion is the maximum peak power of the house.
3. The third criterion is the number for space heater to change its switch status.

As both appliances are TCAs, the performance of which are similar. In the thesis, only the performance evaluation results of the space heater unit is presented.



(a) A cold day in winter (b) A mild day in winter



(c) A warm day in winter

Figure 4.7. Temperature profiles of the cold, mild, and warm days

4.3 Simulation Results for One Simulation Run

The results from one simulation run are presented in Figure 4.8-Figure 4.10. The left figure in Figure 4.8 shows the load profile without using the rule-based control algorithm for the cold day and regular load condition. There are three spikes that exceed a threshold of 10KW. The longer peak load period occurs between 17:00 to 19:00. The left figure in Figure 4.8 reveals that the reason for the spike to occur is the use of hot water during cooking. When the water heater unit is in use together with the range, dishwasher, cloth washer and TVs (See the left figure in Figure 4.8), the power spikes happen more often and last longer.

The right figure in Figure 4.8 shows the load profile with the rule-based control algorithm implemented (Cold/probability1/15-min Timer). As shown in the right figure in Figure 4.9, a huge water use occurs at around 8:00 p.m. and there are multiple appliances working during that period too (see Figure 4.10). However, once the total power consumption [30] exceeds 10KW, the control algorithm will intervene and regulate the consumption of the total load to be below the cap immediately. We can observe from the right figure in Figure 4.9 that the room temperature is not violated when the control is implemented.

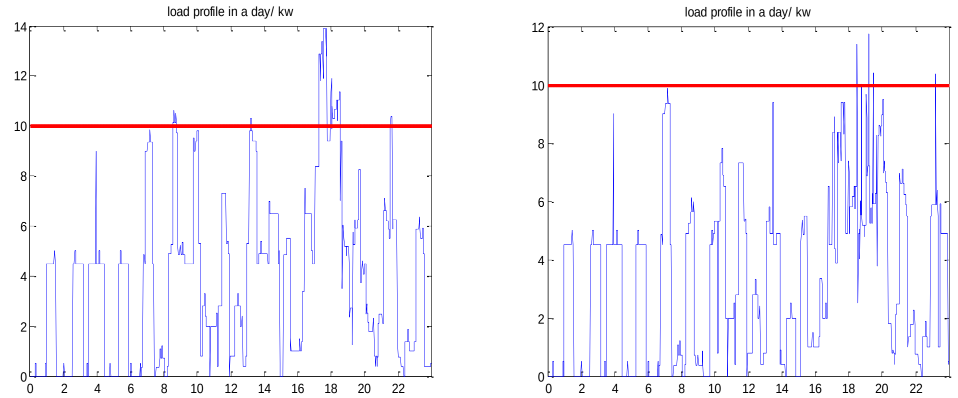


Figure 4.8. Load profiles without control and with control

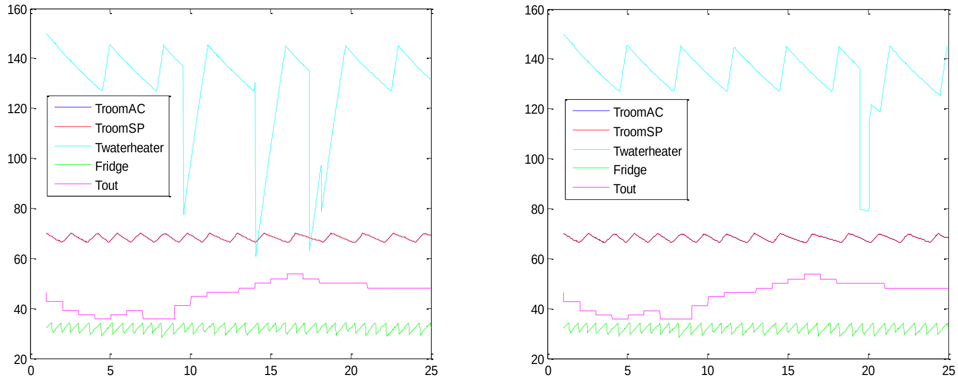


Figure 4.9. Temperature profiles of appliances without control and with control

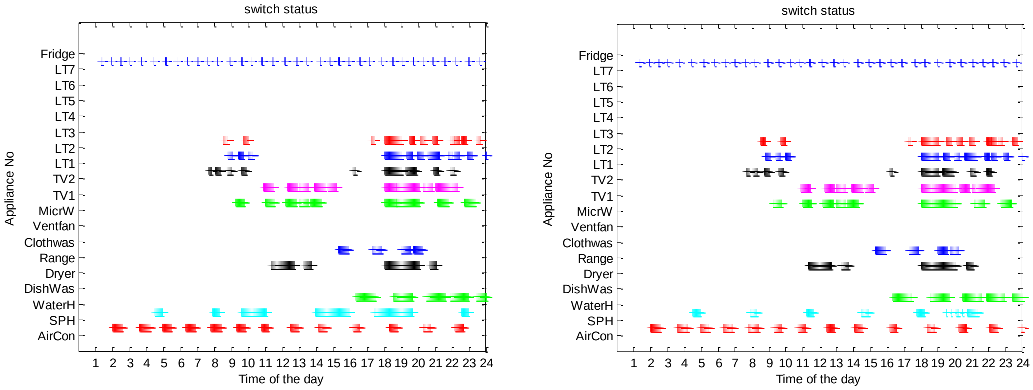


Figure 4.10. Switch Status of appliances without control and with control

Because results of a single run can only demonstrate that the performance of the proposed control algorithm is effective for this specific day and load pattern. To validate the algorithm performance under a range of operation conditions and evaluate the robustness of the algorithm, different house load patterns under different weather conditions will be needed for algorithm testing.

4.4 Simulation Results for Multiple Simulation Runs

As described before, 6480 daily load profiles are created to conduct 90 runs for each of the 72 scenarios. There are 3 day-types: cold, mild, and warm, as shown in Figure 4.7. There are three energy consumption patterns: regular-loading/probability1, light-loading/probability2, and heavy-loading/probability3). For each loading condition, we tested three timer settings: 5-min, 10-min, and 15-min.

The simulation results are summarized in Table 4.2 and Table 4.3. The following observations are made:

1. For the same day-type and loading-level, the algorithm performs very well when the power cap value is high. When power cap is low, the algorithm still performs much better than the no-control case but the violation duration and peak are increasing drastically, showing the capability of shifting energy consumption is weakened significantly.
2. The setting of the timer is very important. The 15-minute timer gives the best performance in nearly all the cases. This is because the average load consumption lasts longer than five minutes but shorter than 15 minutes.
3. The probability distribution plots show the actual distribution of the duration of the power cap being exceeded. It can show us how robust the algorithm is. As shown in Figure 4.11, if using a 8kW power cap, for the cold day with heavy-loading case, the duration of power cap violation can be very long if using a 5-minute timer, for the case with no control, the duration that power cap is exceeded ranges between 100 minutes to 290 minutes, while for the controlled cases, it is between 50 to 100 minutes, a 50% reduction by controlling only two appliances in the home.
4. As we can see that the range for distribution of peak power for worst case with control and no control are the same, however for with control cases the distribution between 15KW to 16KW are smaller than without control, which means that most houses with control have lower peak power than with no control algorithm scenario.
5. As shown in Figure 4.11 and Figure 4.12, even in the worst case, if with control, the average time of violation is 83.97 minutes, which is much smaller than 174.42 minutes of the no control case. The only drawback is that the peak power is 0.5KW higher than that of the no control case. However, the duration of the peak is normally very short. Therefore, considering the reduction in duration, especially knowing that the acceptable tolerate time for transformer to sustain an overloading condition is normally in the range of 5-10 minutes, the performance of the control algorithm is consistently better than the no-control case.
6. As we can see from Table 4.3, the average time for room temperature to violate the dead band are all zero for each case, showing that the algorithm does not compromise the customer comfort. The maximum and minimum average room temperatures are the same for with control implemented and with no control implemented.
7. The number of switching of the space heaters remains the same with or without con-

trol, showing no additional lifetime depreciation due to the implementation of the rule-based control algorithm performs.

8. Because we use timer for locking the appliance operation in a period of time instead of frequently checking the end device status, the communication time between the HEM controller and the end device is also minimized.

In conclusion, the simulation results clearly show that the rule-based control algorithm is robust and performs very well for shaving the peak power that occurred in different time-of-the-day.

Table 4.2. Results for evaluation influence on power grid and appliances

		Temperature1---Cold days									Temperature2---Mild days									Temperature3---warm days								
	Timer Setting (Minute)	POU 1 - regular			POU 2 - Light			POU 3 - Heavy			POU 1 - regular			POU 2 - Light			POU 3 - Heavy			POU 1 - regular			POU 2 - Light			POU 3 - Heavy		
		T_v^{AVE}	P_p^{AVE}	N_{SW}	T_v^{AVE}	P_p^{AVE}	N_{SW}	T_v^{AVE}	P_p^{AVE}	N_{SW}	T_v^{AVE}	P_p^{AVE}	N_{SW}	T_v^{AVE}	P_p^{AVE}	N_{SW}	T_v^{AVE}	P_p^{AVE}	N_{SW}	T_v^{AVE}	P_p^{AVE}	N_{SW}	T_v^{AVE}	P_p^{AVE}	N_{SW}	T_v^{AVE}	P_p^{AVE}	N_{SW}
Cap 8 (KW)	No control	160	12.7	14	147.5	12.8	14	174.4	13.7	14	111.4	12	9.9	108.2	11.8	10	109.9	11.9	9.9	102.4	13.1	5.9	93.6	12.6	5.9	101.2	13.3	5.9
	5	70.9	13.5	14	65.6	13.3	14	84	14.2	14	42.4	12.2	10	37.5	12.1	9.9	37.2	12.5	10	49.9	12.9	5.9	46	12.3	5.9	48.8	13.2	5.9
	10	57.9	13.6	14	52.2	13.1	14	57.4	13.4	14	30.8	12.3	9.9	26.2	12.2	9.9	25	12.3	9.9	44.2	12.9	5.9	39	12.2	5.9	43.3	13.3	5.9
	15	51.8	13.2	14	50.7	13.1	14	53	13.3	14	26.1	12.1	10	23.6	11.6	9.9	23.2	11.9	10	39.9	12.3	5.9	36.8	11.9	5.9	39.5	12.7	5.9
Cap 10 (KW)	No control	42.2	12.9	14	38.1	12.8	14	52.6	13.3	14	26.4	12	9.9	17.7	12	9.9	27.9	12	9.9	38.2	13.1	5.9	18.6	12.7	5.9	31.6	13.2	5.9
	5	11.6	12.8	14	7.7	12.8	14	14.7	13.4	14	4.4	11.7	10.0	2.4	11.6	10	5.8	11.9	9.9	7.8	12.7	5.9	3.5	12.6	5.9	7.7	12.9	5.9
	10	10.6	12.8	14	5.7	13	14	11.4	13.0	14	4.1	11.9	9.9	1.8	11.4	9.9	4.1	11.8	9.9	6.3	12.7	5.9	2.4	12.3	6	5.1	13	5.9
	15	6.9	12.6	14	4.1	12.6	14	10.6	13.3	14	2.7	12	10	1.6	11.5	10	2.9	11.4	9.9	5.0	12.4	5.9	2	12.1	5.9	4.7	13	5.9

N_{SW} : The average number of switching of the space heating unit for the 90 simulation runs in a scenario; T_v^{AVE} : The average of the total time power cap has been exceeded of the 90 simulation runs in a scenario; P_p^{AVE} : The average peak power of the 90 simulation runs in a scenario. POU: Probability of use

Table 4.3. Influence on customer comfort

		Temperature1---Cold days									Temperature2---Mild days									Temperature3---warm days								
	Timer	POU 1 - regular			POU 2 - Light			POU 3 - Heavy			POU 1 - regular			POU 2 - Light			POU 3 - Heavy			POU 1 - regular			POU 2 - Light			POU 3 - Heavy		
	(Minute)	T_v^{AVE}	$Tem_{\max}$	$Tem_{\max}$	T_v^{AVE}	$Tem_{\max}$	$Tem_{\max}$	T_v^{AVE}	$Tem_{\max}$	$Tem_{\max}$	T_v^{AVE}	$Tem_{\max}$	$Tem_{\max}$	T_v^{AVE}	$Tem_{\max}$	$Tem_{\max}$	T_v^{AVE}	$Tem_{\max}$	$Tem_{\max}$	T_v^{AVE}	$Tem_{\max}$	$Tem_{\max}$	T_v^{AVE}	$Tem_{\max}$	$Tem_{\max}$	T_v^{AVE}	$Tem_{\max}$	$Tem_{\max}$
Cap 8 (KW)	**No control**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**
	5	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**
	10	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**
	15	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**
Cap 10 (KW)	**No control**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**
	5	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**
	10	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**
	15	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**	**0**	**70.1**	**66.3**

T_v^{AVE} stands for average time to violate room temperature dead band, $Tem_{\max}$ stands for average maximum room temperature, $Tem_{\min}$ stands for average minimum room temperature, POU: Probability of use

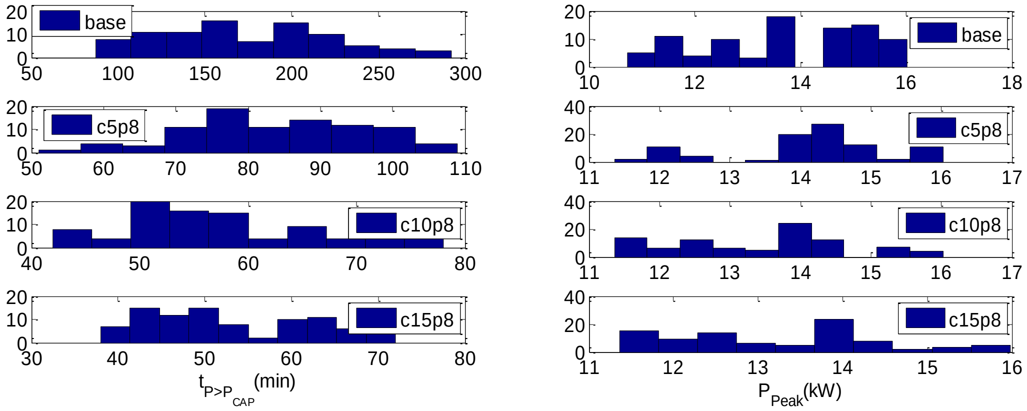


Figure 4.11. Duration and Peak Power distribution for a cold day with heavy loading (8kW power cap)

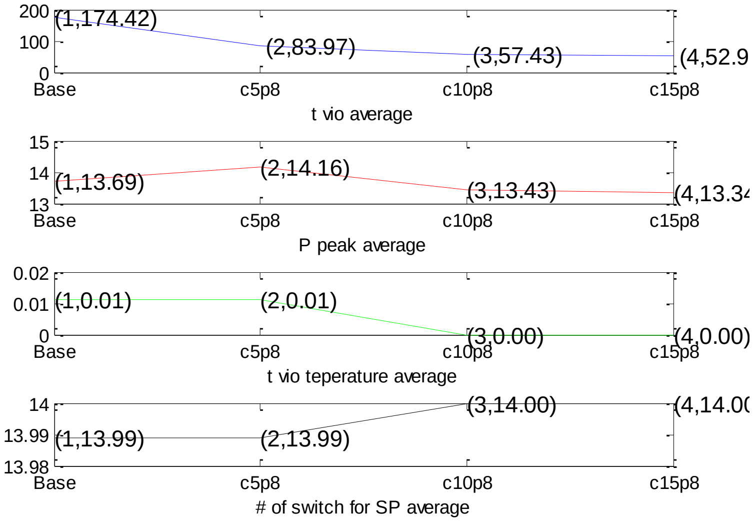


Figure 4.12. Average criterions for cold location POU3 with low power threshold

CHAPTER 5 CONCLUSION AND FUTURE WORK

In this thesis, a graphic user interface (GUI) for home energy management system is developed. Then, the software architecture of the HEM system is introduced. Finally, a rule-based control algorithm is developed, tested and evaluated.

The main contributions of this thesis are summarized as follows:

- Developed a graphic user interface (GUI) for the FREEDM smart home test system. The use of the GUI has substantially simplified the input of parameter settings and the display of simulation results. It is now being used as the main GUI for algorithm development and hardware testing.
- A HEM system software architecture is developed. The architecture design allows the algorithm development to be separated from the test system. Thus all the algorithms can be evaluated using the same simulation environment, offering a common simulation platform for HEM algorithm developers to implement and test their control algorithms on a standardized test bed.
- A rule-based control algorithm is developed for optimizing the energy consumptions of the HEM system by capping the home energy consumptions below a target power peak.

Our future work will focus on following directions:

- Develop the graphic user interface using Java or C/C++ to enhance the functionalities of the GUI interface and make it visual appealing.
- Extend the HEM system software architecture to multiple homes
- Enhance the robustness of the rule-based control algorithm and further improve the performance by incorporating a load forecaster.

REFERENCES

[1] Asare-Bediako, Ballard, Paulo F. Ribeiro, and Wil L. Kling. "Integrated energy optimization with smart home energy management systems." In Innovative Smart Grid Technologies (ISGT Europe), 2012 3rd IEEE PES International Conference and Exhibition on, pp. 1-8. IEEE, 2012.

[2] Xie, Qing, and Atif M. Memon. "Model-based testing of community-driven open-source GUI applications." In Software Maintenance, 2006. ICSM'06. 22nd IEEE International Conference on, pp. 145-154. IEEE, 2006.

[3] Liu, Qi, Hong Wei Qian, Bao Wei Wang, Jian Shen, and Nigel Linge. "An enhanced routing algorithm for congestion control in a home energy management system." In Consumer Electronics (GCCE), 2013 IEEE 2nd Global Conference on, pp. 438-439. IEEE, 2013.

[4] Ali, Dallia Morsi. "Energy capacity and economic viability assessment of the renewable hydrogen energy storage as a balancing mechanism in addressing the electric system inte-gration issues inherent with variable renewable energy resources." (2011): 51-51.

[5] Welch, David, and Mohamed H. Shwehdi. "An energy reading and bill generation database for use in nonintrusive load management." InTransmission and Distribution Conference, 1991., Proceedings of the 1991 IEEE Power Engineering Society, pp. 342-347. IEEE, 1991.

[6] Liu, Baoshi, and Qi Wei. "Home energy control algorithm research based on demand re-sponse programs and user comfort." In Measurement, Information and Control (ICMIC), 2013 International Conference on, vol. 2, pp. 995-999. IEEE, 2013.

[7] Adika, Christopher O., and Lingfeng Wang. "Autonomous appliance scheduling based on time of use probabilities and load clustering." In IPEC, 2012 Conference on Power & Energy, pp. 42-47. IEEE, 2012.

[8] Begg, I. M., D. J. Darvill, and J. Brace. "Intelligent graphic interface design: designing an interactive control room user interface." In Systems, Man and Cybernetics, 1995. Intelligent Systems for the 21st Century., IEEE International Conference on, vol. 4, pp. 3128-3132. IEEE, 1995.

[9] QIU, Haitao, and Yan WU. "Green Air-Conditioner Design." Ecological Economy 4 (2010): 038.

[10] Bates, E. "Development of transportable thermal-storage space heaters."Proceedings of the IEE-Part A: Power Engineering 104, no. 17 (1957): 415-423.

[11] Sun, Xiaofeng, and Xinjun Zhao. "Research on user experience design of household fridge." In Computer-Aided Industrial Design & Conceptual Design, 2009. CAID & CD 2009. IEEE 10th International Conference on, pp. 1244-1248. IEEE, 2009.

[12] Keding, Holger, Markus Willems, Martin Coors, and Heinrich Meyr. "FRIDGE: a fixed-point design and simulation environment." In Proceedings of the conference on Design, automation and test in Europe, pp. 429-435. IEEE Computer Society, 1998.

[13] Wang, Zhanle, and Raman Paranjape. "An Evaluation of Electric Vehicle Penetration under Demand Response in a Multi-Agent Based Simulation." InElectrical Power and Energy Conference (EPEC), 2014 IEEE, pp. 220-225. IEEE, 2014.

[14] Keoun, Bradley C. "Designing an electric vehicle conversion." In Southcon/95. Conference Record, pp. 303-308. IEEE, 1995.

[15] Klontz, K. W., A. Esser, R. R. Bacon, D. M. Divan, D. W. Novotny, and R. D. Lorenz. "An electric vehicle charging system with'universal'inductive interface." In Power Conversion Conference, 1993. Yokohama 1993., Conference Record of the, pp. 227-232. IEEE, 1993.

[16] Ali, Shady, and DoHyeun Kim. "Visualization methodology of power consumption in homes." In Open Source Systems and Technologies (ICOSST), 2013 International Conference on, pp. 55-59. IEEE, 2013.

[17] Zhi-Gang, Liu, and Huang Wei. "The design of smart home system based on Wi-Fi." In Computational Problem-Solving (ICCP), 2012 International Conference on, pp. 454-456. IEEE, 2012.

[18] Vergura, Silvano, and E. Natangelo. "Labview interface for data analysis of PV." In Clean Electrical Power, 2009 International Conference on, pp. 236-241. IEEE, 2009.

[19] Guo, Jiang. "An approach for modeling and designing software architecture." InEngi-neering of Computer-Based Systems, 2003. Proceedings. 10th IEEE International Conference and Workshop on the, pp. 89-97. IEEE, 2003.

[20] Jiang, Xuedong, and Guoji Song. "The database design for the control equipment man-agement system." In System Science, Engineering Design and Manufacturing Informatization (ICSEM), 2012 3rd International Conference on, vol. 2, pp. 261-264. IEEE, 2012.

[21] Lahti, Juha P., Petri Helo, and Ahm Shamsuzzoha. "Information flows and ICT-system interconnections in electricity supply chain wind power modelled." InICT and Knowledge En-gineering (ICT & Knowledge Engineering), 2012 10th International Conference on, pp. 175-181. IEEE, 2012.

[22] Kashimoto, Yukitoshi, Kanayo Ogura, Seiichi Yamamoto, Kiyotoshi Yasumoto, and Mi-nora Ito. "Saving energy in smart homes with minimal comfort level reduction." In Pervasive Computing and Communications Workshops (PERCOM Workshops), 2013 IEEE International Conference on, pp. 372-376. IEEE, 2013.

[23] Fung, C. C., S. C. Tang, and K. P. Wong. "A proposed study on the use of ICT and smart meters to influence consumers' behavior and attitude towards Renewable Energy." In Power and Energy Society General Meeting, 2010 IEEE, pp. 1-5. IEEE, 2010.

[24] Lu, Ning, and Yu Zhang. "Design considerations of a centralized load controller using thermostatically controlled appliances for continuous regulation reserves." Smart Grid, IEEE Transactions on 4, no. 2 (2013): 914-921.

[25] Du, Pengwei, and Ning Lu. "Appliance commitment for household load schedul-ing." Smart Grid, IEEE Transactions on 2, no. 2 (2011): 411-419.

[26] Nutter, Roy S., Y. V. Reddy, John M. Atkins, Ravi S. Raman, Alan W. Butcher, and David F. Tuthill. "An Expert System Design for Ventilation, Emergency Rescue, and Power Peak Shaving." Industry Applications, IEEE Transactions on 1 (1986): 97-101.

[27] Balijepalli, V. S. K. M., Vedanta Pradhan, S. A. Khaparde, and R. M. Shereef. "Review of demand response under smart grid paradigm." In Innovative Smart Grid Technologies-India (ISGT India), 2011 IEEE PES, pp. 236-243. IEEE, 2011.

[28] Abur, A., D. Shirmohammadi, and C. S. Cheng. "Estimation of switch statuses for radial power distribution systems." In Circuits and Systems, 1995. ISCAS'95., 1995 IEEE International Symposium on, vol. 2, pp. 1127-1130. IEEE, 1995.

[29] Enokido, Tomoya, and Makoto Takizawa. "An extended power consumption model for distributed applications." In Advanced Information Networking and Applications (AINA), 2012 IEEE 26th International Conference on, pp. 912-919. IEEE, 2012.

[30] Jomoah, Ibrahim M., Abdulaziz Uthman M. Al-Abdulaziz, and R. S. Kumar. "Energy management in the buildings of a university campus in Saudi Arabia—A case study." In Power Engineering, Energy and Electrical Drives (POWERENG), 2013 Fourth International Conference on, pp. 659-663. IEEE, 2013.

[31] Atipamula, Srinivas, and Ning Lu. "Evaluation of residential HVAC control strategies for demand response programs." TRANSACTIONS-AMERICAN SOCIETY OF HEATING RE-FRIGERATING AND AIR CONDITIONING ENGINEERS 112, no. 1 (2006): 535.

[32] Lu, Ning, David P. Chassin, and Steve E. Widergren. "Modeling uncertainties in aggre-gated thermostatically controlled loads using a state queueing model."Power Systems, IEEE Transactions on 20, no. 2 (2005): 725-733.

[33] Lu, Ning, and David P. Chassin. "A state-queueing model of thermostatically controlled appliances." Power Systems, IEEE Transactions on 19, no. 3 (2004): 1666-1673.

[34] Lu, Ning. "An evaluation of the HVAC load potential for providing load balancing ser-vice." Smart Grid, IEEE Transactions on 3, no. 3 (2012): 1263-1270.

[35] Du, Pengwei, and Ning Lu. "Appliance commitment for household load schedul-ing." Smart Grid, IEEE Transactions on 2, no. 2 (2011): 411-419.

[36] J. Kondoh, N. Lu, and D. J. Hammerstrom, “An evaluation of the water heater load potential for providing regulation service,” IEEE Trans. Power Syst., vol. 26, no. 3, pp. 1309–1316, Aug. 2011.

[37] Pouyioutas, Philippos, Evripides Zantides, Maria Poveda, and Aspasia Papadema. "Redesigning the User Interface of the InterLearning Software-Graphic Design Meets

Computer Science." In Information Visualization, 2006. IV 2006. Tenth International Conference on, pp. 811-834. IEEE, 2006.

[38] Begg, I. M., D. J. Darvill, and J. Brace. "Intelligent graphic interface design: designing an interactive control room user interface." In Systems, Man and Cybernetics, 1995. Intelligent Systems for the 21st Century., IEEE International Conference on, vol. 4, pp. 3128-3132. IEEE, 1995.

[39] Debije-Meessen, A. E. J., and J. A. H. Jansen. "The balance between Aesthetics, Usability and Corporate Identity: Graphic User Interface design within a commercial company." In Information Visualization, 2006. IV 2006. Tenth International Conference on, pp. 357-361. IEEE, 2006.