Demand as
Frequency-controlled Reserve
Implementation and practical demonstration programme
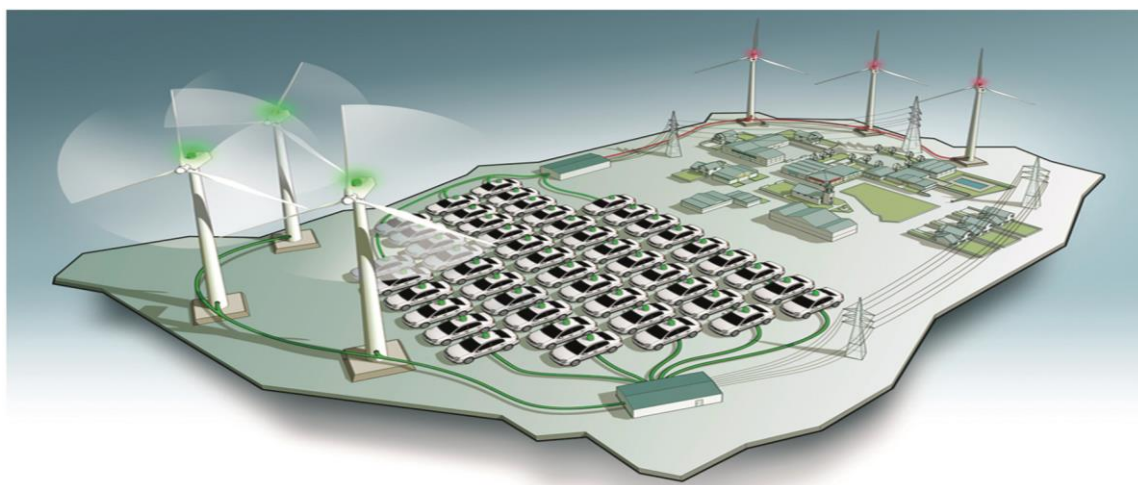
DTU Electrical Engineering
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Demand as
Frequency-controlled Reserve

Preface

This report is based on the main result of articles and papers written during the EUDP founded project: Demand as Frequency-controlled Reserve (DFR or DFCR). The project was started in April 2008, and was ended by December 2012. During the project period, many exciting challenges have been met with great enthusiasm from all DFR project members who have shown a memorable dedication to their work.

Active control of electricity demand is a key technology when creating a more dynamic, wind power friendly energy system. In this demonstration project, we have developed and tested devices, which use electric loads to provide frequency controlled primary reserves. The devices collected data from domestic households and industrial loads covering i.e. circulation pumps, electrical domestic heating, bottle coolers, a wastewater treatment plant etc., that have been analysed and used for the papers and articles included in this report.

A very special thanks to all the partners in the project, EUDP and the patient and understanding trial participants.

DTU Lyngby, May 2013

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Content

Abstract

The project is based upon active control of electricity demand as function of grid frequency. Data have been collected from domestic households and industrial loads covering i.e. circulation pumps, electrical domestic heating, bottle coolers, a wastewater treatment plant etc. A special electronic device, referred to as the "SmartBox", has been developed during the project. The SmartBox has the ability to control a connected load by either on/off (shutting down the mains for the appliance) or by altering the temperature set-point digitally for a thermostat. The box measure all relevant data from the attached demand and sends the data by mobile network to a central server. The SmartBox is configurable from a website where it is possible to i.e.: upload new firmware for the devices, configure of various parameters and access measurement data.

The practical demonstration has included data from about:
- 50 pcs. Carlsberg Vestfrost bottle coolers (control by thermostat)
- 20 pcs. Danfoss DEVI electrical domestic heating (control by thermostat)
- 20 pcs. Bornholm Forsyning water purifying plant (control by SCADA)
- 30 pcs. Various on/off controlling circulation pumps, dehumidifiers, freezers, heaters etc.

Electronic Housekeeper, a consumer product was installed in domestic households connected to i.e. freezers, refrigerators and electrical heating. The product included all necessary hardware to control the attached appliance as function of frequency. The product was customized to deliver data for the project as well.

Basically all tests has shown, that it is possible the postpone electricity demands as a function of frequency and thereby help maintaining the system balance. The flexibility depends on the size of the actual consumption and its capacity. By the capacity means the interaction of factors as: how fast the demand reacts, the probability that it reacts and the timespan of the possible reaction.

Dansk sammenfatning

For integration af vedvarende energikilder som vind- og solenergi er der behov for et mere dynamisk energisystem. DFR projektet er et demonstrationsprojekt der viser eksempler på, hvordan forbrug kan anvendes som hurtige og økonomisk attraktive reserver.

Der skal være balance mellem forbrug og produktion i el-nettet. Denne balance kan, blandt andet, måles på el-nettes frekvens. Når systemet er i balance ligger frekvensen konstant. Falder frekvensen, er det et tegn på for lav produktion i forhold til forbrug og der må i dette tilfælde tilføres yderligere energi i nettet. Stiger frekvensen, er der tale om overproduktion.

I dag bliver reserver hovedsageligt leveret fra produktionssiden og forbindelseslinjer til andre lande som f.eks. DC forbindelsen mellem Sjælland og Tyskland. Det er en forholdsvis dyr form for reserve, især i betragtning af, at disse kunne udnyttes på elmarkedet, hvis de blev frigjort. Som alternativ til en forøgelse af el-produktionen er det også muligt at tilpasse forbrug efter frekvensen, hvilket har umiddelbare fordele som f.eks.: en hurtig reaktionshastighed, økonomisk, en naturlig fordeling over hele el-nettet, m.m. Den vigtigste fordel er dog, at disse reserver vil kunne øge stabiliteten af det fremtidige el-system, hvor der forudses en stor andel af fluktuerende vedvarende energikilder. Den danske regering har besluttet, at 50% af det danske elforbrug skal være dækket af vindkraft i år 2020.

Der er mange eksisterende forbrug der egner sig til anvendelse som reserve. Det er i særdeleshed termostatstyrede forbrug som f.eks. elvarme, kølere og frysere men f.eks. også pumper og andre former for apparatur hvis forbrug kan flyttes tidsmæssigt, uden at det påvirker deres virkemåde, funktion og brugerkomfort nævneværdigt.

Projektet har følgende overordnede formål:
· Udvikling af hardware til frekvensregulering af forbrug.
· Validere og evaludere effektiviteten af teknologien under driftsforsøg.
· Evaluering af teknologiens faktiske påvirkning af apparaters funktionalitet gennem storskala demonstration med hundrede enheder.
· Teste og videreudvikle metoder til monitorering af DFR apparater med henblik på transmission system operatørens (TSO) behov.
· Opnå førstehåndserfaring og tilbagemelding samt evaluering af teknologiens accept hos forsøgsdeltagerne.
· Videreudvikling af DFR kontrollogik til opfyldelse af specifikke regler fra UCTE og Nordel.

Der er til dette forsøg blevet udviklet en såkaldt "SmartBox" der kan tilsluttes et apparat direkte og derved styre apparatet som funktion af frekvensen på el-nettet. Boksen kan styre tilsluttede forbrug på tre måder: 1) simpel tænd/sluk hvor forsyningsspændingen bliver afbrudt 2) digital termostatregulering, hvor der kommunikeres med produktets termostat, hvorved der reguleres som funktion af temperatur og frekvens. 3) Signal til et SRO-anlæg, som efterfølgende styrer udvalgte forbrug (og overholder lokale sikkerheds- eller funktionskrav)

Der er under projektforløbet blevet udført test af forskellige former for frekvensafhængige forbrug. Data fra disse tests er blevet indsamlet og behandlet og har alle ledt til samme konklusion: det er muligt at flytte forbrug som funktion af frekvensen. Fleksibiliteten afhænger af forbrugets størrelse samt dets kapacitet. Med kapacitet menes samspillet mellem faktorer som: hvor hurtigt forbruget kan frakobles, sandsynligheden for, at det vil blive frakoblet, samt det tidsrum hvori det vil kunne forblive frakoblet.

Der har været udført forsøg med basis i et lettere modificeret konsum produkt, Electronic Housekeeper, samt et produkt, kaldet SmartBox, udviklet i projektet specifikt til formålet.

Electronic Housekeeper blev installeret i husstande tilsluttet f.eks. frysere, køleskabe og elektrisk varme. Produktet havde alt hardware, som var krævet for at lade det indbyggede relæ styre efter frekvensen. Efter opdatering af softwaren kunne enhederne virke som frekvensstyrede reserver. Der var en del opstartsproblemer med produktet, hvilket var medvirkende til, at flere af forsøgsdeltagerne var mindre tilfredse med det. Hertil kom, at flere fandt udstyret forældet. Der var dog en grundlæggende positiv holdning til eksperimentet og ønske om mere tidssvarende og moderne udstyr. Det lykkes, trods udfordringerne, at få indsamlet brugbar data under forsøget. På baggrund af udsendt spørgeskema og kontakt til forsøgsdeltagerne lyder det ikke til, at frekvensregulering påvirker brugerkomforten. Der er dog andre faktorer der spiller ind på dette, så det er ikke muligt, alene på dette grundlag, at konkludere, at frekvensregulering af elektrisk forbrug ikke påvirker brugerkomforten.

SmartBoxen er programmerbar og kan kontrollere et forbrug som funktion af frekvensen samtidig med, at den opsamler måledata og sender disse til en central server. SmartBoxen kan styre et forbrug enten ved tænd/sluk (afbrydelse af forbrugets forsyning) eller via digital kommunikation til fx en termostat, hvor termostatens set-punkt flyttes inden for definerede grænser. SmartBoxen viser samtidig, at simpel autonom frekvensregulering kan indføres i produkter med meget få og billige komponenter. De konfigureres fra en tilhørende webside, hvorfra det også er mulig at tilgå indsamlet data.

Der er under forsøget indsamlet data fra ca.:

- 50 stk. Carlsberg Vestfrost flaskekølere (termostatstyring)
- 20 stk. Danfoss DEVI termostat, elvarme (termostatstyring)
- 20 stk. Bornholm forsyning vandrenseværk, styring via SRO-anlæg
- 30 stk. Blandet on/off styring; cirkulationspumper, affugtere, frysere, el-radiatorer m.m.

For optimal udnyttelse af frekvensregulerede forbrug har det vist sig, at det er meget vigtigt at timing er individuelt tilpasset de konkrete forbrug og deres kapacitet. Her tænkes især på samspillet mellem maksimal afbrydelsestid og minimal tilslutningstid.

Det er undersøgt hvordan systemfrekvensen kan benyttes som en smalbåndet kommunikationskanal samt hvordan det ved tilsigtede frekvensvariationer er muligt at aktivere frekvensregulerede forbrug og dermed tilpasse belastningen på de forskellige genererende enheder.

1. Introduction

1.1 Background

In interconnected electricity systems, such as Nordel and UCTE, the balance between electricity demand and generation must be kept in real time. If a power plant trips, the system frequency will decrease, and the balance must quickly be re-established by activating reserves in the system. These reserves are normally provided from generation side and are costly, e.g. 50 MW on the DC connection between Zeeland and Germany was reserved for reserves (until 2011), which cold otherwise be used for transactions in electricity market. In fact, reserves could be also provided by using frequency controlled demands with a number of advantages including low cost and fast speed.

The purpose of this project is to obtain practical experience with implementation of frequency controlled demand. The project will demonstrate, in real-life, the ability of frequency controlled demand to provide primary control, to improve frequency quality in systems with high share of wind power generation (normal frequency reserve), and disturbance frequency reserve to support system security in interconnected power systems.

In our previous research, theoretical investigation of the DFR technology has been carried out. The potential and economy of DFR compatible loads in Denmark has been investigated, several types of DFR control logic has been developed, power system impact has been evaluated, potential business models has been designed, and an implementation strategy has been suggested. The result show that the DFR technology is a promising technology from several perspectives. Technically, using DFR is feasible to provide reserves and enhance power system frequency control, while fulfilling power system requirements such as linear activation. Environmentally, the DFR technology is pollution free in contrast to traditional reserves from generation side. Economically, the cost of such reserves can be low and an attractive business model providing benefit for both society and the involved parties can be established. Seeing that renewable energy with fluctuating natures is continuously increased into power systems, frequency control will become critical in the future, where e.g. 50% electricity consumption will be supplied by wind power by 2020 in Denmark. The DFR is a novel technology that can facilitate such trend by providing quality service in need at a low cost and zero pollution. If implemented, unique advantages in market competition can be gained to realize the business potential for Danish manufacturers.

Bornholm, an island in the Baltic Sea, has been chosen as the foundation for the practical demonstration site. The electrical system at Bornholm can be considered as a microcosm of Denmark, representing 1% of the area, population, electricity consumption and is thereby a directly scalable model. The island has one connection line to Sweden and the ability to be run in islanding mode, which means, that the local power plant takes over the full demand coverage. The Bornholm power network has a high penetration of wind power –more than 30% of the total demand annually.

1.2 Project description

In this project practical experiments will be done with the two generic types of frequency control of demand that have been previously developed by members of the project team:

The external control: an on/off switch controlled by the system frequency. When the frequency is below a set point, e.g. 49.9Hz, the switch and thereby the attached appliance is turned off and will act as an automatic disturbance reserve. The set points (across many units) can be designed so the result is a classic proportional control for reserve.

The integrated control: A system where the set points of a thermostat, are controlled by the frequency. The integrated control is interacting with the normal on/off cycle and only adjusting the length of the on or the OFF cycle. If the frequency falls, the control will start to disconnect those devices that are in the end of their ON cycle. The integrated control is also active in the normal frequency interval (as normal frequency reserves) as well as in the over-frequency range. This makes the integrated control very suitable for normal frequency control reserve, which is important for a system with high penetration of fluctuating renewable generation, such as the Bornholm system under islanding operation condition.

In addition to the control feature, the box will also have capabilities for data collection and communication. The data features are only needed in field test for evaluation purposes. The appliances to be controlled by this type include electric heating and cooling devices, i.e. Danfoss DEVI electric heating controllers and Vestfrost bottle cooler refrigerators from Vestfrost. Electric heating is very attractive from a control perspective, since it can be disconnected and re-connected very quickly. Other types of demand, e.g. compressors for heat pumps or cooling purposes, have restrictions when to disconnect and can only re-connect after a certain resting period. The Danfoss electric heating can be supplied with an advanced control system that allow the user to control set point, check temperatures and receive alarm.

Integrated control will also be implemented based on the consumer home automation product from Electronic Housekeeper A/S to control miscellaneous appliances. This product will be established in domestic households to collect data from both a technical but also a user comfort point of view.

The project will have as objectives to:
· Practical hardware development of the technology for frequency controlled demand (DFR)
· Validate and evaluate the technology's field performance of reserve provision
· Evaluate the technology's actual impacts on appliance operation through large-scale demonstration of hundreds of such devices.
· Test and further develop monitoring methods for DFR appliances concerning the needs of the transmission system operator (TSO).
· Obtain first-hand experience and feedbacks, and evaluate customer's acceptance of the technology.
· Further develop DFR control logics to fulfil specific rules of UCTE and Nordel.

The practical demonstration has included data from about:
- 50 pcs. Carlsberg Vestfrost bottle coolers (control by thermostat)
- 20 pcs. Danfoss DEVI electrical domestic heating (control by thermostat)
- 20 pcs. Bornholm Forsyning water purifying plant (control by SCADA)
- 30 pcs. Various on/off controlling circulation pumps, dehumidifiers, freezers, heaters etc.

An elaborated version of the project description is available in the Appendix A.

2. Results

This chapter contains a summary of the main project result. Most of the results have been published in separate papers, which are included in appendices to this report. The reader is therefore encouraged to read the details in the respective papers.

2.1 Practical hardware development – The SmartBox

The SmartBox is a demand response (DR) device developed for use in smart grid projects with the need of being able to regulate numerous demands while measuring consumption, grid frequency and other related parameters. The box can regulate an attached appliance according to an incoming signal, either digitally or by relay (on/off). Regulating parameters can be measurements like grid frequency and voltage or signals received through the build-in modem, like control parameters, price signals etc. The unit has been developed for the DFR project, but is fully programmable and can be fitted to suit the needs of different projects. A power measurement integrated circuit takes care of measuring and calculating the power, RMS values, angles etc., with a maximum update time of 2 seconds. The frequency is measured using a zero-crossing algorithm and averaging over 8 cycles. Every 250ms the CPU receives and processes frequency measurements. All measurements are timestamped with a real-time clock that is synchronised via the internet time protocol NTP.

Data is send to the SmartBox server database. From the SmartBox website it is possible to configure various parameters for the boxes and data can be downloaded for further investigation. The box firmware can be changed over the air, which makes the SmartBox very suitable for field testing and long-term experiments and data collection.

Figure 1 SmartBox

2.1.1 Hardware description

The SmartBox comes in to variants. One designed for 13A equipped with a standard AC-outlet, and a 16A version for fixed installations. The box measures the grid voltage and the current drawn from the attached device. From the grid voltage waveform the frequency is calculated in parallel with RMS values, powers etc. in the power measurement chip. A central processing unit (CPU) takes care of all data handling, time stamping and control of internal elements.
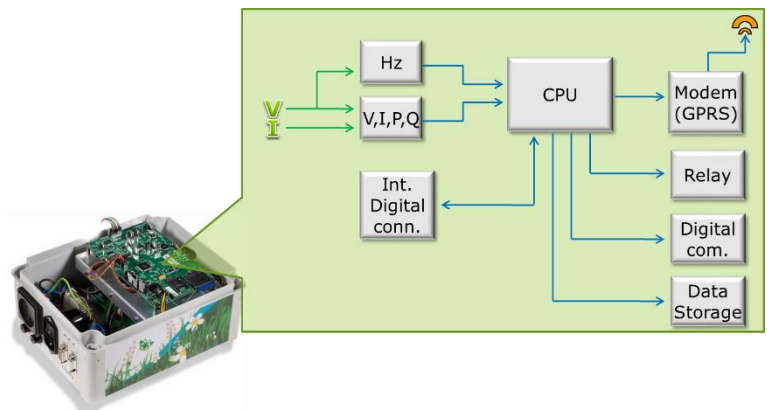

Figure 2 SmartBox hardware overview

Modem (GPRS)
Telit GC864-QUAD V2 GPRS Modem fitted with SIM card slot. The modem supports Python scripting and AT commands.

Relay
All units can be fitted with an internal relay that can disconnect power supply to attached appliance.

Digital communication
RS232 digital serial communication ports can be used for communication with devices like thermostats, PWM modules, PC's etc.

Data Storage
The SmartBox has an internal SD card storage that can store data for about a 1 year period and serves as a data buffer.

Int. digital conn.
Internal digital connectors are accessible for additional use.

2.1.2 Server setup

Communication between the SmartBoxes and the SmartBox Server is established through the GPRS network. The SmartBox server holds the SmartBox Webpage from where the SmartBoxes can be configured, upload of new firmware and collected data can be downloaded.
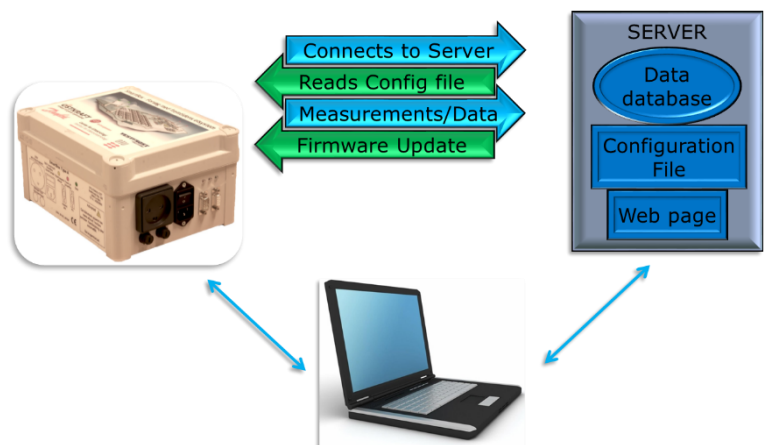
The SmartBoxes connects to the server in specified intervals. For the project usually once every hour. While connected to the server the box will deliver the measured data and reads the configuration file. If a new firmware is available, it will be downloaded and installed.

Figure 3 SmartBox communication

The configuration files includes all the SmartBox specific settings that is setup for all boxes individually. Settings includes i.e. frequency thresholds, data sampling, appliance maximum off/on timings and accepted temperature off-sets.

2.1.3 SmartBox webpage

The SmartBox webpage designed to be the centre for all SmartBox related usage as set-up, maintenance, testing and data download. It also contains information about all installations and SmartBox status.

Further development for the webpage would be an alert system that can sent alerts when a box is offline, abnormal measurements are recorded or boxed reports errors.
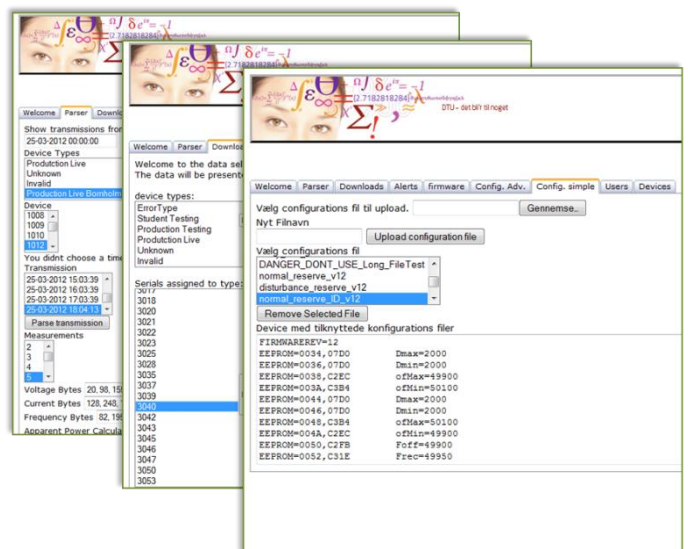

Figure 4 SmartBox webpage

2.1.4   SmartBox data

Data from the SmartBox is send on a binary form to the SmartBox server, which parses and processes this data to human readable values in the database. The boxes can be repro-grammed to support other kinds of project specific measurements that have interests. Following table describes the data that is delivered now.

Device ID		SmartBox serial number
Config ID		Configuration file read for corre-sponding measurement
Firmware ID		Firmware version for corresponding measurement
Timestamp	NTCP time server	
Frequency	[mHz]	Grid frequency
Voltage	[V] RMS 9 decimal	Grid voltage
Current	[A] RMS 9 decimal	Current drawn by attached device
Apparent Power	[W]	Consumption of attached device
Active Power	[W]	Consumption of attached device
Reactive Power	[W]	Consumption of attached device
Angle	[Degrees]	Angle between grid voltage and cur-rent drawn by attached device
Temperature	[C]	Temperature measured in either bot-tle coolers or domestic heating
Vestfrost Carlsberg Bottle cooler specific status		Compressor, Defrost, On/Off, ther-mostat communication error.
Danfoss domestic heating specific status		Temperature off-set, On/Off, com-munication error
Relay specific status		On/Off, Timer state (indicates if, for instance, the relay has just been switched off and a predefined timer makes sure it cannot be turned on again before a defined time period has ended. Same situation when it has just been turned on. Then it can be defined for how long it must be turned on before it can be shut off again.
Resolution Flag		Indicates whether the measurement resolution is a high, low or both. Usually measurements are at low resolution (i.e. 1 min.) until an event has happened. Then it measures with a predefined high resolution (i.e. 2 sec.) for a specified time internal (i.e. 30 sec.).

2.2 Validation and evaluation of DFR field performance

The result presented in this chapter is mainly focused on the papers: *"Demand as Frequency Controlled Reserve – Implementation and Practical Demonstration"*, *"Electricity Demand as Frequency Reserve – Experimental Results"*, *"Smart Demand for Frequency Regulation: Experimental results"* and *"Demand as Frequency Controlled Reserve: Water Treatment, Relay-controlled Loads, Micro-grid"*, all to be found in the appendices section.

2.2.1 Frequency measurements and synchronization

The system frequency is assumed to be the same throughout the synchronous area, so at a given point in time, the difference in frequency measurements from different devices can come from noise in measured signal, clock drift, and lack of precision in the time stamps. Lacking an independent source of frequency measurements we validated DFCR measurements by comparing frequency measurements taken on different devices at the same point in time. For each of the time stamps with 2 or more measurements, the average frequency was calculated and the standard deviation was found. The results from 397,000 measurements was 1.36585 mHz. This level of error is well within the tolerances for our application. This analysis rounded timestamps to the nearest second, but the raw data has a resolution of milliseconds which indicates a potential to further narrow the level of error.
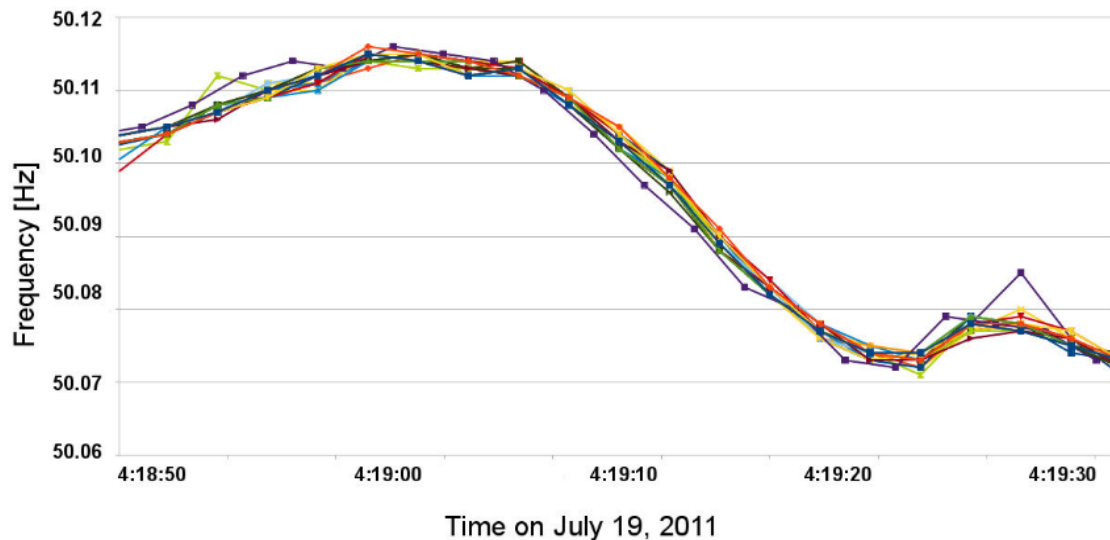

Figure 5 Typical high resolution measurement series during over-frequency with 2s sampling period over 40s.

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2.2.2 Vestfrost bottle cooler thermostats

To validate the functioning of the thermostats, the devices were configured to operate in normal reserve mode.

The parameter values were
Omax = 2 ∘C (Temperature offset)
Omin = −2 ∘C
fmax = 49.90 Hz
fmin = 50.10 Hz
The expected result of this configuration was a positive correlation between refrigerator power consumption and system frequency, and a negative correlation between refrigerator air temperature and system frequency. To demonstrate this correlation, data samples were grouped by frequency in 25 mHz intervals in the range 49.9-50.1 Hz and two additional groups for samples above and below this range. The results plotted in Figure 6 Relation between system frequency and power or temperature respectively show that the average power and average temperatures are with good agreement linearly dependent on the system frequency.

Figure 6 Relation between system frequency and power or temperature respectively

Normal Reserve Operation

Data was taken from 26 refrigerators over 16 weeks. Samples of frequency, power and temperature were taken by each control box every minute. The samples were sorted chronologically and the mean power consumption, and temperature values of the population were found for each minute. This method resulted in power consumption values scaled to the size of a single refrigerator, rather than the aggregate value of the population. The data from each minute was grouped by system frequency value and then the mean power consumption and temperature was found for each frequency group. The results for power consumption, shown in Figure 7 Average frequency response NR, are well fit by a linear least squares approximation. The data set is less dense at frequency extremes because system frequency follows a Gaussian distribution around 50.00Hz. At frequencies above 50.10Hz and below 49.90Hz, the linear trend breaks down because the thermostat's offset has reached the limit of it's deviation from the user given set point.
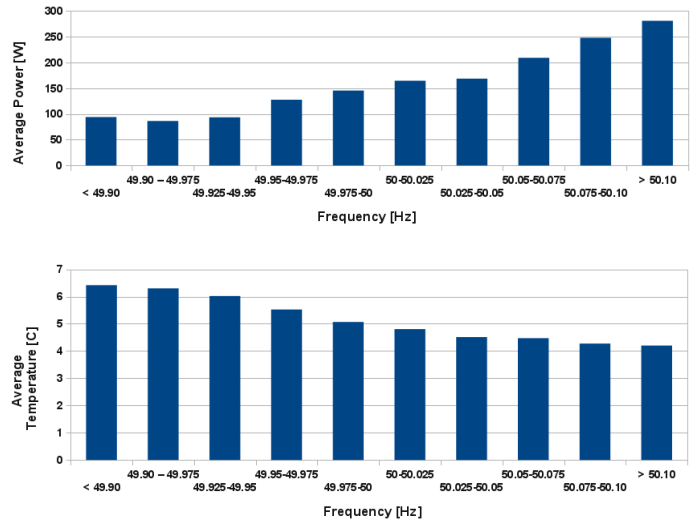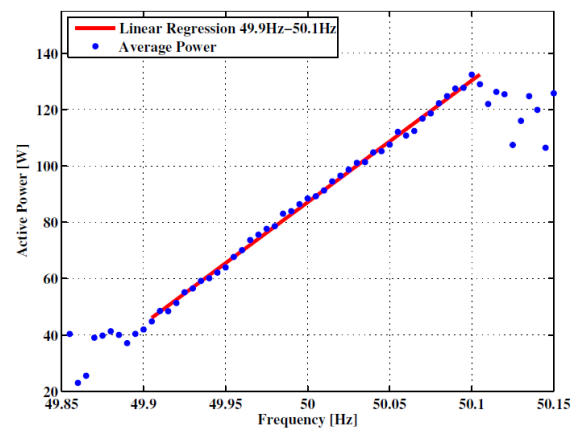

Figure 7 Average frequency response NR

Comparing the compressor's power consumption of 230W, we find that in average 39% of the compressor's power has been mobilized to participate in DFCR service. Continously changing the refregirators set point offset increased the number of times that the compressor cycled ON and OFF by 10% compared to non-DFCR operation.

Disturbance Reserve Operation
The refrigerators were reconfigured to operate as a disturbance reserve for an 8 week period. Analysing the frequency response results shown in Figure 8 Average frequency response DR shows that, despite the noise caused by a relatively small data set at extreme values, a frequency response is apparent at frequency values below 49.90 Hz and frequencies above this value gave no response.
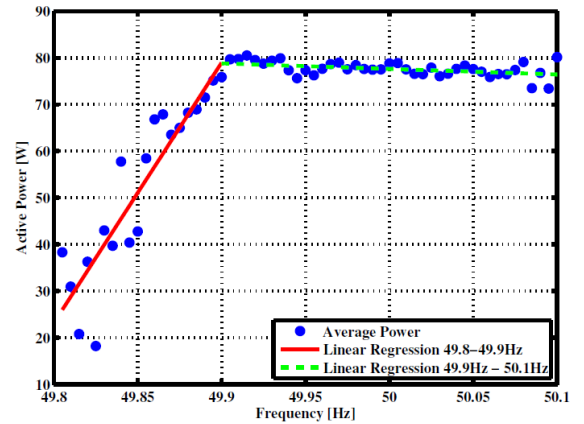

Figure 8 Average frequency response DR

2.2.3 Danfoss DEVI electrical heating

The DFCR system for electrical space heaters was deployed in 22 houses during January 2012. Data was collected during the period 2012/01/23 until 2012/12/14. Due to the complexity in deploying and validating the functionality of the DFCR devices, only some of these devices will be part of the analysis of this report.

The DFCR systems consist of two parts: A commercially available thermostat for electrical space heater (DEVI, Danfoss), which has been modified to expose a serial port to an external controller, and an external controller ("Smartbox") which was produced for this experiment.

Since the rated power consumption of the electrical heaters varies the power consumptions has been normalised in such a way that all boxes have a normalised rated power consumption of 100 % full load

Several of the electrical heaters were used as a secondary heating source the primary being wood stoves, further electrical heating devices, or other types of heating. Due to this, the electrical heaters were off at periods independent of the system frequency thereby impacting the average power usage.

We will start out by looking at all 6 boxes from *2012/10/03 to 2012/12/19*.

The linear response is visible until 49.93 Hz. At this frequency value, the power consumption reaches 7 percent full load and cannot be reduced further. These last 7 percent can be due demand when the maximum disconnection time has been exceeded. At 50.10 Hz, the average power consumption is 61 % full load, giving a frequency response equivalent to 54% of full load. The electrical heater should use the same amount of power with or without normal reserve, so the average power usage should be the same in the both cases. The average power consumption was 26 % full load, so by having a frequency response of 54 % the frequency response can be expressed as 0.317 % Full load/mHz seen as the best fit slope in Figure 9 Frequency response of all 6 boxes with a normalised power usage. Average daily outdoor temperature: 5.5 °C
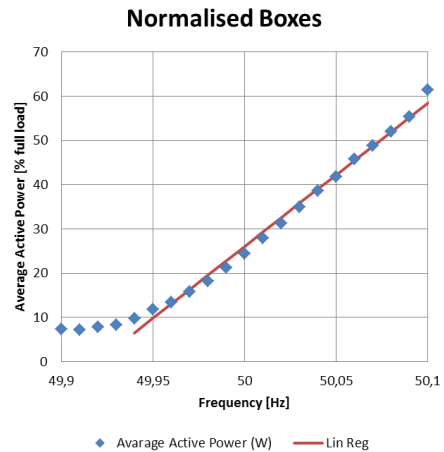

Figure 9 Frequency response of all 6 boxes with a normalised power usage. Average daily outdoor temperature: 5.5 °C

Power consumption

From the result above, the boxes seem to provide the desired frequency response, but the question is: Is this a result of only a few boxes having great frequency response and the rest not at all? The first clear observation should be that the average power consumption at 50.1 Hz is not close to 100 percent full load (because a modest temperature in the period).

In order to analyse whether the 6 boxes all collect valid measurements, we will start by looking at the power consumption independent of the system frequency.
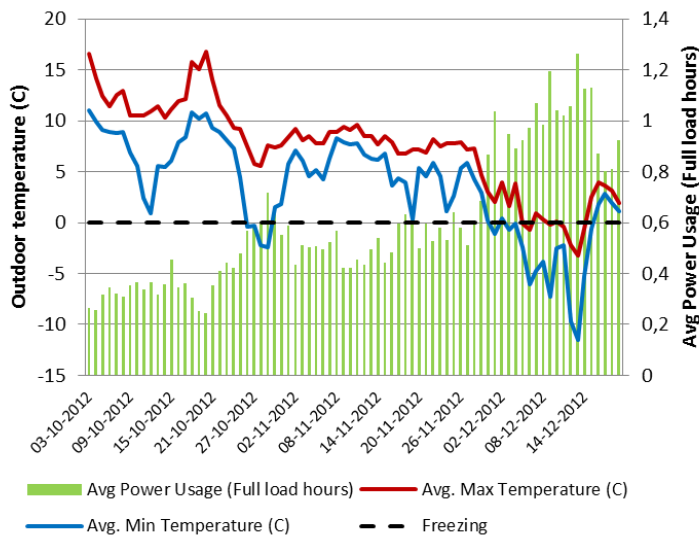

Figure 10: Outdoor temperature for Rønne (Bornholm) during the period 2012/10/03 to 2012/12/19 as well as the normalised average power usage of all boxes.

As seen in Figure 10 the power consumption of the 6 boxes corresponds to the outdoor temperature of the period, so the radiators are obviously on when they need to be.

Temperature and off-set values

Next we will look at whether the electrical radiators react according to their temperature offset value. Below is illustrated the active power usage of Box 2037 as well as the ambient indoor temperature as measured by the thermostat during half a day mid-December (see Figure 11). As seen the temperature rises each time the radiator is on, and drops when the radiator is off.
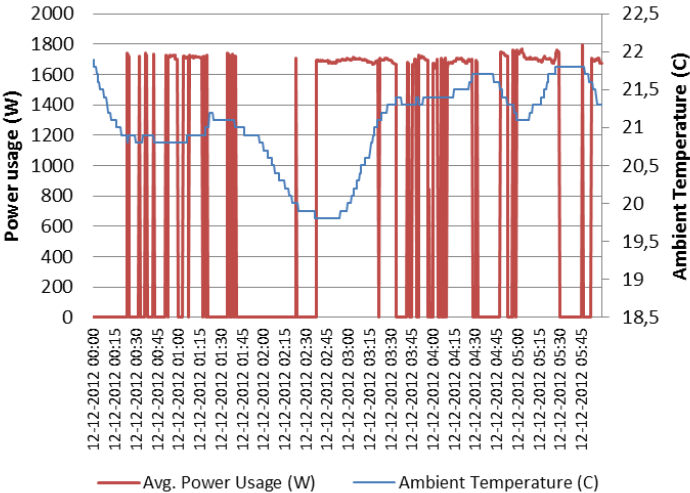
Figure 11: Power usage of Box 2037 as well as the ambient temperature measured by the thermostat

Zooming in on the first 6 hours of that period we now look at whether or not the thermostat actually switches on and off according to the set-point as they change dictated by the system frequency.

This offset is then added to the user defined set-point. In the figure below this shifted set-point is shown with an original set-point of 21^0 C. Furthermore the ambient temperature and on/off indicator of the radiator is shown.
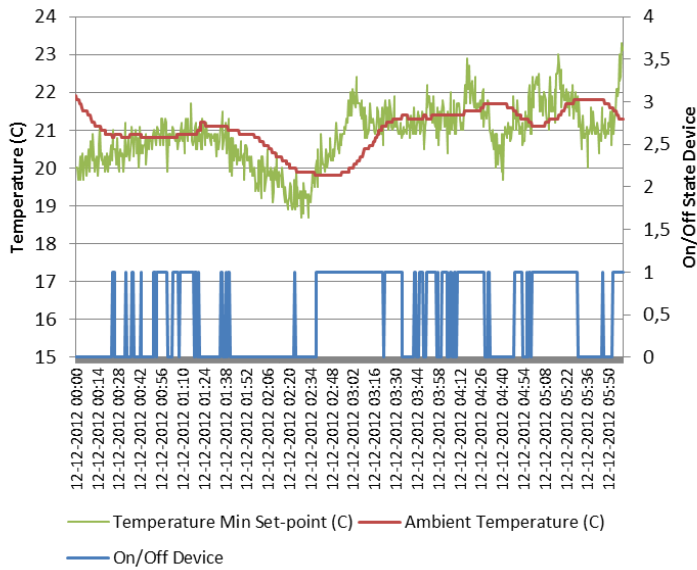
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Figure 12: Temperature offset, ambient temperature, and on/off indicator, SmartBox 2037.

As the temperature rises above the dead-band the device turns off.

Frequency

Turning back to the system frequency we will now analyse the behaviour and volatility of the frequency and how this affect the frequency response of the boxes and thereby how this potentially impact the user comfort.

Looking again at the frequency response of the average power usage of all the boxes as well as system frequency mass we get the following plot.

From this we get that 98.4 % of the frequencies lie within the interval 49.9 Hz and 50.1 Hz and 80.2 % lie within the interval 49.95 Hz and 50.05 Hz. 0.95 % is above 50.1 Hz, 0.58 % is below 49.9 Hz. This correspond to 1620 min/month outside the normal range.
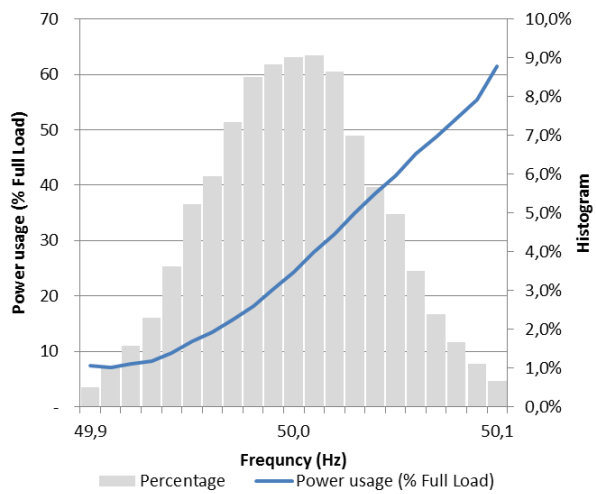

Figure 13 Histogram of frequency and frequency response.

Looking at the frequency response interval of the 6 boxes the normalised power usage quantiles come out as seen in Figure 14.

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It illustrates the degree of predictability. With only 6 units there are quite a spread in the total consumption. With thousands units the quantiles would be closer – and a higher degree of predictability would be possible.

Frequency correlation
How random are the measured frequency of the system and thus how big a role could frequency response play as a method to reduce frequency volatility? In order to analyse this we will perform a time-series analysis.

The correlation between the frequency in one minute and the frequency in the following minutes is calculated by the autocorrelation factor. If the correlation is 1 then the frequency is always the same. A low value (e.g. below 0.3) indicate little correlation.

Figure 14 Power usage quantiles of system frequency group of 0.01 Hz.

The graph below shows that there is little correlation beyond 10 minutes, but frequency is auto correlated in the short term (0-10 minutes).

The relative rapid decrease of the correlation factor indicate that few demand problems would occur, e.g. in relation to electric heating, where a typical time constant is in the order of hours.
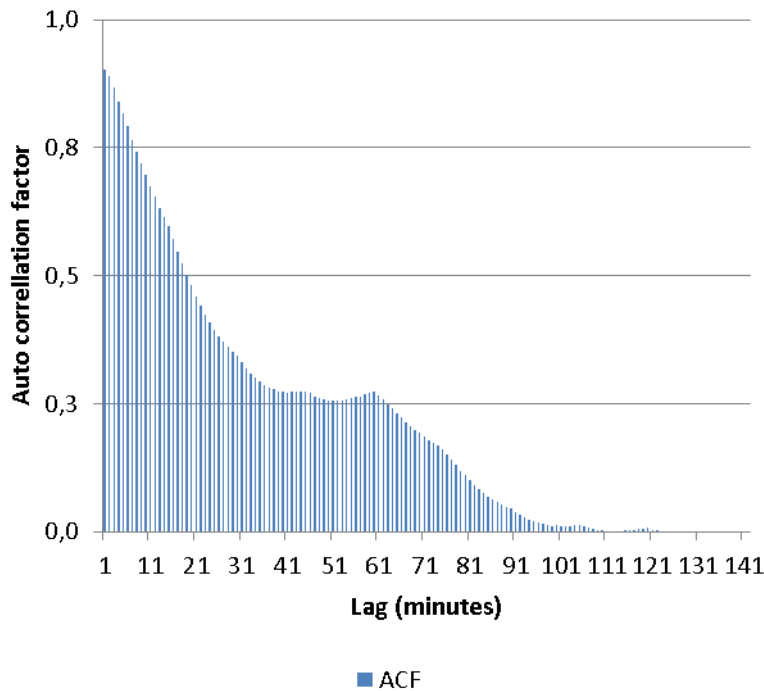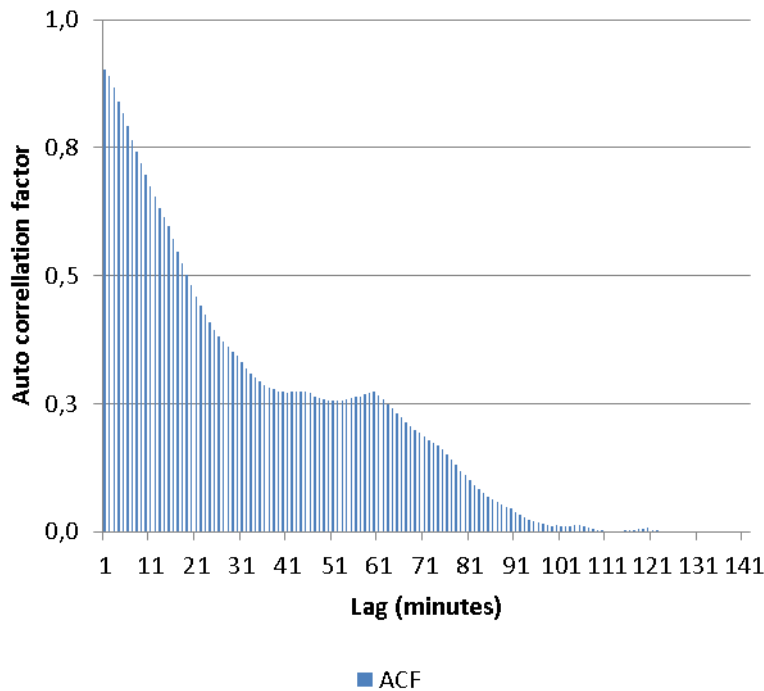
Time dependence and rebound effect

We expect a rebound effect on the power usage after a period of the heating being shut off. While the electrical heating has been turned off the room temperature will drop and thus there will be an additional need for heating in the period after. We would expect that if the frequency has been low (less than 49.98 Hz) in the previous 10 minutes, the electrical radiators would have been off relatively more often. This increases the probability of a higher power usage at the end the time interval rather in order to compensate for the drop in temperature. On the other hand if the average frequency has been high in the previous time interval we would similarly expect at lower usage power at the end the time interval in order to compensate for a relative rise in temperature (the heating is only off if the maximum temperature is reached and not because of frequency control). Thus the temperature in the room is affected by the history of the frequency.
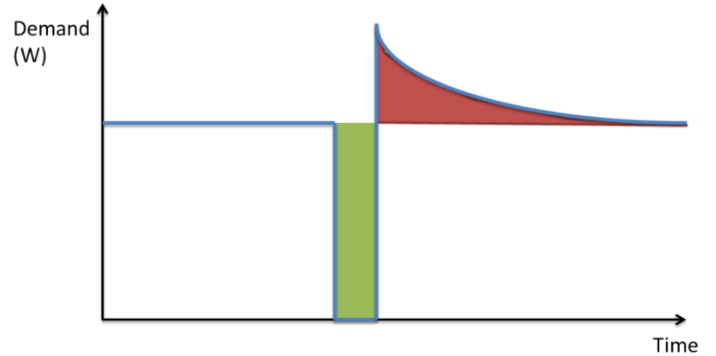

Figure 16 The electrical heater as an "energy storage". The green and red areas are expected to be more or less equal. Minor differences can occur due to change in efficiency and change in heat loss.

Frequency response would thus force the curve of a power usage versus frequency plot of the low frequency group (below 49.98 Hz) to be above the curve of the high frequency group (frequencies being above 50.02 Hz), and still show a frequency response for both curves (see section below, as well as Figure 17, Figure 18 and Figure 19).

We then consider the actual system frequency at progressive time points of 5, 10 and 20 minutes intervals and compare these with the average power usage at these 5, 10, and 20 minutes progressive time points. This is shown in the plots below (Figure 17, Figure 18 and Figure 19). Only points with more than 25 observations are included.
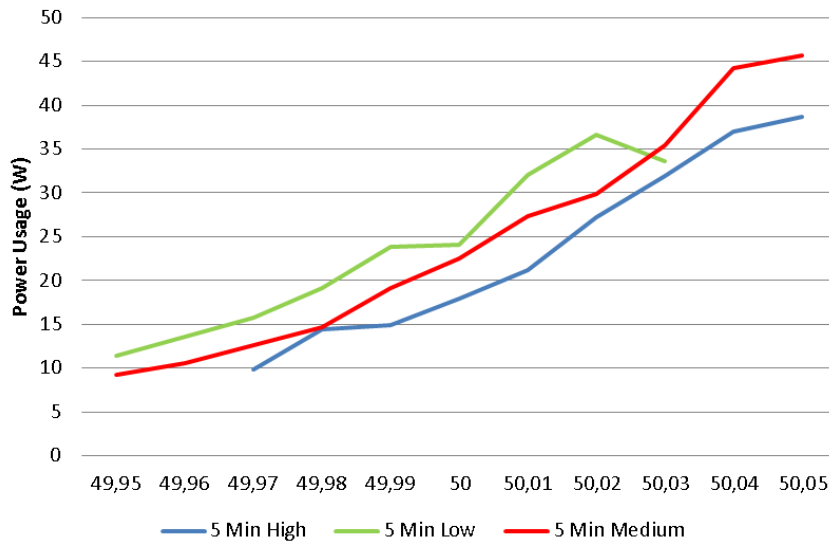
Figure 17: Rebound effect considering 5 minutes periods. Low < 49.98 Hz, Medium 49.98-50.02 Hz, High > 50.02 Hz

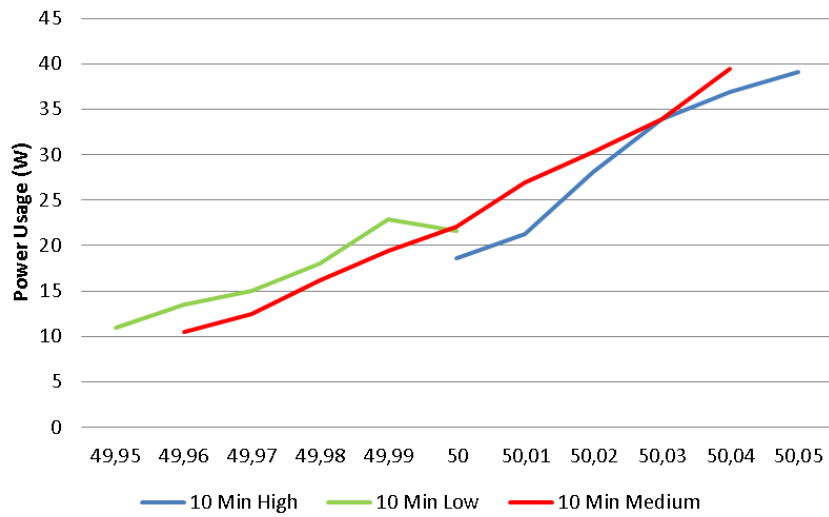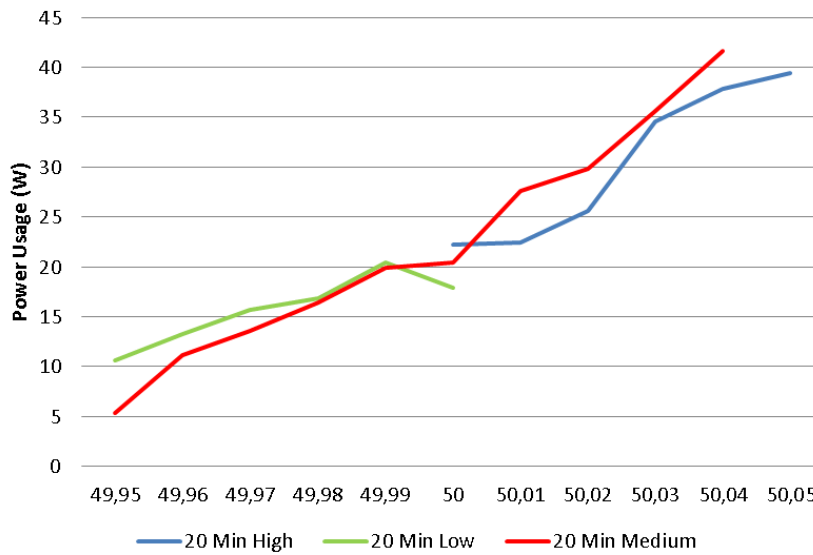**Figure 18: Rebound effect considering 10 minutes periods. Low < 49.98 Hz, Medium 49.98-50.02 Hz, High > 50.02 Hz**

Figure 19: Rebound effect considering 20 minutes periods. Low < 49.98 Hz, Medium 49.98-50.02 Hz, High > 50.02 Hz

From these figures we see that rebound effect is present but that this rebound effect diminishes over longer time spans (above 10 minutes). Increasing the period span also reduce the number of high frequency observations after low frequency periods, as well as the number of low frequencies after high frequency periods.

2.2.4 Bornholm Forsyning Wastewater treatment plant

Treatment of wastewater is an energy intensive service with a large untapped potential for demand response. The central wastewater treatment plant serving Bornholm participated in the DFCR experiment by allowing some non-critical loads to be controlled to provide frequency controlled disturbance reserves. These loads were in the form of induction motors that pumped water and induction motors that moved cleaning brushes. All motors were interfaced with power electronics that limited inrush current (soft-starters) and were actuated by an existing industrial control system (here referred to by the term "Supervisory Control and Data Acquisition", SCADA). A DFCR control SmartBox measured the AC system frequency and provided a binary input signal into the SCADA which indicated when the system frequency had fallen below a given threshold. The SCADA used this signal to interrupt processes that tolerated interruption, while giving first priority to ensuring that process constraints were not violated. Measurement SmartBoxes, with firmware identical in the control SmartBox but without an output signal, were installed at each load to gather data.

A time series showing the typical operation pattern of the plant is shown in Figure 20.
The relative frequency of operation in each of these two states determined the average active power consumption. The aggregate frequency response of all the loads in the water treatment plant measured over a 9 week period is shown in Figure 21.
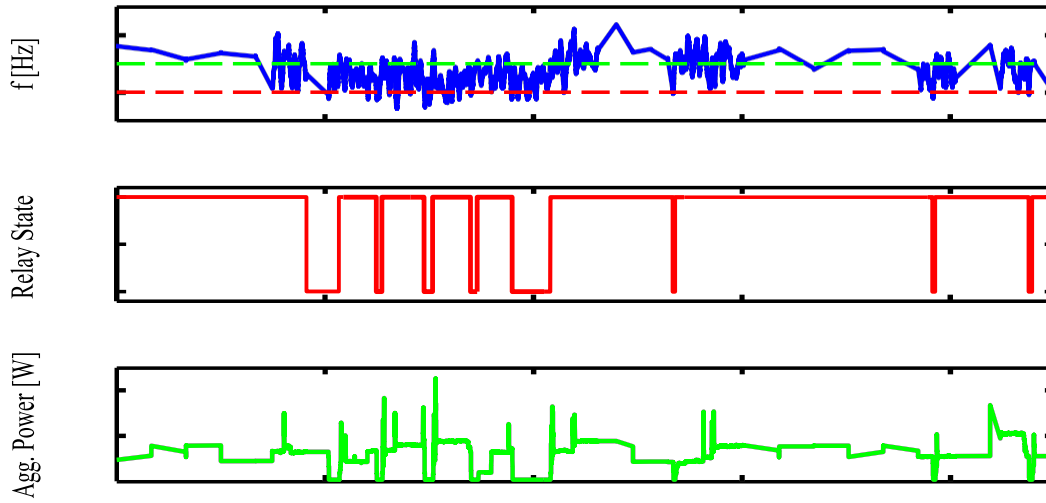
Figure 20 Typical time series from water treatment plant.

The average power consumption above the reconnect frequency was 6.05kW, compared to an average below the cutoff frequency of 2.41 kW, a reduction of 60%
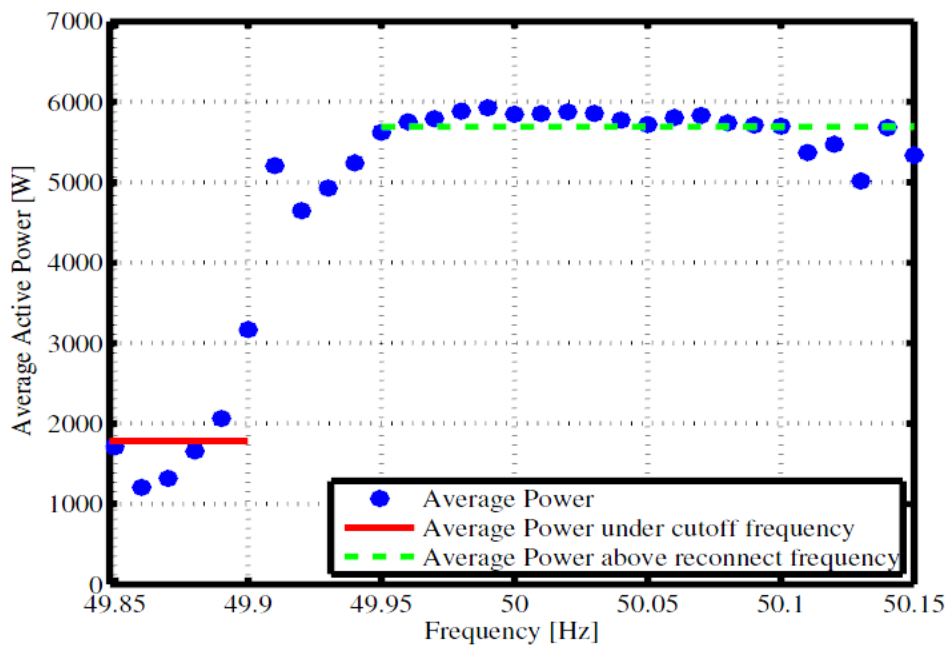

Figure 21 Frequency responce og water treatment plant with disconnect frequency 49.90 Hz

2.2.5 General Purpose Relay-controlled Loads

A variety of loads were tested for frequency regulation service by connecting them to a relay which was controlled by a Smartbox. These units opened the relay when system frequency fell below a given configurable threshold, and reconnected when system frequency returned above a higher threshold, subject to time constraints on the minimum and maximum allowable disconnect time. Another time constraint ensured that after being disconnected, the load remained reconnected for a minimum time span.

During the experimental period, the frequency response of the relay-controlled showed a weak frequency response because of the strong influence of time constraints.

The frequency response is highly sensitive to the parameter values, and in this case the parameter values were not optimized for the Nordic power system. Raising the reconnect frequency would help mitigate the problem associated with the minimum reconnect time, and to work around the maximum disconnect time constraint the cut-off frequency could be lowered, so the reserve is active less often and for shorter time periods.

2.2.6 Christiansø

Christiansø is a decommissioned naval base that is a popular tourist destination. Around 100 people live permanently on the 0.22 km2 island [8]. Their electric power system is composed of 4 diesel powered generators, two with a rating of 180kW, one 130kW and one 60kW. At the moment, there is no renewable electricity generation, though the wind and solar resources are available. Two bottle cooling refrigerators with DFCR functionality have been installed. The refrigerators were configured to provide disturbance reserves, as defined by the Nordic Power system grid codes.

Compared to a large interconnected synchronous system, the frequency on the island has a mean value far from nominal, and frequency fluctuations are larger. The system operated in two distinct frequency regimes, corresponding to the operation of different generators in their fleet.

Because the configuration of the refrigerators did not account for the operation at off nominal frequencies, the refrigerators configured as a disturbance reserve did not offset their thermostats for long periods of time.

While the size of the data set did not allow strong conclusions to be drawn about the frequency response, this is a realistic scenario in the sense that a disturbance reserve is allocated to respond to rare conditions (i.e. large faults).

2.2.7 Electronic Housekeepers

The main idea to include the Electronic Housekeepers (EHs) in the pilot project has been to demonstrate that an existing appliance and existing product (home automation) can be used for frequency control.

The principle of the EHs is very similar to the simple on/off-type of the DTU smart box (the external type):
- it switches power off when the frequency is low (it does not provide frequency control above 50 Hz)
- and switches power on again when the frequency is OK
- or when the maximum duration is reached

An EH consists of the EH-console and two Switchkeepers (SK1 and SK2).

The Switchkeepers measure the frequency and consumption and automatically disconnect and reconnect the appliances. It is a simple on/off switch – only dependant on the frequency. Thus it does not consider the temperature in the fridge any other settings of the appliance.
For more information about the Housekeeper setup and experiment please refer to appendices.

The goal of this part of the pilot project was to investigate the use of the Electronic HouseKeepers, thus the participants were told that they could connect an type of appliance to the EH. Unfortunately there were problems with long disconnections in the early beginning of the project. Some of the equipment was flawed. The basement of one house got flooded as a submersible pump was disconnected and the content of three freezers were ruined. Luckily two of the freezers were almost empty. This led to many participants choosing to connect the Switchkeepers to smaller and less important appliances, like lamps and even to the radio and a toaster.

The graph below shows the average power use for SK1 and SK2 units as a function of frequency. First of all it should be noted that the number of measurements with frequency below 49.9 Hz (or above 50.1 Hz) is very limited, thus the statistical significance is low for these frequency areas. As previously stated the average consumption of all the EHs is very moderate and some EHs are not used for longer periods of time.
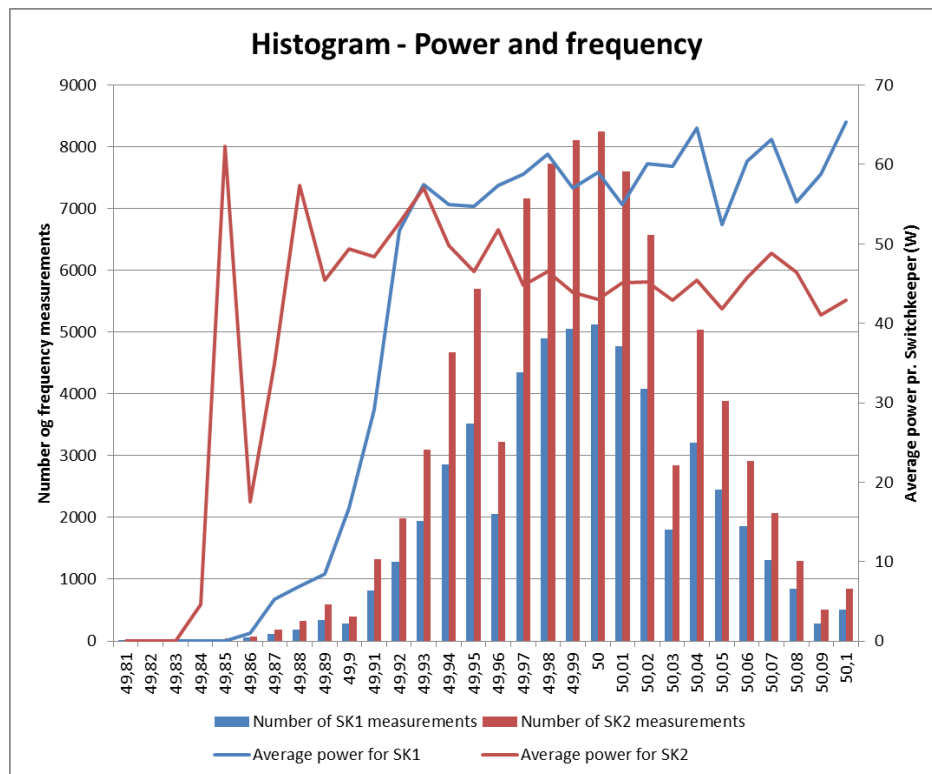
Figure 22: Histogram for 26 EHs (26 SK1s and 26 SK2s) in the period 2011-02-20 to 2011-04-30. The switch-off point for SK1s is at 49,9 Hz and for SK2s it is 49,85 Hz.

In theory the EHs should not have power consumption below the switch-off point for the Switchkeeper except when the maximum disconnection time is exceeded. For the SK1s this point is at 49,9 Hz and for SK2s it is 49,85 Hz. Above this point the average power use should be independent of the frequency (except for the rebound effect). The graph in Figure 22 confirms this theory, taking the statistical variations into account.

2.3   DFR monitoring methods for the TSO

2.3.1   System frequency as information carrier

Load controllers that can measure AC system frequency and react to frequency deviations are approaching commercialization. All power generators contain control systems able to regulate system frequency, but the frequency set point values are only rarely modified from nominal values. A system operator can communicate to frequency sensitive loads by changing the frequency set points of the system's frequency regulation resources. Explicitly signalling system state by generating off-nominal system frequency values can be used is as novel narrowband communications channel between system operators and frequency sensitive distributed energy resources (FS-DER).

A new operating concept, which broadcasts discrete system state information to frequency sensitive distributed energy resources (FS-DER) has been described. System state is communicated to FS-DER by adjusting the generators' frequency controller to target off-nominal frequencies. The number of distinct states that a load can detect is a function of the bandwidth available and the standard deviation of frequency measurements. The standard deviation in turn, can be reduced by a low pass filter on raw frequency samples. The feasibility of this concept was demonstrated by analysing data collected from an operating island power system. The analysis shows that FS-DER loads can be dispatched into 4 discrete states while conforming to standard frequency constraints. Data collected from small power systems shows that it is feasible to encode between 4 and 8 discrete symbols for FS-DER dispatch.

2.4   Evaluation of customer acceptance of DFR technology

2.4.1   Danfoss DEVI

Regarding user comfort we have been in contact with all 6 participants whose SmartBoxes are included in this analysis. The feedback we received was that they did not take any notice towards the boxes being in use and no change in comfort was registered. There have been no rigorous testing of whether the average power usage actually is the same with or without the SmartBox. Also there have been no extensive survey of the user experience. Hence concluding that the user comfort is uncompromised by this kind of frequency response would not be strictly supported by the experiment.

2.4.2   Electronic Housekeepers

After the pilot project testing Electronic Housekeepers an evaluation form was sent out to the participants in order to hear their response to the experiment. 15 participants (out of 28) have responded to the questionnaire. Some did not respond as they only participated very shortly in the project. Most have responded that they found it interesting to participate in the research project – 7 people replied *completely agree* and 4 additional *agree* to this statement (see Figure 23: Results from the evaluation of the EH pilot project.

Even the respondents found the research project interesting, many of them where not thrilled about the Electronic Housekeeper technology. Three of the respondents noted that the Electronic Housekeeper product appears to be outdated - both the user interface, the speed and the stability. One of them suggested that an alternative with 'Ipad style' could be attractive. However the same participant also notes: "Good radio". Despite many technical problems, the participants remained positive towards the project.

Four participants experienced problems with their freezer, fridge, and dryers when connected to the Electronic Housekeeper. In some cases the SK2-unit was defect and the problem was solved by changing the hardware. However, the content of more than one freezer was ruined. These start-up problems in the beginning of the pilot project led to several participants losing their faith in the Electronic Housekeeper. One participant notes in the evaluation that the EH was "an extra and unnecessary electricity consuming gadget". This participant felt that he was very aware of his electricity consumption and had no need for the Electronic Housekeeper. He participated in the project because he found the research project "beneficial for society and technical interesting". He also found that the EH switched his fridge off "rather often".
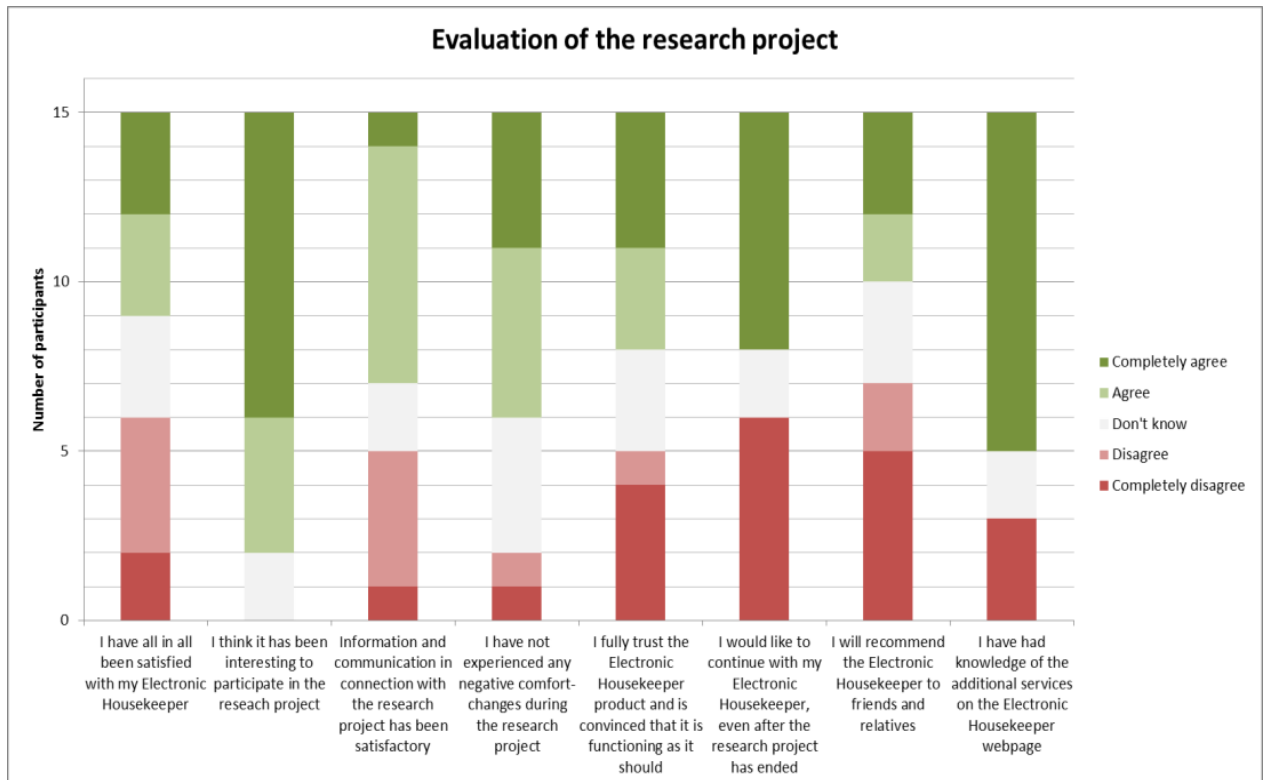

Figure 23: Results from the evaluation of the EH pilot project.

Another participant notes in the evaluation of the project that his radio (connected to a SK1 Switchkeeper) turns off rather often in approximately 30 seconds. Other times it can run for days without interruptions. He has tried finding a relation between the wind (and thus the assumed fluctuations in power production) and the disconnection of the radio (caused by frequency variations). But he found none. This example shows us that some of the participants have been very keen in following the electricity consumption and the research project. Despite problems with both the freezer and the submersible pump, the same participant is still optimistic and is happy to continue the research project, as he finds it interesting.

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2.5 UCTE and Nordel control logics

2.5.1 Direct Load Control by AC Frequency Modulation

Fine-grained under frequency load shedding called "demand as a frequency controlled reserve" (DFCR) has been shown to be a promising method of providing frequency regulation service from distributed loads. Micro-grids with a large portion of intermittent renewable generation will benefit greatly from this technology because their low inertia.

The system operator can use DFCR for energy balancing by adjusting the frequency controller of generators to schedule off-nominal system frequency values. The feasibility of the proposed system is evaluated on an existing small island power system.

A proposal of a new operating concept which utilizes DFCR, a highly distributed under frequency load shedding method, as part of direct load control scheme is presented. Frequency sensitive loads are dispatched by adjusting the generators' frequency controller to target off-nominal frequencies. The feasibility of this concept was demonstrated by simulations, and by analysing data collected from an operating small island power system. The analysis shows that DFCR loads can be dispatched with high reliability without endangering the system's ability to remain within the range of acceptable frequencies.

3. Conclusion

In this demonstration project, we have developed and tested devices (SmartBoxes), which use electric loads to provide frequency controlled primary reserves. The results verify the correct functioning of the developed DFCR devices with respect to their synchronization in time and thermostat response. They were installed on the Bornholm Island with a broad diversity of loads under control and tested doing daily use.

An analysis of the frequency and power consumption data of the temperature controlled loads (TCL) found that while operating as a frequency reserve in the range 49.90 Hz - 50.10 Hz, the frequency response was larger than the average power consumption. The loads under control in the wastewater treatment plant reduced power consumption by an average of 60% during under-frequency events. The response of general purpose relay-controlled loads were sensitive to the time constraints, frequency threshold values and the distribution of frequency values for synchronous system where they are connected. The slope of response measured as W/Hz was larger when the refrigerators operated as a disturbance reserve, though the magnitude of response was smaller.

In a commercial roll out, the DFCR functionality would be built in to the appliance controller. Compared to conventional appliances, DFCR appliances would have the added expense of a circuit to measure the system frequency. This increase in the bill of materials could be subsidized by power system operators or financed by a market approach, e.g., participation in the Nordic ancillary services market. The DFCR technology can be seen as an enhancement to the existing frequency dependent load, which is estimated rather than monitored.

For demand-side resources in the residential sector to become economically viable, the fixed costs of providing this functionality must be small to match the small power demand of each individual unit. The DFCR controllers used in this experiment were not themselves cost effective because of the additional features needed for this research work. By using low-cost components for the core functions of measuring frequency and executing the DFCR algorithm it can be develop. Many products in the market already include the necessary processor power, which means that only few extra low-cost components needs added.

A proposal of a new operating concept which utilizes DFCR, a highly distributed under frequency load shedding method, as part of direct load control scheme is presented. Frequency sensitive loads are dispatched by adjusting the generators' frequency controller to target off-nominal frequencies. The feasibility of this concept was demonstrated by simulations, and by analysing data collected from an operating small island power system. The analysis shows that DFCR loads can be dispatched with high reliability without endangering the system's ability to remain within the range of acceptable frequencies.