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Modelling, flexibility and impact analysis with field experiments

PhD Dissertation,October 2015

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Why does one stop learning till he dies
When it makes all lands and places his?
- Thiruvalluvar.

PREFACE

This dissertation was prepared at the Department of Electrical Engineering at the Technical University of Denmark in partial fulfilment of the requirements for acquiring the PhD degree in engineering.

The Ph.D was funded by the project INCAP (project number 55836). The Ph.D project started on 1st June 2012 and it was completed on 31st August 2015.

This dissertation presents the research results related to Demand Response on domestic thermostatically controlled loads.

This dissertation is composed of 8 chapters and 2 appendices. The appendices include 5 attached papers and 4 technical specifications descriptions about products used. Two among the attached papers have been published in international peer-reviewed conferences. The other three papers have been submitted for journal publications and they are currently under review.

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Venkatachalam Lakshmanan,
30 October 2015.

ABSTRACT

Electricity has become an inevitable part of human life in present day world. In the past two centuries, the electric power system has undergone a lot of changes. Due to the awareness about the adverse impact of the fossil fuels, the power industry is adopting green and sustainable energy sources. For a safe and reliable operation of electric power systems, the balance between electricity generation and consumption has to be maintained. The conventional fossil fuel based power generation achieves this balance by adjusting the generation to follow the consumption. In the electric power system with renewable energy sources, the production cannot be adjusted to match the demand due to the fluctuating nature of the renewable energy sources. Therefore, the demand has to be adjusted to match the power production. The concept of adjusting the demand to match the production is called demand response. In general, the electricity consumers are classified as industrial, commercial and domestic. In this dissertation, only the thermostatically controlled loads (TCLs) in the domestic segment are considered for the demand response study.

The study is funded by Danish Council for Strategic Research (DCSR) and supported by the project “Inducing consumer adoption of automated reaction technology for dynamic power pricing tariffs” (INCAP). As project INCAP provides access to domestic refrigerators, the TCLs considered for the demand response study are domestic refrigerators. In this study an experimental facility is developed to measure parameters from the refrigerators, in order to control them. The experimental facility is also used to communicate pseudo electricity prices to the consumers and has options to unsubscribe the control from the user end, as a part of the INCAP project requirement.

A temperature prediction strategy is developed to predict the refrigerator temperature and to estimate the flexibility available for demand response activation. A field experiment with refrigerators is conducted to study secondary frequency control using demand response activation on TCLs. The response time and the ramp rate characteristics of a real population of domestic refrigerators, as well as their ability to provide frequency control, are analysed. The response characteristics are compared with conventional power plant specifications, indicated in the Danish grid code. The changes in the TCLs flexibility, with respect to different power reduction levels, are analysed. Finally, the impact of demand response activation on the TCLs aggregated power is studied in terms of error in power limit, ramping rates and peak overshoot in different control scenarios. Lastly, the advantage and disadvantage of the different control scenarios are analysed.

RÉSUMÉ

Elektricitet blev en uundværlig del af livet i den moderne verden. I løbet af de sidste to århundreder har el-systemet gennemgået mange ændringer. På grund af bevidstheden om den negative effekt af fossile brændstoffer, går energi industrien over til grønne og bæredygtige energi kilder. For at sikre en sikker og pålidelig drift af el-systemet, er det nødvendigt at opretholde balancen imellem produktion og forbrug. Ved den konventionelle el-produktion, baseret primært på fossile brændstoffer, opnås denne balancen imellem generation og forbrug ved at tilpasse produktionen, så den følger forbruget. I el-systemer med vedvarende energi kilder, kan el-produktionen ikke på samme vis tilpasses forbruget, grundet den svingende produktion fra de vedvarende energikilder. Det er derfor nødvendigt at tilpasses energi forbruget, så det matcher produktionen, et koncept der på engelsk kaldes ”demand reponse” eller “produktionsstyret forbrug". Forbrugerne klassificeres som enten industrielle- eller kommercielle kunder, eller som private husholdninger. I forbindelse med ”demand response” studie i denne afhandling, undersøges kun termostatkontrollerede forbrugsenheder (eng: ”thermostatically controlled loads” eller TCLs) til private husholdninger.

Studiet er finansieret af det tidligere strategiske forskningsråd og støttet af projektet “Inducing consumer adoption of automated reaction technology for dynamic power pricing tariffs”, også kaldet INCAP. Da INCAP projektet giver adgang til private køleskabe, er de termostatkontrollerede forbrugsenheder der er undersøgt som del af forbrugsstudiet, private køleskabe. I dette studie udvikles eksperimentelle faciliteter til måling af parametre fra køleskabene, med henblik på at kunne styre køleskabenes forbrug. Disse eksperimentelle faciliteter bruges også til at kommunikere virtuelle elektricitetspriser til forbrugerne, samt giver forbrugerne mulighed for at fravælge automatisk styring, hvilket var et krav i forbindelse med INCAP projektet.

En strategi til forudsigelses af køleskabstemperaturen er udviklet, da det er nødvendigt for at kunne forudsige og estimere den fleksibilitet der er tilgængelig, hvilket muliggør produktionsstyret forbrug. Et forsøg med rigtige køleskabe er blevet foretaget for at undersøge sekundær frekvenskontrol ved hjælp af produktionsstyret forbrug af termostatstyrede enheder. Reaktionstiden og stigningsgradskarakteristika fra en mængde privatejede køleskabe, samt deres evne til at deltage i frekvensstyring, er analyseret. Tallene er derefter sammenlignet med dem for konventionelle kræftværks, ud fra de officielle krav til det danske energisystem. Ændringerne i de termostatsstyrede forbrugsenheders fleksibilitet, under tests af forskellige energi reduktions niveauer, er analyseret. Endelig er effekten af produktionsstyret forbrug af termostatkontrollerede forbrugsenheders samlede energiforbrug, undersøgt i forhold til fejl i energi grænser, stigningsgrad og spidsoverskridelser under forskellige kontrol scenarier. Sidst, men ikke mindst, er fordele og ulemper ved forskellige kontrolscenarier er analyseret.

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I owe my gratitude to many people who have made this dissertation possible. I take this opportunity to thank everyone.

First, my deepest gratitude is to my principal supervisor, Senior Research Scientist Henrik William Bindner and Anders Troi (former Head of Intelligent Energy Systems group - Risø DTU) for giving me this opportunity to pursue Ph.D studies. I have been amazingly fortunate to have a supervisor who gave me the freedom to explore on my own and at the same time the guidance to recover when my steps faltered. Henrik taught me how to question thoughts and express ideas. His patience and support helped me overcome many crisis situations and finish this dissertation.

My co-supervisors, Senior Research Scientist Oliver Gehrke and Research Scientist Anna Magdalena Kosek, have been always there to listen and give advice. I am also thankful to Per Bromand Nørgård, Senior Engineer and project manager for INCAP, for his insightful comments and constructive criticisms at different stages of my experiments and dissemination activities. I am deeply grateful to them for the long discussions that helped me to sort out the practical issues in the project.

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I owe my gratitude to Administrative coordinators Eva Bülow Nielsen and Helle Faber for taking care of all administrative needs, considering my vegetarian diet requirement in all meetings and festive occasion in the organization and most importantly for providing high positive recommendation about me to the landlords of the houses where I stayed.

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TABLE OF CONTENTS

ABBREVIATIONS

ADS	active distribution system
AGC	automatic generation control
BRP	balance responsible parties
COP	coefficient of performance
CRR	continuous regulation of reserves
DDC	dynamic demand control
DER	distributed energy resources
DERA	Danish energy regulatory authority
DR	demand response
DSM	demand side management
DSO	distribution system operator
EV	electric vehicles
HAN	home automation network
HVAC	heating ventilation and air conditioning
IEA	International Energy Agency
ISE	integral square of error
LED	light emitting diode
MCP	market clearing price
OLTC	online tap changers
PV	photovoltaic
PWM	pulse width modulation
RES	renewable energy sources
SNR	signal to noise ratio
TCL	thermostatically controlled loads
TOU	time of use

1 INTRODUCTION

Energy is life.

1.1 Background

Electricity started to dominate energy other forms especially thermal energy in terms of usage after its invention. Electricity is a form thatis easy to work in terms of transmission and distribution, and has the highest possible efficiency when converted in to other energy forms. Therefore, technological development is centered around electricity as a source of energy, and demand has increased tremendously. As per the 2012 energy balance report of the International Energy Agency (IEA), 32% of the world's total primary energy share is converted into electricity [1]. Four decades before, it was only 21%, and is expected to grow further [1]. Therefore, this research was focused on production of electricity with high efficiency, from every possible source of energy. Bulk production still depends on fossil fuels like coal, mineral oil and natural gas [1]. Fast depletion of fossil fuels and the harm caused to the environment from their combustion to produce electricity forces the world to look into pollution-free renewable energy sources. Even the oil rich Middle Easthas started to focus on clean and green energy and carbon footprint reduction [2].

Denmark has planned to phase-out all fossil fuel based energy sources in all sectors including transportation sector by the year 2050 [3]. The country mainly uses its large potential for wind energy. In 2014, Denmark accounted for 33 TWh of energy consumption in the form of electricity; 30% of total electricity consumption was produced by wind [1]. It is noticeable that wind's share has doubled compared to the figures in 2006 [4]. In addition, solar photovoltaic (PV) installations in Denmark had a peak capacity close to 606 MW as of May 2015 [5]. The Danish government has an energy policy with a goal of producing 100% of electricity and heating from renewable energy sources (RES) [3]. Therefore the penetration of renewable energy sources in the Danish electric power system will continue to grow in future.

In electric power systems, electricity production and consumption have to go hand in hand, which is called balance in the electric power system. This balance is disturbed when the production is in excess or when there is shortage in production compared to demand. Unlike conventional electric power generation units, the RES like solar and wind energy cannot support the demand as and when needed. Also bulk storage of electricity is not feasible and cost-effective with the technology available today. The most efficient and effective way as of today to store electricity is pumped-hydro storage [6]. The installed capacity of wind power in Denmark as of January 2015 is 4905 MW [7]. The average power production by the wind turbines for the year 2014 was 27% of the installed capacity. On 19th January 2014, between 4– 5 am (local time GMT+1), the electricity produced from the wind turbines exceed the country's demand by 32% [5]. Similarly, on 29th September 2014 between 5–6 pm, wind turbine production was zero [5]. The pumped-hydro storage requires suitable geography with mountains and feasibility for reservoir and power plant construction. The terrain of Denmark does not have such landscapes. The Danish power system manages these fluctuations in wind and solar power production by adjusting the thermal power plant's power dispatch and also by exchanging the power with their neighbours. The Danish government has a plan to phase-out all fossil fuel based power plants by the year 2035 [3]. One of the challenges for the reliable and economical operation of a power system with a high penetration of renewable energy is the availability of energy resources that can participate in balancing supply and demand on a short-term basis. In contrast to the conventional power system, in a system with high percentage of renewable energy, the demand has to be adjusted to match the production. For example, by influencing the operation of electrical loads at customer premises the demand can be adjusted to balance supply. Here the demand response (DR) plays an important role.

1.2 Demand response

Demand response is defined as the change in electricity consumption by the end-use consumer from their normal consumption pattern in response to a signal sent when the power system reliability is affected [8]. The signal can be for example the changes in electricity price over time, or incentives intended to reduce electricity consumption [8–10]. DR methods can be broadly classified as load reduction, load shifting and on-site generation [11]. Here on-site-generation enables load reduction to the power system.

The way DR is enabled may vary from simple time of use (TOU) to a complex time varying load control. In TOU, clear distinct electricity price discrimination for particular hours of a day is given. During peak hours the consumer is charged with a high price and during off-peak hours a low price is charged for electricity consumption. The price difference motivates the consumers to move part of their consumption from peak hours to off-peak hours. DR activation by TOU is best suited for the conventional power system as the load is predictable with low errors and the production can be adjusted accordingly. In power systems with high penetration of RES, the electricity production varies with the availability of RES like sun and wind. Though the RES production can be predicted to some extent from metrological predictions, as there will be an uncertainty in the prediction, time varying load control is the best suited for such situations. In time varying load control the load is adjusted at every moment to follow the electricity production, in order to maintain the power system balance.

1.3 DR in domestic sector

Earlier, DR was practised in industry due to the possibility of electricity consumption reduction in bulk quantities. Also the information communication technology cost for load control was affordable when the demand reduction was high. Due to technological development, the cost of control equipment and communication infrastructure reduces day by day. This could be an opportunity to consider the domestic sector of consumers with a small amount of possible power reduction to participate in DR programs. Residential and commercial buildings in the Nordic countries have a share of 34% of total electricity consumption [12]. The residential houses account to two-thirds of this amount. The household appliances consume around 17% of total energy [12]. Therefore, it is beneficial to study the different aspects of these appliances' usability for DR activation and their impacts upon the power system by conducting a large field experiment.

1.4 Appliances selection for DR activation

In domestic sector, electricity utilisation is mainly for human comfort [13]. The time varying load control may interrupt electric supply to the domestic appliance at any time. Therefore, the selected appliance should be able to provide service even if the electric supply is removed for a short duration by DR activation. Among the household appliances, thermostatically controlled loads (TCLs) like water heaters, space heaters, heat pumps, air conditioners, refrigerators and freezers have the capacity to store the energy in terms of their thermal inertia. Interrupting these loads for a short duration will not interrupt their service to a larger extent compared to the other appliances, for example, light bulbs. TCLs have similarities in their periodic operation and thermal behaviour during their operation. They vary in their power rating, temperature operational range and hours of the day usage. These similarities enable us to study DR activation on one of them that has the higher operational hours in a day and has the possibility of installing a control device easily. The results can be scaled to appliances of higher power ratings.

When a large field experiment is planned for the DR activation study involving TCL, a suitable TCL has to be selected from the different TCLs available within a household. The TCL should be commonly available in most houses to obtain greater from the appliance owner even if a small proportion of total houses control their appliance. The TCL should be easy to control with a simple and cost-effective control device. The control device installation could be as easy as any common domestic gadget installation. At the same time, the TCL should be able to represent the behaviour of other TCLs in the household during normal operations and also during control. The user interference with the TCL operation should be minimal, especially when the DR activation impact on the power system is studied as the user interactions will influence the results.

A refrigerator has some advantages among the other domestic TCLs for the field experimental study of DR activation. Refrigerators are commonly available in most houses. Refrigerators are available all day for DR activation and control. Refrigerators' operation can be known from two measurements: namely, compressor power and the temperature of the cool chamber in the refrigerator. The refrigerator can be considered as a small-scaled model representing other TCLs at home. The control device can be a pluggable relay installed in the power socket. The devices for sensing temperature, to control the compressor of the refrigerator and for communication to the centralised control center, are easily installable by normal users without a presence of a skilled technician.

1.5 Thesis objective and author's contributions

As the development in the power system allows high RES penetration, and DR is an important method to provide power system services both for system stability and its economic operation, it is worth evaluating the DR opportunities available in the domestic setting. The thesis objective is to evaluate the flexibility available with domestic TCLs to provide power system services, evaluate the suitability of domestic TCLs to provide power system services and to analyse the impact of enabling DR activation on domestic TCLs.

The author's contributions on the 3 thesis objectives are as follows.

1. Estimate the flexibility available with domestic TCL for DR activation: The author has developed a temperature prediction strategy for domestic TCLs with only one temperature measurement and the power consumption measurement. The temperature prediction strategy is evaluated with different types of domestic refrigerators for its prediction accuracy. Furthermore, the author estimates the available flexibility with domestic TCLs using the temperature prediction strategy, to provide power system services for any given duration.
2. Evaluate domestic TCLs' suitability for providing power system critical services: the author has taken one power system services by DR activation for study. The service considered for study is the secondary frequency control with domestic TCLs. The author has studied the possibility of providing secondary frequency with domestic TCLs by controlling refrigerators and emulating their consumption in an island network. The advantages and disadvantages are analysed.
3. Analyse the impact of enabling DR activation on domestic TCLs: The author has studied the impact of DR activation and control removal on aggregated power of TCLs with an experiment using domestic refrigerators as an example of TCL. Different control scenarios are taken for the consideration of impact analysis and their advantages and disadvantages are analysed.

1.6 Publications

The author's contributions are presented as the main content in this dissertation and also as a number of papers that have been written during the thesis period which are included in the Appendix A. The Appendix A contains 5 papers from A.1 to A.5. The papers are referenced in the corresponding chapters of this dissertation. The papers A.1 to A.5 contain the main findings of the thesis and the paper 6 contains other contributions from the author that are not directly related to this dissertation.

A.1: Lakshmanan, V.; Marinelli, M.; Kosek, A.M.; Sossan, F.; Norgard, P., "Domestic refrigerators temperature prediction strategy for the evaluation of the expected power consumption," in Innovative Smart Grid Technologies Europe (ISGT EUROPE), 2013 4th IEEE/PES, pp.1-5, October 6-9, 2013.

A.2: Lakshmanan, V.; Gudmand-Hoyer, K.; Marinelli, M.; Kosek, A.M.; Norgard, P., "Energy shift estimation of demand response activation on refrigerators — A field test study," in Power Engineering Conference (UPEC), 2014 49th International Universities, pp.1-6, September 2-5, 2014.

A.3: Lakshmanan, V.; Marinelli, M.; Junjie H.; Bindner, H.W., "Provision of secondary frequency control via demand response activation on thermostatically controlled loads: Solutions and experiences from Denmark", Applied Energy, in submission, 2015.

A.4: Lakshmanan, V.; Marinelli, M.; Junjie H.; Bindner, H.W., "Experimental analysis of flexibility change with different levels of power reduction by demand response activation on thermostat-controlled loads", Electric Power Components and Systems, in submission, 2015.

A.5: Lakshmanan, V.; Marinelli, M.; Kosek, A.M.; Norgard, P.; Bindner, H.W., "Impact of thermostatically controlled loads' demand response activation on aggregated power: A field experiment", Energy, in submission, 2015.

6: Sossan, F.; Lakshmanan, V.; Costanzo, G.T.; Marinelli, M.; Douglass, P.J.; Bindner, H.W., "Grey-box Modelling of a Household Refrigeration Unit Using Time Series Data in Application to Demand Side Management", Sustainable Energy, Grids and Networks, in print, 2015.

1.7 Thesis outline

This dissertation is organised into 8 chapters and 5 attached papers in the Appendix A. The chapters other than chapters 2 and 3 relay the papers A.1 to A.5. The main contents of the papers are presented in the respective chapters.

Chapter 2 describes the recent developments in the power system, state of the art in DR, TCL technologies, power system services with TCL DR and recent projects demonstrating DR on TCL and their study objectives.

Chapter 3 focuses on the experimental setup. The INCAP project objectives and experimentation facility created for the study and the devices and technologies used are discussed in detail in chapter 3.

Chapter 4 focuses on the modelling of refrigerator in a suitable way for large field experiment with the measurement constraints. Different methods of modelling are explained and the method adopted for this work is detailed. The main results have been published in separate paper and the paper is included in Appendix A.1.

Chapter 5 deals with the usage of the model described in chapter 4 to estimate the available capacity for load shifting. The errors in estimation, the possible causes for the error and the possible ways to improve the estimations are discussed. The main findings have been published in separate paper which is included in Appendix A.2.

Chapter 6 details the demonstration of one of the power system services, secondary frequency control for upregulation of frequency in in the power system by centralized control of refrigerators. The response time of the appliances, time to bring the frequency to nominal value and the shortfalls of utilising such a method for frequency regulation are discussed. The study is further extended to investigate how long such power limiting services can be provided with different power reduction limits and the consequences in the temperature variations. The results presented in this chapter have been communicated as two separate journal papers as included in the Appendix A.3 and A.4.

Chapter 7 studies the impact of demand response activation to provide power-limiting services from the aggregated power consumption of DR activated TCLs. The study is focused on the power reduction rate, error variation in service delivery, peak overshoot of power consumption on removal of DR activation with different type of DR activation. The results presented in this chapter have been communicated as a journal papers as included in the Appendix A.5.

Chapter 8 concludes with the thesis findings and opens up the discussion for future work with suggestions for improving the experimental infrastructure.

2 REVIEW OF STATE OF THE ART

2.1 Distributed energy resources

Technological advancement in the recent decades has improved the efficiency of energy conversion at the demand side, reduced the cost of small scale electricity generation from the renewable energy sources (RES)[14], and reduced the cost of electric energy storage. Such developments have changed the concept of the power system operation from conventional bulk production and distributed consumption to distributed production, storage and consumption. These small-scale manageable units that participate in the power system operation are not only limited by power generation, but also the technologies and strategies for energy management such as demand response, load shifting and peak-shaving, and storage are called distributed energy resources (DER) [15,16] . DERs provide increased power reliability and participation of a greater number of RES in the power system. Therefore the carbon emissions are reduced and the energy utilisation is focused on the use of local energy resources [17,18], which results in the reduction of losses associated with power transmission. The DER capacity in terms of power rating can range from as low as 3 kW [19]. For example, most of the rooftop residential grid connected photovoltaic generations are between 3–5 kW [20,21]. As the power system operation efficiency and reliability depends on the power production and consumption balance, the DERs have to be well managed in order to achieve the balance [22]. Coordinated operation of demand side management (DSM), which includes demand response (DR), is key for efficient power system operation with DERs [23–26].

2.2 Demand side management

Demand side management (DSM) focuses on adjusting demand to follow power production and infrastructure availability for effective and efficient power system operation. DSM is contrary to generation control that follows consumption. DSM can vary from a temporary short time demand adjustment to a permanent change in the load. DSM is broadly classified as an energy efficiency and demand response [27].

Energy efficiency in DSM deals with improvements in at the load type by adapting to the latest technology that has higher efficiency. For example, changing a low efficiency incandescent light bulb to a light emitting diode (LED) light bulb improves the energy efficiency by 76% [28]. The DSM like energy efficiency helps in long term power system planning.

As stated in section 1.2, demand response is defined as the change in electricity consumption by the end-use consumer from their normal consumption. DR can be enabled as simple time of use (TOU) or a complex time varying load. The TOU changes the energy consumption pattern to suit the intraday energy availability. In TOU, consumers are motivated to change the consumption pattern with different energy prices that follows the energy availability. For example, a low price during off-peak hours and a high price at peak hours motivate consumers to shift their flexible loads from peak hours to off-peak hours [29]. In this way, TOU can help power system operation planning.

The DSM-DR in the form of complex time varying load can adjust the power consumption for shorter duration, when it is needed for power system stability. For example, the charging power of electric vehicles (EVs) as DR can be adjusted according to power system parameters like voltage and frequency, to maintain the power system stability. For power system stability, temporary adjustments at the demand side that can respond in a short time span are useful. Among the DSMs, DR with complex time varying load has a greater attraction as the system can respond in a short time and can help the power systems with more RES penetration. Also it can be activated with many signals like energy price and power system parameters (viz., voltage and frequency).

The demand in the power system can be broadly classified as industrial, commercial and domestic [30–33]. The demand adjusted from the industrial consumers is large compared to the other two segments [34–36]. Though the demand adjusted may be large in quantity, the real-time control is not easy. Most industrial equipment needs specific startup and shutdown procedures and associated skilled man power. Therefore they are more suitable for planned demand adjustments like TOU rather than for complex real time load control.

The commercial and domestic consumers are suitable for real time load control due to their load time availability and less complex loads that are easy to control for example, changing the temperature set point of the space heater [37]. The residential sector has similar appliances in all households. This gives an opportunity to divise and test technology for one type of load to implement in all houses. The total load that can be adjusted by controlling small domestic loads may not match the capacity of the large controllable industrial loads. However, the unavailability of the large loads for control has a substantial impact on the service committed to the power system. Therefore, many studies have been carried out with a focus on exploiting the potential available in the residential sector [38–44].

The study in this dissertation focusses on the DR with complex time varying load in domestic segment for energy shift and for providing power system ancillary services. The energy shift with DR is explained in Chapter 5 and the chapter 6 deals with power system ancillary service by DR activation.

2.3 Thermostatically controlled loads

The main purpose of domestic household electric appliances is to provide comfort service to the users [13]. During the appliance control, the service provided by the appliance should not be affected by the control event. Such a constraint makes the appliances that deliver temperature services the most suitable for real time complex load control DR applications. As the temperature service is their main objective, their operation is controlled by temperature limited switches called thermostats, and they can be generally termed thermostatically controlled loads (TCLs). The thermostat is either to cut-off or to limit the device operation as the rate at which the thermal energy is supplied by these equipment is greater than the rate of consumption. The temperature effect is stored in the thermal mass of the TCLs that can sustain the impact of their electric power interruption. The deviation in their service can be easily assessed from the temperature change.

In Denmark, the TCLs share 32% in a domestic electricity demand scenario and 26% in commercial electricity demand [45]. In a domestic household, there are two types of TCLs. They differ in their principle of operation. They are:

1. Resistive loads (i.e. heat generation equipment)
2. Compressor operated loads (i.e. heat pumping equipment).

2.3.1 Resistive loads

Resistive loads convert the electrical energy into thermal energy with the use of resistive elements. The heat conversion is governed by Joule’s law of heating. The amount of thermal energy generated is same as the amount of electricity consumed. The household appliances, water heaters, electric room heaters, electric kettles, electric ovens and electric cooking stove (not induction stove) are based on this principle. Though their efficiency is 100%, their performance is lower than the compressor operated loads. Their simple construction, easy installation and portability make them attractive to the user. The resistive loads have less startup time after their operational interruption. [46] evaluates the DR activation study by simulating 1000 electric water heaters to evaluate the capacity for load shifting and balance reserve. A proof of concept experimental study for the utilization of electric water heaters as a voltage controlled load is carried out in [47]. The flexibility available with domestic water heater is studied in [48]. A simulation work is carried out in [49] and [50] to study the potentials of space heating from heating ventilation and air conditioning (HVAC) to provide load balancing services.

2.3.2 Compressor operated loads

Unlike resistive loads, compressor operated loads transport thermal energy from one temperature zone to another that is separated, by thermal insulation [51]. The compressor operated loads' principle of operation is governed by the second law of thermodynamics. For the same amount of electric energy consumption, compressor operated loads can transport more thermal energy from one temperature zone to other compared to resistive loads. The ratio of the thermal energy transported to the electrical energy consumed is called coefficient of performance (COP) [51].

Household equipment such as refrigerators, freezers, air conditioners and heat pumps work on this principle. Refrigerators and freezers are intended for the service of providing or maintaining lower temperature than the ambient temperature and the heat pumps are intended for higher temperature than the ambient temperature. Air conditioners are intended for climate maintenance. If the heat is pumped from the lower temperature zone to a higher temperature zone, and the temperature difference between the two thermal zones is greater, the COP will be lower [51]. All of the domestic compressor operated loads have COP greater than 1, which means their performance is better than the resistive loads. A simulation study of the potential available with heat pumps as a demand side management (DSM) device is carried out in [52].

2.3.3 Properties of TCLs

Among two types of TCLs, room heaters, heat pumps and air conditioners have the capacity to store the thermal energy in the thermal mass of the ambient air inside the building, refrigerators and freezers can store the thermal energy in the thermal mass of the food and the air in their cold chamber and for the water heaters the storage element is the water. The key parameters of the domestic TCLs are listed in the following Table 2-1 [53].

Table 2-1: Properties of major domestic TCLs.

Parameter	Air conditioners	Refrigerators	Heat Pumps	Water Heaters
Power consumption (kW)	2 – 7.2	0.1 – 0.5	4 – 7.2	4 – 5
COP	2.5	2	3.5	1
Thermal time constant (h)	2.25 – 6.25	32 – 80	2.25 – 6.25	20 – 84
Energy transfer rate (kW)	5 – 18	0.2 – 1.0	(−25.2) – (−14)	(−5) – (−4)
Service temperature (°C)	18 – 27	1.7 – 3.3	15 – 24	43 – 54
Dead-band (°C)	0.25 – 1.0	1 – 2	0.25 – 1.0	2 – 4

Electric room heaters and air-conditioners share similar thermal properties whereas the COP is 1 for the electric room heaters and the energy transfer rate is correspondingly low. Similarly, refrigerators and freezers have similar thermal properties except the operational temperature range which is in the range of -25 ˚C to -18 ˚C. Therefore the COP of the system is low compared to the refrigerator and the value close to 1. The energy transfer rate is also correspondingly low.

Both the positive (hot) and negative (cold) thermal energy reserves in the TCLs creates the interest for utilising these devices to provide power system services. As long as the user's service is not affected, their electricity consumption is not increased and also the wear and tear of the appliance shortens its life span, the user is not concerned with the power cycle of these appliances.

The TCL considered in this dissertation for DR experimental study are domestic refrigerators which are compressor operated TCLs.

2.4 Power system services

Power systems have undergone many changes from early 19th century until the present day. Initially it was a one entity producing electricity and providing services to the consumer. The socio-economic and political changes and technological advancements created opportunities to involve multiple entities to operate power systems and to divide the responsibilities. The electricity market today demands power plants to be responsible for their unit commitment and dispatch and primary frequency control. The transmission system operators are responsible for power transport and maintaining the system frequency [54]. The distribution system operators are responsible for the quality of service in terms of power delivery within the specified voltage levels [54]. The distributed generation with high penetration of RES creates requirements for contingency management [37]. In future power systems, the utilities will concentrate on the security of power delivery [55] and the regulation will be an ancillary service provided by aggregators [56]. Aggregators will play appreciable role in the future electricity market [57], [58]. The different services required by the DSOs based on power curtailment are described in [54]. They can be classified as power limiting to minimise the power procurement cost (during a high-price period), frequency regulation services and voltage regulation services. The DSM can provide such services during power system contingencies, as the duration of service requirement is short. TCLs such as a DSM will not notice interruptions to provide such services for short durations [59].

2.4.1 Power limit

Power limiting in the modern distribution network could be needed for multiple reasons. It could be for matching the demand with the production from RES as the power production from the RES will not follow the load [60], [61].

As already stated, the electricity produced with RES like wind and solar power will not follow the load. It is necessary to adjust the demand with the production to achieve the proper operation of the power system. The system operator could use other conventional power production methods to balance the capacity of production from the RES. DR will be a more cost-effective method than balancing the production with different sources [54].

In most cases the power utility company sells the electricity for a fixed price per unit (kW) of consumption to a particular type of consumer [62,63]. However, the market price varies with time, for example in Nordpool market, the power price varies every day [64]. In the fluctuating power price, the utility company would like to postpone the consumption during high price to low price duration for maximising their profit [65], or to improve the system reliability [66]. The network operational constraints like congestion could also be a reason for power limit [67,68]. Other than the aforementioned reasons, the power system operational requirements like voltage control and frequency support could also be a requirement for power limiting. They are discussed in detail in the following subsections.

In this dissertation, the change in available flexibility with domestic TCLs on different levels of limitation of their aggregated power consumption by DR activation is presented in chapter 6. The impact of power limit by DR activation on domestic TCLs is described in the chapter 7.

2.4.2 Voltage control

The DSO is responsible for the voltage level at the distribution grid. Any electrical equipment is designed to operate at particular voltage level [69]. A violation in the voltage levels may cause a malfunction or a permanent damage. Therefore, the DSO is obliged to deliver power within specific voltage limits. The voltage drop in the power carrying cables is inevitable due its impedance. The voltage drop in the cables is a function of both the cable impedance and the amount of power flow. As the distance between the distribution transformer and the load increases, the length of the cable and its impedance increases. If the voltage level drops below 10% of its nominal value, it is considered as under voltage [69]. Some transformers in the network series are equipped with online tap changers (OLTC). These tap changers are used to increase the voltage levels. Similar to the under voltage case, if the voltage level goes above 10% of the nominal value, it is considered as over voltage [69]. Apart from the OLTC, line regulators, and shunt capacitors are used at feeder level to control the voltage [70]. Beyond the controllable limits, load shedding is one option to avoid grid instability [71] and load shedding is the cost-effective method to manage under voltage challenges faced by the electric utility companies [72]. The impacts of distributed generation on different voltage control methods are detailed in [73]. In the conventional unidirectional power flow network, the capacities of the load and the source are known and conventional OLTC method works well. The distribution system with multiple generation system becomes an active distribution system (ADS), where the conventional distribution system is passive [74]. In ADS, OLTC cannot control voltage at every node. The voltage variation in a distribution network with distributed generation is analysed in [75] and [76]. A cooperative control between the OLTC and distributed generation sources is studied in [74]. Other than controlling the power sources, the second approach is by controlling the storage with respect to production. An active and reactive power control of distributed storage by broadcast signal is studied in [77]. The third option is to control the load in accordance with the production. A real-time DR based primary voltage control using TCLs is studied with a simulation on IEEE 13 node feeder in [78]. A simulation work with DR load curtailment and controlling switchable capacitor banks for voltage control is studied in [79]. A comparison between the conventional single point controls with static compensator and demand side management with DR is carried out in [80].

2.4.3 Frequency control

The frequency in the power system represents the active power flow balance. In Europe the frequency is standardized at 50 Hz. During normal operation, the steady state frequency variation is 1% of the nominal value [69], [81]. It is the transmission system operator's responsibility to monitor and maintain the frequency [82]. During the large imbalances like a tripping of a large power plant, the frequency may vary to the allowed levels of 47–52 Hz. Frequency control comprises 3 steps. They are primary, secondary and tertiary. The primary control is effected by the spinning reserves drop controllers. On the frequency variation the drop controller adjusts the generator's power output. Primary control can act rapidly and can adjust the power output in 10–15 seconds. Due to the primary control's ability the system frequency settles at the deviated value and not restored to the nominal value. Therefore, the primary control is referred to as frequency containment process [83]. The secondary controls are operated by the automatic generation controllers (AGC). The secondary may be a local generation or multiple generation units distributed in the network [84]. The secondary control delivers additional power to restore the system frequency to the nominal value. Therefore, secondary control is called frequency restoration process [83]. The response time is longer for the AGC to deliver the required power to release the primary controller to act further on frequency changes. The response time for the secondary controllers is in minutes. The secondary control, however, is not a permanent solution. The secondary control gives additional time to the TSO to arrange replacement power. Replacement for the secondary control reserve is the tertiary control, which is called reserve replacement [83].

As discussed earlier, in a power system with high penetration of RES, the production cannot be increased as and when required. The DERs in such systems should be managed very well to regulate the frequency. There are many simulation studies available for frequency control with DER management [85–98]. The studies can be classified as source control [86,88] storage control [24,85,87] and load curtailment [89–98]. In source control, control of PVs and wind turbines are studied for frequency support [86]. The impact of communication delay in controlling PVs for secondary frequency control is presented in [88]. Control of different types of storage elements like batteries and flywheels in a micro-grid environment is studied in [24,85,87]. In load curtailment study main focus is on TCL control. Large scale (~17.5 MW) and small scale (~180 kW) simulations for primary frequency control by ON-OFF control of TCLs are described in [89]. Another study modelled 1000 refrigerators for the simulation and studied grid frequency stabilisation with TCLs [90]. A simulation study of centralised primary frequency control by curtailing domestic loads including critical loads like lighting at different frequency thresholds is studied in [91]. Another similar study with autonomous controllers is presented in [92]. An experimental proof of concept for primary secondary frequency control with autonomous control of TCLs especially the freezers is demonstrated in [93]. Decentralised primary control with stochastic control of TCLs in sudden outage of power plants is simulated in [94]. [97] proposes a distributed frequency control with DR to minimise frequency oscillations. In [98] frequency restoration with DR activation for load shedding is presented.

In chapter 6, the secondary frequency control by DR activation on domestic TCLs is detailed. The properties of secondary frequency control by DR activation are compared with the requirements described in the grid code of Danish TSO Energinet.dk.

2.5 Control stretegies

The control of TCLs to provide various power system services can be classified into two different types in the ways the final controll element is activated. They are

1. Direct control
2. Indirect control

Based on the decision-making intelligence location, direct and indirect controls can be autonomous or centralised control.

2.5.1 Direct control

In domestic sector, the loads that have higher power-flexibility for example water heaters, and air conditioners are utilised for DLC [99]. The direct control method is by sending a specific signal or command to the load controller [100] or even controlling the load directly [101] through a unidirectional or bidirectional communication link. If a unidirectional link is used for communication, the load or the load controller has to oblige to the command. The bidirectional communication link facilitates an acknowledgement by the load or the load controller [100] and has the freedom of deciding load curtailment. The command signal can be initiated by the utility (DSO-Distribution system operator) [101] or by an aggregator [102], who bridges the gap between the consumer and the DSO. Four load control schemes based on the type of information exchange between the two parties are described in [103]. As per the description in [103], the control scheme can be

1. Shift in time of operation, which is suitable for load of non-interruptible type, for example washing machines and dishwashers.

2. Reduction in power consumption, which is suitable for the loads that can reduce their power consumption and extend their duration of operation, for example room heaters or water heaters.

3. Schedule of power consumption with a time series of allowable power consumption and its duration.

4. Direct power control, which can alter the power consumption.

In the DLC method of direct power control, the appliance owner signs a fixed payment contract irrespective of the DR activations for a limited number of hours in a day with the company [101]. Often the user is not informed about the load curtailment. Furthermore, the user should not notice any inconvenience due to the load curtailment. Therefore, in continuous regulation of reserves (CRR) the user must be provided with an option to override the DLC controller [50]. Two-way communication is mandatory for the CRR DLC [50]. In most cases, DLC is activated only in the times of emergencies [104] to provide power regulation and mostly associated with the power system stability relevant situations [105]. As DLC is used in emergency situations, its full flexibility may not be utilised to its potential [104].

In this dissertation, the control strategy adopted to control domestic refrigerators is centralised direct control. In Chapter 3, section 3.2, the devices used for control are described. In section 3.3, the control and data centre setup for the centralised control is described.

2.5.2 Indirect control

The unidirectional broadcast communication to avail at least a partial flexibility available at the demand side is the motivation for indirect control [106]. In indirect control the signal for control is the quality parameter of service delivery. It could be the electricity price or the variation in the service set points; for example, variations in the temperature set points of a room heater. The indirectness in the relationship between the controlled parameter and the observed parameter characterises them [107]. The controller for the load is not obliged to react to the signal [100]. The indirect control becomes non-deterministic due to the local decision making ability of the controller [100,107]. The intelligence for decision-making is distributed and final control option is limited to the local control. The indirect control method is not intended for critical power system services [105]. The control decision on signal can be taken by a central controller that has the information of the device consumption, operational status, their service set points and flexibility. In the case of distributed controllers, the control signal (namely, the power price) is broadcast to all consumers [100,107]. Electricity price based indirect control has gained increased interest in recent years [106]. The controllable price-elastic flexibility with consumer consumption on price based indirect control is observed with varying prices [108]. The indirect control can be of interest to the electricity retailer to maximise revenue [109], or it can be of interest to the aggregator to deliver power service [110].

Although the indirect control method is not used for any of the experiments in this dissertation, the shadow electricity price indication is sent to the consumers participating in the project for consumers' behaviour analysis which is beyond the scope of this thesis. In chapter 3, section3.1 explains in detail about the need for consumer behavioural study and the method of study. Section 3.2 describes the devices used for shadow price indication.

2.5.3 Automnomus and centralised control

In autonomous control, the parameters of the power system are measured locally and the local controller has the knowledge about the power system as well as the appliance to be controlled. In general, in power system the sources are controlled autonomously. The droop control governors work autonomously for primary frequency regulation. Similarly the OLTC in the MV distribution transformers act in response to the local voltage changes. [90] proposes a dynamic demand control (DDC) algorithm for TCLs by varying their set point as a function of line frequency. Domestic refrigerators were considered for the study in [90]. [90] states that a power system with considerable wind energy penetration, the DDC can act faster than the droop controller of the conventional system in the occasions of sudden wind power changes. The similar case can be taken for any power system with large RES share for example with solar PV. In [111] was studied frequency control by autonomous control of electric water heaters. The study proposes that cooperative control has a greater potential than independent control. In [112], a new approach to communicate the electricity price as function of frequency is proposed and the autonomous frequency controlled loads can respond for the same. [113] demonstrates the possibility of smart charging a discharging of electric vehicle in response to the system frequency using autonomous control. Similar to the frequency control by autonomous control, the EV charging in response to the local voltage condition is explained in [114]. The harmonic distortion reduction on the local voltage by a power quality improvement instrument is demonstrated in [115]. Current control to a water heater by pulse width modulation (PWM) to reshape the voltage variation created due to the other household appliance opperations is key for this application.

In centralised control, the control intelligence is concentrated at one place and the control decisions are communicated to the individual elements. The advantage is that the centralised control has better predictability [116]. On the other hand, the cost of computational and communication infrastructure will be high as the number of controllable elements and their distance from the central controller increases. Also, the control delay will be higher. [116] proposes a form of centralised control of DSM for power system services like spinning reserve and load following (production) and decentralised control for the regulation of voltage and frequency as they require fast responses. [117] discusses the design considerations of a centralised load controller using TCLs for continuous regulation reserves. The technical challenges mentioned in [117] are communication delays, data errors, and limitation of communication bandwidth. [117] insists on duplex communication and user override function of control for centralised control. With the centralised control, it will be easy to introduce a new entity and evaluate their performance (for example a demand side management aggregator), to power system operation [116].

2.6 Recent research projects

2.6.1 IFIV

IFIV (Intelligent Fjernstyring af Individuelle Varmepumper) is a project to demonstrate the DR capacity available with heat pumps to provide power system services to Danish power operators in the Nordpool market scenario. The project is funded by Energinet.dk the TSO in Denmark. A diagram of the overall setup is given in Figure 1. A Smartgrid ready heat pump controller was developed to receive signals from the control centre and send indoor outdoor temperatures and solar radiation measurements from the houses. Some 300 heat pumps have been installed. The control centre server predicts the power consumption for 24–48 hours. The available capacity is traded in the day ahead and intraday market similar to a CHP production banlce system to balance the fluctuations in the wind power production.

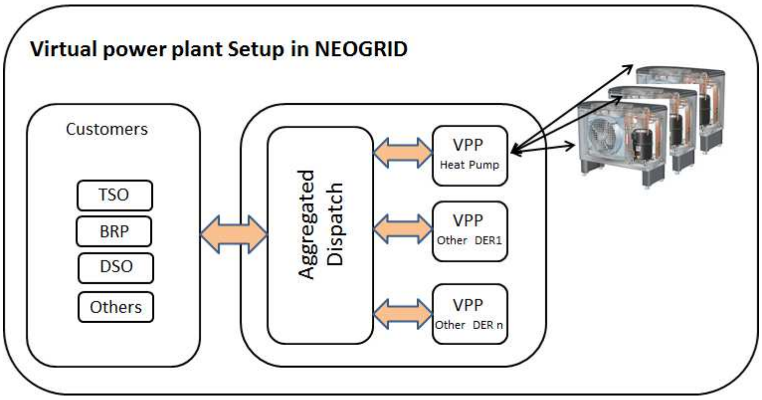

Figure 1. Virtual power plant setup in IFIV project.

(Adopted from the figure source: http://bit.ly/1WdltVD accessed on 26 October 2015)

2.6.2 INTrEPID

The INTrEPID (INTelligent systems for Energy Prosumer buildings at District level) project focuses on energy management and energy optimisation in residential buildings. It is a FP7-ICT project. The monitoring is at controllable load level and also at the building level. The objectives are to provide

1. At device level: optimisation of individual devices energy consumption supported by continuous monitoring and diagnostics to detect deteriorated performance. Devices considered include white goods and AV equipment.
2. At home/building level: optimisation through the coordinated control of local consumption, generation and storage devices.
3. At district level: optimisation through the ability to perform energy exchange with other participants connected to the electricity grid.

The overall architecture is shown in Figure 2. The device level controllers are connected to the home automation network (HAN). The HAN is connected to the INTrEPID software platform. Energy optimisation and capacity estimation can be performed at the INTrEPID software and the services can be traded with the power system operator and other external parties.

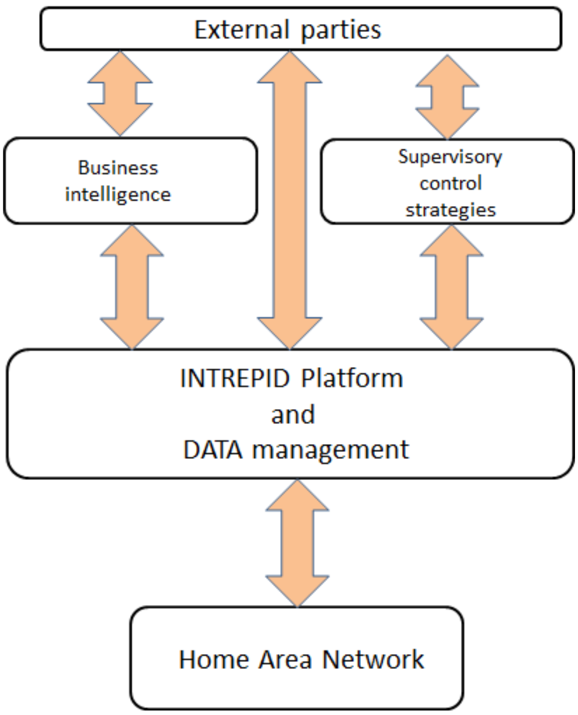

Figure 2. INTrEPID system architecture

(Adopted from the figure source: http://bit.ly/1WdKElT accessed on 26 October 2015)

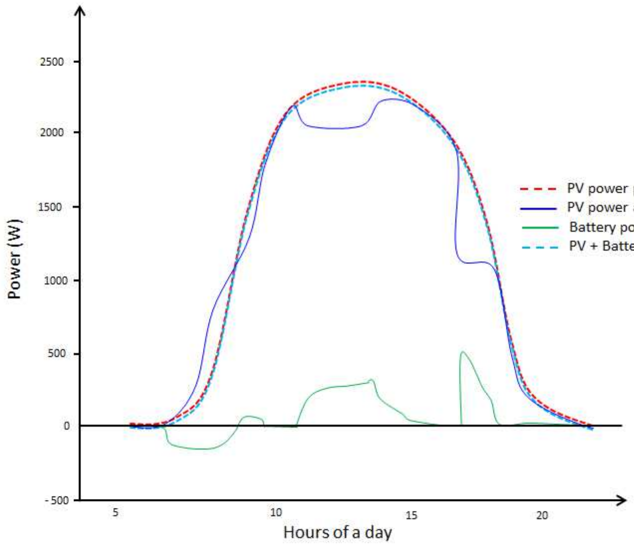

Figure 3. PV power balance with storage.

At present the fridge and the other schedulable loads (washing machine and dishwashers) in residential buildings are controlled to balance the forecasted power output from the residential solar PV installations. One of the test scenarios is explained in Figure 3. There are 50 installations (35 in Italy and the rest in Denmark) for this study.

The project, IFIV focuses on power limit either by following one day load profile which is committed a day ahead or in an intraday period. However, in both cases, there are few research questions unanswered. As the TCLs will consume the amount of energy that is reduced by DR activation back when their normal operation is restored, it is important to study the impact of power limitation on DR activation. Similarly, the flexibility changes in TCLs with different amount of power limitation need to be quantified.

The project INTrEPID considers all household appliances and energy sources like solar PV in one house as single cluster. The cluster is managed by a home area network (HAN) controller to follow a committed load profile at building level. In such scenario, the individual appliances capacity and their flexibility cannot be characterized for particular DR application. Secondly, although there is a possibility of demand adjustment to support power system operation in an unexpected time frame, the load capacity cannot be utilized as the HAN controller optimises the control to follow a specific load profile.

This dissertation addresses these unanswered research questions regarding the flexibility change and the impact of DR activation on one category of domestic appliance namely TCLs.

3 EXPERIMENTAL SETUP

In this chapter, the experiment platform developed for the project INCAP is presented. The INCAP experiment platform is developed as a part of this Ph.D research work. The experimental platform development project work consists of selection of suitable hardware devices to convert a normal domestic refrigerator into a smart grid friendly refrigerator without any alteration in the refrigerator system, software application development for assert and measurement data management, software application development for DR control applications and mock trials to standardise the hardware installation procedure at the consumer houses. The chapter starts with the broad introduction about the project INCAP, project objectives, project partners and their interest and responsibilities. In the further sections 3.2 and 3.3, the INCAP experiment platform is detailed. All the experiments presented in the chapter 5, 6 and 7 are conducted using INCAP experiment platform.

3.1 Project INCAP

INCAP stands for Inducing consumer adoption of automated reaction technology for dynamic power pricing tariffs.

The domestic household can change its electricity consumption in reaction to electricity supply variations. In the wholesale electricity market, the hourly prices indicate the supply demand variations. The technological advancement can make the household gadgets smart in future, and they can be made to respond automatically to supply demand variations. But the barrier foreseen is the customer adaptation for such dynamic response by their household gadgets. INCAP analyses the possibility of inducing the customer to accept varying tariffs and automatic response technology at an attractive cost. The method here with a large field experiment allows for estimating the distribution of adaptation barriers on a large population of electricity consumers involved in the field experiment from their natural consumption setting. The study results will identify the consumer groups where the focused polices will be cost-effective and also the policy design.

Domestic consumers can adjust their demand to variable supply in response to the tariff that varies with real-time system conditions. These demand adjustments can be seen as a supply of regulating power. Earlier studies [118] have shown that in response to day-ahead dynamic prices, a larger amount of demand reduction from consumers is possible through smart technologies. Studies on real-time demand reduction with market prices are limited. Therefore, INCAP will focus on automated response at the household level on real-time system conditions. As the number of participants for the experiment needs to be larger, the household gadget selected for the experiment should be commonly available in every house. The gadget should be available all time of the day for control. Its interruption for a short duration should not cause inconvenience to a great extent. The device installations to add the smartness to the gadget could be done easily by the consumer without any additional special skills. Therefore, a refrigerator is selected as the controllable gadget.

3.1.1 INCAP objectives

The objectives of the project are

1. To establish a blueprint of quantitative measures of consumer motives and barriers regarding their adoption of varying tariffs and automated supply of regulating power from appliances.
2. To investigate important dimensions of behavioural heterogeneity based on a sound field experimental methodology and a large representative sample of Danish power consumers.
3. To utilise results for designing policy strategies and investigating the consequences of these policies using macro models of the Danish energy system.
4. To provide sound guidance to national policy makers and private energy system operators about
    a. The guidelines to design effective policies for inducing different types of consumers to supply regulating power.
    b. The costs and benefits of implementing effective policies taking account of heterogeneity across different types of consumers.

3.1.2 Project partners and responsibilities

There are 2 academic and research institutions, a distribution system operator and a smart grid-friendly home automation product manufacturer are participating in the project.

1. Technical University of Denmark (DTU): DTU Electrical Engineering is responsible for developing system level architecture user-installable, “smart” household unit for adding demand response capabilities to ordinary refrigerators and developing software applications for the experiment. DTU Management is responsible for design and evaluation of National strategies for the adoption of “smart” technologies and increasing demand flexibility.
2. University of Copenhagen (Københavns Universitet-KU) is responsible for identifying consumer motives and barriers and to develop the experimental design for the estimation of the motives, barriers, policy and price effects. KU is also responsi-

ble for running the field experiment in coordination with the distribution system operator SE (formally SYD ENERGI).

3. Develco Products: Develco Products A/S provides the control and sub-metering device, temperature sensor, user interface device and communication devices and the support for interfacing these devices and application software developed for the project.

4. SE: SE is the distribution system operator in Denmark with state of art energy metering infrastructure. The consumers in the SE's distribution network are considered for the field experiment. SE can provide the hourly energy meter readings of their consumers who are participating in the experiment. The historical data available with SE from one year previous to the experiment are used for the analysis of the motives, barriers, policy and price effects.

3.2 Experiment plan and control requirements

The consumers, who volunteer for the experiment, sign a contract with their electricity company (SE). They are provided with a set of devices to upgrade their refrigerators and receive electricity price information. They will be informed with shadow qualitative prices of electricity as high, low and normal prices. The actual price values are informed in their contract agreement. The technical requirements for the devices are

1. An ON/OFF switch for control
2. A sub-metering device to measure refrigerator consumption
3. A temperature sensor to measure the refrigerator temperature
4. A simple interface to inform the qualitative price information

All these devices should be accessible from a remote computer.

3.2.1 Control and measurement devices

The control devices make the ordinary refrigeratror to a smart and suitable for any smart grid application. There are 4 devices used for the refrigerator upgradation, control and measurement.

The devices are

1. Smart relay: A 'relay unit' with active power measurement function is used to control the refrigerator. The relay unit is used to switches the refrigerator ON and OFF in response to the command from the remote computer. Also the relay unit has the capability of measuring and transmitting active power, RMS voltage and current consumption by the refrigerator.

2. Temperature sensor: The thermostat in the refrigerator maintains the refrigerator cool chamber temperature within the set limits. When the refrigerator is controlled from a remote computer, the refrigerator temperature needs to be measured and send to the remote computer. The temperature sensor used is portable wireless and battery operated device.

3. User interface: The main purpose of the user interface device is to communicate the real-time electricity price information to the user. The second requirement is to receive the user's feedback if the refrigerator is not to be controlled on a daily basis. The user interface device has red and green lights to inform the qualitative price information to the user and two buttons (keys) to receive the user's feedback. Similar to the temperature sensor, the user interface device is also a battery-operated device.

4. Gateway device: The aforementioned 3 devices are capable to communicate in the Zigbee wireless communication protocol. A Zigbee-Ethernet gateway device is used to translate the information from Zigbee protocol to Ethernet protocol to enable interaction of these devices with the remote server through a home internet connection.

3.2.2 Device selection and installation

Switching device

Develco Products A/S has 3 different smart relay products in their listed product line. The 3 smart relay products differ in the load current rating and physical construction for mounting. The available products are

1. Wall mountable 30 A Zigbee meter relay
2. DIN rail mountable 16 A Smart relay
3. Danish 107-2-D1 AC socket mountable 16 A Smart plug

The communication interface in all 3 smart relays is Zigbee wireless protocol. The power plug used in the domestic refrigerators in Denmark is as per the Danish 107-2-D1 standard. The maximum load current rating of the domestic refrigerator complies the 13 A current limit of Danish 107-2-D1 standard.

Table 3- 1: Technical specification of smart plug

Voltage range	207 to 253 VAC
Current range	16 A
Optimum accuracy	1 %
Max. switch voltage	250VAC
Max. switch current	16 A
Operation temperature	0 to +50°C
RF sensitivity	-101 dBm @ 1% PER
RF output power	13 dBm
Power consumption	0.4W
Standards & directives	CE compliant, ETSI compliant, RoHS compliant according to the EU Directive 2002/95/EC

Therefore the Danish 107-2-D1 AC socket mountable 16 A Smart plug is selected for control. The short technical specifications list of the smart plug is given in the Table 3- 1 and the detailed technical specification sheet is attached in Appendix B.1.

Temperature sensor

The temperature sensor is not a separate product in the listed products of Develco Products A/S. There are 3 battery-operated combined sensor modules that include the temperature sensor. The available sensor combinations are

1. Smoke and temperature sensor
2. Occupancy, light and temperature sensor
3. Magnetic and temperature sensor

Among the available sensor combinations, the occupancy, light and temperature sensor combination is selected to be used as the temperature sensor. The light sensor and the occupancy sensors in the sensor module could be used to sense the event of refrigerator door opening for food exchange. The short technical specifications list of the temperature sensor is given in the Table 3- 2 and the detailed technical specification sheet is attached in Appendix B.2.

Table 3- 2: Technical specification of temperature sensor

Temperature range	0 to +50°C
Resolution	: 0.1°C
Accuracy	± 0.5°C
RF sensitivity	-92 dBm
Output power	+3 dBm
Power	Battery CR123 (exchangeable)
Battery life	5 years, hourly reporting
Standards & directives	RoHS compliant according to the EU Directive 2002/95/EC.

User Interface

The user interface device is not a separate product in the list of products of Develco Products A/S. One of the products in the list is Zigbee wireless Key fob / remote control. This product has 4 ON keys. This product was modified to accommodate two LED lights (red and green) to communicate with the consumers. The short technical specifications of the Key fob / remote controller are given in the

Table 3- 3 and the detailed technical specification sheet is attached in Appendix B.3.

Table 3- 3: Technical specification of user interface

Input interface	2-push button key
Output interface	2 LEDs
Power	Battery (2 x AAA, exchangeable)
RF sensitivity	-92 dBm
RF output power	+3 dBm
Operation temperature	0 to +50°C
Standards & directives	RoHS compliant according to the EU Directive 2002/95/EC, DIN EN 14604 and DIN 14676 Certified

Gateway device selection

There are two types of gateway devices available in the listed products. They are

1. Zigbee GSM gateway
2. Zigbee Ethernet gateway

The Zigbee GSM gateway needs separate GSM subscription and involves associated data usage costs. The control and measurement data for each consumer are very small. Most of the houses in Denmark have an internet connection with an ADSL router. Therefore the Zigbee Ethernet gateway device is selected as the communication interface. The short technical specifications of the zigbee Ethernet gateway are given in the Table 3- 4 and the detailed technical specification sheet is attached in Appendix B.3.

Table 3- 4: Technical specification of zigbee Ethernet gateway

Ethernet interface	10BASE-T/100BASE-T
RF performance	TX: +18dBm (EU: 12dBm) - RX: -100dBm Range: LOS ≤ 1600m, Indoor ≤ 100m
Power consumption	Average of 1.8W
Supply voltage	PoE or ext. PSU, 15-40 V
Operation temperature	-10 to +65°C
ZigBee stack version	2007
ZigBee application profile	Home Automation
Standards & directives	CE compliant, ETSI compliant, RoHS compliant according to the EU Directive 2002/95/EC

The device installation is simple and is done by the refrigerator users. An illustration of the devices installed is shown in Figure 4. Upon installation, the devices identify the control center server and are authorised to join the Zigbee network. The devices were configured by the server on joining for the measurement sampling rate.

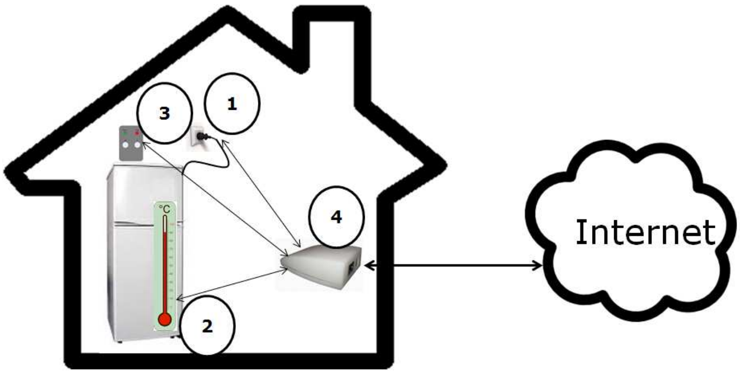

Figure 4. Refrigerator control device installation in a house.

3.2.3 Measurement parameters and sampling rate

Temperature: As the temperature sensor is battery operated, the manufacturer Develco Products A/S preconfigured the transmission rate for a long battery life over the whole INCAP project duration. The temperature sensor is configured to transmit the temperature measurement at 2 minute intervals. The refrigerator temperature changes very slowly due to the thermal inertia, the measurement at every 2 minutes interval is sufficient to appreciate these dynamics. The temperature sensor has an accuracy of ±0.5 °C and a resolution of ±0.1 °C.

Fridge active power and voltage: The active power consumption by the refrigerator is measured by the smart rely with 1 W resolution. The phase RMS voltage is measured with 1 V resolution and the measurement interval for both measurements is 10 s.

3.3 Central control and data centre

For the INCAP project, a central control and data centre was established at the Risø campus of the DTU. The necessary software that establishes the communication between the devices and the controller and database is hosted by a virtual server at the central computer server at the computer. Figure 5 shows the communication between the devices installed in each household and the data centre at DTU.

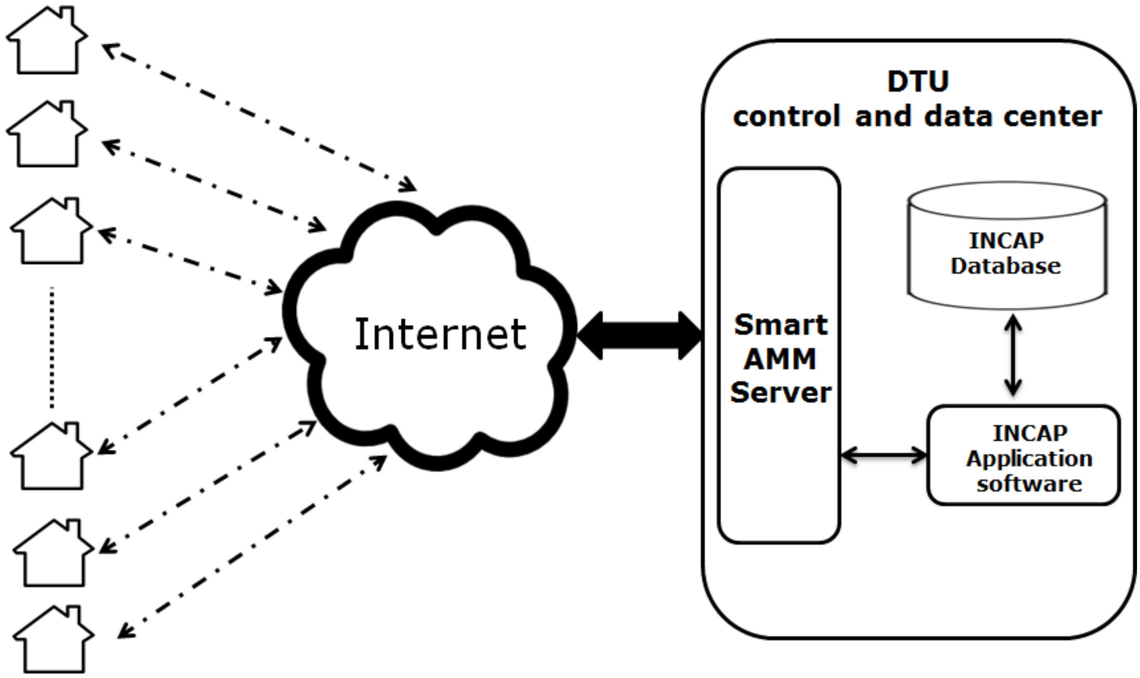

Figure 5. Data flow from the fridges to the controller.

Develco Products A/S provides software called 'Smart Advanced Meter Mmanagement Server' (Smart AMM Server). The smart relay, temperature sensor and the user interface device send their respective parameters in a form of short messages to the gateways device. The gateway device is configured with the DTU control center server address. Therefore the messages received from the devices are sent to the DTU control centre computer in which the Smart AMM Server software is hosted. The Smart AMM Server acts as a message transfer agent. Any client software that is subscribed to the Smart AMM Server can receive a copy of incoming messages from the devices. In a similar way, the command messages for the smart relay, light blink message corresponding to the price information can be sent to the corresponding devices through the Smart AMM Server.

The Zigbee-Ethernet gateway device is factory configured with the domain name of DTU control and data computer server. When the consumer installs the devices, the Zigbee-Ethernet gateway device automatically connects to the control and data computer server in which the Smart AMM server software is running. An application developed at DTU for the INCAP project is given with a list of devices and their addresses. The application software authorises the 4 devices from the consumer's household and the data from these devices are logged in the database.

The software for control application can be executed either in INCAP server or in another computer by subscribing to the Smart AMM Server for message exchange. The experiment for available flexibility estimation with TCLs is described in chapter 5. The software application for the control of refrigerators is executed in the INCAP server. In contrast, the software applications for experiments: secondary frequency control with DR activation (chapter 6), analysis of change in flexibility at different levels of power reduction (chapter 6) and the impact of DR activation on refrigerators (chapter 7) are executed in a remote computer.

3.3.1 Safety interlock

The communication from the end device like smart relay to the INCAP application software has multiple layers in between. Communication failure may happen for multiple reasons, for example due to poor internet connection, Zigbee-Ethernet gateway device failure or application software failure. In the event of any of the failures stated above the food content in the refrigerator should get affected. The smart relay is programmed to hold the ON OFF command from the remote computer valid for only for 5 minutes. After 5 minutes, the smart relay will switch back to its normal status (ON). If the control software needs to keep the refrigerator switched OFF for more than 5 minutes, then the command has to be sent multiple times. In such a way the food content in the refrigerator is saved from any failures except from the smart relay failure and the control software malfunction.

3.3.2 Data security

The DTU computer-sever in which the software Smart AMM server, INCAP database and INCAP application software are installed is protected by the DTU's firewall for the information security from the external network. The sensor and control devices in the houses can communicate only to the DTU computer-sever as the Gateway device is programmed with DTU computer sever the domain name. The sensor and control devices in the houses accept the commands from the specific Smart AMM server only. In this way the communication and data base are secured. This level of security is sufficient for the INCAP project. However, for a real smart grid data and communication scenario, the security measures considered for the INCAP project are not sufficient and better cyber security infrastructure as per the latest standards is required.

4
MODELLING OF REFRIGERATOR

In this chapter the main results concerning the first part of the first research topic are presented. The main results have been published in separate paper and the paper is included in Appendix A.1 of this dissertation. The chapter starts with general modelling methods for TCLs. Then, the chapter introduces the measurement constraints in the project INCAP and the suitable modelling method. In the further sections of this chapter, the temperature prediction strategy is explained. Finally, the chapter presents the results of the experimental validation of the temperature prediction method.

4.1 General modelling methods

A mathematical model of a system governs its behaviour with equations. The equations represent the output of system as a function of system inputs and also the factors influencing the system output. The purpose of developing a model can be to predict the future behaviour of a system or to design a new system or to characterise the system or even to test the system in its extreme conditions in a non-destructive method. Based on the method the system is modelled, the model can be classified as white-box model, grey-box model or black-box model.

4.1.1 White box model

In a white box model of a system, the model parameters are determined using first principle of operation or the basic physics equation. If the properties of the system elements are well known at the given circumstances, then it is easy to develop a white box model. [119] is an example of white box modelling of a HVAC system. Each subsystem is individually modelled and their collective behaviour is separately modelled. The white box model is more generalised one and can be modified to represent a specific system with its parameters.

4.1.2 Grey box model

The grey-box modelling method still follows the first principles and yet a physical one. But, the model parameters are estimated from the historical measurements of system inputs and outputs. The model parameter estimation process is model training. As it is difficult to collect all system specific parameters, the grey-box modelling method is practised to model TCLs for power system applications. [121–128]. The model can be simple first order one as represented in [121],[127] and [128] or the complexity by improving the order to represent more dynamics in the performance as shown in [122]. The complexity in the model parameter estimation has to be considered before improving the order of the model.

4.1.3 Black box approach

The black-box modelling method doesn't follow the first principles of the system to be modelled. The modelling method governs the relation between the inputs and outputs of the system only from the historical measurements of inputs and outputs. The black-box modelling method facilitates to model even a nonphysical system. As the model depends on the historical measurements, model cannot predict the output for the input conditions which are not governed by the historical data. In [129] the black-box model of heat exchange in a variable speed refrigeration system is explained. Black-box modelling of complex power system is explained in [130]. A state queue approach to model TCLs is detailed in [131]. The uncertainties in the aggregated TCL are modelled in [132]. Performance evaluation of state queue model based control of TCLs is presented in [133].

4.2 INCAP measurement constraints and black box model

In the INCAP experiment, the access to control domestic refrigerators is provided, which is the example case TCLs. The refrigerator type and capacity are unknown as they are not collected from the users. There is only one temperature measurement from the INCAP consumers refrigerator is available. As the temperature sensor is a small portable device, the user may not perform a fixed installation of the sensor inside the refrigerator. Therefore there is no control over the position of the temperature sensor.

In such circumstances, the white-box model is not possible without any details about the refrigerators. Even a simple grey box model that considers the refrigerator as a first order system needs at least two temperature measurements, one from the refrigerator cool chamber and the other from the ambient around the refrigerator. As the historical measurements are available, a black-box model is possible with the historically measured temperature and power data.

As far as the DR application is concerned, the purpose of the refrigerator temperature prediction is to estimate the time that is required to attain the thermostat set points from the present temperature if the compressor is switched off, or vice versa. The error in temperature prediction will be reflected in the time estimation.

4.2.1 Types of refrigerators

Domestic refrigerators are available in different capacities and types. The basic classical refrigerator has a one cool chamber with evaporator that acts a freezer and the cooling element. The classical refrigerator has a single cooling circuit consisting of a compressor, condenser and expansion valve and evaporator. There are sophisticated refrigerators with multiple cool chambers. In such refrigerators with single compressor, one cool chamber comparatively at a lower temperature (that could be a freezer chamber) mounted with the thermostat for compressor control acts as a master. The advanced refrigerators have multiple cooling circuits with variable speed compressors and advanced electronic controllers. As the functionalities in the refrigerator increases, the complexity also increases.

In general, refrigerator temperature is maintained by the thermostat by controlling the compressor operation. The thermostat is mounted in the evaporator. The thermostat maintains the temperature within two temperature limits namely T_{max} and $T_{min.}$ The thermostat switches OFF the compressor when the temperature reaches the lower limit T_{min} and temperature inside the refrigerator increases due to the natural heat seeping into the cool chamber from the ambient which is at higher temperature. As the temperature reaches the T_{max}, the thermostat switches the compressor ON and the cooling starts. The temperature inside the cool chamber is not uniform [134]. The temperatures at different places inside the cool chamber can represent the thermostat switching limits.

4.2.2 State queue model of TCLs

In [131], a state queue model (SQ model) of TCLs with only two measurements (viz. system status and temperature) is explained. The model divides the temperature cycles of the refrigerator into two parts: namely, cooling and heating. The example case considered for this study is a water heater system. The cooling and heating parts are identified from the water heater system status. During the cooling part of the cycle the water heater system is OFF and the heating part occurs when the water heater system is ON, which can be identified from the power consumption of the water heater system. The cooling and heating parts of the temperature cycle are divided into different states as shown in Figure 6. As the heating duration is less than the cooling duration, the number of states in heating part is less than that of cooling. The duration of cooling or heating can be obtained from the system status (ON or OFF) and present state (temperature). On a control event that changes the system status from ON to OFF or vice versa, the temperature state is swapped with the similar one in the counterpart. For example, when the water heater at the temperature state 3 is switched OFF by the control will move to the temperature state 11 as shown in the Figure 6. Similarly, the water heater at the temperature state 13 will move to the temperature state 2, when it is switched ON as shown in the Figure 6. The SQ model is adopted for DR activation study of HVAC in [133]. In the study presented in [133], the SQ model is used to change the temperature state of individual HVAC to the required temperature states, to control them to achieve desired aggregated load profile.

This model is a very simple black-box model and is suitable for simulation studies of DR activation on a large number of TCLs. However, there are some disadvantages with the SQ model. The model considers the temperature cycle parts are linear with constant slope, which represents a zero-order system. In reality the TCL elements (i.e. the material inside the cool chamber and the air) has a certain thermal mass. This thermal mass provides thermal inertia and the system order becomes greater than zero. For a good prediction of cool chamber temperature, the dynamics of the two temperature cycle parts have to be included rather than approximating them to a simple linear one. Another black-box model is developed to overcome the disadvantages of the SQ model. The following section will explain the temperature prediction strategy developed to model the refrigerator behaviour in this dissertation.

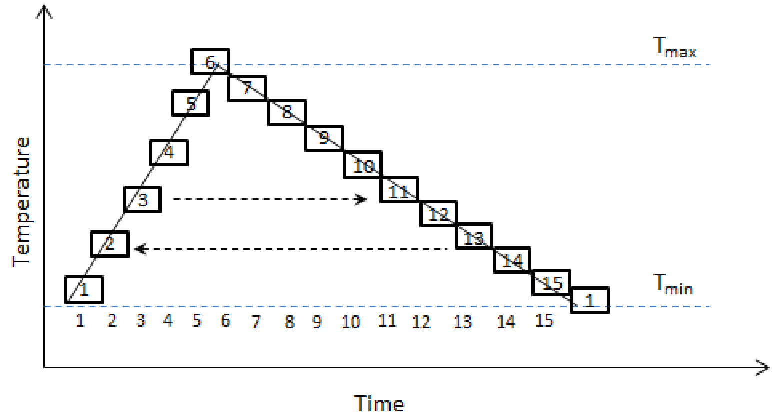

Figure 6. SQ model of water heater load [132]

4.3 Temperature prediction strategy

The parameters that govern the temperature behaviour of a refrigerator are the thermal insulation of the refrigerator, compressor power and COP, thermal mass of the food content and air, the ambient temperature and the variations in the thermal mass due to exchange of food content and air. The basic assumption in this modelling approach is the domestic refrigerator operational characteristics will not change for most of the day. The temperature variations of the cooling and heating part of the temperature cycles follow a similar trend. Therefore, the heating part of the temperature can be predicted from the characteristics of the previous heating part of the temperature cycle. Similarly the cooling part also can be predicted. The variations in the ambient temperature are less as the refrigerator is placed inside the house. A typical refrigeration cycle (heating and cooling) last for an hour or two as shown in Figure 7. The variations in the ambient temperature will be considerably less in such duration of refrigeration cycle. Also, if the refrigerator model is developed in such a way that the present temperature prediction is always based on the previous actual measurements, the variations in the ambient temperature will have a minimal impact on the prediction errors. Figure 7 shows the temperature cycles and the compressor power consumption of a refrigerator. In the temperature cycle T1-T2-T3, T1-T2 is the cooling part and T2-T3 is the heating part. Similarly, in the temperature cycle T3-T4-T5, T3-T4 is the cooling part and T4-T5 is the heating part. If the characteristic cooling part T1-T2 is known, the cooling part T3-T4 can be predicted as the variations in the successive thermostatic cycles are less. Similarly the heating part T4-T5 can be predicted from the previous cycle's heating part T2-T3.

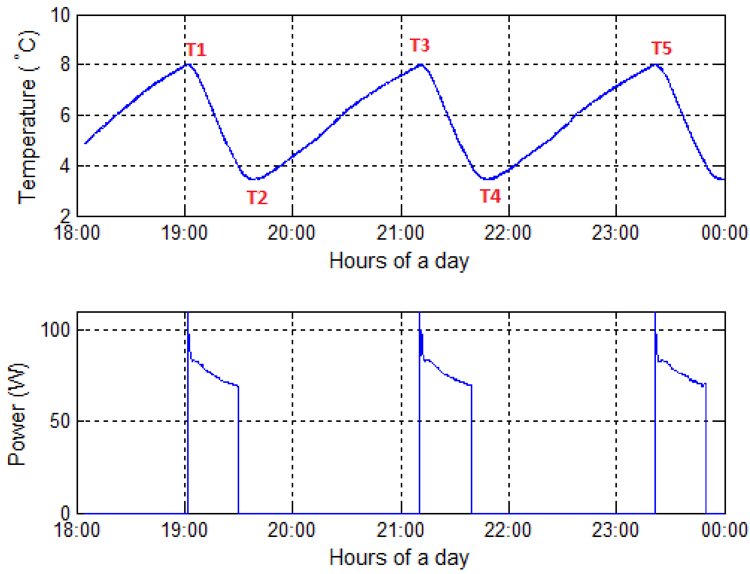

Figure 7. Temperature cycles and power consumption of a refrigerator

Instead of considering the whole heating part as a one line, as assumed in the SQ model, the temperature curve of each cooling and heating part can be characterised as a piece-wise linear curve. The slopes of each segment can be used to construct the next temperature cycle's heating part. The linear segment can be the one between two temperature measurement samples. The heating and cooling parts can be identified from the compressor power consumption. The temperature prediction black-box model with historical measurements is illustrated in Figure 8.

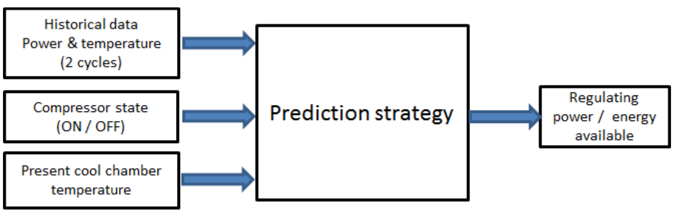

Figure 8. Block diagram of fridge model showing input and output.

4.4 Prediction error

To evaluate the developed model, an evaluation method has to be formed. The black-box model predicts the temperature profile of the refrigerator for the successive cycle. The purpose of the temperature prediction is to estimate the time that is required to attain T_{max} or T_{min} from the present temperature if the compressor is switched off or vice versa. The error will be at its maximum at the end of the predicted part of the cycle. The Figure 9 illustrates the actual temperature cycles and the predicted temperature cycles. The error in the heating part and the cooling part can be evaluated separately as they are predicted separately.

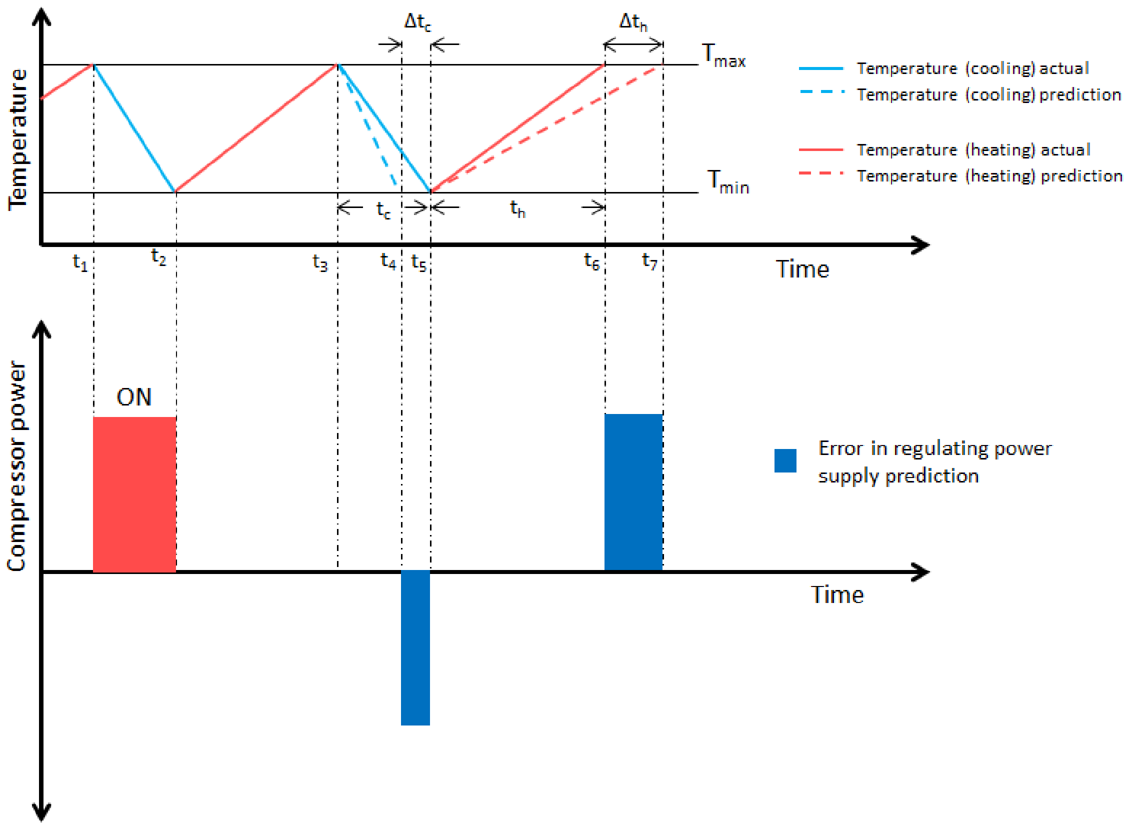

Figure 9. Prediction error calculation in cycle duration.

The prediction error is the ratio of the difference between actual time for each (cooling or heating) part of the temperature cycle and the predicted time to the actual time, as illustrated below.

$$e_p = \frac{\Delta t_{c,h}}{t_{c,h}}$$

4.5 Experimental setup

The experiment measurement requirements are cool chamber temperature measurement and refrigerator power consumption measurement. The experimental setup is shown in Figure 10. More details about the experimental setup, specifications of measurement data collection setup and the temperature sensor characterization are given in the conference paper attached in Appendix A.1.

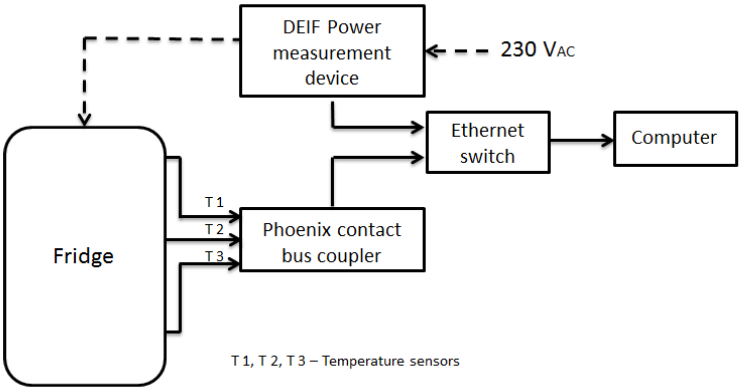

Figure 10. Experimental setup and sensor position.

4.5.1 Sensor placement

The temperature inside a refrigerator is not uniform throughout the cool chamber. It is necessary to identify the best place inside the cool chamber where the temperature variations are good enough to follow the cooling and heating parts of the temperature cycles. Three sensors are used to measure the temperatures at 3 different places inside the cool chamber. The temperatures are measured in 3 locations inside the cool chamber. One measurement is at the top (close to the evaporator, the cooling element), the next is at the bottom (far away from the cooling element) and the third sensor is placed equidistant between the two sensors. The measurements from the 3 sensors are shown in Figure 11.

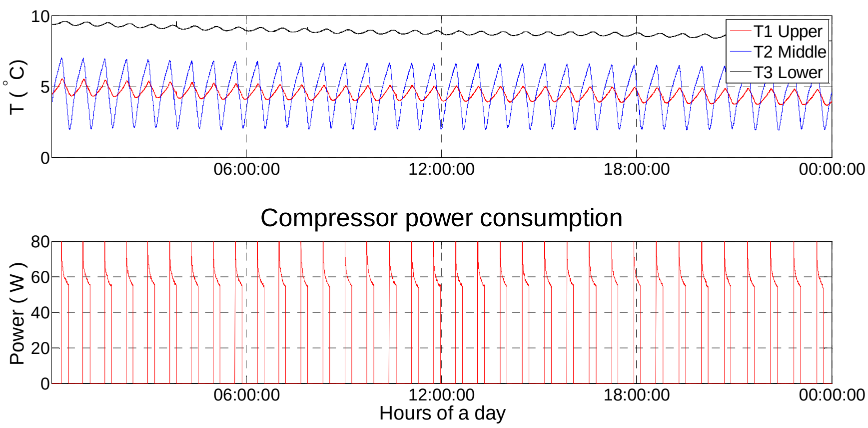

Figure 11. Temperature variations in 3 locations inside the cool chamber of a refrigerator.

It is noticeable that the temperature at the top portion is higher than the temperature at the bottom. The measured temperatures are air temperatures at different highs inside the cool chamber. Tough the cooling element is at the top, due to the higher density, the cold air always moves to the bottom of the refrigerator and air at relatively higher temperature and low density moves to the top portion of the refrigerator. The refrigerator used in this experiment has deli tray (similar to a drawer) at the bottom. As the deli tray is enclosed from all directions, the air inside the tray does not participate in the natural air circulation. Therefore the temperature measurement at the bottom shows less variations compared to measurement at the middle of the refrigerator. A detailed study of temperature and heat flow dynamics inside domestic refrigerators is presented in [135], [136]. The temperature variations are greater in the middle segment of the cool chamber compared to the top and bottom segments. As the temperature variations are greater in the middle segment, the model can extract more details of the temperature curves of the heating and cooling parts of temperature cycles. The middle sensor measurements are considered as the representative temperature of the refrigerator and are used for the temperature predictions.

4.5.2 Experiment plan

The experiment is planned for model development, model verification and validation. The model development and verification is done with one type of refrigerator and the validation is done with different type of refrigerator with different load condition and user interaction. The refrigerator used for model development is a VESTFORST brand model CW 375 M 75 liters fridge with separate fridge and freezer compartments with separate doors. The freezer compartment is the master unit of this refrigerator. The thermostat is mounted in the freezer compartment and the temperature set point for the refrigerator is the temperature of the freezer. The fridge compartment is a slave unit. The coldness flows from the freezer to the fridge compartment through a low thermal resistance (compared to the walls and doors) membrane separating the fridge and freezer. The construction of the refrigerator and the direction of coldness flow are shown in Figure 12.

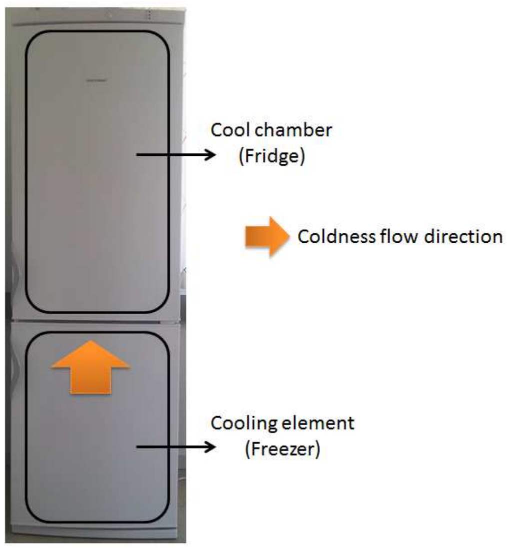

Figure 12. Physical construction and coldness flow directions in the double door refrigerator.

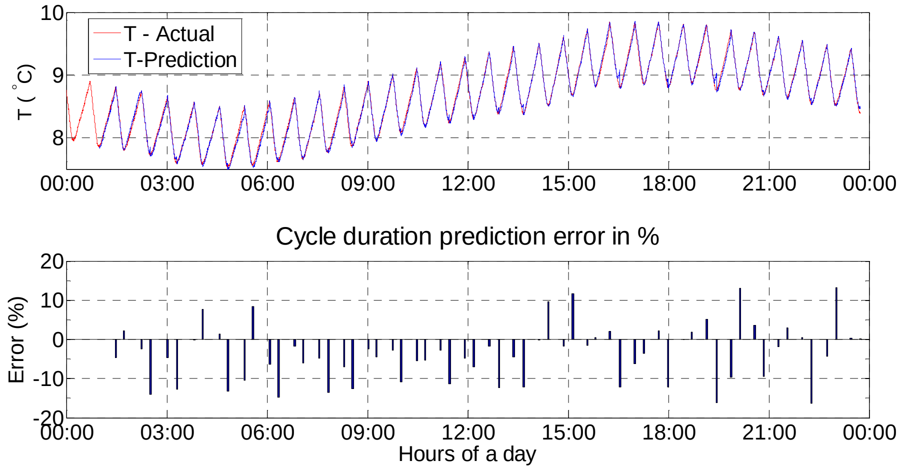

Figure 13. Temperature prediction and prediction error for the full day.

4.5.3 Temperature prediction

As the temperature and power consumption of the refrigerator are collected with a common time stamp, the cooling and heating parts of the temperature cycles are identified with the compressor power consumption. The curves are assumed as piecewise linear and the slopes of each segment are derived. The slopes of each segment are used to construct the next temperature cycle. The slopes of the cooling part are used to predict the next cooling part until the thermostat minimum temperature of the current cycle is reached. Due to the thermal inertia of the system, the temperature continues to drop even after the compressor is switched off. Therefore the system minimum temperature is lower than the thermostat minimum threshold.

Similarly the temperature continues to increase at the end of heating part even after the thermostat switches on the compressor. The model considers the thermostat thresholds as mark to end prediction. Figure 13 shows the actual and predicted temperatures for the refrigerator and the prediction errors for each cycle. The mean errors and the standard deviations for the prediction for a full day are given in Table 4-1.

Table 4-1: Prediction error.

	Mean error	Standard deviation	Maximum error
Cooling	-7.4%	14.2%	16.1%
Heating	-2.3%	3.6%	3.2%

4.6 *Performance validation*

The model performance is validated with a different type of refrigerator. The refrigerator has a capacity of 50 L. There is difference in the refrigerator construction compared to the previous refrigerator. The refrigerator has an evaporator unit mounted inside the fridge compartment (i.e. in the cool chamber). The evaporator serves as a cooling element and freezer. The refrigerator has a single door. The coldness flows from the top to bottom as shown in Figure 14.

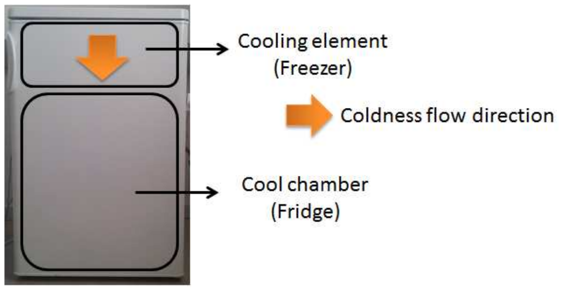

Figure 14. Physical construction and coldness flow directions in the single door refrigerator.

The performance evaluation is planned for prediction under normal operations and for the predictions under load changes and user interactions. For the normal operation, the refrigerator is filled with 18 L of water (i.e. 60% of the actual volumetric capacity) and is allowed to attain stable temperature cycles. The load changes and user interactions are introduced as listed below.

- Random door openings for the duration of 30 s and 60 s.
- Removal of thermal mass (12.5% of present mass)
- Addition of thermal mass (5% of present mass)

The actual and predicted temperature cycles and the percentage error in prediction are shown in Figure 15. The disturbances are introduced between 08:00–12:00 . The mean and maximum error and the standard deviation are given in Table 4-2.

Table 4-2: Prediction error on validation.

	Mean error	**Standard deviation**	**Maximum error**
Cooling	-1.0%	4.8%	9.5%
Heating	0.5%	5.5%	10.4%

The normal user interaction of 30 s to 1 minute, load removal of 12.5% and load addition of 5% do not show any considerable error in the predictions compared to the errors during normal operation.

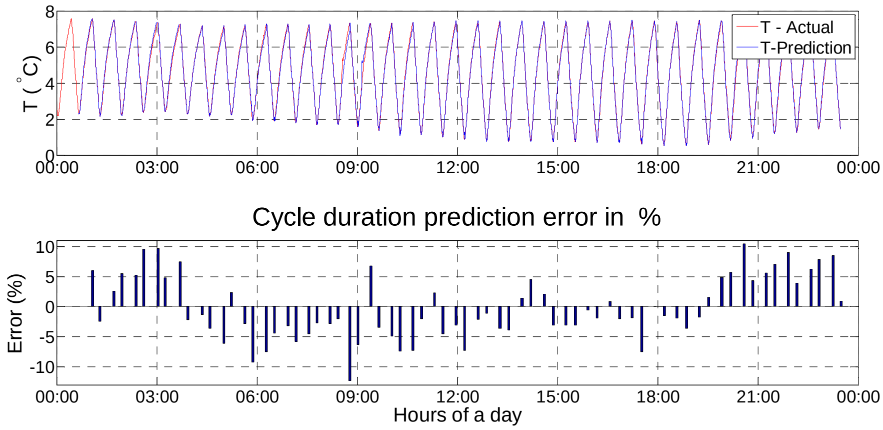

Figure 15. Temperature prediction and prediction error on validation.

As the small load addition does not show any considerable error pronouncement, another load addition of 13% is made. The actual and predicted temperature cycles and the percentage error in prediction are shown in Figure 16.

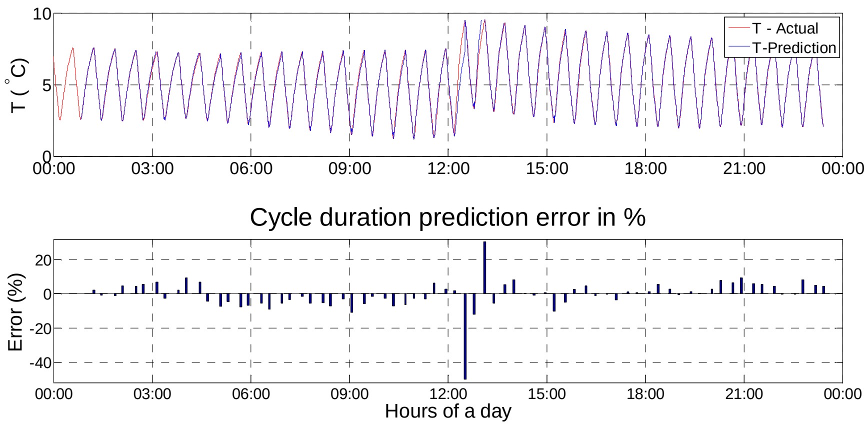

Figure 16. Temperature prediction and prediction error for 13% load addition.

The prediction error means and standard deviations are given in Table 4-3.

Table 4-3: Prediction error for 13% load addition.

	Mean error	Standard deviation	Maximum error
Cooling	-0.5%	10.8%	9.5%
Heating	-0.3%	6.1%	47.5%

The prediction error shoots up above 40% in the heating part on the load addition of 13%. In the two refrigerators, the black-box model prediction has fewer errors on the refrigerator in which the thermostat is mounted in the same compartment as the measurement is taken. In the other refrigerator, the temperature controller is mounted in the freezer compartment. Such a situation can be considered as the worst case scenario. The prediction errors for the worst case scenario are within 10%.

4.7 Model qualities

1. Fewer input parameters: The model developed requires only 2 parameters (i.e. power consumption and temperature) for the temperature and time prediction.
2. Simple model: This model is a very simple model and does not involve complex calculations. Therefore, it is scalable for DR applications involving a large number of TCLs.
3. Error: The best possible prediction seen during validation is with an error of 0.3%
4. Adoptability: The model adapts to the change in system dynamics within one thermostat cycle.
5. Suitability: The model suits well different types of refrigerators and does not require any special modification.

4.8 Suitability of the model for DR application

The demand response applications can be classified as applications that focus on power reduction and application for energy shifts. In power reduction, it is important to know the duration for which power has to be reduced. Similarly, in energy shift applications, estimation of the duration is important. The main objective of the model described in this chapter is time estimation of the refrigeration cycles using temperature predictions.

[137] analyses different error thresholds for the prediction models for smart grid applications. The error threshold suggested for DR application is 10%. The prediction error for the model described in this chapter is far below the limit prescribed by [137].

5 AVAILABLE FLEXIBILITY ESTIMATION

In this chapter the main results concerning the second part of the first research topic are presented. The main results have been published in separate paper and the paper is included in Appendix A.2 of this dissertation. The chapter starts with the formulation of energy estimation scenario. Then, the chapter introduces the control constraints and energy estimation method. Finally, the chapter presents the results of the experimental validation of the estimation method.

5.1 Scenario

Demand response (DR) is a widely accepted operational procedure carried out by power system operators [138–141]. The DR activation on TCL has two aspects. One is the amount of power reduction and the other is the sustainability of the power reduction. The power reduction capacity depends on the total number of TCLs, which are on and operational at any time (in the population of controllable TCLs, some may be off because of their thermostatic cycles) The TCLs will consume the amount of energy that is reduced by DR activation back when their normal operation is restored. This is due to their objective of temperature maintenance. Here the assumption is the TCL parameters do not change. The entity responsible for providing power system service by controlling TCLs should be able to estimate the energy shift. The method and the experiment presented here use domestic refrigerators from real households for the demonstration. The refrigerator model described in chapter 4 is used for the calculations.

5.2 Control constraints

The refrigerator operation is limited to the two temperature limits as shown in Figure 7. The thermostat maintains the temperature within the limits by switching the compressor on and off. In the experiment scenario of INCAP, the control relay for the refrigerator is placed at the power outlet. Since the refrigerators are not modified, there are some control constraints imposed by the thermostat in the given INCAP experimental setup.

1. The refrigerator cannot be cooled below T_{min}. The thermostat switches off the compressor as soon as the temperature reaches T_{min}.
2. Once the refrigerator is switched off by the thermostat, the compressor cannot be controlled by the external control relay until the thermostat is on again.

5.3 Estimation method

The control constraints limit the possibility of temperature control by the external relay only above T_{min}. The energy shift estimation method described in this section calculates the energy shift for a control method that keeps the refrigerator cool chamber temperature between T_{max} and ΔT °C above T_{max}. A pictorial representation of the temperature changes during the control period (DR) is shown in Figure 17.

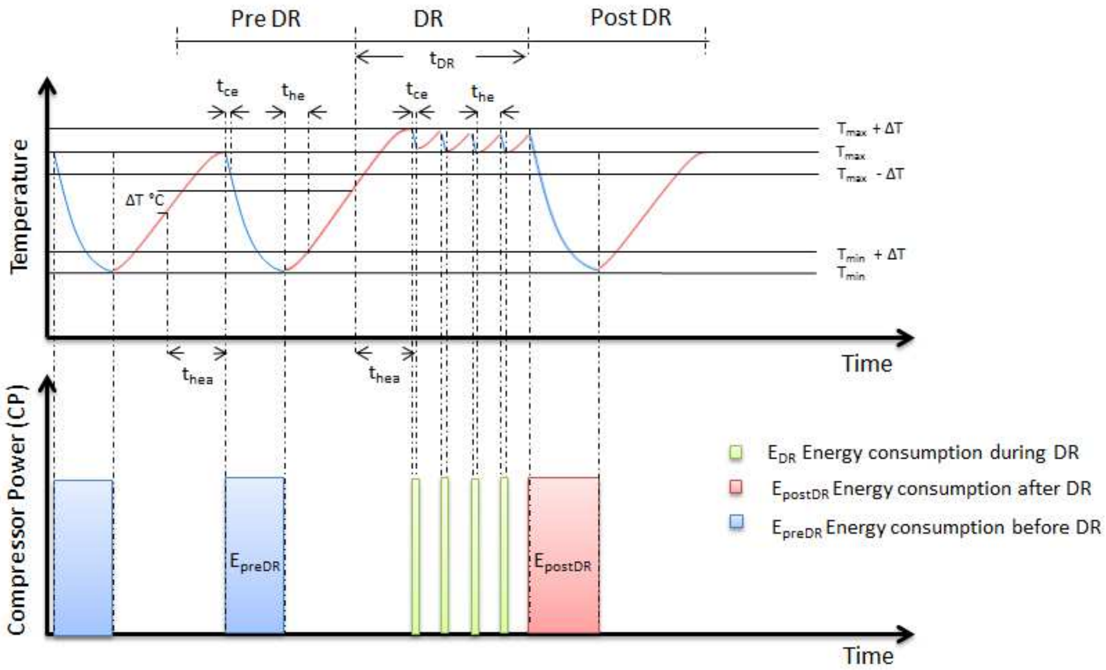

Figure 17. Refrigerator energy consumption estimation during demand response activation.

For the energy prediction during the control period, only 3 parameters are needed. They are the compressor power, the cooling duration and the number of temperature cycles in the control period. The energy consumption during the control period is given by Equation (1). The compressor power is a known parameter. As the control is activated for a known duration, the number of cycles can be calculated, if the temperature cycle duration is known. The temperature cycle duration can be calculated by predicting the temperatures of the refrigerator. The black-box model described in the previous chapter can be used to calculate the temperature cycle duration by predicting the temperatures. Here the heating and cooling behaviour of the refrigerator is expected have similar properties of the previous temperature cycles, as the new cool chamber temperature range with control is close to the old temperature range without control (practically close to T_{max}). In Figure 17, there are 3 time intervals marked as preDR, DR and post DR. The duration DR is the period when the control is enabled for DR activation and the refrigerator temperature is increased. The preDR is the period of same length of DR. The temperature cycles during the preDR period are used to train the black-box model of the refrigerator. Also, the energy consumption for the preDR period is considered as reference for the energy shift calculation. A time duration of same length of DR and preDR is considered after DR period (after the control is released) to validate the energy shift calculation.

Energy consumption during DR activation $$E_{DR} = N \times (CP \times t_{ce}) \quad (1)$$

where,
CP is compressor power,
t_{ce} is cooling time in each temperature cycle and
N is the number of cycles during the control period.

The number of cycle is calculated as follows,

Number of cycles $$N = \frac{(t_{DR} - t_{hea})}{(t_{he} + t_{ce})} \quad (2)$$

Where, t_{DR} is the control duration, t_{hea} is the heating time elapsed before the control activated for the particular refrigerator, and t_{he} and t_{ce} are the heating and cooling durations respectively, predicted using the refrigerator model.

As the energy consumption during preDR is known, the energy shift is calculated as follows

Estimated energy shift $$E_s = E_{preDR} - E_{DR} \quad (3)$$

Estimated energy during postDR $$E_{postDR} = E_{preDR} + E_s \quad (4)$$

which is

Estimated energy during postDR $$E_{postDR} = \left(2 \times E_{preDR}\right) - E_s \quad (5)$$

5.4 Experimental validation

The INCAP fridges are used for the experimental verification of the energy shift estimation method described in the previous section. As explained in section 3.3, the controller program has to subscribe for a data link to the smart AMM server hosted for INCAP project at DTU server. The controller is a JAVA program executed in a virtual machine on the same DTU server. There is no restriction to host and execution in any computer as for the data link to the Smart AMM server can be established. More details about the experimental setup, specifications of measurement data collection setup and the temperature sensor characterisation are given in the conference paper attached to Appendix A.2.

5.4.1 Controller description

The controller receives the temperature measurements at a 2 minute interval and the power measurements at a 10 s interval. The power measurements are used to distinguish between the heating and cooling parts of the temperature cycles. A classical thermostat refrigerator should have zero power consumption during the heating part, as the compressor is off. However, there could be some power consumption during the heating part of the temperature cycle due to two reasons. The light bulb inside the refrigerator is illuminated when the refrigerator door is opened. This causes a nonzero consumption even if the compressor is off. In addition, advanced refrigerators have electronic controllers in the place of classical thermostats, which cause a nonzero consumption. Therefore a threshold of 30 W is considered to distinguish the compressor states. The temperature that corresponds to T_{max} and T_{min} of the temperature cycles of all refrigerators participating in the experiment are stored locally in the program.

5.4.2 Controller objectives

The controller has 3 objectives during the control period. They are

1. Temperature control: The controller will maintain the temperature of the refrigerator cool chamber between the T_{max} and ΔT °C above T_{max}.
2. Compressor safety: The refrigerator compressor should not be turned on immediately after it is switched off due to the back pressure on the evaporator. The compressor manufacturer advises a switch on delay of 5 minutes.
3. User support: In the event of refrigerator door being opened, the controller will switch on the refrigerator to illuminate the light bulb inside the refrigerator to assist user. 5 minutes' duration is considered before switching off to support multiple door openings. The compressor safety is also considered for the user support.

The control is enabled between 20–23 hours of the local time. The user has an option of withdrawing from the experiment by pressing a button in the user interface device provided. The user's selection is valid for only one day. Every refrigerator participating in the experiment may have different temperature set points, which correspond to the T_{max} and T_{min} temperatures. A fixed ΔT °C increase above T_{max} to all refrigerators may spoil the food in the refrigerators in which the T_{max} temperature is violated more. Therefore the ΔT temperature is individualised for every refrigerator as half of their normal operational temperature band (i.e. half of the difference between the T_{max} and T_{min}). An example case of temperature control is shown in Figure 18.

The control loop is executed at a 2 minute interval when the new temperature measurement is received from the refrigerator. If the temperature data for any refrigerator is not received due to any reason of failure (communication or device failure), the corresponding refrigerator is not controlled. As the validity of the switch off command is only for 5 minutes, the refrigerator will be switched on if a new command is not received. In this way the safety against the food contamination is ensured.

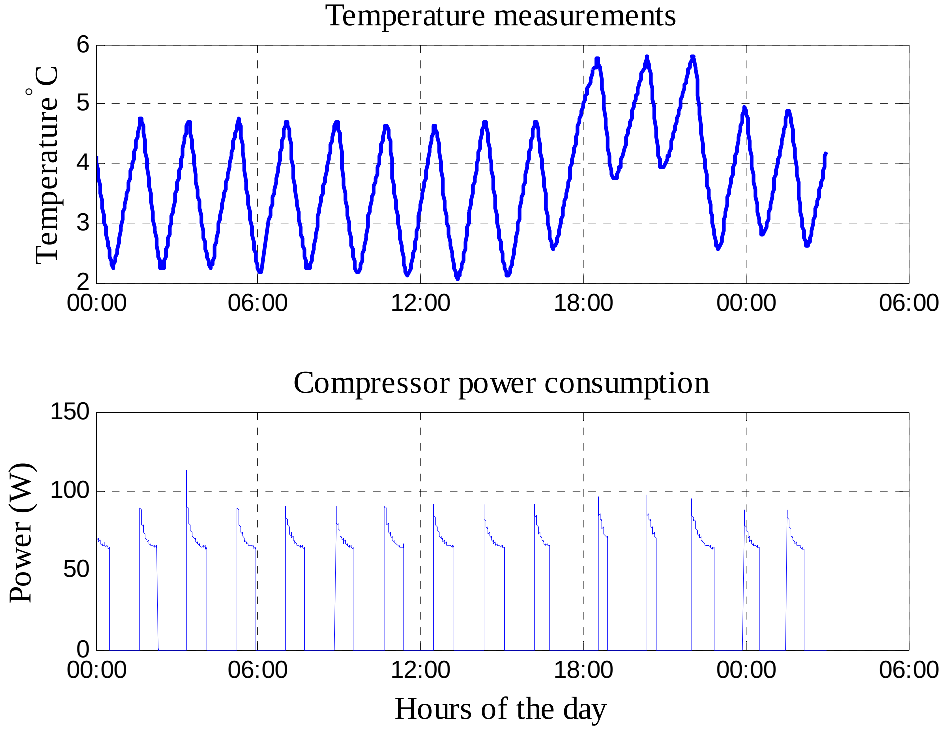

Figure 18. Temperature variation inside the fridge and the power consumption.

5.4.3 Consumer participation for DR activation

The experiment is conducted with 10 INCAP project participants for 9 days. Thought all the participants are involved in the experiment, not all offer to participate all the time. This is good example of variation in user preferences. The number of participants on each day is given in Table 5-1. A daily participation percentage and overall participation can be derived with a base number of 10 (total number of participants). The daily participation varies from 60–100%. The overall participation is 86%. The refrigerator control does not affect the comfort of the user directly. In the case of other TCLs, which influence the user comfort directly may have less participation.

Table 5-1: Participation percentage

Day	1	2	3	4	5	6	7	8	9
Number of fridges	10	9	9	10	8	7	8	6	10
Participation %	100	90	90	100	80	80	70	60	100
Overall participation %	86								

5.4.4 Energy consumption calculation

The actual energy consumption by the refrigerators for each day during the preDR, DR and postDR periods is calculated separately. As explained in section 5.3, the duration for preDR, DR and postDR has to be same. In the case of the experiment, the DR duration is 3 hours. Therefore, 3 hours of preDR and post DR are considered. As the power measurement is at a 10 s interval, the energy calculation in Wh is as follows:

$$E = \frac{\sum_{i=1}^{n}\sum_{k=1}^{K} Pik}{360} \tag{6}$$

where

E is energy consumption in Wh in each segment of preDR, DR and postDR.

N is the number of fridges participating in the experiment on each day,

K is the number of power measurement samples in each segment of preDR, DR and postDR.

P_{ik} is the power consumption by the individual refrigerator.

As the measurement interval and the duration are known, the data integrity is checked for any discontinuity in the measurements from their timestamps. The refrigerator compressor is operated by a single phase induction motor. The single phase induction motor has an inrush current consumption during the startup. The inrush current is typically 10 times the magnitude of the maximum current. The inrush current lasts 1–2 s. If the power measurement by the relay unit synchronises with the compressor startup, the power measurement will show a very high value. As the power measurement interval is 10 s, a wrong power measurement will be mistaken as a large consumption for 10 s. The power measurements are clipped to the maximum value of compressor capacity. The estimation is close to the actual consumption for most of the days.

The error in the estimated value is the difference between the actual energy consumption and the estimated value. The percentage error is calculated with the actual value as a base as shown in the following equation.

$$e(\%) = \frac{(E_{act} - E_{est})}{E_{act}} \times 100 \tag{7}$$

The total energy consumed by the fridges is reducing during the DR period as the cool chamber temperature is increased. Also the reduction in the consumption is compensated in the postDR period. The estimated energy consumption and actual energy consumption during the DR activation period for the 9 days are listed in the Table 5- 2.

Table 5- 2: Estimated and actual energy consumption in DR activation period.

Day	Estimated [Wh]	Actual [Wh]	Error [%]
1	1082.3	1069.5	-1.2
2	774.3	783.0	1.1
3	712.2	714.2	0.3
4	1018.1	1003.4	-1.5
5	629.2	621.1	-1.3
6	502.4	496.6	-1.2
7	713.4	700.7	-1.8
8	629.7	625.2	-0.7
9	1187.3	1180.2	-0.6

Similarly, the error percentage in the estimation for post DR period is also calculated as per Equation (7). The error in estimation is within ±10%. the estimated energy consumption and actual energy consumption during the post DR activation period for the 9 days are listed in the Table 5- 3.

Table 5- 3: Estimated and actual energy consumption in post DR activation period.

Day	Estimated [Wh]	Actual [Wh]	Error [%]
1	1358.6	1333.8	-1.9
2	1165.7	1264.8	7.8
3	1200.0	1244.3	3.6
4	1424.2	1297.9	-9.7
5	1027.0	1129.6	9.1
6	1167.6	1245.9	6.3
7	870.9	924.7	5.8
8	767.9	814.3	5.7
9	1479.0	1495.9	1.1

The energy estimation is based on the estimation of the duration of the cooling part of temperature cycle and the number of temperature cycles. In the 9-day experiment, there are 118 cooling durations from all of the fridges. The cooling duration varies with the refrigerator capacity, food content and other parameters that affect the system dynamics.

The error for each cooling duration estimation is calculated as given as Equation (8):

$$e_T(\%) = \frac{(Tcact - Tcest)}{Tcact} \times 100 \quad (8)$$

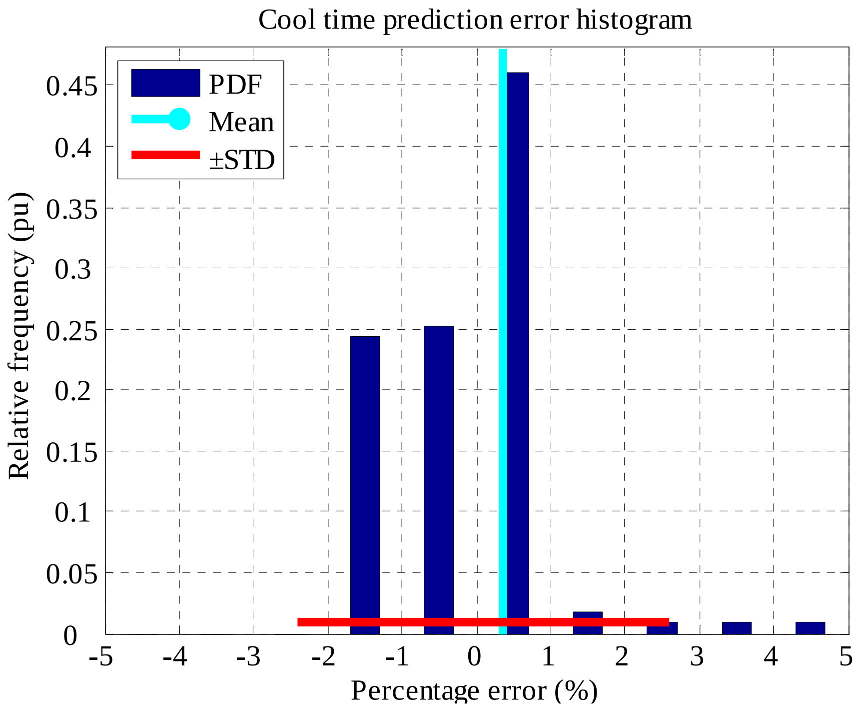

Figure 19. Histogram of cool cycle time prediction error.

Figure 19 shows the histogram of cool cycle time prediction error. The percentage error in each cooling time estimation is less compared to the energy shift estimation. The maximum, mean and standard deviation of the error in cooling duration estimation is given in Table 5-4.

Table 5-4: Cycle by cycle estimation error.

Number of cycles	Maximum	Minimum	Mean	Standard Deviation
118	4.67	-1.00	0.36	2.76

The prediction of individual cool time has less percentage error compared to the error in total energy estimation during postDR period. The part of the shifted energy is consumed in the thermostatic cycles after the 3 hours of postDR period. This signifies the time required for the system to attain a steady state is greater than the 3 hours that are considered for the analysis.

This method can estimate the energy shift with maximum error of 10%. A more detailed refrigerator model can estimate the energy shift with better accuracy. The detailed model needs more computational power depending on the complexity involved in the model. This method is better for a quick evaluation of available capacity with a large population of refrigerators and can be used in aggregated calculation.

6 SECONDARY FREQUENCY CONTROL BY DEMAND RESPONSE ACTIVATION

In this chapter the main results concerning the second research topic are presented. The main results have been submitted for publication in journals as separate papers and the paper preprint versions are included in Appendices A.3 and A.4 of this dissertation. The chapter starts with first part, frequency control in power system by describing the importance of the power system frequency and conventional methods for frequency control. Then, the chapter introduces the secondary frequency control with demand response activation, method for testing in an island low voltage network and further, the results of the experimental validation of the secondary frequency control are presented. Later the chapter presents the results of the experimental validation of the secondary frequency control. Then, the chapter introduces the second part of the same research topic flexibility analysis. In continuation, the testing methods and the scenarios for flexibility analysis are described. Finally, the chapter presents the main results of the experimental validation.

6.1 Frequency – An indicator

In an electric power network, the balance between the electricity production and consumption is indicated by the system frequency. As the load increases compared to the power production, the system frequency starts to decrease and vice versa. Frequency in the power system has to be maintained always within the admissible range of its nominal value, as it affects the performance and life expectancy of the power system components. For example, the frequency has a direct impact on the speed of asynchronous machines at the demand side and causes reduction in their efficiency and life span. In the conventional power system, the power production follows the demand.

6.1.1 Frequency control in conventional power systems

The TSO is responsible for maintaining the frequency by maintaining power system balance. The frequency control in the conventional electric grid can be classified into primary, secondary and tertiary control. The power plants' generators supplying the base demand have droop controllers that adjust the generators' power output for the frequency deviations. This serves as the primary control. Power plants are responsible for providing primary control as per the response time specified by the TSOs' grid code.

As the additional demand needs to be supplied immediately to arrest further frequency deviation, the primary frequency control acts typically within seconds. The primary control stabilises the system frequency at a value with a steady state error. The secondary frequency control restores the frequency to nominal system frequency i.e. the steady state error in the frequency is eliminated. The secondary frequency control is normally taken care of by TSO through automatic generation control (AGC) [4]. The TSO makes contracts with balance responsible parties (BRP) for the secondary frequency control. The BRPs obey TSO's AGC signal. BRP's production facility must comply with the ramp rate specifications of the grid code provided by the TSO. An illustration of frequency deviation and frequency control by different reserves is shown in Figure 20 [5]. As shown in the figure, the secondary reserves are activated after minutes to upregulate the frequency to the nominal frequency.

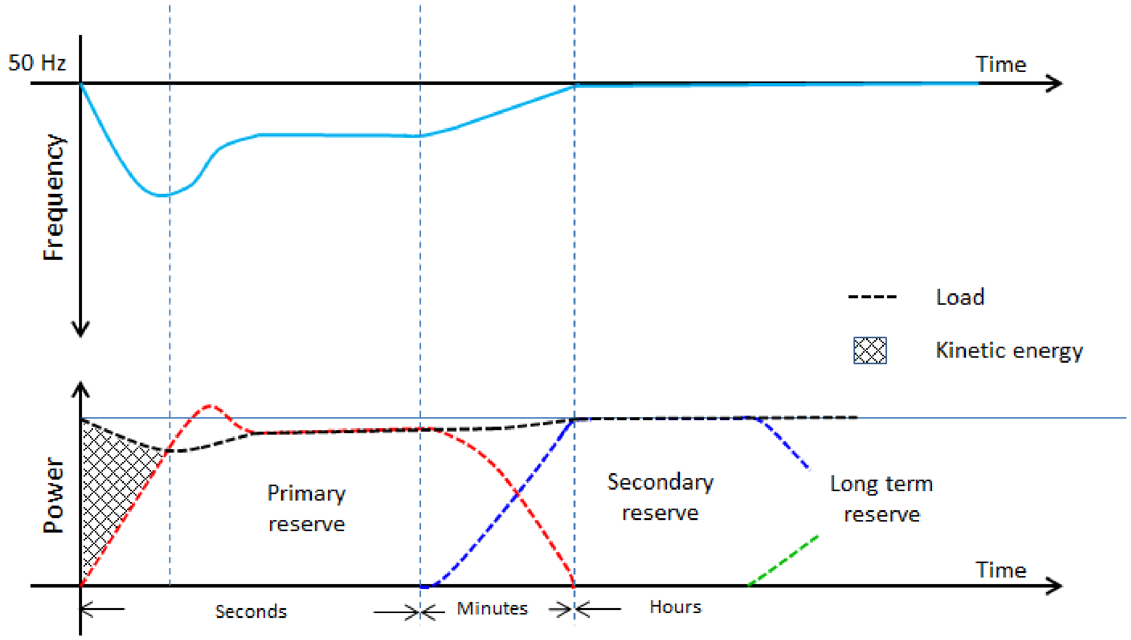

Figure 20. Primary and secondary frequency control and their response times.

6.1.2 Frequency control by DR activation on TCLs

The frequency control can also be provided from the demand side. DR aggregators can provide load reduction for frequency control in contrary to the BRPs' power production. In Section 2.6, the aggregators' role as an entity in DR market in providing services to the power system operators is explained.

TCLs are very much suitable for frequency control applications [21,22] due to their fast response [23] and their ability to provide thermal inertia with thermal storage. In this experimental study, refrigerators are used as they are easy to work with, in order to analyse and validate DR applications of TCLs for smart grid applications. In Danish electricity demand scenarios, refrigerators and freezers contribute 18% of total domestic electricity demand and are regarded as important demand responses in the smart grid [32].

The aggregators' capacity can be pre-assessed and agreements can be made similar to the one with the BRPs for service delivery in-term of power reduction and duration of power reduction. The illustration of aggregator playing BRPs role is shown in Figure 21.

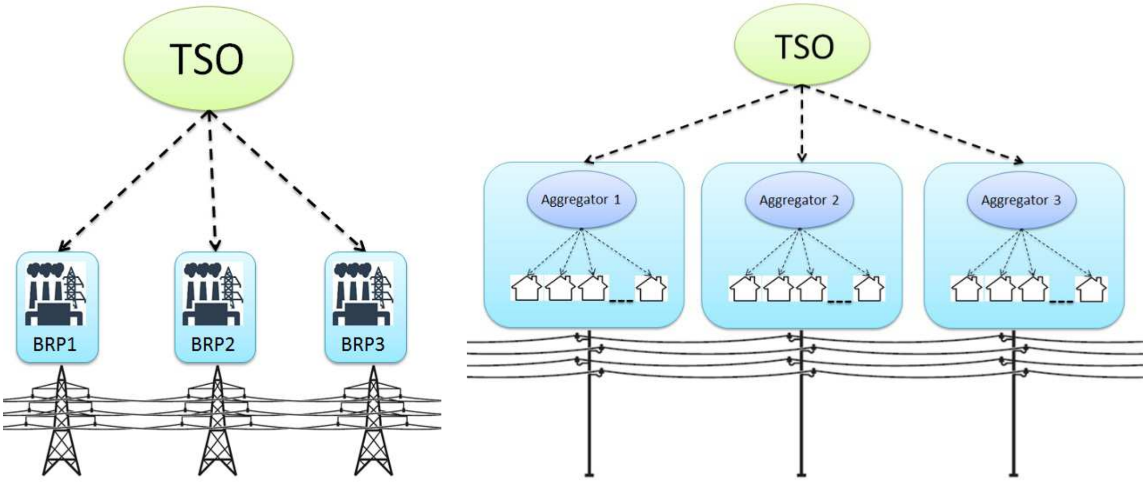

Figure 21. Secondary frequency control with AGC of BRP units and with DR activation by different aggregators.

6.2 Method

The secondary frequency control by DR activation on TCLs is tested in an islanded LV network. The refrigerators representing the TCLs are emulated with a vanadium battery. In reality, the refrigerators participating in the experiment are not present in the island network. The refrigerators aggregated power consumption can be emulated with a variable load whose power consumption can be adjusted in real-time. The island network is equipped with a vanadium battery. The charging power value of the vanadium battery can be changed in real-time with the aggregated value of the power individual refrigerator's power consumption which is measured in real-time. The frequency disturbances are introduced with a controlled load variation to achieve a steady state frequency error as shown in Figure 22.

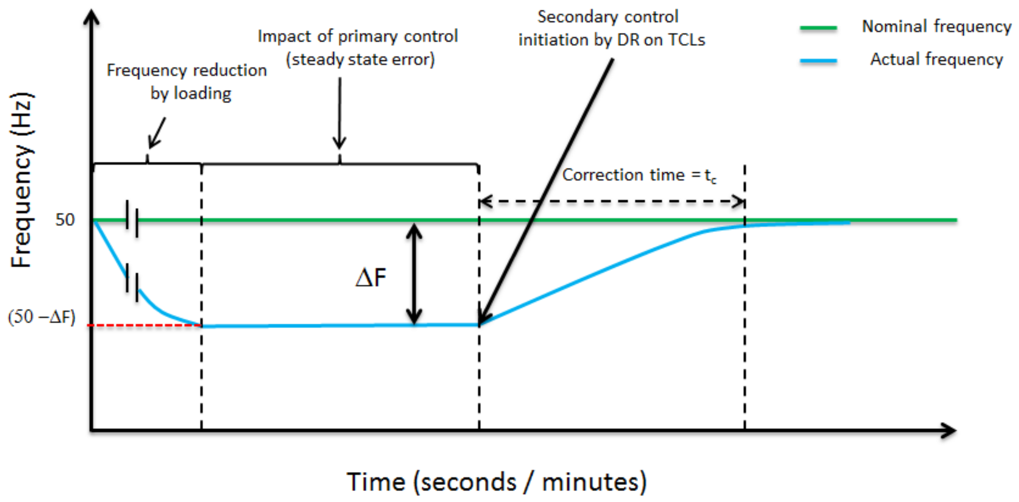

Figure 22. Illustration of secondary frequency control by DR activation.

The secondary frequency control is performed by the frequency controller by switching OFF the refrigerators in order to reduce the load to bring system frequency back to the nominal value. The time required for the frequency to attain the nominal value depends on the inertia of the power system and the load imbalance. The greater the load reduction, the smaller the amount of time required to restore the frequency. In order to sustain the effect of load reduction, the refrigerator selection is based on their ability to stay OFF for longer. The OFF time of the refrigerator is calculated using the black box model described in chapter 4. More details about the controller are given in the paper attached to Appendix A.3.

6.2.1 Test setup

The regulation capacity available with the refrigerator participating in the experiment was 1.25 kW, which is negligibe compared to the DK1 power grid capacity; it will not be feasible to visualise the frequency restoration process with the refrigerator control if the experiment is conducted with the grid connection. Therefore, the experiment was conducted in an islanded grid with capacity of 12 kW, which is comparable to the available regulating power 1.25 kW with the refrigerators. The island system's capacity is comparable to the generation (6000 MW) and regulation (750 MW) capacities of DK1 region (Western Denmark).

The experiment was conducted in an islanded LV network in the SYSLAB facility in Technical University of Denmark (DTU) with a vanadium battery bank as load and a 50 kVA diesel generator as a source. The network configuration diagram is shown in Figure 23. The SYSLAB islanded low voltage grid is formed by connecting two busbars in series to a 200 kVA distribution transformer through a circuit breaker, which is opened in order to island the system. Busbar 1 has a 50 kVA diesel generator and the 200 kVA transformer, while busbar 2 has a vanadium battery in order to emulate the fridges' consumption and to provide the base load and load variations.The description for the setup to measure temperature and power consumption from the refrigerators is presented in sections 3.2 and 3.3.

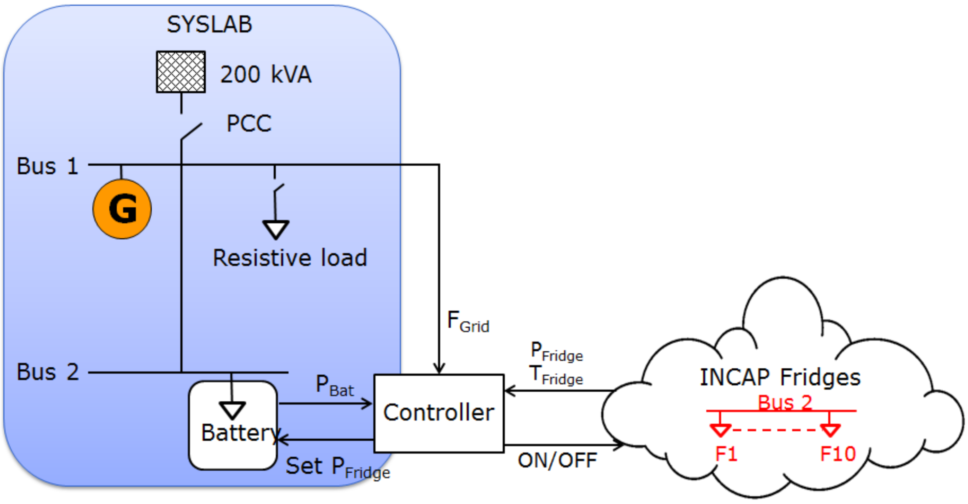

Figure 23. Block diagram of the experimental setup.

Details about setting up the island network, network synchronisation, system balance and controlled load variation for steady state frequency error are given in the paper attached to Appendix A.3.

6.3 Performance analysis

The parameters of the system, during the experiment are shown in Figure 24. The first plot – (a) shows the system frequency, the second plot – (b) shows the generator power output and the third plot – (c) shows the refrigerator power consumption during the experiment. The generator synchronisation with the network is shown in the plot – (c) near 300 s. The controlled load variation to attain the steady state frequency error is shown in the plot – (c) between 400–500 s. The system frequency decreases to 49 Hz in 60 s. The secondary frequency controller is initiated at 600 s, which is marked with vertical red line mark in all of the plots.

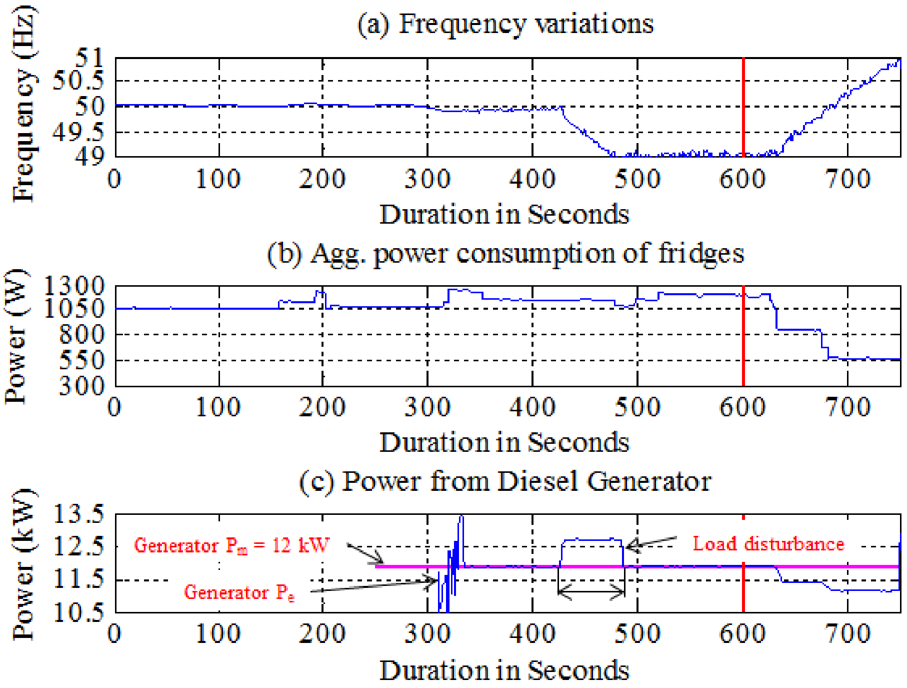

Figure 24. System frequency, aggregated fridge power and generator production.

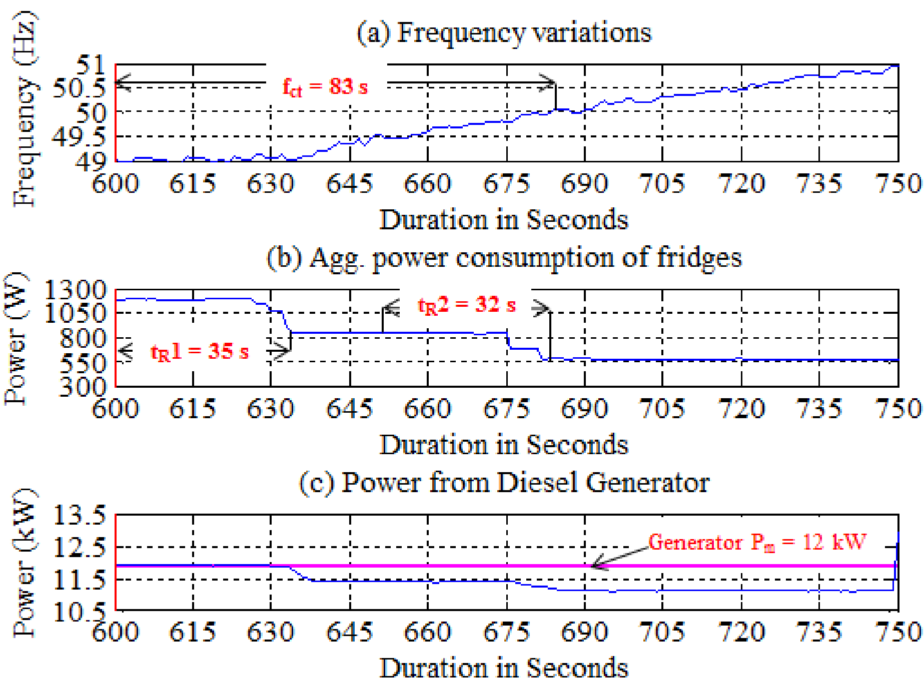

Figure 25. Close-up view of the secondary frequency control period.

A closer view of the events during the frequency controller is active is shown in Figure 25. The controller reduces the load in two iterations. The power reduction during first iteration is 350 W and the second iteration causes a power reduction of 275 W. The controllers target is to reduce 300 W on each iteration. The difference in the actual power reduction is due to the compressor capacities of the refrigerators as the refrigerators considered in this experiment have different compressor ratings. The round trip response time of the control command for the first and second iterations are 35 s and 33 s, respectively. They are marked as t_R1 and t_R2 in the plot – (b) of Figure 25. The time required for the system frequency to restoration to nominal system frequency of 50 Hz is 83 s, which is shown in the plot – (c) of Figure 25 as f_{ct}.

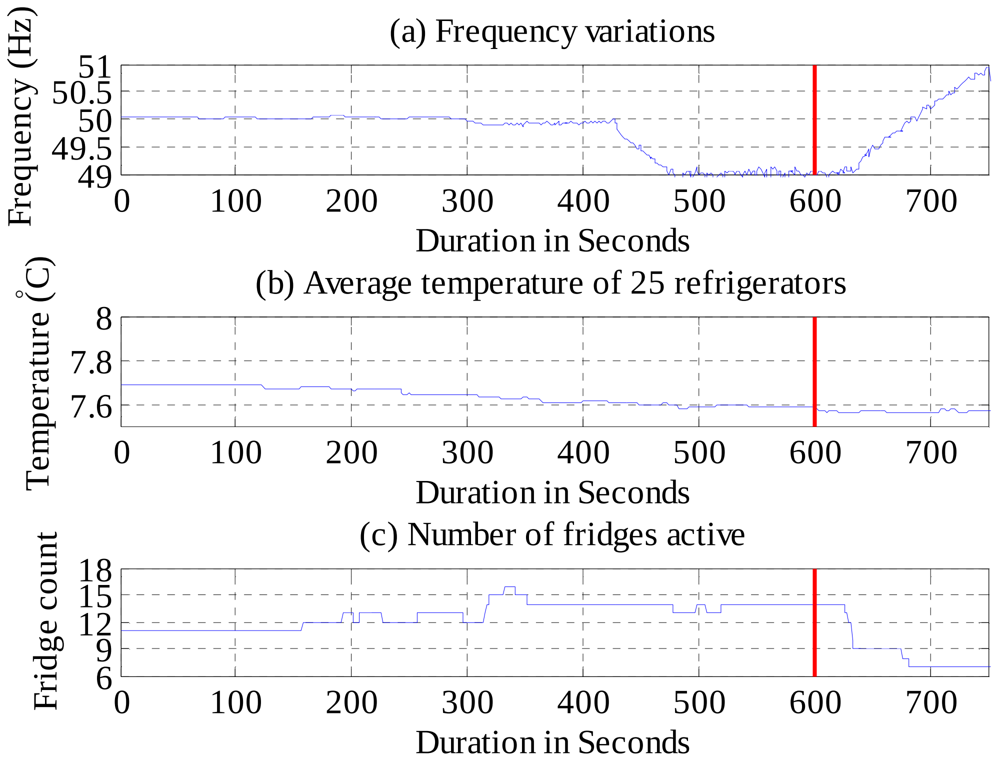

Figure 26. System frequency, instantaneous temperature average and number of fridges active.

The variations in the population and the temperature during the control are shown inFigure 26. As shown in the plot – (c), 14 fridges are active at the beginning, 7 and 2 fridges are switched OFF during the first and second iterations of the control. The instantaneous temperature average of the refrigerators is shown in the plot – (b). The instantaneous temperature average continues to follow the trend of decreasing temperature. The individual refrigerator temperatures are shown in Figure 27 in different colours.

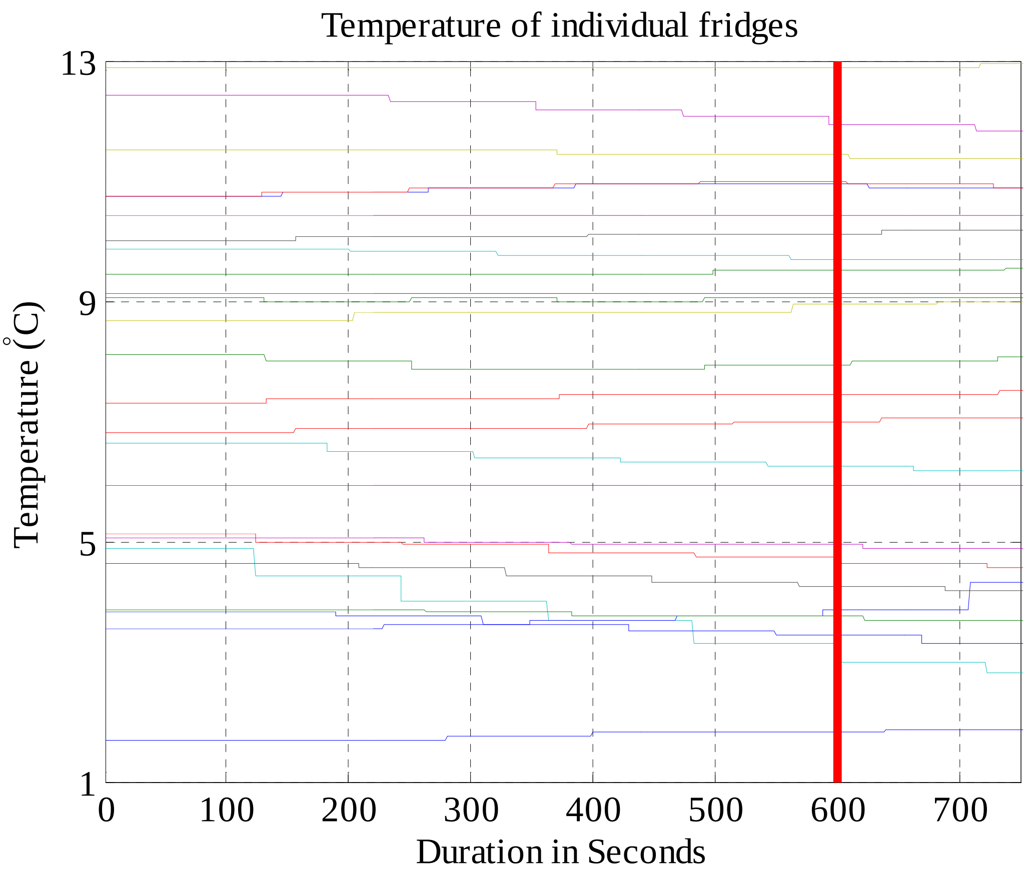

Figure 27. Temperature of the refrigerators in different colours.

The controller activation time is shown by the red line. The cool chamber temperatures are shown 200 s after the control period. As the control period is very short, the cool chamber temperature of the refrigerators does not show any appreciable change due to the thermal mass and thermal inertia of the refrigerator content. Therefore the instantaneous temperature average also does not change its trend.

Table 6-1: Average response time and ramp rate of the TCL DR control and DK1 grid requirements.

Parameter	Secondary frequency control	
	Experimental values	Girid code for DK1
Average control response time [s]	33.5	900
Ramp rate [%/minute]	41.2	10 (Gas 20-100%) 20 (Diesel 20-100%)

Table 6-1 compares the performance of the frequency control with the DK1 region's requirements for BRPs. The results showed that the average response time to the control signal is 33.5 s, whereas the requirement for the DK1 region is 15 minutes (i.e. 900 s). As the response time is very small, it can be comparable to the response time for the primary frequency control requirements. The primary frequency control in DK1 requires increasing the production by 50% in 15 s and the 100% capacity has to be reached in 30 s in the scenario of up regulation.

The ramp rate achieved is 41.2 %/minute, which is almost twice the ramp rate of diesel engine power plants that are considered as the power plants with highest ramp rate (20 %/minute).

6.4 DR resource upscaling

The computational system performance for OFF time calculation and resource sorting depends on the computational power and memory available to perform different tasks. The system performance will be affected as the number of refrigerators increases. To understand the computational time requirement of different sections of the algorithm, a simulation study with a large number of refrigerator populations is carried out and the performances are mentioned in Table 6-2. The assumptions for the simulation are 1. The maximum temperature cycle length is 60 minutes; and 2. The maximum sorting time is experienced when the resource order is to be reversed. Though the computational power of the computer used is a major factor for computational delay, the calculated times will give an indicative representation.

Table 6-2: Computational delays

Number of fridges	Time for temperature prediction [ms]	Time for resource sorting [ms]
1,000	1	5
10000	2	80
100000	5	7609
1000000	21	906146

The time required for resource sorting increases exponentially with the increase in the number of refrigerators. Therefore, the sorting technique used and number of times the resource sorting is carried out in a scenario of large population of refrigerators will be one of the major factors determining the performance.

6.5 Flexibility analysis

The second part of the experiment is to understand the duration for which the service can be provided by power reduction. The effect on temperature and the average power that can be achieved are also analysed. The experimental setup for this study requires only the INCAP experimental platform and the control can be executed from any computer. More details about the experimental setup is given in section 3.2. The controller architecture and control task timings are detailed in the paper attached in Appendix A.4.

6.5.1 Definition and quantitation of flexibility

The thermostat in the refrigerator will switch off the refrigerator's compressor as soon as the cool chamber temperature reaches Tmin. Therefore the refrigerator will not be available for control till the thermostat enables the compressor at Tmax. Thus, any refrigerator is available for control only during the cooling part of the thermostatic cycle, as shown in Figure 28. The refrigerator has no capacity when the cool chamber temperature is close to Tmax and the flexibility is 100% when the cool chamber temperature is close to Tmin. The refrigerator capacity can be used only when the thermostat is ON, i.e. during cooling. The refrigerator has no usable capacity when the thermostat is OFF and thus the flexibility is 0% as shown in Figure 28.

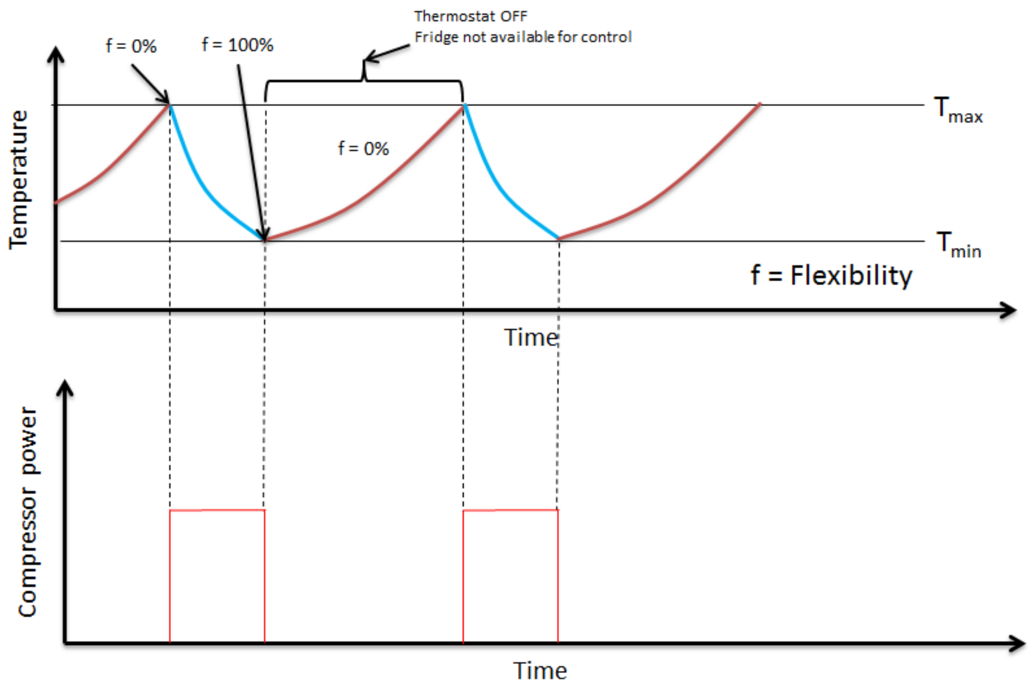

Figure 28. Flexibility change during natural thermostatic cycle

6.5.2 Experiment scenario definition

The experiment is conducted with 4 scenarios as explained below.

Scenario 1: Scenario 1 is the base case without any control. The refrigerator power consumption and the temperature were observed for 24 hours. The observation without control will give an idea about the aggregated power consumption variation with time. The power limitation set point for the control in for the following scenarios is derived from the base case scenario 1.

Scenario 2: In scenario 2, the controller objective is to maintain the aggregated power to the average value of power consumption in the scenario 1, without violating the temperature limits of individual refrigerators.

Scenario 3 and 4: Scenarios 3 and 4 are used to understand the limits of the possible power reduction by DR activation on TCLs. The power limits for the controller are set as 50% and 25% of the average power for scenarios 3 and 4 respectively.

The aggregated power consumption of the refrigerators and the instantaneous temperature average of the population for the scenarios 1 and 2 is given in Figure 29. Similarly, Figure 30 shows the aggregated power of the population and the instantaneous temperature average of the population for scenarios 3 and 4.

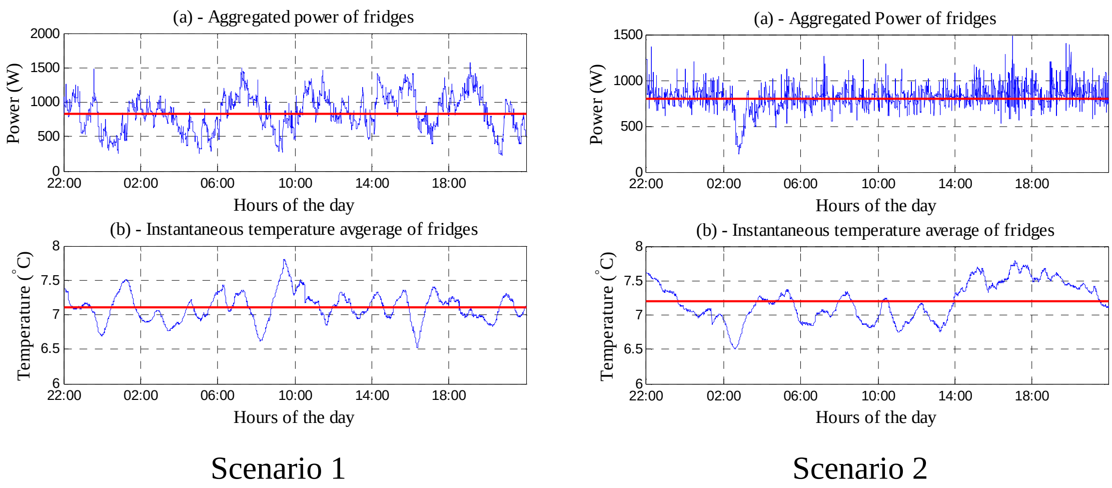

Figure 29. Aggregated power consumption and temperature variations in scenarios 1 & 2

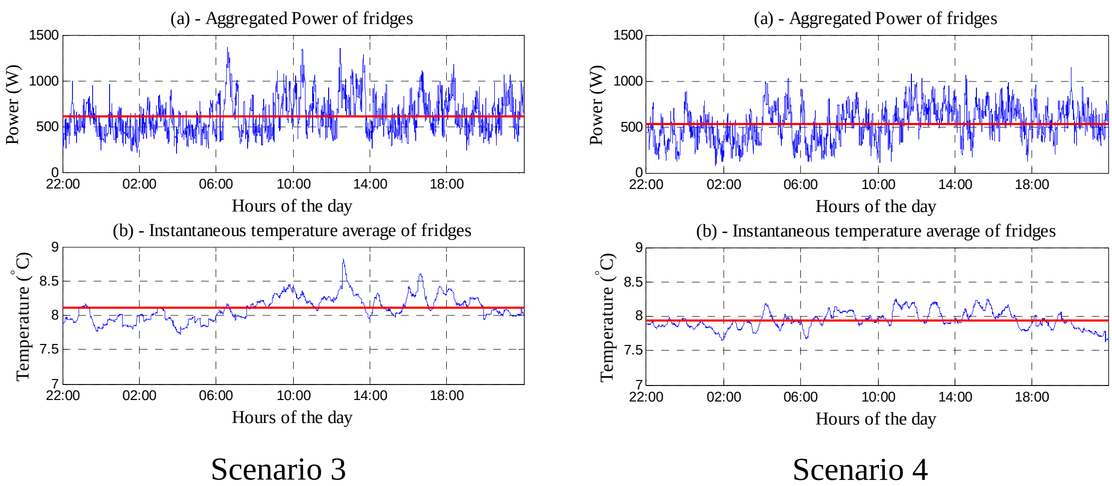

Figure 30. Aggregated power consumption and temperature variations in scenarios 3 & 4

6.5.3 Change in flexibility

On different levels of power delivery, the flexibility of the population varies in different levels. Table 6-3 shows the change in controller target power reduction value, achieved average aggregated power, average temperature of the population, energy consumption and the average flexibility value for the 4 scenarios. As the power reduction increases from scenario 2 to 4, flexibility decreases. Figure 31 shows the flexibility variation and the aggregated power variation for scenario 1. The flexibility variation follows the trend of aggregated power variation. This is due to the natural thermostatic cycles. As the number refrigerators connected increases, the control flexibility increases also, and thus the flexibility increases too. In Figure 35, the variations in flexibility for 3 control scenarios 2, 3 and 4 are given.

Table 6-3: Average aggregated power, energy consumption and flexibility for the 4 scenarios.

Scenarios	Power reduction [%]	Power limit [W]	Avreage temperature [°C]	Avreage power [W]	Energy consumption [kWh]	flexibility [%]
1	NA	-	7.1	837.0	20.1	27.9
2	50	800	7.2	801.0	19.2	43.3
3	75	400	8.1	607.2	14.6	10.3
4	87.5	200	8.0	527.0	12.6	4.5

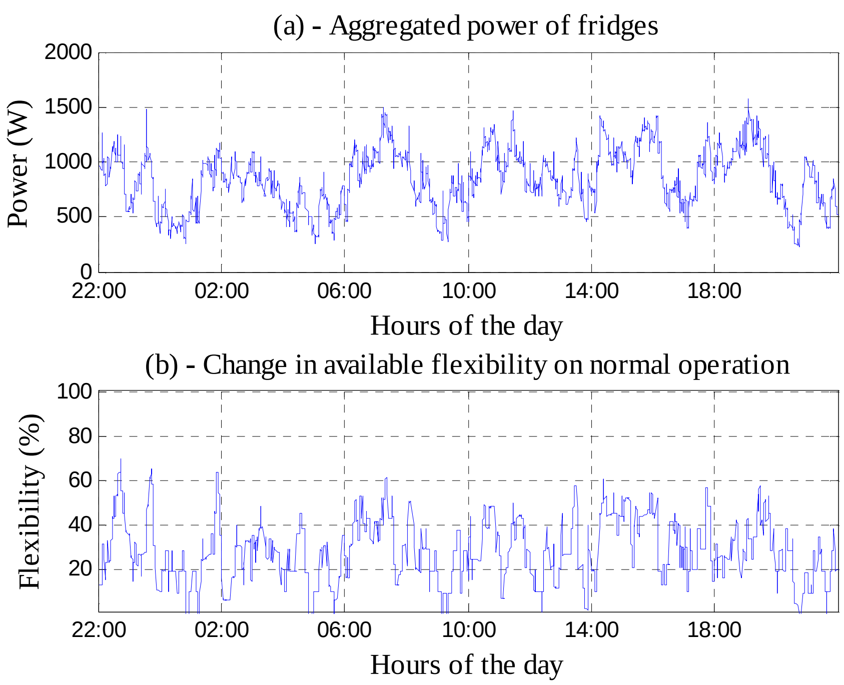

Figure 31. Change in available flexibility without control

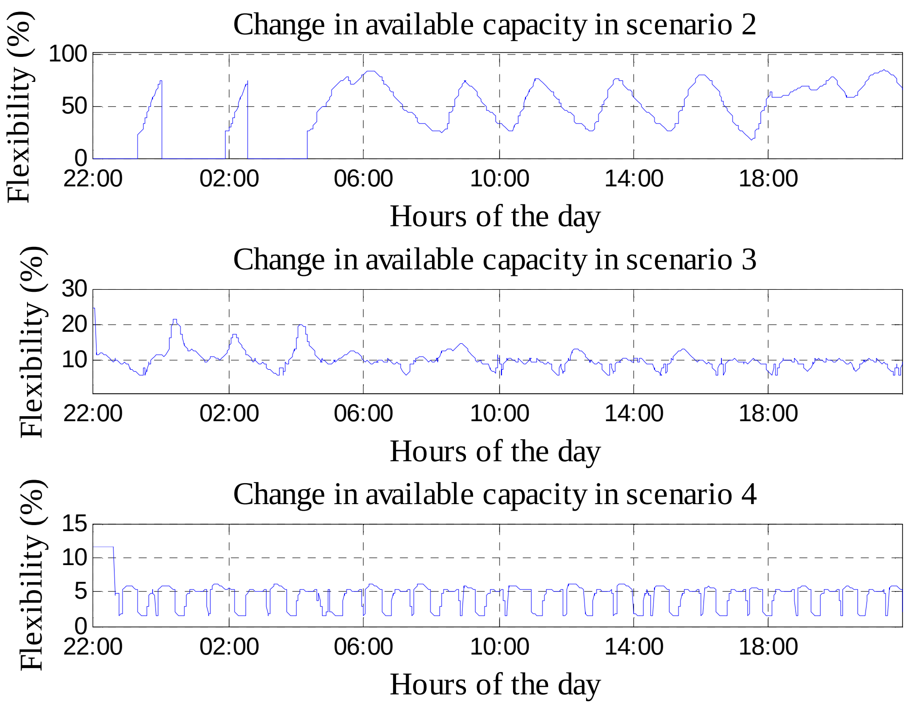

Figure 32. Change in available flexibility with different power reduction levels.

In scenario 2, as the refrigerators are controlled, the flexibility increases compared to scenario 1. The average aggregated power consumption is same in both scenarios 1 and 2. In scenario 2, a greater number of refrigerators moves from their natural thermostatic cycle to the controlled population. Their flexibility increases. Furthermore, as the power reduction increases in scenarios 3 and 4, the flexibility decreases. This phenomenon is due to less thermal charging of the refrigerators. This is indicated by the increase in the average temperature of the population.

The histogram of the aggregated power consumptions of the 4 scenarios is shown in the Figure 33. As the control is enabled, more number of occurrences is close to mean power consumption. The standard deviation for scenarios 2 and 4 is high compared to scenario 3. The higher standard deviation in scenario 2 signifies the underutilisation of the flexibility. In scenario 4, the higher standard deviation signifies the overutilisation of the flexibility.

Therefore, scenario 3 can be considered as the best possible power reduction by DR activation on TCLs. The power reduction possible is 75% from the maximum value of normal consumption without control and the elevation in the temperature is 14.3%.

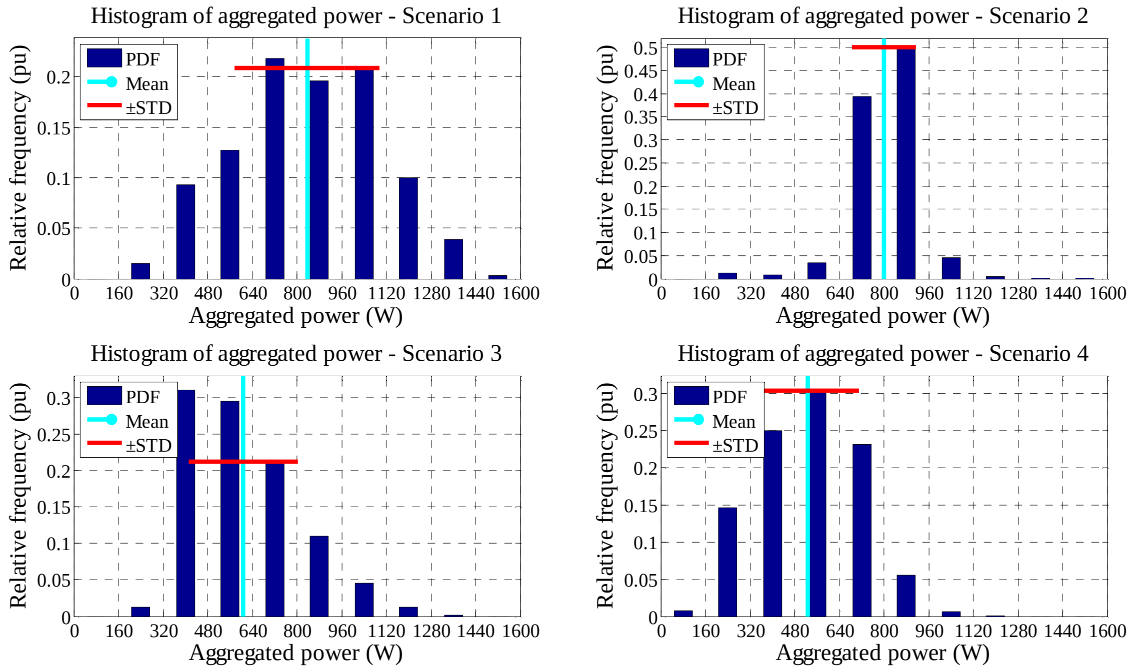

Figure 33. Histograms of the aggregated power consumptions in the 4 scenarios.

7 IMPACT OF DEMAND RESPONSE ACTIVATION ON REFRIGERATORS

In this chapter the main results concerning the third research topic are presented. The main results have been submitted for publication in a journal as a separate paper and the paper preprint version is included in Appendix A.5 of this dissertation. The chapter starts with describing TCL energy consumption behavior. Then, the chapter introduces the factors considered for impact analysis. Further, the roles of aggregators in an unbundled electricity market are presented. Later the chapter presents the method for the experimental analysis. Finally, the chapter presents the main findings of the experimental validation.

7.1 DR activation on TCL

The main objective of TCLs is temperature maintenance. The DR activation on TCLs alters their energy consumption. The objective of DR activation is either to reduce power consumption to provide power system services or to shift energy consumption for effective resource utilisation. Researchers have reported that simultaneous control of multiple TCLs will cause synchronisation of their thermostatic cycles both in the DR control period and after the control period. The synchronisation of thermostatic cycles in multiple TCLs will cause oscillations in power flow. The oscillations in power flow are not acceptable for the power system stability as the power system stability depends on the balance between generation and consumption. Apart from the synchronisation issues, the functioning method of new electricity market creates more challenges for the system operators when they adopt DR solutions.

7.1.1 Impact analysis

For the performance analysis, there are 3 factors considered. They are

1. The deviation from the committed Pmax_limit value

The deviation is calculated as a square root of Integral Square of Error (ISE) as a method given in [142].

2. Ramp down and ramp up rate

The ramp down rate is calculated as the ratio of power difference and the time elapsed. The power difference is the difference between the power at the time of DR activation and the local minimum power reached as the consequence of DR activation. Similarly the ramp up rate is calculated considering the end of DR activation time.

3. Peak overshoot

The peak overshoot is taken as the maximum power consumption after the DR activation removal.

7.2 Unbundled electricity market and DR aggregators

Deregulation in the electricity market entertains multiple suppliers to participate in the trading. The suppliers that offer market clearing price (MCP) or lower than MCP are selected for the electricity supply [143]. On market deregulation, the energy price variation is inevitable. For example, the Nordpoolspot energy market has an hourly energy price variation [144]. The Danish TSO EnergiNet.DK considers intelligent DR as one of the promising service in the future Danish smart grid [145]. In the Danish electricity retail market, consumers are allowed to choose a regulated energy price or deregulated energy price. However, the Danish Energy Regulatory Authority (DERA) sets the maximum allowed retail price to consumersby the electricity companies [146]. If the demand is reduced during high price hours, the profit will be maximised as far the DSO is concerned. In domestic sector, the demand adjusted in every household will be very small. Their aggregated value will be considerable large. As explained in Section 2.6, the aggregator as an entity will play a major role in DR market providing services to the DSO. The aggregator's capacity is pre-assessed by the DSO and the aggregator makes an agreement to deliver the service by power reduction to DSO [142]. A simplified paradigm of the ancillary service market is shown in Figure 34.

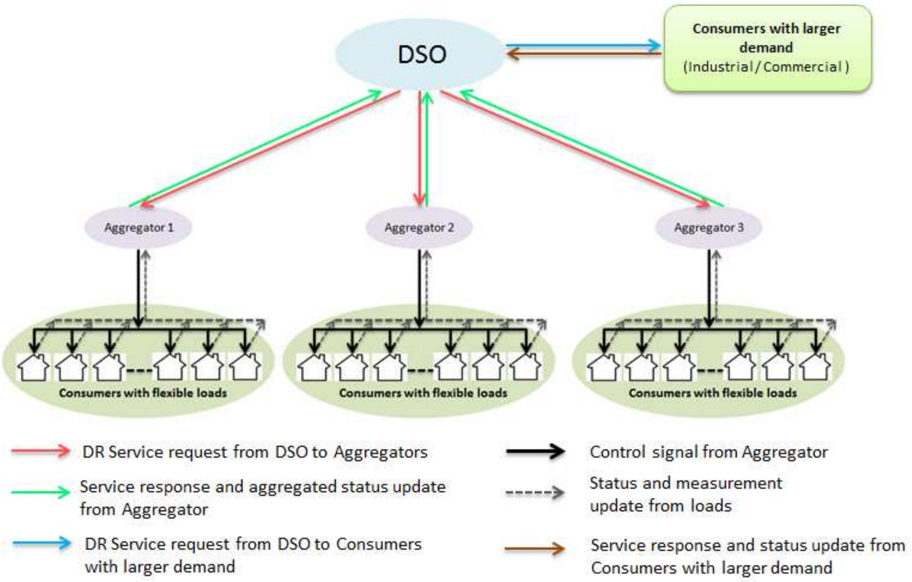

Figure 34. Paradigm of the 3 participants in the DR market.

7.3 Method for study

Any power system service delivery by DR activation is fundamentally realised by demand adjustment. In [142], the ancillary service realisation is explained with the example case of demand reduction with Pmax limit. Pmax can be considered for the DR activation study with TCLs. An example case is explained here with a peak hour scenario.

During peak hours DSO need a service to limit demand. The amount of power reduction ΔP is purchased from the aggregator as a service. The aggregator controls the loads of the consumers to reduce aggregated consumption by ΔP as agreed with the DSO. An example peak hour scenario where the aggregator reduces the demand by ΔP and limits the consumption to Pmax_limit during the time between 20–23 hours of a day is shown in Figure 35. The Pmax_limit is decided by DSO by accessing the aggregator's capacity and performance [142]. The experiments carried out here involve the usage of domestic refrigerators as controllable loads.

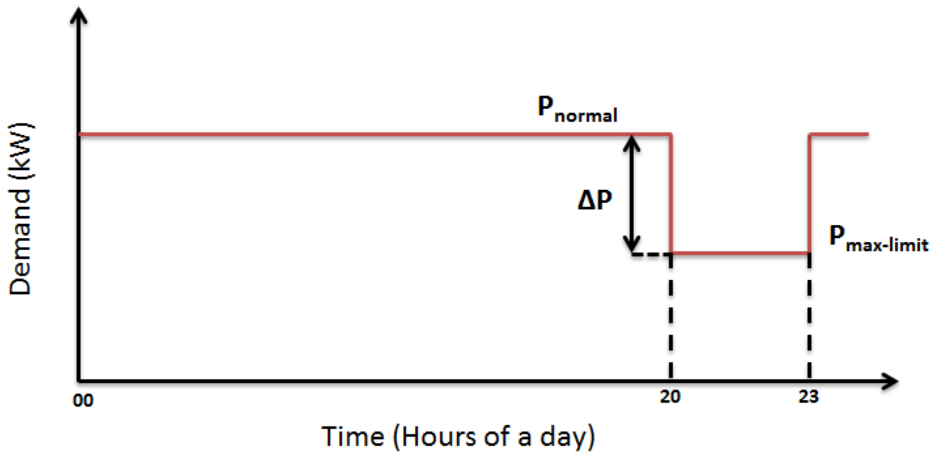

Figure 35. Illustration of DR service activation during a particular time of a day.

Other than the power limitations, the rate at which the power consumption is reduced at the beginning of the DR activation and the rate at which the power consumption increases at end of the DR activation are also important. The ramp down and ramp up rates are critical for the power system as the generation units have to adjust power production as the demand changes which is critical for the power system stability. For example, the technical regulations set by the Danish TSO EnergiNet.dk for the thermal power plants demands a ramping rate in the range of 2–8% of the nominal power per minute for the conventional power plants, depending on the typology and operating point. The ramp up rate requirement for the gas and diesel power plants ranges from 10–20 %/minute [147].

7.3.1 Experimental setup and control implementation

The experiment for the impact analysis was conducted with the real-time household refrigerators of the participants in the INCAP project. The details of the sensor and control devises and their installations are explained in chapter 3 as well as in the paper attached to Appendix A.5. The control algorithm and the controller implementation are explained in the paper attached to Appendix A.5.

7.4 Control scenario definition

The experiment is conducted with 5 scenarios. The first case is a normal case without control, which can serve as a base case, and allows for identifying the Pmax limit for the other cases. The 5 scenarios including the normal case are listed below.
Scenario 1: Normal operation without control.
Scenario 2: DR activation without delay.
Scenario 3: DR activation with delay sequence S1-S1.
Scenario 4: DR activation with delay sequence S1-S2.
Scenario 5: DR activation with delay sequence S135-S246.

In Scenario 2, the DR activation is started and ended at the same time for all TCLs. Scenarios 3–5 are realised to reduce the ramp down, ramp up and the peak overshoot values by delaying DR activation from one TCL to another.

There are 25 fridges available for control and study the DR activation impact. The total compressor power consumption capacity of all 25 fridges is 2.5 kW. In the normal case without control, the aggregated average power consumption over a day by all fridges is 660 W. The average consumption is 26.5% of the total compressor capacity. Therefore, the power limit value can be fixed to the nearest value of 25% of the total capacity, which is 625 W. The DR activation is conducted only for 3 hours a day from 20–23 hours of a day by considering the duration a peak hour. The population of the fridges is low. Therefore the experiment for each scenario is conducted for 3 consecutive days and their measurements are aggregated to one day to emulate a higher population and also to increase the signal to noise ratio (SNR).The overview of the scenarios 3–5 is given in Figure 36.

The different types of delay sequences followed in the scenarios 3–5 are explained as follows.

Scenario 3: DR activation with delay sequence S1-S1
In scenario 3, the control for all the refrigerators is enabled sequentially with a delay of 1 minute between each refrigerator. The 25th refrigerator is enabled for control after 25 minutes from the 1st refrigerator. Similarly, at the end of DR activation time, the control is disabled sequentially with the same delay. Here, the sequences followed at the beginning and at the end are same. In this way, all refrigerators are controlled for the same amount of time.

Scenario 4: DR activation with delay sequence S1-S2

Scenario 4 is similar in most aspects to scenario 3. The only difference is the sequence in which the refrigerators are enabled for the control at the beginning and at the end are different. In this way the refrigerators have different DR activation durations.

Scenario 5: DR activation with delay sequence S1,3,5-S2,4,6

In scenarios 3 and 4, the test is the same for all the 3 days. In scenario 5, each day a different sequence is selected at the beginning and at the end of the DR activation time. In this way the experiment on each day is different and this case will only emulate a larger population of refrigerators.

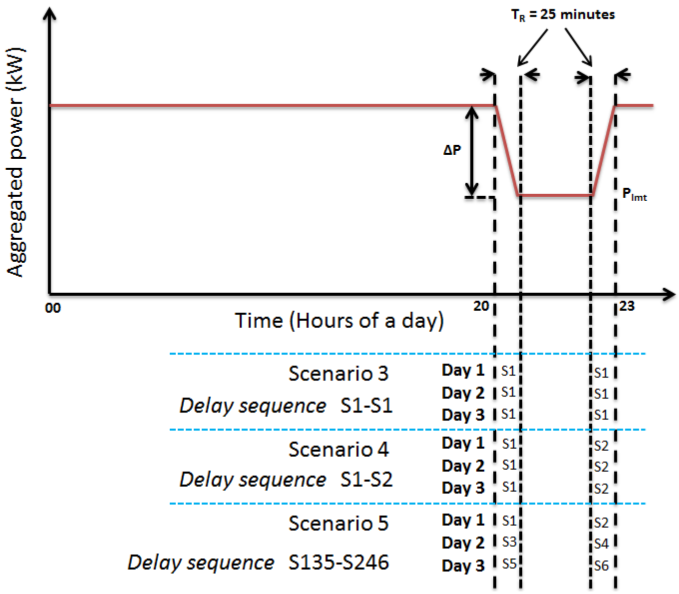

Figure 36. Scenarios 3–5 overview

The aggregated power consumption and the instantaneous temperature average of the fridges for the 5 scenarios are reported in Figure 37 - Figure 41. As the power is aggregated for 3 days, the Pmax_limit becomes 1875 W. The Pmax_limit is marked as a red line in the upper plot of each figure.

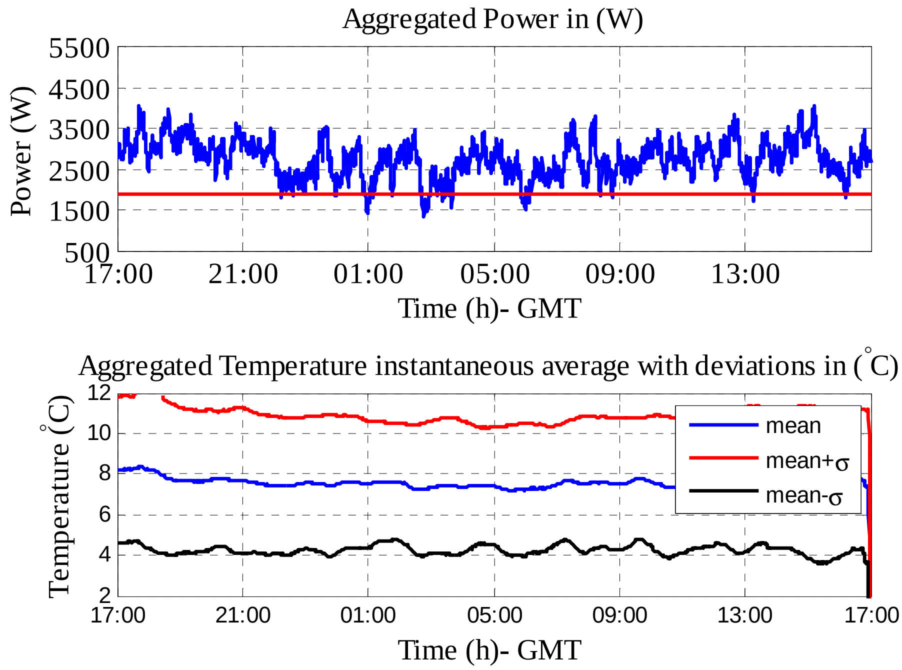

Figure 37. Aggregated power from the fridges and instantaneous average of temperatures all fridges without control scenario 1.

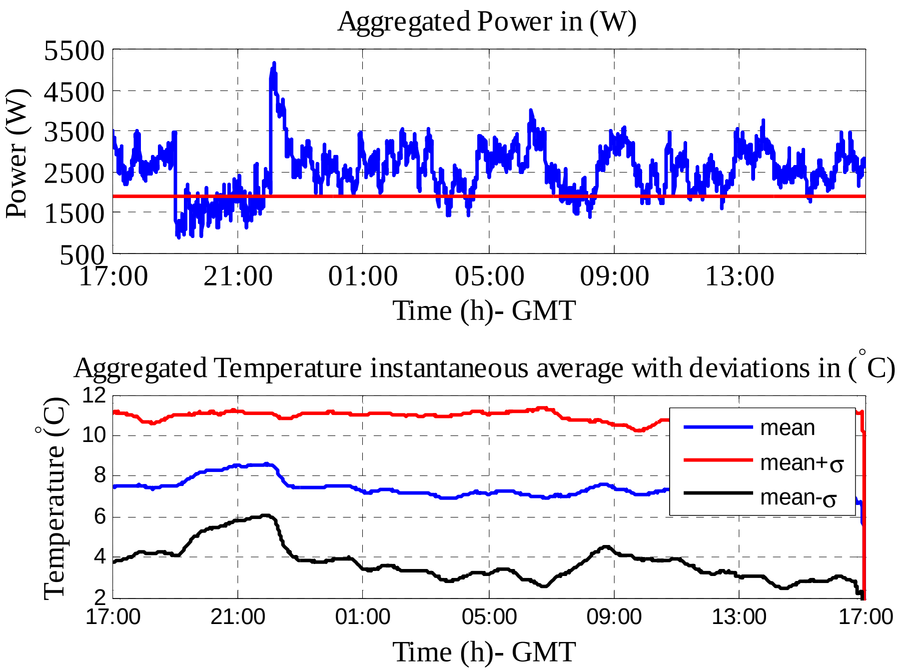

Figure 38. Aggregated power from the fridges and instantaneous average of temperatures all fridges in scenario 2.

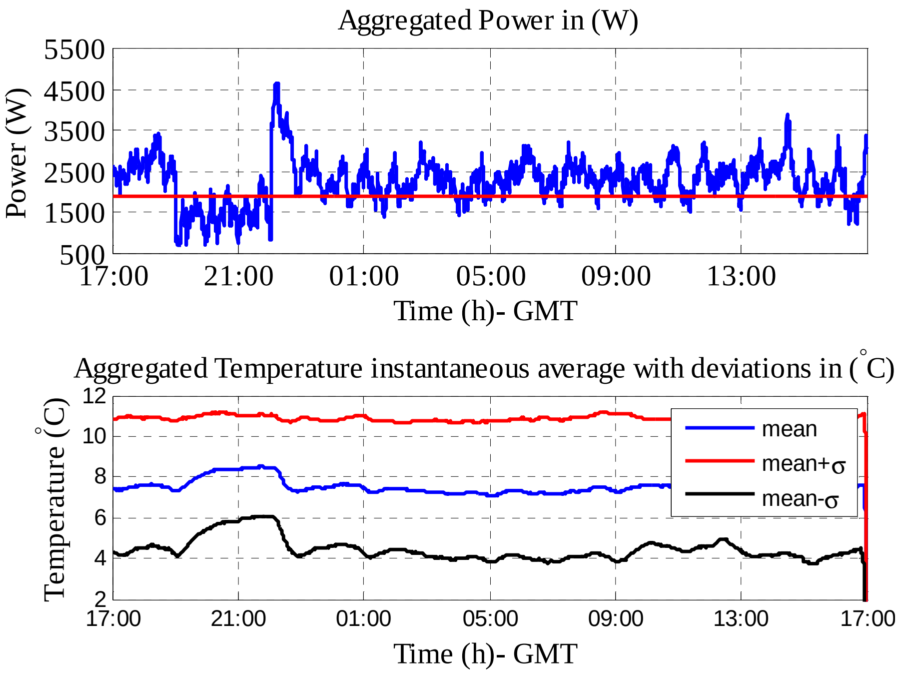

Figure 39. Aggregated power from the fridges and instantaneous average of temperatures all fridges in scenario 3.

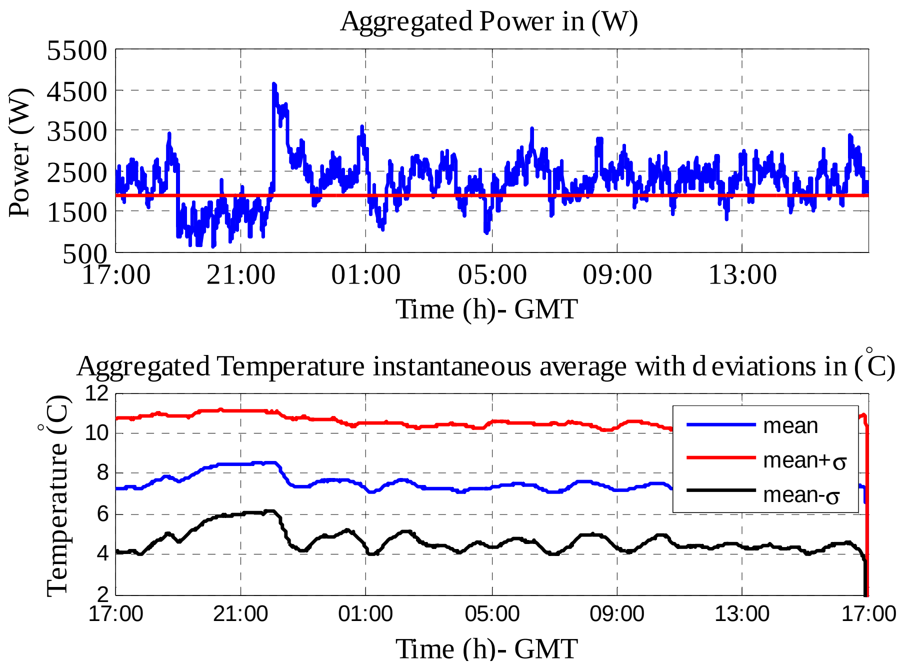

Figure 40. Aggregated power from the fridges and instantaneous average of temperatures all fridges in scenario 4.

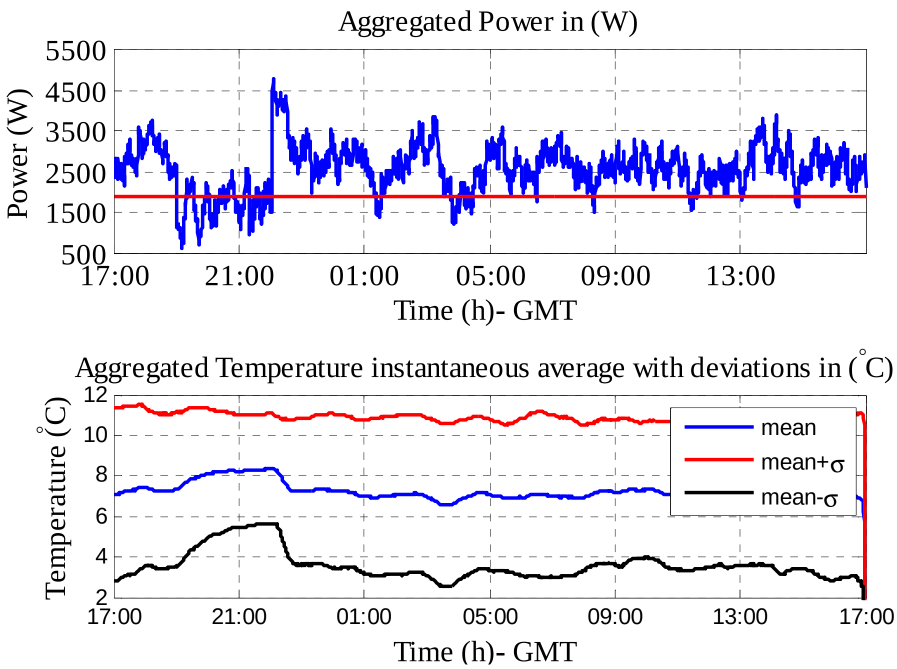

Figure 41. Aggregated power from the fridges and instantaneous average of temperatures all fridges in scenario 5.

Table 7-1: Effect of control on aggregated power of the refrigerators.

Parameter	Scenario			
	2	3	4	5
ISE [W]	36.44	28.40	26.07	36.78
Ramp down rate [%/minute]	8.77	7.37	5.27	8.70
Ramp up rate [%/minute]	20.33	18.00	16.00	19.70
Average of instantaneous temperature [◦C]	7.35	7.50	7.45	7.24
Standard deviation of instantaneous temperature [◦C]	0.52	0.45	0.47	0.49
Peak overshoot after DR activation removal [kW]	5.2	4.7	4.7	4.8

7.5 Findings

The experimental results are listed in Table **7-1**. They show that withdrawing all loads abruptly (scenario 2) produces a high error in terms of square root of ISE (36.44 W) in power limitation and also causes higher ramp down (8.77 %/minute) and ramp up (20.33 %/minute) rates and higher peak overshoot (5.2 kW).

The efforts taken to reduce the ramp down and ramp up rates and peak overshoot by delaying the DR activation on the refrigerators improved the control performances in all terms. However, among the 3 delay sequences used in scenarios 3, 4 and 5, the best results are with two different sequences of refrigerators for the delay as explained in scenario 4. The error in the power limitation also is the lowest for scenario 4 (26.07 W).

The energy trends for the 5 scenarios are given in Figure 42. The maximum difference in total energy consumption between the scenario without control and the scenarios with control is around 15%. The difference in total energy could be due to many factors such as a change in the thermal mass due to food exchange, user interactions by refrigerators door openings and prediction errors for control schedule. The energy treands do not meet each other at the end. This could be due to the large time constant of the system so that the time between each control action (24 hours) is not sufficient for the system to attain steady state.

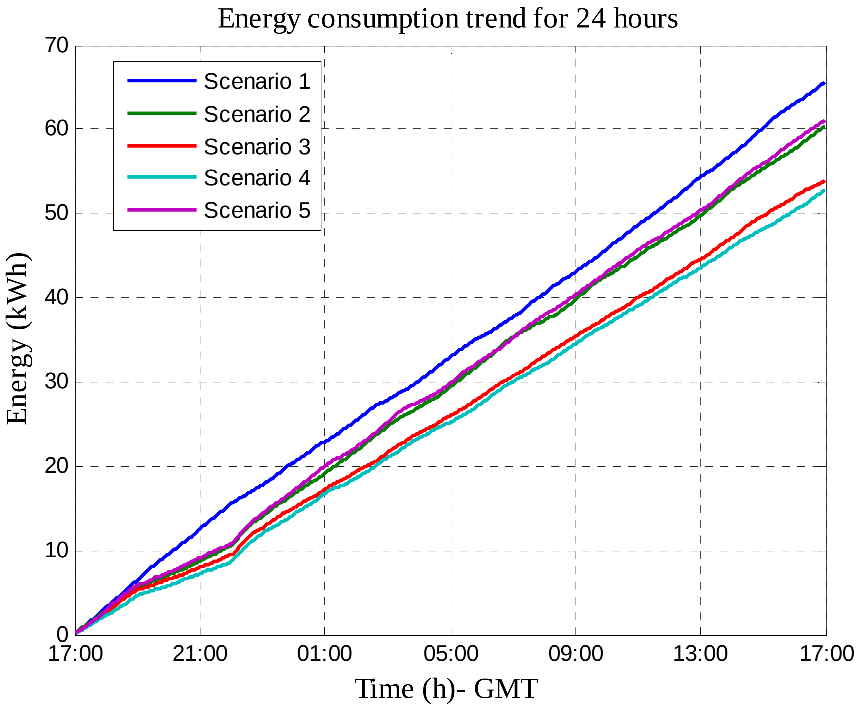

Figure 42. The energy consumption trends of the refrigerators for scenarios 1–5.

8 CONCLUSIONS AND FUTURE WORK

This thesis has examined the flexibility of domestic TCLs for DR applications and has analysed the effectiveness in providing one of the ancillary services: secondary frequency control by real-time centralised direct control of TCLs. The impacts of DR activations on TCLs are also analysed.

Besides these 3 main research contributions, during the PhD course, an infrastructure to conduct a field experiment for DR study using real Danish domestic refrigerators has been created as a part of the project INCAP. The infrastructure for the field experiment consists of a control and data centre at DTU and devices for sensing and control at every individual house that participated in the experiment. There are 3 pieces of application software that were developed. Two are associated with activities of control and data centre namely: 1. Device management and data collection, 2. Consumer electricity price information display. The third piece of software is to control refrigerators for all the experimented conducted as a part of the DR study in this thesis. The project implementation demonstrated the modularity in hardware and software implementation. The project used commercially available devices for sensing, control and communication. The commercial telecommunication infrastructure was used for communication.

This chapter presents a number of key results from this study and recommends several topics for future work.

8.1 Conclusions

The 3 main objectives of the thesis are stated in section 1.5; the following are the corresponding conclusions:

1. Estimate the flexibility available with domestic TCL for DR activation:
When domestic sector is considered for DR, the number of flexible resources that participate in DR will be greater. Therefore the prediction strategy should be simple to calculate the flexibility available with the resources and should require minimum information from the flexible resources for calculation.

The prediction strategy presented in chapter 4 for predicting TCL temperature profile and cooling and heating durations exhibits promising results with only two measurement parameters and unknown refrigerator types. It is tested with two refrigerators that are constructed differently. The mean error in predicting the heating cycle time or the energy discharge time with the two types refrigerators are -2.3% and 0.5%, respectively. Similarly the mean errors in predicting cooling cycle time or the energy charging time with same refrigerators are -7.4% and -1.0%. The prediction error is low in predicting heating time or the time for reduced power consumption. Also, the prediction error is lower in the refrigerator in which the temperature measurement for prediction is from the same chamber where the refrigerator thermostat is mounted. The prediction error largely depends on the ambient temperature change and the temperature sensor position.

Aggregated flexibility estimation using the prediction strategy developed is tested with the real domestic refrigerators participating in the INCAP project. The experiment and the results presented in chapter 5 show that the energy consumption during demand response activation can be estimated within the error limits of ±1.5%. The estimation of energy during the post DR period has errors up to ±10%. This is mainly due to the high time constant of thermodynamic system of the refrigerators. The refrigerators take time that is longer than 3 hours considered for the experiment to consume the reduced energy back to its nominal value. Earlier research reported that the thermal time constant of refrigerators ranges from 32–80 hours. The energy trends presented for the different power reduction experiments in chapter 7 also show that the thermal time constant is greater than 24 hours.

In real life conditions, the quantity and type of the food content in the refrigerators change on a daily basis. Therefore, the thermal mass associated with the food content also changes. With a changing thermal mass, it is difficult to estimate the system time constant accurately.

2. Evaluate domestic TCLs suitability for providing power system critical services:

The power system operators require many ancillary services in their day-to-day operation practice. In chapter 6, one of the power system ancillary services, secondary frequency control by DR activation on domestic TCLs is evaluated. Since the DR in the domestic sector involves many appliances with a small flexibility, a study of their overall performance is useful. The experimental study showed a ramp rate achievement of 41.2 % /minute. The achieved ramp rate is almost twice the ramp rate of diesel engine power plants, which are considered as the power plants with the highest ramp rate (20 %/minute). The average response time to the control signal by the TCLs is 33.5 s. The response time shows that the domestic TCLs are rapidly responsive loads for DR practice.

The simulated results show that the time required to compute the flexibility of 1000 TCLs is 1 ms and the computational time requirement for 1000000 TCLs is 21 ms. The computational time required for sorting the TCLs based on their individual flexibility increases exponentially for 5 ms for 1000 TCLs to 906146 ms for 1000000 TCLs. Greater care must be taken for proper computational resource selection while the system is scaled up to control a larger population of TCLs.

The change in TCLs' flexibility with different power reduction levels is analysed. The thermostat hysteresis is overridden by the controller during DR activation. Therefore, the results show that the TCL flexibility increases by 55% on control, compared to their normal operation. The maximum power reduction for DR service is 75% from the maximum value of normal consumption. When the DR is activated for maximum possible power reduction, the average temperature of the TCL population increases by 14.3%.

3. Analyse the impact of enabling DR activation on domestic TCLs:
TCLs are rapidly responsive loads. The demand response activation on TCLs will cause energy shifts and payback loads. Therefore the impact of DR activation on TCLs has to be analysed.

In chapter 7, the impact of enabling DR activation on TCLs for providing power system services is analysed by considering the parameters namely deviations in the power reduction, power ramp down rate and ramp-up rate, and peak overshoot after the control activation removal. The power system operator can decide the values for these parameters as per the power system requirements. The ramp down and ramp up rates can be controlled with a delay in activating DR on TCLs. The experimental results show that withdrawing all TCLs abruptly for power reduction causes a high error in terms of ISE (5.8%) in power limitation and has higher ramp down (8.77 %/minute) and ramp up (20.33 %/minute) rates and a higher peak overshoot.

The ramp rates can be controlled by enabling the TCLs control sequentially with a time delay. The delay DR activation reduces the ramp down rate by 39.90%, and the ramp up rate by 21.30%. Furthermore, the integral square error (ISE) in power limitation reduces by 28.46% and the overshoot reduces by 7.69%. The instantaneous average temperature of the TCLs increases by 0.13%.

Among the different electricity consumer types, the potential of the domestic consumers can be utilised for DR activities without violating consumers' comfort boundaries. The experimental analysis shows that DR can be used as an operational procedure for power system operation and also for peak load reduction and energy shifts.

8.2 Future work

A systematic study has been performed of domestic TCLs' suitability for DR application using a refrigerator as an example case. However, there are some questions unanswered at every stage of the work conducted. This opens the possibility of further study.

1. Temperature prediction strategy: The temperature prediction strategy is developed for the refrigerators with a single compressor and a two control states. Refrigerators with a larger capacity have more than one compressor. The power measurement carries the signature of different compressors in the refrigerator. Therefore, the temperature prediction strategy can be extended for the refrigerators with multiple compressors.

The error in temperature prediction is dominant when the change in ambient temperature is large. The temperature prediction method can be improved by including the ambient temperature measurement.

The temperature prediction strategy can be validated for the TCLs with a higher power rating, for example electric water heaters and space heating and cooling appliances, as their power regulation capacity is high.

2. Voltage control and congestion management: the present research covers only secondary frequency control with DR activation on TCLs. The electric power distribution network has localised problems such as voltage variation and congestion. This work can be further extended for voltage control and congestion control in the electric distribution network.

3. Resource selection strategy: this study has used the predicted OFF time of the TCLs to prioritise their selection for control. This method is very simple and does not effectively utilise the flexibility available with TCLs. The resource selection method can be modified either with the actual thermal capacity or with the available percentage flexibility with each TCL or in a combination of both.

4. Experiment with a larger population: here, a small population of TCLs was used. The INCAP project will have a greater number of participants in the future. Therefore, the experiments can be repeated with a larger population and the suitability of the methods proposed can be analysed for the larger method.

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Appendix A
PUBLICATIONS

Five paper associated with this dissertation are attached in this appendix. The topics of the papers are as follows.

A1: Domestic Refrigerators Temperature Prediction Strategy for the Evaluation of the Expected Power Consumption

A2: Energy Shift Estimation of Demand Response Activation on Refrigerators – A Field Test Study

A3: Provision of secondary frequency control via demand response activation on thermostatically controlled loads: Solutions and experiences from Denmark

A4: Experimental analysis of flexibility change with different levels of power reduction by demand response activation on thermostat-controlled loads

A5: Impact of thermostatically controlled loads' demand response activation on aggregated power: A field experiment

A1: Domestic Refrigerators Temperature Prediction Strategy for the Evaluation of the Expected Power Consumption

This paper was published in the Proceedings of the 4th IEEE/PES Innovative Smart Grid Technologies Europe (ISGT EUROPE), 06-09 October, 2013, Copenhagen, Denmark.

Domestic Refrigerators Temperature Prediction Strategy for the Evaluation of the Expected Power Consumption

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***Abstract*—This paper discusses and presents a simple temperature prediction strategy for the domestic refrigerator. The main idea is to predict the duration it takes to the cold chamber temperature to reach the thresholds according to the state of the compressor and to the last temperature measurements. The experiments are conducted at SYSLAB facility at DTU Risø Campus having a set of refrigerators working at different set point temperatures, with different ambient temperatures and under different thermal load conditions. The prediction strategy is tested using a set of different refrigerators in order to validate the performances. The challenges to calculate the time with less error pronouncement in temperature, regulating power supply and its duration are also discussed.**

***Index Terms*—Regulating power, Energy Storage, Grid Integration, Demand response.**

I. Introduction

The rise in energy demand, the threat of depleting fossil fuels and their impairment to the environment is pushing the usage of more renewable energy sources with increased small distributed production units rather than large localized traditional power plants. In Denmark solar and wind generation accounted to 21% in 2010 and ambitious national targets suggest 50% consumption to be supplied from wind in 2020 [1]. Increase of an uncontrollable and variable power production disturbs balance between supply and demand and a shift to production driven consumption is inevitable. Smart Grid technology is expected to provide benefits by reducing distribution and transmission losses, and help to optimize the use of existing power grid infrastructure [2].

One of the challenges for the reliable and economical operation of a power system with a high penetration of renewable energy sources with high fluctuations (solar, wind) is the availability of energy resources which can participate in balancing supply and demand on a short-term basis. Demand response paradigm suggests that such resources can be found on the demand side rather only in the supply side. The increase of not controllable variable power production and the displacement of conventional generation require power system services, such as regulating power provision, to be reallocated. A possible source of regulating power is offered by so called Demand Side Resources (DSRs), which are electric loads whose power consumption can be deferred without compromising the quality of the services they are providing to the users. Demand response paradigm is based on the idea that contribute in terms of electric power of the single unit is modest but the aggregated response of a very large number of units might be of relevant size for the power system [3]. In Nordic countries in 2010 buildings energy consumption was 34% of total consumption, where appliances and miscellaneous equipment accounted to 24% of energy consumption in the building sector [4]. Among appliances found in a household, refrigerators, washing machines, dryers and dishwashers are considered to be suitable for load shifting [5]. Loads with thermal capacity and continuous operation are even more suitable for shifting. Using, for example, a thermal energy storage capacity in a refrigerator, consumption can be shifted away from peak hours, while managing a stable temperature within set range.

Availability of a refrigerator in most of households, ability to shift its consumption due to presence of thermal storage and continuity of operation, with thermostat cycles, makes a refrigerator a suitable unit for a large field experiment controlling appliances in private premises. The main challenge in such a context is to predict if and for how long a refrigerator is available to defer its power consumption. In order to have a realistic estimate of the fridge power consumption flexibility, a thermal model for predicting the future temperature of the cold vane can be used.

The aim of this paper is to present a simple thermal prediction strategy of a refrigerator that can capture its main thermal dynamics. The strategy will be validated on real domestic refrigerator units which work at different indoor and ambient temperatures and under different thermal load conditions. Particular emphasis will be put on creating an adaptive model which can estimate and update its parameters

This work is part of INCAP project (INducing Consumer Adoption of automated reaction technology for dynamic Power pricing tariffs), funded by The Danish Council for Strategic Research, running from 2012 to 2016.

on-line. The rest of this paper is organized as follows: in Section II the problem outline and prediction strategy are introduced, and the thermal model of the fridge is briefly presented. Section III illustrates how the work will be carried out and preliminary experimental data which were used for fitting the model. Section IV discusses about the work plan in detail and the conclusions and future work are reported in section V.

II. PREDICTION STRATEGY

A. Problem outline and prediction strategy description

The domestic refrigerator's operation during most of the time of a day is very much defined by the operation of the thermostat. The major disturbances are introduced only during certain time of the day while the food is removed from and fresh food is loaded into the fridge. During rest of the day, the internal temperature of the fridge is not affected by user behavior and it can be predicted using a simple strategy tuned with historical measurements. This allows predicting the duration for which the regulatory power can be supplied or consumed.

The quantity of the available regulating power is the fridge power consumption at any time. Regulating power supply duration is the duration for which the fridge operation can be interrupted without violating upper and lower threshold of internal temperature of the fridge. The regulating power supply duration can be estimated by predicting the time that it takes for the temperature to reach upper or lower threshold of the respective thermal cycle from the present temperature inside the cold chamber. Thermal cycles examples are shown in Figure 2 with cooling cycle between time t_1 and t_2, and heating cycle between time t_2 and t_3. Because of the thermostatic cycles, the thermal behavior of the fridge follows the earlier respective heating or cooling cycle with minor or no variations. In the work presented in this paper, predictions for the present heating and cooling cycle are based on the previous respective cycles.

To predict the duration of present cycle, the previous respective cycle's temperature curve can be traced till the threshold temperatures of the cycle and applied on the present cycle. For example, in the illustration shown in Figure 2, to predict the cooling cycle between the time period t_3 and t_5, previous cooling cycle from time period t_1 to t_2 can be used. Similarly, to predict the heating cycle between the time period t_5 and t_6, previous heating cycle from time period t_2 to t_3 can be used. The shape of the temperature curve is characterized by its slope at different segments. One of the ways to trace the temperature curves of these cycles is by considering them a piecewise linear. The slopes can be derived for each segment of a curve by considering the segment as a linear with one slope. These slopes of different segments of the previous cycle can be used to construct the temperature curve of the cycle under prediction.

The block diagram in Figure 1 shows the prediction strategy with the expected input and output quantities with temperature prediction strategy that is discussed in this paper.

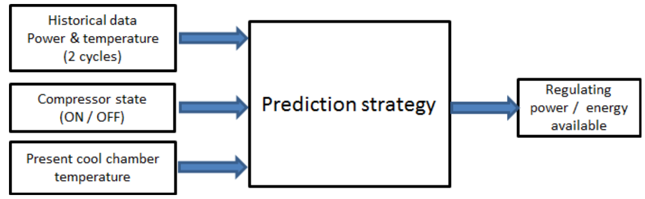

Figure 1. Block diagram of fridge model showing input and output.

B. Prediction error

The temperature prediction error has a direct impact on the prediction of regulating power supply duration. The prediction error in duration is calculated as shown in Figure 2. In the cooling cycle, the prediction error is the ratio of the difference in time between the actual temperature and the predicted temperature reaching lower threshold temperature and the actual cooling duration. Similarly, in the heating cycle the prediction error is the ratio of the difference in time between the actual temperature and the predicted temperature reaching higher threshold temperature and the actual heating duration. The errors in prediction are defined as follows:

$$\text{Prediction error} = \Delta t_{c,h} / t_{c,h}$$

Where $\Delta t_{c,h}$ is the difference between actual time and the predicted time for the temperature to reach upper or lower threshold temperature and $t_{c,h}$ is actual heating or cooling cycle duration. The positive error represents the under estimation and vice versa.

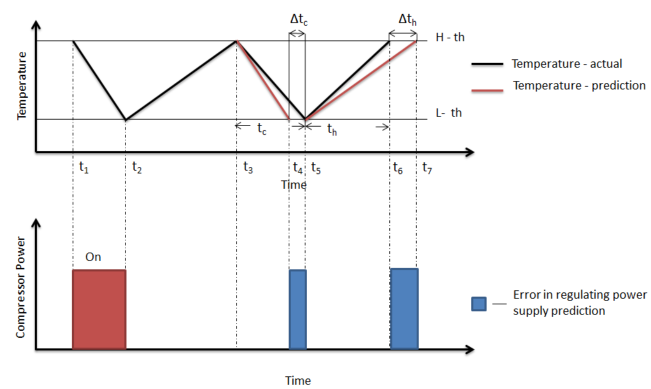

Figure 2. Prediction error calculation in cycle duration.

III. EXPERIMENTAL SETUP

Preliminary measurements of two consecutive thermostatic cycle of one refrigerator unit are shown in Figure 3. Upper plot of Figure 3 shows the cold chamber temperature while lower plot shows the refrigerator power consumption. The power consumption shows an initial spike due to the inrush current of the induction motor which drives the compressor. Electric power consumption is afterwards decreasing along with the rate of the fridge indoor temperature. Time series of the electric power consumption and fridge indoor temperature is used for fitting on-line the refrigerator prediction strategy.

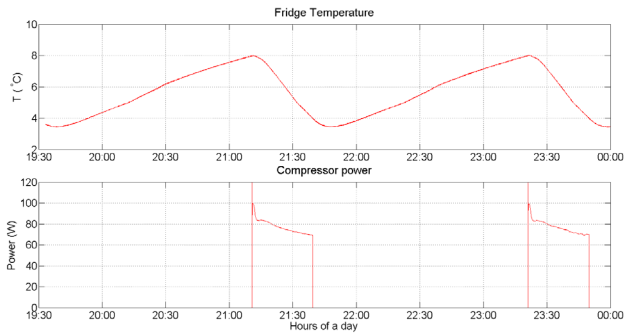

Figure 3. Fridge temperature profile and compressor power profile for two cycles.

In this paper the proposed thermal model will be fitted using two refrigerator units at different working conditions (cool chamber temperature set point, ambient temperature, food thermal mass) and its performances, accuracy and reliability in estimating the indoor temperature and refrigerator power consumption is assessed.

A. *Measurement and data collection*

The aim of the presented experiments is to collect different set of temperature data to train the model and test the self-tunability (to adopt the changes in variations in the cycle) of the model for the temperature prediction in order to calculate the duration of regulating power supply. The prediction error in terms of heating and cooling duration can be calculated from the actual cycle time and the predicted time. The block diagram of the experimental setup is shown in the Figure 4.

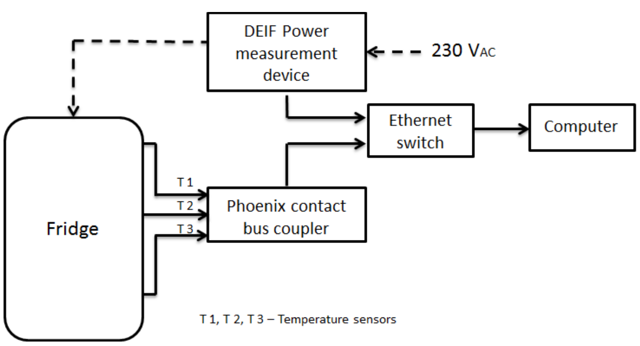

Figure 4. Experimental setup and sensor position.

The power was measured with Multi-instrument, MIC-2 from DEIF A/S with accuracy Class 0.2. The temperature was measured with TEL NTC 10 thermistors from Produal A/S with temperature range from -30 to 80 °C and accuracy ±0.2°C (at 25°C) connected to Phoenix bus coupler which reads the resistance of the thermistors. The temperature data and the power consumption along with a common time stamp were logged in a CSV file.

IV. Experiments

A. *Sensor characterization and placement*

The temperature measurement was done with three sensors. To ensure there is no considerable difference in their readings, they were placed together in single place inside of the cold chamber and the measurement of the same temperature was taken from different sensors. The measurements from the sensors and the difference in their readings are shown in Figure 5. Two of the sensors were measuring the temperature with difference of ±0.2 °C and the third one differs with the others with ±0.5 °C.

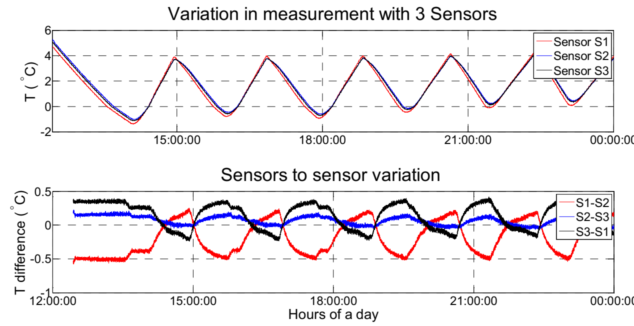

Figure 5. Temperature measurement variation in the sensors.

B. *Experiment plan*

In order to properly place the sensor and to minimize the prediction error, large sets of experimental data were analyzed. The fridge temperature was measured at three different places inside the cold chamber. Based on measurements presented in Figure 5, the final placement of the sensors for the experiment was determined. One measurement was placed close to the cooling element (the evaporator), the second one was as much as far away from the cooling element and the third one was in between the former two sensors. The sensor which gives more variation was placed in the middle of the cold chamber whereas the other two sensors were placed at top and bottom of the cold chamber of the fridge during the experiment.

Two fridges with different thermal characteristics were selected. One fridge of volumetric capacity of 75 liters with separate doors for fridge and freezer compartments, in which the temperature is controlled by the thermostat mounted in the freezer and the fridge compartment is separated from the freezer with high thermal conductive layer compared to the fridge wall insulation layer. The fridge compartment is above the freezer which is the cooling element and the coldness flows from the bottom to the top. This unit is called *Fridge-1*. The second fridge of volumetric capacity of 50 liters with a single door, evaporator is mounted inside the fridge cold chamber. The evaporator is the cooling element and the freezer. Here the coldness flows from the top to the bottom. This unit is called *Fridge-2* in the experiment. The Figure 6 shows the construction and direction of coldness flow in *Fridge-1* and *Fridge-2*.

The thermostat settings in refrigerators from different manufacturers are not following common set points indications. Some fridges have only qualitative indications of coolness only allowing setting low, medium and high. Some of the fridges have numeric coolness indicators, for example numbers 1 to 5, where 1 is the lowest and 5 is the highest temperature setting. It was decided to conduct the experiment at three different levels of thermostat setting and with three different levels of thermal mass, in order to examine fridge flexibility with different settings and loads.

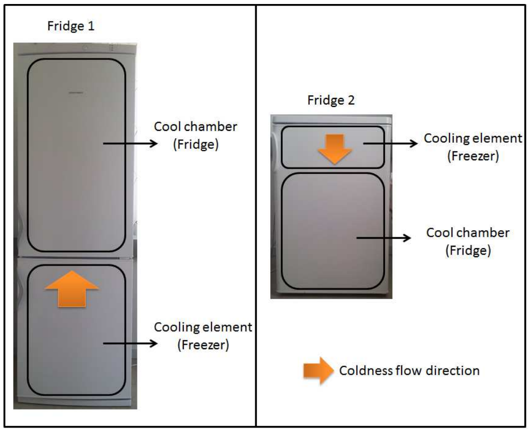

Figure 6. Construction and heat flow direction in Fridge-1 and Fridge -2.

C. *Inference from the temperature cycle*

The temperature cycles of cold chamber of the two fridges during a full day operation are shown Figure 7 and Figure 8. The temperature variations at different zones of the fridge are different.

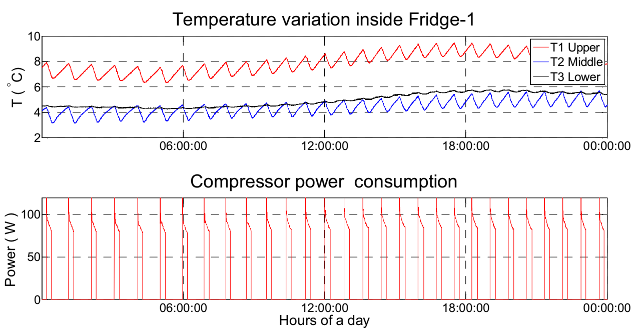

Figure 7. Temperature variation in Fridge-1.

The variations in the temperature are more pronounced in the middle than the one at the top or bottom. Figure 7 shows the measurements taken in the fridge in which the cooling element is at the bottom and in the Figure 8, shows the measurements in a fridge in which the cooling element is at the top. Also in the fridge driven by the freezers (Figure 7), the upper and lower threshold varies in wide range with the change in ambient temperature.

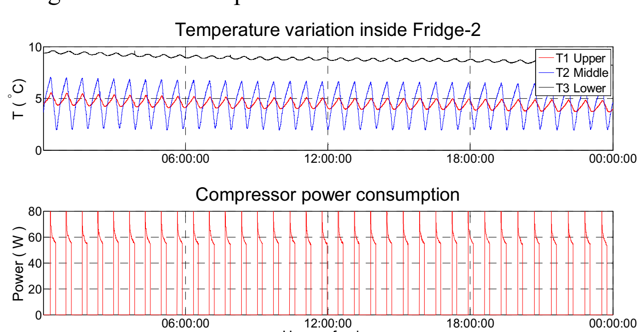

Figure 8.Temperature variation in Fridge-2.

D. *Temperature prediction for Fridge-1*

The temperature curves of cooling cycle and the heating cycle follows different trends. They are considered as two different systems. Predictions for the present heating and cooling cycle are based on the previous respective cycles. The measurement from sensor mounted at the middle of the cold chamber was used for the temperature prediction as the temperature cycles are more visible in the measurement. The temperature curve of a cycle is traced by its slopes at different segments and the slopes were used to construct the curve under prediction. The Figure 9 shows the closer view of actual temperature, predicted temperature for two cycles of cooling and heating.

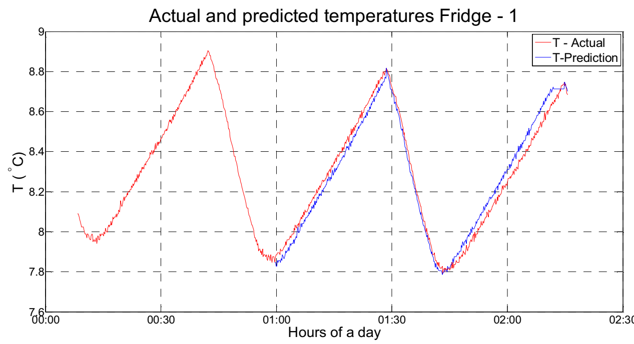

Figure 9. Temperature prediction for two cycles in Fridge-1.

The Figure 10 shows the actual temperature, predicted temperature and the difference between them for a whole day period.

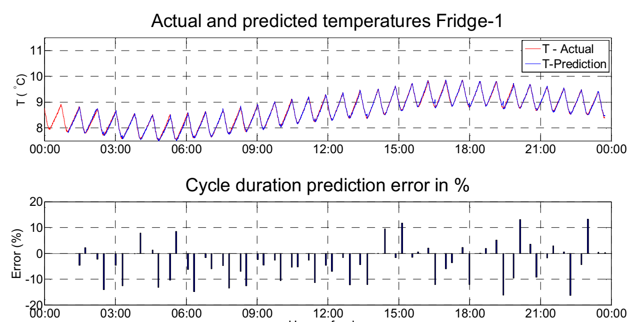

Figure 10. Temperature prediction and prediction error in Fridge-1for the full day.

The mean errors and the standard deviations for the prediction for a full day are given in the TABLE 1.

TABLE 1. PREDICTION ERROR FOR FRIDGE-1

	Mean error	Standard deviation	Maximum error
Cooling	-7.4 %	14.2 %	16.1 %
Heating	-2.3 %	3.6 %	3.2 %

E. *Temperature prediction for Fridge-2*

The ability of the model to predict the temperature was tested with the Fridge-2 in normal operation and with user interaction. The fridge was partially loaded (60% by the volumetric capacity, i.e. 18 L of water) with water bottles and the thermostat was set at medium level. After the regular cooling and heating cycles were achieved, the disturbances were introduced. The disturbances were:

- Random door openings for the duration of 30 seconds and 60 seconds.
- Removal of thermal mass (12.5 % of present mass)
- Addition of thermal mass (5 % of present mass)
- Addition of thermal mass (13 % of present mass)

The prediction for a whole day with normal operation without any user interaction is shown in the Figure 11. The prediction error means and standard deviations are given in the Table 2.

TABLE 2. PREDICTION ERROR FOR FRIDGE-2

	Mean error	Standard deviation	Maximum error
Cooling	-1.0 %	4.8 %	9.5 %
Heating	0.5 %	5.5 %	10.4 %

The first three disturbances mentioned above were introduced between 08:00 and 12:00 hours of the day and have no considerable impact on the prediction error which is shown in Figure 11.

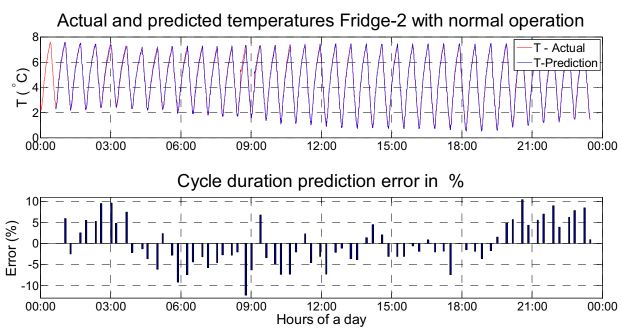

Figure 11. Temperature prediction and prediction error in Fridge-2 with normal operation for a day.

Addition of 13% thermal mass, causes a huge drift in the lower and upper thresholds of the thermal cycles, the prediction error was above 40% in the first two cycles after the change in thermal mass as shown in Figure 12. The actual temperature, the predicted one and their difference are shown in the Figure 12. The prediction error means and standard deviations are given in the Table 3.

TABLE 3. PREDICTION ERROR FOR FRIDGE-2 WITH USER INTERACTION

	Mean error	Standard deviation	Maximum error
Cooling	-0.5 %	10.8 %	9.5 %
Heating	-0.3 %	6.1 %	47.5 %

The prediction errors are less pronounced for the fridges where the thermostat is mounted in the cold chamber where the measurement is taken for the prediction as the variation in the upper and lower threshold temperature are less.

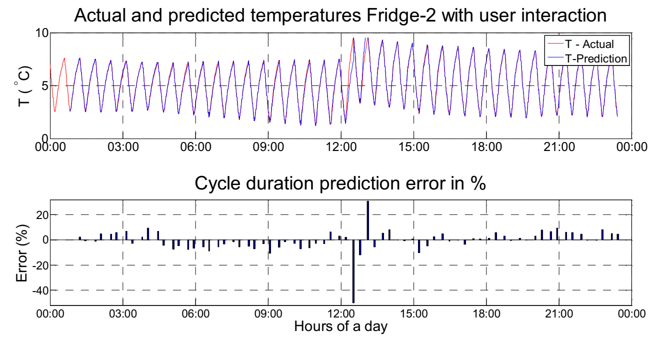

Figure 12. Temperature prediction and prediction error in Fridge-2 with user interaction.

V. CONCLUSIONS AND FUTURE WORK

The paper main idea is to predict the duration that it takes for the cold chamber temperature to reach the lower or the upper threshold temperatures, according to the state of the compressor and the series of temperature measurements from the last cooling or heating cycle. The aim is to be able to predict the temperature behavior of large set of fridges, and thus evaluate the expected power consumption. The presented fridge model was fitted with experimental data from a test fridge. The proposed prediction strategy for power consumption estimation was verified using two different fridges and the results showed a standard deviation in the prediction error of 14.2% and 4.8% for the cooling cycle. The heating cycle errors are respectively 3.6% and 5.5%.

The prediction strategy used here is simple and needs little computing power and only two measurements: temperature and compressor state, but it is usable for predicting the power consumption of a fridge of unknown type, size and load, fitting its prediction to previous heating and cooling cycles. From the results obtained, it seems that the method is more suitable for the fridges where the thermostat is mounted in the cold chamber, such as Fridge-2. The temperature sensor cables cause thermal leak in the system which introduces minor disturbances in to system. Usage of wireless temperature sensors can solve this problem. Further field implementations are aimed at evaluating aggregated behavior of a larger set of fridges in domestic households.

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A2: Energy Shift Estimation of Demand Response Activation on Refrigerators – A Field Test Study

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Energy Shift Estimation of Demand Response Activation on Refrigerators – A Field Test Study

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***Abstract*- This paper presents a method to estimate the amount of energy that can be shifted during demand response (DR) activation on domestic refrigerator. Though there are many methods for DR activation like load reduction, load shifting and onsite generation, the method under study is load shifting. Electric heating and cooling equipment like refrigerators, water heaters and space heaters and coolers are preferred for such DR activation because of their energy storing capacity. Accurate estimation of available regulating power and energy shift is important to understand the value of DR activation at any time. In this paper a novel method to estimate the available energy shift from domestic refrigerators with only two measurements, namely fridge cool chamber temperature and compressor power consumption is proposed, discussed and evaluated.**

***Index Terms*-- Demand Response, Energy estimation, Field experiment, Load shifting.**

I. Introduction

The shift from consumption based production to production driven consumption is driven by the increasing percentage of unpredictable renewable resources. The large centralized traditional power plants are being replaced with many small distributed production units. Danish ambition is to move from 21% of wind and solar production in 2010[1] to 50% consumption being supplied from wind is set for 2020 [2]. A large amount of uncontrollable renewable production brings several challenges for future power systems. Production fluctuations influences power system stability, in expected days with low wind and sun power system require energy storage facilities or shiftable consumption [3]. The solution offered by Demand Response (DR) suggests that resources that can be used for power system balancing can be found on the demand side rather only in the supply side [4].In DR demand is adjusted either by load reduction, increase or shifting. DR includes all controllable loads with ability to differ consumption without compromising the quality of service delivered to the user.

Consumption form both residential and commercial buildings accounts to 34% of total consumption in Nordic countries. Residential houses account to two-thirds of this amount and within the houses all appliances consume around 17% of total energy [5]. Domestic appliances considered to be suitable for load shifting are fridges, freezers, dishwashers, washing machines and driers. Among these devices only fridges have periodical operation and thermal capacity, making it more suitable for time-of-the day independent load shifting. A fridge is also available in most of households and it's the most important objective: keeping a low temperature, is easily measurable with a simple temperature sensor. An assessment for fridges and freezers for smart consumer load participation have already been done [6]. The remote control of refrigerator for demand side participation is demonstrated in [7].

In [8] simulated domestic fridges were used to stabilize the grid frequency. In this work a fridge model based on a data from a single fridge was used to simulate 1000 fridges. The flexibility of a fridge was based on a model of appliance without any disturbances, for example opening the ridge door, adding and removing the load. An adaptive model based on the historical data of a single fridge was presented in [9]. The model presented in [9] estimates thermostatic cycles of the fridge based on a recent cycle taking under consideration recent disturbances. In [10] a fridge thermostat cycles are shifted based on the electricity price. In this work a fridge is assumed to have the same flexibility during all time, which is a size of one thermostat cycle. In reality there are more factors influencing the flexibility of a fridge and amount of energy that can be shifted.

The aim of this paper is to present a simple method to estimate the amount of energy that can be shifted during demand response (DR) activation on domestic refrigerator using the temperature prediction strategy given in [9]. The method will be validated on real refrigerator units in 10 domestic households, which work at different indoor and ambient temperatures and under different thermal load conditions. The rest of this paper is organized as follows: in Section II the principle of the estimation method and problem outline are introduced, and the control strategy adopted for energy reduction is briefly presented. Section III explains the experiment platform, hardware devices used for control and measurement and their configuration. Section IV discusses about the control strategy, practical limitations and safety constraints in detail. The results of the experiments are discussed in section V and the conclusions and future work are reported in section VI.

II. Methodology

The refrigerator temperature swings between two temperature levels namely higher threshold (HT) and lower threshold (LT) controlled by the internal thermostat as shown in the Fig. 1. The temperature set by the user namely the set point can be considered as the temperature in between these two threshold temperatures. The fridge cool chamber temperature depends

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on different parameter like compressor run time, thermal mass of the food content inside, ambient temperature, thermal insulation of the envelope material and user interaction which alters the thermal mass due to food and air exchange. Predicting cool chamber temperature is the only way to predict the energy consumption by the compressor, as the temperature prediction can provide compressor runtime. There are varieties of refrigerator models available to predict the temperature of the refrigerator's cool chamber [9], [11].

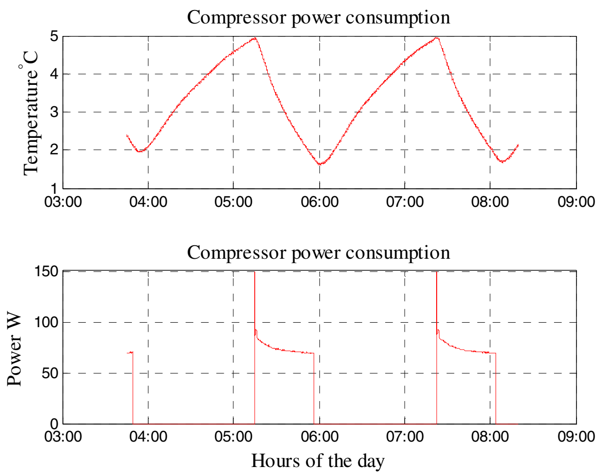

Fig. 1 Refrigerator cool chamber temperature variation and compressor power consumption.

More details the model has more complex the model will be and tailored for a particular refrigerator. A detailed model needs to produce accurate prediction results when the dynamics of the refrigerator are changing. The change in the refrigerator dynamics are predominantly due to change in thermal mass when the food is exchanged and also due to change in ambient temperature. A detailed thermal modelling of household refrigerator is presented in [12]. When the dynamics of the refrigerator are not changing, a simple model [9] can predict the refrigerator cool chamber temperature with considerable accuracy during the cooling and heating cycles. The temperature prediction enables predicting the duration it takes to reach a particular temperature in heating or cooling cycle. If the temperature durations are predicted, then the compressor ON and OFF time can be estimated. From the compressor power and ON/OFF time, the amount of energy that is consumed and the amount that can be shifted can be estimated.

The proposed method maintains the cool chamber temperature at ΔT degree above the HT during the demand response activation duration (t_{DR}) in order to have minimum impact on quality of service. The quality of service is maintenance of cool chamber temperature as much as close to the set point temperature. The overall objective is to reduce energy consumption by maintaining the fridge temperature close to HT by reducing the compressor ON time. As explained in the black box model [9], the heating and cooling cycle duration and their dynamics don't change much compare to their previous cycles. The different heating (t_{he}) and cooling time (t_{ce}) during DR activation can be extracted from the previous heating and cooling cycles as shown in Fig. 2. The energy consumption during DR activation can be estimated by integrating corresponding compressor power (CP) over that time. The number of cycles and the associated energy consumption can be calculated as follows:

- Number of heating and cooling cycles $N = (t_{DR} - t_{hea}) / (t_{he} + t_{ce})$
- Energy consumption during DR activation $E_{DR} = N \times (CP \times t_{ce})$
- Estimated energy shift $E_s = E_{preDR} - E_{DR}$

Where t_{hea} is the time elapsed during initial heating time at the beginning of DR activation.

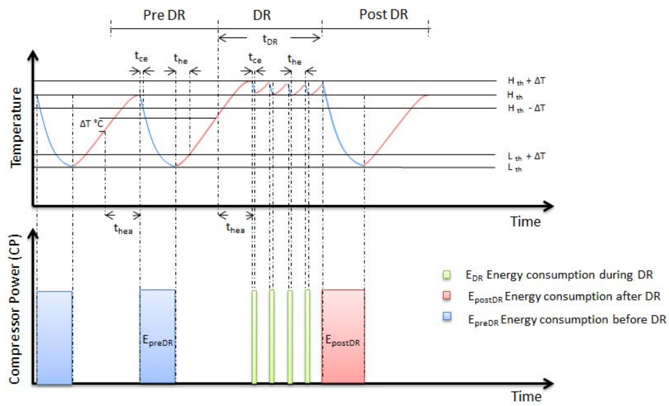

Fig. 2 Refrigerator energy consumption estimation during demand response activation

III. Experimental Procedure

A. Experimental setup

The experiment was conducted on the INCAP project platform which facilitates the control of domestic refrigerators. The INCAP project platform connects multiple domestic consumers' refrigerators to a control server. Ten fridges from selected households were considered for the control. The block diagram of the setup in one household is shown in the Fig. 3. There are four devices used for sensing and control purpose. They are

1. Contact unit which switches the fridge ON and OFF in response to the command from remote.
2. Temperature-light – PIR sensor which senses temperature, light and human occupancy.
3. A user interface device with red and green lights and two buttons.
4. A Zigbee- Ethernet gateway device for communication with the control server.

All these devices are part of Zigbee wireless home automation network products commercially available from a manufacturer Develco Products A/S. In Zigbee wireless network environment, the network is hosted by a network coordinator. In this experiment, the Zigbee- Ethernet gateway device is the network coordinator. All other devices are connected to the network as a Zigbee end device as authorized by the control server. The Zigbee- Ethernet gateway device is connected to the control server through a wired broad band ADSL internet connection. All these devices send and receive data from the control server through the Zigbee- Ethernet gateway device. The temperature sensor and the user interface device are battery powered devices while the contact unit and the Zigbee- Ethernet gateway device are powered from mains supply.

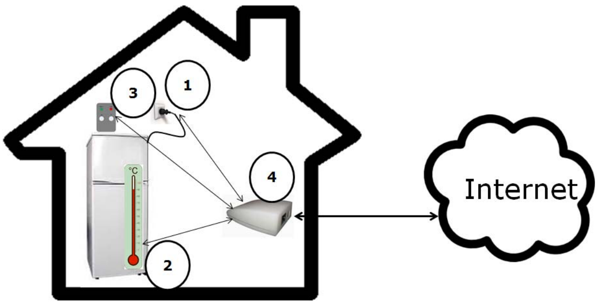

Fig. 3 Refrigerator control device installation in single house

These devices were sent to the fridge owners for installation and were installed by them as per the instruction manual attached. The Zigbee- Ethernet gateway device is connected to mains supply for power and to one of the Ethernet ports of ADSL modem for communication with control server. The contact unit was connected in series with power input of the refrigerator.

The temperature sensor was placed inside the cool chamber of the refrigerator. The user indicator can be placed anywhere in the user's vicinity. On installation, the control server receives the joining requests from all devices. The control server verifies the addresses of these devices with the data base and authorizes them to join the network. Once the devices are joined in the network, they are configured for measurement sampling rate.

B. Measurement parameters and sampling rate

Temperature: To have a long battery life span, the temperature sensor has a sampling restriction of 2 minutes which cannot be modified. It sends the temperature and light measurements every 2 minutes and the occupancy information as event driven message. The temperature sensor has an accuracy of ±0.5 °C and a resolution of 1/6 °C. The light sensor reports the light measurement in lux.

Active power and voltage: The contact unit has ability to measure active power consumption at 1 watt resolution and RMS value of line voltage at 1 volt resolution. This device was configured to send the measurement every 10 seconds. The 10 seconds interval was selected in trial and error to avid network data congestions.

All configuration details were stored permanently in the non-volatile memory of these devices. On configuration the devices send measured parameters to the control server in a form of short messages. The received data were stored in a temporary array for control purpose and in a SQL data base for the future data analysis. The next section describes the controller for DR activation and the additional necessary software components for control commands and measurement data communication.

IV. Controller Description

A. Controller architecture

The refrigerators are controlled by a central controller. The central controller is a JAVA program executed in a virtual windows machine acquired from the central server of DTU. The sever hosts a software called Smart AMM server given by the company Develco Products A/S who provide control devices for the experiment. Smart AMM server establishes the data connection between the devices and controller. A block diagram of the data flow is shown in the Fig. 4.

The devices, which are connected to the refrigerators, send all measurement data in a form of short messages to the Smart AMM server. Any client software that is subscribed to the Smart AMM Server can get a copy of these messages. Similarly the client software also can send command and configuration messages to the devices through the Smart AMM Server.

B. Fridge temperature and controlling capability

The control software receives temperature measurement message every two minutes and the voltage and power measurement data every ten seconds. The temperature measurement corresponding to the higher threshold which is the maximum value at the end of previous heating cycle for every refrigerator is stored locally in the program. Similarly the temperature measurement corresponding to the lower threshold which is the minimum value at the end of previous cooling cycle for every refrigerator is stored locally in the program. The heating and cooling cycles were identified from the fridge power measurement message.

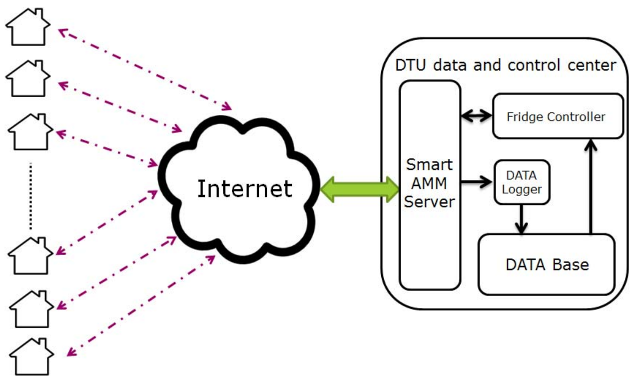

Fig. 4 Data flow from the houses to the central server.

During cooling, the compressor is activated and running. There is definite power consumption during the compressor operation. During heating cycle the compressor is switched off by the internal thermostat and consumes no power. There is a possibility of power consumption during heating cycle while the compressor is off by the internal light bulb. The light bulb is illuminated when the fridge door is opened. While considering heating and cooling cycle identification, power measurements above 30 watts are considered to avoid the confusions caused by the power consumption by the light bulb when the fridge door is opened. The controller has the following functions.

1. During the demand response time, the controller maintains the fridge cool chamber temperature between the maximum threshold and ΔT above maximum threshold.

2. If the refrigerator door is opened during the demand response period, the control relay is switched ON for a short period of 5 minutes to illuminate the light bulb to avoid the inconvenience to the user.

3. A five minutes of switch OFF time is maintained before switching ON the compressor on every compressor shut off to avoid compressor damage by the evaporator back pressure. The user has an option to avoid his/her fridge to be controlled for another 24 hours.

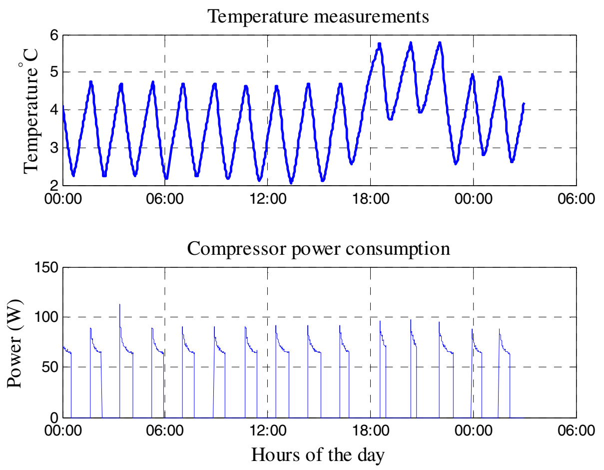

Fig. 5 Temperature variation inside the fridge and the power consumption.

The demand response control is activated for a period of three hours in the evening from 8 pm till 11 pm local time. The time for demand response activation is selected in a way that the users have less interaction with the refrigerator and at the same time they are aware of the control. To register the maximum and minimum threshold temperature, at least one cycle of each cooling and heating are required. The measurements from the fridges were started one day prior to the actual control period. Different fridges have different temperature set points. A fixed temperature rise during demand response may violate the temperature set point a lot, which may spoil the food stored and cause in convenience to the user. So it was decided to rise the temperature corresponds to half of the band between the higher and lower thresholds as shown in Fig. 5. In a normal operation, the control loop runs every two minutes. The control loop for each fridge is driven by the temperature measurement data as it is received every two minutes. If the user opens the fridge, the occupancy sensor sends a message about door opening and the fridge is switched ON if it is OFF and the five minutes duration after the previous switch OFF is elapsed.

V. RESULT

A. *Energy consumption calculation*

The experiment was conducted with 10 fridges for 9 days. All of the 10 fridges were not participating in the experiment on all of the days. The users have the flexibility to unsubscribe from the experiment on daily basis. The number of fridges participating in the experiment on each of the day is given in the TABLE I. If all of the 10 fridges were participating in a day, it is considered as 100% participation with participation factor of 1. Each day's participation factor is given in the TABLE I. The overall participation factor is the average of individual day's participation factor. The overall participation factor for the 9 days is 0.86.

TABLE I
PARTICIPATION FACTOR

Day	1	2	3	4	5	6	7	8	9
Number of fridges	10	9	9	10	8	7	8	6	10
Participation factor	1	0.9	0.9	1	0.8	0.8	0.7	0.6	1
Over all participation factor	0.86								

The demand response activation period was 8 pm till 11 pm local time (GMT+1) in the month of February 2014. During demand response activation, the temperature of the cool chamber was maintained between higher threshold temperature (HT) and half of the temperature band above the higher threshold temperature. This method individualize the control for every fridge and enables same quality of service to all consumers. The active power consumption by the compressor is measured every 10 seconds and logged in the database. The temperature profile and power consumption of one of the fridges on control activation is shown in the Fig. 5

A. *Data integrity and inrush current*

The data integrity is checked for any discontinuity in the measurement. As every measurement values are logged with their synchronized server timestamp, the time difference between each power measurement from a particular refrigerator should be 10 seconds. All measurement from every fridge for the demand response activation period is continuous. As the compressor in the refrigerator is driven by single phase induction motor, there will be a high inrush current consumption during the compressor start up. The inrush current is typically 10 times the maximum current. The inrush current normally stays for 1 or 2 seconds and then fall to the nominal value corresponding to the load. If the power measurement instant synchronizes with compressor start up time, then there will be a high active power measurement due to the inrush current value. These high values of measured power causes a huge error in the energy calculation, as the power is measured once in ten seconds. For every fridge, the power measurements above full load values are clipped. The full load power is identified from the previous compressor cycles. The energy consumption during the demand response activation period is calculated by integrating the measured power over demand response activation period which is 3 hours in this case. The energy consumption by individual fridges was summed to get the aggregated consumption. The error in the estimate is found by subtracting the actual consumption from the estimate. The error percentage is calculated by considering the estimate as base. The error percentage in estimation is plotted for all days and show in the Fig. 8. The resulting estimation errors and the possible causes are discussed in the next section.

B. Discussion

The aggregated actual energy consumption for the three periods before (Pre DR), after (Post DR) and during DR activation for the fridges for 9 days are given in the Fig. 6.

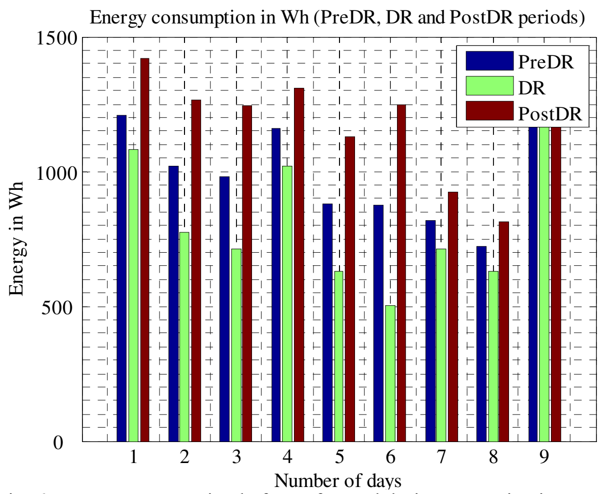

Fig. 6 Energy consumption before, after and during DR activation

The time periods for the Pre DR and Post DR periods were taken 3 hours similar to the DR activation period. From the Fig. 6, it is evident that there is an energy reduction on DR activation by elevating the temperature of the fridge cool chamber. The reduced energy is consumed back in the Post DR period as a payback. The aggregated estimated and actual energy consumption is shown in the Fig. 7. For most of the days, the estimation is close to the actual consumption. The error percentage in the aggregated energy estimation is shown in Fig. 8. The error in estimation is less than 10 % for all of the days. The percentage error in each cooling cycle time prediction of every individual fridge during the DR activation time is calculated from their actual cooling cycle time and presented in the Fig. 9. The number of cooling cycles between the fridges and between different days will depends on their individual thermal mass and system dynamics.

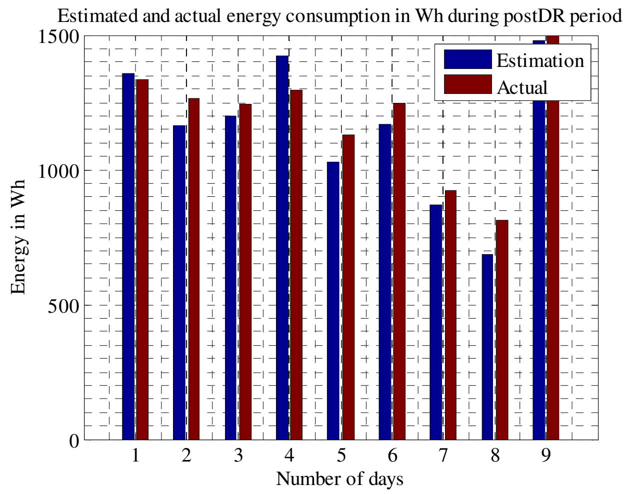

Fig. 7 Estimated and actual energy in Post DR period

In total, there are 118 cooling cycles during DR activation period from the fridges those participated in the experiment. The percentage error in each cooling cycle is very less. The histogram of cycle by cycle prediction error is shown in Fig. 10. The maximum error is 4.67. The mean value of percentage prediction error is 0.35 and the standard deviation is 2.5.

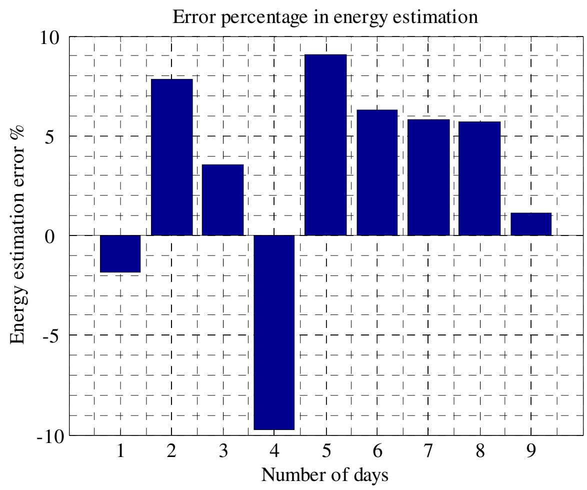

Fig. 8 Energy estimation error in of energy in Post DR period

Out of 118 values, 3 were very high which were around 10%, 11% and 25% respectively. Such huge error was due to temperature measurement data loss during the last cooling cycle before DR activation period. Those values were excluded for the statistical test, as they don't fit in the set under test. TABLE II shows the maximum, minimum, mean and standard deviation of the errors.

TABLE II
CYCLE BY CYCLE ESTIMATION ERROR

Number of cycles	Maximum	Minimum	Mean	Standard Deviation
118	4.67	-1.00	0.36	2.76

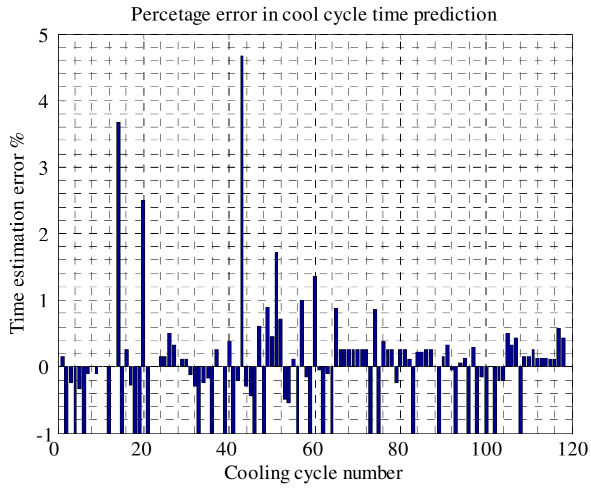

Fig. 9 Time estimation error in each cooling cycle during DR period.

Though the prediction error in the individual cooling cycle is very less, the error in aggregated energy estimation is higher. This is due to the additional compressor operation for short durations on fridge door openings. The controller activates the power to the refrigerator to illuminate the light bulb when the user opens the refrigerator's door. This power activation also starts the compressor.

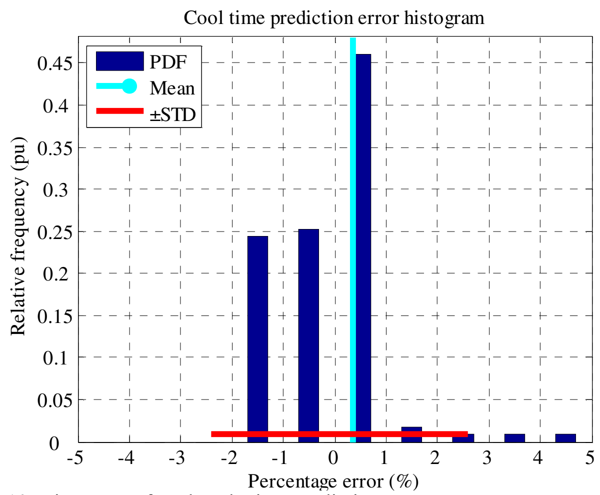

Fig. 10 Histogram of cool cycle time prediction error

The activated power is not cut-off for 5 minutes, to avoid multiple compressor start-ups, if the door is opened multiple times with in these 5 minutes.

VI. CONCLUSION

This papers main idea is to estimate the energy shift by demand response activation on set of fridges in real domestic household. The amount of energy shift is estimated by estimating the consumption by the fridges on operating elevated temperature band. The method used is a simple and produces results with error limit of ± 10 % in energy estimation on nominal conditions. The user interactions and change in refrigerator dynamics influence the estimation and push the error limits away from zero. This method is suited best for field experiments in which large numbers of domestic fridges are controlled. Operating the fridge in an elevated temperature band definitely reduce its energy consumption. At the same time the reduced consumption is paid back once the control is released. The estimation of cool and heat cycle duration can help to identify the time at which the compressor will be ON and OFF, which can be used to find available power with the population of fridges at any time. By identifying the available power at any time, a further study can be done to utilize these fridges for network congestion management. Another possible study can be to utilize these fridges for voltage and or frequency control in an island distribution grid.

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A3: Provision of secondary frequency control via demand response activation on thermostatically controlled loads: Solutions and experiences from Denmark

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Provision of secondary frequency control via demand response activation on thermostatically controlled loads: Solutions and experiences from Denmark

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Abstract

This paper studies the provision of secondary frequency control in electric power systems based on demand response (DR) activation on thermostatically controlled loads (TCLs) and quantifies the computation resource constraints for the control of large TCL population. Since TCLs are fast responsive loads, they represent a suitable alternative to conventional sources for providing such control. An experimental investigation with domestic fridges representing the TCLs was conducted in an islanded power system to evaluate the secondary frequency control. The investigation quantifies the flexibility of household fridge performance in terms of response time and ramp-up rate, as well as the impact on fridge temperature and behaviour after the control period. The experimental results show that TCLs are fast responsive loads for DR activation, with the average control signal response time of 33.5 seconds comparable with the response requirement for primary frequency control.

Keywords: Secondary frequency control, demand response, domestic energy resources, flexible electricity demands, smart grid.

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Abbreviations

AGC: Automatic generation control
BRP: Balance responsible party
COP: Coefficient of performance
DR: Demand response
DSO: Distribution system operator
EWH: Electric water heaters
HVAC: Heating ventilation and air conditioning
ICT: Information and communications technology
RES: Renewable energy sources
SLA: Service level agreement
TCL: Thermostatically controlled load
TSO: Transmission system operator
V2G: Vehicle to grid

1. Introduction

In electric power systems, frequency control relies on the balance between generation and demand. Frequency must always be maintained within the admissible range of its nominal value [1], since it affects the performance and life expectancy of the power system components. For example, the frequency has a direct impact on the speed of asynchronous machines at the demand side and causes a reduction in their efficiency and life span. In modern power systems, electricity production follows demand, and frequency stability is achieved by controlling the generation. As an electric power network grows in capacity and area, its operation is managed by multiple parties: power production by different power plant owners, power distribution by distribution system operators (DSOs), and power system balance by transmission system operators (TSOs). Frequency control in a conventional electric grid can be classified into primary, secondary and tertiary components. Primary control is achieved via the droop control of the generators [2]. Power plants are responsible for providing primary control as per the response time specified by the TSOs' grid code. As any additional demand must be supplied immediately in order to arrest further frequency deviation, the primary frequency control acts typically within seconds [2], [3]. Secondary frequency control restores the frequency to nominal system frequency, i.e. the steady state error in the frequency is eliminated. Secondary frequency control is achieved by TSOs through automatic generation control (AGC) [4]. The TSO establishes contracts for secondary frequency control with balance responsible parties (BRP), who must then obey the TSO's AGC signal. Each BRP's production facility must also comply with the ramp rate specifications of the grid code provided by the TSO. An illustration of frequency deviation and frequency control by different reserves is shown in Figure 1 [5]. As shown in the figure, secondary reserves are activated in minutes to upregulate the frequency to the nominal frequency.

In recent years, the adverse impact of greenhouse gases on the environment has created an awareness to reduce carbon footprints in every part of the world. For example, Denmark has the goal of fossil-free energy usage in every sector, including transportation, by the year 2050 [6]. As energy industries are being pushed to reduce carbon footprints, the focus for energy sources is shifting towards green and environmentally friendly renewable energies. Future power systems will thus have to cope with the high penetration and participation of renewable energy sources (RESs). RESs such as solar and wind are ephemeral due to their nature and this is reflected in their production [7]. One very obvious option is to balance RES fluctuations via the use of conventional generation units, while a second option would be to adjust the demand side to match production. Demand response (DR) is typically employed to improve power system efficiency in such scenarios [8], with the end consumer motivated to adjust their demand in response to a signal, such as control/price signal.

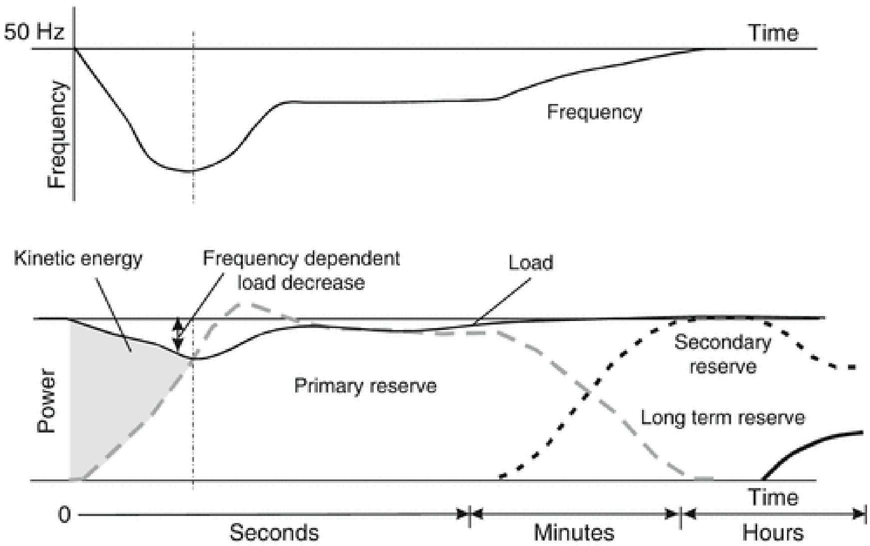

Figure 1. Primary and secondary frequency control and their response times.

DR programs mainly focus on three sectors: industrial, commercial and domestic [8]-[10]. In the industrial and commercial sectors, the demand that could be adjusted by a single entity is very large in comparison to that in the residential sector [11]. The focus in the industrial sector is placed on improving efficiency and energy shift from one time of day to another [8]. For power system stability control via DR, a requirement for load reduction may occur at any time and thus loads must respond sufficiently rapidly to meet the control time requirements. Here the residential sector could provide support; although the demand adjusted in a single household is very small, the total aggregated demand from multiple households will be large [12]-[14]. For power system operators such as TSOs, it is a challenge to aggregate small loads from multiple consumers and remain in control. A new type of business entity known as an aggregator can act as a bridge between power system operators and consumers [15]-[17] by installing the required infrastructure for appliance control at the consumer premises, and trade the available capacity with the TSO. Aggregator consumer commitments are covered by a service level agreement (SLA) between two parties [18], [19], with the aggregators delivering the service provided by the BRP by reducing the load based on the application of DR on consumer controllable loads. An illustration of aggregators playing the role of BRPs is shown in Figure 2, which represents a simplified scenario of power system set-up with demand side management as presented in [20].

The service offered by appliances to consumers should not be affected even if their operation is interrupted by power system stability control processes, such as secondary frequency control. Thermostatic controlled loads (TCLs) such as heating ventilation and cooling (HVAC) and electric water heaters (EWH) are considered highly suitable for such applications [21], [22] due to their fast response [23] and their ability to provide thermal inertia with thermal storage. Chillers in both commercial and residential buildings are examined for use in smart grid DR application in [24], while refrigerators are easy to work with in order to analyse and validate TCL DR application for smart grid purposes [25] – [31]. In terms of Danish electricity demand, refrigerators and freezers contribute 18% of total domestic electricity demand and are regarded as important demand responses in the smart grid [32]. A black-box model [26] and a grey-box model [31] of refrigerators have been developed for smart grid application and their flexibility for DR application are analysed in [27], [31]. Simulation studies investigating grid frequency stability with respect to residential TCL appliance demand response are presented in [25]. In a simulation study presented in [29] and [30], refrigerators are considered for the management of RES supply fluctuation.

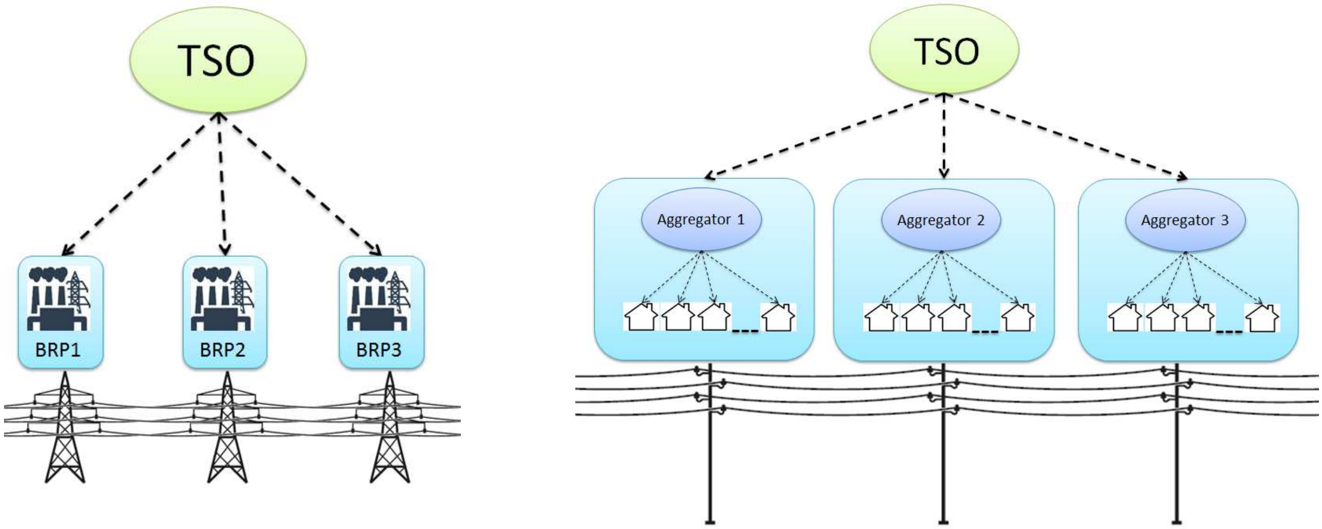

Figure 2. Secondary frequency control with AGC of BRP units and with DR activation by different aggregators.

The aim of the present work was to investigate the potential of secondary frequency control via DR activation on TCLs, using domestic refrigerators as an example. The investigation expected to quantify the flexibility of household TCL performance in terms of response time and ramp up rate, as well as the impact on TCL temperature and behaviour after a control period. An experimental investigation with domestic fridges used by real customers was conducted, taking into account the unknown users' behaviour, with the adaptive fridge model presented in [26] used to predict fridge behaviour for their selection and subsequent control.

The rest of this paper is organized as follows. Section 2 introduces the developed method of secondary frequency control and an outline of the studied problem. Section 3 presents the experimental platform, the hardware devices used for control and measurement, and their configuration. Section 4 provides a detailed discussion of the control strategy, practical limitations and safety constraints. The results of the experiments are reported in Section 5 and discussed in Section 6, and conclusions and future work are reported in Section 7.

2. Methodology

A refrigerator is essentially a climate- (in this case temperature-) controlled box containing a thermally insulated chamber (cool chamber) fitted with a compressor to pump heat and a thermostat to control compressor operation. The thermostat maintains the temperature inside the cool chamber between two limits, namely T_{max} and T_{min}. When the temperature is above T_{max}, the thermostat switches the compressor ON; the compressor then pumps heat from the cool chamber to the ambient and the temperature inside the cool chamber is reduced. As the temperature decreases to T_{min}, the thermostat switches the compressor OFF; the temperature inside the cool chamber then starts to increase due to heat flow from the ambient into the cool chamber through the walls and during refrigerator door opening for food exchange. The duration of these thermostatic cycles for heating and cooling depends on many parameters. For example, the cooling cycle length required to reach T_{min} from T_{max} depends on compressor power and its coefficient of performance (COP), ambient temperature, the refrigerator wall's thermal insulation, and the thermal mass of the cool chamber's content. The duration of heating required to reach T_{max} from T_{min} depends on the same parameters as above with the exception of those related to the compressor. As a refrigerator has the ability to store the temperature effect with its thermal inertia, this can be used to provide secondary frequency control.

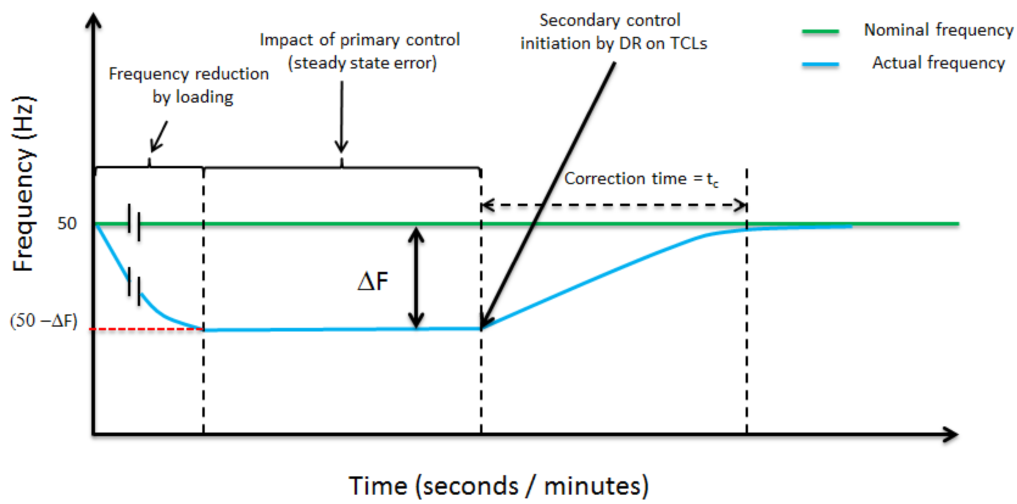

Figure 3. Illustration of secondary frequency control via DR activation.

The method described here introduces load disturbance into a balanced islanded system in order to create steady state frequency error, as shown in Figure 3. The frequency controller reduces the load by switching the refrigerators OFF to perform secondary frequency control and thus bring system frequency back to the nominal value. The time required for the frequency to attain its nominal value depends on the inertia of the power system and the load imbalance, with the greater the load reduction, the smaller the amount of time required to restore the frequency. The proposed method reduces the load in steps. In order to sustain the effect of load reduction, refrigerator selection is based on their ability to stay OFF for longer. Refrigerator OFF time is calculated using the black box model described in [26], which considers the temperature curves of the thermostatic cycles as piece-wise linear, and uses the slopes of temperature curves from previous thermostatic cycles to predict the present cycle's OFF time. The black box model is a generalised model for any TCL and has been validated for different types of refrigerator [26], with model prediction errors within 5% under normal conditions [27]. The control procedure for secondary frequency control is given in the following Algorithm 1.

Algorithm

Initialisation:

```
mark all fridges not active for service
create an empty scheduling queue
```

Procedure 1:

```
for all fridges{
        get fridge cool chamber temperature
        if fridge is activated for service{
```

```
                    if temperature above T_max{
                            turn the fridge ON
                    }
            }
            else{
                    put the fridge into the scheduling queue
                    sort scheduling queue descending by length of OFF time
            }
    }
Procedure 2:
if frequency is lower than the 50 Hz{
    mark power reduction of 300 W
    while power reduction is larger than 300 W{
            get the first fridge from the scheduling queue
            mark the fridge to be activated for service
            subtract the fridge power from the power reduction
    }
}
```

Algorithm 1. Frequency control algorithm.

The controller runs two procedures in parallel: Procedure 1 manages refrigerator operation and procedure 2 manages the frequency control by selecting fridges to be turned off in order to deliver the power reduction.

3. Experimental procedure

The experimental setup used for secondary frequency control is explained in this section, including details of the test grid formed, a description of the information and communication technology (ICT) infrastructure supporting the experiment, and a description of the collected measurements.

3.1. Experimental setup

The experiment was designed to study secondary frequency control by controlling refrigerators. Regarding frequency deviations, especially for those toward low frequencies, balance responsible parties were asked by the TSO to provide the additional power required to bring the frequency back to the normal value. The power flow in the Nordic synchronous zone, of which Denmark is a part, is close to 45 GW [33], with the DK1 region (Western Denmark) possessing a generation capacity close to 6000 MW and a power regulation capacity close to 750 MW [34]. The regulation capacity available for the refrigerators participating in the experiment was 1.25 kW, which is negligibly low in comparison to the DK1 power grid capacity and thus it was not feasible to visualise the frequency restoration process with the refrigerator control if the experiment was conducted using the grid connection. Therefore, the experiment was conducted in an islanded grid with a capacity of 12 kW, which is comparable to the available refrigerator regulating power of 1.25 kW. The experiment was conducted in an islanded LV network in the SYSLAB facility at the Technical University of Denmark (DTU), with a vanadium battery bank as the load and a 50 kVA diesel generator as the source. A network configuration block diagram is shown in Figure 4. The SYSLAB islanded low voltage grid is formed by connecting two busbars in series to a 200 kVA distribution transformer through a circuit breaker, which is opened in order to island the system. Busbar 1 has a 50 kVA diesel generator and the 200 kVA transformer, while busbar 2 has a vanadium battery in order to emulate refrigerator consumption and to provide base load and load variations.

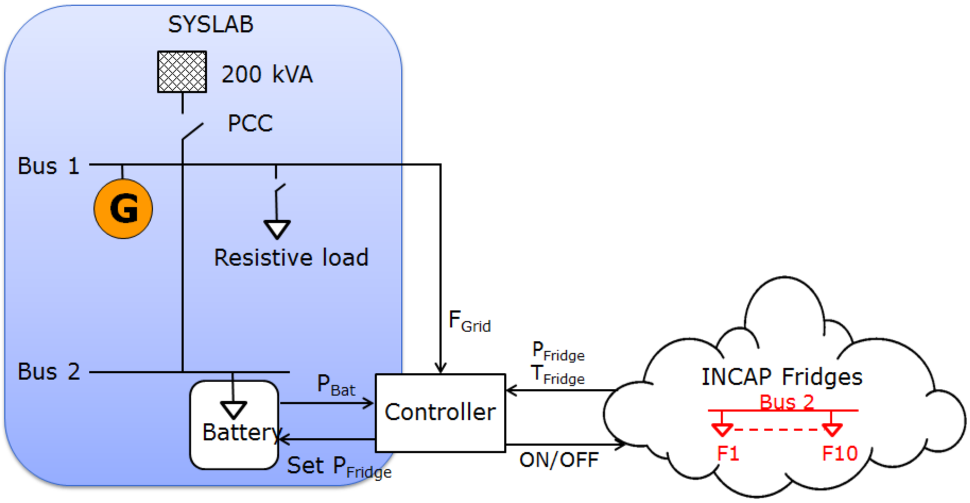

Figure 4. Block diagram of the experimental setup.

3.2. Refrigerator emulation in the SYSLAB LV island network

In project INCAP, an ICT infrastructure for the real-time measurement and control of the temperature and power of domestic fridges located in real households in Denmark is implemented. As the real time measurement and control of fridges is viable, those fridges can be emulated in the SYSLAB LV grid by the vanadium battery.

Refrigerator emulation is carried out by changing the vanadium battery charging set point with the aggregated power consumption of all refrigerators, with the latter value calculated by summing the active power measurements sent via relay unit to the INCAP server. Data flow from every household participating in the INCAP project to the INCAP server is shown in Figure 5.

3.3. INCAP fridge data and control access

The devices connected to each refrigerator participating in the INCAP project are shown in the block diagram presented in Figure 6, with the control, measurement and user interface devices listed as follows:

1. Control device: A ‘relay unit’ with a power measurement function is used to control the refrigerator. The relay unit not only switches the refrigerator ON and OFF in response to the respective command from the remote computer, but also has the ability to measure and transmit active power, voltage and current.
2. Sensor: A temperature sensor is used to measure the temperature of the fridge cool chamber.
3. User interface: A user interface device with red and green lights and two buttons is used to communicate with the user.
4. Communication device: All of the above devices use Zigbee wireless protocol for communication. A Zigbee Ethernet gateway device enables interaction between these devices and the remote server.

All of the above devices are commercially available from Develco Products A/S, one of the official partners of project INCAP. An ADSL home Internet connection is used to establish communication with the control server. Two of the devices, namely the temperature sensor and the user interface device, are battery powered, while the other two are mains supply powered. Device installation is simple and can be carried out by the refrigerator owner. Upon installation, devices identify the control centre server and obtain authorisation to join the Zigbee network.

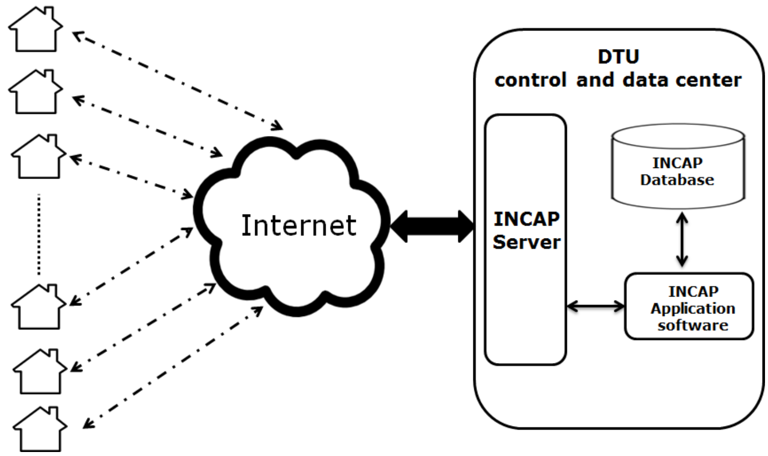

Figure 5. Data flow from fridges to controller.

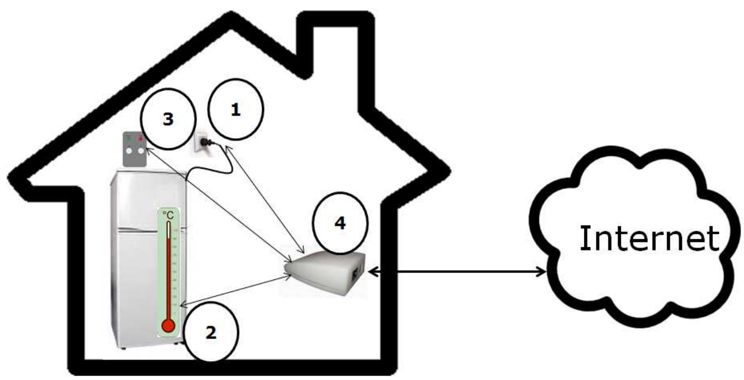

Figure 6. Refrigerator control device installation in a house.

3.4. Measurement parameters and sampling rate

As the temperature sensor is battery operated, the manufacturer preconfigured the transmission rate. The temperature sensor is configured to transmit temperature measurements at 2-minute intervals, which is considered sufficient as refrigerator temperature changes very slowly due to thermal inertia. The temperature sensor has an accuracy of ±0.5 °C. Active power consumption by the refrigerator is measured by the relay unit at 1 watt resolution every 10 seconds.

SYSLAB grid power measurements: SYSLAB is equipped with the multi-instrument MIC-2 (DEIF A/S) for all grid parameter measurements. MIC-2 has a standard Ethernet interface, which is here connected to the SYSLAB SCADA system, and is classified as belonging to accuracy class 0.2. SYSLAB SCADA can be polled for power measurements of the diesel generator and vanadium battery bank, as well as the frequency of the island network. Each measurement in SYSLAB is recorded every second.

4. System set up description

4.1. Islanded system set up

The balanced islanded network comprises a diesel generator running in fixed power mode and with the loads matching the power production. Initial system balance is achieved via the following steps:

1. The SYSLAB LV network is connected to the external grid.

2. The loads are configured for a consumption of 12 kW.
3. The generator is started, with a fixed power output set point of 12 kW.
4. Islanding - Once the generator is stabilised with the configured power production, the circuit breaker to the external grid is opened to form the islanded network.

In order to study secondary frequency control based on TCLs, the frequency must drop and stabilise at a lower value due to additional load in the network. It is assumed that the primary frequency control manages to supply additional power to stabilise the frequency at a lower value without allowing any further frequency drop. Primary control can be realised by limiting the additional load duration until the frequency is lowered to the required value. Other than the additional load serving a disturbance, the system must be in balance.

The aggregated power from the refrigerators varies as the status of individual refrigerators changes with their temperature and thermostat status. Considering the small population of refrigerators in the system, the change in aggregated power is sufficient to disturb system stability. Therefore, a base load with variations is added to keep the total load value constant. The base load is retained with the last value before the secondary frequency controller is started.

4.2. Controller description

The controller has two functions: 1) Refrigerator emulation as described in section 3.2; 2) System balance and frequency restoration. The frequency correction loop of the controller runs at 30-second intervals. During frequency correction, the controller calculates the difference between system frequency and nominal frequency (50 Hz). If the former is less than 49.5 Hz, load reduction is initiated. For load reduction, the controller switches off the refrigerators one by one until the specified reduction limit is reached. The order of refrigerator selection is based on their ability to stay OFF without violating the temperature limit, with that able to remain OFF for the longest time being selected first. The length of time a refrigerator can stay OFF is predicted by using the refrigerator model described in [26].

The model uses the slopes of the temperature curves when the compressor is ON and OFF to predict the length of OFF time. These slopes are derived from the most recent compressor cycles, which are identified based on power consumption. Unlike the compressor, the refrigerator light bulb and electronic controllers consume only a few watts of power; as a result a 30-watt threshold is used to separate compressor power consumption from that of the refrigerator auxiliaries.

4.3. Control task timings

During the first 10 minutes after initiation, the controller program executes those tasks related to refrigerator emulation, base charging value adjustment for system balance, OFF time calculation for active refrigerators, and resource queue preparation. These first 10 minutes are required in order to prepare the islanded network, to lower the system frequency, and to collect refrigerator temperature and power data. The battery charge set point is adjusted every second with the aggregated value of power measurements received from the refrigerators. The OFF time calculation for active refrigerators is carried out for every temperature measurement update received from each refrigerator. After the 10 minutes have elapsed, frequency control is activated, with the estimated maximum time delay for control action being 20 seconds, and 30 seconds allowed for the power system to respond to the load change. Therefore, frequency correction is carried out at 50-second intervals.

5. Experimental results

The experiment was conducted using 25 refrigerators with a total compressor power consumption capacity of 2500 W. Due to their thermostatic cycles, some of the refrigerators were OFF. Average power consumption was around 1250 W, with power reduction planned in steps of 300 W, or around 25% of the available load for control. Before starting the experiment, refrigerator temperatures and power consumption were recorded until at least one thermostatic cycle of all refrigerators was completed. This observation was necessary in order for the black box model to calculate the switch OFF time for each refrigerator upon receiving the temperature measurement from the corresponding refrigerator. The vanadium battery and controllable resistive load were then connected to the SYSLAB network, with the controller program initiated to emulate refrigerator consumption by changing the vanadium battery's charging set point. The diesel generator was configured to produce fixed power at 25% of generator nominal capacity of 48 kW, or 12 kW, and was connected to the network for synchronisation to the nominal power system frequency of 50 Hz. As the aggregated power consumption of the refrigerators was close to 10% of the generator set point (i.e., 1.2 kW), a base, constant charging value was added. After the synchronisation of the generator with the grid frequency, the SYSLAB network was islanded from the external grid.

5.1. *Controlled frequency reduction*

Once the network was islanded, the system frequency was brought down via additional loading, with the controllable resistive load set to consume 1 kW for 60 seconds. Based on a fixed power set point, the generator droop controller was disabled, causing the frequency to drop. In the power system, as the load increases, the system frequency starts to decrease. The primary reserves produce the additional power on load variations and thus the system frequency stabilises at a lower value rather than reducing further. In the experimental set up, there was no primary reserve. Therefore, the controllable load was manually disabled as soon as the system frequency reached 49 Hz. At this instant the system was in power balance in terms of production and consumption, and the system frequency was stable at the lower value.

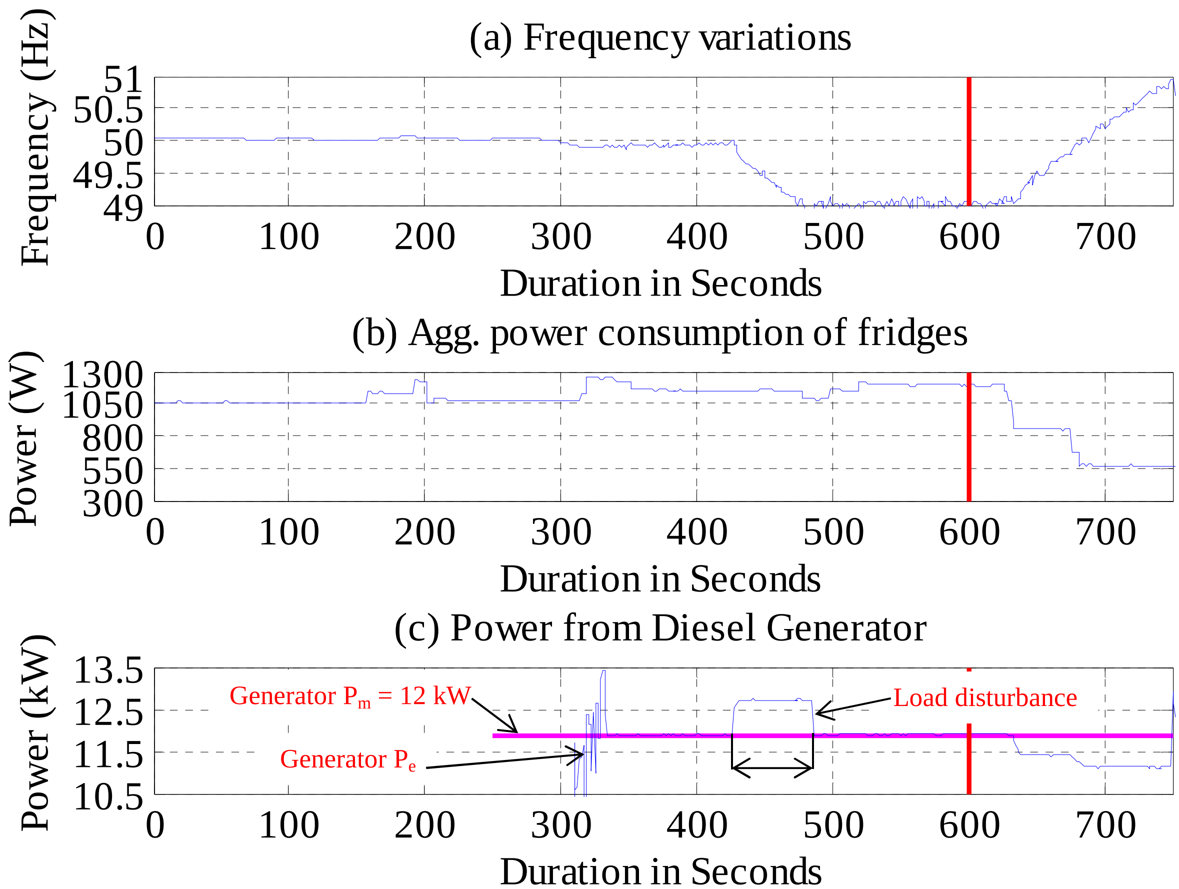

Figure 7. System frequency, aggregated fridge power, and generator production.

5.2. Secondary frequency control

The control action for secondary frequency control was initiated after 600 seconds, with the controller checking the difference between system frequency and nominal frequency (50 Hz). If the difference was greater than 0.05 Hz, a 300 W load reduction was scheduled. Fridges were prioritised according to their OFF time, with the longer the OFF time the higher the priority. Those refrigerators corresponding to the power limit of 300 W were marked OFF, and the switch off command sent in response to the reception of power measurement data. The maximum round trip delay in sending the command, receiving the updated power measurement value and the change in battery charge power set point value was 20 seconds. After the load reduction, a 30-second response time was allowed for the system to respond to the frequency control. The frequency control loop was executed at 50-second intervals.

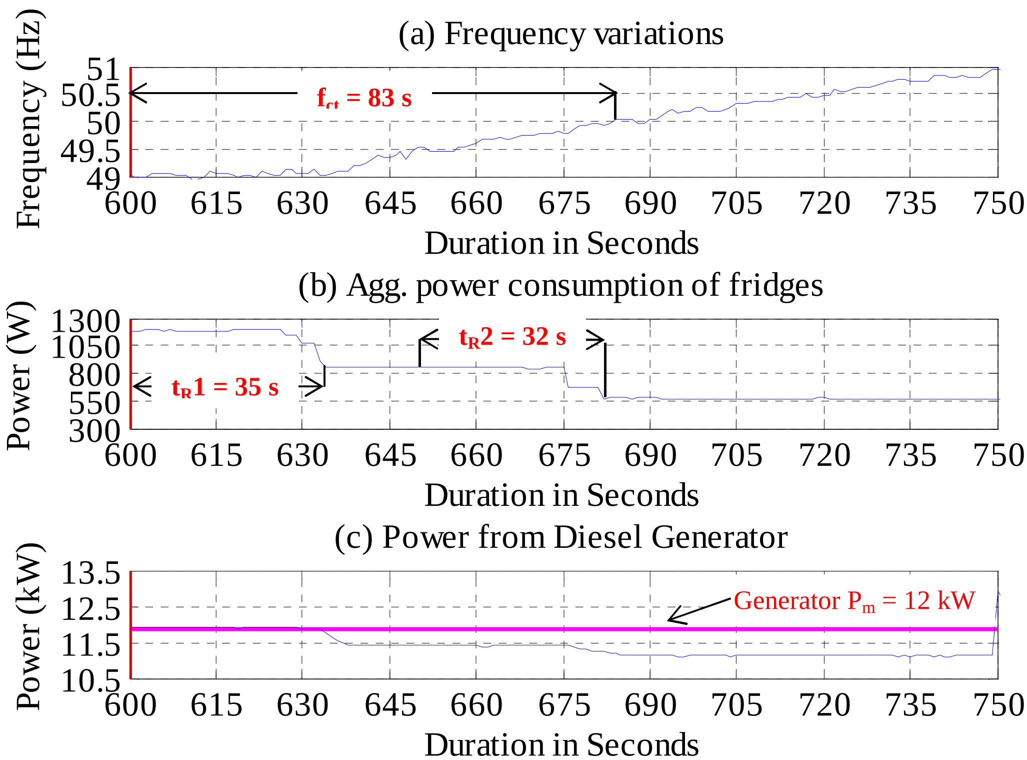

Figure 8. Close-up view of the secondary frequency control period.

5.3. System response

The power system parameters during the experiment are shown in Figure 7, in which plot – (a) shows the system frequency, plot – (b) the generator power output, and plot – (c) refrigerator power consumption during the experiment. At between 400 and 500 seconds, the system was loaded with an additional load of 1 kW, as seen in plot - (c) (Power output from Diesel Generator) of Figure 8. System frequency decreased, with the length of time required for a decrease of 1 Hz being 60 seconds. Frequency correction took place in two steps, as shown in Figure 8. In the first iteration, although the target power reduction was 300 W, the actual reduction was 350 W due to the granularity of the aggregated power. This granularity was, however, limited to the last refrigerator compressor power capacity selected for load reduction in each frequency correction iteration. The round trip control delay or response time for the first correction iteration is marked as t_R1 in Figure 8, and was here equal to 35 seconds. As the frequency did not reach the threshold limit after the delay of 30 seconds, the second correction iteration was initiated. The power reduced after the second iteration was 275 W, with the round trip control delay or response time for the second correction iteration marked as t_R2 in Figure 8 and equal to 32 seconds. Thus, the total time required for the system to restore a nominal system frequency of 50 Hz was 83 seconds, shown in Figure 8 as f_{ct}.

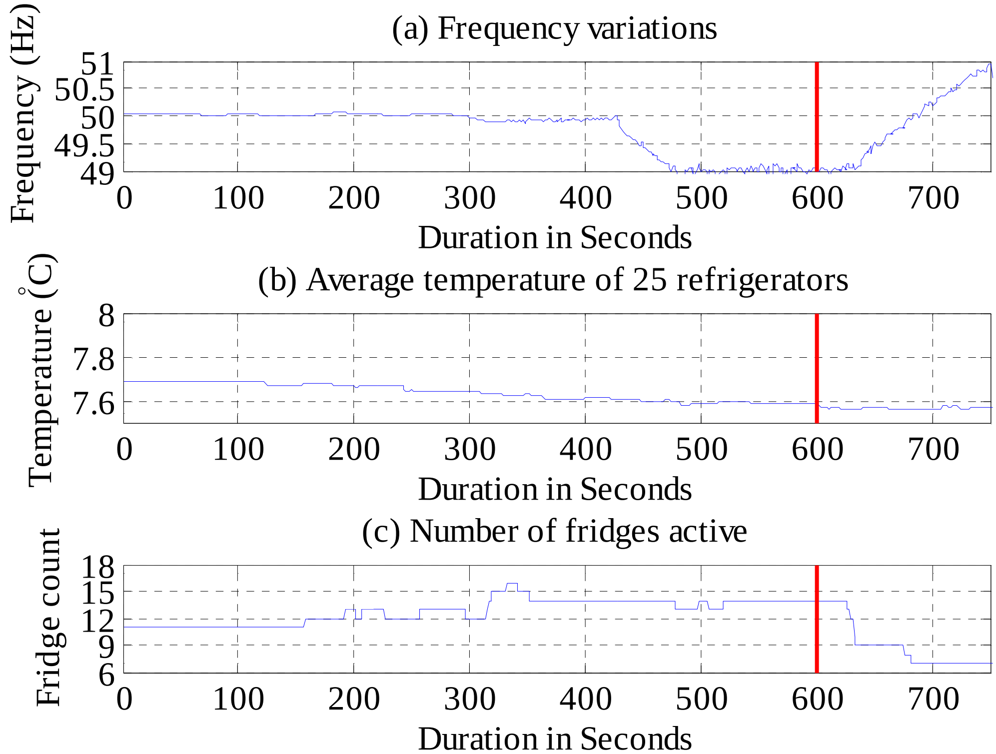

Figure 9. System frequency, instantaneous temperature average, and number of active fridges.

6. Discussion

6.1. Response time

The response time is calculated as a total time in seconds between the time instants of the control action initiation and the time instant when the vanadium battery power consumption reaches the stable value after power reduction as marked in the plot – (b) of Figure 8. The response time can be broken in to three parts as a. Controller delay, b. Command dispatch delay and communication delay over internet, and c. Status update delay and.

a. Controller delay

The frequency controller compares the measured frequency value with the nominal value and marks the refrigerators to be switched off in the scheduling queue maintained controller. The switch-off commands are dispatched to the individual refrigerators as a response to their power measurement message.

b. Command dispatch delay

The maximum command dispatch delay is the refrigerator power measurement sampling rate (10 seconds in INCAP experimental setup), as the power measurement messages are used as the resource (refrigerator) status check message. The communication delay over internet is within 1 second.

c. Status update delay

The status update delay includes the communication delay over internet, the next measurement update from the refrigerators and the island power system response.

6.2. DR resource upscaling

When the system is used with higher population of refrigerators, the performance of the temperature prediction algorithm and the resource sorting algorithm will increase with the number of refrigerators. A simulation study with different large number of refrigerator populations are carried out and the performances are mentioned in the following Table 2. The refrigerators' temperature cycle length is assumed with a maximum value of 60 minutes to calculate the performance of temperature prediction algorithm. The resource sorting method used here a simple method to sort an array of number corresponding to the number of refrigerators. The maximum sorting time is simulated by reversing the array with ascending numbers representing the resource flexibility (switch-off time). Though the computational power of the computer used is a major factor for computational delay, the calculated times will give an indicative representation.

Table 1. Computational delays

Number of fridges	Time for temperature prediction [ms]	Time for resource sorting [ms]
1,000	1	5
10000	2	80
100000	5	7609
1000000	21	906146

The time required for sorting the resources is increasing exponentially with the increase in the number of refrigerators. Therefore, the sorting technique used and number of times the resource sorting is carried out in a scenario of large population refrigerators will be one of the major factors determining the performance.

6.3. Control impact on fridge temperature and population

Figure 9 displays, along with the frequency variations, the number of refrigerators active during the experiment and the instantaneous temperature average of all 25 refrigerators. As shown in plot – (c) of Figure 9, 14 refrigerators were active during the experiment, and 7 were switched OFF upon the first iteration of power reduction during frequency correction. At the second iteration, 2 more refrigerators were switched OFF. The instantaneous temperature average of all refrigerators, shown in plot – (b), continued to follow the trend of decreasing temperature. The cool chamber temperatures of all refrigerators participating in the experiment are shown in Figure 10, in which the controller activation time is marked by the red vertical line and cool chamber temperatures shown 200 seconds after the control period. As the control period was very short, refrigerator cool chamber temperatures did not show any appreciable change due to the thermal mass and thermal inertia of the refrigerator contents. Therefore, the trend in the instantaneous temperature average also did not vary. As the control period was very short, refrigerator cool chamber temperatures did not show any appreciable change due to the thermal mass and thermal inertia of the refrigerator contents. Therefore, the trend in the instantaneous temperature average also did not vary.

6.4. Ramp rate performance and gird code requirements

Table 2 lists the performance parameters of the secondary frequency control experiment, as well as the secondary frequency control requirements for the western Denmark power system (DK1). The average control response time of the two power reduction iterations of 33.5 seconds is comparable to primary frequency control parameters. Primary frequency control in the Danish power system (DK1) requires production to be increased by 50 % in 15 seconds, with 100 % capacity reached in 30 seconds in the scenario of up-regulation. Although the power reduction obtained in the conducted experiment was 25 % for each correction step, it is possible to achieve 100 % reduction within the same response time. The ramp rate required for secondary frequency control by different fuel-based steam power plants is in the range of 2 to 4 % per minute for a power capacity range of 20 to 100 %, with the highest requirement associated with diesel engines at 20 % per minute for a power capacity range of 20 to 100 %. The ramp rate requirement for gas fuel-based power plants (gas turbines, gas engines and gas fired combined cycles) is 10 % per minute for a power capacity range of 20 to 100 %. During refrigerator secondary frequency control, the ramp rate obtained here was 41.2 % per minute. It is possible to activate all refrigerators at the same time, representing a 100 % load reduction in the same 33.5-second response time (179 % per minute ramp rate).

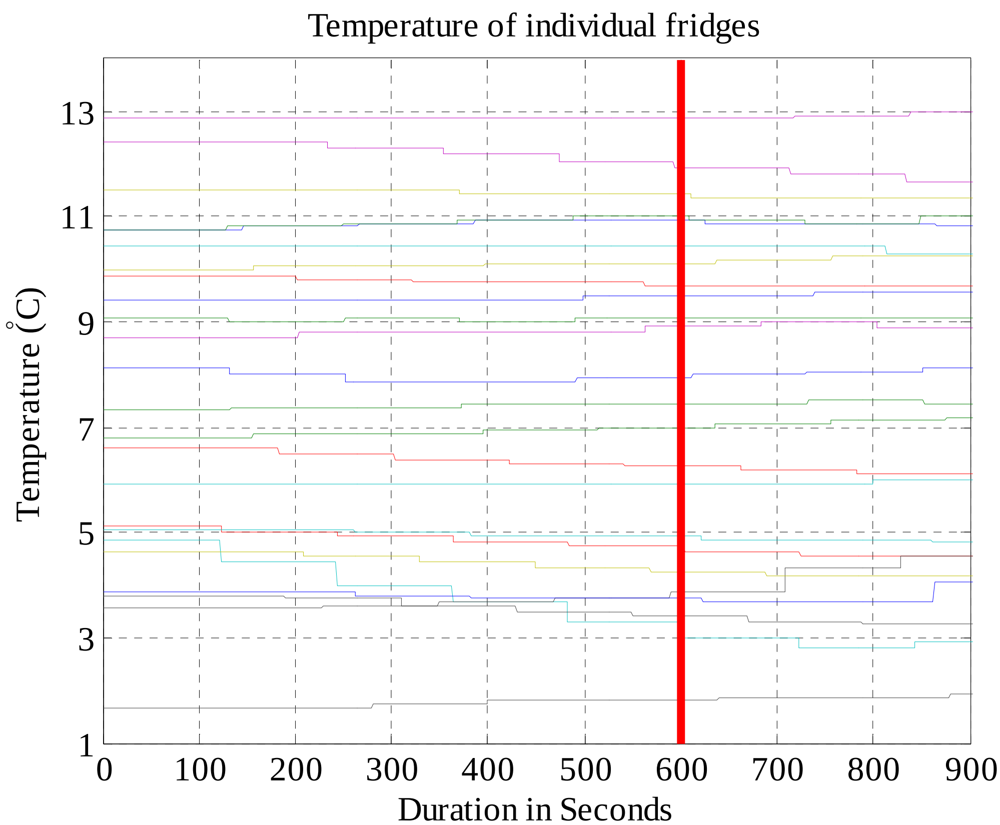

Figure 10. Temperature of each refrigerator, as represented by the different coloured lines.

Table 2. Effect of control on aggregated refrigerator power.

Parameter	Secondary frequency control	
	Experimental values	Grid code for DK1 [35]
Average control response time [s]	33.5	900
Ramp rate [%/minute]	41.2	10 (Gas 20-100%) 20 (Diesel 20-100%)

The refrigerators require a switch ON delay during a power cycle in order for the back pressure in the evaporator to be discharged, with the duration of this delay ranging from 5 to 15 minutes depending on the size of the refrigerator unit. If the delay is not maintained, the compressor will consume a high startup current for a longer duration due to the compressor split phase asynchronous motor construction and the high startup torque requirement. Such high startup current may cause long-term motor winding damage due to overheating. This scenario creates limitations on control signal withdrawal after the system frequency reaches the nominal value; primary frequency control in the generation units should thus possess down regulation capability in such situations. The compressor motor consumes inrush current, which is typically 5 times maximum load current, for several seconds when it is switched ON. Therefore, compressor switch ON synchronisation should be avoided after control signal withdrawal, as their aggregated impact may produce unwanted transients in the power system.

7. Conclusions and future work

This paper studied secondary frequency control via DR activation on TCLs using an experiment involving refrigerators in real domestic households as an example. The results revealed that the average control signal response time was 33.5 seconds, considerably lower for secondary frequency control and comparable to that for primary frequency control. The ramp rate achieved was 41.2 % per minute, or almost twice that of diesel engine power plants, which are considered to have the highest ramp rate of any power plant type. Furthermore, it is possible to achieve 100 % load reduction in 33.5 seconds, which corresponds to a ramp rate of 179 % per minute. The obtained response time and ramp rate values demonstrate that TCLs can be considered rapid responsive loads for DR activation and can be utilised for power system control operations. Because of the minimum switch-off time requirement of the running TCL compressor, it is disadvantageous to switch it ON immediately after frequency restoration. In large populations of compressor-operated TCLs, the minimum switch-off time requirement can be solved using a better control algorithm. Such a problem will not arise with resistive loads such as space heaters and water heaters. The temperature prediction method is best suited even for a large population of TCLs. But the sorting method has to be optimized for the large population of TCLs. Further investigations will focus on the combined study of primary and secondary frequency control, including the analysis of vehicle to grid (V2G) electric vehicles and DR activation on TCLs.

Acknowledgements

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A4: Experimental analysis of flexibility change with different levels of power reduction by demand response activation on thermostat-controlled loads

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Experimental analysis of flexibility change with different levels of power reduction by demand response activation on thermostat controlled loads

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Abstract

This paper studies the flexibility available with thermostatically controlled loads (TCLs) to provide power system services by demand response (DR) activation. Although the DR activation on TCLs can provide power system ancillary services, it is important to know how long such services can be provided for when different levels of power reduction are imposed. The flexibility change with different levels of power reduction is tested experimentally with domestic fridges used by real customers with unknown user interaction. The investigation quantifies the flexibility of household fridges and the impact of DR activation in terms of deviation in the average temperature. The maximum possible power reduction with the cluster of refrigerators is 67% and the available flexibility with the cluster of refrigerators is 10%. The resulting deviation in the average temperature is 14%.

Keywords: controllable load, demand response, demand side management, domestic energy resources, flexible electricity demands, smart grid.

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Abbreviations

BRP: Balance responsible party
COP: Coefficient of performance
DR: Demand response
ICT: Information and communications technology
QOS: Quality of service
RES: Renewable energy sources
TCL: Thermostatically controlled load
TSO: Transmission system operator
UFLS: Under-frequency load shedding

1. Introduction

The reliability of electric power system operation depends solely on the balance between power production and consumption. In a conventional power system, the balance is achieved by consumption-driven production. In such a scenario, long-term [1] and seasonal [2], [3] load and change forecasting is used to plan new power plants and power production. As the electricity market has become unbundled, one-day-ahead demand forecasting helps to schedule the power procurement [4], [5]. The transmission system operator (TSO) is responsible for the power system balance. The errors in the demand forecast are managed by additional local procurement or consumption at short notice to avoid large deviations from the unit commitments of the power plants [6], [7]. Such services are called ancillary services and are provided by balance responsible parties (BRPs) and the regulating power providers on request from the power system operators. Due to increasing awareness of the negative environmental impacts of greenhouse gas emissions from conventional power plants' exhaust gasses, motivation for the usage of renewable energy resources (RESs) in the electric power system is high. Therefore, the participation and penetration of RESs increases as time goes on. The RES electricity supply varies, as RESs like wind and solar power fluctuate [8], [9]. The fluctuations in the electric power production by RESs need to be compensated either by an additional supply of power from fossil based power plants [10], [11] or by controlling demand to achieve a balance in the power system [12]. Demand response (DR) is a widely accepted operational procedure carried out by power-system operators [13]–[16].

Electricity consumers can be broadly classified into three classes: industrial, commercial, and domestic [17], [18]. The demand adjustment from industrial consumers is large in comparison to the other two segments [18]. Industrial consumers can support only a scheduled demand adjustment, as the machinery used may require a complex start-up and shutdown procedure and skilled manpower to execute the procedures. But the ancillary service requirement of demand adjustment may arise at any time. Domestic and commercial consumers are suitable for ancillary service provision by DR due to their time availability and less complex electrical gadgets, which are easy to control.

In Nordic countries, the share of domestic electricity consumption is 26% [19] and the domestic segment has great potential for DR services [15]. During appliance control, the service provided by the appliance should not be affected by the control event. Such a constraint makes thermostatically controlled loads (TCLs) most suitable for DR applications. TCLs provide a temperature service. The temperature effect is stored in the thermal mass of the TCLs, which can sustain the impact of power reduction. In a single household, the flexibility for demand adjustment may be a small quantity. When the flexibility from multiple households is aggregated, their potential is very high. To manage the massive distributed TCLs, the aggregators can play an important role similar to the BRPs [20]. The aggregator may be a separate entity or a part of the BRP.

When the power system operator requires an ancillary service related to power reduction, the aggregator will serve the request by controlling the loads of the consumers. Under control, the service provided by the loads to the consumer should not be affected or the deviation in the quality of the service should be within the limits guaranteed to the consumers by the aggregator. The service provided by the TCLs is quantified in terms of temperature. Therefore, the deviations in the quality of service at different power-reduction levels can be analysed with the temperature variation. Also, the temperature of the TCL system represents the amount of thermal energy stored within the system, or in other words the flexibility available with the TCL. By predicting the temperature profile, the duration for which the system can support the service of power reduction can be predicted. Therefore, the variation in the available capacity with respect to different levels of power reduction can also be analysed. Further, the maximum possible power reduction by respecting the temperature limits of individual TCLs can be studied and the deviation in QOS can be analysed.

The aim of this work is to investigate the potential and capacity for power reduction by DR activation on TCLs using domestic refrigerators as an example. In Denmark, refrigerators and freezers contribute 18% of total domestic electricity demand and they are regarded as important DRs in the smart grid [21]. Refrigerators are considered for DR study in many research activities [22]–[24]. A simulation study with large-scale control of domestic refrigerators for reduction of peak demand in distribution systems is presented in [22]. In [23], a simulation study to support the primary reserve by under-frequency load shedding (UFLS) is studied. The energy consumption optimization of refrigerators is studied with a grey-box model developed using time series data from experimental measurements in [24].

The investigations of the work presented in this paper quantify the flexibility of household TCLs for DR activation and the impact on TCL temperature. An experimental investigation with domestic fridges used by real customers is conducted which takes into account the unknown users' behaviour. The adaptive fridge model presented in [25] is used to predict the fridge behaviour for control purposes, as the model requires only two measurements and the prediction errors are within 5% [26].

The rest of this paper is organized as follows. In Section 2 the method of flexibility analysis of power reduction with DR activation and the problem outline are introduced. Section 3 explains the experimental procedure, experiment platform, the hardware devices used for control and measurement, and their configuration. Section 4 discusses the control strategy and practical limitations in detail. The results of the experiments are reported in Section 5. The discussion and conclusion are presented in Sections 6 and 7 respectively.

2. Methodology

The refrigerator is a thermally insulated box fitted with a compressor to pump heat out of the box to the ambient. The compressor is controlled by a thermostat. The temperature inside the refrigerator is maintained between two limits, namely Tmax and Tmin, by the thermostat. The thermostat switches the compressor ON when the temperature is above the temperature limit Tmax. The heat from the refrigerator is pumped out to the ambient by the refrigeration system. This causes the temperature inside the refrigerator chamber to decrease. As soon as the temperature decreases to the limit Tmin, the thermostat switches the compressor OFF. As the ambient temperature is higher than the temperature inside the refrigerator chamber, the heat flows from the ambient into the refrigerator cooling chamber through the walls and also during opening of the refrigerator door for food exchange. The heat flow causes the temperature of the cooling chamber to increase when the compressor is OFF. The heating and cooling cycles of the refrigerator can be called thermostatic cycles. The duration of the thermostatic cycle for heating and cooling depends on many parameters. The cooling duration required for the temperature to reach the value Tmin from the temperature value Tmax depends on the compressor power and its coefficient of performance (COP), the ambient temperature, the insulation parameters of the refrigerator, and the thermal properties of the cooling chamber's content (food). The duration of heating required for the temperature to rise from the value Tmin to Tmax depends on the parameters listed above, except for the compressor specifications. As the refrigerator has the ability to store the temperature effect with its thermal inertia, it can be used to provide the power system ancillary services. The method described here controls the refrigerators' state (ON/OFF) in order to keep their aggregated power consumption at a given set-point value without violating the temperature limits of the individual refrigerators. On controlling the refrigerator, one of the constraints is that the temperature Tmax of the refrigerator cool chamber should not be exceeded. The change in the available flexibility provided by the refrigerators can be analysed at different levels of power reduction from the normal consumption.

In the presented control architecture, a central controller for refrigerators collects the temperature measurements and power consumption from all refrigerators. The central controller can predict the temperature of fridges and the duration for which they can be switched OFF or ON without violating the temperature boundaries with the use of a simple black-box model [25]. The black-box model considers the temperature curves of the thermostatic cycles as a piece-wise linear one and uses the slopes of the temperature curves to predict the temperature cycle duration.

In the proposed algorithm, the fridge flexibility is measured by the duration for which the refrigerator can be switched OFF without violating the individual refrigerator's temperature limit. The switch OFF time can be calculated by predicting the temperature inside the cooling chamber. In order to calculate the prediction of the cooling chamber temperature, the fridge's thermal behaviour has to be modelled. The black-box model [25] used in this study requires only two measurements and predicts a cooling chamber temperature close to the actual one when the dynamics of the system are not changing. It is also a generalized model suitable for any thermostatically controlled loads such as space heaters, heat pumps, air conditioners, refrigerators, and so on. Such a model is suitable for experiments with a large number of refrigerators, where the number of parameters measured is limited.

3. Experimental procedure

3.1. Test scenarios

The experiment is conducted for four scenarios with different values of power reduction as shown in the Figure 1.

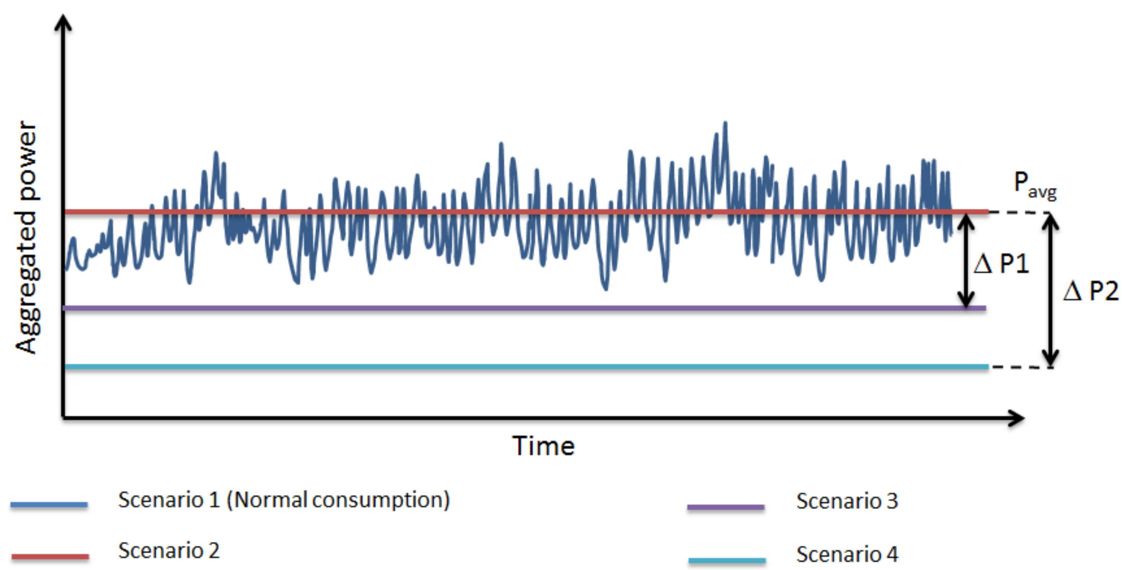


Figure 1. Scenario description.

Scenario 1: Scenario 1 is the base case without any control. The refrigerator power consumption and the temperature were observed for 24 hours. The observation without control gives an idea about the variation in aggregated power consumption with time. The power limitation set-point for the control in the following scenarios is derived from the base case scenario 1.

Scenario 2: In scenario 2, the control objective is to maintain the aggregated power at the average value of power consumption in scenario 1 without violating the temperature limits of individual refrigerators.

Scenarios 3 and 4: Scenarios 3 and 4 are used to understand the limits of the possible power reduction by DR activation on TCLs. The power limits for the controller are set as 50 and 25% of scenario 1 average value in scenarios 3 and 4, respectively.

The proposed method for TCL flexibility analysis is tested with refrigerators in real households with unknown user interaction. The following section introduces the experimental set-up and provides a description of the information and communication technology (ICT) infrastructure supporting the experiment and a description of the gathered measurements.

3.2. *Experimental setup*

The experiment utilized the infrastructure and the refrigerators of the participants in the project INCAP. The INCAP project has established an ICT infrastructure for the real-time measurement and control of temperature and power of domestic fridges in the western part of Denmark for a field experiment. Figure 2(a) shows the experimental set-up. The block diagram in Figure 2(b) shows the devices installed for control and data collection in each household participating in the project INCAP. The devices used for control and data collection are as follows:

1. Relay unit with power measurement facility to switch the fridge ON and OFF in response to a remote command and to measure the active power consumption by the fridge.
2. Temperature sensor to measure the temperature inside the fridge cooling chamber.
3. A user interface device with red and green lights and two buttons to communicate with the user.
4. A Zigbee-Ethernet gateway device to enable interaction of these devices with the remote server.

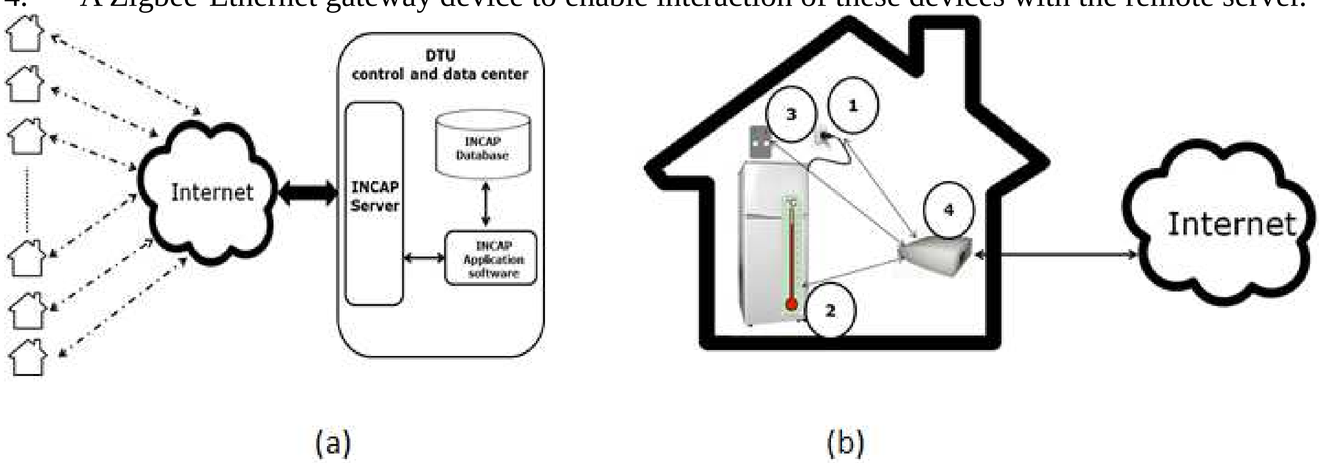


Figure 2. Data flow from the fridges to the controller and refrigerator control device installation in a house

Develco Products A/S, one of the partners in the project INCAP, provides these devices from its Zigbee wireless home automation network products line. The Zigbee-Ethernet gateway device hosts the local Zigbee home network as a coordinator, and other devices become the child of the local Zigbee network. The Zigbee-Ethernet gateway device establishes the connection to the control server through a wired ADSL home Internet connection. Two of the devices, namely the temperature sensor and the user interface device, are battery-powered devices, while the other two are mains supply powered. For the field experiment in INCAP, devices were sent to the consumers. Once installed, the devices sent authorization requests to the server and were authorized by the server to join the Zigbee network. The temperature sensor was placed in the cooling chamber of the fridge and the relay unit was connected in series with the power input to the fridge. The measurement sampling rates for the different devices were configured by the server.

3.3. Measurement parameters and sampling rate

The temperature sensor sends the temperature measurements at two-minute intervals. The sampling interval was preconfigured by the manufacturer in order to have a longer battery life. This sampling rate cannot be changed. As the temperature inside the refrigerator changes very slowly due to the thermal inertia of the food content, the two-minute sampling rate is sufficient to appreciate these dynamics. The temperature sensor has an accuracy of ±0.5 °C. The relay unit measures the active power consumed by the fridge. The resolution of the measurement is 1 W. The RMS voltage is also measured with 1 V accuracy. The measurement is taken every 10 seconds and sent to the server.

4. Controller description

4.1. Controller architecture

The controller has the following objectives: a) to predict the switch-OFF time of the fridges using the fridge model described in [25], and b) to limit the aggregated power consumption by controlling the fridges without violating their temperature limits. The controller execution is carried out according to the following Algorithm 1.

Algorithm

Initialization:

```
    Mark all fridges that are not active for service
    Create an empty scheduling queue
Procedure 1:
    For all fridges{
        get fridge cooling chamber temperature
        if fridge is activated for service{
            if temperature is above Tmax {
                turn the fridge ON
            }
        }
        else{
            put the fridge into the scheduling queue
            sort scheduling queue in descending order by length of OFF time
        }
    }
Procedure 2:
If aggregated power is higher than the set-point{
    calculate the power reduction required
    while power reduction is positive{
        get the first fridge from the scheduling queue
        mark the fridge to be activated for service
        subtract the fridge power from the power reduction
    }
 }
Procedure 3:
If aggregated power is lower than the set-point {
    calculate the power addition required
```

```
        while power addition is positive{
                get the first fridge from the activated scheduling queue
                mark the fridge to be deactivated from service
                subtract the fridge power from the power addition
        }
    }
```

Algorithm 1. Aggregated power control algorithm.

The controller receives temperature measurements from the fridges at two-minute intervals and the power measurements at 10-second intervals. As the model described in [25] requires the temperatures of the previous heating cycle and cooling cycle, the control software stores those temperature values corresponding to previous cycles (heating and cooling) locally. The heating and cooling cycles were identified by the compressor power consumption. During cooling the compressor is active and consumes power; during heating, there is no power consumption by the compressor. Some of the fridges have a power consumption of a few watts for their internal electronic components and for light bulb illumination while the fridge door is open. A 30 W threshold is used to separate the compressor power consumption from the power consumption by the light bulb and other components.

The aggregated power is calculated every time the power measurement from the refrigerators is updated. If the aggregated power is higher than the set limit, the coolest refrigerator among the active refrigerators is switched OFF. The procedure continues until the aggregated power reaches the control set-point. On the other hand, if the aggregated power is less than the control set-point, the hottest refrigerator among the group of controlled refrigerators is switched ON and the procedure continues until the aggregated power reaches the control set-point.

4.2. Control task timings

The temperature measurement from each fridge is received at two-minute intervals. The switch-OFF time for the active fridges (in which the compressor is ON) is calculated using the fridge model [25] every time the temperature is updated. The fridges are sorted in an order based on their switch-OFF time; the fridge that would otherwise turn off soonest would be the first priority. Although the fridge power is measured every 10 seconds, there is a time delay of 10 seconds when sensing a change in power from the fridges. When the aggregated power is limited to the reference value, the fridges which have to be switched OFF are marked internally in the software. The switch-OFF command is sent to the fridge every time, while the corresponding fridge’s power measurement is received. If the temperature of the fridge reaches its Tmax, then the corresponding fridge is removed from the control list.

5. Experimental results

The experiment was conducted for 24 hours for each scenario. After the experiment for one scenario, 24 hours’ relaxation time was allowed for the refrigerators to return to their normal thermostatic cycles before conducting the experiment for the next scenario. Twenty-five refrigerators participated in the experiment. The maximum aggregated compressor capacity of the refrigerators is 2500 W.

The aggregated power consumption of refrigerators in scenario 1 without control is shown in of Figure 3(a) and the instantaneous temperature average of refrigerators is shown in Figure 3(b).

Their average values are marked on the respective plots as a red line. The average value of the aggregated power consumption of the refrigerators is 836 W. The average value of the instantaneous temperature average is 7.1 °C. The maximum value of the aggregated power is 1575 W. Therefore the experiment for scenario 2 is conducted with the power limit set at a value of 800 W for the controller. The power limit value is close to 50% of the maximum power value (1575 W) and close to the average value (836 W) of scenario 1. The aggregated power consumption of the refrigerators in scenario 2 is shown in Figure 4(a). The instantaneous temperature average of the refrigerator is shown in of Figure 4(b). Their average values are marked as a red line on the respective plots. The average value of the aggregated power is 801 W and the average value of the instantaneous temperature average is 7.2 °C.

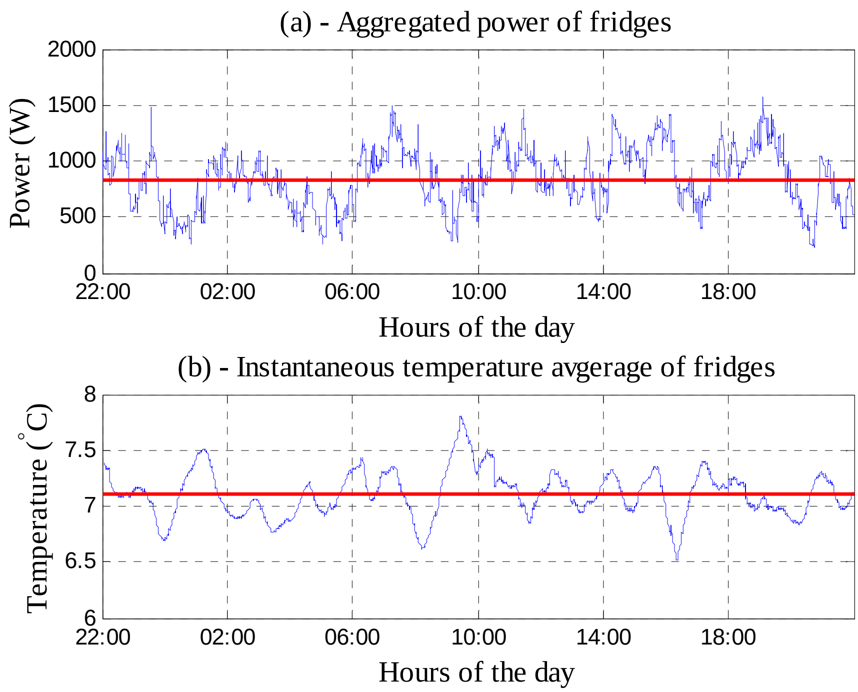


Figure 3. Aggregated power and instantaneous temperature average – Scenario 1

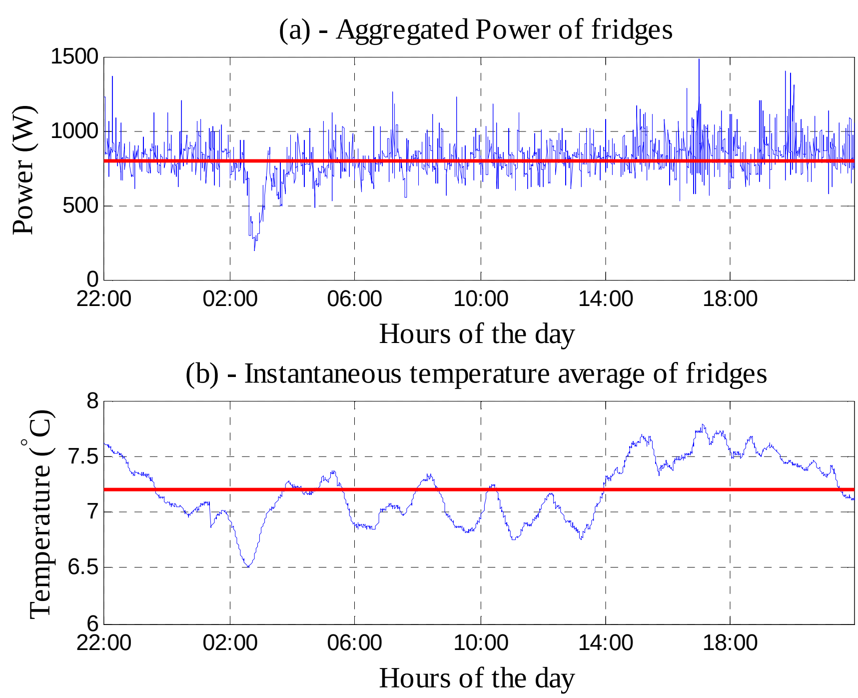


Figure 4. Aggregated power and instantaneous temperature average – Scenario 2

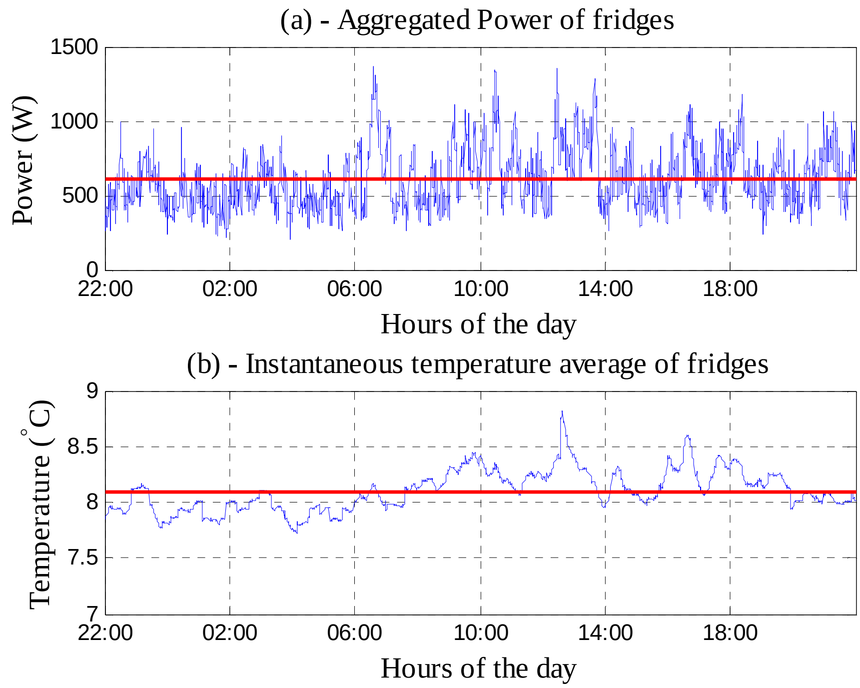


Figure 5. Aggregated power and instantaneous temperature average – Scenario 3

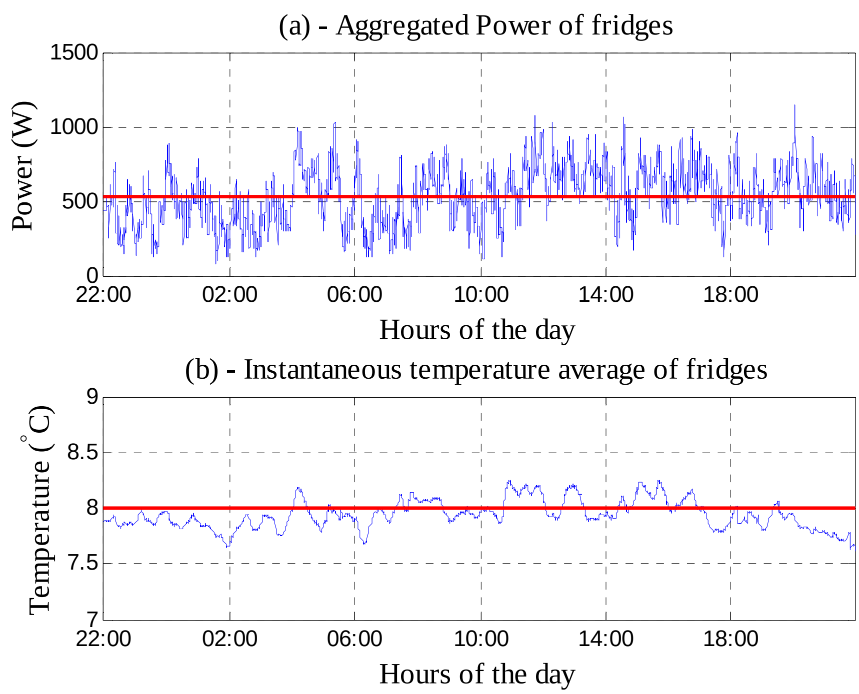


Figure 6. Aggregated power and instantaneous temperature average – Scenario 4

The experiments for scenarios 3 and 4 help to understand the change in flexibility of the overall population of refrigerators participating in the experiment. The experiment for Scenario 3 is conducted with a power limit value of 400 W for the controller. Similarly the experiment for Scenario 4 is conducted with a power limit value of 200 W for the controller. The aggregated power consumption for scenario 3 is shown in Figure 5(a). The instantaneous temperature average is shown in Figure 5(b).

The power average and average of instantaneous temperature average are marked as a red line on the respective plots. The average value of the aggregated power value for scenario 3 is 607 W and the average value of the instantaneous temperature average is 8.1 °C.

Similarly, the aggregated power consumption for scenario 4 is shown in Figure 6(a). The average aggregated power consumption for scenario 4 is 526 W. The instantaneous temperature average is shown in Figure 6(b). The average value of the instantaneous temperature average is 8.0 °C. The experimental results of the four scenarios are summarized in Table 1. The overall energy consumption for scenario 1 is 20.1 kWh and that for scenario 2 is 19.2 kWh. The difference in energy consumption is only 4.5%, taking scenario 1 as the base. In scenario 2, the controller maintains the aggregated power close to the average value of the aggregated consumption in scenario 1, which is the normal consumption. In scenario 3, when the power reduction is 50%, the overall average temperature of the population increases by 14%. The overall temperature average of the population is 8.1 °C. Although the controller aims to maintain the aggregated power at close to 50% (400 W) of the average consumption of scenario 1, the achieved average aggregated power value is 73% (607 W). This is due to one of the control constraints: that the temperature of every individual refrigerator must not exceed its Tmax value. The objective of conducting the experiment for scenario 4 is to understand the maximum limit of power reduction without violating the temperature conditions of the individual refrigerator of the population. The controller is provided with an objective power set-point value of 200 W, which is close to 25% of the average power consumption in scenario 1 (836 W). The achievable average power reduction in scenario 4 is 37% instead of 75%. The average aggregated power consumption in scenario 4 is 526 W. The temperature elevation is 13% and the average temperature of the population is 8.0 °C.

Table 1. Effect of control on the aggregated power of the refrigerators.

Scenario	Power reduction [%]	Power limit [W]	Average temperature [°C]	Average power [W]	Energy consumption [kWh]
1	NA	–	7.1	836	20.1
2	P_{avg}	800	7.2	801	19.2
3	50% of P_{avg}	400	8.1	607	14.6
4	25% of P_{avg}	200	8.0	526	12.6

Figure 7(a) shows the average value of the aggregated power of refrigerators for every 15 minutes in scenario 3. Similarly the plot for scenario 4 is shown in Figure 7(b). The controller set-point is marked as a red line in both plots. The controller is able to limit the aggregated power consumption up to 02:00 hours in the case of scenario 3. The synchronized thermostatic operation of the refrigerators starts from 02:00 hours, as most of the refrigerators reach their maximum temperature limit. Therefore, the controller was not able to limit the aggregated power after 02:00 hours. Similarly, in scenario 4, the refrigerators reach their maximum temperature limit much earlier, in less than 2 hours (at 23:45 hours), as the controller set-point is much lower. The hours of controllability are circled in green on both plots in Figure 7. Due to the synchronization of temperature cycles, as the temperature of all refrigerators reaches the maximum, the refrigerators are switched ON at the same time. Their aggregated power consumption increases, which is unavoidable. When the temperature of the refrigerators decreases, the refrigerators are switched OFF until the aggregated power limit set by the controller is reached.

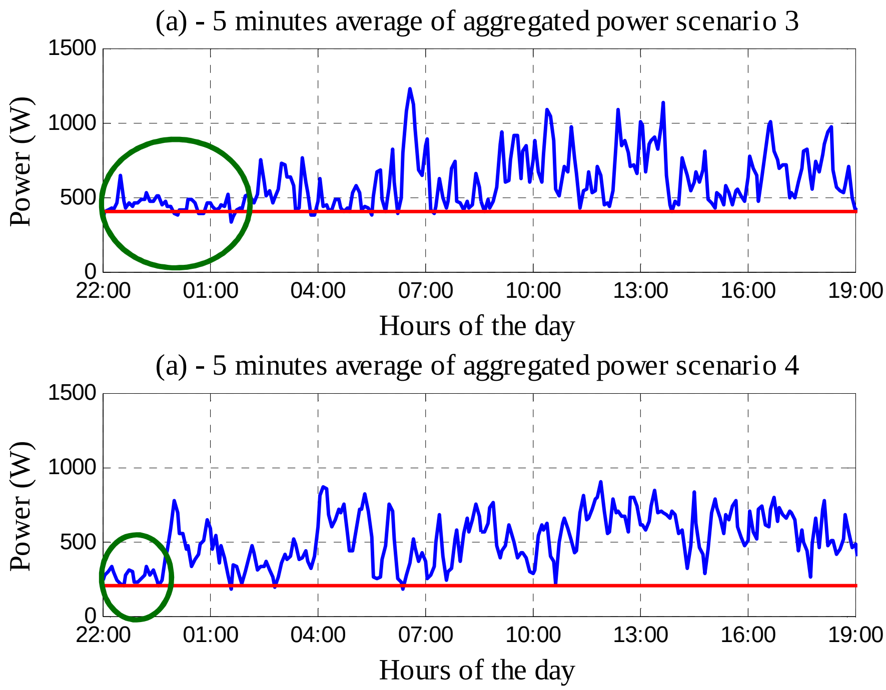


Figure 7. Aggregated power plotted with 15-minute average values for scenarios 3 and 4.

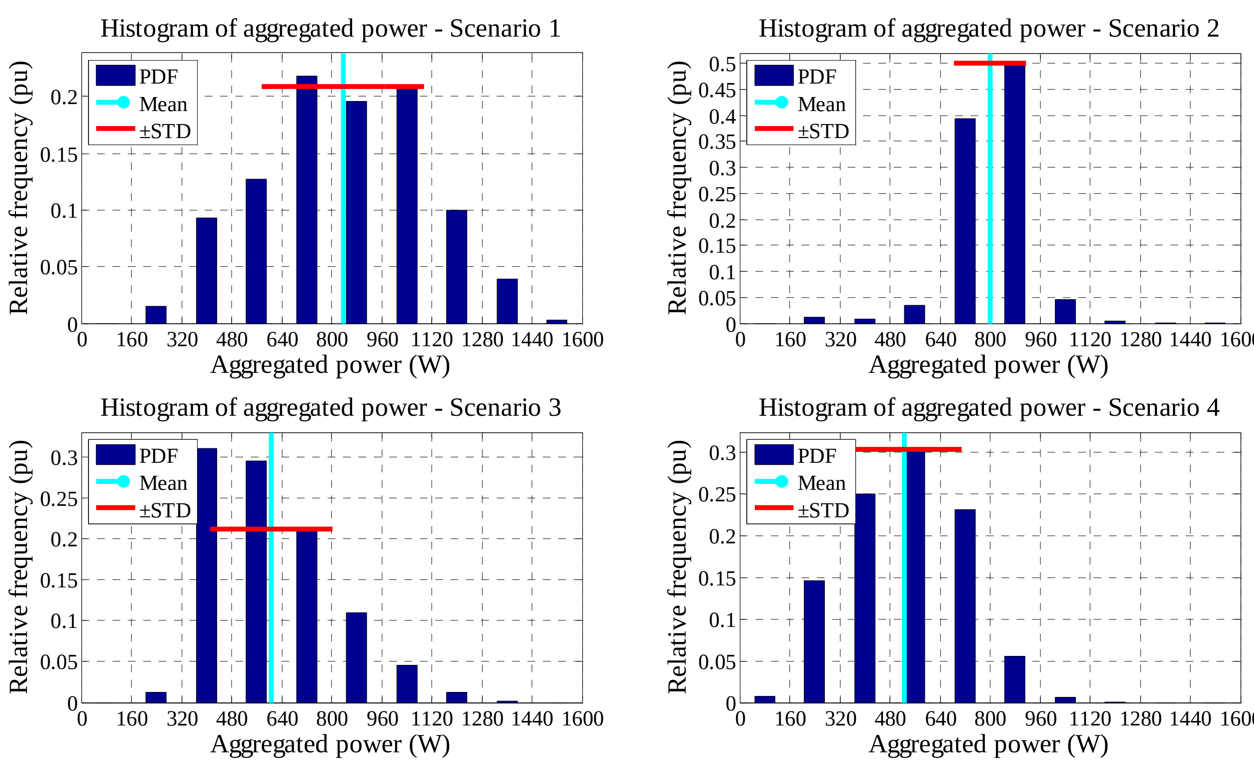


Figure 8. Histograms of the aggregated power in four scenarios.

The histograms of the four experimental scenarios are shown in Figure 8. The histograms show the occurrences of aggregated power values as a probability distribution function (PDF) in the given range from 0 to 1600 W along with the mean value and the standard distribution. In scenario 1, the distribution is even around the mean value and the standard deviation is high. Scenario 2 has more occurrences around the mean, and the standard deviation decreases. The mean value is also close to the controller set-point (800 W).When control is enabled to reduce aggregated power consumption by 50% in scenario 3, the number of occurrences close to the controller set-point value (400 W) increases, but the standard deviation increases in comparison to scenario 2. The mean value is higher than the controller set-point value. Similarly, in scenario 4, the standard deviation increases and the occurrences around the mean value are evenly distributed. In both scenario 3 and scenario 4, the average power consumption is higher than the controller set-point. This is due to the synchronization of the refrigerators' temperature cycles, as shown in Figure 7. As the controller set-point of scenario 4 is lower than that of scenario 3, a greater number of refrigerators are switched OFF in scenario 4 and consequently the overall average of the aggregated power consumption is low in scenario 4. This is visible on the histogram of the aggregated power consumption of scenario 4. The number of occurrences of aggregated power below 600 W is higher for scenario 4 than for scenario 3.

6. Discussion

6.1. Definition and quantitation of flexibility

As the refrigerators' operations are controlled by thermostats, the refrigerator compressor will be switched OFF as soon as the temperature of the refrigerator reaches Tmin. Once the refrigerator compressor is switched OFF, the refrigerator is not available for control until the thermostat switches the compressor ON after the temperature reaches the limit Tmax. Thus, any refrigerator is available for control only during the cooling part of the thermostatic cycle, as shown in Figure 9.

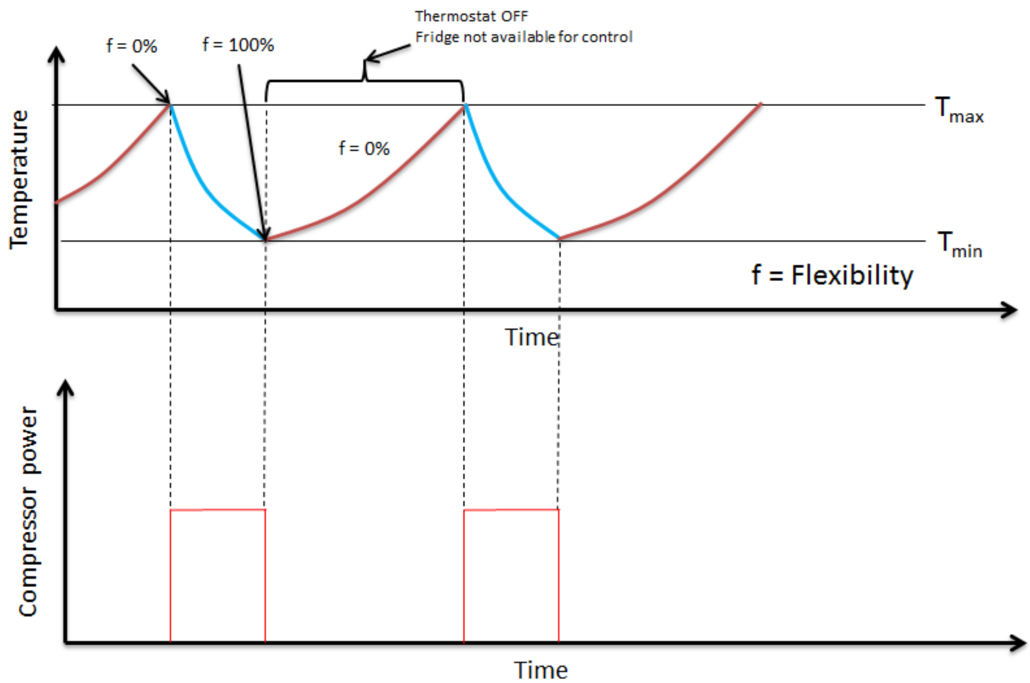
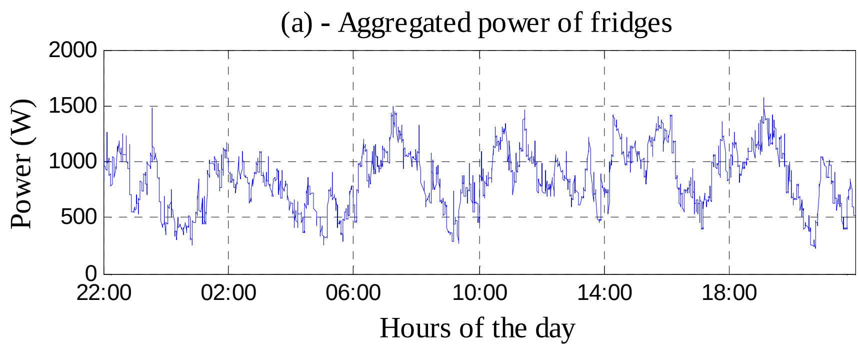


Figure 9. Flexibility change during natural thermostatic cycle.

At the beginning of the cooling, when the temperature is near Tmax, the flexibility is 0%. At the end of the cooling, when the temperature is close to Tmin, the flexibility is 100% as the refrigerator can support the maximum duration of control. All of the above statements about flexibility are valid only when the compressor is ON. If the compressor is switched OFF by the thermostat, then the refrigerator is not available for control anymore. Therefore, the refrigerators that are switched OFF by the thermostat are considered to have no flexibility.



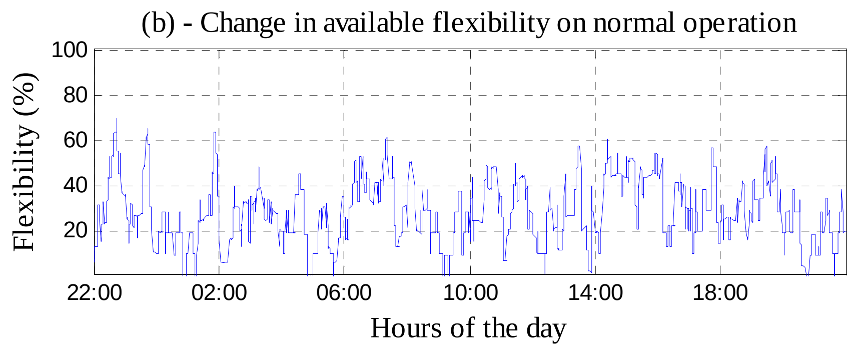


Figure 10. Change in available capacity without control

6.2. Impact on flexibility

Figure 10(b) shows the variation in the flexibility during normal consumption without control. The aggregated consumption is shown in Figure 10(a). It is interesting to notice that the aggregated power and the flexibility of the population follow a similar trend. A scatter plot of the aggregated power consumption versus flexibility is shown in Figure 11.

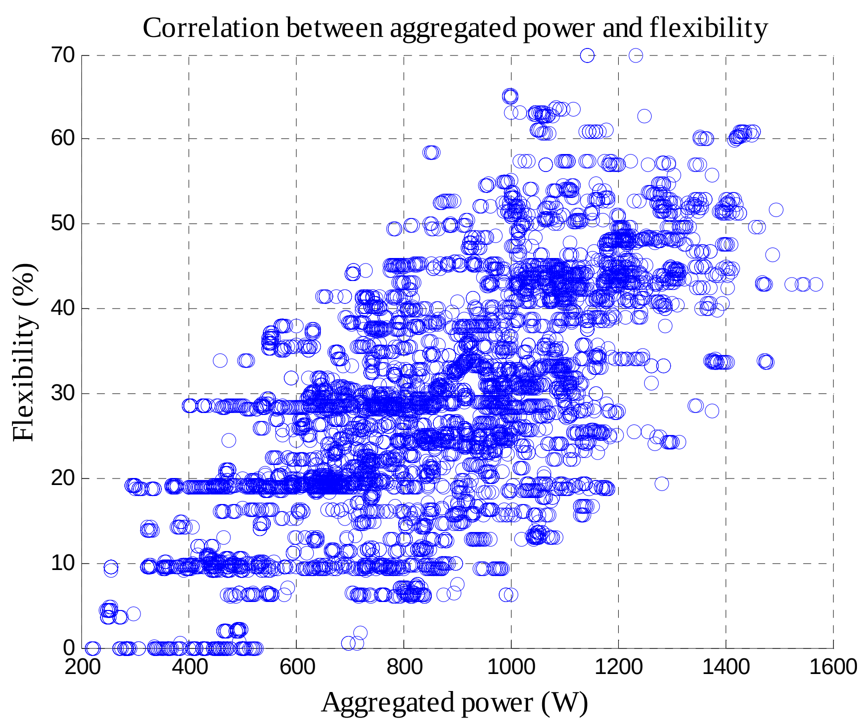


Figure 11. Correlation between aggregated power and flexibility

As the power consumption increases, a greater number of refrigerators become available for control and the flexibility also increases. The coefficient of the correlation is 0.68. The overall average flexibility of the population of refrigerators is 28%. Table 2 summarizes the achieved average power consumption, average temperature, and quantized flexibility as percentages for the four different scenarios. The change in the flexibility during different levels of power reduction is shown in Figure 12. The change in the flexibility for scenario 2 is shown in Figure 12(a). The overall average of the flexibility for scenario 2 is 43%.

Table 2. Change in flexibility in different control scenarios.

Scenario	Achieved average power [W]	Average temperature [°C]	Available flexibility [%]
1	836	7.1	28
2	801	7.2	43
3	607	8.1	10
4	526	8.0	5

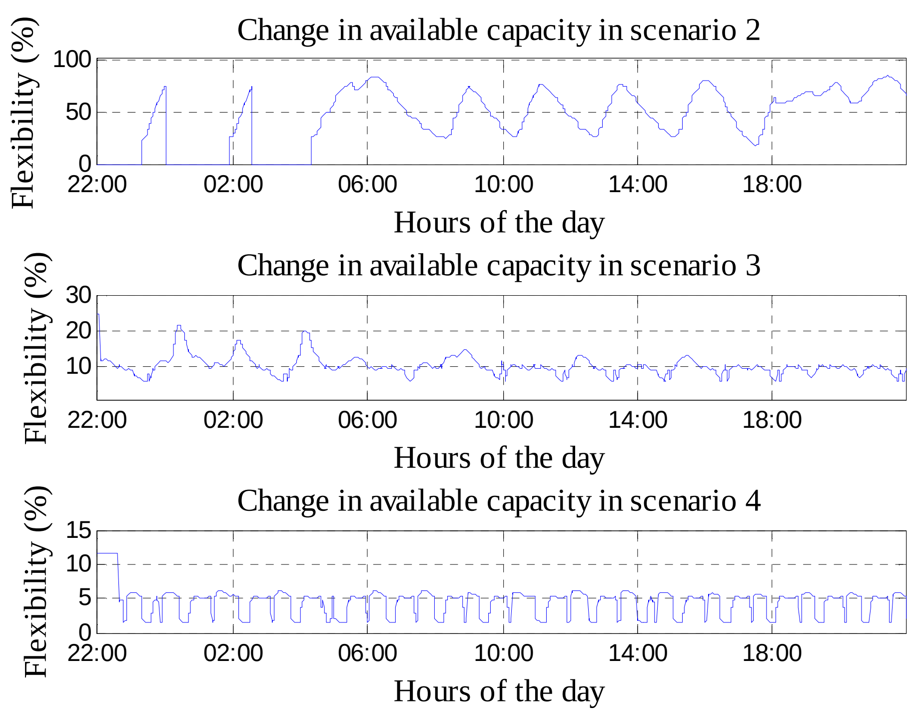


Figure 12. Change in available capacity with different power reductions.

In scenario 2, the controller maintains the aggregated power close to the average value of the aggregated consumption in scenario 1, and the flexibility of the population increases from 28% to 43%. Therefore, flexibility in scenario 2 increases by 54% compared to the base case, scenario 1. This phenomenon is due to the control of a greater number of refrigerators to maintain the aggregated power close to the set value. The overall average temperature of the population increases by 1% in scenario 2 in comparison with scenario 1. In scenario 3, when the power reduction is 50%, the flexibility decreases by 64% in comparison with scenario 1. The flexibility of the population is 10%. The flexibility of the population decreases to 5% in scenario 4, which can be considered as a residual capacity which cannot be utilized further. The residual capacity is due to the minimum switch-off time requirement of the refrigerator in order to avoid compressor damage due to fast switching and the high in-rush current during start-up.

7. Conclusions and future work

This paper studied the impact of DR activation on TCL flexibility variation with different levels of power reduction through a field experiment using refrigerators as an example case. The normal operation of refrigerators shows large variations in power consumption. The flexibility available with the refrigerators under normal operation is 28%. Due to the natural thermostatic cycles, half of the population is not available for control. The flexibility available with the population of refrigerators in terms of flexibility increases by 54% when the refrigerators are controlled for the average aggregated consumption. Therefore, if the aggregator has direct access to the compressor control, an average flexibility of 50% is possible. When the refrigerators are controlled to reduce their power to 50% of their average consumption, as seen in scenario 1, the overall average temperature of the population increases by 14% and the flexibility decreases to 10%. If the aggregated consumption is reduced by 75%, due to the temperature limit restriction, the maximum possible reduction is 37%. This causes the maximum reduction in the flexibility: to the value of 5%. It will be interesting to carry out a further study by changing the selection criteria of the refrigerator. The controller ability for refrigerator selection can be modified by considering the available watt-hour capacity of individual refrigerators or by considering the available percentage flexibility of the individual refrigerator instead of making a selection based on the length of the switch-OFF time. The new resource selection strategy may improve the performance by avoiding refrigerator synchronization.

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A5: Impact of thermostatically controlled loads' demand response activation on aggregated power: A field experiment

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Impact of thermostatically controlled loads' demand response activation on aggregated power: A field experiment

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Abstract

This paper describes the impacts of different types of demand response (DR) activation on thermostatically controlled loads' (TCLs) aggregated power. The different parties: power system operators, DR service providers (or aggregators) and consumers, have different objectives in relation to DR activation. The outcome of this experimental study quantifies the actual flexibility of household TCLs and the consequence for the different parties with respect to power behaviour. Each DR activation method adopts different scenarios to meet the power reduction, and has different impacts on the parameters. The experiments are conducted with real domestic refrigerators representing TCL. Activating refrigerators for DR with a delay reduces the integral square error (ISE) in power limitation by 28.46%, overshoot by 7.69%. The delay in refrigerator activation causes reduction in power ramp down rate by 39.90%, ramp up rate by 21.30% and the instantaneous average temperature increases by 0.13% in comparison with the scenario without activation delay.

Keywords: Demand response, domestic energy resources, aggregator, load management, flexible electricity demands, smart grid.

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Abbreviations

AMM: Advanced meter management
COP: Coefficient of performance
DR: Demand response
DSO: Distribution system operator
HVAC: Heating ventilation and air conditioning
ICT: Information and communications technology
INCAP: Inducing consumer adoption of automated reaction technology for dynamic power pricing tariffs
ISE: Integral square error
RES: Renewable energy sources
SLA: Service level agreement
SNR: Signal to noise ratio
TOU: Time of use
TSO: Transmission system operator

1. Introduction

Power systems are operated by different entities and span production to distribution; however, consumers pay a single commercial entity for electricity consumed. Power production companies are responsible for unit commitment and for selling the produced power to the companies responsible for its transportation, namely transmission system operators (TSOs). The company which makes the infrastructure for distributing power to the end-consumer is known as a distribution system operator (DSO), and buys power from the TSOs in order to sell it to its consumers. There is a complication in that the consumer can buy electricity from a company which is a trader and does not own any infrastructure for production, transmission and distribution. Similarly, in the DR market, there are three parties: namely, the DSO, aggregator, and consumers. Differently from the power system operation, where the DSO sells the service to its consumers, in this situation the consumers sell their flexibility to the DSO. Figure 1 shows a paradigm of the three participants in the DR. The illustration is a simplified scenario of the power system set-up with demand side management presented in [1]. Power system operators are increasingly being encouraged to accept demand response as an operational practice [2] - [5]. DR methods can be broadly classified as load shifting, load reduction and on-site generation [6]. Load shifting is mostly performed by the time of use (TOU) method. TOU motivates the consumers to shift their consumption by means of a time-sensitive price structure [7]. Several critical system events require unscheduled load reductions. The main objective of domestic electric appliances is to provide user comfort. On DR activation, the service provided by the appliance should not be affected, as the inconvenience to the user cannot be quantified [6]. In such cases the TCLs are most suitable for load reduction, as they have the ability to store the effect by means of their thermal inertia. Though the load dispatched in a single household is very small, their aggregation from multiple households makes it high enough to deliver this kind of power system service. This creates opportunities for a new entity called an aggregator.

Aggregators act as a bridge between consumers and DSOs [8] - [10]. Aggregators may install the ICT infrastructure in the consumers' premises to control their load with a service level agreement (SLA) not to affect the service provided by the controlled appliances [11], [12]. The aggregator buys the available DR capacity from different consumers and sells that in bulk to the DSO. The commitment made by the aggregator to the consumer is to maintain the service provided by the appliances.

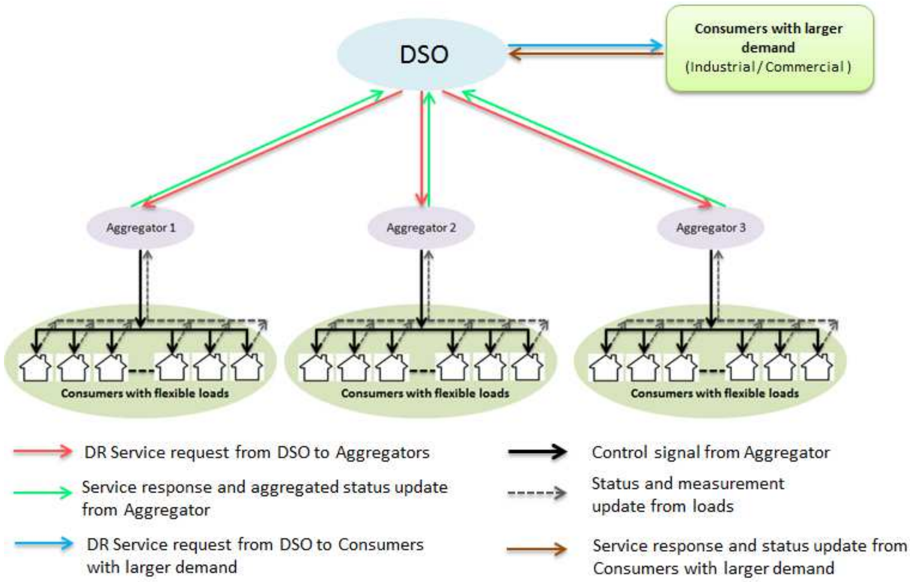


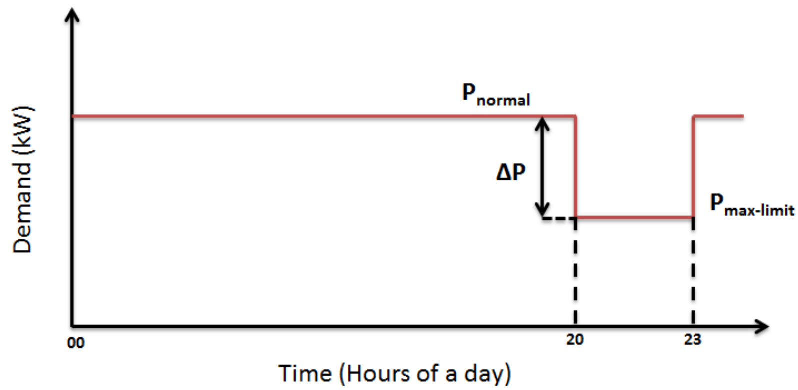
Figure 1. Information and service flow between DSO, aggregators and customers.

In Nordic countries in the year 2013, the electric consumption from residential buildings accounted for 26% of the total consumption. Household appliances consume around 17% of this amount [13], accounting therefore for 4.4% of the total consumption. Though the demand adjusted in an individual house is small, the aggregated capacity is considerably high and many DR research activities focus on domestic segment [12], [14]. In terms of domestic loads TCLs are considered for fast response power system services because of their size, population and ON/OFF capacities [15]. Refrigerators are the most suitable TCL for an experimental study of DR activation in household TCLs. DR with fridges has been studied for several smart grid applications [16] - [24]. Refrigerators are a small-scale representation of other TCLs. The refrigerator in the home has the capacity of load shifting because of its thermal capacity and has all-day availability because of its periodic operation. The user interference during the control period is less, because user discomfort is not affected directly, as it is in the case of HVAC. The control devices are cheap thanks to the simple ON/OFF control. The main objective of the refrigerator is to maintain a low temperature in the cool chamber. This temperature can be easily measured with a low-cost sensor and the refrigerator operation can be controlled with a simple ON/OFF switch. Load reduction using TCLs cause energy shifting by virtue of their service delivery in terms of climate maintenance. This in turn causes an increase in load in another time segment after the DR activation is removed [25]. The aim of this work is to investigate the impact of DR activation on TCLs' aggregated power consumption using domestic refrigerators as an example. The investigation is expected to quantify the flexibility of household TCLs and the consequence for the different parties (consumer, DSO and aggregator) with respect to power behaviour. An experimental investigation with domestic fridges used by real customers is conducted which takes into account the unknown users' behaviour. The adaptive fridge model presented in [17] is used to predict the behaviour of a fridge in different control scenarios.

The rest of this paper is organised as follows. In Section 2 the principle of the load reduction method and problem outline are introduced, and the control strategy adopted for energy reduction is briefly presented. Section 3 explains the experiment platform, the hardware devices used for control and measurement and their configuration. Section 4 discusses control strategy, practical limitations and safety constraints in detail. The results of the experiments are reported in Section 5 and discussed in Section 6 and conclusions and future work are reported in Section 7.

2. Methodology

The principle of DR activation and the control strategy for power reduction are explained herein. During peak hours because of either high consumption or low local production, the DSO may need a service to limit the power flow in lines or transformers. The DSO buys a capacity of ΔP power reduction from the aggregator.



3.

Figure 2. Illustration of DR service activation during a particular time of day.

The aggregator fulfils the requirement of the DSO by controlling the consumers' controllable flexible appliances. A sample peak hour scenario where the aggregator reduces the demand by ΔP and limits the consumption to P_{max_limit} between 20 and 23 hours of a day is shown in Figure 2. The flexible load from the refrigerators can be used as various DR products to serve the ancillary service requirements [26]. As the capacity of the loads and the aggregator are already assessed by DSO, the DSO and the aggregator enter into a service contract [1]. The aggregator reduces the consumption of the controllable loads by ΔP and commits to a maximum consumption by the controllable loads of P_{max_limit}. The experiments realised in this paper involve the usage of domestic refrigerators as controllable loads.

2.1 Refrigerator operation and OFF time prediction

The refrigerator is a thermally isolated box (cool chamber) in which a temperature in a lower range than the ambient temperature is maintained by a compressor controlled by a thermostat. The temperature inside the refrigerator varies continuously between two threshold limits, namely T_{max} and T_{min} [17]. At any time the temperature inside the cool chamber of the refrigerator is maintained between these two limits. As soon as the temperature of the cool chamber reaches the higher limit, namely T_{max}, the compressor is switched ON and the cooling starts. As the compressor pumps heat out of the cool chamber, the temperature starts to decrease from T_{max}. The thermostat switches off the compressor when the temperature reaches the lower limit, T_{min}. The temperature starts to increase because of 1) heat gains from external environment (as the environment is at higher temperature), 2) openings of the fridge door for food exchange, 3) heat contained in the food stored. The heating duration and the cooling duration depend on 1) refrigerator parameters (compressor capacity, coefficient of performance (COP) and thermal insulation of refrigerator walls and door), 2) environmental condition (ambient temperature) and 3) others (amount of food content and its thermal capacity, number of door openings by the user, etc.).

The refrigerator's operation pattern is similar and defined by the thermostatic cycles during most time of the day. The major disturbances like food exchange are introduced only during certain time of the day. The refrigerator's thermal behaviour (cool chamber temperature) can be predicted using a thermal model trained from the previous thermostatic cycles as shown in Figure 3. The temperature prediction allows assessing how long the DR service can be provided. The duration of the DR service by switching off a refrigerator is constrained by temperature threshold T_{max}. The duration of the current temperature cycles (cooling and heating) can be derived from the slopes of the previous temperature cycles. The temperature profile of the refrigerator can be considered as piece wise linear. For example, the segment with the duration t_s in the cooling cycle between the temperature measurements T_{c2} and T_{c3} is considered to be linear with a slope CS_2, as shown in the Figure 3. Similarly in the heating cycle, the segment with the duration t_s between the temperature measurements T_{h3} and T_{h4} is considered to be linear with a slope HS_3. The slopes of the heating cycle segments are used to predict the temperature and the duration of OFF time t_{off}.

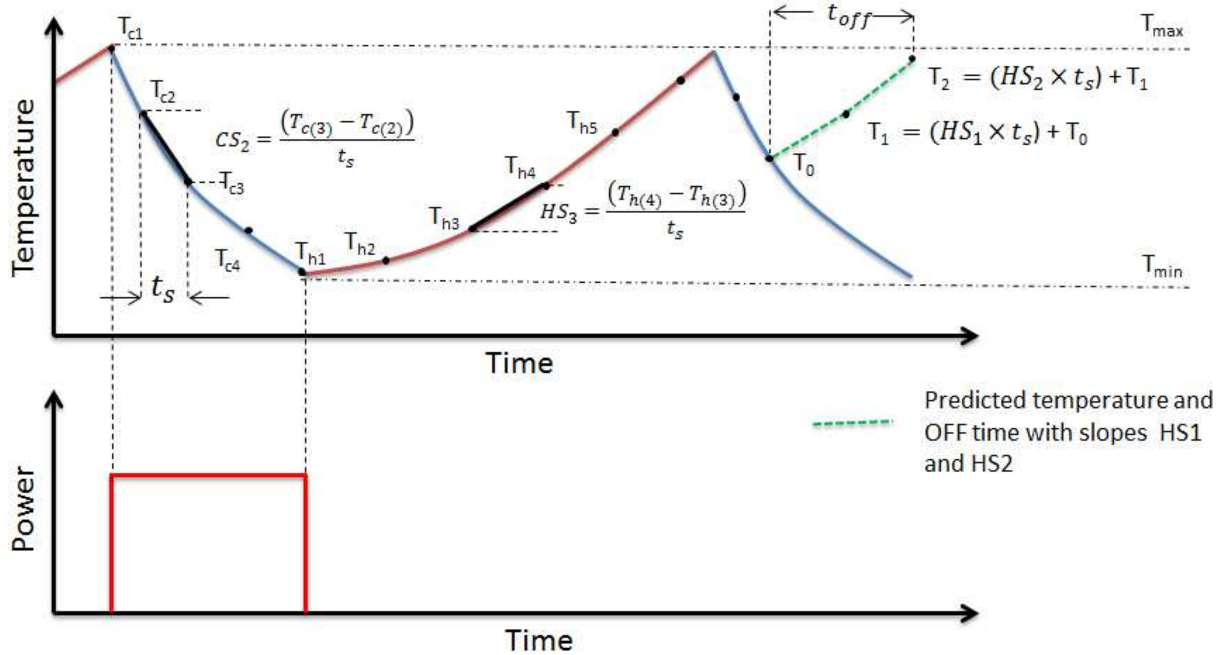


Figure 3. OFF time calculation form the temperature measurements.

The slopes of the heating cycle HS is calculated as follows:

$$HS_i = \frac{(T_{h(i)} - T_{h(i-1)})}{t_s} \qquad \begin{cases} 1 < i < N_{sh} \\ P < 30\,W \end{cases}$$

where HS_i is heating cycle slope of individual segment of temperature curve, $T_{h(i)}$ is heating cycle temperature sample, t_s is sampling interval, N_{sh} is number of temperature samples in the heating cycle and P is compressor power. Similarly the slopes of the temperature curve when the refrigerator compressor is ON are derived as follows:

$$CS_i = \frac{T_{c(i)} - T_{c(i-1)}}{t_s} \qquad \begin{cases} 1 < i < N_{sc} \\ P < 30\,W \end{cases}$$

Where CS_i is cooling cycle slope of individual segment of temperature curve, $T_{c(i)}$ is cooling cycle temperature sample and N_{sc} is number of temperature samples in the cooling cycle. When performing the refrigerator OFF time calculation, the temperature prediction is carried out from the present temperature $T_{(0)}$ as follows:

$$T_{(i)} = (HS_i \times t_s) + T_{(i-1)} \qquad \begin{cases} 1 < i < N_{sh} \\ T_i < T_{max} \end{cases}$$

Where $T_{(0)}$ is present temperature measurement when the compressor is ON ($i = 0$) and $T_{(i)}$ is predicted temperature after the time interval of t_s if the refrigerator is switched OFF. The OFF time is calculated as follows:

$$t_{off} = t_s \times N \qquad \begin{cases} T_N \le T_{max} \\ T_{N+1} > T_{max} \end{cases}$$

where t_{off} is calculated OFF time and N is number of sampling intervals.

The temperature prediction strategy is verified with different types of refrigerators. The mean errors in predicting the OFF time are within ±3% [17]. The temperature prediction strategy is used in a field experiment for energy shift estimation of DR activation on real Danish domestic refrigerators. The compressor duty cycle prediction with the black box model is within a ±5% error limit [18] under normal operating conditions. The errors in energy shift estimation is within ±10% [18].

2.2 DR activation

The proposed method manages to limit the power by controlling the refrigerator operation without violating the temperature limits. The architecture of a central controller for refrigerator control is presented in Listing 1. The controller collects temperature measurements and power consumption from each refrigerator. The power limitation service is delivered by a central controller with two simultaneous procedures designed with the following algorithm.

Listing

```
Initialisation:
    mark all fridges not active for service
    create an empty scheduling queue
Procedure 1:
    for all fridges{
        get fridge cool chamber temperature
        if fridge is activated for service{
            if temperature above Tmax{
                turn the fridge ON
            }
        }
        else{
            put the fridge into the scheduling queue
            sort scheduling queue descending by length of the OFF time
        }
    }
Procedure 2:
while consumption is larger than the power limit{
    get the first fridge from the scheduling queue
        mark the fridge to be activated for service
        subtract the fridge power from the consumption
 }
```

Listing 1. Congestion management algorithm.

Procedure 1 in Listing 1 runs every second and manages the fridge operation. In the proposed algorithm the fridge flexibility is measured by the duration the refrigerator can be switched off in order to assist the power limitation. As the new temperature measurement is received from the uncontrolled refrigerator with active compressor, the switch OFF time for the refrigerator is calculated by predicting the temperature inside the cool chamber using the black box model [17]. This model requires only two measurements and predicts the cool chamber temperature. It is a generalised model suitable for refrigerators of different types. Such a model is suitable for experiments with a large number of refrigerators, where the number of parameters measured is limited. The scheduling queue of uncontrolled refrigerators is sorted on every new OFF time calculation as per the newly calculated OFF time. In this way, the number of refrigerators and their priority for control in the scheduling queue changes dynamically by appreciating the latest available flexibility. In the procedure 1, the controlled refrigerators are switched ON when their temperature exceeds its higher temperature threshold T_{max}. In this way, the temperature limit of each refrigerator is respected.

Procedure 2 targets the power limitation. If the aggregated power consumption exceeds the power limit, the required number of fridges is selected from the scheduling queue of uncontrolled refrigerators in order to keep the power limit during the DR activation interval.

3 Experimental procedure

This section provides a description of the experimental set-up: domestic refrigerators, supporting ICT infrastructure and measurements collection.

3.1 Requirements

In domestic segment, the compressor used in most of the refrigerators is single speed, hermetic reciprocating compressors [27], [28]. The single speed hermetic compressor operates with only two states (ON/OFF). The refrigerators with multiple compressors and advanced multistage refrigeration cycle (for example; inverter compressors) are excluded in this experiment. The experiment is designed to study the impact of DR activation on the aggregated power of domestic refrigerators. The only requirements are the measurements of refrigerators' parameters and the control of refrigerators' operation from a remote computer acting as aggregator. The necessary devices to control a refrigerator from a remote computer are: a temperature sensor which can measure the refrigerators' cool chamber temperatures and send data to the central computer, remotely controllable power switches which can receive commands from the central computer to turn the refrigerators' compressors ON and OFF, and power measurement devices which can measure the compressors' power consumptions and send them to the remote computer.

The INCAP (Inducing consumer adoption of automated reaction technology for dynamic power pricing tariffs) project has established the ICT infrastructure for controlling and measuring multiple household refrigerators in Denmark. These fridges were considered for the experimental study.

3.2 INCAP fridge data and control access

The devices connected to the refrigerators for control and data collection purposes of each household refrigerator participating in project INCAP are shown in the block diagram in Figure 4. Four devices are used for data collection and control of each refrigerator:

1. Relay or a contact unit with power measurement facility, to switch the fridge ON and OFF in response to the command from the remote computer and to measure the active power consumption of the fridge.
2. Temperature sensor to measure temperature inside the fridge cool chamber.
3. A user interface device with red and green lights and two buttons to communicate with users.
4. A Zigbee-Ethernet gateway device to enable interaction of these devices with the remote server.

All these devices communicate with the Zigbee-Ethernet gateway device in the Zigbee wireless communication protocol and the Zigbee-Ethernet gateway device communicates with the INCAP server through an ADSL home internet connection. The devices were sent to the consumers of one of the INCAP project partners and to a DSO. Once installed, the devices send authorisation requests to the remote computer and are authorised by the computer and configured to send the measurements. The temperature sensor is placed in the cool chamber of the fridge and the relay unit is connected in series with the power input to the fridge.

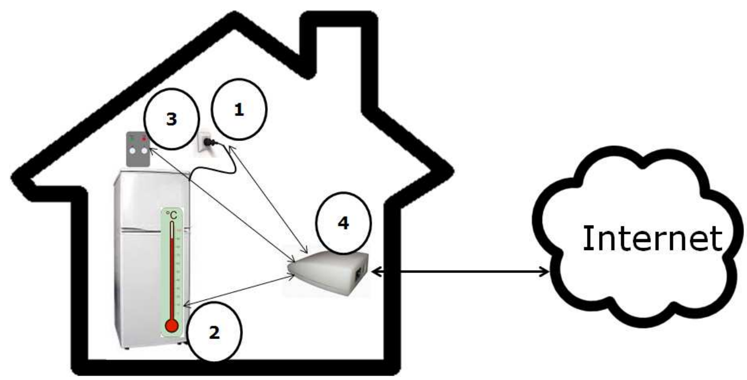


Figure 4. Refrigerator control device installation in a house.

3.3 Measurement parameters and sampling rate

Temperature: the temperature sensor sends the temperature measurements once every two minutes. The sensor manufacturer preprogrammed the sampling and transmission rate of two minutes to obtain longer battery life and it cannot be changed. As the refrigerator has very slow thermodynamics because of the thermal inertia of the food content, the temperature inside the refrigerator changes very slowly. The two-minute sampling rate is sufficient to appreciate these dynamics. The temperature sensor has an accuracy of ±0.5 °C.

Fridge active power: the relay unit measures the active power consumed by the refrigerator compressor with a resolution of 1 W. The measurement is performed every 10 seconds and sent to the central computer.

4 Controller description

4.1 Controller architecture

All of the devices connected to the fridge in the household send data to the Zigbee-Ethernet gateway device. The device sends the data to the INCAP server. The INCAP server hosts a software ‘Smart AMM server’ (AMM - advanced meter management) provided by the device manufacturer. The Smart AMM server acts as a gateway for sending commands to the devices and receiving data from them. The communication is in the form of short messages. A smart AMM server can send a copy of received messages to the controller. A block diagram of the data flow from the fridges to the controller is shown in Figure 5. The controller aims to deliver a power-limiting service during a particular time of the day. In the INCAP project, the control is set to three hours, from 20:00 until 23:00 local time (GMT+1). The controller switches off the refrigerators one by one until the power limit is reached. The order of refrigerator selection is based on how long it can stay OFF without violating its temperature limits. The refrigerator which can stay OFF for the longest time is selected first. The length of time a refrigerator can stay OFF is predicted by using the refrigerator model described in [17].

The refrigerator model uses a strategy to predict the cooling and heating duration using the previous corresponding temperature data. The temperature data associated with cooling and heating are identified with corresponding compressor power consumption. The compressor is active and has power consumption close to its rated value while the refrigerator is cooling. The compressor consumes no power after the temperature reaches its T_{min}, as the thermostat switches OFF. Some of the fridges have electronic controllers instead of classical mechanical thermostats. Also, the light bulb is illuminated while the fridge door is open. Therefore a 30-watt threshold is used to separate the compressor power consumption and the power consumption of the light bulb and other components.

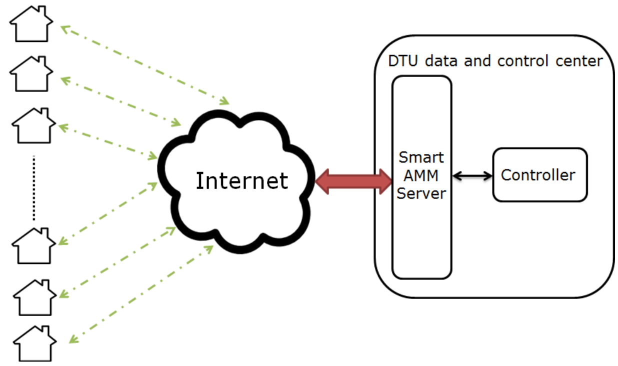


Figure 5. Data flow from the fridges to the controller.

4.2 *Control task timings*

The controller is activated for three hours, from 20:00 until 23:00. The temperature measurement from each fridge is received at two-minute intervals. The temperature update from those refrigerators which are operational (in which the compressor is ON) is used to calculate the switch OFF time using the refrigerator model [17]. Switch OFF time is calculated on every temperature update. The controller maintains a queue in which the fridges are sorted according to their switch OFF time, the one with the highest switch OFF time being first. For power limitation, the fridges which have to be switched OFF to limit the power are marked internally in the software. The first switch OFF command is sent to the refrigerator when the corresponding refrigerator sends the power or temperature message (whichever is earlier). In this way the control delay is minimised. On every switch OFF command the control relay maintains the state for five minutes. This is a safety interlock feature of the relay to avoid the fridge being OFF permanently in the case of any communication failure, so the OFF command is repeated every two minutes in response to the temperature message received. If the temperature of the fridge reaches its T_{max}, then the corresponding fridge is switched ON. The maximum delay in the congestion correction is 10 seconds, as the power measurement is performed once every 10 seconds.

5 Experimental results

5.1 *Scenario definition*

The experiment is conducted with 25 fridges to test four different scenarios of controls. The total compressor power capacity of all 25 refrigerators is 2.5 kW. The day average power consumption is 660 W which is 26.5% of the total load capacity. A power limit of 625 W, which is 25% of the capacity, is selected as a set point for the controller. The DR activation happens once a day between 20:00 and 23:00. The experiment is conducted with five scenarios.

Scenario 1: Normal operation without control.
Scenario 2: DR activation without delay.
Scenario 3: DR activation with delay sequence S1-S1.
Scenario 4: DR activation with delay sequence S1-S2.
Scenario 5: DR activation with delay sequence S135-S246.

Scenario 1 is the base case to illustrate the normal condition without power limitation. Scenario 2 is the case when the power system operator buys power from an unbundled market and sells for a single tariff to the consumer. In such situations the electricity company wants to reduce the power consumption, when the actual consumption exceeds the forecasted demand, as the additional power is procured at a much higher cost. Here the aggregator is used to meet the demand forecast by demand response activation. In scenario 2, the aggregator enables demand response as quickly as possible. Scenarios 3-5 present the cases when the obligation for the aggregator is to meet the generation requirements like ramp up and ramp down rates and overshoots as defined in the national grid code, for example as defined in [29].

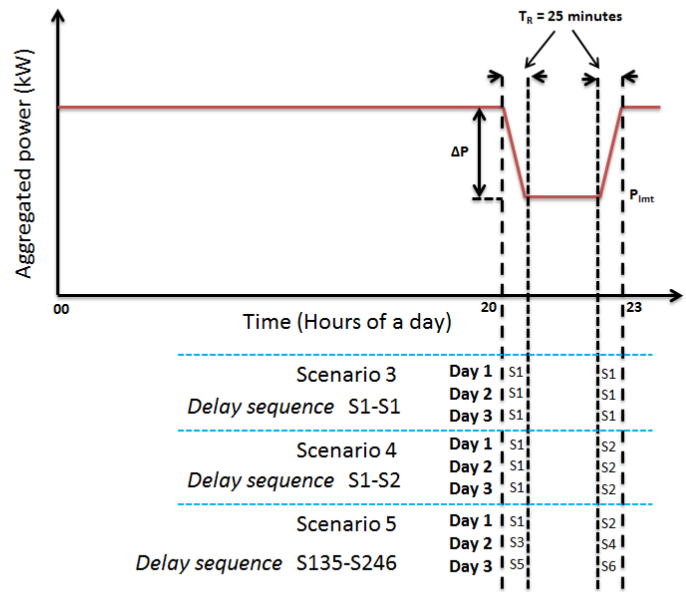


Figure 6. Scenario3-5 overview.

The test for each scenario is conducted for three days. In scenario 3 to scenario 5, the focus is to control the ramp up and ramp down rates along with power limitation. Therefore, the control for the refrigerators is enabled sequentially with a delay of one minute between each refrigerator. Similarly, at the end of DR activation time, the control is disabled sequentially with the same delay. The delay sequence used in each scenario on each day is shown in the Figure 6. The refrigerators selection for sequences from S1 to S6 is random to avoid any biased selection. The power consumption for the three days is aggregated to one day. Similarly, the average of instantaneous refrigerator temperature average is calculated. The aggregation is done to improve the signal to noise ratio (SNR) and also to emulate a population three times larger.

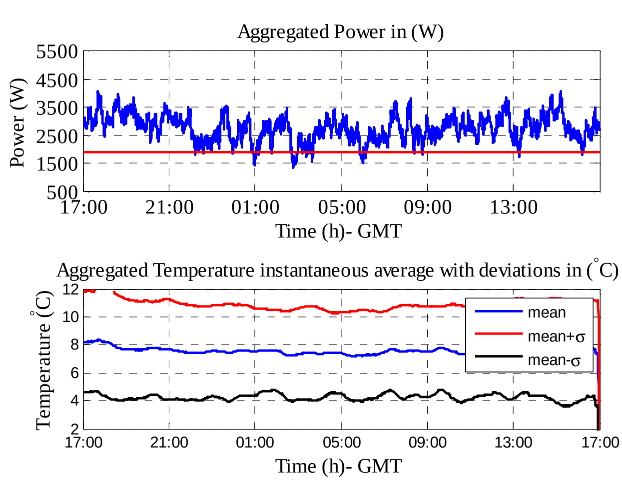


Figure 7. Aggregated power from the fridges and instantaneous average of temperatures of all fridges without control (scenario 1).

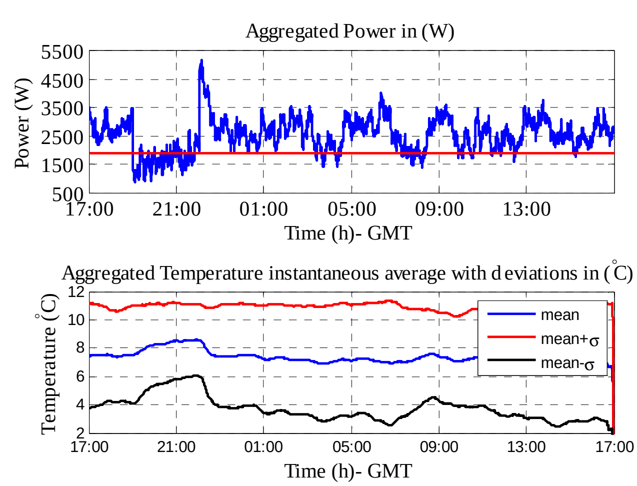


Figure 8. Aggregated power from the fridges and instantaneous average of temperatures of all fridges in scenario 2.

5.2 Scenario 1: Normal operation without control

The compressor power consumption and temperature of all 25 refrigerators are logged without any control. This scenario will serve as a base case for comparing the other scenario results. The power consumption is presented in the upper plot of Figure 7. The average of the aggregated power is 1875 W. The instantaneous average of the temperature is shown in the lower plot of Figure 7. The average of the instantaneous temperature average is 8.75 °C.

5.3 Scenario 2: DR activation without delay

In scenario 2, the controls for all the refrigerators are enabled simultaneously at the beginning of DR activation time and disabled simultaneously at the end of DR activation time. The DR controller has the P_{max_limit} set point of 625 W (which, when the three days of data are aggregated, becomes 1875 W). The aggregated power consumption is reported in the upper plot of Figure 8 with the P_{max_limit} marked as a red line. The instantaneous temperature average is shown in the lower plot of Figure 8.

5.4 Scenario 3: DR activation with delay sequence S1-S1

In scenario 3, the control for all the refrigerators is enabled sequentially with a delay of one minute between each refrigerator. The twenty-fifth refrigerator is enabled for control 25 minutes after the first refrigerator. Similarly, at the end of DR activation time, the control is disabled sequentially with the same delay. The delay sequences followed at the beginning and at the end are same and the delay sequence is denoted as S1. In this way, all refrigerators are controlled for the same amount of time. The DR controller has the same P_{max_limit} set point of 625 W. The aggregated power consumption for scenario 3 is reported in the first plot of Figure 9 with the P_{max_limit} marked as a red line. The instantaneous temperature average is shown in the lower plot of Figure 9.

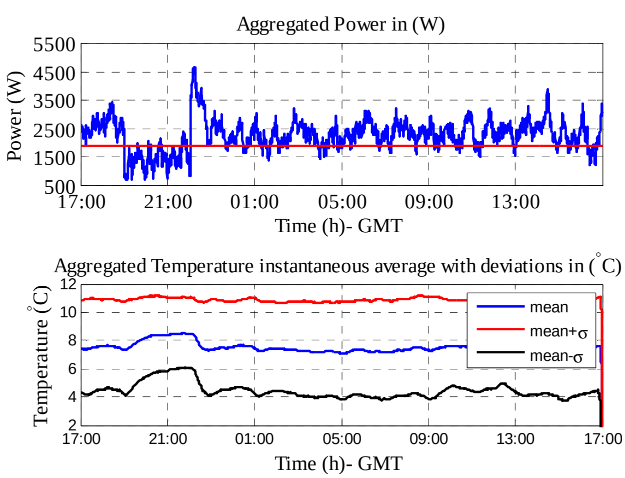


Figure 9. Aggregated power from the fridges and instantaneous average of temperatures of all fridges in scenario 3.

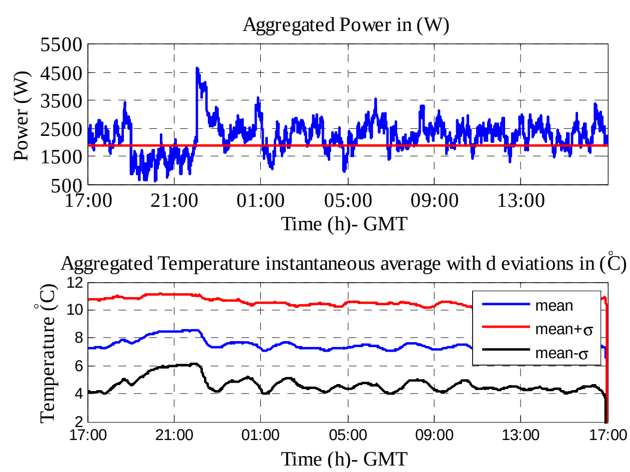


Figure 10. Aggregated power from the fridges and instantaneous average of temperatures of all fridges in scenario 4.

5.5 Scenario 4: DR activation with delay sequence S1-S2

Scenario 4 is similar in all aspects to scenario 3. The only difference is the sequence in which the refrigerators are enabled for the control at the beginning and at the end. The delay sequence followed at the beginning of the DR activation is S1 for all the three days of the experiment and the delay sequence followed at the end of DR activation period is S2 for all the three days of the experiment. The refrigerators have different DR activation durations. The aggregated power consumption is reported in the upper plot of Figure 10 with the P_{max_limit} marked as a red line. The instantaneous temperature average is shown in the lower plot of Figure 10.

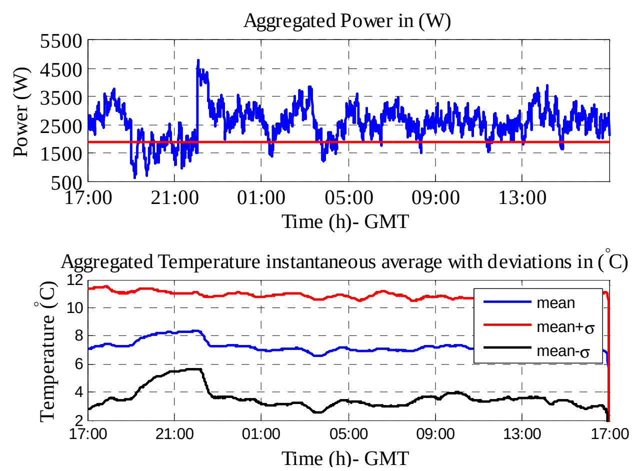


Figure 11. Aggregated power from the fridges and instantaneous average of temperatures of all fridges in scenario 5.

5.6 Scenario 5: DR activation with delay sequence S1,3,5-S2,4,6

In scenarios 3 and 4, the test is the same for all three days. In scenario 5, each day a different sequence is selected at the beginning and at the end of the DR activation time. On the day 1, the delay sequence at the beginning of DR activation is S1 and the delay sequence at the end of DR activation is S2. On day 2, the delay sequence at the beginning of DR activation is S3 and the delay sequence at the end of DR activation is S4. And on the day 3, the delay sequence at the beginning of DR activation is S3 and the delay sequence at the end of DR activation is S6. In this way the experiment each day is different and it allows emulating a bigger population of refrigerators. The aggregated power consumption is reported in the first plot of Figure 11 with the P_{max_limit} marked as a red line. The instantaneous temperature average is shown in the lower plot of Figure 11.

6 Discussion

The number of refrigerators active and consuming power for cooling in scenarios 2 to 5 is given in the upper plots of Figure 12 to Figure 16. The variances of the instantaneous temperature of the refrigerators for scenarios 2 to 5 are given in the lower plots of Figure 12 to Figure 16. The number of refrigerators active is reduced after the DR activation is enabled. As the control is enabled, the refrigerator temperatures are driven to their maximum. Therefore the instantaneous temperature variance of the population decreases. After the DR activation is removed, the refrigerators are allowed to run on their natural cooling cycle (thermostatic cycles).

The impact of the control is reflected on the aggregated power, after the DR activation is removed. The increase in the variance indicates more refrigerators are active and consuming power for cooling. The variance different values reported in the lower plots of figures from Figure 13 to Figure 16 show that there is synchronisation of the refrigerators' operation and thus the oscillations in the power flow. The numerical results for four different control scenarios are reported in Table 1. The effectiveness of the control method is analysed by considering three parameters. The amount of deviation from the set power control limit is calculated as the square root of integral square error (ISE). The power ramp down rate during DR activation and the power ramp up rate during the DR activation removal are also considered to evaluate the effectiveness of the control. The ramp down and ramp up rates are critically important for the power system as the generation units have to adjust power production as the demand changes. For example, the technical regulations set by the Danish TSO EnergiNet.dk for thermal power plants demands a ramping rate in the range of 2 to 8% of the nominal power per minute for conventional power plants, depending on the typology and operating point. The ramp up rate requirement for the gas and diesel power plants ranges from 10-20 %/minute [29].

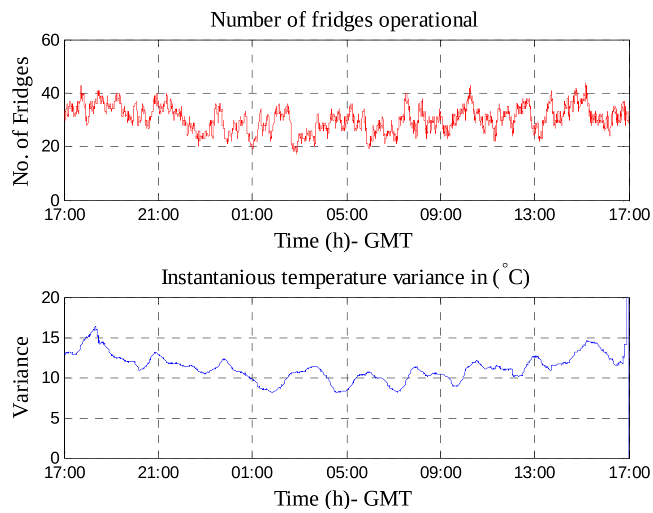


Figure 12. The number of fridges operational at any time and the instantaneous temperature variance of the population for scenario 1.

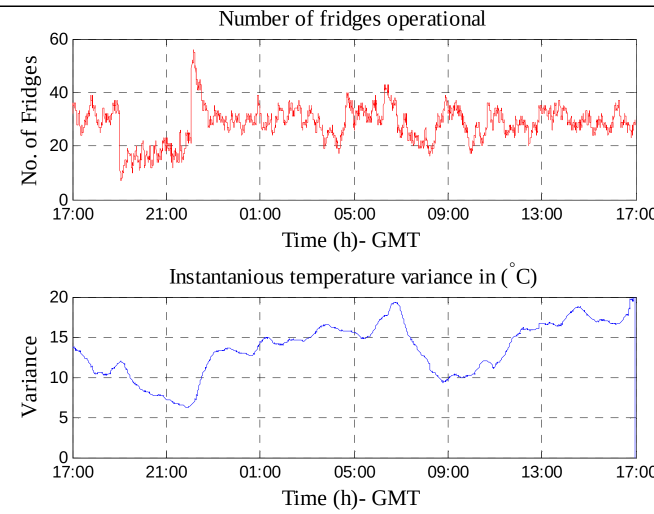


Figure 13. The number of fridges operational at any time and the instantaneous temperature variance of the population for scenario 2.

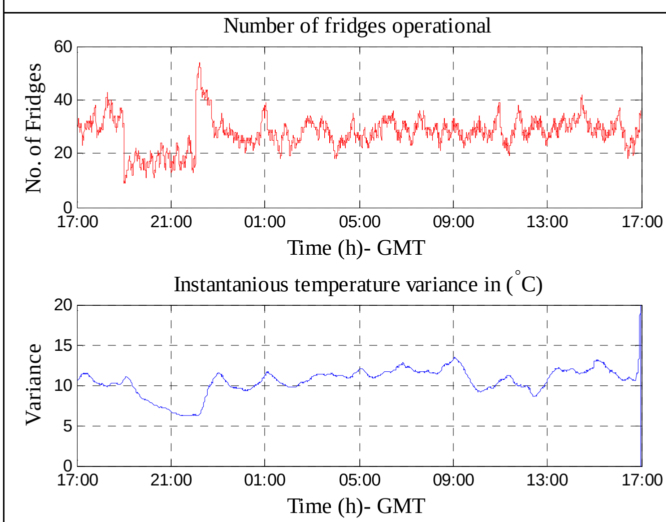


Figure 14. The number of fridges operational at any time and the instantaneous temperature variance of the population for scenario 3.

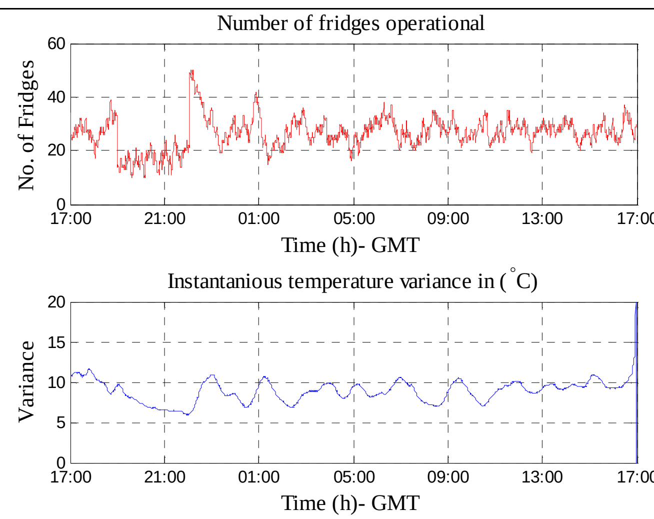


Figure 15. The number of fridges operational at any time and the instantaneous temperature variance of the population for scenario 4.

In the analysed experiment, the ramp down rate is calculated as the ratio of power difference to the time elapsed. The power difference is the difference between the power at the time of DR activation and the local minimum power reached as the consequence of DR activation. Similarly, the ramp up rate is calculated considering the end of DR activation time. The ramp up and ramp down values are normalised to the power base of 7.5 kW to achieve per unit (pu) value, since the total rating of the refrigerators is 2.5 kW and the measurements are aggregated for three days.

It is very evident in Figure 8 to Figure 11 that the DR activation reduces the load. In Figure 8 it can be seen that in scenario 2 the targeted P_{max_limit} is violated more often than in the other three scenarios.

The square root of ISE for scenario 2 is 36.44 W. Also, scenario 2 has higher ramp down and ramp up rates than the other three control scenarios. The ramp down rate for scenario 2 is 8.77 %/minute and the ramp up rate is 20.33 %/minute. In scenario 3, the controller performance is improved in terms of keeping the power under the targeted P_{max_limit} on DR activation. The square root of ISE for scenario 3 is 28.40 W. Scenario 3 also shows improvement in reducing the ramp down and ramp up rates. The ramp down rate for scenario 3 is 7.37 %/minute and the ramp up rate is 18.00 %/minute. Scenario 4 shows the best results in terms of reducing power below P_{max_limit}. The square root of ISE in this case is 26.07 W. The ramp down and ramp up rates are also minimal in comparison with other scenarios. The ramp down rate for scenario 4 is 5.27 %/minute and the ramp up rate is 16.00 %/minute. As the sequence followed for the DR activation and DR activation removal are different for all three days, the results change dramatically in scenario 5. The square root of ISE becomes 36.78 W. The ramp down and ramp up rates increase. The ramp down rate is 8.70 %/minute and the ramp up rate is 19.70 %/minute.

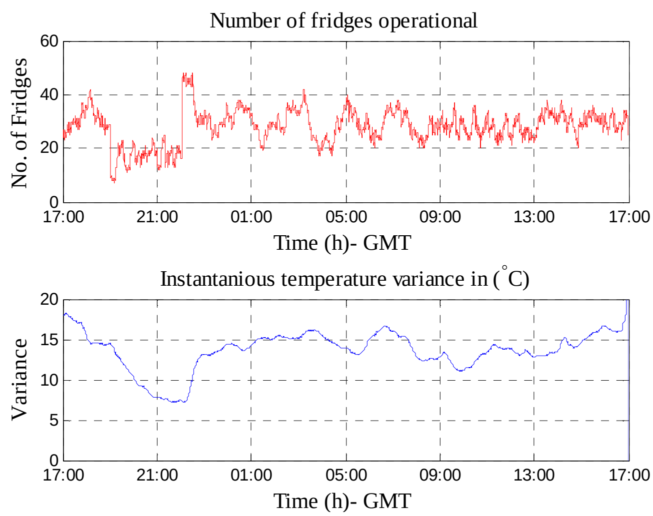


Figure 16. The number of fridges operational at any time and the instantaneous temperature variance of the population for scenario 5.

In order to compare the metrics of the scenarios, scenario 2 is taken as a benchmark. In comparison to scenario 2, the overshoot in scenario 3 is reduced by 9.62%, in scenario 4 by 9.62% and in scenario 5 by 7.69%, as shown in the Table 1. The delay in refrigerator activation causes reduction in power ramp down rate in scenario 3 by 15.96%, in scenario 4 by 39.91% and in scenario 5 by 0.80%. Similarly the ramp up rate is reduced by 11.46% in scenario 3, by 21.30% in scenario 4 and in scenario 5 by 3.10%. The instantaneous average temperature in scenario 3 increases by 2.04%, in scenario 4 increases by 1.36% and in scenario 5 decreases by 1.50%.

The TCL control for load reduction will cause energy shift and payback load [25]. The control of a group of TCLs may cause synchronisation in their operation. The synchronised operation of TCL with payback load will cause overshoot in power consumption after the DR control is removed. The power overshoot can be so high that there may be violation of security limits of the power system. The proposed algorithm has the advantage of controlling the ramp up and ramp down rates by controlling the delay sequence. The overshoot is unavoidable unless the TCLs operation can be desynchronised. The proposed algorithm explicitly desynchronise the operation of TCLs to limit the overshoot at the end of DR activation period. The desynchronization achieves 7.69% overshoot reduction between scenarios 2 and 4, as presented in Table 1. However, the disadvantage is that after the activation period is finished, the algorithm has no control over the TCLs.

Table 1. Effect of control on the aggregated power of the refrigerators.

Parameter	Scenario			
	2	3	4	5
ISE [W]	36.44	28.40	26.07	36.78
Ramp down rate [%/minute]	8.77	7.37	5.27	8.70
Ramp up rate [%/minute]	20.33	18.00	16.00	19.70
Average of instantaneous temperature average [◦C]	7.35	7.50	7.45	7.24
Standard deviation of instantaneous temperature average [◦C]	0.52	0.45	0.47	0.49
Peak overshoot after DR activation removal [kW]	5.2	4.7	4.7	4.8

7 Conclusions and future work

This paper investigated the impacts of different types of DR activation on TCLs' aggregated power using domestic refrigerators as a sample case. The experimental results show that withdrawing all loads abruptly (scenario 2) produced a high square root of ISE (36.44 W) in power limitation and also produced instability in terms of higher ramp down (8.77 %/minute) and ramp up (20.33 %/minute) rates and higher peak overshoot (5.2 kW). The same effect was obtained for the delay during the start and end of DR activation if refrigerators were selected randomly (scenario 5). In case the network operator needs fast response to maintain the network stability during the critical situations, scenario 2 with high ramp down rate is most suitable based on obtained results. In this case the ISE in power reduction will be high as well as the ramp up rate and the overshoot, which may affect the network stability after DR activation. The performance improves in scenario 3 in terms of low ISE in power reduction and low ramp up and overshoot. If the consumer response time is not critical to provide the DR service, scenario 4 with lowest ISE in power reduction as well as low ramp up rate and overshoot is most suitable. The controller can be modified to switch on some of the refrigerators when the aggregated power consumption is far below the P_{max_limit} to improve performance in terms of reducing the square root of ISE. Apart from the power limit service, further studies will investigate the provision of other types of power system services such as grid frequency control.

Acknowledgements

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Appendix B
PRODUCT TECHNICAL SPECIFICATIONS

Technical specifications of 4 devices from Develco products are listed in this appendix as follows.

B1: Smart relay - ZHWR202 - ZigBee Wall Plug Meter Relay HA

B2: Temperature sensor - ZHOT101 - ZigBee occupancy, temperature & light sensor

B3: User interface - ZHKF101 - ZigBee key fob

B4: Ethernet Gateway - ZHEG101 - ZigBee-Ethernet Gateway HA

B1: Smart relay - ZHWR202 - ZigBee Wall Plug Meter Relay HA
(Available on line at http://bit.ly/1kVzG9c)

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ZHWR202 - ZigBee Wall Plug Meter Relay HA

ZigBee based on/off wall plug relay

The ZigBee based on/off wall plug relay enables you to switch your equipment on or off remotely, e.g. by SMS, GPRS, ethernet or by another communications path depending on the gateway.

The relay consists of a plug unit with built-in relay, and communicates with a ZigBee gateway. The relay is plugged directly into the AC power outlet.

Besides being able to switch your equipment on or off remotely, you can also do this manually by pressing the push button on the front of the device.

Energy Optimisation and Awareness

The relay also includes built-in power meter. This enables the user to monitor the power consumption of each appliance in the building, resulting in sharpened awareness of power waste and energy optimisation.

All data loggings are transmitted to a data concentrator.

Specifications:

- Dimensions: 106 x 61 x 54 mm
- Colour: White
- Power consumption: 0.4W
- Max. switch voltage: 250VAC
- Max. switch current: 16A
- Operation temperature: 0 to +50°C
- Supply voltage: 230V
- Sensitivity: -101 dBm @ 1% PER
- Output power: 13 dBm

Specifications Power Meter:

- Voltage range: 207 to 253VAC
- Current range: 16A
- Accuracy: typ. ± 3.0%
  Optimum: 1%

Key Features:

The ZigBee based wall plug relay is configured as router in a ZigBee Pro 2007 network.

Key features are:

- On/off functionality implementerd as an MPO device referring to the ZigBee HA profile.
- Phase dropout alarm according to the Develco proprietary ZigBee profile.
- Energy metering implemented as Metering device complying with the ZigBee SE profile.
- Certified ZigBee Home Automation application profile (stack profile 2).
- Available plug types: Danish , UK, FR, EU (Schuko), others by request.
- Communication based on DevCom04HP ZigBee Module.
- ETSI compliant.
- RoHS compliant according to the EU Directive 2002/95/EC.

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ZHDR201 - ZigBee DIN Meter Relay HA

ZigBee based on/off Relay for DIN Rail Mounting

The ZigBee based on/off relay for DIN rail mounting enables you to switch your equipment on or off remotely, e.g. by SMS, GPRS, ethernet or by another communications path depending on the gateway.

The relay consists of a DIN rail unit with built-in relay. It communicates with a ZigBee gateway. The ZigBee based DIN relay makes the user capable of configuring his home appliances in clusters and hence control a whole group of units instead of controlling each device separately.

Energy Optimisation and Awareness

The DIN relay also includes built-in power meter functionality. This enables the user to monitor the power conumption of each group of appliances in the house, resulting in sharpened awareness of power waste and energy optimisation. All data loggings are transmitted to a data concentrator.

Specifications:

- Dimensions: 90 x 58 x 17.5 mm
- Colour: Light grey
- Power consumption: 0.4W
- Max. switch voltage: 250VAC
- Max. switch current: 16A
- IP-class: 20
- Operation temperature: 0 to +50°C
- Supply voltage: 230V
- Sensitivity: -101 dBm @ 1% PER
- Output power: 13 dBm
- Frequency band: 47 to 53 Hz

Specifications Power Meter:

- Voltage range: 207 to 253VAC
- Current range: 16A
- Accuracy: typ. ± 3.0%
  Option: 1%

Key Features:

The ZigBee based relay for DIN rail mounting is configured as router in a ZigBee 2007 Pro network.

Key features are:

- On/off functionality implementerd as an MPO device referring to the ZigBee HA profile.
- Phase dropout alarm according to the Develco proprietary ZigBee profile.
- Energy metering implemented a Metering device complying with the ZigBee SE profile.
- Certified ZigBee Home Automation application profile (stack profile 2).
- Communication is based on DevCom04HP ZigBee Module.
- ETSI compliant.
- RoHS compliant according to the EU Directive 2002/95/EC.

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B2: Temperature sensor - ZHOT101 - ZigBee occupancy, temperature & light sensor (Available on line at http://bit.ly/1RfZebe)

ZHOT101 - ZigBee occupancy, temperature & light sensor

ZigBee based Home Automation multi sensor for occupancy, temperature, and light

The multi sensor enables you to detect movement and light as well as measuring temperature. The sensor is battery powered and can be mounted in four different ways: flat on the wall, flat on the ceiling, in the corner (using a 45° bracket), or standing (on a shelf, table, or similar).

The sensor has three ZigBee end points, one for each sensor. Each end point can be used separately.

Occupancy

The occupancy sensor is PIR based, sensing moving objects up to 6 meters from the sensor. The sensor has two outputs: one for Occupancy and one for Alarm. The sensitivity is individually configurable for the outputs. The off-time for Occupancy is adjustable remotely via ZigBee. The end points are configured as Home Automation profiles „Occupancy Sensor", and „IAS Zone".

Light

The light sensor is a low-accuracy sensor reporting light level. The end point is configured as Home Automation profile „Light Sensor".

Temperature

The temperature sensor measures temperature with a resolution of 0,1°C. It supports standard ZigBee reporting (on change or interval). The end point is configured as the Home Automation profile „Temperature Sensor"

Battery survaillance:

The sensor includes a battery monitor, providing battery level in volts as well as an „Low battery" Warning.

Specifications:

- Dimensions: 106 x 61 x 54 mm
- Colour: White
- Battery: CR123, exchangeable
- Battery life: 5 years, hourly reporting
- Operation temperature: 0 to +50°C
- Sensitivity: -92 dBm
- Output power: +3 dBm
- Alive telegram using ZigBee Basic cluster

Specifications Occupancy:

- Range: 6m
- View angle: 45° up/down, left/right
- Off-time: configurable 2 s - 65,000 s

Specifications Light:

- Resolution: dark, light, bright
- Sample time: config.: 2 s -65,000 s
- Reporting: configurable

Specifications Temperature:

- Range: 0 to +50°C
- Resolution: 0.1°C (accuracy ± 0.5°C)
- Sample time: config.: 2 s -65,000 s
- Reporting: configurable.

V.0514

Specification Battery monitor:

- Resolution: 0,1 Volt
- Battery Warning: V <2,5V

Key Features:

The ZigBee Home Automation multi sensor is configured as End Device in a ZigBee Pro 2007 network.

Key features are:

- Temperature sensor
- Occupancy sensor
- Light sensor
- Battery voltage
- ZigBee Home Automation Compliant (stack profile 2).
- Communication based on DevCom07 ZigBee Module.
- RoHS compliant according to the EU Directive 2002/95/EC.

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Develco Products provides communication systems for AMR, AMI and Smart Metering combined with Home Automation.

Modules are integrated into various meters from different vendors. Develco Products also provides Data concentrators with back-office communication via GPRS, SMS, internet, Fiber and PLC enhanced with the capability of handling Home Automation products without any additional cost.

In addition to the large range of communication products, Develco offers a high level of system customization.

SmartAMM

SmartAMM is a modular concept ensuring a flexible and forward-looking Smart House solution. SmartAMM combines automated meter reading with home automation, and includes:

- AMR for existing metering solutions
- AMR for meter manufacturers
- Communication modules for integration in meters or appliances (ZigBee, Z-Wave, PLC, GPRS, GSM and others)
- Data concentrators with back-office communication (GPRS, SMS, Internet, Fiber, or PLC)
- Home Automation

Energi Midt testimonial

"Develco Products has provided E nergiMidt with a smart metering solution for existing meters.

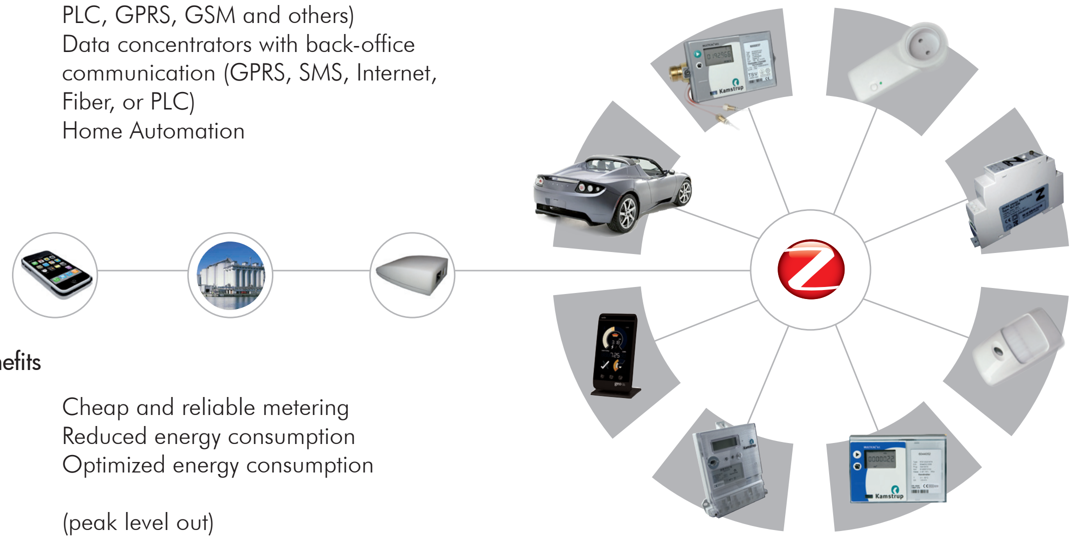
It comprises SmartAMM modules for power meters with the opportunity to expand with readouts of water and heating. A wireless energy display brings awareness and consequent energy savings as well as cost savings.

Thanks to Develco Products' solution, we can now offer control, savings, comfort, and alarm services to our customers, constituting an important new business area for EnergiMidt".

Erling Klemmensen, EnergiMidt

SmartAMM is also used by:

- DONG Energy Gas
(AMR of gas meters via GPRS data concentrator)
- Dong Energy Power
(control and alarm via SmartRead power meter)
-



Benefits

- Cheap and reliable metering
- Reduced energy consumption
- Optimized energy consumption

  (peak level out)
- Readout of several meters by diverse manufacturers and types
(water, heating, gas, electricity)
- Surveillance & comfort
- Alarms

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B3: User interface - ZHKF101 - ZigBee key fob
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ZHKF101 - ZigBee key fob

ZigBee based 4-button remote control designed as a key fob.

The remote control enables you to adjust various settings such as door opener, energy optimisation via controlling light via smart plugs, burglaralarm or a wireless home automation system.

The remote control has four buttons (arming, disarming, night-arming, and alarm)

It is battery powered with two standard AAA batteries.

The sensor has one ZigBee end point, for key-inputs.

The remote control will report the status every two minutes via e.g. a Home Automation system, via e.g. sms, e-mail, or web. Any changes on the key-inputs will be reported.

Specifications:

- Dimensions: 72 x 30 x 18 mm
- Colour: Black
- Battery: : 2 x AAA, exchangeable
- Battery life: 2 years, reporting every 2 min
- Operation temperature: 0 to +50°C
- Sensitivity: -92 dBm
- Output power: +3 dBm
- Alive telegram using ZigBee Basic cluster
-

Key features:

The ZigBee Home Automation key fob is configured as End Device in a ZigBee Pro 2007 network.

Key features are:

- 4-button key fob
- Certified ZigBee Home Automation application profile (stack profile 2).
- RoHS compliant according to the EU
- Directive 2002/95/EC.
- DIN EN 14604 and DIN 14676 Certified

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Develco Products provides communication systems for Smart Metering and Home Automation. We have been working with wireless communication solutions since 2004, and the products are the result of more than 80 man-year development.

Develco Products provides products for:

-- Metering

-- Demand Side Management

-- Energy savings

-- Alarms

We also integrate communication modules based on different technologies into various meters from different vendors. Data concentrators with back-office communication via GPRS, SMS, internet, Fiber, and PLC enhanced with the capability of handling Home Automation products without any additional cost are also part of our product line.

Develco Products is a network driven company engaged in many partnerships and technological alliances.

Customers:

-- Utilities

-- Meter manufacturers

-- Energy system providers

-- Home Automation manufacturers

-- Telcos/ISPs

-- Alarm companies

-- ESCOs

Products

ZigBee HA

Gateways:

-- Ethernet

-- GPRS

-- USB dongle

Devices:

-- Smart Plug

-- DIN relay

-- Multi sensor (occupancy, temp., light)

-- Smoke sensor

-- Key fob/ remote control

-- Magnetic sensor

ZigBee SE

Gateways/Energy Hubs:

-- Ethernet

-- GPRS

-- Echelon built-in (PLC)

Meter interfaces:

-- Electricity

-- Gas

-- Water

-- Heat

-- External meter interfaces

Devices:

-- 30A relay

-- IHDs (in home displays), 3rd party

-- USB IHD

Others

Energy hubs:

-- Echelon - ZigBee+Wireless M-Bus

-- Echelon - Wireless M-Bus

-- GPRS - ZigBee+Wireless M-Bus

-- Ethernet - ZigBee+Wireless M-Bus

Devices:

-- External meter interface Wireless M-Bus

Customer driven:

-- Communication modules for meters

-- New products

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B4: Ethernet Gateway - ZHEG101 - ZigBee-Ethernet Gateway HA
(Available on line at http://bit.ly/1P02SbD)

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ZHEG101 - ZigBee-Ethernet Gateway HA

The ZigBee – Ethernet gateway serves as data concentrator. It is capable of collecting meter readings from more than 25 different meter units in a system. The number of units can be configured and is only limited by the memory capacity. The meter units can e.g. be different kind of meters like power, water, gas and heating connected to the wireless ZigBee network established and managed by the gateway.

All data loggings are stored in a data flash. From this, is it possible to read out the data classified by:

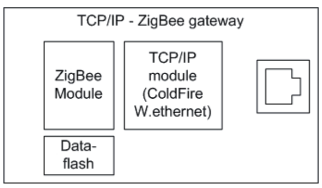
- Dates (start and end)
- Logs recorded since last read out
- Number of logs from oldest log
- Number of logs from newest log

The gateway can handle different logging intervals for every single meter unit, ranging from one minute to 24 months.

In addition to the meter data, the gateway also contains an alarm log capable of storing the latest 48 alarms from each meter unit in the system. Furthermore, the gateway can configure and control all ZigBee compliant devices such as relays with integrated power meter function, temperature and motion sensors.

Updating the application firmware of the gateway is rendered possible by a TFTP server. Allocation of IP addresses during power-up takes place dynamically from a DHCP server.

Specifications	
Dimensions:	104 x 73 x 33.3 mm^3
Storage temperature:	-40 to +85°C
Operation temperature:	-10 to +65°C
Supply voltage:	PoE or ext. PSU, 15-40 V
Power consumption:	Average of 1.8W
RF performance:	• TX: +18dBm (EU: 12dBm) - RX: -100dBm • Range: LOS ≤ 1600m, Indoor ≤ 100m
Ethernet interface:	10BASE-T/100BASE-T
Micro controllers:	• MCF52235 ColdFire • DevCom 04HP
SW stack:	InterNiche's ColdFire TCP/IP Stack
ZigBee stack version:	2007
ZigBee stack profile:	1 (ZigBee) + 2 (ZigBee Pro)
ZigBee application profile:	Home Automation
ZigBee HA device profile:	Combined interface
Standards & directives:	• CE compliant • ETSI compliant • RoHS compliant according to the EU Directive 2002/95/EC



ZigBee Control your world

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Server System Architecture- SmartAMM

Purpose

The SmartAMM Server System is capable of handling communication with several SmartAMM gateways (the number depends on the selection of network type), as well as a number of "backend applications". The system can be used for configuration/consolidation of the SmartAMM gateway deployments as well as delivery and reception of all types of data to and from the gateways.

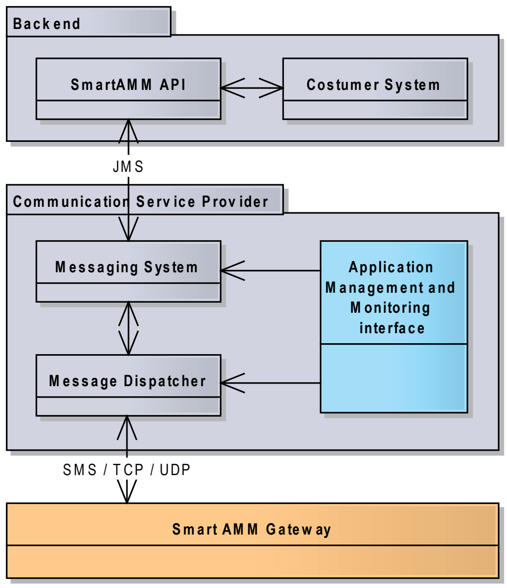
Examples could be:

- A billing systems receiving meter readings
- An end user system, i.e. a webapplication enabling the end user to see his meter data or monitor/control his Smart House installation
- An adminstrative (CRM) system containing knowledge of the distribution and configuration of the Smart AMM gateway installations.

Communication Service Provider

This is the SmartAMM server service which transmits and receives messages to and from the SmartAMM gateways.

It consists of a Messaging System and a configurable Message Dispatcher which provides transport for a specific network type. The Communication Service Provider is delivered with Message Dispatchers for SMS and TCP/IP based communication, but others may be developed and added dynamically.



The SMS Dispatcher is capable of using serial/usb and ip modems as well as online messaging services for transmitting and receiving messages.

Application Management and Monitoring

An interface providing informational events regarding the state of the Communication Service Provider and its components as well as a JMX monitoring interface, which provides runtime access to the internals of the system. The detail level if the informational messages and the availability of the JMX inteface can be specified in the configuration.

Communication

The communication between the Backend Applications and the Communication Service Provider is based on JMS compliant message queuing, enabling asynchronous delivery of billing data, alarms and other information from the SmartAMM Gateways. The Communication Service Provider can deliver data to any JMS compliant messaging system, making it ready for enterprise deployment.

SmartAMM API

This is the API to be used by costumer systems wishing to utilize the Communication Service Provider. It consists of methods used for reading and writing the content messages as well as sending and receiving messages.

Costumer System

The cosutmer System is one or more systems controlling or using data from SmartAMM Gateways.

Requirements

The Communication Service Provider and the SmartAMM API requires Java 6.

The Communication Service Provider can be delivered as an installer for Windows (2000/XP/Vista) (tm), or as a standalone package for usage on either Linux(tm) or Windows(tm) or other operating systems where Java 6 is available.

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