AALBORG UNIVERSITET
Student report

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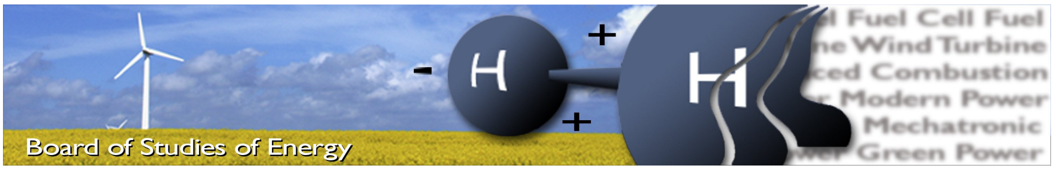
Flexible load management in Smart-grids

Master Thesis for Msc Energy Technology

Project report, May 2013



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SYNOPSIS:

This report describes the implementation of a demand side management system in a residential area. A study on washing machine and refrigerator operation is conducted, as well as the use pattern design. The optimal control of the appliances is done using the Matlab Optimization Toolbox for the purpose of minimizing the losses in the distribution lines, and the final price of the electrical energy for the customers. Finally the optimal operation pattern for the appliances is implemented in a model of the grid in DIgSILENT, to validate the line losses reduction an control the power quality.

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Copies:	3
Pages, total:	82
Appendix:	14

By signing this document, the author confirms that he has participated in the project work and thereby he is liable for the content of the report.

Preface

This Master Thesis project report, called *Flexible load management in Smart-grids* is written by Eloy Rodríguez Moldes in the period 1^{th} of September 2012 to 29^{th} of May 2013.

Reading Instructions

- Figures are numbered sequentially in their own chapter. For example Figure 1.3 is the third figure in the first chapter.
- Equations are numbered in the same way as figures but they are shown in brackets.
- References are specified in the text in square parentheses according to Harvard method. The bibliography is on page 43.

Acknowledgements

The author of this report would like to thank Pukar Mahat for his excellent guidance as a supervisor for this project.

Contents

Chapter 1

Introduction

1.1 Background

According to the *Energy Strategy 2050* of the Danish Ministry of Climate and Energy, 30% of total electricity is to be covered by renewable energy consumption by 2020.

During last years the Danish Power system has moved from a centralized model supported by large power production plants to a decentralized system. This change has been motivated by the introduction of renewable energy resources like wind and photovoltaic. However, the increases of this kind of generation facilities turn into in a stochastic energy supply system due to the high weather reliance.

One of the main problems in electricity networks, which becomes even bigger in grids with large renewable resources, is the load balancing. The imbalance between electricity production and consumption leads to the necessity of power plants with fast response (as CHP) and storage systems (as batteries), which are able to compensate random renewable generation. However, even with this solution, there is still a need for the conventional power plants which should run during the period of lower availability of renewable energy.

Other possibility is the actions on the demand side. The Demand Side Management (DSM) is load profile variation in order to change the consumption with production. By this management, it is possible to shift electricity consumption with respect to production or prices considerations, or both. Thereby, it is possible to take advantage of a possible prices policy with different time-variant tariff schemes. Various tariff schemes are discussed in detail in reference [1].

The adaptation to power production becomes of special interest in Smart-Grids where the energy available is not only limited, but also fluctuating. Furthermore, the energy efficiency can also be improved in large system with smart grid. That improvement bases on more efficient distribution, since the consumption power peak decreases, and consequently the losses should decreases too. Besides, it is possible to flatten the load profile, which leads to a better use and exploitation of the production systems, avoiding need of over-sizing.

Another use of DSM is the real-time response to fast variations on the production, which could be originated by wind gusts or any other stochastic generation. The dynamic response of thermal storage appliances as freezers and air conditioning could help to manage these by frequency regulation.

The objective with DSM is not to decrease the amount of energy consumed at a dwelling, but to increase the utilization and efficiency of the production, and transportation systems and decrease the total cost for the user [4].

1.2 Solutions approach

This project starts with a literature study in following fields:

- Study of Demand Side Management methods and relevance in Danish electrical system.
- Modeling of appliances and Time of use patterns.
- Programing optimization.

The next step is to fulfill the objectives in the problem formulation.

1.3 Prior work in the field

The optimal control of different scenarios of variable energy production in combination with a battery storage system has been presented in [8].
The current status for Demand Side Management and their challenges for integration in the network has been presented in [5].
Many pilot DSM projects have been developed around the world, reference [13] makes a comprehensive study on them.
Surveys referents to people time of use have been conducted in many countries in recent years [9].
Linear and nonlinear programing optimization is highly studied in [27].

1.4 Problem Statement

Demand side management (DSM) is able to adapt the electrical energy consumption by acting on the behavior of the loads. Today the control of loads is based in different tariff schemes to motivate the customer to move its consumption. Smart grids make possible monitoring and control of those individual electrical loads. The implementation of these systems improves the use of renewable energy, distribution system and can help to the customers to decrease the electrical bill.

The objective for this Project is to develop a demand side management based on household appliances. The specific objectives are as follows:

Objective 1: Identify and simulate two of the most important appliances in a household, dividing in subtasks;

Objective 2: Design an optimal control to manage the loads according to cost and electrical requirements;

Objective 3: Develop a realistic model of the system in DIgSILENT and test the controls designed according to voltage and frequency requirements;

1.5 Key assumption and limitations

In order to simplify the calculations only active power is considered.
Flexible pricing have not been considered.
Calculations are based on the combination of UK time use survey, and data from a residential area in Denmark.
The same washing program have been considered for all the washing machines.
Refrigerator opening doors is not considered, and food mass is taken as a constant value.
Communication infrastructure between utility company and final user is not considered.

Chapter 2

Flexible loads

As mentioned before, the Danish Power System's evolution has led to a decentralized power production scenario, contributing to significant power production of renewable resources. According to the annual report of the Danish Energy Agency, in 2011, the generation from RE was of 14% of the total energy production, and shows a growing trend in the use of this kind of energy.

The following table 2.1 summarizes the share of final energy consumption in Denamrk.

Table 2.1: Electrical Sectors in Denmark in 2011[6]

Concept	Energy in GWh	Percent
Total supply	45456	-
Exports	10375	-
Danish Consumption	35081	100%
Households	10156	29%
Total industries (transport, industry and services)	22537	64.2%
Losses	2388	6.8%

From the table above 2.1, it is seen that third part of energy is used to domestic supply. It is interesting indicate that the residential electricity has experienced a growth of 17% in EU-27 between the period 1999 to 2008, whereas in Denmark, it has even decreased [3]. Nevertheless it is a very significant part of the total Danish electrical system, and becomes of a special interest to apply a DSM, in order to decrease costs for end-user and losses in the distribution system.

2.1 Introduction to Demand Side Management

According to [2] "demand side management is is the planning, implementation, and monitoring of those utility activities designed to influence customer use of electricity in ways that will produce desired changes in the utility's load shape".

This definition covers the reduction in total energy consumption, but also the load shifting and customer generation, getting a more beneficial load profile. These benefits include economical and efficiency improvements, from generation utilities as well as distribution system or final consumer. In general a DSM considers loads able to react to external parameters. This consideration introduces the concept of *flexible load* with which, an utility will be able to adapt its consumption within a certain constraints.

The correct implementation of a DSM should maintain the same final services that the electrical grid provides to the users today. However, it is also possible to change the user habits, while maintaining the same comfort label.

In addiction, the security of supply is improved by DSM when renewable energy such as wind or solar are used. These type of electrical generation is associated with a high temporal variability since it can not be reliably dispatched or accurately predicted. Due to this, match generation and consumption becomes of a special interest. A correct combination of valley filling and peak shaving could aid to reduce this problem.

By using DSM programs, it is possible change the load profile shape as shown in Figure 2.1. The most common applications of DSM are as follow:

Peak shaving: Concerns the reduction of energy usage during intervals of high demand.

Valley filling: Refers to the increment of consumption during off-peak periods.

Load Shifting: Peak usage rescheduled to fit under lower threshold.

Other load-shape objectives are detailed in [2], *Strategic conservation*, *Strategic load growth* and *Flexible load shape*.

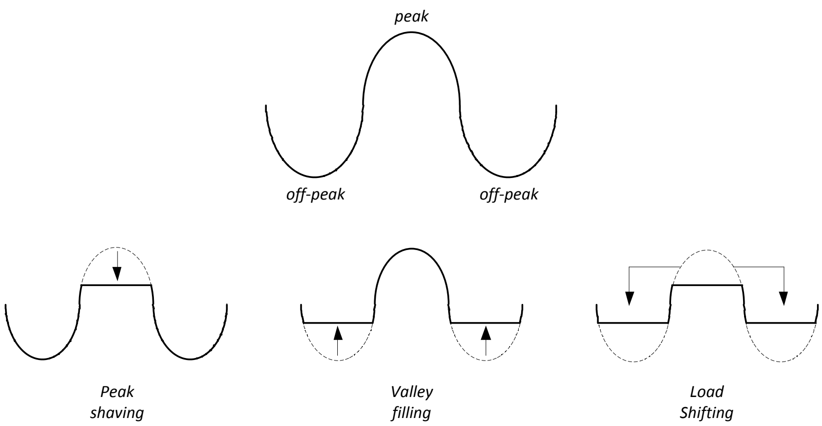

Figure 2.1: Load profile shapes

The peak reduction concerns the use of energy in critical periods. A reduction on power demand leads to a decrement in power losses. Higher the total demand, larger the transmission losses. Furthermore, other advantage of peak shaving, is a lower dependence of peak generators. This may be motivated by a economic reasons so as to, decrease the usually high operating costs and fuel dependence of generators during critical periods.

A proper load management could help to flatten the load profile, avoiding effects of intermittent generation and improving the efficiency of the system. The modification of the load shape by increasing the consumption in *off-peak* periods results in a better use of base generators. In that periods, the cheap energy from renewable sources or from sources with high disconnection costs, such as nuclear power plants, could be used.

DSM are intended to benefit both customers and suppliers. While the suppliers try to maximize profits by saving cost on production and distribution, the customers try to minimize invoice amount by using more efficient loads and adapting consumption with a price schedule. In this report, both problems have been considered. On one hand, the losses in the distribution line will be minimized by adjusting the loads and, on the other hand the cost of consumption will also be minimized by the rescheduling different process within some specific load.

2.1.1 DSM methods

The different methods of DSM are defined according to the interaction level between consumer and supplier [10], some of the most common methods are summarized below.

1. **Energy saving and Load efficiency**

It refers to efficiency improvements in electrical equipment, which results to a reduction in energy consumption. New control is required once the new equipment has been installed. The effects on the electrical demand are indirect, since it focuses on power reduction regardless of consumption schedule.

2. **Pricing models**

It bases on energy regulation by means of price incentives. The main idea is the introduction of various energy prices at different periods during the day. The differences in price might be adequate both in quantity and time, to motivate customers to vary its consumption habits [1]. That prices can be established in advance, for example in the energy supply contract, or it can be daily updated or even in real time, basis on many parameters factors. Three of these managements are briefly explained in next paragraphs.

Time of use tariff (TOU): This method is based on the definition of time blocks with different prices, which reflect the average energy cost during these periods. For example lowest prices during the night.

Critical peak pricing (CPP): The high prices are allocated in periods where the generation cost is very high, usually due to a lack in generation or an excessive consumption. The objective is to promote a peak shaving (Figure 2.1).

Real time pricing (RTP): This kind of tariff reflects the variations in the market, usually in hourly periods. For example fluctuations in fuel price. This method moves the prices uncertainty from the supplier to the final user.

3. Direct load control

A centralized control system is able to connect or disconnect a specific load. This method requires a direct communication between client and supplier. DLC is normally used for loads of the same type. The most suitable appliance to implement this method are those with a thermal inertia, due to the possibility of be disconnected for some time and still keep its temperature in an adequate range [28].

4. Demand side bidding

This concept refers to the offers of energy reduction from the customers to the suppliers. It opens a new market with energy offers from both sides. The possibilities to sell energy from distributed generation systems, like solar panels, already exist, but demand side bidding will enable a new way of interaction.

5. Frequency control

The frequency represents very effective method to measure power imbalances. From a nominal value of 50 Hz, a decrement means a decrement in production, which should be properly compensated with a reduction in the consumption, and conversely.

6. Energy storage

Different systems of energy storage are used to balance the power. The main idea is to store energy when there is excess of production or the price is low, and discharge the energy when the production is low or the price of electricity is high. This kind of systems includes for example chemical batteries, appliances with thermal inertia or large hydroelectric power plants with pumping systems.

In general this activities involves the introduction of power monitoring (measurement), control and actuation systems such smart meters, which exceeds the scope of the present report. Apart from that, the policies to assist the development and implantation of DSM are not considered.

2.2 Residential electricity demand

The Energy consumption of domestic appliances has been widely measured in European countries. The following table 2.2 shows the results of a study conducted in 2007 in EU-15 [7]. The table includes the most common appliances in EU and its contribution to annual electrical consumption. The power rating is also summarized, however this data is based on [20], which includes a concrete model for each appliance and may vary for different models and types (e.g. Filament bulbs or fluorescent tube are included on lights). Nevertheless the values fit with other publications such as [4].

According to [7], lights and appliances represent more than 50% of the electrical consumption of which 33% corresponds to refrigerators and washing machines. Many reports which describe a DSM in household appliances make a group differentiation on it according to the use priority [4], [11]. That means the possibility to

Table 2.2: Household appliances consumption[7][20]

Appliance type	Relative contribution (%)	Power Rating (Watts)
Residential electric heating (c)	21.3	2200
Refrigerators (c)	14.5	177
Miscellaneous	13.3	-
Lighting	10.8	60
Electric storage water heater (p)	9.2	2000
Consumer electronics and standby equipment	6.4	-
Electric hobs (c)	5.3	2509
Central heating circulation pumps	4.3	-
Washing Machines (p)	3.7	2056
TV-on mode	2.8	130
Electric ovens (c)	2.1	2500
Dishwashers (p)	2	2200
Driers (p)	1.8	2700
Office equipment	1.4	-
Room air-conditioners (c)	1	-

defer the start of a concrete appliance according to the characteristics of the task which it does. If the running of an appliance could be postponed, the electrical consumption which corresponds to that particular machine could also be shifted, helping to adapt the load profile to any requirements considered.

The ability of an appliance to be postponement is indicated on the table 2.2 by (p). These appliances are washing machines, dishwashers and drier machines. The large consumption corresponds to the washing machine and it is also a more common appliance than drier or dishwasher [7]. A detailed study of washing machine management and division in subtasks is presented in chapter 3. Other devices as electronic chargers could be also included, however the impact in terms of energy is too low in comparison to the three mentioned before. One of the most interesting management ways is the subdivision of the profile, in different tasks as proposed in [12]. It is also important to consider the maximum deferrable time, according to user choices or to the necessity of be completed to run other appliance after the first one (e.g. drier after washing machine).

The table 2.2 also provides information about less flexible equipment. This refers to utilities which are used continuously, indicated by (c). However some of them may have some possibilities to shift as briefly explained before. The electrical heaters, coolers and refrigerators are appliances which have the biggest impact in load consumption, as it can be seen in the relative contribution from table 2.2. These appliances have, in common, the function of a temperature maintenance, which could be assumed as a thermal storage [14]. Hobs and ovens, although are not running at all time, can be also considered as an adaptive device. The main advantage of implement a DSM on these devices, is the possibility of activate and deactivate the appliance, and at the same time keep the temperature in an acceptable range. The refrigerator is one of the most appropriate device to implement a

DSM due to the relatively big range of temperatures for the food to be preserved.

The third group of appliances includes those that are not possible to shift, and any change in their power consumption profile could affect to its operation. This group includes appliances like lights, TV or some office equipment.

2.3 Study cases

For this project, a residential area in Aalborg has been considered. The place consists of 15 houses in three streets. A 10.5/0.42 kV transformer, whose main characteristics are included in table 2.3, supplies the power into the grid. The grid is made of 15 PVC and 4 paper distribution lines, the reference number, length and resistance are listed in table 2.4. Figure 5.1, in Chapter 5 shows the modeled grid in DIgSILENT.

Table 2.3: Transformer data

Nominal Power	400 kVA
High voltage side	10.5 kV
Low Voltage side	420 V
Frequency	50 Hz
Internal Impedance	4.0 %

Table 2.4: Distribution lines

Reference number	Length (meters)	Resistance (ohms)
Line 1	28.4	0.0055
Line 2	50.3	0.0097
Line 3	86.6	0.0167
Line 4	130.7	0.0252
Line H1	31.8	0.0062
Line H2	38.5	0.0075
Line H3	16.9	0.0033
Line H4	20.9	0.0041
Line H5	28.1	0.0055
Line H6	34.8	0.0068
Line H7	15.1	0.0029
Line H8	20.3	0.0040
Line H9	14.1	0.0028
Line H10	28.4	0.0055
Line H11	20.3	0.0040
Line H12	45.9	0.0090
Line H13	63.6	0.0124
Line H14	26.2	0.0051
Line H15	22.3	0.0043

The dwellings consumption have been calculated from the Danish hourly consumption for houses without electrical heating, and the measured annual energy consumption for each household. The load profile for the whole system is shown in Figure 2.2.

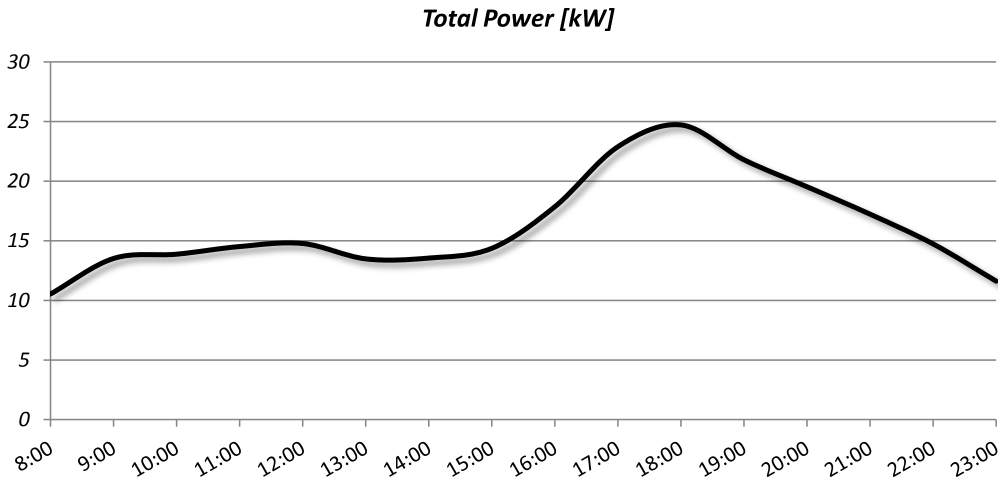

Figure 2.2: Total Power profile for the system

Chapter 3

Appliances

As explained before, two of the most appropriate appliances, in a household, for DSM according to the amount of energy consumption, are washing machines and refrigerators. This chapter provides an analysis of both devices, in order to understand their operation and decide a correct management of flexible consumption.

3.1 Washing Machine

The first considered domestic appliance for DSM has been the washing machine. It is seen from the table 2.2 that the annual energy consumption of the washing machine represents the largest among the deferrable appliances.

Basically, there are two different types of washing machines (horizontal axis and vertical axis) which have been produced by leading manufacturers for the last years. The main difference between them is the drum rotational axis direction. However, nowadays the vertical axis is not popular due to the biggest water and energy consumption [15]. As a result of the low energy consumption, horizontal axis is the most used in Europe and all the models considered as the most energy efficient household washing machines are with horizontal axis [16].

The basic design of a horizontal axis washing machine consists on an electrical motor, connected to the drum where the laundry is washed, and a water heater. As it is explained in next paragraphs, during a wash cycle, high and fast variations occur in the drum. Thus it needs a motor capable of satisfying these requirements. One of the motors, which can be easily used to this purpose and also generally used in washing machines is an induction motor [19] [17].

In a normal washing cycle, three different processes occur, wash mode, rinse mode and spin mode [18]. These mode are briefly explained in the next section in order to get a better understanding of the washing process. These modes can be different for each manufacturer and program.

1. **Wash mode**

The objective of this mode is to remove the dirt of the laundry. The drum speed for a wash mode is typically 30-45 rpm [17]. During this mode hot water is supplied at the chosen temperature program. As it is shown in the load profile (Figure 3.3), the water heater increases the energy consumption compared to rinse and spin modes, and it is the main energy consumer. The wash mode uses a small amount of water which generates high torque in the load when wet and heavy clothes drop from the drum's highest point [17][18].

2. **Rinse mode**

During this process, the cleaner is removed from the clothes by using cold water. The speed is the same as in wash mode however the torque decreases as shown in Figure 3.1. It is because of the greater use of water. The maximum torque is developed when the laundry drops from the drum's highest point to the bottom. During this cycle the drop distance is decreased due to the bigger water height in comparison with wash mode, and therefore the torque is less. It is not necessary to heat the water; consequently the energy consumption for this mode is smaller than in wash mode.

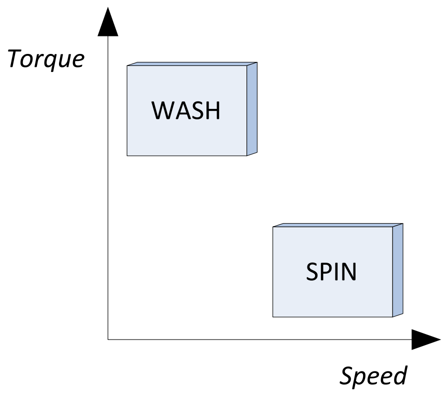

Figure 3.1: Comparison of the wash mode and the spin mode[18]

3. **Spin mode**

During this mode, the water is removed from the laundry due to high speed drum revolution. The spinning speed varies for different programs, however for ten of the most efficient washing machines in Europe, the maximum spin speed are between 1400 and 1800 rpm [16] . During this mode the high speed precludes the laundry drop due to centrifugal force, therefore the torque developed by the motor is smaller than in other modes. This explains the low energy consumption in Figure 3.3. The maximum speed is raised by steps of lower speed as shown in Figure 3.2.

Figure 3.3 shows the energy consumption measured for a washing machine at 1200 rpm maximum spin speed and 40°C water temperature for the wash mode [20].

In order to develop a flexible demand for the washing machine the understanding of the whole cycle is necessary. From the Figure 3.3, it can be seen that during wash mode the heater is working continuously for 20 minutes and the drum turns

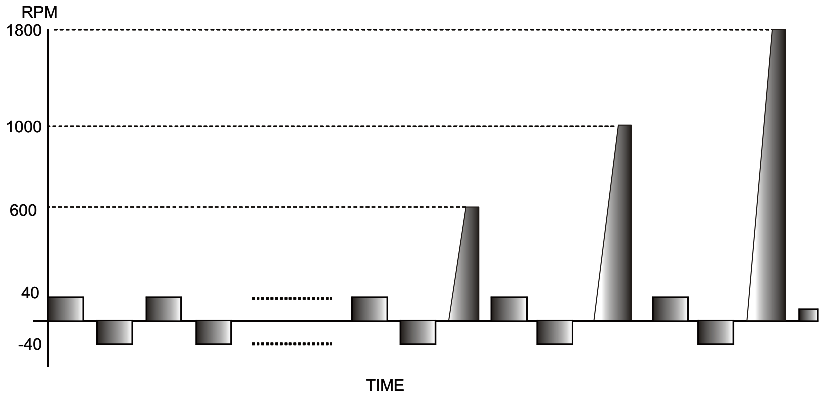

Figure 3.2: Speed Profile of the Washing Cycle[17]

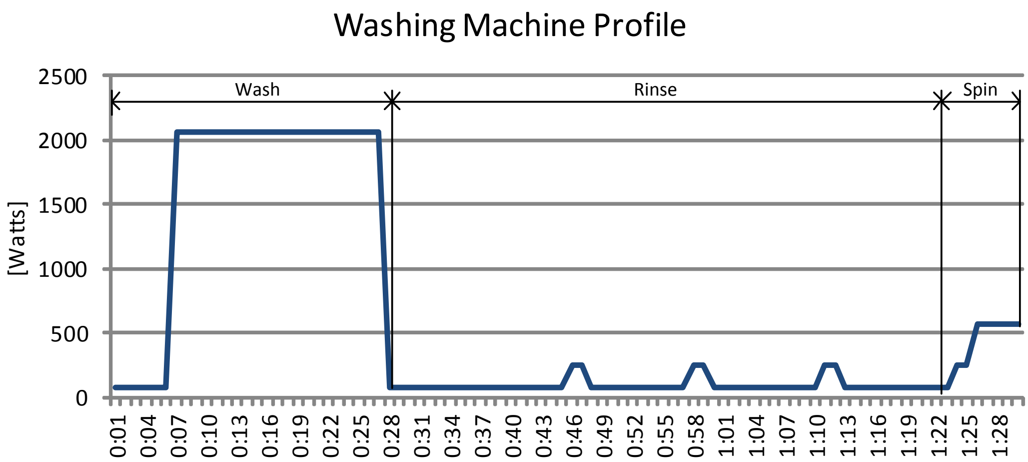

Figure 3.3: Consumption of a washing machine cycle in Watts and modes

have a low influence in the energy consumption. However in raise and spin modes the drum turn consume all the energy in four peaks between 250W and 568W. That indicates three turns at maximum speed in rinse and one in spin mode.

In order to develop a flexible demand for the washing machine the consumption profile has been divided in according to the three cycles, also shown in Figure 3.3:

Cycle 1: 30 minutes, 2056W peak consumption, 730Wh.

Cycle 2: 50 minutes, three peaks of 250W, 78.5Wh.

Cycle 3: 10 minutes, 568W peak , 60Wh.

The subdivision in three cycles does not introduce any problem in the total wash since, as explained they are different processes, with different objectives, which start in a specific time and have a discrete duration. Also almost all the washing machines include a stop function which is able to halt the cycle and restart it again after some time. Usually the wash is restarted from the beginning of the cycle (Zanussi ZWI 71201 WA), but some of them are able to restart from the same point into the cycle within a restart time less than 10 minutes (Whirlpool W10468366A). For this project, the possibility of introduce a delay of 30 minutes between cycles is considered. This is a similar option to the technology *Tumble Fresh Option* of Whirpool which provides a periodic tumbling after a wash when the laundry is not unloaded.

3.1.1 Use Pattern

The system is implemented in the test scenario in Aalborg as explained before, however it is not realistic that all the houses use the washing machine at the same time. In this section the most probably time to wash for each of the 15 dwellings is studied.

According to the directive 2010/30/UE, which is the regulation followed to determine the yearly consumption of appliances in the European Union, a washing machine performs 220 cycles/year. Base on this assumption, the probability of wash on a normal day is 0.65. For the considered case in Aalborg with 15 houses, the number of houses which uses the washing machine per day is 10. This high number of washes is not only justified by different loads for color and white clothes, but also because around 85% of the washes are not a full load cycle [15].

The behavior of a typical home washing machine and its effects as a flexible load has been analyzed in previous section. An efficient DSM should try to adapt the behavior of the appliances to operate in a most proficient schedule, without depending on the habits of the users. It should adapt its operation within the range between users' preferred start and finish time. For example if a user runs the washing machine at 24:00, it is possible to run the wash during the whole night, since it is very likely that the clothes are not need before the morning. In order to determine the most probably washing time for each household, a study on the washing habits is necessary.

Models to predict the load profile of a dwelling has been widely studied [21],[22],[23]. Most of these methods are based on time of use surveys, by relating a particular activity with the use of an appliance. Some of the most complete time of use surveys have been conducted in Sweden, Norway or UK. Reference [9] reviews most of these reports. In Denmark, the *ELMODEL-bolig forecast model* has collected data for the last 30 years, however the unavailability of data in English is a limitation for use. In this project, the UK time use survey conducted in 2000 has been provided by the UK Data Archive, University of Essex, and it has been considered.

The Time Use Survey (TUS) shows how people use their time in a 24 hours basis, with ten minutes resolution. Two different data are obtained according to weekdays and weekend days. The TUS indicates, each 10 minutes, the proportion of households where at least one occupant is engaged in a particular activity (in that case using the washing machine). From this data, the most probable time for wash is calculated, and represented in Figure 3.4.

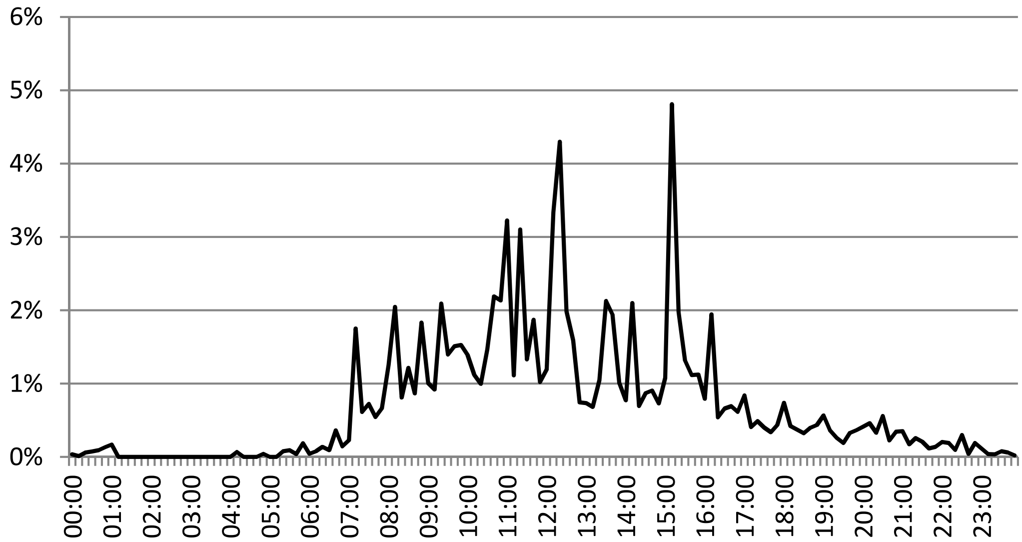

Figure 3.4: Houses using the washing in a week day from TUS

From Figure 3.4, it is not easy to see clearly tendency in washing times due to the large discontinuity in daily profile between 7:00 and 16:00. The number of houses, using the washing machine in a specific time, are lower than 5% of the total houses in the best cases, and values adjacent to these maximum points have a large deviation from them. Therefore, it seems to be difficult to extract a clear trend with the available data.

Some papers, which develop models for daily electricity consumption, based in user practices, obtain a high correspondence with measured values; however they identify the washing machine profile as the most critical predictable appliance. In general, deferrable activities, denoted in table 2.2 by (p), introduce the most frequently discrepancies [22].

The accumulative frequency graphic shown in Figure 3.5 represents the proportion of wash cycles which have been started by a specific time, and it is a good indicator to establish a use pattern basis on the most probably wash time during each wash cycle.

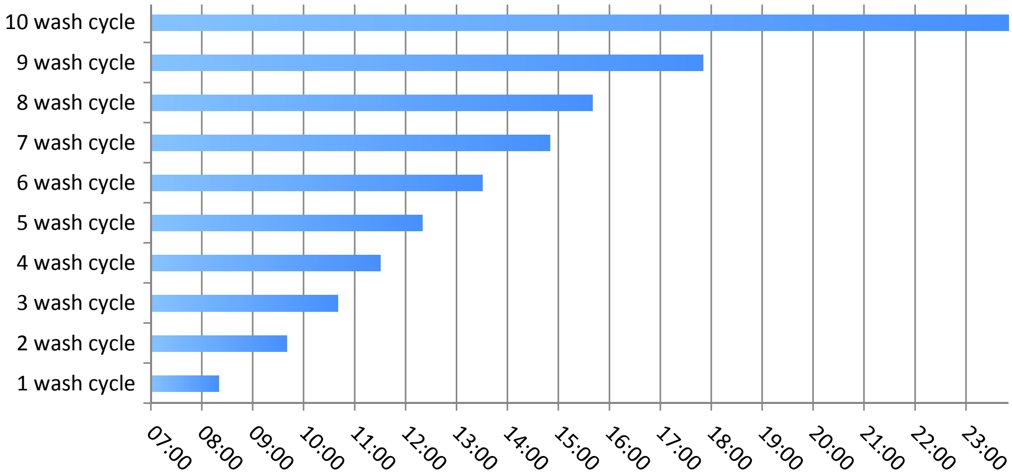

Figure 3.5: Accumulative frequency graphic for 10 washes

However, this information is not enough to determine the start time. With the aim of improve the accuracy for washing time prediction, another relation between washing machine use and household occupancy level, is considered. The use of some kind of appliances is not related with people's habits, for example the refrigerator is running regardless of the user. However, other appliances usage pattern, is strongly related to the occupied period. For example, when people are not at home, microwave is not be used. The washing machine start is included in the second group [24].

In order to obtain a more detailed simulation, the households have been divided in five different occupancy patterns as proposed in [24]. The unoccupied periods have been based in job time and child care considerations. Table 3.1 summarizes the unoccupied periods for each kind of household.

Table 3.1: Occupancy pattern for a three-person household [24]

Pattern	Unoccupied period
a	9:00-13:00
b	9:00-16:00
c	9:00-18:00
d	13:00-18:00
e	Always occupied

The occupancy profile is not included in the TUS, however some studies on this database have determined the occupancy level by using sophisticated methods basis on Markov-Chain technique [25]. Moreover the relation between household occupancy and watching TV activity has been considered. The connection of these parameters have been analyzed by the Pearson correlation coefficient (r). It provides a measurement about the degree of linear relationship between two parameters, regarding the goodness of fit. Pearson correlation coefficient leads in a strong correlation of 0.8. The determination factor (R^2) indicates how much variance of the data is explained by the linear regression, and for this case it is of 64%. These values shows a high relation between dwelling occupancy evolution and watching

TV activities. Moreover, the TV using is a easily measurable factor, and could be used for a real time implementation of the system based on smart meters and communication systems.

Watching TV values cannot be assumed as occupancy levels, since it is possible be at home without watch the TV. However the proportion of houses watching TV and the proportion of occupancy experiment a similar evolution [25], consequently TV watching activities has been used to compare occupancy at different times.

According to Table 3.1, it is assumed that there is full occupancy from 18:00. Relating a 100% occupancy on this time with the average of TV-watching for the same period, it is possible to obtain the unoccupancy level as the difference between this value and the value of people watching TV in a specific time. The results of these calculations and the association with the 15 households considered are shown in table 3.2.

Table 3.2: Unoccuped houses

Period	TV watching (%)	Unoccupied houses	nr of houses
18:00-0:00	73.6%	0%	0
9:00-13:00	39.4%	46.5%	7
13:00-16:00	41.4%	43.7%	7
16:00-18:00	47.6%	35.3%	5

From this data it is possible to define the following equations:

$$A + B + C = 7$$

$$A + B + D = 7$$

$$A + D = 5$$

where A, B, C and D represents the number of houses which follow the occupancy pattern a, b, c and d respectively. Since there must be at least one for every pattern, the constraints below have been also considered:

$$\begin{gathered} A + B + C + D \leq 14 \\ A \geq 1 \\ B \geq 1 \\ C \geq 1 \\ D \geq 1 \end{gathered}$$

The feasible solutions for the equation system are shown in Table 3.3. The first solution has been randomly taken. It leads in the less number of dwellings with full occupancy (26.7%). This solution results in a 6.6% of houses of type a, 13.3% of type b and 26.7% of types c, d and e. Figure 3.6 summarizes the occupancy level for each household, where the continuous line represents the occupancy. The houses 1 to 10 are those which use the washing machine.

Finally, the accumulated frequencies, presented in Figure 3.5, are used to determine which house uses the washing machine, placing the start time for a wash

Table 3.3: Occupancy pattern for a three-person household [24]

A = 1	B = 2	C = 4	D = 4
A = 2	B = 2	C = 3	D = 3
A = 3	B = 2	C = 2	D = 2
A = 4	B = 2	C = 1	D = 1

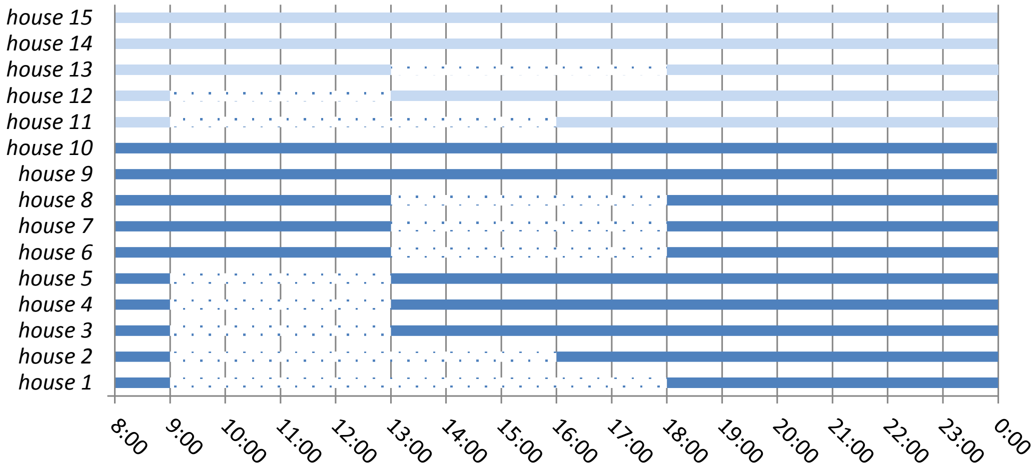

Figure 3.6: House occupancy pattern

in a period of occupancy. For example, it is not possible start a wash at 10:00 in house 1, since Figure 3.6 shows that the house is not occupied. The exact time has been determined by calculating the most probable time from TUS data, for each accumulated period. The finish time is the first time when the house is occupied again after an unoccupied period, or the duration of the total wash cycle (90 minutes) plus 1 hour (30 minutes between each mode). The possible time for use for the washing machine for the 10 houses are shown in Figure 3.7.

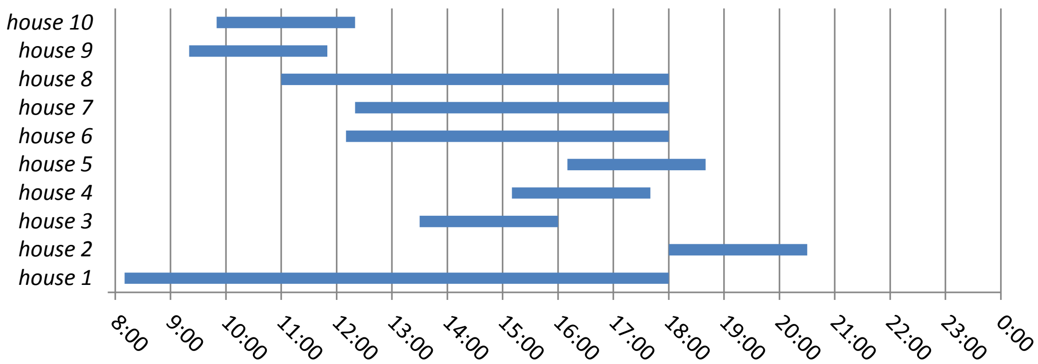

Figure 3.7: Washing machine using time

3.2 Refrigerator

Refrigerators and freezers represent the second largest energy consumption in a household (Table 2.2). In this category, chest freezers, fridge freezers, upright freezers and refrigerators are included. The most common freezer appliance is the fridge with refrigerator and chest freezer [20], however for this project a simple refrigerator has been considered due to simplicity reasons. Moreover, the simulation of a fridge freezer is based on the same principles than a refrigerator, but considering two cooling devices: refrigerator and chest freezer. Another limitation for the model is the temperature variation due to number of door openings. Variations in food stored is neither considered.

In recent years, the improvement in refrigerators design has made possible a consumption of 156 kWh/year [16]. However most of the refrigerators reviewed consume between 200 and 300 kWh/year with a rated power around 90 and 150 W. This amount of peak power is not very significant, however the possibility of coordinating various refrigerators of different households, becomes interesting in order to adapt consumption in real time [4]. The use of a thermal storage device to DSM has been already studied in the literature [29] [30], based on this idea the thermal characteristics of a refrigerator are studied, and related with its load profile.

The function of a refrigerator is to preserve the aliments in a correct temperature, which usually is between 3 and 8°C [31]. The operation to maintain the temperature in the desired range is shown in Figure 3.8, and it consists of basically in running the compressor when the superior temperature is reached; stop the cooling at inferior limit, and keep off the cooling until the temperature increases again.

The DSM is done by changing the temperature limits (which always should be included in the original limits, set between 3 and 8°C) according to the necessities of the system. That is, when an optimal point (according to economic and energetic considerations) is reach, it is possible turn off the refrigerator, decreasing the total cost and power losses in moments with high prices, and high power request. In the case of a reduction in energy price or consumption decrement the refrigerator is turned on.

A very important factor in the energy consumption is the temperature of the room where the refrigerator is placed and the number of times of door opening [32]. For this project the room temperature is assumed as constant in 21°C, since the freezer is usually placed at kitchens, and it is the standard temperature for a house [31]. As mentioned, the effect of door opening is not taken into account.

The temperature evolution related with electrical power required has been described by [33] and is characterized by equation 3.1.

$$T(t+1) = \varepsilon \cdot \mathrm{T}(t) + (1-\varepsilon)(T_{amb}(t) - \frac{\eta \cdot P(t)}{A}) \tag{3.1}$$

The parameters are described in table 3.4. In [30] the differential equations from 3.1 are presented in order to obtain the temperature evolution for warming or

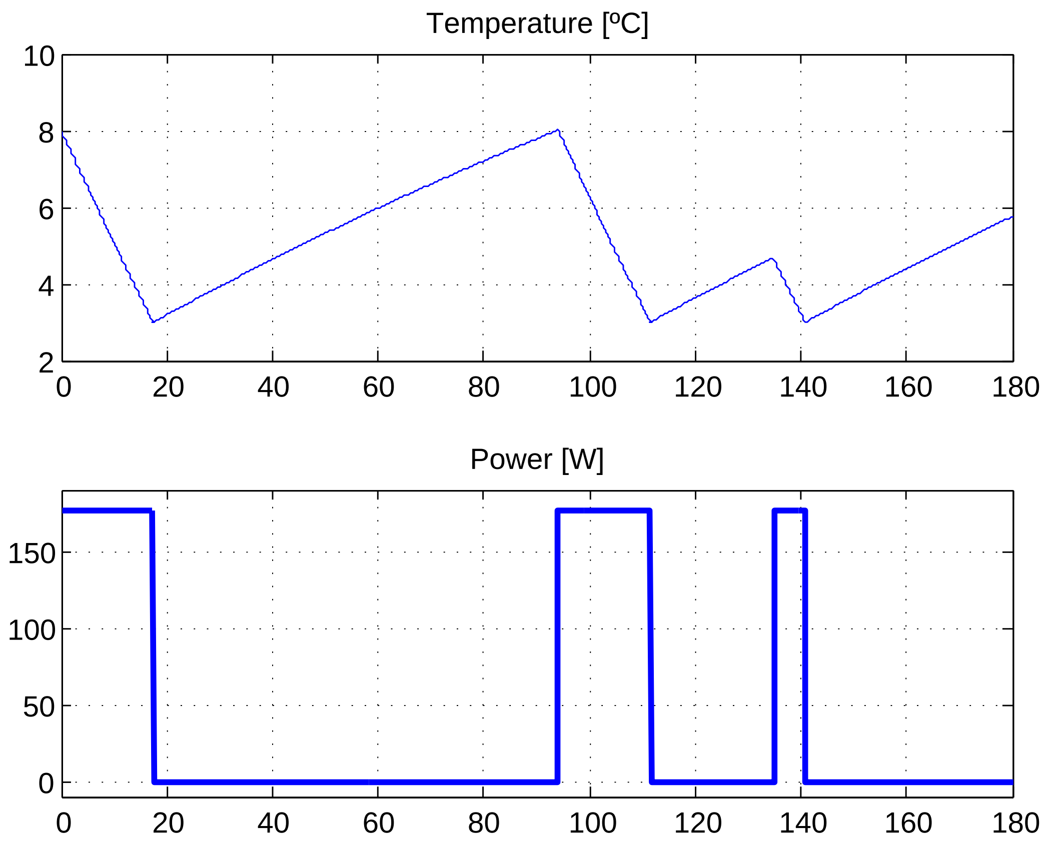

Figure 3.8: Power vs Temperature evolution in the refrigerator for 180 minutes

cooling. This equations determines when the compressor is switched *on* 3.2 or *off* 3.3.

$$T_1(t) = \frac{T_1(t_1) - T_{ON}(t_1)}{e^{-\frac{A}{mc}t_1}} e^{-\frac{A}{mc}t} + T_{ON}(t) \tag{3.2}$$

where $T_{ON}(t) = T_{amb}(t) - \frac{\eta \cdot P(t)}{A}$

$$T_2(t) = \frac{T_2(t_1) - T_{amb}(t_1)}{e^{-\frac{A}{mc}t_1}} e^{-\frac{A}{mc}t} + T_{amb}(t) \tag{3.3}$$

where,

Table 3.4: Refrigerator parameters

ε	factor of inertia	-
η	coefficient of performance	3
A	thermal insulation	6 W/°C
mc	thermal mass	1500 J/°C
$Tamb$	ambient temperature	22 °C

From equations the system has been simulated in *Matlab*. The scrpit, allows the introduction of a switching schedule, in order to obtain the power profile. The numerical values used for the simulation are included in table 3.4. This values, used in [29], represent a good approximation to the refrigerator dynamics. Figure 3.8 presents a 3 hours simulation from the *Matlab* model. As can be seen a complete cycle takes 95 minutes. The considered refrigerator has a nominal power consumption of 177 W during 18 minutes. For simplification reasons the complete cycle will be considered as 100 minutes and the working time per cycle of 20 minutes. This assumption leads in an energy demand of 59 Wh for a complete cycle.

The model runs autonomously, keeping the temperature in the limits, and provides the power profile as shown in Figure 3.8. However, it is able to respond to an external order. If an increment in consumption is required, the refrigerator power output will increase if the temperature is decreasing, and similar process is followed for a consumption decrement. However, if an increment is required and the compressor is already running, or the temperature is in the lower limit, no modification will occur. This phenomenon occurs in the minute 135 of the Figure 3.8, when an increment in consumption is required. After the temperature hits the lower limit, the compressor switches off and the temperature increases until 8°C.

Although the refrigerator is a continuous run appliance, some modifications can be done in its load profile in order to obtain a better performance. As mentioned before, the variations are based in an external signal which activates or deactivates the compressor. This idea is based on direct load control (DLC). By this management, it is possible to introduce the optimal control schedule for the refrigerator.

For this project, two different scenarios has been considered to manage the refrigerator. The first one refers to a normal operation, where the temperature never exceeds 8°C. However, it is possible to move the cooling periods within the time range in order to obtain a better performance in price or energy losses. For example it is possible bring forward a cooling period, as shown in Figure 3.8 in minute 135, if there is a lower price at that time.

The extension of the temperature range, results in a larger cycle duration. This management makes possible to maintain the refrigerator in *on* or *off* during continue periods of more than 20 or 80 minutes respectively. It is because, decrease from a temperature greater than 8°to 3°needs more energy, and consequently a larger *on* period. In contrast it is possible maintain the refrigerator in *off* during more time starting from 3°C, until a temperature greater than 8°C. The benefit of longer periods in *on* or *off* is to take advantage of time intervals, where running the refrigerator entails a lower price or energy losses, and on the contrary avoid unfavorable periods.

Due to simplicity reasons, in order to match up the time intervals from power consumption with the washing machine use pattern, the activation periods are of 10 minutes durations. A increment of temperature from 8°C, during an extra period of 10 minutes, results in a maximum temperature of 10.5°C. This second scenario considers a cycle duration of 150 minutes and 30 running minutes. The optimal control will be obtained for both cases and compared with the original management.

Chapter 4

Optimization

In order to achieve the minimum losses in distribution lines, and electricity cost for final user, an optimization of the washing machine and refrigerator use has been conducted. This chapter provides a detailed explanation of how the grid is modeled in Matlab. Chapter 3 focused on the behavior of the washing machine and refrigerator from the point of view of technical operation and time of use. These characteristics and limitations are used here to model the electrical system according to operation requirements.

4.1 Problem Formulation

The representation of the power system, presented in section 2.3, can be simplified as a power source (the transformer) connected to multiple loads (the houses). For each household, five different loads have been considered. Four of them are variable loads, which corresponds to the three washing cycles and one to the refrigerator, as Figure 4.1 clarifies. This design have been chosen in order to consider loads with the same power consumption along the time, and implement an on/off actuator in that loads. Finally the last load represents the remaining household energy consumption.

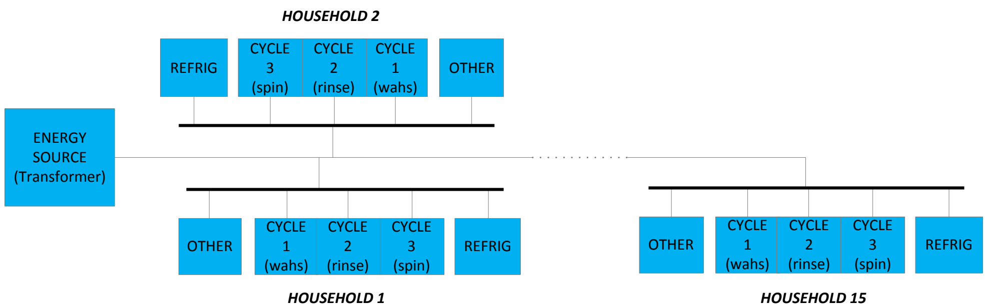

Figure 4.1: Block diagram of smart grid system

The washing machine pattern limits the time of use from around 8:00 to 0:00 Figure 3.7, in order to simplify the optimization system and reduce the calculation time this has been considered as the optimization period. The analysis resolution (time steps) is determined by the smallest operation time of the appliances, in this case it is 10 minutes, which corresponds to the last washing cycle (spin). A smaller resolution will result in a better control of the temperature in the refrigerator, since increments of 1°C or even 0.5°C could be considered. However it implies an increase in the number of studied steps, which results in a much higher run time of the optimization algorithm.

Therefore 96 *steps* of ten minutes has been considered from 8:00 to 23:50. Hence for each of the variable loads represented in Figure 4.1, a vector of 96 elements is defined. According to the on/off control technique, the values are limited to one when the specific load is activated, and zero otherwise. This vector is denoted by x_{app}, where *app* represents the considered appliance (wash, rinse, spin or refrigerator).

$$x_{app} = \left(\begin{array}{cccc} x_{app}^{1}, & x_{app}^{2}, & \dots & x_{app}^{96} \end{array} \right) \tag{4.1}$$

The load profile of a particular appliance is then calculated with equation 4.2, where P_{app} symbolizes its rated power. On the other hand if the energy consumption E_{app} is multiplied element by element to the activation vector, the sum of the result is the total energy consumption from 8:00 to 0:00 (equation 4.3).

$$Appliance\ power\ profile = x_{app} \cdot P_{app} = \left(\begin{array}{cccc} P_{app}^{1}, & P_{app}^{2}, & \dots & P_{app}^{96} \end{array} \right) \tag{4.2}$$

$$Total\ energy = \sum_{i=1}^{96} x_{app} \cdot E_{app} \tag{4.3}$$

The extension of this vector x_{app}, to include all the flexible loads, leads in a 5670 elements vector which contains all the desing variables for the smart power system. Consequently, this is the solution to the optimization problem.

$$\overbrace{\underbrace{x_1 \quad \dots \quad x_{96}}_{wash} \quad \underbrace{x_{97} \quad \dots \quad x_{192}}_{rinse} \quad \underbrace{x_{193} \quad \dots \quad x_{288}}_{spin} \quad \underbrace{x_{289} \quad \dots \quad x_{384}}_{refrigerator}}^{house1} \quad \dots \quad x_{5670} \tag{4.4}$$

Once the electrical network has been mathematically modeled, next step is to define objective functions for the optimization problem. Next sections describe the energy cost function as well as the power losses function.

4.2 Energy cost function

The energy cost function refers to the total price that the customers pay for use the washing machine and refrigerator. The appropriate activation and deactivation of appliances is directly related with the spot market, so that the activation occurs at a minimum, while the user requirements are not modified. The energy cost function is formulated as follows:

$$C = \sum_{h=1}^{15}\sum_{i=1}^{96}({x_{wash}}_i^h \cdot E_{wash} + {x_{rinse}}_i^h \cdot E_{rinse} + {x_{spin}}_i^h \cdot E_{spin} + {x_{ref}}_i^h \cdot E_{ref} +) \cdot Price_i \tag{4.5}$$

4.3 Losses function

The studied scenario, presented in 2.3, corresponds to a radial network. Consequently the real power loss has been calculated according to the equation 4.6 presented in [34], but leaving out the imaginary part as explained in limitations.

$$P_{Loss} = \sum_{m=1}^{N}\sum_{n=1}^{N} \alpha_{mn} \cdot P_m \cdot P_n \tag{4.6}$$

where: $\alpha_{nm} = \frac{r_{mn}}{V_m \cdot V_n} cos(\delta_m - \delta_n)$

variables:

- P_{Loss}= Power loss on the distribution lines.
- P_m, P_n= Power at bus *m, n*.
- N= number of busses.
- r_{mn}= resistive part of the element *m, n* in the impedance matrix of the system.
- V_m, V_n= Voltage at bus *m, n*.
- δ_m, δ_n= Phase angle at bus *m, n*.

The adaptation of the general power loss equation to the study case results in equation 4.7.

$$\begin{aligned} P_{Loss} = \sum_{i=1}^{96}\sum_{m=1}^{20}\sum_{n=1}^{20} \alpha_{mn}(P_m^i + {x_{wash}}_m^i + {x_{rinse}}_m^i + {x_{spin}}_m^i + {x_{ref}}_m^i) \\ \cdot(P_n^i + {x_{wash}}_n^i + {x_{rinse}}_n^i + {x_{spin}}_n^i + {x_{ref}}_n^i) \end{aligned} \tag{4.7}$$

Although the voltage and phase angle change with power variations, it remains almost constant because it may not vary much, and consequently α has been considered as constant. The values of V and δ have been obtained from a load flow conducted in the DIgSILENT model, which is presented in Chapter 5.

The result of equation 4.7 does not represent any final result for minimization, since it is the sum of power loss for each period. However, it represnets the total power loss, and it is an effective value to account for the minimization of total energy losses. The real value of energy loss will be calculated by using the DIgSILENT model.

4.4 Optimization using Matlab Optimization Toolbox

For this project, the optimization solvers implemented in Matlab are used. Matlab Optimization Toolbox includes several optimization methods, which can be used according to the specific requirements and characteristics of each problem. These algorithms allows users to solve constrained and unconstrained continuous and discrete optimization problems. Functions for linear, nonlinear, quadratic, integer and multiobjective programing are included. The standard form, for a minimization problem in the optimization toolbox [35], is as follows:

$$\begin{aligned} \overset{min}{x}\ f(x) \\ \text{subject to} \\ G_i(x) = 0 : \text{ equality constraints evaluated at x} \\ G_i(x) \leq 0 : \text{ inequality constraints evaluated at x} \\ x_{low}, x_{upper} : \text{ parameter bounds} \end{aligned} \tag{4.8}$$

It is seen from equations 4.5 and 4.7, that the cost minimization is defined by a linear function, while the power loss function is nonlinear. The explanation of the mathematical model of section 4.1, shows that a integer programing with 0-1 boundaries is required.

4.4.1 Constraints

Equality and inequality constraints have been designed for both washing machine and refrigerator. The main constraints refer to the total energy consumption per appliance. The implementation of this equation has been already presented in 4.3. This expression includes the design parameter vector x, which corresponds with activation periods. Consequently its sum results in the total time when a specific appliance is running. According to Figure 3.3, these times are 30, 50 and 10 minutes for wash, rinse and spin respectively. However the refrigerator activation time depends of the total period considered (16 hours) but also of the initial temperature. For this project three different temperatures has been considered: 3, 5.5 and 8°C. These values have been randomly assigned for each of the 15 households. Hence this consideration leads on three total running times of 18, 19 and 20 minutes, which have been calculated using the Matlab script for the refrigerator dynamics.

Besides the general energy constraints, other particular limitations have to be considered for each kind of appliance. For the washing machine, it can have only one cycle at a time and maintain the correct order of operation (wash, rinse and spin). In addition, the cycles cannot be broken.

Finally, the constraints necessary for the refrigerator have been designed depending on the initial temperature, and the maximum temperature which could be reach for each individual refrigerator. The upper bound temperature can be chosen from the scenarios described in section 3.2, a normal operation on 8°C (scenario 1) or 10.5°C (scenario 2). While the initial temperature has been randomly assigned to each refrigerator, the temperature range leads in two different kind of inequality constraints.

The bounds have been set according to the use pattern calculation (Figure 3.7) for the washing machine, while for the refrigerator the whole period is considered as feasible, and the limitations are introduced exclusively by the constraints equations.

4.4.2 Solver Functions

As conclusion the minimization problem includes the following requirements:

- Integer boundaries solution set (binary).
- Linear Cost function.
- Nonlinear Loss function.
- Inequality linear constraints.
- Equality linear constraints.

However any of the solvers present in Matlab Optimization Toolbox fulfills all the requirements. In order to achieve a proper optimization, the minimization problem has been divided in two subproblems. First refers to the cost optimization, which has been processed by using the *bintprog* solver. This algorithm is based in dual-simplex and branch&bound methods. Dual-simplex is a common method to solve linear functions, widely explained for example in [27]. Branch&bound method is an iterative optimization algorithm which finds the best integer solution for a given problem, based in a tree structure of feasible solutions [36]. The bounds are 0-1 non selectable.

On the other hand, the loss power function has been solved using the optimizer *fmincon*. *Fmincon* solves nonlinear functions, with linear and nonlinear constraints, within a selectable range of bounds. This solver uses gradient based search methods. That means that the minimum is obtained by computing the values pointed by the gradient of the objective function, until a minimum is found. This method is based on the knowledge that the gradient vector points in the direction of maximun increase of a function [37]. Hence one of the task of the optimizer is to calculate the search direction. Some methods can be chosen in *fmincon* solver, in this project the *interior point* method has been used due to a smaller run time in contrast with other methods with a better accuracy but much longer run time.

Gradient search methods need an initial point from where the gradient is calculated. The initial point for *fmincon* is the optimal for a minimum energy cost (result of the cost optimization with *bintprog*). However the result is not an integer solution.

The noninterger result is actually a weighted solution of the optimal integer point. It means that each single objective value has a significant value for the minimum result, and the greater numbers represent the most beneficial activation intervals. The proposed methodology carries several optimizations using *fmincon*, and after each optimization the solution and the boundaries are improved.

It is done by fixing to 1 (activate) the biggest value of the solution, and adapt the boundaries according to the characteristics of this point. For example if it corresponds to a spin cycle all the other points for this cycle are set to 0. This iterative optimization procedure is repeated until an integer solution is obtained.

Figure 4.2 presents a overview of the optimization process, the complete code as well as the constraint construction is included in Annexes. In summary, a linear optimization based in Dual-simplex method is conducted for minimize the price of the energy that the user pays. Based on that solution several nonlinear gradient search optimizations, find the closest activation schedule to the cost optimization, which makes minimum the power losses on the system. It is important to note that while the optimal solution for cost is a global minimum, the result from losses optimization may not be. This is because a nonlinear function is not necessarily convex, and consequently the solution point can be a local minimum.

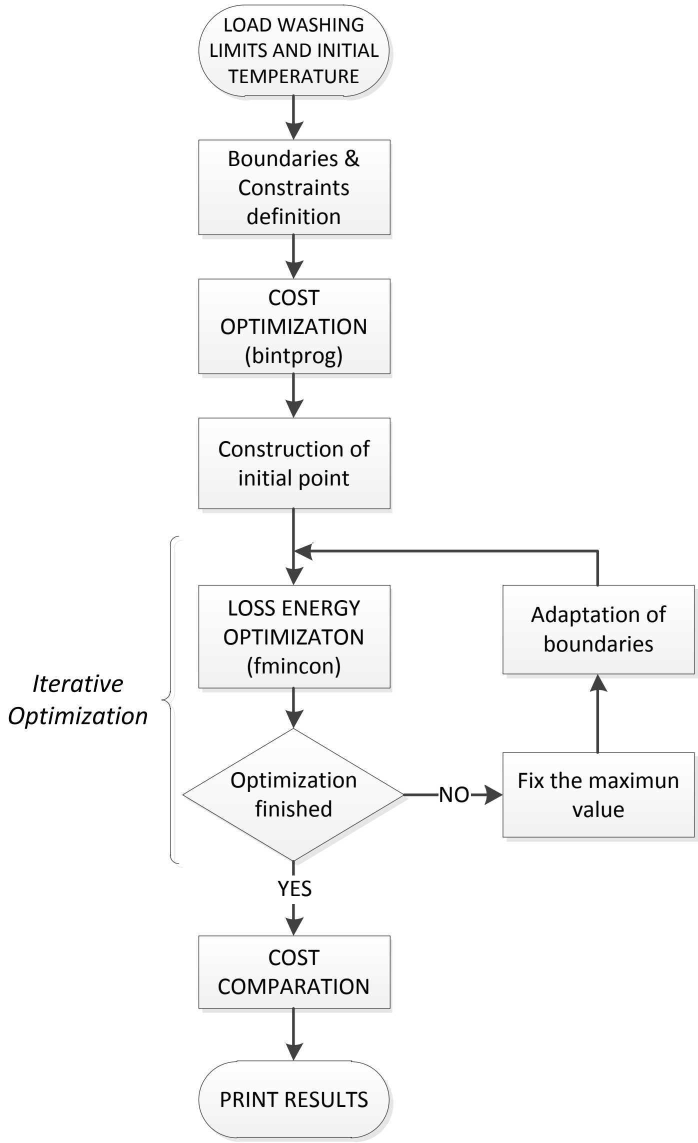

Figure 4.2: Flow Chart general algorithm

4.5 Optimization results

This section presents the results of the optimization process explained in Figure 4.2. The specific study place has been described in 2.3, as well as the power profile and the transmission lines characteristics, which are necessaries to compute the power losses in equation 4.7. The use pattern of the washing machine is deduced in Figure 3.7. The behavior of the refrigerator has led in two different scenarios of maximum temperature (8°C and 10.5°C) described in 3.2.

Finally the price evolution of the spot market from 8:00 to 23:00 is shown in figure 4.3.

Table 4.1 shows the time interval where the washing machine can be used, as

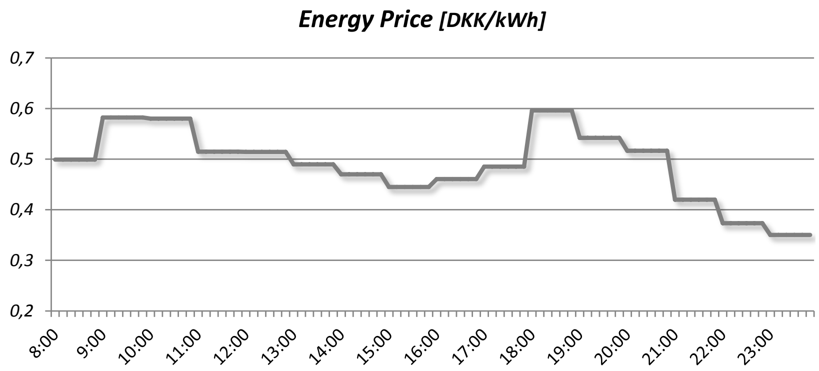

Figure 4.3: Spot Market price for electricity

well as the total duration of this interval. The initial temperature for each house is also included. Finally, the optimal schedule times for each washing cycle is shown. The results are for the Scenario 1, however the schedule for Scenario 2 is similar, except in four houses, where the variations are less than 30 minutes, and it is not shown.

		INPUTS				*OUTPUTS*	
House	Start	Finish	Duration	Initial temperature	Wash	Rinse	Spin
1	9:20	11:50	2:30	3	10:00	10:40	11:30
2	-	-	-	5.5	-	-	-
3	11:00	18:00	7:00	8	15:20	16:10	17:00
4	12:10	18:00	5:50	3	15:10	15:40	17:00
5	15:10	17:40	2:30	5.5	15:10	15:40	16:30
6	8:10	18:00	9:50	8	15:10	15:40	16:40
7	-	-	-	3	-	-	-
8	13:30	16:00	2:30	5.5	14:10	14:40	15:40
9	-	-	-	8	-	-	-
10	9:20	11:50	2:30	3	15:10	15:40	16:30
11	-	-	-	5.5	-	-	-
12	9:50	12:20	2:30	8	10:40	11:10	12:00
13	16:10	18:40	2:30	3	16:10	16:40	17:30
14	-	-	-	5.5	-	-	-
15	18:00	20:30	2:30	8	18:00	19:10	20:10

Table 4.1: Optimization inputs and washing time results (Scenario 1)

Figure 4.4 presents a comparison of the refrigerator temperature of house 1, for the three cases. In this case the solution for the Scenario 2 never decreases to 3 °C, it is a good example about how the optimization algorithm maintains the temperature in the range between 3 and 10.5 °C. However, the optimal activation to decrease cost and energy losses results in frequent activations of small duration during peak hours, which keeps the temperature between around 6 and 8 °C, but still inside the temperature range for Sceanrio 2.

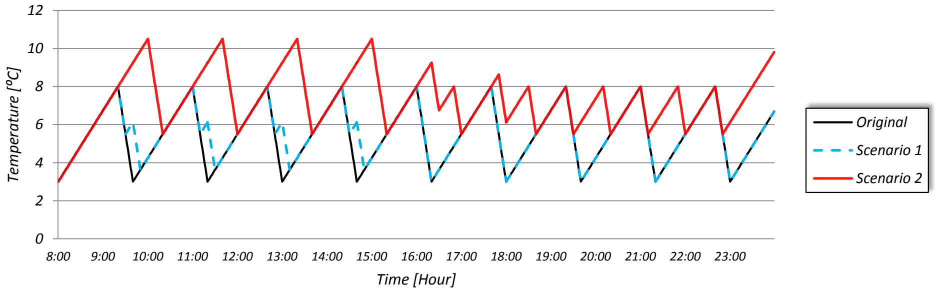

Figure 4.4: Temperature in refrigerator of house 1 for the three scenarios

As seen in table 4.1 above, the new washing times have been placed in the cheapest periods of energy price in Figure 4.3. The total prices for each house, before (Original) and after the optimization for scenarios 1 and 2, are shown in Figure 4.5.

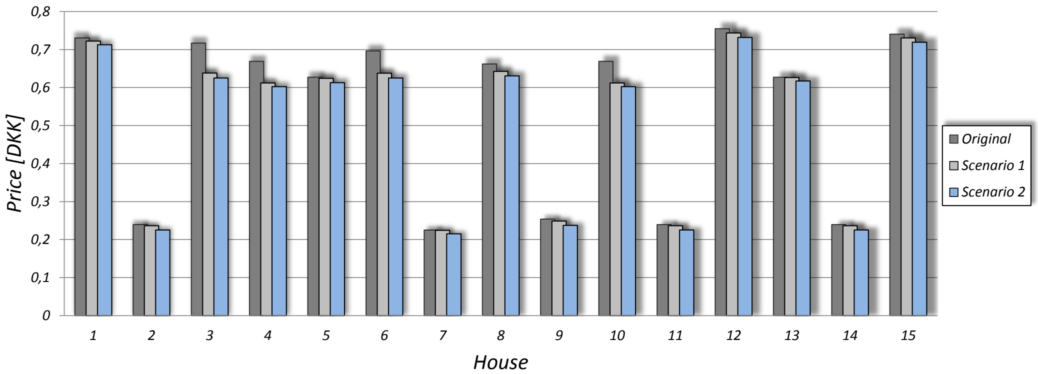

Figure 4.5: Prices per house for each Scenario

For the Scenario 1 the total price reduction is 3.9%, while for Scenario 2 the reduction is of 6.0%. The annual amount of money saved is 116.67 DKK and 177.23 DKK respectively. However, it is important to remark that the real amount is bigger than the current, since the simulation is conducted from 8:00 to 24:00, and a 24 hours simulation will result in a higher amount of money saved, since 8 hours more will be computed. Besides, that result is based in the spot market price, while the price for the final user is higher. As conclusion the algorithm presented conducts a successful minimization of the price paid for the final user. As expected the scenario 2 presents a profitable result. Figure 4.6 summarizes this results.

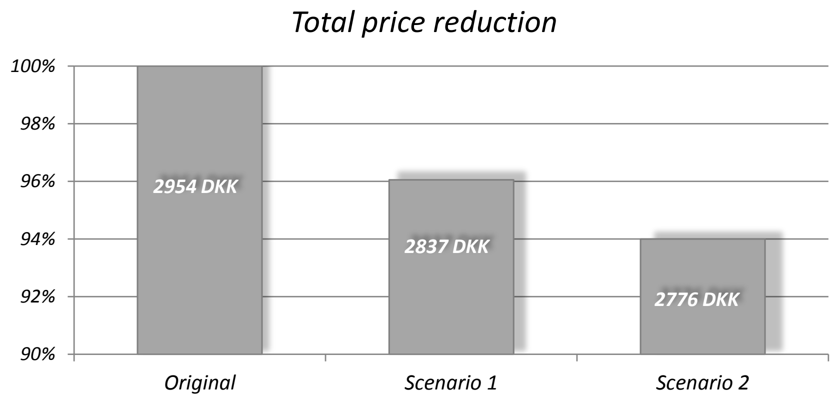

Figure 4.6: Annual prices for each scenario

Despite the fact that the total amount of the price reduction is not very significant, the investment required to implement the optimal control will not be that much in the future. This is due to the fact that the houses will be equipped with smart meters and some smart flexible devices in the future. Furthermore according to [38] demand response is one of the main drivers for introduction of smart meters in Denmark. However, demand response itself is not economically profitable.

Chapter 5

Modeling

This chapter provides a description of the topology and modeling of the network in DIgSILENT Power Factory. The model is used to obtain the necessary data to implement the power loss function as well as to compare the results after the optimal management with the original case.

5.1 System description

The test system is based on Section 2.3. The external grid supplies the energy necessary for the households. The control is based in a DLC (direct load control) model of flexible loads. Hence two different load elements represent each household. A fix load represents the normal power profile, while a variable load implements the optimal consumption of washing machine and refrigerator. Figure 5.1 shows the DIgSILENT implementation.

The values included in the model are the result from a power flow simulation, conducted with average power consumption values, in order to obtain V and δ for each bus (section 4.3).

5.2 Implementation of optimal results

The optimal control calculated in Chapter 4 has been implemented in the model. Figure 5.2 presents a comparative of the total active power, supplied by the main grid, for each scenario. The resultant curve for both scenarios, 1 and 2, shows how the optimal control of the appliances leads in a flatten curve than the original. Moreover, the peaks have been reduced or avoided.

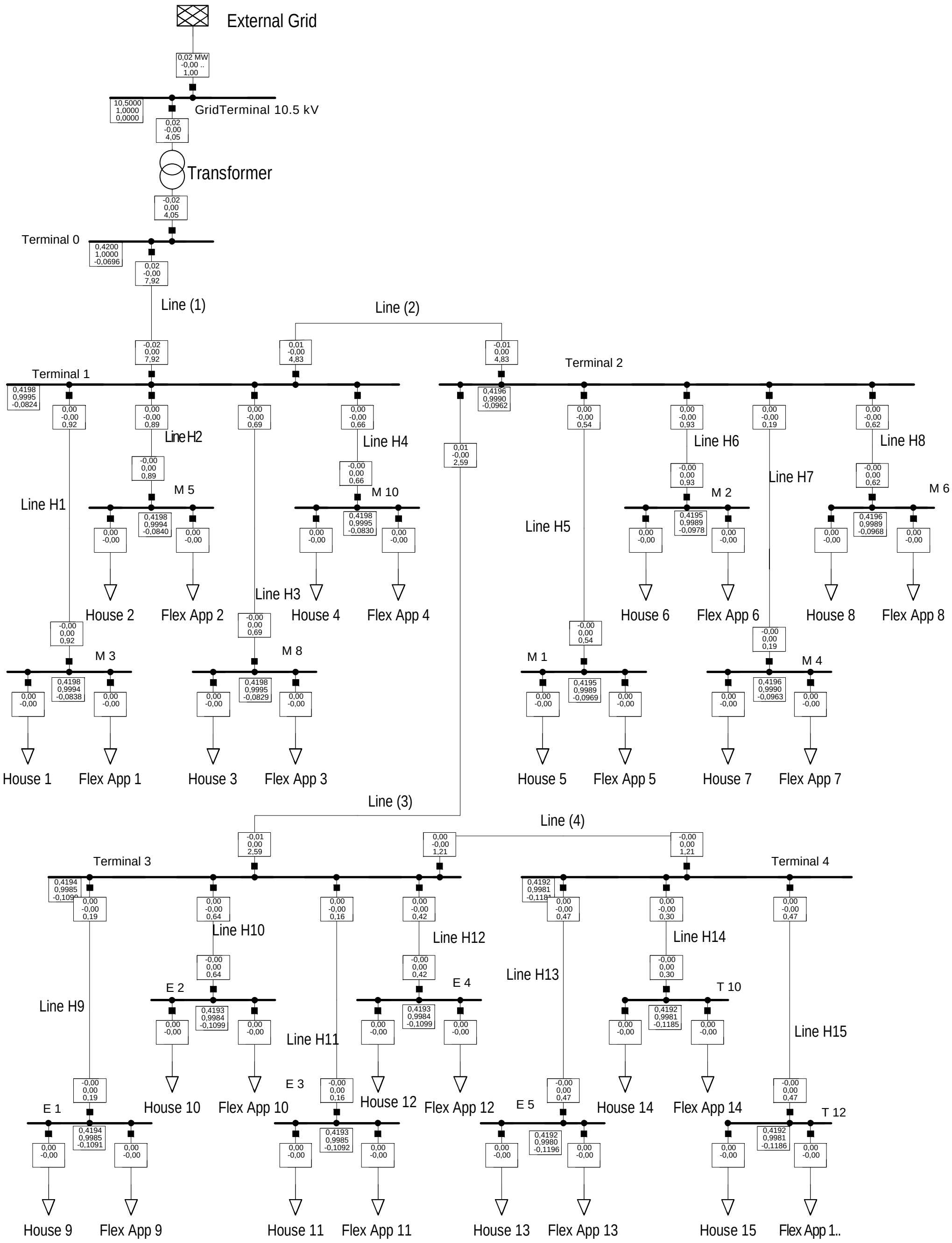

Figure 5.1: Grid modeled in DigSilent

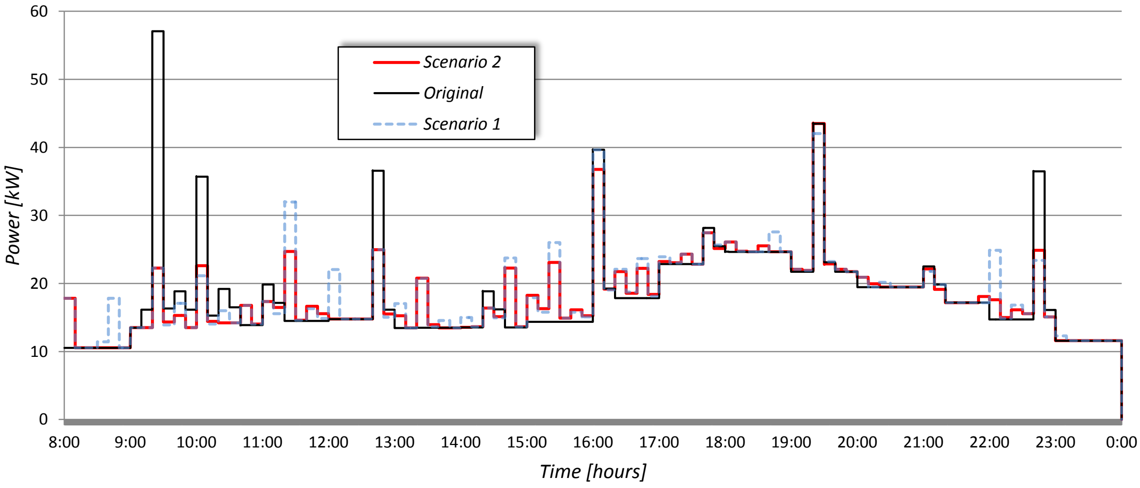

Figure 5.2: Power profile of the system for each scenario

As expected, a better performance on the power profile results in less voltage droops. Figures 5.3 and 5.4 shows the voltage in pu for the houses nearest and the furthest from the transformer respectively, houses 3 and 13.

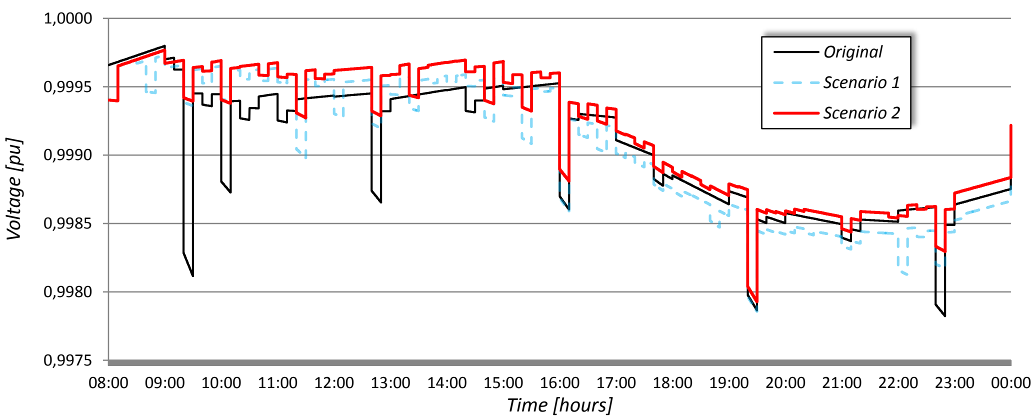

Figure 5.3: Voltage in house 3

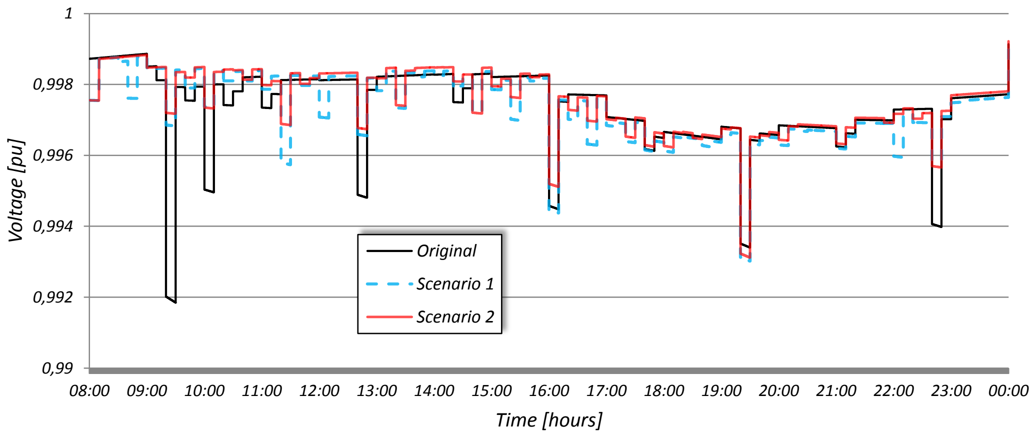

Figure 5.4: Voltage in house 13

5.3 Energy Losses

The power loss profiles from DIgSILENT is shown in Figure 5.5, for each scenario. The energy losses for each case, and the percent of reduction respect the original case, are summarized in table 5.1. Again, it is important to remark that this values of energy losses only represent the period between 8:00 to 0:00, and consequently, the daily value should be greater.

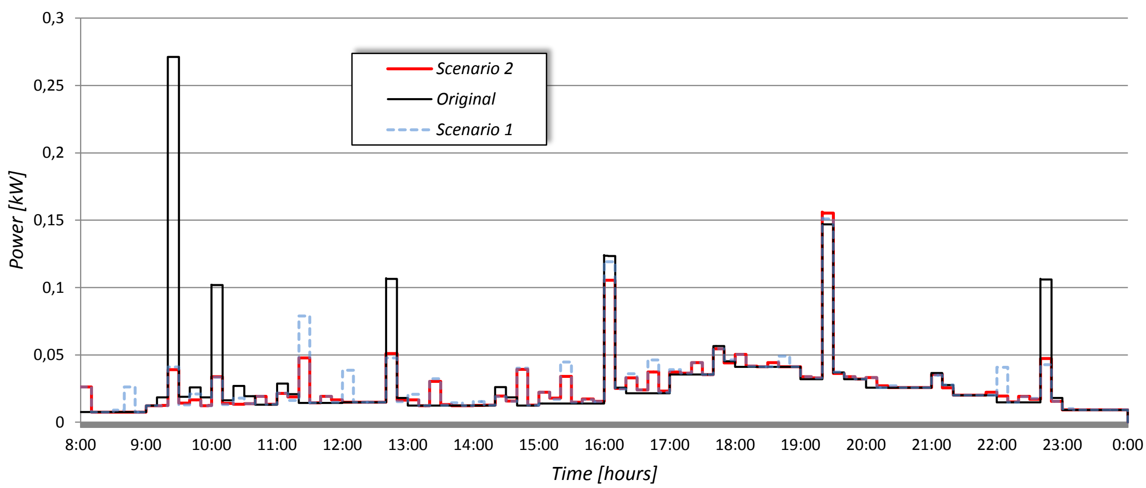

Figure 5.5: Power loss in the network

Table 5.1: Energy Losses for each scenario

Case	Enegy Losses [KWh]	Reduction
Original	0.4524	0%
Scenario 1	0.4323	4.45%
Scenario 2	0.4088	9.65%

The simulation results show that the method proposed is able to decrease the energy losses for both scenarios.

Chapter 6

Conclusion and future work

The objective of this project was to develop an intelligent management system for residential loads. The project includes the study of residential loads, use pattern, optimization and modeling.

The distribution of residential electricity energy consumption in different loads have been studied, and the most convenient appliances to implement a DSM have been presented. A way to convert washing machine and refrigerator in flexible loads, has been developed. Two different methods have been proposed: so that the user experience does not change and increasing the temperature of the refrigerator during some periods.

An optimization was conducted to find the best operation for the washing machine and refrigerator. The operation results show the benefits of the DSM. The price that the user pays for the electrical energy and in the energy losses in the distribution system have been properly reduced. The results of the simulations show that the energy quality, measured by the voltage drop, experiment a significant improvement.

As future work this report recommends, to investigate the control of other appliances. A real time control for the refrigerator based on frequency variations could be studied. Finally a longer simulation period will lead on a more accurate result.

Bibliography

[1] G. Deconinck, B. Decroix, Smart Metering Tariff Schemes Combined with Distributed Energy Resources, K.U.Leuven, ESAT ELECTA Belgium

[2] Clark W. Gellins, The Concept of Demand-Side Management for Electric Utilities, IEEE, 1985

[3] Bettina HIRL, Residential Energy Consumption and Efficiency Trends, European Commission, Joint Research Centre, Institute for Energy, EEDAL 11 Conference, Copenhagen, Denmark, 2011

[4] David G. Infield, Joe Short, Chris Horne, Leon L. Freris, Potential for Domestic Dynamic Demand-Side Management in the UK, IEEE 2007

[5] Demand-Side Management: Concepts and Methods, Clark W. Gellings, John H. Chamberlin, The Fairmont Press Inc.,Lilburn, GA, 1987

[6] Statistics Denmark - StatBank. ENE1N: Energy Accounts in physical units by industry and type

[7] B. Atanasiu, P. Bertoldi, Residential electricity consumption in New Member States and Candidate Countries, European Commission-DG JRC, Institute for Environment and Sustainability, Italy 2008

[8] J. E. Jimenez, S. H. Haug, I. G. Szczesny, K. E. Pollestad, E. R. Moldes, Intelligent Management of the Micro-grid, student report, Aalborg University

[9] H Saele, E. Rosenberg, N. Feilberg, State-of-the-art Projects for estimating the electricity end-use demnad, SINTEF Energy Research, 2010

[10] Demand side management:Benefits and challenges, Goran Strbac, Department of Electrical and Electronic Engineering, Imperial College London, 2008

[11] M. Castillo Cagigal, A. Gutierrez, F. Monasterio Huelin, E. Caamaño Martin, D. Masa. J. Jimenez Leube, A semi-distributed electric demand-side management system with PV generation for self-consumption enhancement, 2011

[12] M. Newborough, P. Augood, Demand-side management opportunities for the UK domestic sector

[13] Gestión activa de la demanda de la energía eléctrica, Miguel Angel Cerezo Moreno, Master Thesis, Universidad Carlos III Madrid, 2010

[14] M.Stadler, W. Krause, M. Sonnenschein, U. Vogel, Modelling and evaluation of control schemes for enhancing load shift of electricity demand for cooling devices, 2008

[15] J.J. Tomlinson, D.T. Rizy, Bern Clothes Washer Study, Oak Ridge National Laboratory U.S. Department of Energy, 1998

[16] TopTen Europe, Washing Machines, 26 February 2013, topten.eu

[17] P.Sustek, P.Stekl, Washing Machine Three-Phase AC-Induction Direct Vector Control, Freescale Semiconductor, 2007

[18] L. Jung-Hyo, K. Tae-Woong, L. Won-Chul, Y. Jae-Sung, W. Choon-Yueng, Load modeling for the drum washing machine system simulation, Sungkyunkwan University, 2007

[19] D. W. Novotny, T. A. Lipo, Vector control and dynamics of AC drives, Oxford Science Publications, 1996

[20] I. Richardson, M. Thomson, Domestic Electricity Demand Model-Simulation Example, Loughborough University Institutional Repository, 2013, http://hdl.handle.net/2134/5786

[21] I. Richardson, M. Thomson, David Infield, Conor Clifford, Domestic electricity use: A high-resolution energy demand model, 2010

[22] Joakim Widén, Magdalena Lundh, Iana Vassileva, Erik Dahlquist, Kajsa Ellegard, Ewa Wäckelgard, Constructing load profiles for household electricity and hot water from time-use data-Modelling approach and validation, 2009

[23] Joakim Widén, Ewa Wäckelgard, A high-resolution stochastic model of domestic activity patterns and electricity demand, 2009

[24] Runming Yao, Koen Steemers, A method of formulating energy load profile for domestic buildings in the UK, 2004

[25] I. Richardson, M. Thomson, David Infield, A high-resolution domestic building occupancy model for energy demand simulations, Loughborough University, UK

[26] Ipsos-RSL and Office for National Statistics, United Kingdom Time Use Survey, 2000 [computer file]. 3rd Edition. Colchester, Essex: UK Data Archive [distributor], September 2003. SN: 4504.

[27] Arora, Jasbor S. Introduction to optimum design, third edition, 2012

[28] A. Molina, A. Gabaldon, J.A. Fuentes, C. Alvarez, Implementation and assessment of physically based electrical models: application to direct load control residential programmes, 2002

[29] M. Stadler, W Krause. M. Sonnenschein, U. Vogel, Modelling and evaluation of control schemes for enhancing load shift of electricity demand for cooling devices, 2008

[30] N. Baghina, I. Lampropoulos, B. Asare-Bediako, W. L. Kling, P. F. Ribeiro, Predictive Control of a Domestic Freezer for Real-Time Demand Response Applications, 2012

[31] O. Laguerre, E. Derens, B. Palagos, Study of domestic refrigerator temperature and analysis of factors affecting temperature: a French survey, 2002

[32] R. Saidur, H.H. Masjuki, I.A. Choudhury, Role of ambient temperature, door opening, thermostat setting position and their combined effect on refrigerator-freezer energy consumption, 2001

[33] P. Constantopoulos, F.C. Schweppe, R.C. Larson, ESTIA: A real time consumer control scheme for space conditioning usage under spot electricity pricing, 1991

[34] Naresh Acharya, Pukar Mahat, N. Mithulananthan, An analytical approach for DG allocation in primary distribution network, 2006

[35] Matlab® Optimization Toolbox™ User's Guide R2012b

[36] SAS/OR 9.22 User's Guide: Mathematical Programing, SAS Institute, 2010.

[37] Lunk Erik, Lecture 4, Optimization Theory, Institute of Energy Technology, Aalborg University

[38] European Smart Metering Landscape Report, S. Renner, M. Albu, H. Elburg, A. Lazicki, Intelligent Energy Europe, 2011