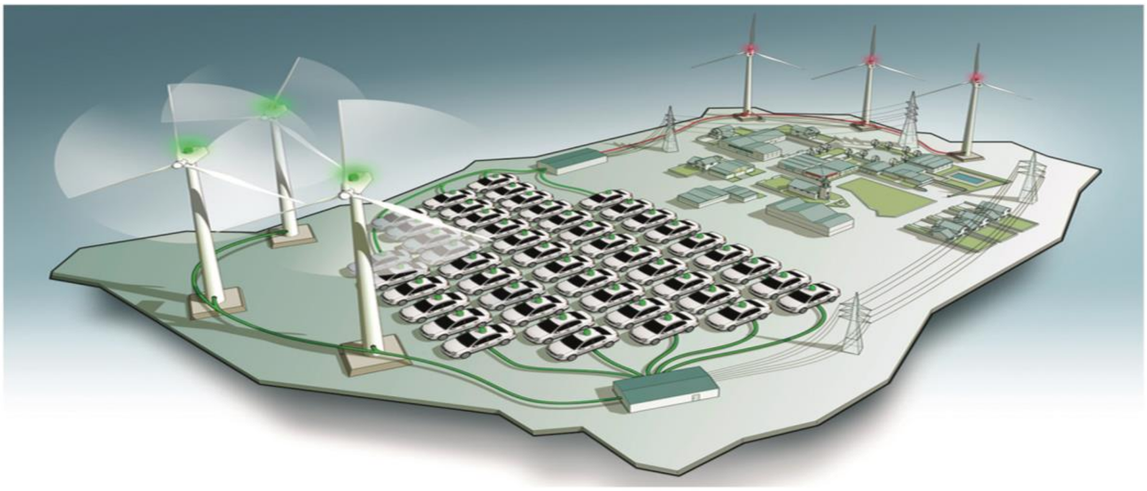
Demand as Frequency-controlled Reserve

Implementation and practical demonstration programme



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Demand as
Frequency-controlled Reserve

Report 1
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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.

Figure 1 SmartBox

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.

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.

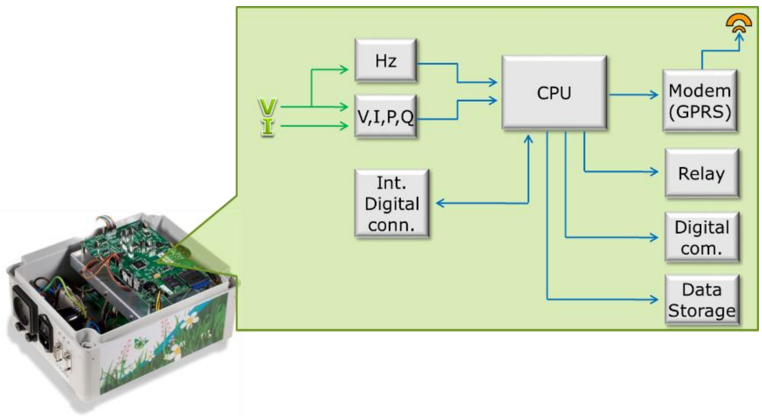

Figure 2 SmartBox hardware overview

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.

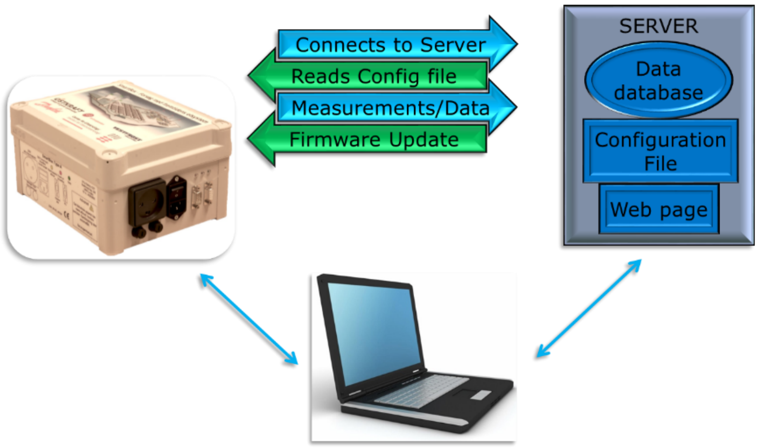

Figure 3 SmartBox communication

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.

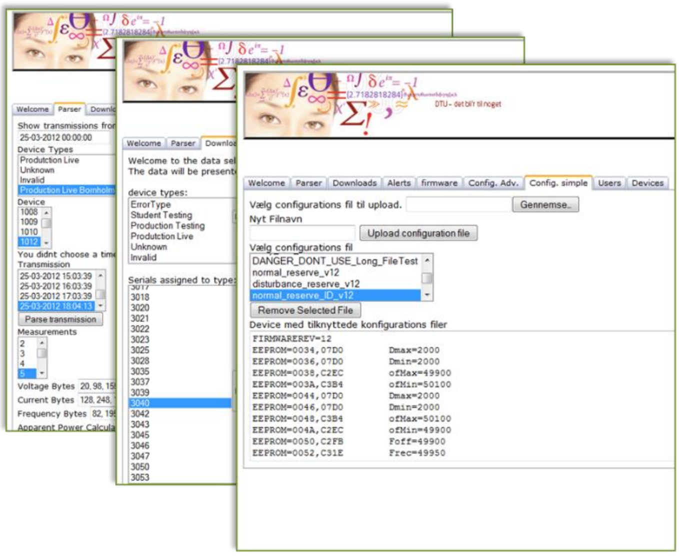

Figure 4 SmartBox webpage

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 reprogrammed 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 corresponding 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 current drawn by attached device
Temperature	[C]	Temperature measured in either bottle coolers or domestic heating
Vestfrost Carlsberg Bottle cooler specific status		Compressor, Defrost, On/Off, thermostat communication error.
Danfoss domestic heating specific status		Temperature off-set, On/Off, communication 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.

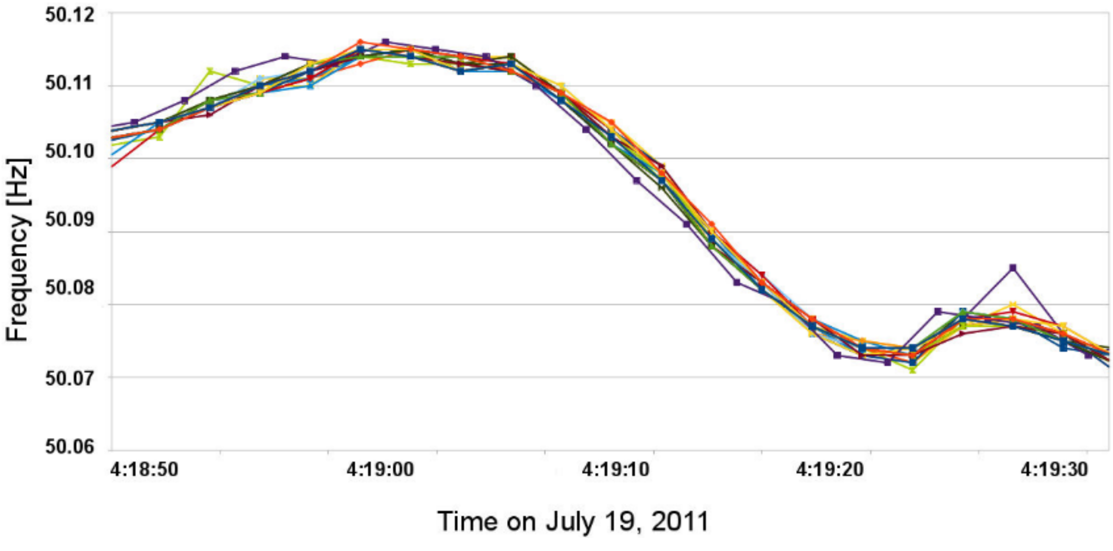

Figure 5 Typical high resolution measurement series during over-frequency with 2s sampling period over 40s.

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.

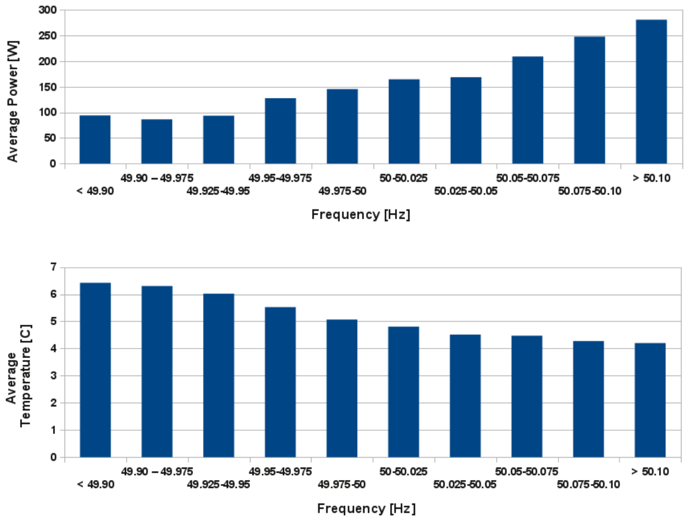

Figure 6 Relation between system frequency and power or temperature respectively

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.

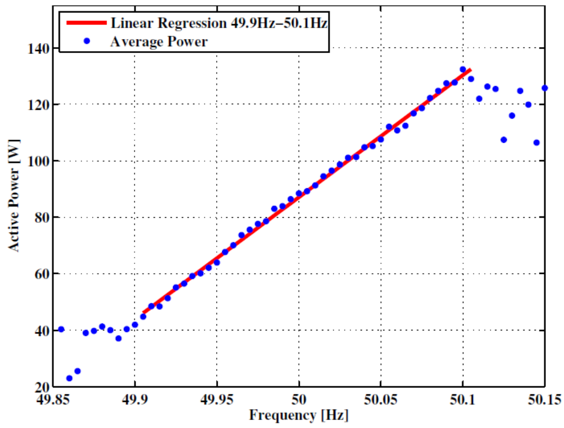

Figure 7 Average frequency response NR

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.

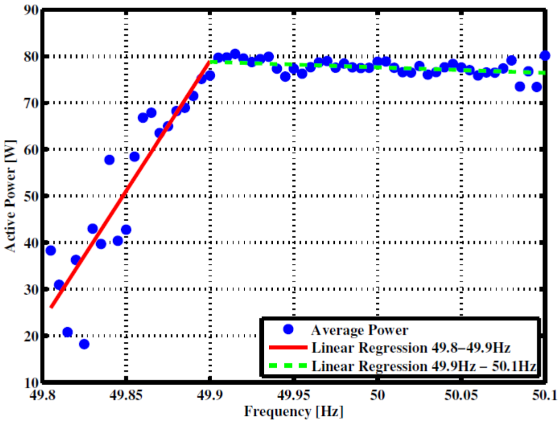

Figure 8 Average frequency response DR

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

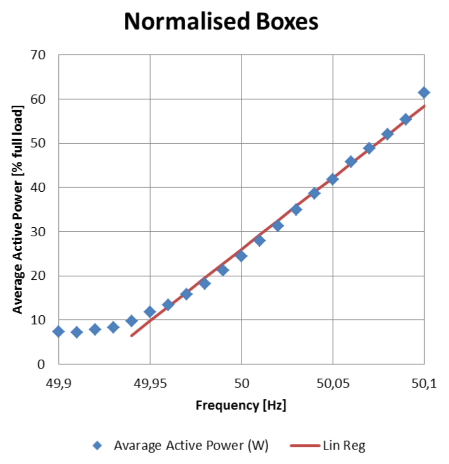

Figure 9 Frequency response of all 6 boxes with a normalised power usage. Average daily outdoor temperature: 5.5 °C

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.

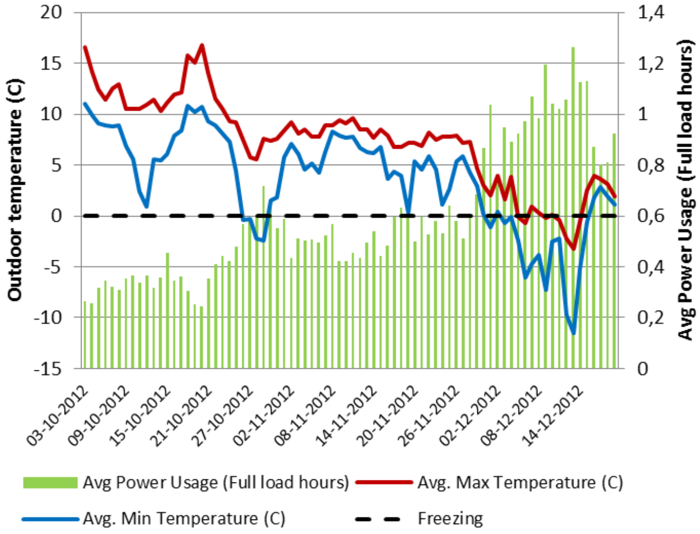

Figure 10: Outdoor temperature for Rønne (Bornholm) during the period 2012/10/03 to 2012/12/19 as well as the normalised average power usage of all boxes.

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.

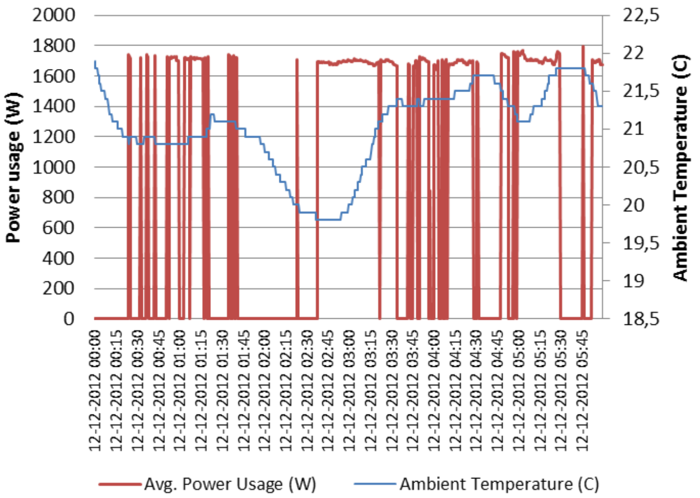

Figure 11: Power usage of Box 2037 as well as the ambient temperature measured by the thermostat

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.

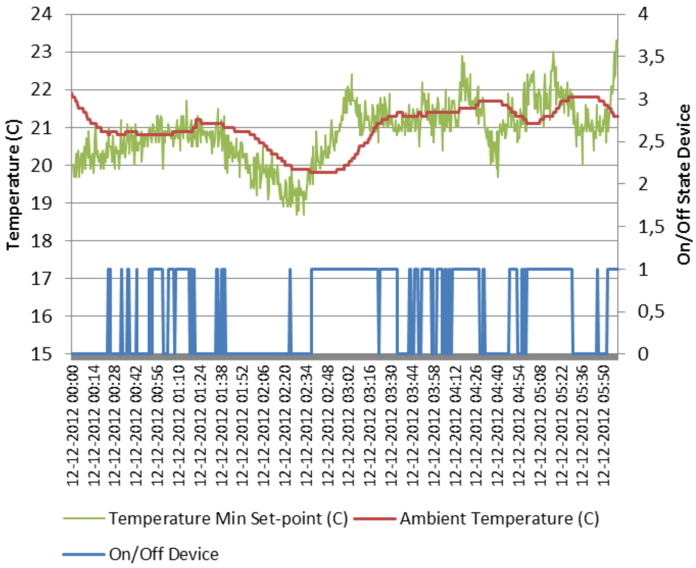

Figure 12: Temperature offset, ambient temperature, and on/off indicator, SmartBox 2037.

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.

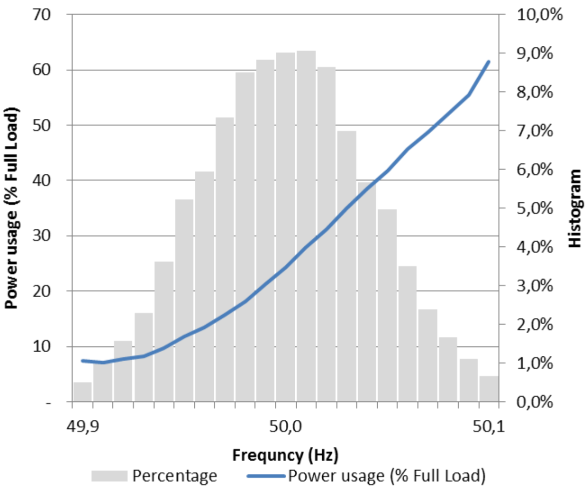

Figure 13 Histogram of frequency and frequency response.

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

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.

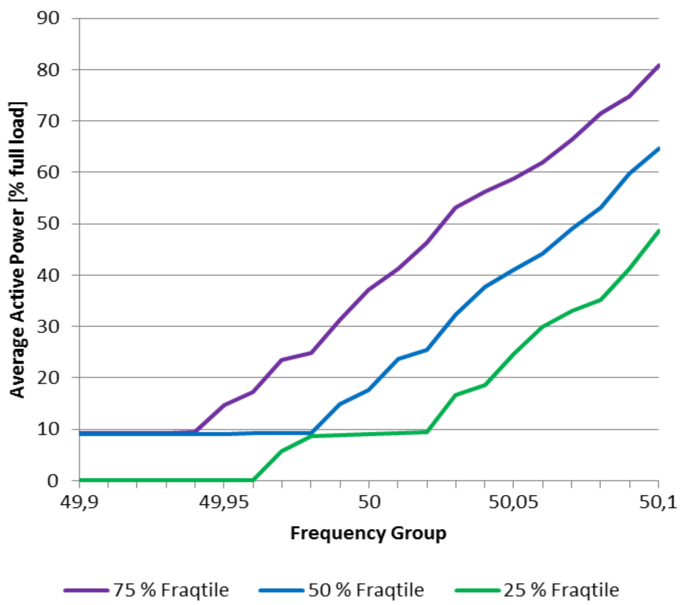

Figure 14 Power usage quantiles of system frequency group of 0.01 Hz.

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.

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.

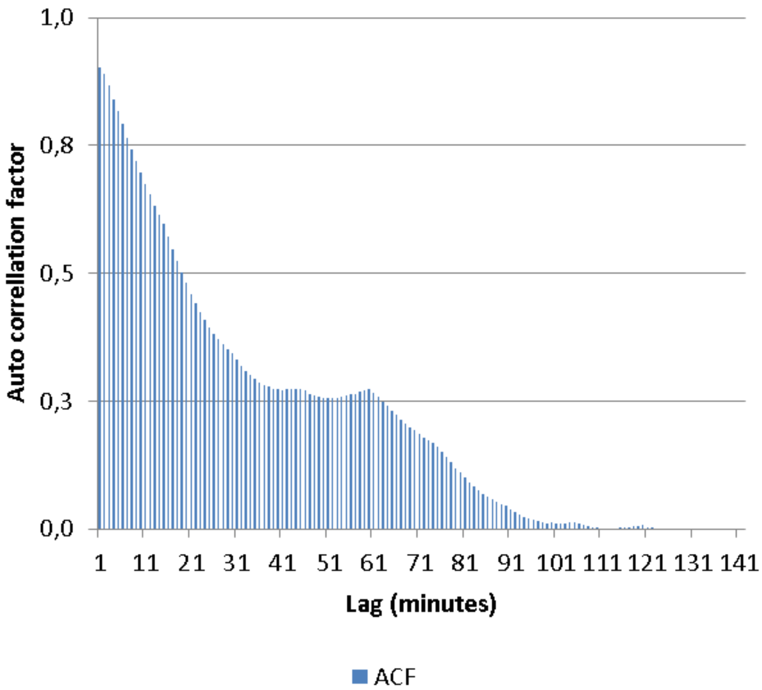

Figure 15: Autocorrelation of system frequency.

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.

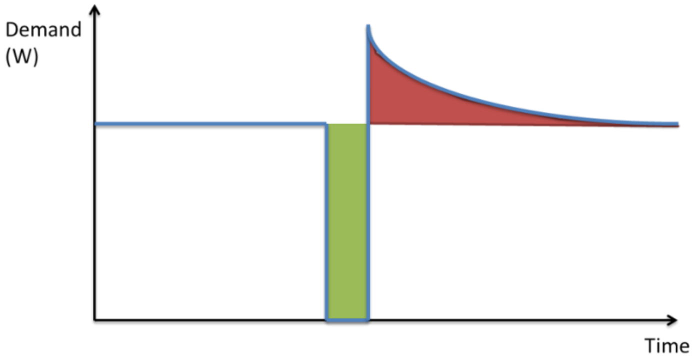

Figure 16 The electrical heater as an "energy storage". The green and red areas are expected to be more or less equal. Minor differences can occur due to change in efficiency and change in heat loss.

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.

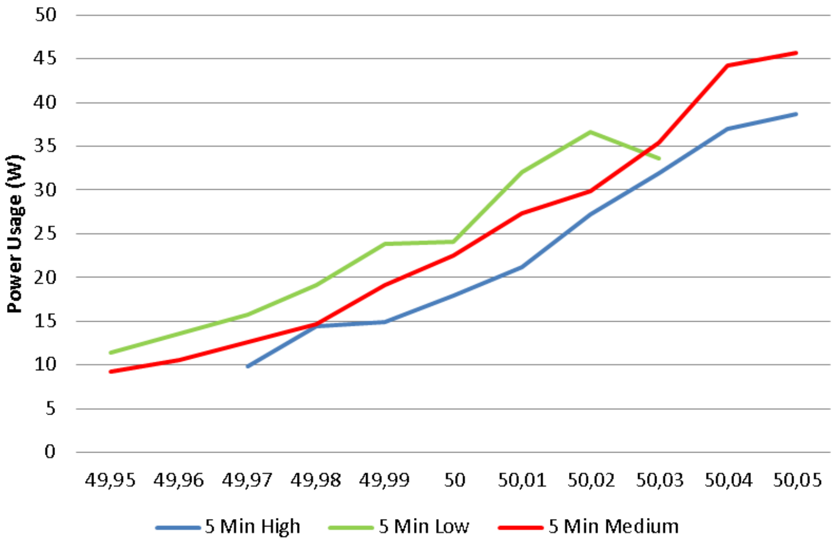

Figure 17: Rebound effect considering 5 minutes periods. Low < 49.98 Hz, Medium 49.98-50.02 Hz, High > 50.02 Hz

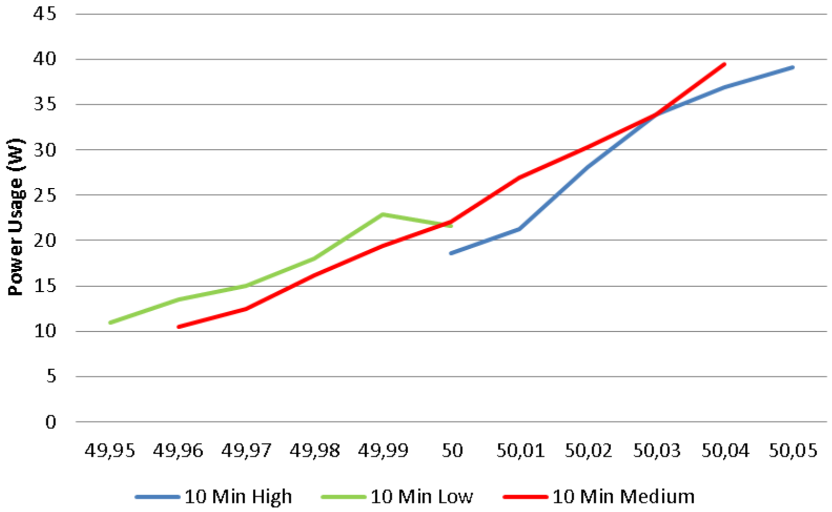

Figure 18: Rebound effect considering 10 minutes periods. Low < 49.98 Hz, Medium 49.98-50.02 Hz, High > 50.02 Hz

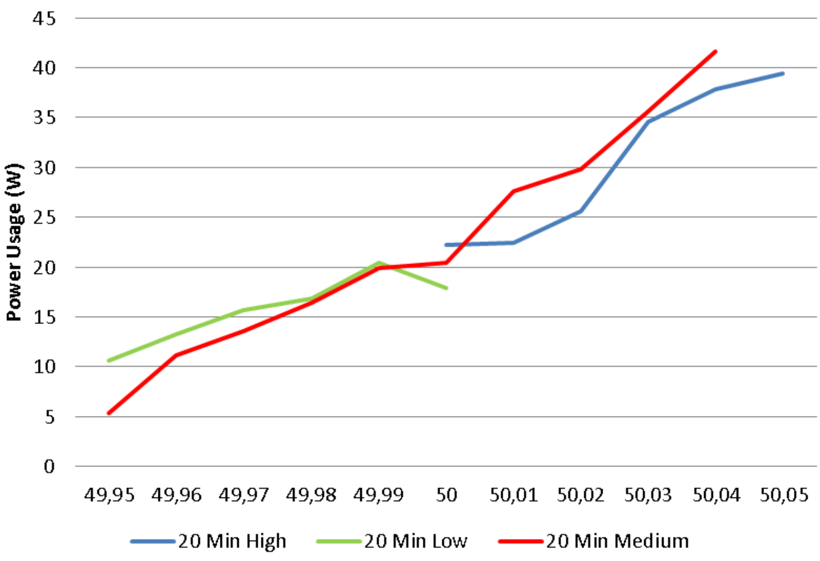

Figure 19: Rebound effect considering 20 minutes periods. Low < 49.98 Hz, Medium 49.98-50.02 Hz, High > 50.02 Hz

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.

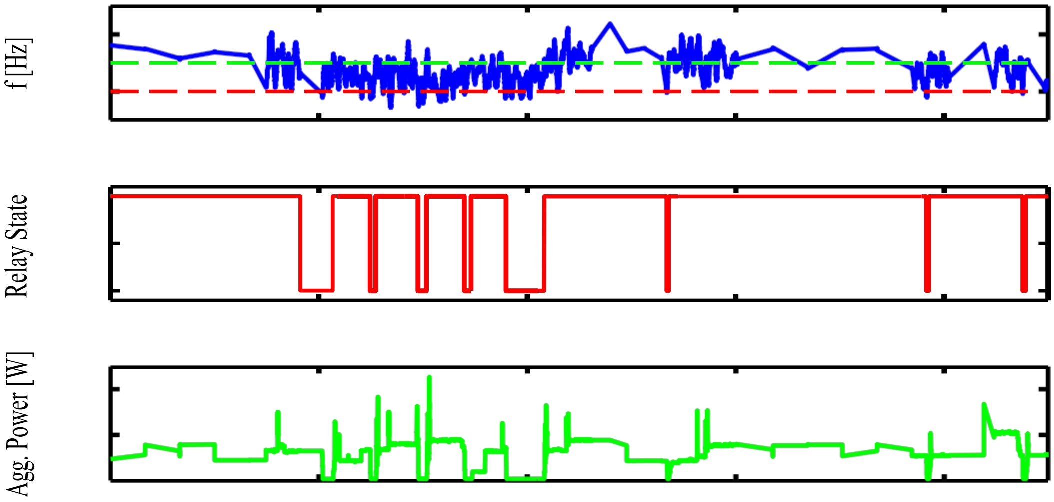

Figure 20 Typical time series from water treatment plant.

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%

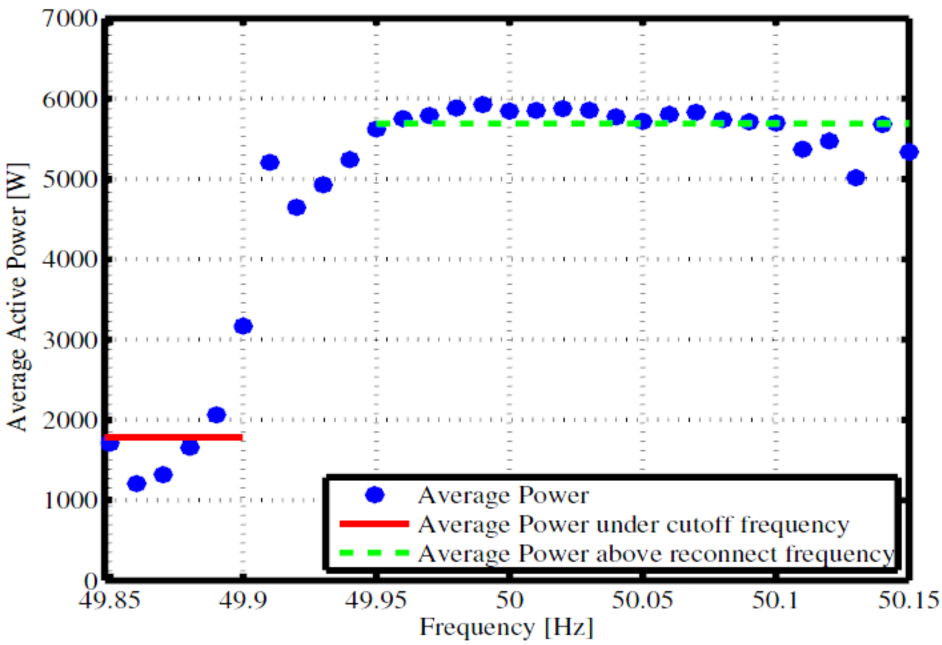

Figure 21 Frequency responce og water treatment plant with disconnect frequency 49.90 Hz

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.

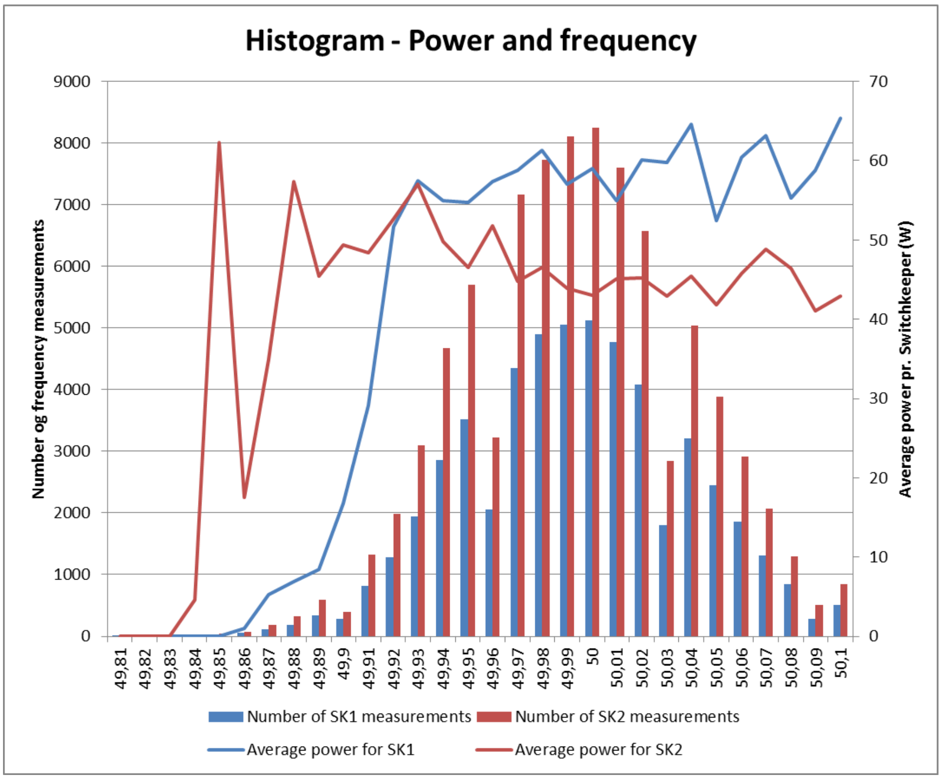

Figure 22: Histogram for 26 EHs (26 SK1s and 26 SK2s) in the period 2011-02-20 to 2011-04-30. The switch-off point for SK1s is at 49,9 Hz and for SK2s it is 49,85 Hz.

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”.

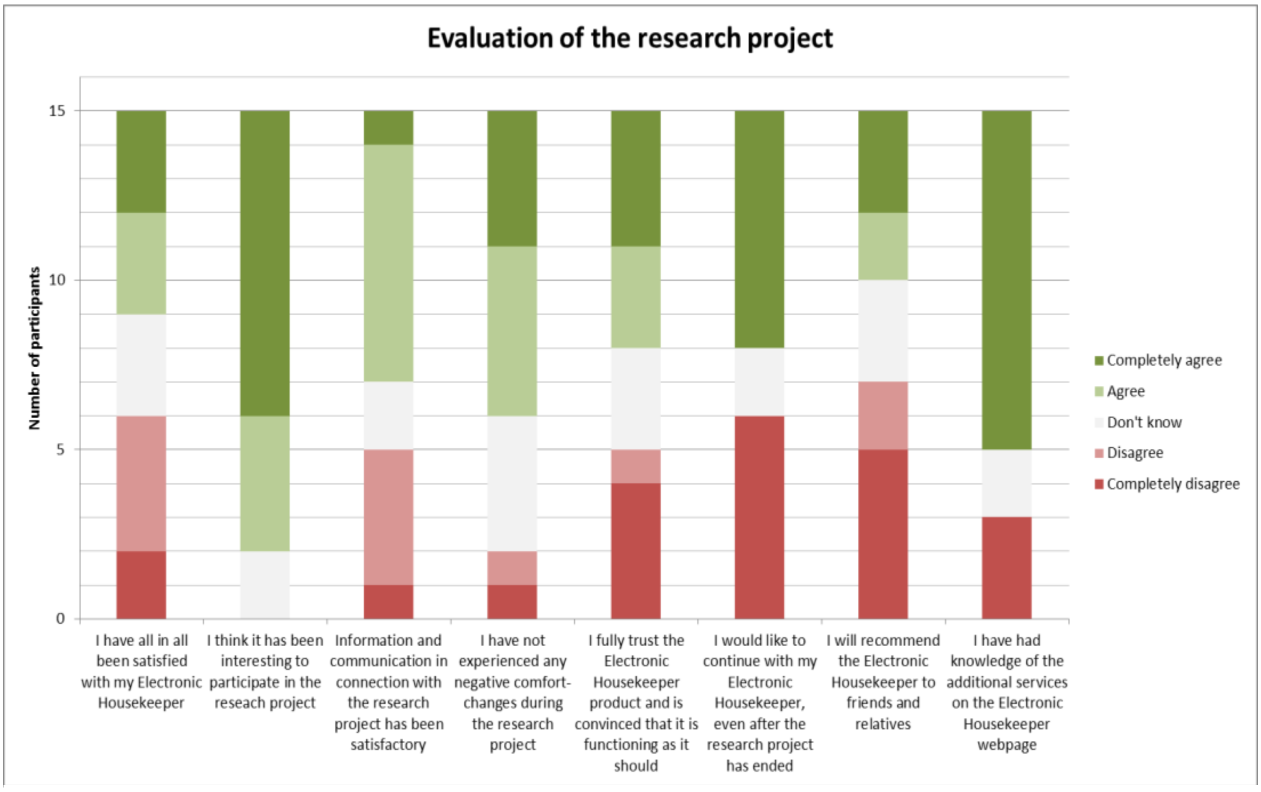

Figure 23: Results from the evaluation of the EH pilot project.

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.

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.

Appendix A Elaborated Project Description

Centre for Electric Technology
Department of Electrical Engineering

08. April 2008

Elaborate Project Description

Electricity Demand as Frequency Controlled Reserve - Implementation and practical demonstration

Active control of electricity demand is a key technology when creating a more dynamic, wind power friendly energy system. This demonstration project is about using electricity demand as fast reserves. This is an alternative to some of the most expensive reserves in the current electricity system.

Maintaining the power balance between supply and demand is of highest priority in power system operation. If a power plant trips, the system frequency will decrease, and the balance must quickly be re-established by using reserves. Today, the reserves are provided mainly by generation side resources, including extra capacity of generators and interconnection lines. The reserves are costly, e.g. in Nordel system 50 MW on the DC connection between Zeeland and Germany is reserved for reserves, which could otherwise be used for transactions in the electricity market.

The reserves can be also provided by using frequency controlled demands with several advantages, e.g. fast responding speed, low costs and high dispersion at feeder level etc [1]. Most importantly, it can enhance the system stability for the future power system, where a high penetration of fluctuating renewable energy is foreseen, e.g. the new Danish Energy Policy recommends that 50 % of national electricity consumption should be supplied by wind generation by 2025 [11]. There are many demands existing in power system that can be used as reserve. Particularly, the thermostatically controlled loads such as heaters and refrigerators have cyclic on/off characteristic with considerable volume, which make them ideal to be used as frequency controlled reserve.

Using demand as reserve is not a new idea but with focuses on large size industrial loads in the past. In [2], a market based demand management program using low frequency relay to control industrial loads is reported. A similar program is implemented in the New Zealand power sys-

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tem [3]. In Finland, 1000 MW industrial demands from wood processing, chemical and metal industrials are used as frequency controlled as well as manual reserve [4].

Domestic demands with small electricity consumption can also provide reserve, which was proposed as early as in 1979 [5]. The recent availability of low cost micro electronics makes the idea more attractive and motivates many researches in the field. The Pacific Northwest National Laboratory (PNNL) has suggested that individual household appliances suitable for temporary disconnection can provide fast reserve that can react within seconds, e.g. refrigerators and air conditioners [6, 7]. Similar suggestions have been made in UK by Short and Leach and Hirst [8, 9]. A pilot project using the *ComfortChoice* technology for controlling air conditioners to provide frequency activated reserve was carried out by the Long Island Power Authority in 2003 [10]. Due to the communication (two way paging) system used, the reserve is to be activated relatively slow within about 90 seconds.

Inspired by all relevant research activities, we have started our research on demand as frequency controlled reserve since the previous PSO project. 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 results 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 reserve 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 is recommended to be supplied by wind power by 2025 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. The draft report of the PSO project is attached with the application.

This project is our continual research effort of the same subject with extension for practical demonstration. The power system at Bornholm island is chosen to host the demonstration, and the local system operator Øskraft has committed their full support. The Bornholm system has encountered serious difficulty in maintaining system frequency during islanded operation period, where wind power has to be largely reduced. This challenge is also foreseen for future power system with an increased share of renewable energy. As such new technology including the DFR is needed to ensure the security of supply, and Øskraft has already been actively collaborating with several partners in this project to carry out research in their system. It should be highlighted that the research outcome from Bornholm system will be universal and can play a key role in developing new technology for Danish power system in the future. A detailed introduction to the Bornholm including power system information and relevant research projects ongoing therein is attached in the Appendices.

In our previous research project, focuses have been put on theoretical investigations and analyses. In the demonstration project, practical experiments will be done with the two generic types of frequency control of demand that have been developed:

- The external control: An on/off switch is controlled by the system frequency. When the frequency is below a set-point, e.g. 49.9 Hz, the switch is turned off. This is essentially "a box" that can control any device, and will act as an automatic disturbance reserve. The set-points can be designed so that the result is a classic proportional control for reserve. Figure 1 illustrates the control logic of this type.

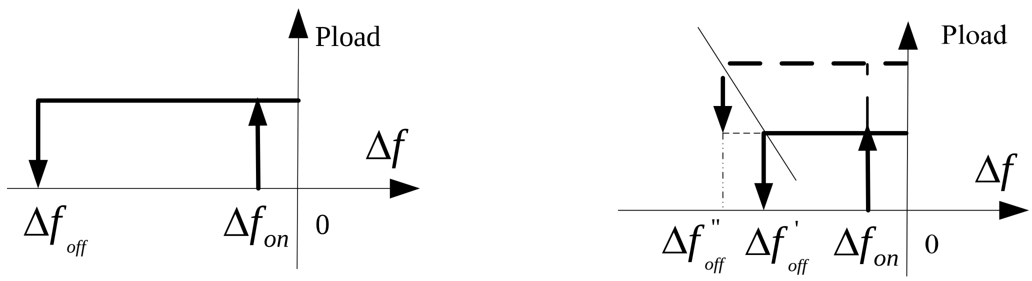

Figure 1 Illustration of external control type DFR for single load on the left and aggregated loads with proportional reserve activation design on the right

- The integrated control: A system where the set-points, e.g. a thermostat, are controlled by the frequency. The integrated control will be less disturbing for the end-user because it 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 in islanding operation mode [13]. Figure 2 illustrates the integrated control logic for aggregated heaters.

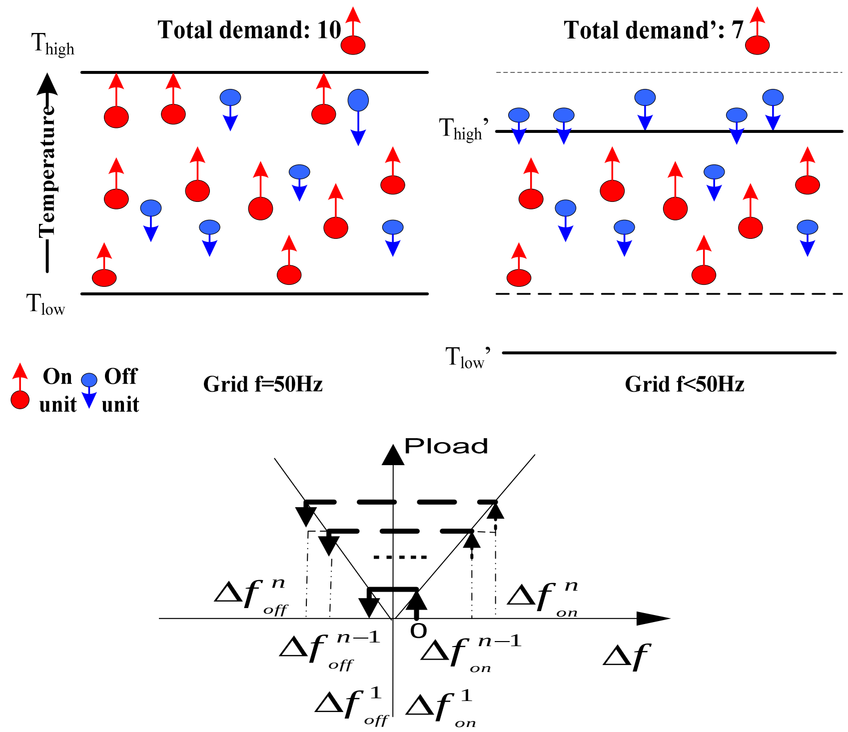

Figure 2 Illustration of integrated control of aggregated heater loads: the upper illustrates the behavior of aggregated 16 heaters with integrated control in response to a frequency dip, and the lower shows the control logic accordingly

For this project a prototype of the external control will be produced. In addition to the control feature, the box will also have capabilities for data collection and communication. The data features are only needed in the prototype for evaluation purpose. The prototype will be developed according to various devices, including Danfoss electric heating and Vestfrost cooling devices including refrigerators and freezers. It will also be developed for miscellaneous devices that can be tested in the demonstration. Some of the prototypes will be developed based on the home automation product from Electronic Housekeeper A/S, which is able to measure grid frequency [12].

The integrated control will be developed and tested in relation to Danfoss electric heating. Electric heating is very attractive from a control perspective, since it can be disconnected and reconnected very quickly. Other types of demand, e.g. compressors for heat pumps or cooling devices, have restrictions when to disconnect and can only re-connect after a certain resting period. Electric heating exists in more than 100,000 Danish houses and is expected to a certain market share in future low energy houses.

The Danfoss electric heating can be supplied with an advanced control system that allow the user to control set point, check temperatures and receive alarms. The system can be used via an internet or mobile phone interface. This system will be developed in a proto type to include the frequency control, and this system will be tested in a comprehensive field test.

The project will include a number of work packages:

WP1. Development of a practical device for external control. This includes hardware design for frequency measurements, control logic and data collection and communication for data management. CET will be responsible for this work package.

WP2. Development of integrated control in relation to the Danfoss electric heating. This will use the several features from the external control, but will be extended to include correction of temperature set-points for the electric heating. Danfoss will be responsible for this work package with assistance from CET.

WP3. Development of external control in relation to the product from Electronic Housekeeper A/S. Since the hardware for frequency control is ready in the product, this will only involve re-programming the software inside. Ea will be responsible for this work package in close cooperation with CET.

WP4. Development of frequency control for freezers or refrigerators of Vestfrost. Vestfrost will be responsible for this work package in close cooperation with CET.

WP5. Laboratory test of devices that have been developed in Work Packages 1 to 4. The test will be conducted in the laboratory of DTU, and CET will be responsible for this task in close collaboration with all partners.

WP6. Design and development of central data collection system (database-system) in order to collect data from all DFR devices in field test. CET will be responsible for the task with close collaboration from all partners.

WP7. Design and implementation of demonstration. End users will be invited to take part of the practical test. The goal is to include: a) 50 end-users for the external control, b) 50 end-users for the integrated control in relation to electric heating, c) 50 miscellaneous appliances with external control based on the product from Electronic Housekeeper and d) 50 cooling devices from Vestfrost. In total 200 appliances. The setup of the field test is illustrated in Figure 3 below. This task includes developing a questionnaire to collect participants' evaluation of user impact of the tested system. It is the goal that a number of the end users are located on Bornholm to make synergy with other actual projects. Ea Energy Analyses is responsible for this work package in close cooperation with Østkraft.

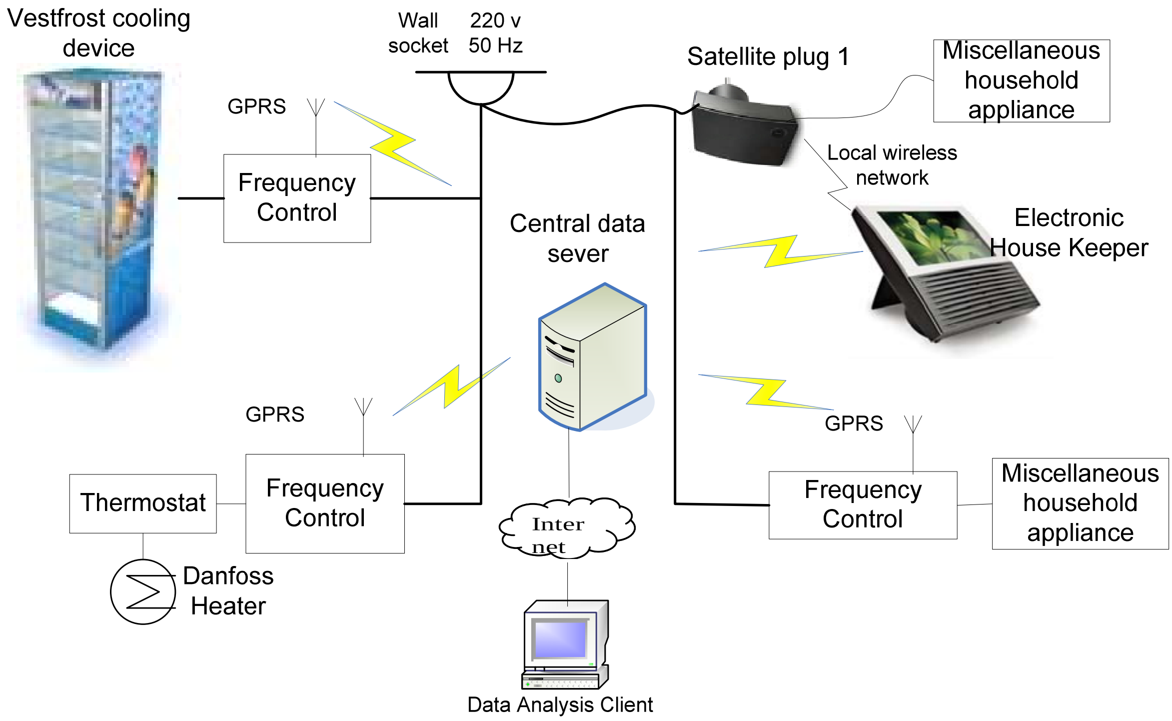

Figure 3 The setup of DFR appliances in the field test, including 50 end-users for the external and integrated control in relation to Danfoss electric heating respectively; 50 end users for Vestfrost cooling devices; 50 miscellaneous appliances with external control based on Electronic Housekeeper; and 50 miscellaneous appliances with external control

WP8. Field test of devises over a one year period. This includes a hot line for end users and monitoring of data collection system and quality control of data. Ea Energy Analyses is responsible for this work package in close cooperation with Østkraft.

WP9. Analyses of data. This includes comparing the predicted amount of reserves with actual delivered reserves. Ea Energy Analyses is responsible for this work package in close cooperation with CET.

WP10. Theoretical development. The project will be followed by a Post Doc study that will extend the activities from the previous work, including developing possible designs for more advanced system, e.g. including voltage control in combination with the frequency control of demand, and use of hot water tank of heating system as dump load. CET will be responsible for this work package. Analysis of applying DFR technology in other relevant appliances, e.g. heat pumps and circulation pumps will also be carried out. The Post Doc is 50% financed by DTU.

WP11. Reporting and project management will be done by Jacob Østergaard, CET in cooperation with Mikael Togeby, Ea Energy Analyses.

In addition to these work packages, various activities will be organised throughout the project to report and summarize the progress, disseminate the research outcomes, and communicate with relevant parties in the field. Three progress reports and two workshops are planned during the course of the project. An advisory group will be set up with representatives from utilities and manufactures to review and give inputs into the research work. In addition, writing of several conference and journal papers have been also planed. To support the project manager in managing and organising the project, a steering group will also be setup by important project participants who have the control of issues like staffing and resources allocation in their own organisations.

A number of similar research activities are taking places worldwide, including the Grid Friendly research program at PNNL [6, 7], and the Dynamic Demand and Responsive Load research in UK [8] [14]. The research team has contacts with these environments. Particularly, the team already has good collaborations with PNNL in previous project.

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Appendix B Demand as Frequency Controlled Reserve – Implementation and Practical Demonstration

Demand as Frequency Controlled Reserve: Implementation and practical demonstration

Philip J. Douglass *Student Member, IEEE*, Rodrigo Garcia-Valle *Member, IEEE*, Preben Nyeng *Member, IEEE*, Jacob Østergaard *Senior Member, IEEE*, and Mikael Togeby

***Abstract*—One of the challenges in electric power systems with a high penetration of renewable generation is the provision of ancillary services. Traditionally these services have been provided by conventional generation, but as power from renewable sources (wind and PV) displaces conventional generation, new providers of ancillary services are needed. Frequency regulation is critical because fluctuating energy sources increase the need for this service. At very high levels of renewable penetration, all available frequency regulation services will be called on, including demand-side resources. Electric loads that provide thermal energy services are attractive because their heat capacity allows electric power consumption to be moved in time without degrading the quality of service. This concept is being demonstrated in field tests on the island of Bornholm, Denmark.**

***Index Terms*—Demand side, frequency control, demonstration project.**

I. Introduction

NON-DIPATCHABLE renewable energy sources (RES) especially wind, photo-voltaic (PV), and run-of-river hydro have been successfully integrated into existing power systems with modest system balancing costs, but as RES come to dominate in some locations, fundamental changes to the electric power system may be needed.

In 2010 22% of Danish electricity production came from wind turbines [1] and on the windiest nights, all of domestic electricity demand has been satisfied by wind turbines. The national government road-map for the Danish energy system calls for a continued build-out of wind generation reaching 42% of electricity production by 2020 [2]. This level of RES production will lead to significant periods when the power delivered by wind turbines is large enough to satisfy all demand. The large thermal power plants that historically have been the backbone of the power system will not be needed to deliver energy into the electric system, but replacing the ancillary services these generators provide (e.g. short-circuit current, voltage regulation, frequency regulation) is an unresolved issue. The frequency controlled reserve in particular is interesting because the service from central power plants does not only need to be replaced, the total amount provisioned must be increased because the fluctuating output of wind and PV increases the need for this service.

Modern wind power plants have control functions for curtailing production which allows them to provide frequency regulating service [3]. However unlike thermal power plants which save on fuel costs when not producing at full capacity, wind energy is “spilled“ during curtailment.

Domestic demands with small electricity consumption are an untapped resource for providing a frequency regulated reserve [4]. The recent availability of low cost micro electronics makes the idea feasible and has motivated much research in the field. The Pacific Northwest National Laboratory (PNNL) and others have suggested that individual household appliances suitable for temporary disconnection can provide fast reserve that can react within seconds, e.g. refrigerators and air conditioners [5]–[7].

Inspired by these relevant research activities, we have started our research on demand as frequency controlled reserve in Phase I of our research [8]–[11]. This paper is a continuation of that research effort with a practical demonstration under real-life conditions. Phase I focused on theoretical investigations and analysis. In Phase II, practical experiments will be done with the generic types of frequency control of demand that have been developed in Phase I [8].

The reserves that are provided by using frequency controlled demands have several advantages, e.g. fast responding speed and low cost. Most importantly, it can enhance the system stability for the future power system, where a high penetration of fluctuating renewable energy is foreseen [8], [12]. Compared to the under-frequency load shedding schemes commonly in use today which disconnect loads at the substation level during extreme contingencies, this concept is a fine grained response from loads which allows for both up and down regulation, and is invisible to the end user.

The next section describes in more detail the concept of using demand for frequency regulation. It is followed by a description of our implementation used for demonstrating the concept. Data from the demonstration are presented.

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II. Demand as a frequency controlled reserve (DFCR)[1]

The system frequency is a universally available parameter that signals the balance between power injection from generators and power withdrawal from loads within a synchronous area. When generation and consumption are not in balance, the frequency changes at the rate of

$$\Delta\omega = \frac{P_m - P_e}{M} \tag{1}$$

Where P_m is the mechanical torque provided by the prime movers, P_e is the electrical torque on the generators, M is the system's inertia, and $\Delta\omega$ is the change in angular velocity. Island power systems typically experience poor frequency quality because of low M values. The Nordic power system sees the largest frequency excursions during periods of low loading (nights and summer) when M is relatively low.

DFCR has been proposed as a means of providing frequency regulation services by utilizing the ability of certain loads to shift their power consumption in time without compromising the provision of energy services. Individual electrical appliances can measure the system frequency and react to deviations from nominal frequency by adjusting their consumption up or down. This is done without the expense of introducing external communication channels between the DER and a dispatcher.

Loads that provide services such as cooling (refrigerators, freezers, air conditioners) and heating (space heating, water heating) can use the heat capacity inherent in the devices to store energy typically for a period of hours. These loads can be interrupted for several minutes and still maintain temperature within the targeted range. This flexibility can be used to defer power consumption to avoid moments when demand exceeds supply as reflected by an actual system frequency below the nominal value. Similar functionality can be delivered by pumping systems with storage.

Even though each individual device operates in an on/off manner, with a large population of devices their frequency response in aggregate will be smooth.

III. The Bornholm Power System

The island of Bornholm is located in the Baltic Sea, and is the site of ongoing experiments testing concepts for new Smart Grid technologies. Bornholm has been chosen for these experiments because the electric energy system is a microcosm of Denmark, representing 1% of the nation's area, population, and electric load. In 2007 there were around 28,000 customers on the island, with a peak load of 56 MW, a minimum load of 13 MW. The topology of the MV and LV grid are typical for Denmark except that Bornholm maintains the ability to operate in planned island mode. At more than 30%, wind energy represents a larger portion of total energy supply than for Denmark as a whole [13]. Over half the electric energy consumed on Bornholm is imported, which contributes to the relatively poor continuity of service because the single connection to the Nordic transmission system via an undersea cable has been severed on several occasions. When Bornholm is disconnected from the Nordic transmission system, the wind turbines must be shut down to maintain acceptable quality of frequency. A previous experiment found that when running as an electrical island with less that 4% wind production, frequency quality was lower than the Nordic grid codes allow [14]. In [15], it was shown in planning future scenarios, the availability frequency regulation resources were a limiting factor to increased wind penetration in island operation.

[1]Other references have abbreviated this concept as DFR, but DFCR is used here to avoid confusion with digital fault recorders.

IV. Demonstration Setup

We have designed and produced approximately 200 DFCR devices which each can interface to one of 3 types of appliances: refrigerators, electric heaters and arbitrary loads via a relay. The DFCR hardware was custom made for the experiment using off the shelf components. A low-cost micro-controller is used as the main CPU, while secondary processors are used to make frequency measurements, and control a GSM/GPRS modem. Fig. 2 depicts a close up of the installed DFCR devices.

The block diagram of the device is illustrated in Fig. 3. The mains voltage is run through a measurement transformer and an analog filter before being fed into a 16-bit A/D converter. The A/D converter samples the voltage and calculates the system frequency using a zero-crossing

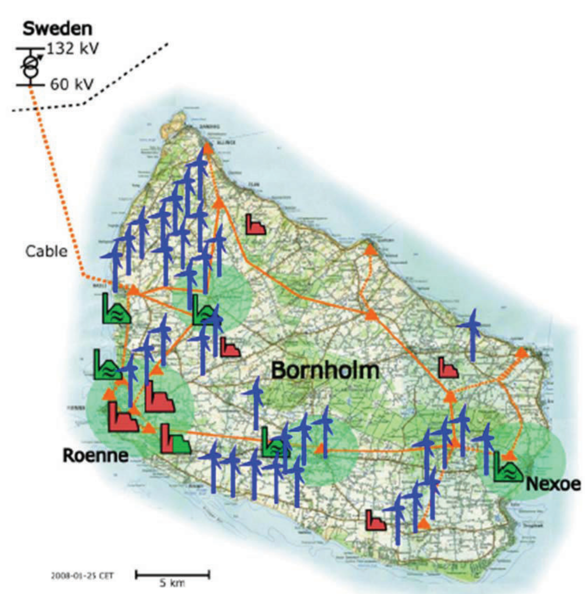

Figure 1. Map of the island of Bornholm showing 60kV transmission system (orange), wind turbines (blue), combined heat and power (red) [13].

Figure 2. Close up of the DFCR device with cover removed.

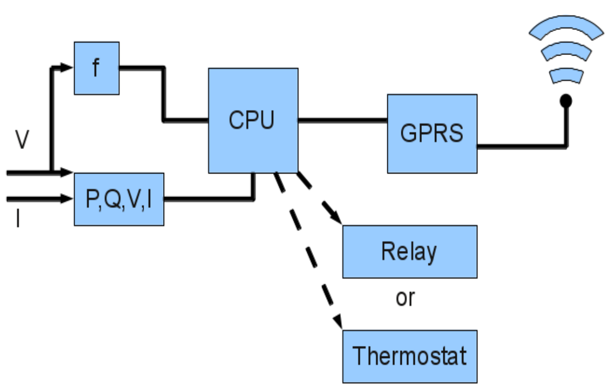

Figure 3. DFCR block diagram.

algorithm, averaging the measurements of 8 cycles. To document the operating characteristics of the device, an integrated circuit of a type often found in smart meters calculates the active and reactive power consumption at 2 second intervals. Measurements of frequency, power consumption, and device parameters (temperature, relay state) are recorded to an internal flash memory and uploaded to a server at regular intervals. Measurements are taken at a low resolution to build an image of the normal operation of the devices and when under/over-frequency events occur, the sampling frequency is increased to record high-resolution data. Both the low and high resolution sampling frequencies are configurable which was needed to throttle the quantity of data sent across the GPRS link.

HTTP is used to upload data, and download new configurations and firmware. Using a serial port connected to the GPRS modem, the CPU sends commands to the modem to establish HTTP connections [16], the TCP/IP stack is contained entirely within the modem firmware. Our server was written in the .NET framework and is hosted on a commercial web hotel. The server scripts interface to a database when adding and retrieving measurement data.

All measurements contain a time stamp. The clocks of the devices are synchronized to UTC by using the SNTP protocol [17].

The current measurement transformer was subject to significant parameter variations which required that each unit be individually calibrated.

A. Thermostatally Controlled Devices

In [11], a controller for a bottle cooler was developed and tested under labratory conditions. The ongoing experiment uses the same refrigerator model but increases the number of devices and tests them during normal usage conditions to reveal the aggregate behavior of a population of devices. Fifty bottle coolers like the one shown in Fig. 4 were installed restaurants, hotels and stores around Bornholm. The refrigerators contain a thermostat with two features necessary to interface with DFCR hardware: the ability to externally program temperature setpoint offsets, and an anti-short cycle feature which prevents damage to the compressor caused by restarting it before cooling liquid pressure has equalized [18]. There is no noticeable delay between changes in the setpoint offset and the thermostat's reaction.

Four parameters are given to control the response of the refrigerators:

- O_{max} Maximum temperature offset above user given value.
- O_{min} Minimum temperature offset below user given value.
- f_{max} Frequency where O_{min} is reached.
- f_{min} Frequency where O_{max} is reached.

The relationship between these parameters is shown in Fig. 5.

The experiment will test two types of frequency controlled reserve which roughly correspond to Nordel's specification of primary reserve (also called normal reserve), and secondary reserve (also called disturbance reserve) [19]. Both reserves specify a linear response to frequency deviations. Primary reserve mode is defined by $O_{min} = -O_{max}$, $f_{min} = 49.90Hz$ and $f_{max} = 50.10Hz$. Secondary reserve mode is defined by $O_{min} = 0$, $f_{min} = 49.50Hz$ and $f_{max} = 49.90Hz$.

Heater devices adjust the thermostat temperature down as frequency declines, so the definition of f_{max} and f_{min} are reversed.

B. Relay device

The on-off nature of the relay DFCR devices make them most appropriate for providing secondary reserve. To signal to users when the load was disconnected, a LED on the device turns on. The following parameters are specified:

- T_{maxd} Maximum duration of disconnection

T_{mind}	Minimum duration of disconnection
T_{minc}	Minimum connection duration after disconnection
T_{rdel}	Reconnection delay
f_{off}	Disconnect below frequency
f_{rec}	Reconnect above frequency

Figure 4. DFCR device placed on the top of refrigerator, with serial communication wire visible.

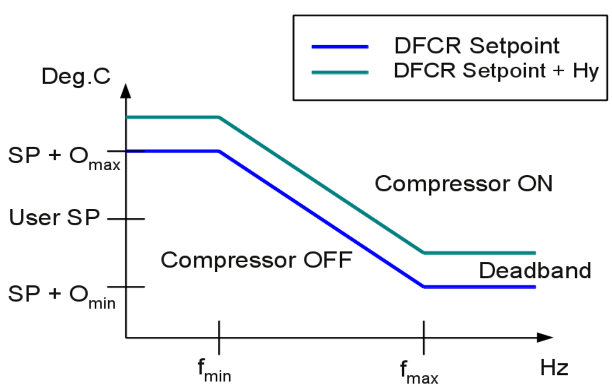

Figure 5. Relation between frequency and temperature setpoint offset for cooling application.

V. Preliminary results

In the start-up period, we focused on validating the data from the refrigerator devices to create a solid foundation for further experiments and analysis. To verify the frequency measurements and synchronization of time stamps, data was collected over one week. To verify the functioning of the thermostats, data from one day was analyzed.

A. Frequency Measurements and Time Stamp 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 $\sigma = 1.36585$ 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 6 shows an example of high resolution frequency measurements taken over 40 seconds by 35 different devices.

B. Thermostats

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

O_{max} = $2\,°\mathrm{C}$
O_{min} = $-2\,°\mathrm{C}$
f_{max} = 49.90 Hz
f_{min} = 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. For each group, the average power consumption measured by built-in metering circuit, and the average temperature as measured by the thermostat was found. The results plotted in Figures 7 and 8 show that the average power and average temperatures are with good agreement linearly dependent on the system frequency .

The only exception to the linear trend is the power consumption for the group $f < 49.90$ which is slightly

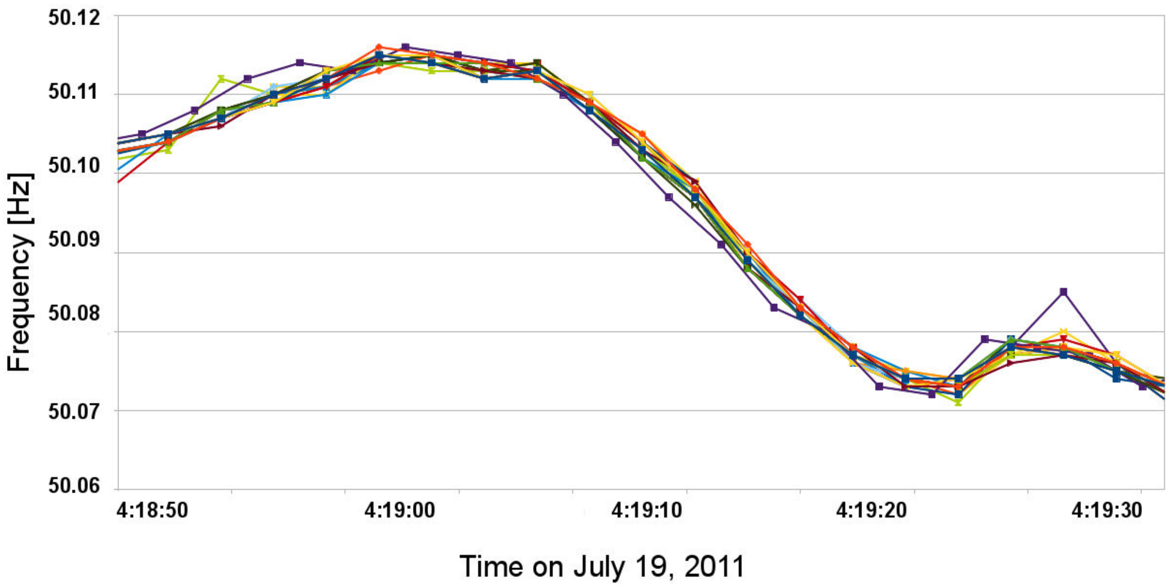

Figure 6. Typical high resolution measurement series during over-frequency with 2s sampling period over 40s. Measurements from 35 devices are superimposed.

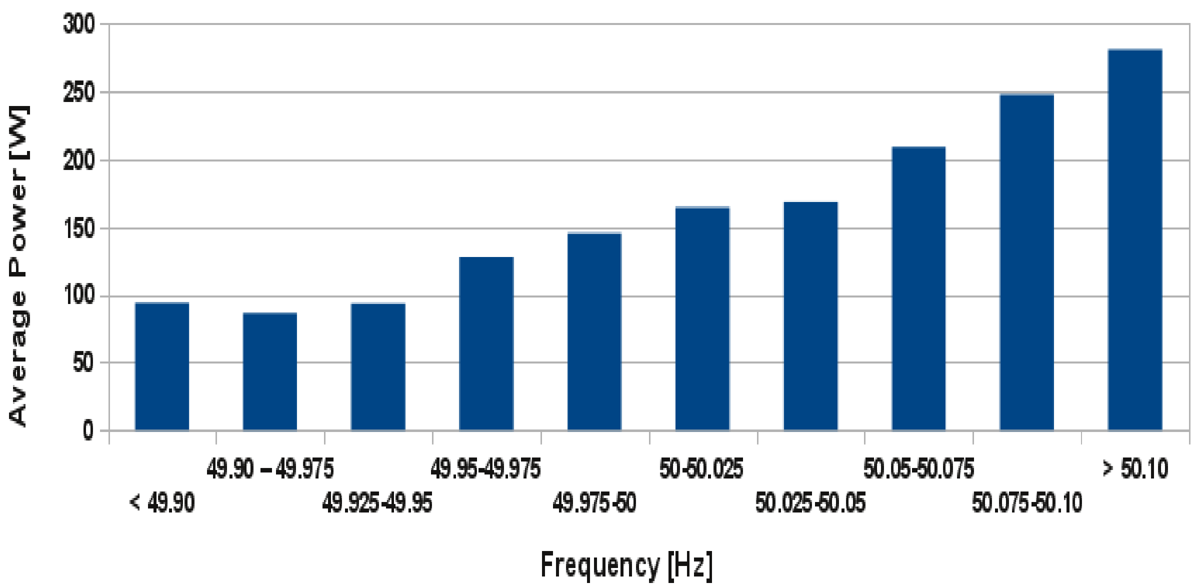

Figure 7. Relation between system frequency and power index.

higher that for $49.90 < f < 49.925$. Because the DFCR was configured to operate as a normal reserve, the thermostat setpoint was not changed at frequency values below 49.90. At the same time, the average temperature for the group $f < 49.90$ is above that for $49.90 < f < 49.925$. This indicates the presence of prolonged under frequency events, where the the increased power consumption of the low frequency group shows that the ability to shift power consumption in time has been exhausted.

VI. Discussion

In this demonstration project we have developed and tested devices which use electric loads to provide frequency controlled primary reserves. The results above verify the correct functioning of the developed DFCR devices with respect to their synchronization in time and thermostat response. While the DFCR increased the variation in air temperature of the refrigerators, earlier laboratory experiments have shown the variation in temperature of the goods stored inside is significantly less [11].

The devices we developed allowed existing products

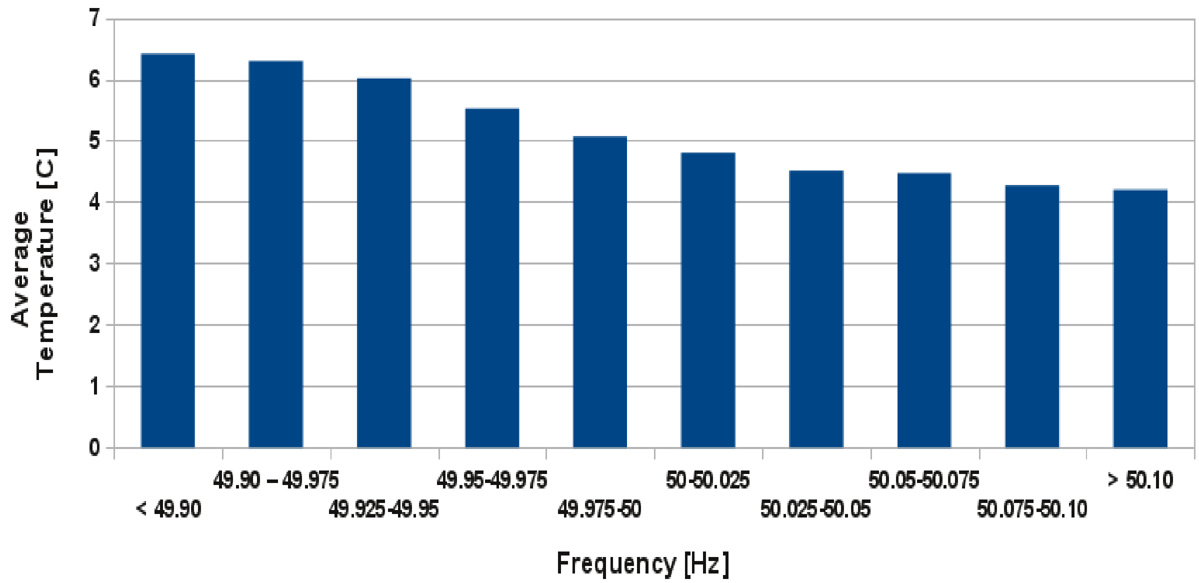

Figure 8. Relation between system frequency and average refrigerator air temperature.

to be retrofitted with DFCR functionality, but 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. In a large scale roll out, monitoring many DFCR units can be achieved by estimation based on statistical sampling of a limited number of such appliances [20], [21]. Such a monitoring method may require the present reserve monitoring practice to be extend to specify the quality requirements including accuracy of the amount and availability.

For the DFCR to respond correctly during periods when the scheduled frequency deviates from the nominal frequency (i.e. during time correction), an external communication channel is required.

VII. Future Work

At the time of writing, the refrigerator DFCR devices had been deployed for only a couple weeks. The full experiment including refrigerators, floor heaters, and relay devices will run for the remainder of 2011, to provide a large data set for further statistical analysis. During this time, configuration parameters will be adjusted to allow the units to act as both primary reserve and secondary reserve. The highly accurate time stamps allows the units' transient response to large changes in system frequency to be studied.

A water treatment plant on Bornholm will participate in the experiment, allowing their large pumps to be controlled by DFCR.

In the future, the software on the devices will be extended to respond to an external control signal. This will be used in a follow-up experiment to demonstrate real-time pricing schemes.

During the development of the DFCR concept, the authors have also considered its coordination with other functions, such as DVCR for short-term voltage control [9], [10].

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Appendix C Electricity Demand as Frequency Controlled Reserve – Experimental Results

Ea Energy Analyses

26-02-2013
NH, RB

Electricity demand as frequency controlled reserve – experimental results

Introduction

The power system frequency (present in all power outlets) reveals the energy balance in the synchronous electricity system. In order to control power system frequency and ensure a stable operation of the power system, transmission system operators use ancillary services. One of the important ancillary services is automatic frequency control (also called primary reserves), which reacts fast to frequency deviations. During the past one to two decades the quality of the power system frequency in the Nordic power system has decreased. As seen on **Fejl! Henvisningskilde ikke fundet.** the number of minutes pr. month that the frequency is outside the "normal" ±100 mHz band has more than 10-doubled over the six years.

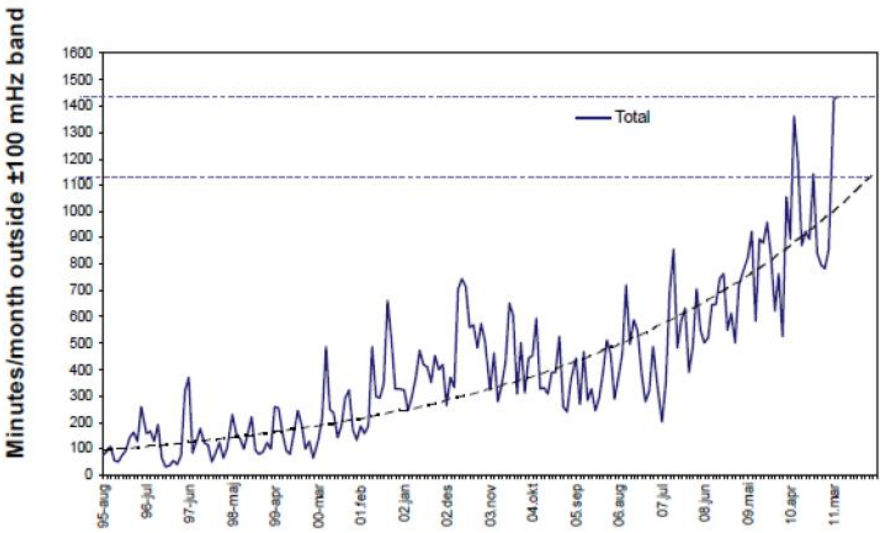


Figure 1: Graph showing the Nordic frequency quality. Development in the number of minutes/month that the frequency was outside the ± 100 mHz-band from summer 1995 to primo 2011.

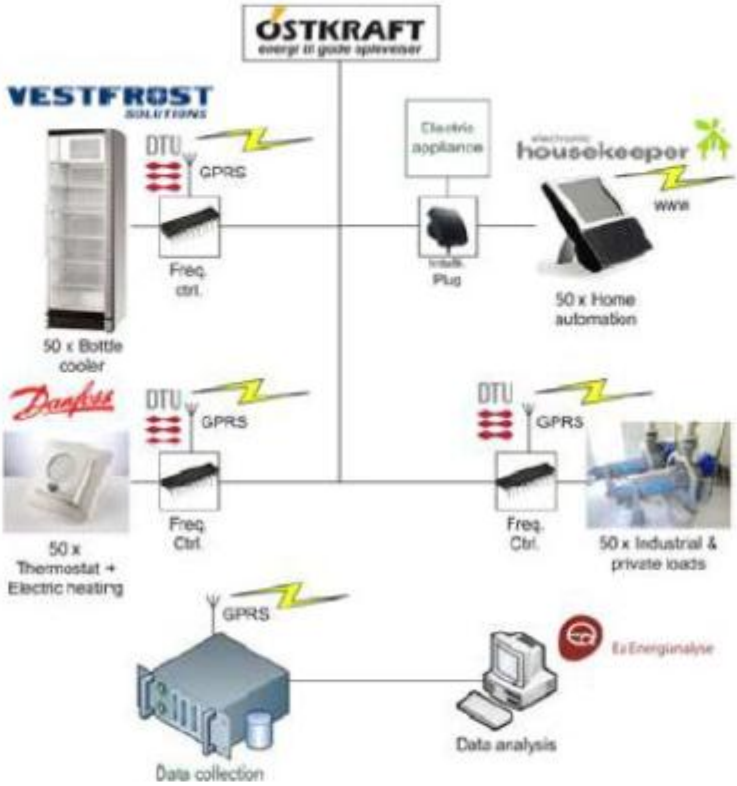
As renewable energy sources increase their penetration in the electricity market, some of the traditional providers of frequency regulation services, will be displaced, motivating the search for novel providers such as demand-side resources. The potential of using electricity demand as frequency controlled reserves has been investigated in Short et al. (2007), Lu and Hammerstrom (2006) and Xu et al (2011).

Demand side options include both reduction and increase of electricity demand as a response to frequency deviations. Decreasing frequency indicates an imbalance towards too little power generation, and thus disconnection of electricity demand can help to re-establish the energy balance in this case. On the other hand, higher consumption can help to stabilizing the system in case of overfrequencies.

Response to frequency deviations should happen quickly, i.e. with a delay of less than 1 second. Many underfrequency events have duration of less than 30 seconds – only the very serious events call for a disconnection of load for more than 1 minute up to maximum 10 minutes.

The pilot project on Bornholm

This paper presents the results of field experiments using demand as a frequency controlled reserve (DFCR) on 1) household appliances via an home automation unit: “Electronic Housekeeper” and 2) Devi electrical heaters in homes and offices with a Smartbox developed and programmed by Center for Electric Power and Energy (CEE) at the Technical University of Denmark. Furthermore the project includes field experiments with bottlecoolers and other appliances. These experiments and results are reported in Douglass et al. (2013). Read more about the pilot project on Bornholm in Centre for Electrical Technology, DTU (2008).



The first section describes the 22 electrical space heaters and their response as normal reserves and disturbance reserves as defined by the Nordic Grid Codes.

The second section will summarize the results and lessons learned from the experiment with 15 Electronic Housekeepers on Bornholm from 2011 to spring 2012.

DFR design

The electrical heaters used in the experiment are resistive radiators in private residences with a rated power consumption ranging from of 500 W to 2000 W. The resistive radiators are controlled by thermostats using a dead band around the desired temperature. The thermostat shuts off the radiator when the surrounding temperature rises above the high set point and turns on the radiator, when the surrounding temperature falls below the lower set-point.

The DFCR controller adds an offset to the set points depending on the system frequency. The set points are are thereby lowered in such a way that the thermostat turn off at a lower temperature than normal, making the radiator less likely to be on at low system frequency. The set point offset is proportional to the fall in system frequency.

The frequency controlled reserves are in the Nordel area divided into two subcategories: Normal Reserve and Disturbance Reserve. For the electrical heaters only the requirements for normal reserve were used in the experiment. The normal reserves are active in the range 49.90 Hz - 50.10 Hz.

The plot below shows an indealised control of an electrical heater with an average power usage of 225 W and a max capacity of 450 W. When Normal Reserves are active we would therefore expect the average power usage to reflect this with a linear frequency response in the 49.90 Hz - 50.10 Hz interval. The slope of the curve is proportional to the actual heat demand.

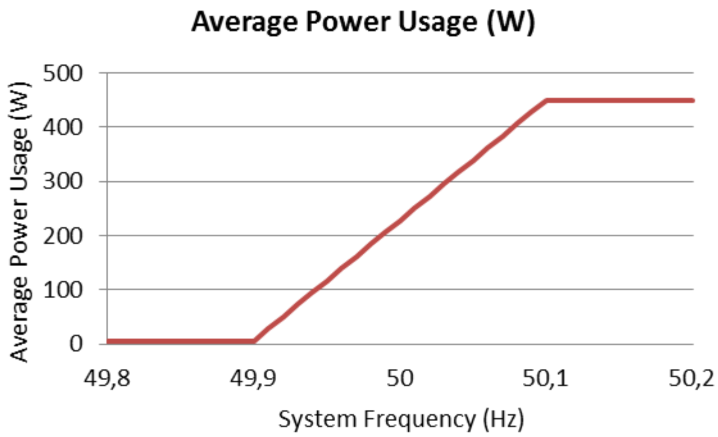


Figure 2: Average power usage under normal reserve of an electrical heater with a normal average power usage of 225 W.

DEVI Electrical Space Heaters

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 from off-the shelf components. The appliance modification was carried out by an electrician, but the firmware install and component test of the external controller was done by DTU. Due to logistics it was not possible to validate and test the external controller functions during the hardware installation. Because of this no valid data from 16 DFCR devices was collected during the research experiment, either because of defect installations or defect controller firmware. Only 6 devices will therefore be part of the analysis of this report.

Due to lack of heating demand during the summer period the focus of analysis will be on the period 2012/10/03 to 2012/12/19. The electrical heaters used in the analysis are resistive radiators in private residences with a rated power consumption of ranging between 500 W and 2000 W.

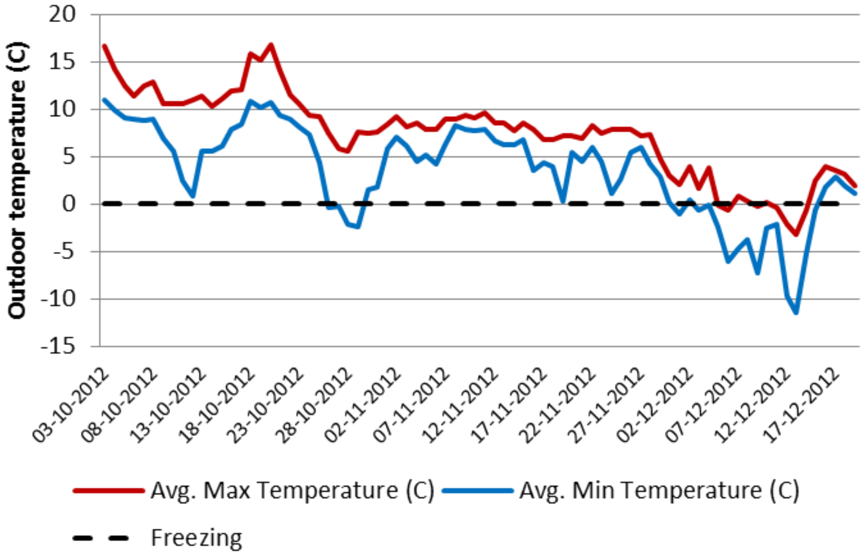


Figure 3: Daily outdoor temperature of Rønne, Bornholm druing the periode 2012/10/03 to 2012/12/19. [KILDE: http://www.bornholmervejr.dk/]

Data on power consumption and system frequency, as well as parameters specific to the appliance under control are sampled once per minute, and stored into a large internal memory. In addition, when a large frequency excursion occurs, data is collected at a high resolution (as often as every 2 seconds). This data is periodically uploaded to a database. All measurements are time stamped. The 6 boxes have an average of 2823 to 2888 measurement a day with a standard deviation of the number of measurements ranging from 128.5 to 25.2 during the period in focus. We therefore have a uniform an comparable data set for all days and all 6 boxes.

Since data is not collected uniformly every 1 minute the measurements are aggregated into 1 minute average values. Thus high resolution measurements are represented as an average over 1 minute.

The results

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.

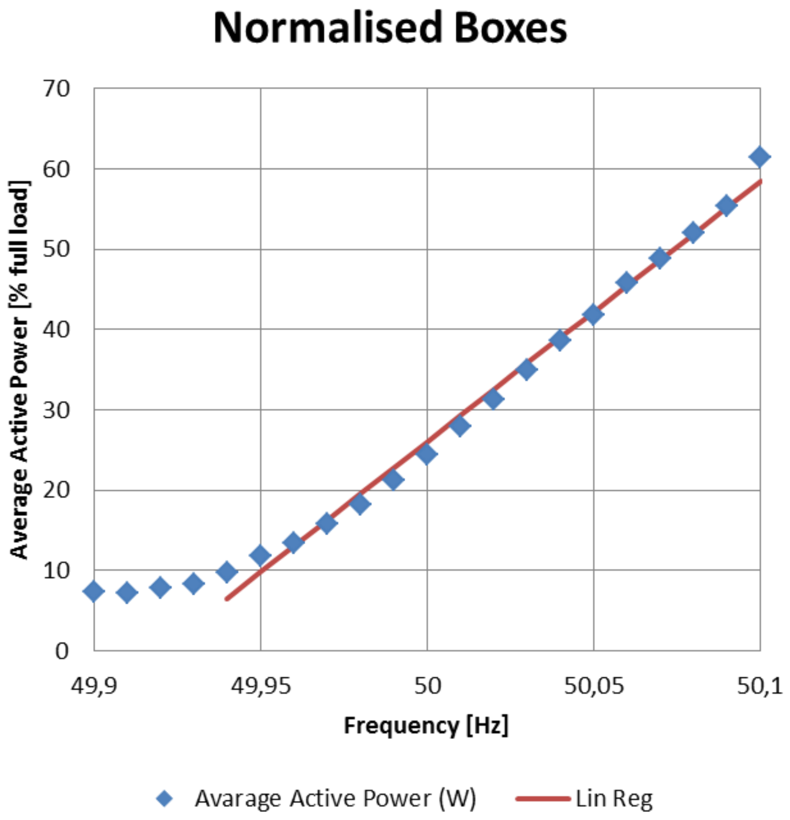


Figure 4: Frequency response of all 6 boxes with a normalised power usage. Average daily outdoor temperature: 5.5 °C.

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 exedded. 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 4.

We then consider the same type of plot while deviding the data observation into two separate groups; a group containing all frequency and power usage observation while the outdoor temperature is below the average outdoor temperature of the observation period and vice versa. The power consumption of the low temperature period should be higher than the power consumtion of the high temperature period. This higher average power consumtion during the low temperature period should result in steeper slope of the frequency response and likewise a flatter slope during the high temperature period.

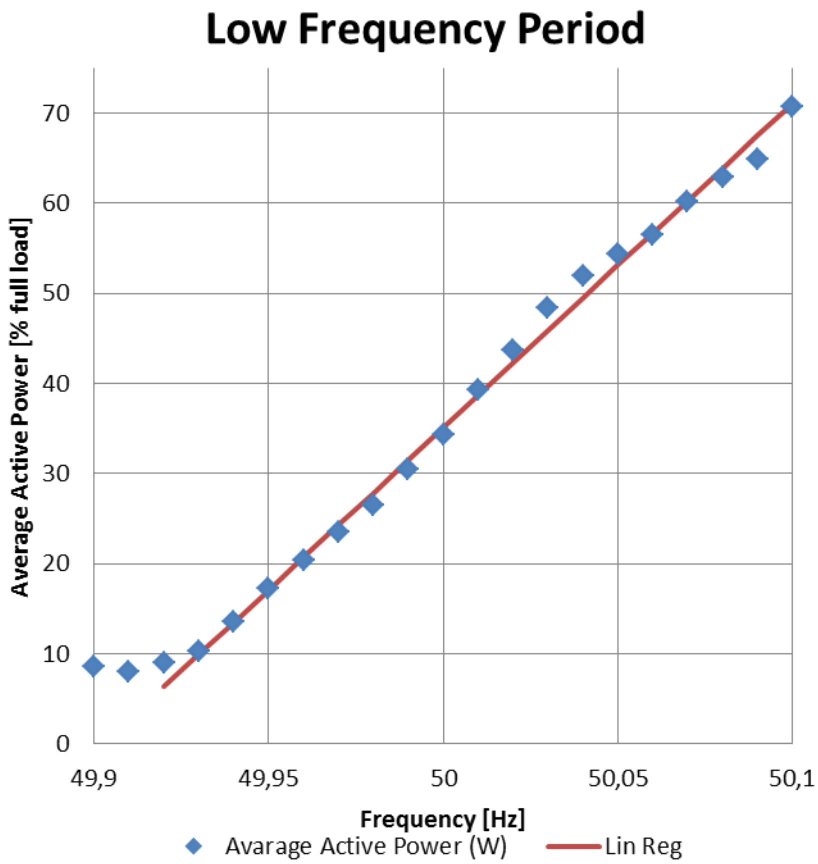


Figure 5: Frequency response of all 6 boxes with a normalised power usage. Average daily outdoor temperature below: 5.5 ^{o}C.

Here the frequncy response is visible down to 49.92 Hz and at 50.1 Hz the average power consumption is 70 %. This results in a frequency response of 63 % and can be expressed as 0.35 % Full load/mHz .

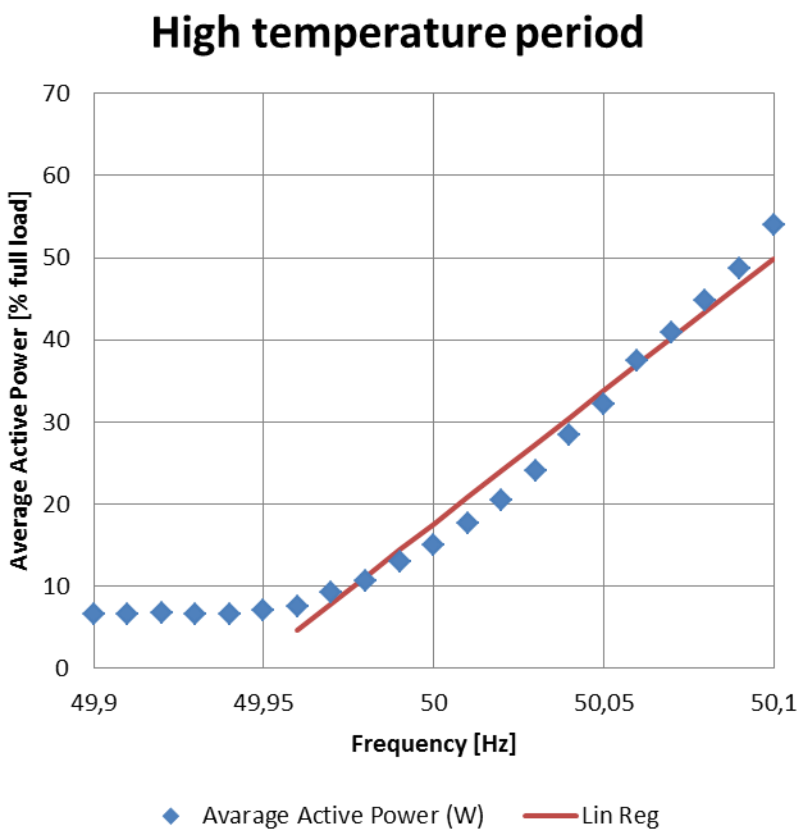


Figure 6: Frequency response of all 6 boxes with a normalised power usage. Average daily outdoor temperature above 5.5 ^{o}C.

Here the frequncy response is visible down to 49.96 Hz and at 50.1 Hz the average power consumption is 54 %. This results in a frequency response of 47 % and can be expressed as 0.385 % Full load/mHz .

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 temepratiure 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.

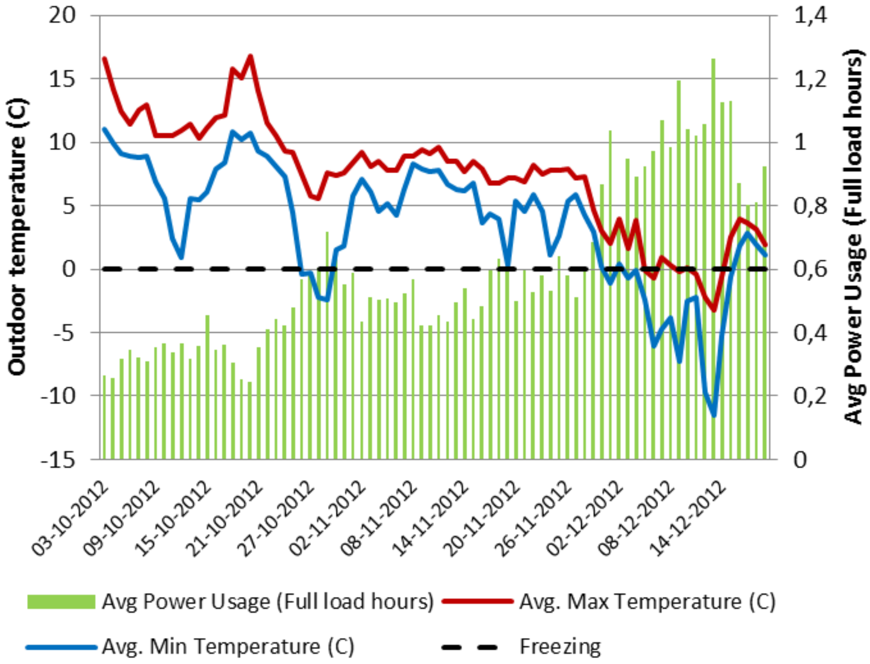


Figure 7: Outdoor temperature for Rønne (Bornholm) during the period 2012/10/03 to 2012/12/19 as well as the normalised average power usage of all boxes.

As seen in Figure 7 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. As mentioned above some of the electrical radiators are only used as a secondary heating source. This can be illustrated by comparing box number 2021 and 2042. The household of Box 2021 uses a wood stove as their primary source of heating and have the following power usage (see Figure 8).

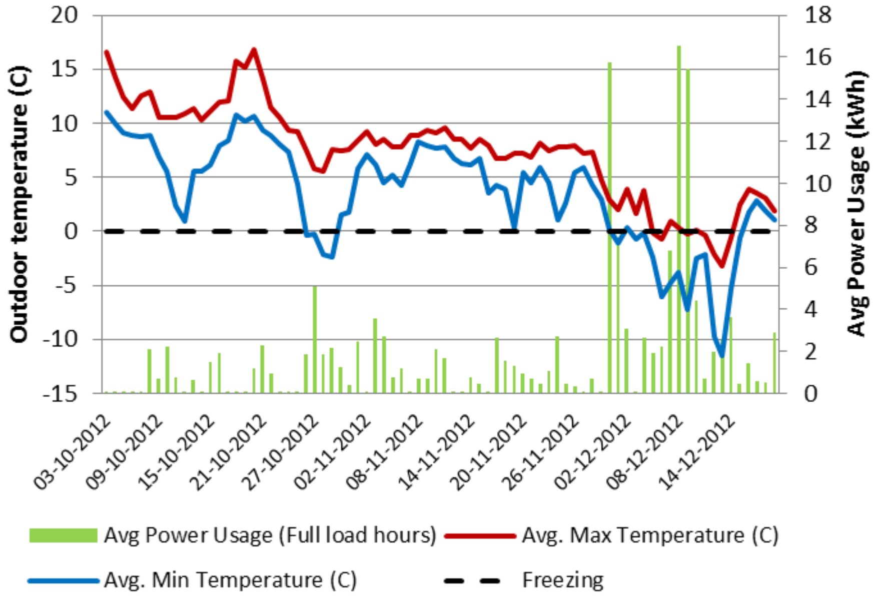


Figure 8: Average power consumption kWh/day of box 2012.

The household of Box 2042 exclusively uses electrical heating and have a measured power usage as shown on Figure 9.

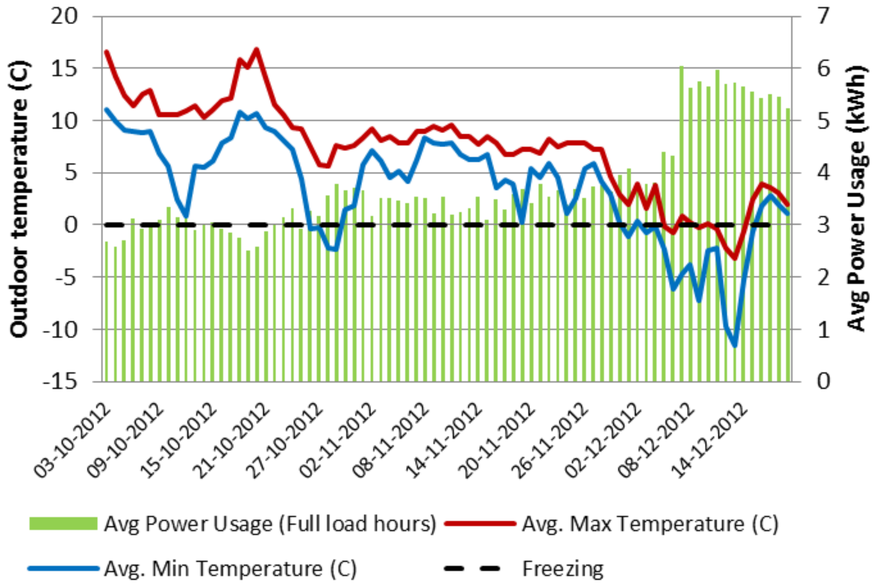


Figure 9: Average power consumption of box 2042.

This illustrates that these two boxes will have different influence on the frequency response.

To further highlight the relation between outdoor temperature and power consumption a plot of all outdoor temperatures can be observed.

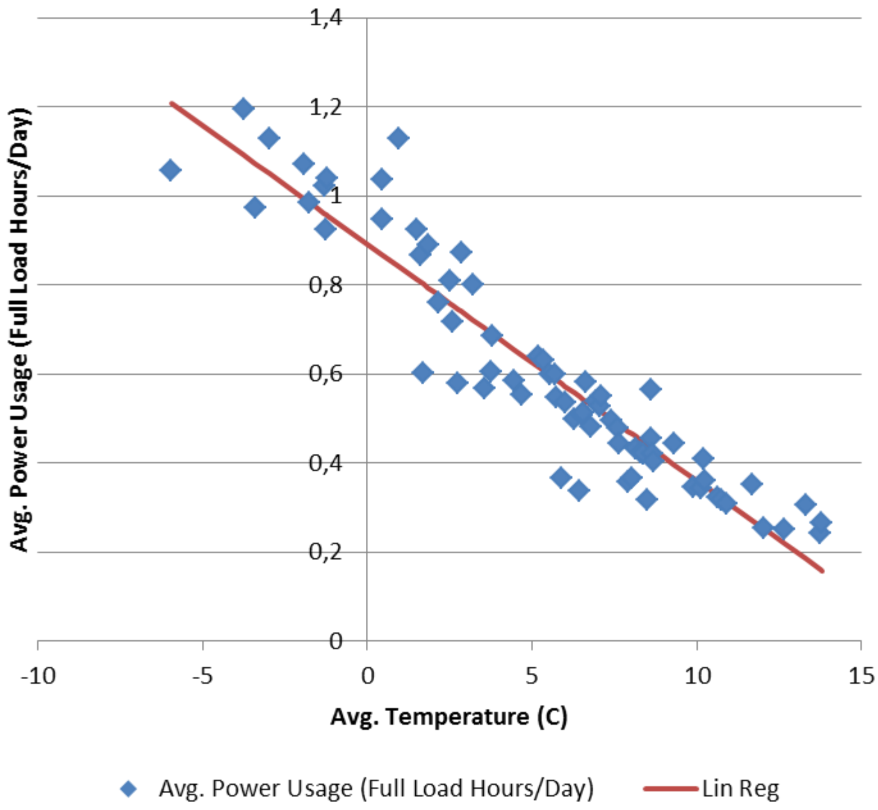


Figure 10: Outdoor temperature and Average power consumption from 2012-10-03 to 2012-12-19.

As seen in Figure 10 the average power consumption follows the outdoor temperature. This would then confirm that the boxes are collecting valid power consumption measurements.

Temperature and offset 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.

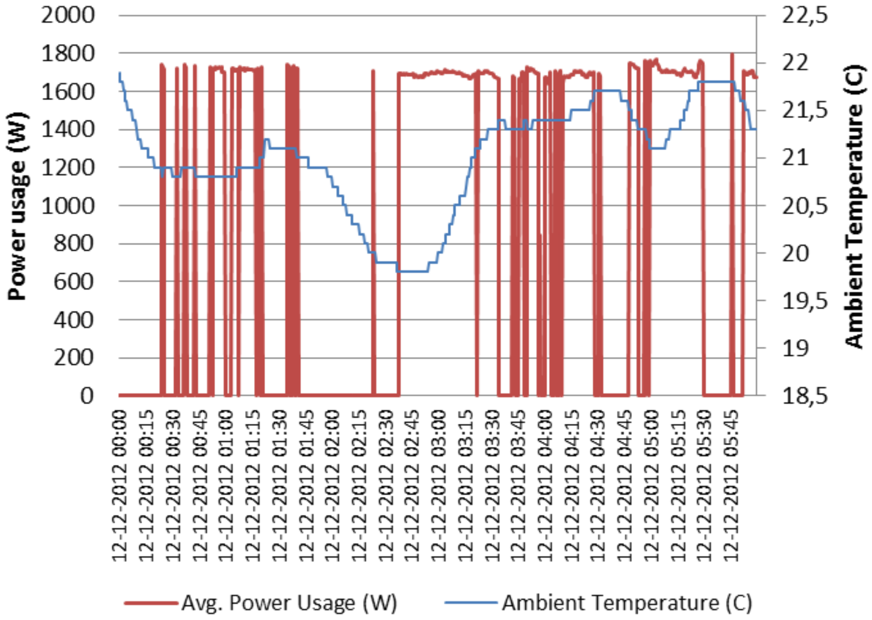


Figure 11: Power usage of Box 2037 as well as the ambient temperature measured by the thermostat

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. The box changes the set-point with a precision of 1/10th of a degree. The result of this behavour seen in the figure below.

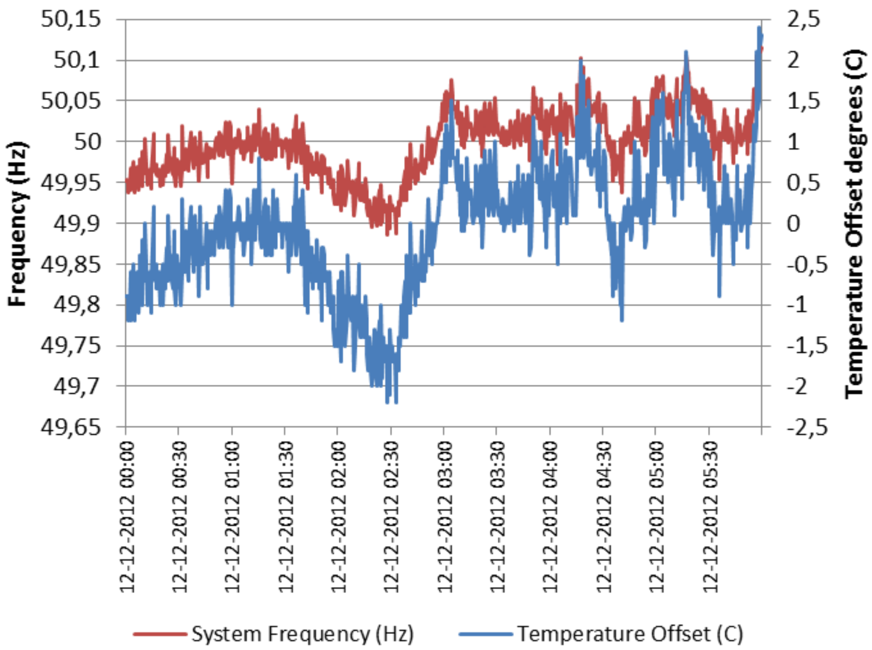


Figure 12: System frequency (Hz) and device offset values in ^{0}C

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^{o} C. Furthermore the ambient temperature and on/off indicator of the radiator is shown.

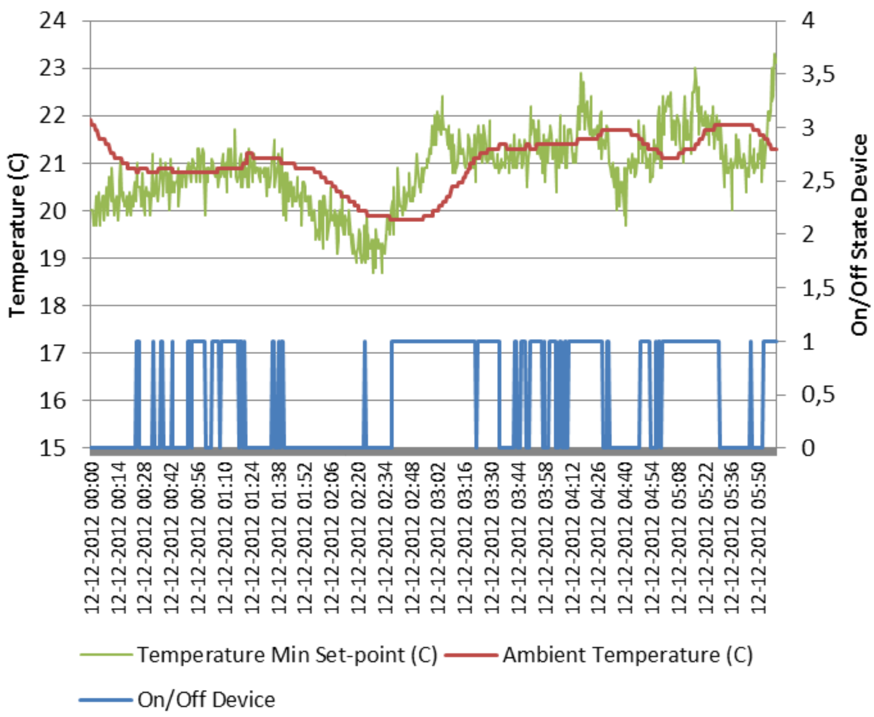


Figure 13: Temperature offset, ambient temperature, and on/off indicator.

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.

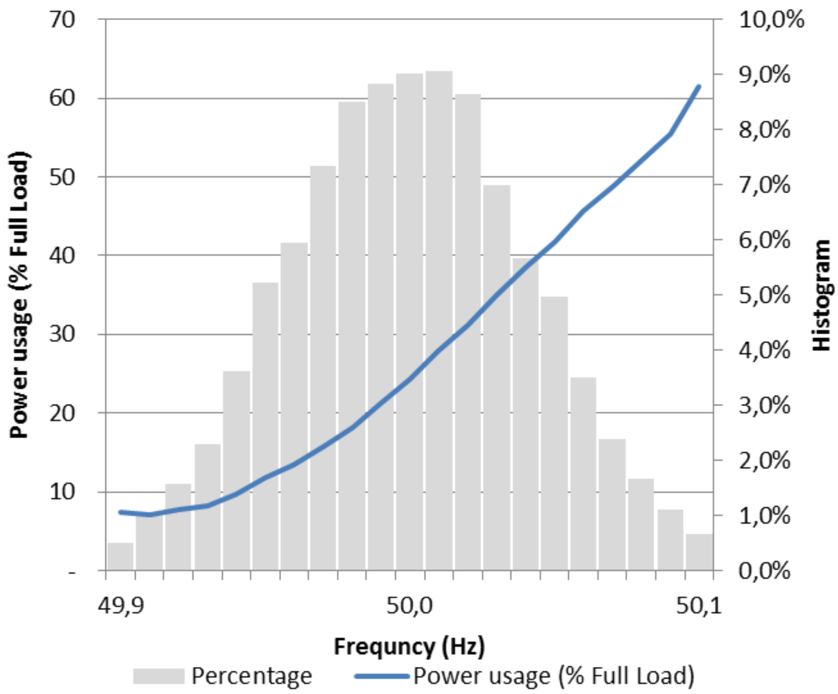


Figure 14: Histogram of frequency and frequency response.

From this we get that 98.4 % of the frequencies lie wihtin 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 (this should be evaluated against the data in **Fejl! Henvisningskilde ikke fundet.**).

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

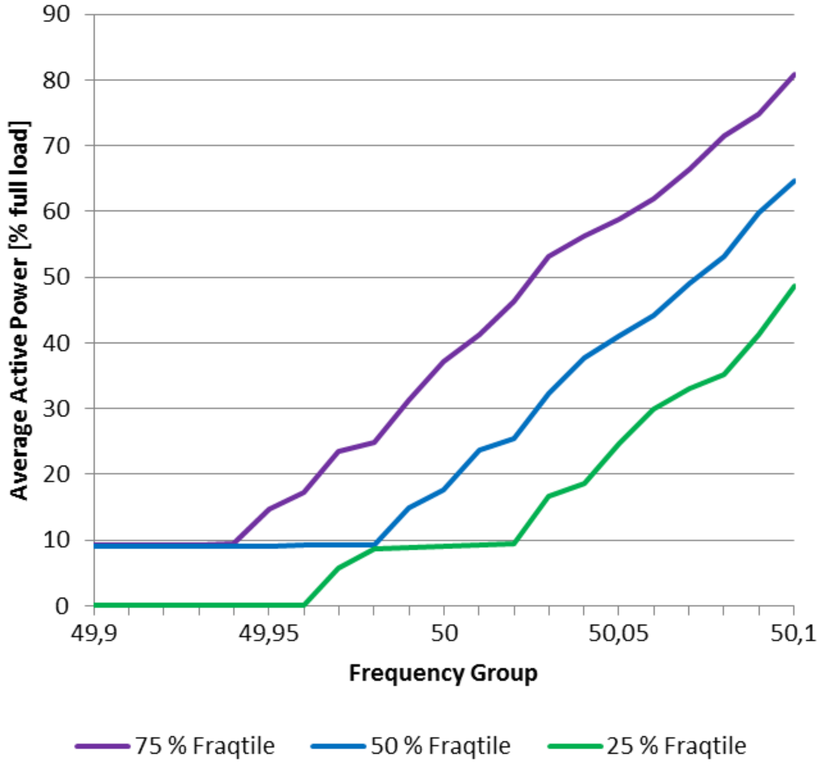


Figure 15.

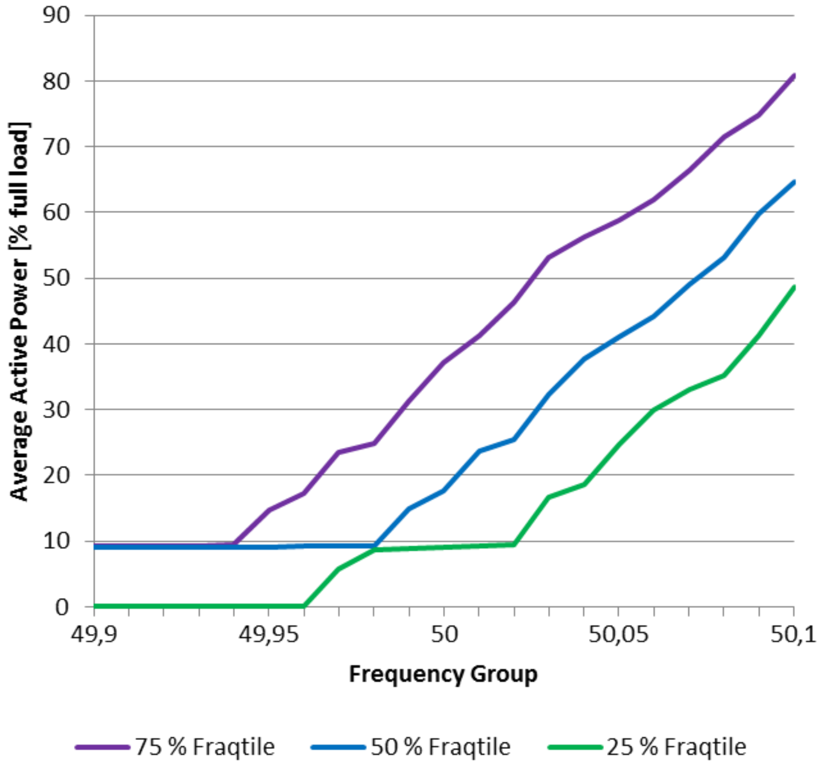


Figure 15: Power usage quantiles of system frequency group of 0.01 Hz.

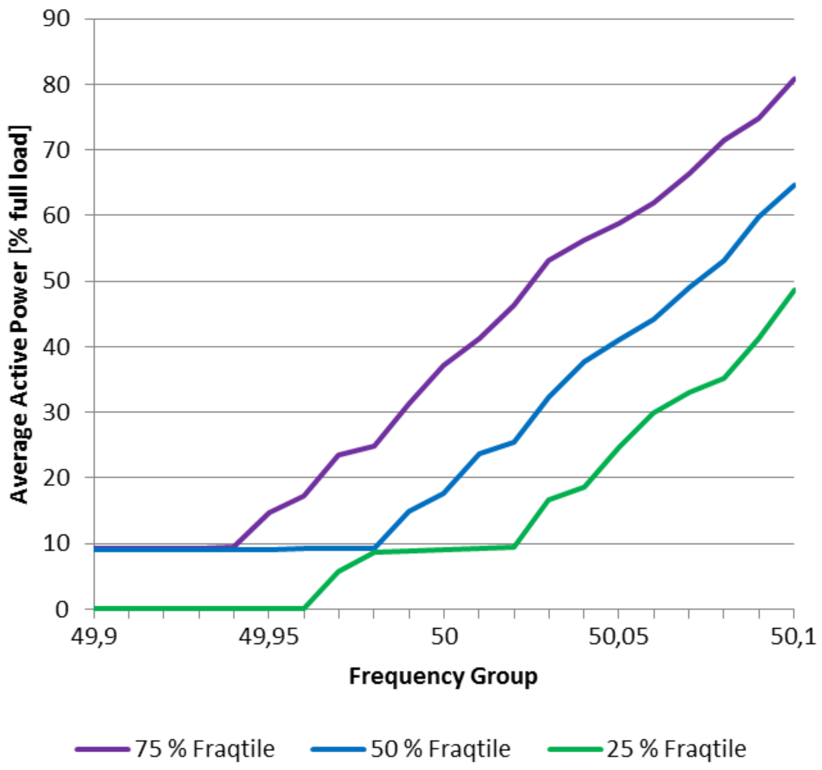


Figure 15 shows that regardless of variation in the load there is still a significant frequency response. As seen form the figure half of the meassurements at 50 Hz are between 9% load and 37% load. But at high loads (75 % fraqtile) as well as lower loads (25 % fraqtile) there is a clear linear frequency response. The lower loads can be because of the use of alternative heat sources, the heater temperature settings or the outdoor temperature.

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 corolation is 1 then the frequency is always the same. A low value (e.g. below 0.3) indicate little correlation.

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 the few demand problems would occur, e.g. in relation to electriv heating, where a typical time constant is in the order of hours.

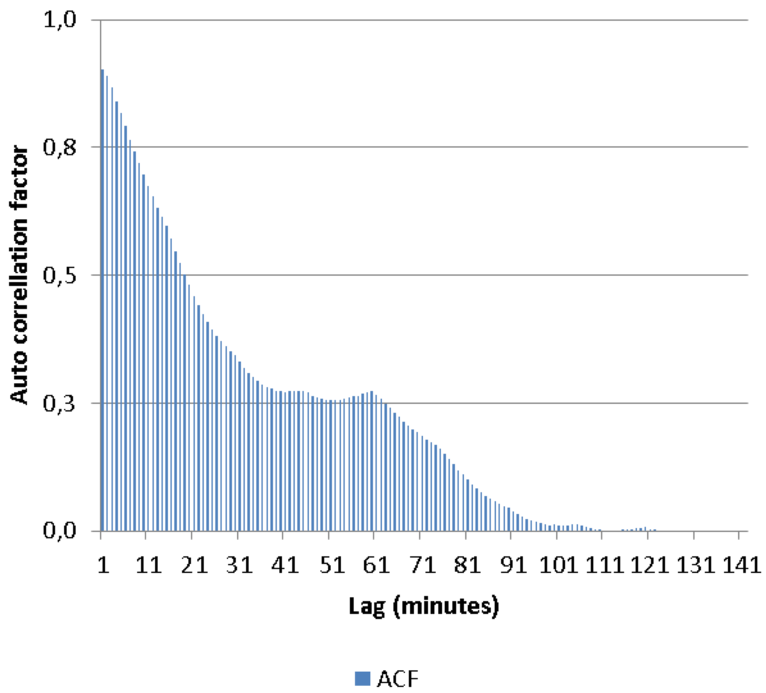


Figure 16: Autocorrelation of system frequency.

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.

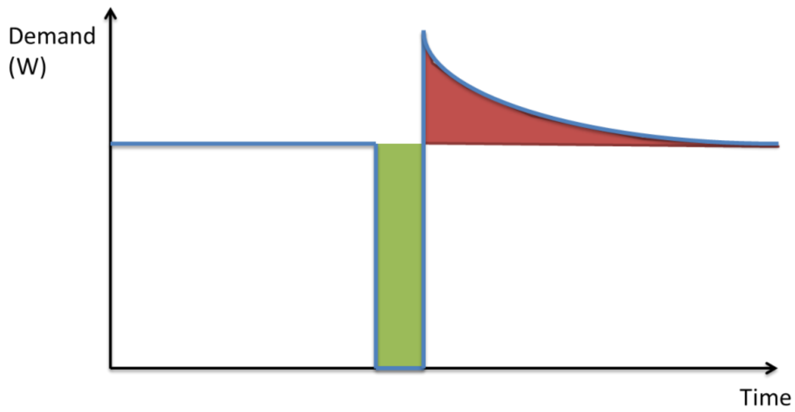


Figure 17: The electrical heater as an "energy storage". The green and red areas are expected to be more or less equal. Minor differences can occur due to change in efficiency and change in heat loss.

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 weel as Figure 18, Figure 19 and Figure 20).

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 18, Figure 19 and Figure 20). Only points with more than 25 observations are included.

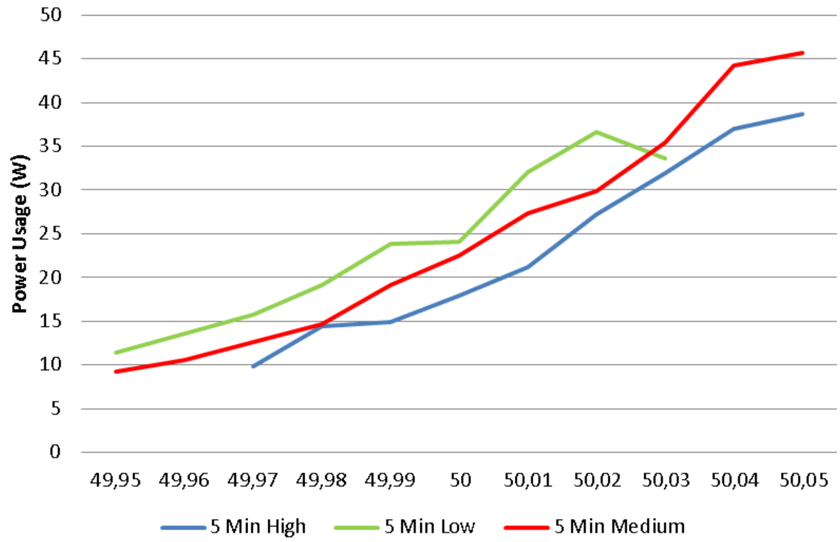


Figure 18: Rebound effect considering 5 minutes periods. Low < 49.98 Hz, Medium 49.98-50.02 Hz, High > 50.02 Hz

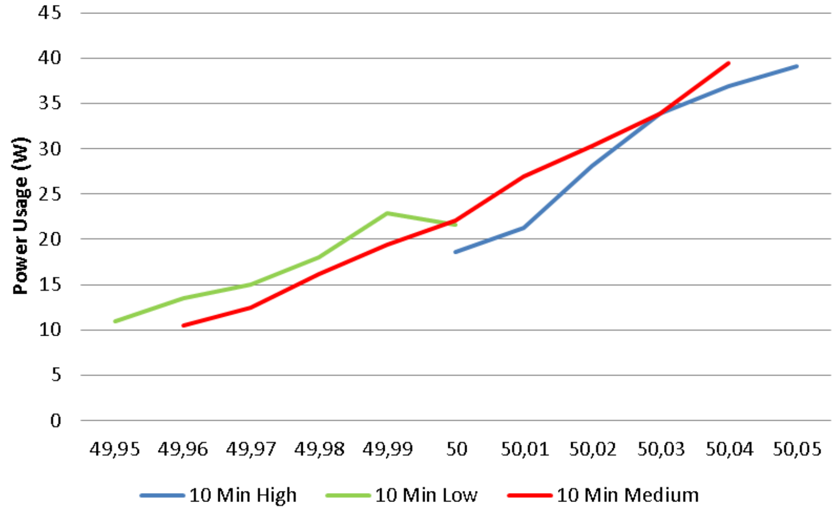


Figure 19: Rebound effect considering 10 minutes periods. Low < 49.98 Hz, Medium 49.98-50.02 Hz, High > 50.02 Hz

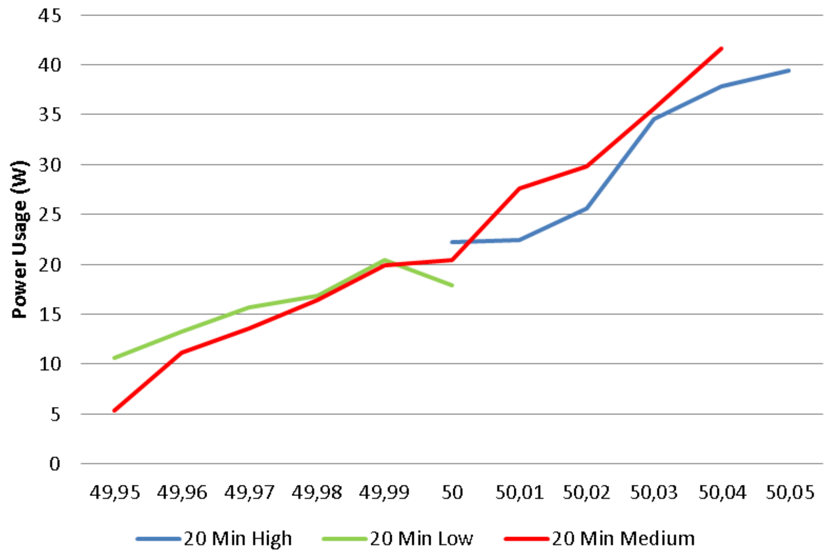


Figure 20: Rebound effect considering 20 minutes periods. Low < 49.98 Hz, Medium 49.98-50.02 Hz, High > 50.02 Hz

From these figures we see that rebound effect is present but that this rebound effect diminishes over longer time spans. 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.

Evaluation of the experiment

Electric heating is very relevant for the purpose of creating frequency controlled reserves. Electrical space heating is very influenced by climatic conditions and is thus only relevant during some periods of the year. Hot water production take place all year round.

As seen in Figure 4, Figure 5, and Figure 6 no frequency response was achieved for lower end frequencies within the normal reserve requirement. This seems to be correlated to outdoor temperature, and may suggest, that setpoint offsets should be adjusted according to outdoor temperature. In that case, frequency response is only linear for constant outdoor temperatures.

This experiment has demonstrated that the boxes are able to provide consistent and proportional frequency response. Regarding user comfort we have been in contact with all 6 participants whos 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 confort was registrated. 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 confort is uncomprised by this kind of frequency response would not be strictly supported by the experiment.

The delivered reserve is slightly affected by history of the frequency. If needed the effect could be minimised by adjusting the control parameters.

Some challenges have arisen during the experiment, especially exogenous influences on the power usage of the electrical heaters. Weather conditions and the presence of primary or secondary heat sources prevent the verification of whether an electrical radiator is off because of a low system frequency or other reasons.

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 software has been updated to include the DFCR-control. However, the marginal cost of including this function is zero for users that already have the hardware.

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. See the pictures below.

Figure 21: The Electronic Housekeeper console and the two Switchkeepers

The Electronic Housekeeper is a console that can make it easy to switch off all electronic equipment and appliances in order to save electricity. It can also play music, stream online TV and send and receive SMS. It is a relatively simple plug-and-play appliance. The communication from the console to the Swithkeepers is wireless. The console requires electricity and a good wired internet connection.

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.

The two Switchkeepers (called SK1 and SK2) used in the research project are programmed differently. See the table below.

	SK1	SK2
Swith off frequency	49.9 Hz	49.85 Hz
Switch on frequency	49.93 Hz	49.92 Hz
Minimum duration of switch off	0.5 min.	4.25 min.
Maximum duration of switch off	5 min.	10 min.

Table 1: The settings of the Switchkeepers SK1 and SK2

As the SK2 Switchkeeper can be turned off for longer periods of time it is more suitable for devices with a compressor, such as refrigerators, freezers, heat pumps etc.

Data quality

The data collected from the EHs are in 2 series – one measuring the frequency and the consumption every 5 minutes and one measuring the frequency when an event occurs (when the Switchkeeper turns on or off).

The sampling period with 5-minutes values makes it difficult to document impact as many of the responses and reactions occur in seconds. Most disconnections are very short - the duration of the ”switch off” is less than 5 minutes.

Another issue is that many of the dataseries are flawed. There is a lack of consistency between collection of meter-data (5 minute measurements) and event-data. Sometimes the EHs have registered events without there being meter-data available (for weeks and months), or there are meter-data for longer periods without any events despite the frequency varying. Also it varies how many EHs are online. Some EHs are only online for very short periods during the research project. For the analysis we have tried looking at periods where as many EHs are online at the same time (20. February 2011 – 30. April 2011).

A small percentage of the data - 0,1% of total number of meter-data – have a frequency below 49 Hz or above 51 Hz. These flawed meassurements have not been included in the analysis. Also in some 5-minute intervals (0,1% of meter-data) the consumption was measured to be over 1 kWh for 5 minutes (equivalent to >12 kW effect). These has also not been included in the analysis.

When looking at a single unit it becomes evident that there are more errors. There are some double events where the same event is registered the same time twice. And there are examples of two ”switch off”-events in a row, without the unit being ”switch on” in the meantime. Also two ”switch on”-events in a row are observed.

In the design of the frequency control there where one reason for the unit to switch off:

- the frequency was measured to be under the “switch off frequency”

And two reasons for turning the unit back on:

- when the frequency has increased above the “switch on frequency”,
- or the maximum time for switch off was reached.

However if the time limit has been reached and the frequency is still low the unit will switch off immediately again. See the figure below showing the events of a SK1-unit and the frequencies. (More on this issue under “Evaluation of the experiment”).

It was the intention in the design of the EHs to protect the appliances with a minimum “on” time after disconnection. This could have been adapted to the individual appliance as in the case with some of the DTU Smartboxes. This is, however, a more expensive solution. It was included in the design, but unfortunately never implementet.

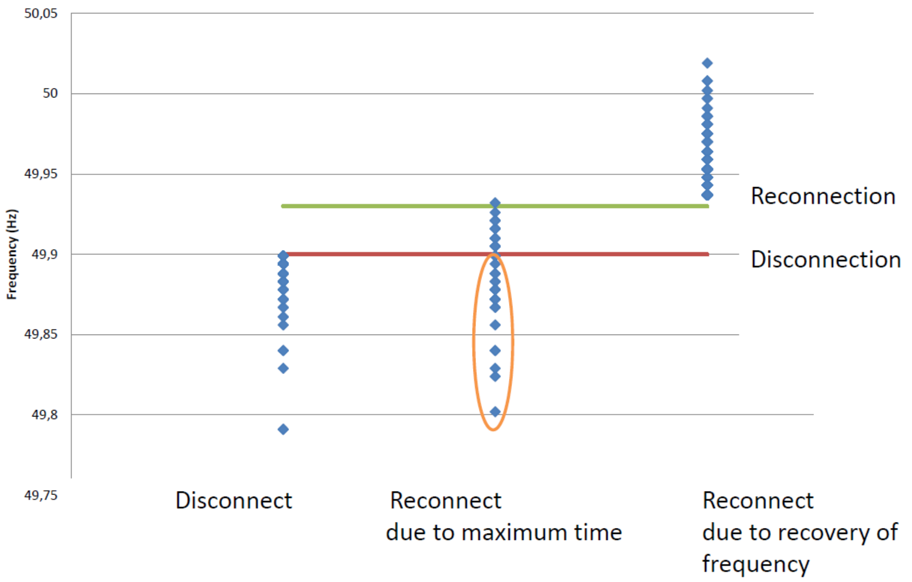


Figure 22: Example for an Electronic Housekeeper (SK1-type) connected to an electrical heater. 623 times the EH reconnected due to the time limit, however almost half the time the frequency was still below 49,9Hz.

The results

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 ant type of appliance to the EH. Unfortunately there were a lot of 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. Luckyly 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 ta a toaster.

Consumption

The average consumption of all the EHs is around 6 kWh/day per Switchkeeper (around 250 W effect per Switchkeeper). The graph below shows the daily consumption for all EH from 20th February 2011 to 30th April 2011. Many of the EHs have a relatively low consumption and only a few register a significant consumption in shorter periods. One Electronic Housekeeper is connected to an electrical heating unit and therefore has a higher consumption that all other boxes. This EH alone accounts for almost half the total consumption in the period.

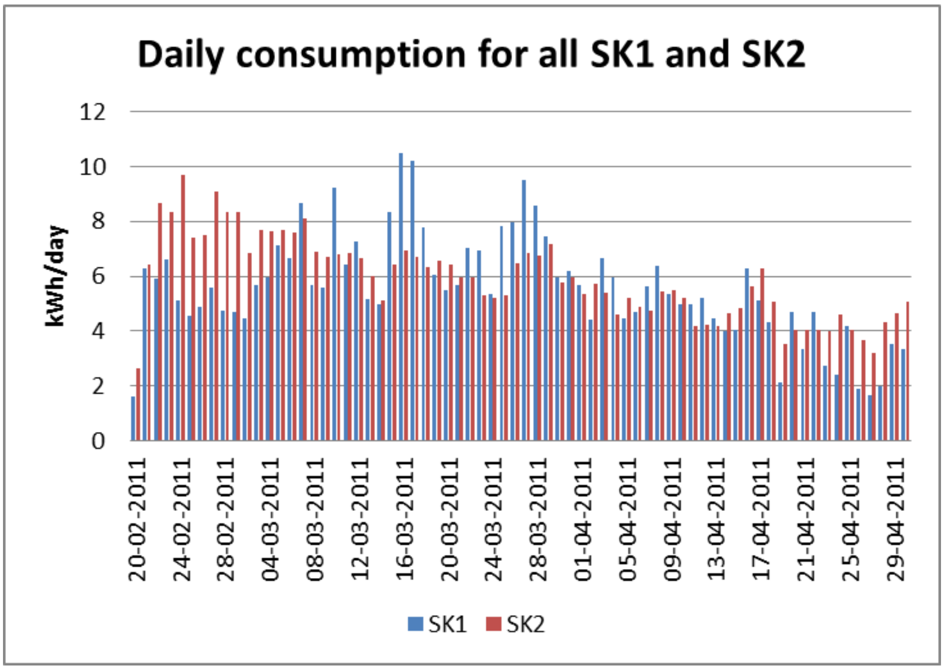


Figure 23: The consumption of all appliances connected to the switchkeepers SK1 and SK2 in the period from 20th February 2011 to 30th April 2011. This period is chosen as it was the period with

most EHs online and therefore one of the highest total consumption. Switchkeeper SK2 for the EH number 49e06 has a consumption of 2 kWh/day to 30 kWh/day in the week starting from 6th April.

There is a clear variation of the consumption over 24 hours for the EH connected to electrical heating, as the electrical heating is turned off at night and has a peak consumption when warming the hosue in the morning hours. However for the other EHs there is not a lot of variation – neither during the day nor during the year.

The units most suitable for frequency control is heating and cooling units as well as circulations pumps. Especially for heat pumps and electrical heaters there is be a significant variation of the consumption during the year. Depending on what type of appliances that will be regulated via frequency control in the future, the reserve might vary significantly in size.

Frequency

The graph below shows the frequency for all the EHs connected on the 5th of January 2011 in the 10-hour-period from 5:00 to 15:00. The frequency is measured every 5 minutes. As seen by the graph the frequency measurements are very close to each other. The variation can be due to small variation in the clocks. The standard deviation is usually below 0,05 Hz.

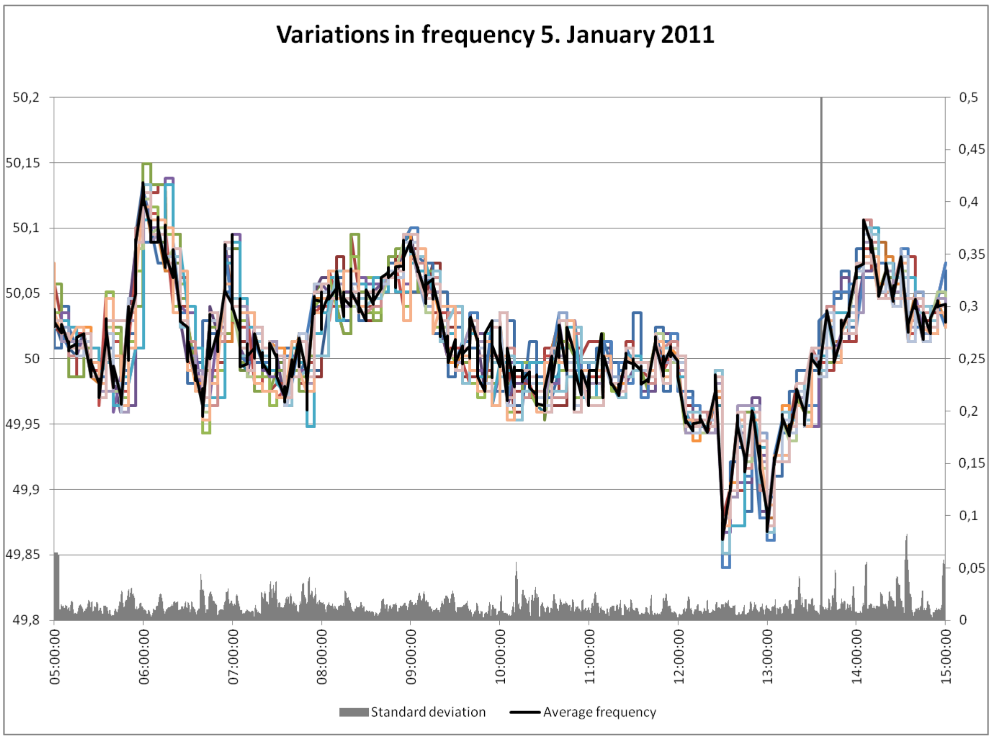


Figure 24: The frequency and the standard deviation of the frequency measured for the Electronic housekeepers.

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.

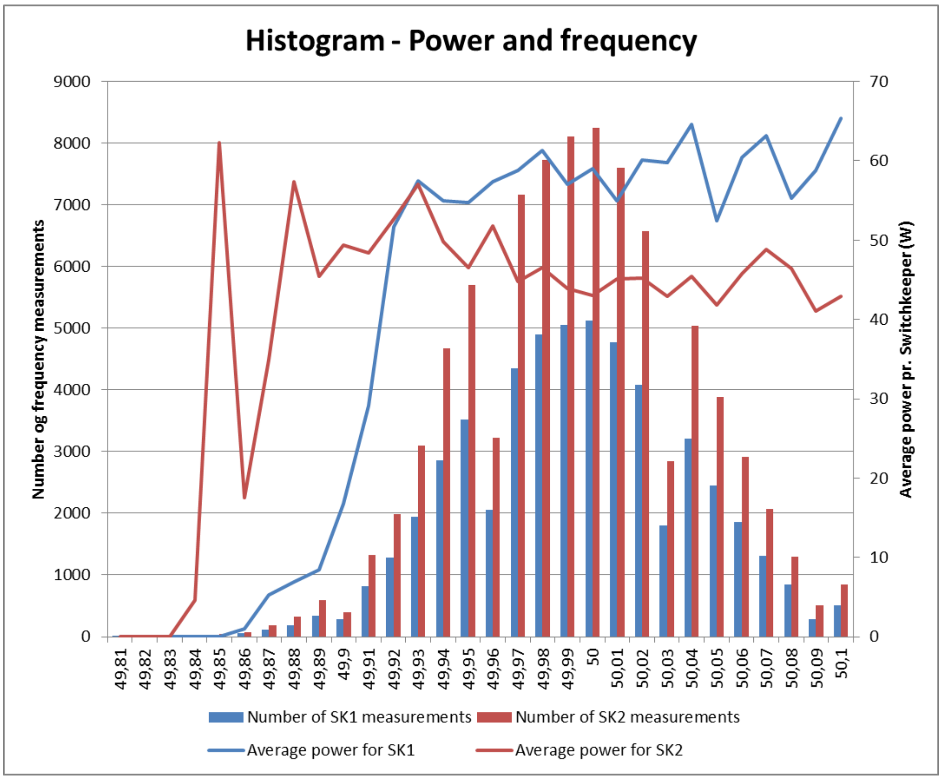


Figure 25: Histogram for 26 EHs (26 SK1s and 26 SK2s) in the period 2011-02-20 to 2011-04-30. The switch-off point for SK1s is at 49,9 Hz and for SK2s it is 49,85 Hz.

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 25 confirms this theory, taking the statistical variations into account.

Examining the rebound effect

We have tried examining if we can find a rebound effect in the consumption for the Electronic Housekeepers. The rebound effect is an expected increase in the consumption after an interval where the EH has been turned off.

However because the consumption is only measured every 5 minutes, it is difficult to evaluate this. For example: for a specific Housekeeper, out of 3273 observations only for 17 observations the EH was off in more than 30% of the previous 5-minut interval. This leaves very little statistical significance.

Evaluation of the experiment

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.

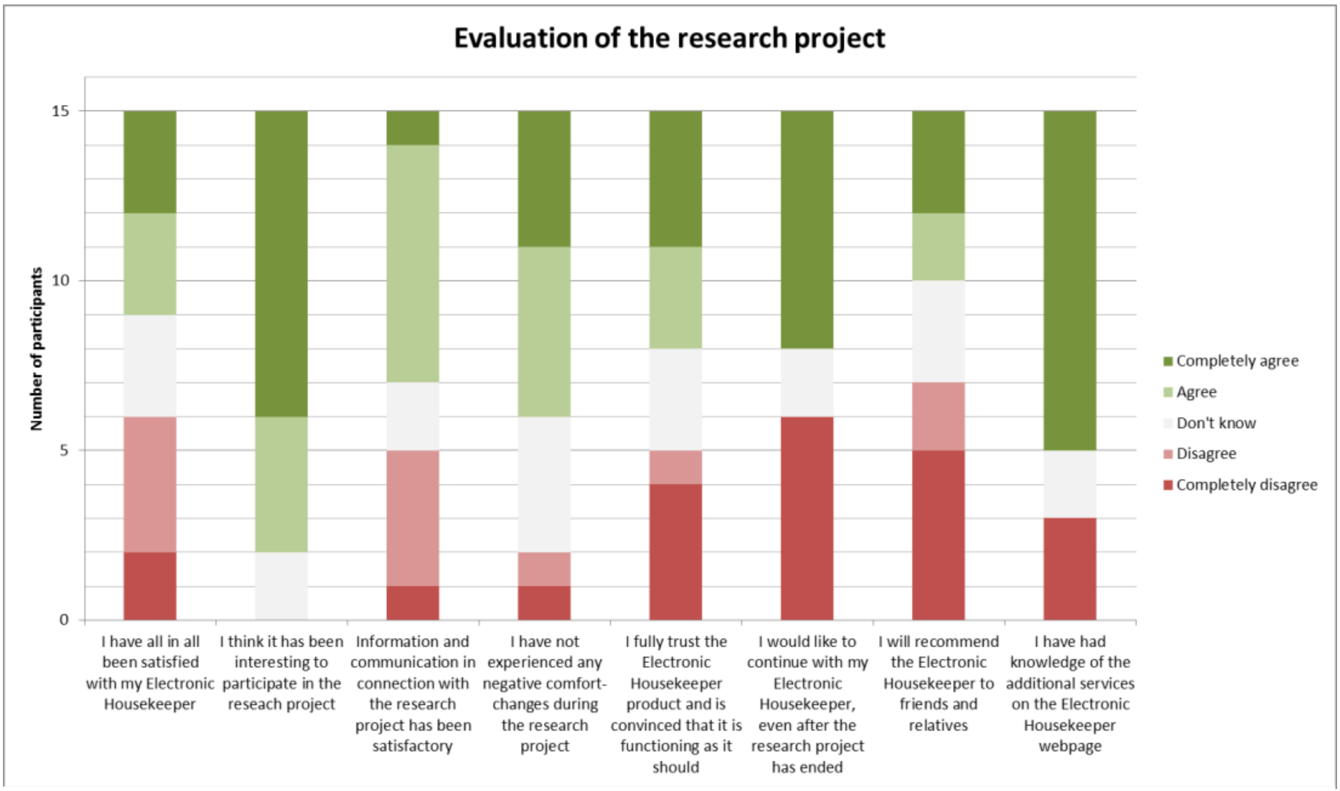


Figure 26: Results from the evaluation of the EH pilot project.

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 startup 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 reseach project “beneficial for society and technical interesting”. He also found that the EH switched his fridge off “rather often”.

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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Appendix D Smart Demand for Frequency Regulation: Experimental Results

Smart Demand for Frequency Regulation: Experimental Results

Philip J. Douglass *Student Member, IEEE*, Rodrigo Garcia-Valle *Senior Member, IEEE*, Preben Nyeng *Member, IEEE*, Jacob Østergaard *Senior Member, IEEE*, and Mikael Togeby

***Abstract*—As renewable energy sources increase their penetration, the traditional providers of frequency regulation service, i.e. fossil fueled thermal power plants, will be displaced, motivating the search for novel providers such as demand-side resources. This paper presents the results of field experiments using demand as a frequency controlled reserve (DFCR) on appliances with programmable thermostats. The experiments conducted showed the response of a population of thermostatically controlled loads acting as normal reserves (up and down regulation) and disturbance reserves (up regulation only) as defined by the Nordic Grid Codes [1]. In addition, industrial pump loads and relay-controlled loads were tested as DFCR. The tests show that a population of refrigerators was able to deliver frequency reserves approximately equal to their average power consumption. Electric space heaters in the autumn season were able to provide frequency reserves of a magnitude 2.7 times their average power consumption.**

***Index Terms*—Demand side, Frequency control, Demonstration project, Smart grids.**

I. Introduction

TRADITIONALLY, electric generators are dispatched to follow passive loads. This mode of operation is infeasible with non-dispatchable stochastic energy sources such as wind and PV and one possible remedy is to dispatch loads to follow production. Today, many loads are equipped with microprocessors running firmware for controlling local processes. These loads could be programmed to actively monitor the state of the power system as a whole and schedule their own power use to help balance consumption with production.

Loads providing thermal energy services (e.g. refrigerators, heat pumps and resistive heaters) are well suited to following fluctuating generation because their inherent heat capacity acts as an energy storage device allowing electricity consumption to be shifted in time without compromising the quality of service. Thermostat controlled loads (TCLs) are a significant portion of total electric loads, representing around half of household electricity consumption in the USA [2].

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Despite the declining cost of communications devices, providing a real-time digital communications interface from a system operator to small loads represents a significant cost barrier to widespread deployment. However, there is already a parameter which is universally available to indicate the instantaneous balance of electric energy production and consumption, namely the system frequency.

The relation between power generated, $P_{\mathrm{M}}(t)$, power consumed, $P_{\mathrm{L}}(t)$, and deviations in system frequency,$\Delta f(t)$, is given by the swing equation [3]

$$\Delta P_{\mathrm{M}}(t) - \Delta P_{\mathrm{L}}(t) = 2\mathrm{H}\frac{d\Delta f(t)}{dt} + \mathrm{D}\Delta f(t) \qquad (1)$$

where H is the inertia constant, and D is the load damping coefficient.

Loads may measure the system frequency and by adjusting their power consumption up or down as the system frequency rises or falls, they are able to provide reserves for frequency regulation. This concept is known as demand as a frequency controlled reserve (DFCR) [4], or alternatively Frequency Adaptive Power Energy Rescheduler (FAPER) [5], Dynamic Demand [6], Frequency-Sensitive Gridfriendly™Appliances [7], or Frequency Responsive Load Controller [8].

This paper presents the result of a field experiment where, for the first time, DFCR loads have been installed in an uncontrolled working environment and their performance as a group has been monitored.

The load damping coefficient captures the behavior of motors, which constitute a large portion of total load. Similar to motors, DFCR loads' power use in aggregate is proportional to system frequency, but there are several aspects that cause DFCR loads to be poorly modeled by their contribution to the load damping coefficient. These aspects are:

1) **Time Dependency**: DFCR loads imply an energy storage buffer, and this buffer's "state of charge" (SOC) depends on the historical progression of the system's frequency. The appliance's frequency response depends on the SOC the energy storage buffer.
2) **Discrete nature of loads**: many types of loads are either ON/OFF, it is only in aggregate that they can provide a gradual, linear frequency response.

3) **Parameter Design**: The damping coefficient of traditional loads is a natural property, rather than a design decision. With DFCR loads, the system planner has the freedom to specify the frequency response, rather than be constrained by the inherent properties of passive loads. The frequency response can be specified over at limited range of frequencies and be flat outside that band.

While the DFCR loads are physically located in the low voltage distribution system, it is the transmission system operator who needs to account for their behavior when specifying the requirements for frequency regulation reserves.

This paper is structured as follows: Section II describes the experimental setup including the design of the DFCR controller and loads, Section III describes the parameter configuration for operation in the Nordic power system. Section IV presents and discusses the results of the experiment. Finally, Section V concludes with a description of future work.

II. Experimental Setup

We have currently deployed approximately 70 DFCR appliances out of a planned 200 units, primarily on an island in the Baltic Sea, Bornholm, which is connected to the Nordic transmission grid by a 60 kV under-sea cable. Bornholm has a peak load of 55 MW and a high penetration of wind energy (over 30% of electric energy production annually), but when the island is disconnected from the Nordic grid, wind production must be curtailed to maintain acceptable frequency quality [9], [10].

Each DFCR system consists of two parts: a commercially available appliance which has been modified to expose a serial port to an external controller, and an external controller which we have produced for this experiment from off-the-shelf components [11]. The TCLs are composed of bottle coolers located in hotels, restaurants and convenience stores, and resistive electric heating systems placed in single family homes. Industrial loads were tested in a water treatment facility.

A. DFCR Controller Hardware

Fig. 1 shows a block diagram of the DFCR controller. The DFCR controller measures frequency using a zero-crossing algorithm and averaging over 8 cycles. Every 250 ms the CPU receives and processes frequency measurements. The controller timestamps all measurements with a real-time clock that is synchronized via the internet time protocol NTP. The accuracy of the timestamps and frequency measurements was evaluated by finding examples when multiple controllers took frequency measurements within the same second, and the resulting standard deviation of frequency measurements was 1.3 mHz [11].

An integrated circuit dedicated to power measurement measures voltage and current, and calculates active and reactive power consumption of the attached loads. Data on power consumption and system frequency, as well as parameters specific to the appliance under control are sampled once per minute, and stored into a large internal memory. In addition, when a large frequency excursion occurs, data is collected at a high resolution (as often as every 2 seconds). This data is periodically uploaded to a database using a GSM/GPRS wireless modem and the HTTP protocol.

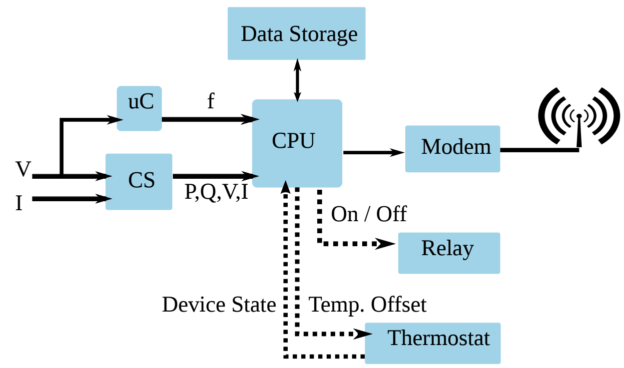

Figure 1. DFCR block diagram. The CPU is a low cost micro-controller with 8 kB of RAM. The system frequency is measured by a secondary micro-controller (uC). Power consumption (real and reactive) is calculated by a dedicated component (CS). The measurements are buffered to an SD card (Data Storage), and uploaded periodically to a database via GSM/GPRS (Modem). Some boxes have a relay built into the device, others communicate to programmable thermostats via a serial cable.

The DFCR controller parameters are configurable, and the firmware can be remotely upgraded. This facility was used to test different types of frequency reserves.

B. Loads

1) Bottle Cooling Refrigerators: The refrigerators used in the experiment are all identical bottle coolers with a glass door and internal light that remains on when the door is closed. They contained a programmable thermostat that, via a serial cable, delivered data to the controller about the internal state of the device and accepted configuration commands. The DFCR controller utilized a mode of the thermostat that added a temperature offset to the user-given setpoint. Only the operation of the compressor is affected by the external controller, the light and other internal processes which account for a residual power consumption are not affected by the DFCR function. Comparing power consumption before and while the compressor runs reveals that the compressor itself consumes on average 230 W. When the compressor is off but the light is on the refrigerator consumes 30 W and when the light is off it consumes 13 W. The daily load profile of the refrigerators reveals that the maximum consumption occurs at noon, when the power consumption is 20% higher than during the night.

The user configures the refrigerator thermostat with a temperature setpoint. The thermostat turns the compressor on when the internal air temperature rises above the deadband of 2°C, and turns the compressor off when the air temperature reaches the setpoint. The thermostat includes an "anti-short cycle" feature, which ensures that at least 3 minutes elapse between stopping and restarting the compressor. This feature protects the motor from over loading at startup due to high pressures in the condenser. During normal operation, without introducing setpoint offsets, the ON/OFF cycle repeats every 15 minutes, where the compressor has a duty cycle of 32%.

The normal operation of the thermostat is periodically interrupted by the defrost cycle which turns the compressor off for approximately 30 minutes and allows the internal air temperature to rise well above the deadband. A refrigerator is in the defrost state 6% of the time. To analyze the effect of DFCR functionality, refrigerators in defrost state are excluded from the data set. The "anti-short cycle" feature also interferes with the ideal operation of the refrigerators, but unlike with the defrost state, there was no feedback from the thermostat to the DFCR controller as to when this feature was active, so its effect could not be explicitly accounted for.

In total, 40 refrigerators were deployed, and data was available from 35 of them for the time period chosen for analysis. The refrigerators that did not deliver data failed because of problems such as poor GSM connectivity, faulty thermostats or missing serial connection between the external controller and thermostat.

2) Electric Space Heaters: The electric heaters used in the experiment are resistive radiators in private residences with a rated power consumption between 0.5 kW and 2 kW. As with the refrigerators, the user gives a temperature setpoint, and the DFCR controller adds an offset to the setpoint depending on the system frequency. The operation of the thermostat is not as straightforward as the refrigerators because temperature measurements are filtered before being compared to the setpoint and deadband. This filtering is done to compensate for the heat generated by the microelectronics in the thermostat itself, and to optimize power consumption while accounting for the heat capacity of the home and the behavior of its occupants.

The heat load is highly influenced by ambient temperatures. The test period occurred from the beginning of October to the end of November where ambient temperatures on Bornholm averaged 8.0°C [12], and indoor temperatures of the test houses averaged 21.2°C.

3) General Purpose Relay-Controlled Loads: Data was collected from 10 controllers equipped with a relay that de-energized all attached loads. 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. A more detailed presentation of this algorithm can be found in [4].

The loads connected to this controller were diverse including pumps for circulating water, resistive heaters, and small refrigerators. These loads were located in educational institutions, offices and homes.

4) Wastewater Treatment Plant: Treatment of wastewater is an energy intensive service with a large untapped potential for demand response. In Denmark wastewater treatment consumed 528 GWh of electric energy in 2009, accounting for 1.6% of all electricity consumption [13]. The central wastewater treatment plant serving Bornholm's largest city (pop. $\approx 14,000$) 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 moved cleaning brushes. The DFCR control box provided a binary input into an existing industrial control system which was responsible for actuating the loads. A signal from a DFCR controller indicated when the system frequency had fallen below a given threshold, and the industrial control system was reprogrammed to use this signal to interrupt processes that tolerated interruption, while giving first priority to ensuring that process constraints were not violated. The behavior of these loads are comparable to the relay-controlled loads, with the exception that the time constraints are handled by the industrial control system, not the DFCR controller.

DFCR units acting exclusively as power measurement devices were attached to each of the controlled loads. Data from 13 loads representing an aggregate average power consumption of 5.7 kW was analyzed.

5) Summary of Loads: A representative time series of the system frequency and aggregated power consumption of 3 types of DFCR loads is shown in fig. 2. During this time period the refrigerator loads are configured as a disturbance reserve (up regulation only), and show a weak response during the under-frequency excursion around minute 20. The water treatment plant, the largest load group, interrupts consumption for 15 minutes during the under-frequency excursion, and displays a short spike in consumption upon reconnection. Heater loads concentrate their consumption to time periods when frequency is above nominal, providing down regulation as well as up regulation.

III. Configurations of DFCR for the Nordic Power System

System operators seek to minimize the extent and duration of frequency deviations from the nominal value. The Nordic power system has been experiencing declining frequency quality for the past 10 years, in 2011 system frequency was outside the acceptable range of 50 Hz$\pm$100 mHz for more than 2% of the time [14]. During periods when frequency was below the acceptable range,

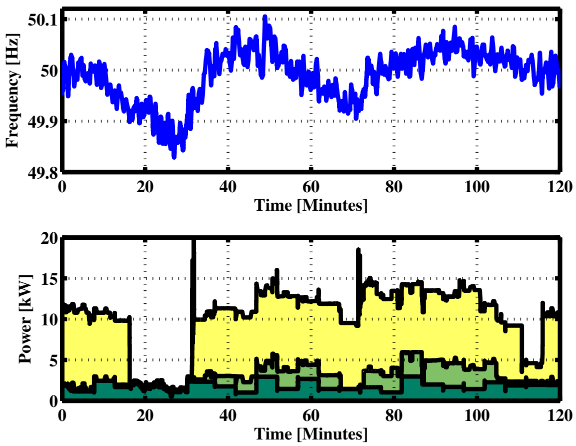

Figure 2. Time series of system frequency (top) and aggregate response of DFCR loads (bottom) over a representative two hour period. In the bottom sub-figure the consumption of different devices is stacked, with the refrigerators is dark green at the bottom, heaters in light green in the middle, and the water treatment plant in yellow at the top.

insufficient frequency controlled reserves were available to satisfy the n-1 reliability criteria.

The Nordic grid maintains frequency stability by purchasing frequency controlled reserves from central power plants in 4 hour blocks one day in advance. In the hour of operation, the system operator monitors system frequency for off-nominal excursions and tie lines for deviations from scheduled transfers, and manually activates the least cost up or down regulation resources to correct any imbalances. In the event of an imbalance between power supply and demand, the frequency controlled reserves act to stop the system frequency from changing, but they do not restore the frequency to the nominal value. At present, the Nordic system lacks an automatic frequency restoration reserve, and this results in long periods when the system frequency operates at off-nominal values.

The frequency controlled reserves are divided into two subcategories: Normal Reserve and Disturbance Reserve. The normal reserve is active in the range 49.90 Hz - 50.10 Hz, and requires a linear response from generators within 180 s. Generators which participate in this reserve are continuously adjusting their output to match the small fluctuations in system frequency, but their slow response, while favorable to operators of thermal power plants, has a negative effect on frequency quality. The disturbance reserve is active in the range 49.50 Hz - 49.90 Hz, providing an up regulation service. It is also a linear response, but it must act faster than the normal reserve, being 50% activated within 5 s, and fully activated within 30 s [1]. This type of reserve is intended to act on rare occasions, such as when a transmission line, or power plant trips. At present, because of the poor frequency quality mentioned previously, the disturbance reserve is overused, being activated about once an hour.

Table I
PARAMETERS FOR NORMAL RESERVE

Controller Type	Parameter Name	Value
TCL	Minimum Temperature Offset	-2°C
TCL	Maximum Temperature Offset	2°C
TCL	Lower Frequency Response Limit	49.90 Hz
TCL	Upper Frequency Response Limit	50.10 Hz

A. DFCR for Normal Reserve

The TCLs are well suited for continuous operation as a normal reserve, because the setpoint offsets can be effectively done in 0.1°C increments. When the devices were configured to operate as a normal reserve, the temperature setpoint given by the user corresponded to the thermostat setting at the nominal system frequency, 50.00 Hz. The thermostat temperature setpoint was offset from the user-given setpoint by a value linearly proportional to the deviation of the system frequency from nominal as described in [15].

The range of setpoint variations was chosen to exceed the size of the thermostat's deadband, so that a sudden change from 50.00 Hz to 49.90 Hz would turn all devices off, including those that had recently turned on. Values for the controller's parameters are given in table I. The relay-controlled loads, and the loads of the wastewater treatment plant are not suitable for operating continuously as a normal reserve.

B. DFCR for Disturbance Reserve

For the TCLs, operation as a disturbance reserve is similar to the normal reserve, with the differences being that the the thermostat is rarely offset, and when it is the offset is always towards the ambient temperature. The temperature offset range of the TCLs operating as disturbance reserve is -3°C at 49.70 Hz and 0°C at 49.90 Hz. This is a smaller range, but a larger deviation of temperature from the user-given setpoint than the normal reserve. A sustained setpoint deviation of -3°C could be unacceptable to users, but is allowable for a disturbance reserve because of the short time periods spent in this frequency range.

The relay-controlled loads, and the loads of the water treatment plant were all programmed to shed load at 49.90 Hz. Using a single cutoff threshold simplified the implementation and analysis of the devices, but from a system operator's perspective this is undesirable behavior. The risk caused by this implementation is exemplified by the large cohort of PV inverters in Germany which are all programmed to cut off production at 50.20 Hz [16]. In a large scale deployment, the threshold frequency would need to be spread over a range of values to avoid introducing disturbances caused by step changes in load.

The general purpose relay-controlled loads were given conservative time constraints to accommodate the diversity of load types, shown in table II. The time constraints on

Table II
PARAMETERS FOR DISTURBANCE RESERVE

Controller Type	Parameter Name	Value
TCL	Minimum Temperature Offset	-3°C
TCL	Maximum Temperature Offset	0°C
TCL	Lower Frequency Response Limit	49.70 Hz
TCL	Upper Frequency Response Limit	49.90 Hz
Relay	Minimum Disconnect Time	30 s
Relay	Maximum Disconnect Time	120 s
Relay	Minimum Reconnect Time	240 s
Relay/Water	Cutoff Frequency	49.90 Hz
Relay/Water	Reconnect Frequency	49.95 Hz

the signal sent to the wastewater treatment plant were set to very permissive values, and were rarely active.

IV. RESULTS AND DISCUSSION

This section presents the results of the experiment, grouped by configuration type and load type.

A. Normal Reserve

1) Refrigerators: 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 fig. 3, 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 50.00 Hz. At frequencies above 50.10 Hz and below 49.90 Hz, the linear trend breaks down because the thermostat's offset has reached the limit of it's deviation from the user-given setpoint.

The slope of the least squares linear regression is 0.431 kW/Hz. Given that the thermostat was changed with 20 °C/Hz, the relation of temperature offset to power consumption is 21.6 W/°C. The difference in average power consumption at 50.10 Hz and 49.90 Hz was 90.1 W. Compared to the compressor's power consumption of 230 W, we find that 39.2% of the compressor's power has been mobilized to participate in DFCR service. The average power consumption of the refrigerators (including light and residual consumption) was 89.4 W, slightly less than the power provided for the frequency response.

The distribution of values within each frequency group was analyzed by finding the quartiles, as shown in fig. 4. The difference between quartiles increases as frequency increases. For frequencies below 49.95 Hz, the first quartile is where all compressors in the population are off.

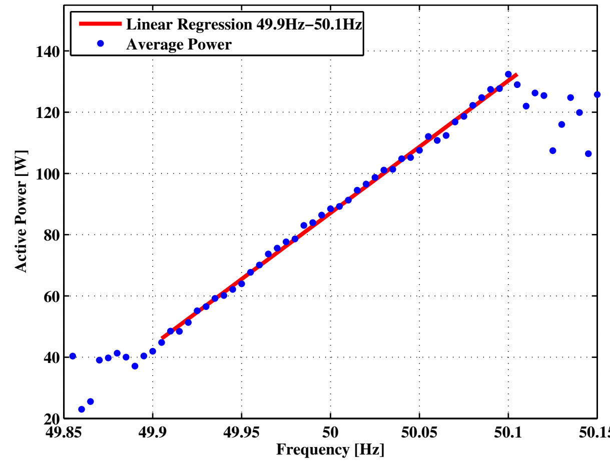

Figure 3. Average frequency response of a refrigerator with least squares linear regression. Temperature offset varied linearly with ±2°C in the range 49.90 Hz - 50.10 Hz, with 0°C offset at 50.00 Hz.

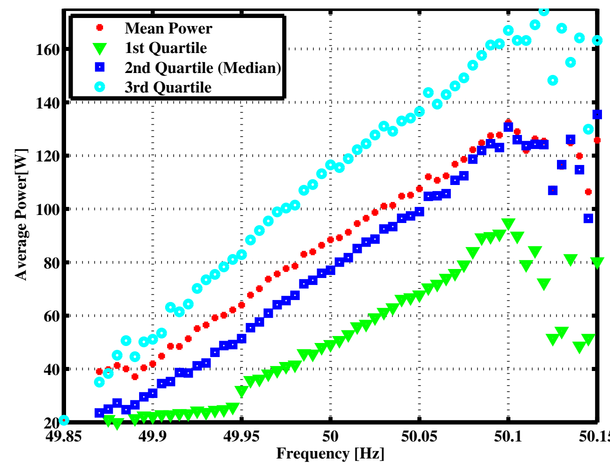

Figure 4. For each frequency group, mean power is shown together with the median, 1st and 3rd quartiles.

The power consumed by the refrigerators' compressor is used to cool the air inside, but the air temperature changes more slowly than power consumption, and is delayed by the heat capacity of the heat transfer circuit. Plotting average internal air temperature against average frequency for each minute, fig. 5 shows an inverse correlation of temperature to system frequency, as expected. The average temperature varies by approximately ±1.3°C from 49.90 Hz to 50.10 Hz, even though the thermostat setpoint has been offset by ±2°C.

Continuously changing the refrigerators setpoint offset increased the number of times that the compressor cycled ON and OFF by 10% compared to non-DFCR operation.

To reveal how the frequency response changed due to the frequency history, the data was divided into 3 groups based on the average historical frequency: low historical frequency ($\overline{f} < 49.975$ Hz), middle historical frequency (49.975 Hz $< \overline{f} <$ 50.025 Hz) and high historical frequency ($\overline{f} >$ 50.025 Hz). The frequency

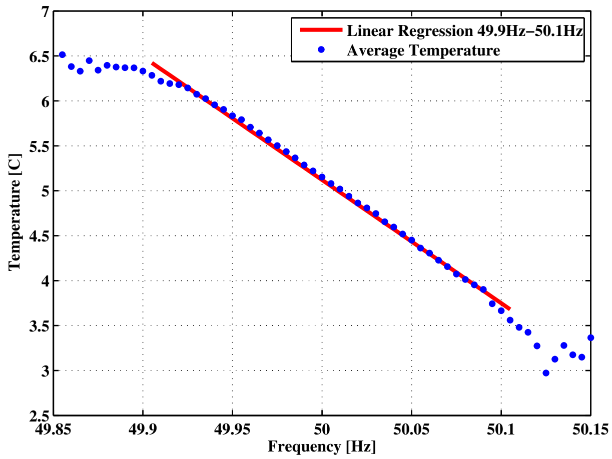

Figure 5. Average internal air temperature of refrigerators vs frequency with least squares linear regression.

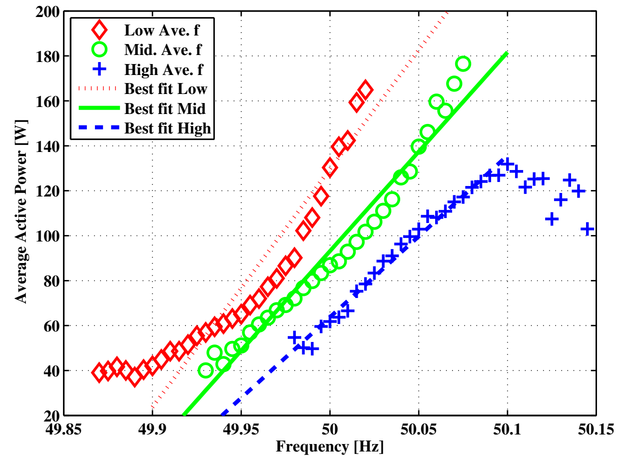

Figure 6. Frequency response at low, middle and high historical frequencies when calculating average frequency over 6 minutes, with best fit lines.

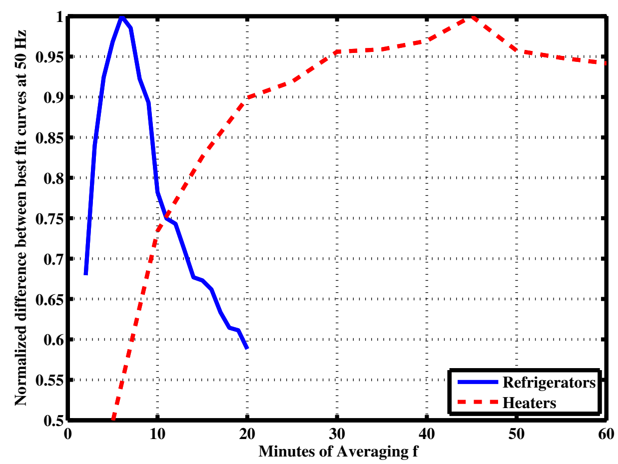

Figure 7. The difference between low, middle and high frequency best fit lines at nominal frequency for different sizes of time windows for calculating average frequency. The y-axis is normalized relative to the maximum difference observed for each device.

thresholds dividing groups were chosen to balance the number of samples falling into each group, with 50% of samples in the middle group. Comparing the frequency response of the 3 groups shows how it is influenced by the progression of frequency in the recent past. When the historical frequency has been high, the average power consumed at nominal frequency is lower than when the historical frequency has been in the middle or low range. The inverse happens when the historical frequency is lower than nominal. Fig. 6 shows the frequency response of the 3 groups when averaging the historical frequency over 6 minutes. The time period for averaging frequency values was varied from 2 to 20 minutes to reveal that time scale which has the most impact on the frequency response. The difference between the 3 groups is quantified by finding a linear best fit of each group, and then comparing the expected values at nominal frequency. The difference in expected values, shown in fig. 7, rises to a peak at 6 minutes before declining. This result indicates that frequency response is best predicted by combining the influence of the instantaneous frequency value and the average frequency of the preceding 6 minutes.

2) Electric Heaters: For a period of 8 weeks in autumn data was collected from 5 houses with electric heaters with a combined rating of 6 kW. The power consumption data was aggregated to reveal the total frequency response of the population, shown in fig. 8. The frequency response is asymmetric around the nominal frequency, with a steeper slope for up regulation (3.55 kW/Hz) than for down regulation (0.834 kW/Hz). Capacity of down regulation is exhausted around 49.93 Hz when the thermostat had been offset by 1.4°C. An asymmetric frequency response similar to the one shown in fig. 8 was observed in laboratory experiments with a refrigerator [15]. This behavior was attributed to a low duty cycle which gives a greater capacity for down regulation than for up regulation.

The frequency response between 49.90 Hz and 50.10 Hz was 435 W, 2.7 times the average power consumption of 160 W. The frequency response will depend greatly on the ambient temperature, and the time period under consideration contained periods when no heat demand was present. A subset of data from 2 houses over 11 days of favorable weather conditions showed a frequency response equivalent to 92% of the rated power of the heaters.

Fig. 7 shows that the time dependence of the frequency response is greatest when averaging historical frequency values over 45 minutes.

B. Disturbance Reserve

1) Refrigerators: The refrigerators were reconfigured to operate as a disturbance reserve for an 8 week period. Analyzing the frequency response results shown in fig. 9 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

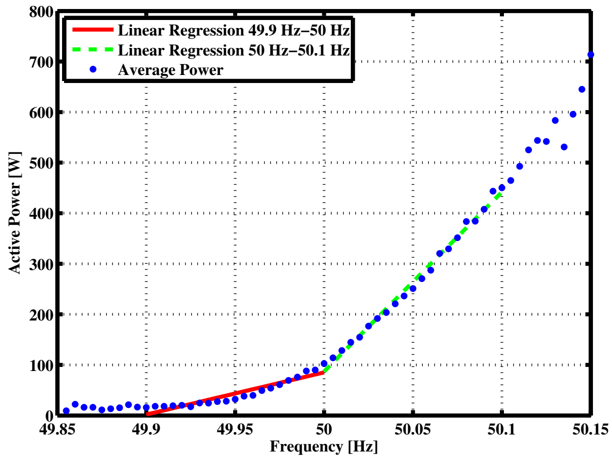

Figure 8. Frequency response of electric heaters with piecewise linear regression. The average power consumption approached 0W before the thermostat's offset limit at 49.90 Hz was reached.

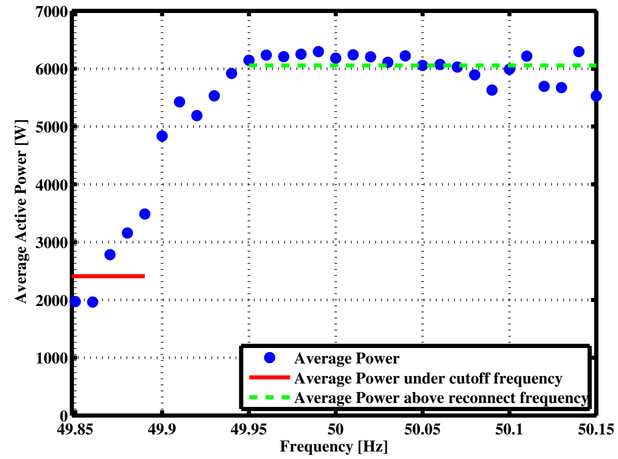

Figure 10. Frequency response of water treatment plant configured with disconnect frequency 49.90 Hz and reconnect frequency 49.95 Hz. Solid line shows average power consumption below cutoff frequency, dashed line shows average power consumption about reconnect frequency.

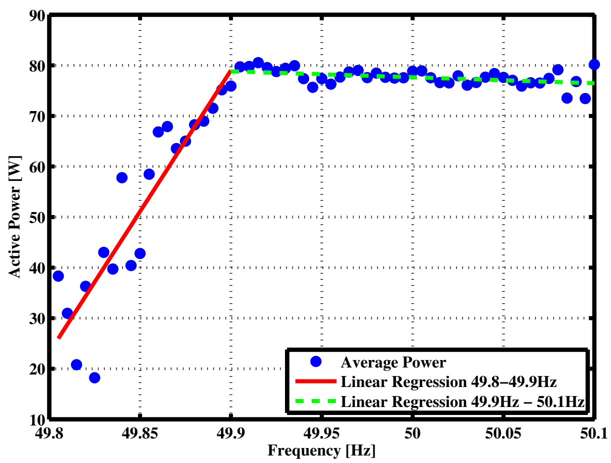

Figure 9. Frequency response of refrigerators acting as a disturbance reserve, shown with piecewise least squares linear regression in regions above and below 49.90 Hz.

above this value gave no response. The slope of the best fit line in the range 49.80 Hz - 49.90 Hz is 558 W/Hz, or 37 W/°C. Despite the fact that the slope of the temperature offset as a disturbance reserve (15°C/Hz) is lower than in the normal reserve (20°C/Hz), the frequency response per degree of temperature offset is almost twice as much. An explanation of this behavior can be found by considering that when a disturbance occurs the internal temperatures of the refrigerators are most likely in the nominal state, giving large room for deferring power consumption for the short duration of extreme under-frequency events. In the normal reserve case, system frequency is seen to dwell at off-nominal values for extended periods of time, weakening the average response.

The size of the data set at extreme frequencies is too small to conclude the total amount of frequency response provided by the refrigerators. For measurements takes below 49.85 Hz, the average power consumption was 42 W, indicating that at this frequency the response was 36 W, equivalent to 46% of the average power and 16% of the compressor's power.

2) Water Treatment Plant: The water treatment plant displayed two modes of operation: normal and curtailed. In normal operation, load was measured to lie between 3 kW and 9 kW most of the time. When load was curtailed, the residual power consumption was around 0.25 kW. 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 fig. 10. As expected, a step change in power consumption is observable at the cutoff frequency (49.90 Hz). Below the cutoff frequency, the average power consumption shows a linearly increasing trend because of time constraints on the DFCR signal, and because the plant controller occasionally overrides the DFCR signal to prevent violations of process constraints. The linearly increasing trend of average power consumption between the cutoff frequency and the reconnect frequency (49.95 Hz) was the result of hysteresis in the DFCR signal, as well as time constraints and process controller overrides.

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

3) Relay-Controlled Loads: During the experimental period, the frequency response of the relay-controlled was the opposite of what we intended: lower frequencies corresponded to higher power consumption. This is explained by the dominating influence of time constraints on the state of the relays. When the system frequency was below the cutoff value, 60% of the time the loads were energized because of the constraint on the maximum disconnect time and minimum reconnect time. When frequency was above the cutoff value, 1% of the time the relays had de-energized loads because of the minimum disconnection time constraint. The peak in power consumption occurs at the reconnect frequency, 49.95 Hz, and this is because of an inrush current and rebound effect as the loads restore their desired state after being interrupted. But the maximum disconnect time constraint meant that the loads could be energized at other low frequency values, and this resulted in power consumption at all low frequencies values being higher that when operating at nominal frequency.

The controller algorithm itself is not invalidated by these results, it is the parameter values need to be revised. The implementation behaved as specified, the problem was that the time constraints were not tuned to the actual frequency conditions of 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 cutoff frequency could be lowered, so the reserve is active less often and for shorter time periods.

V. Conclusion and Future Work

This paper presents work on DFCR appliances that builds on previous laboratory experiments by scaling up the number of frequency controlled devices, increasing the diversity of loads under control, and testing them during daily use.

In absolute terms, the amount of power under DFCR control in this experiment was rather modest, on the order of 10 kW. However, relative to the power demand of each of the loads, the frequency response was significant. 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, but the use of low-cost components for the core functions of measuring frequency and executing the DFCR algorithm support cost assumptions made in previous cost benefit analyses such as [4] and [17].

An analysis of the frequency and power consumption data of the TCLs 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.

Because the DFCR controllers allow all control algorithms to be remotely upgraded, the experimental platform is generally useful for other demand response studies. When the DFCR study in concluded, the controllers will be reprogrammed to respond to an external price signal, rather than system frequency [18].

Acknowledgements

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Appendix E Demand as Frequency Controlled Reserve: Water Treatment, Relay-controlled Loads, Micro-grid

Demand as Frequency Controlled Reserve: Water Treatment, Relay-Controlled Loads, Micro-grid

Philip J. Douglass *Student Member, IEEE*

Abstract

This report is part of the "Demand as Frequency Controlled Reserve" project funded by the Danish EUDP. This report presents the results from 3 tests of frequency sensitive loads acting as primary frequency reserves: a water treatment plant with an industrial control system, diverse loads controlled by means of a relay, and refrigerators with programmable thermostats which were connected to a micro-grid.

I. Introduction

FREQUENCY regulation is an essential service for AC power systems. Providing this service using power generators is costly in financial and environmental terms because it requires part-loaded units. Using loads to provide frequency regulation service has been previously described in [1]–[5]. This report provides results from Demand as Frequency Controlled Reserve (DFCR) field experiments conducted with Bornholm's Forsyning's water treatment plant, general purpose relay-actuated loads, and refrigerators connected to a micro-grid on the small island of Christiansø.

II. Bornholm Forsyning's Wastewater Treatment Plant

Treatment of wastewater is an energy intensive service with a large untapped potential for demand response. In Denmark wastewater treatment consumed 528 GWh of electric energy in 2009, accounting for 1.6% of all electricity consumption [6]. 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, shown in fig. 1. The SCADA used this signal to interrupt processes that tolerated interruption, while giving first priority to ensuring that process constraints were not violated, shown in fig. 2. The behavior of the control Smartbox is identical to the relay-controlled loads (discussed later) except that the time constraints were relaxed, as these were handled by the SCADA, not the Smartbox.

Measurement Smartboxes, with firmware identical in the control Smartbox but without an output signal, were installed at each load to gather data. The complete system is shown in fig. 2. Data was collected over a period of 9 weeks from 11 loads and 1 control Smartbox.

A. Results

The water treatment plant displayed two modes of operation: normal and curtailed. In normal operation, load averaged 5.8 kW. When load was curtailed, the residual power consumption averaged

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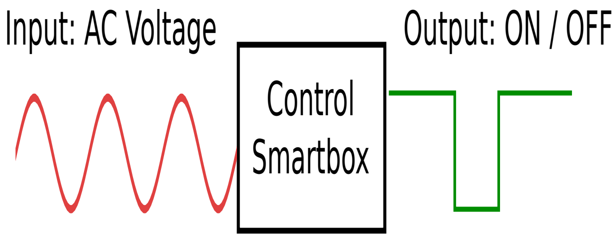

Figure 1. Diagram of control Smartbox. It takes an AC power supply as input, and produces a binary ON/OFF signal for which is then used an input to the SCADA.

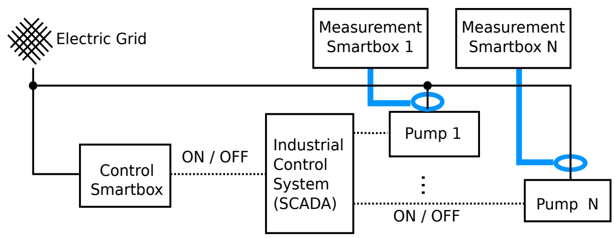

Figure 2. Diagram of Bornholm Forsyning's system. The grid AC power supply is given to a control Smartbox which generates an ON/OFF signal to the SCADA. The SCADA then controls the pumps based on the Smartbox signal and internal process constraints. A Measurement Smartbox is attached to each load to gather data on power consumption.

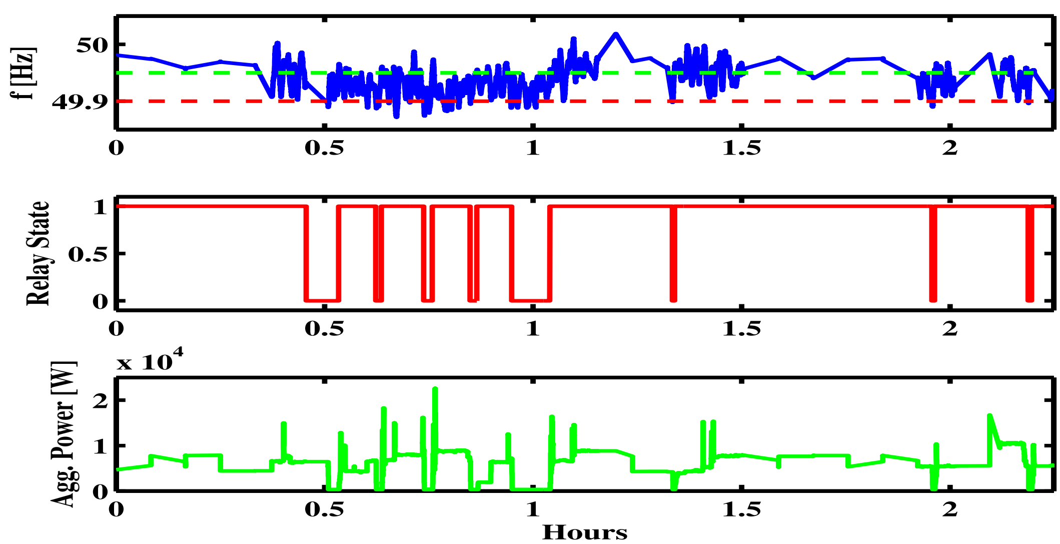

Figure 3. Typical time series from water treatment plant. Sampling frequency is 5 minutes and increases to 2 s for 5 minutes after each under-frequency event. In the top plot, frequency is shown with the cutoff frequency (dashed red) and reconnect frequency (dashed green). Every time the relay state changes to the off state, power is curtailed. When the relay state changes to the ON state, a spike in power consumption is observed as motors accelerate.

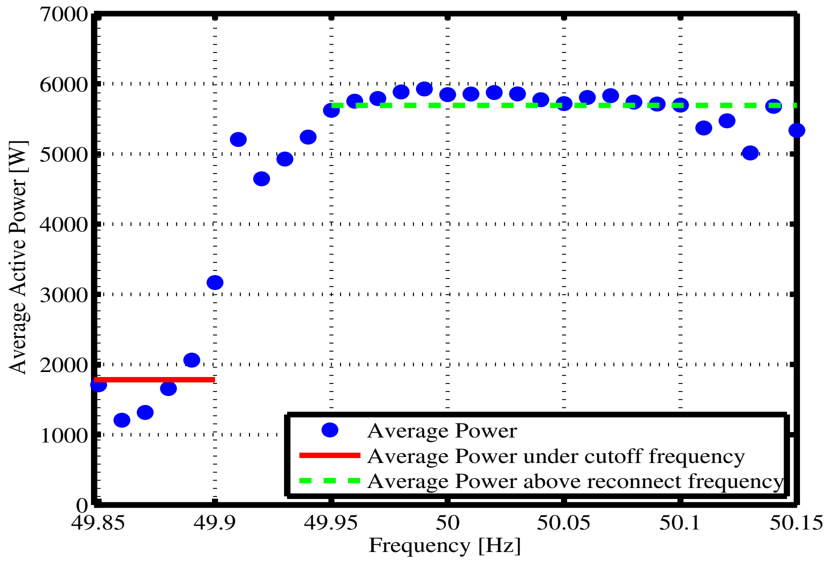

Figure 4. Frequency response of water treatment plant configured with disconnect frequency 49.90 Hz and reconnect frequency 49.95 Hz. Solid line (red) shows average power consumption below cutoff frequency, dashed line (green) shows average power consumption about reconnect frequency.

0.34 kW. A time series showing the typical operation pattern of the plant is shown in fig. 3. 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 fig. 4. As expected, a step change in power consumption is observable at the cutoff frequency (49.90 Hz). Below the cutoff frequency, the average power consumption shows a linearly increasing trend because of time constraints on the DFCR signal, and because the plant controller occasionally overrides the DFCR signal to prevent violations of process constraints. The linearly increasing trend of average power consumption between the cutoff frequency and the reconnect frequency (49.95 Hz) was the result of hysteresis in the DFCR signal, as well as time constraints and process controller overrides.

The average power consumption above the reconnect frequency was 5.69 kW, compared to an average below the cutoff frequency of 1.78 kW, a reduction of 69%. The average power consumption, and hence, potential for frequency regulation, as a function of time of day did not display significant diurnal variation.

The speed of the load curtailment, and the effect of the SCADA on delay was analyzed by extracting time series of high-resolution data each time the control Smartbox change the state of the control signal. Data from 763 events was extracted. The timestamps of the time series' were normalized to the moment the control signal changed, and the power consumption was normalized to the level before load curtailment. Average power consumption, and quartiles describing the lowest 25% and highest 25% of samples was found at two second intervals (the sampling frequency), shown fig. 5. The results show that the load has a weak response in the first 2 s period after the curtailment signal is given, and is almost fully curtailed after 6 s. To see the effect of the SCADA, the state of the unused relay within the measurement Smartboxes was found. The measurement Smartboxes ran the same firmware as the control Smartbox, so differences between the relay state of the measurement Smartbox and the actual power consumption can be attributed to delays introduced by the SCADA. Fig. 6 shows the response of measurement Smartboxes. The respone in fig. 6 appears similar to fig. 5 at all time points, except at 4 s after the start of the event, where the measurement Smartboxes

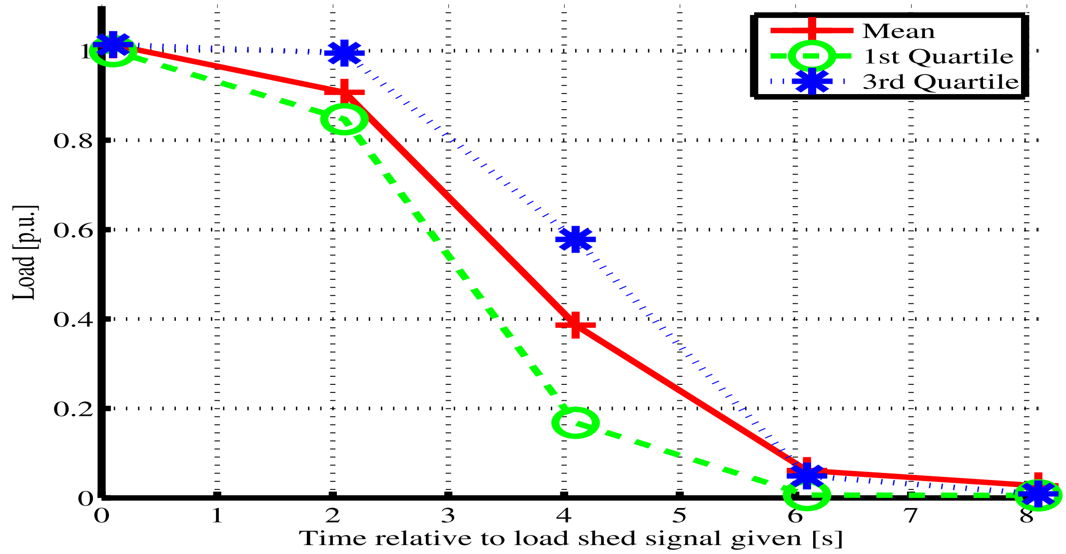

Figure 5. The response of water treatment plant to load curtailment signal. Average, and quartiles of power consumption of 763 events. Normalized in time relative to the time when the control Smartbox gave the load shed signal, normalized in power relative to the pre-curtailment load.

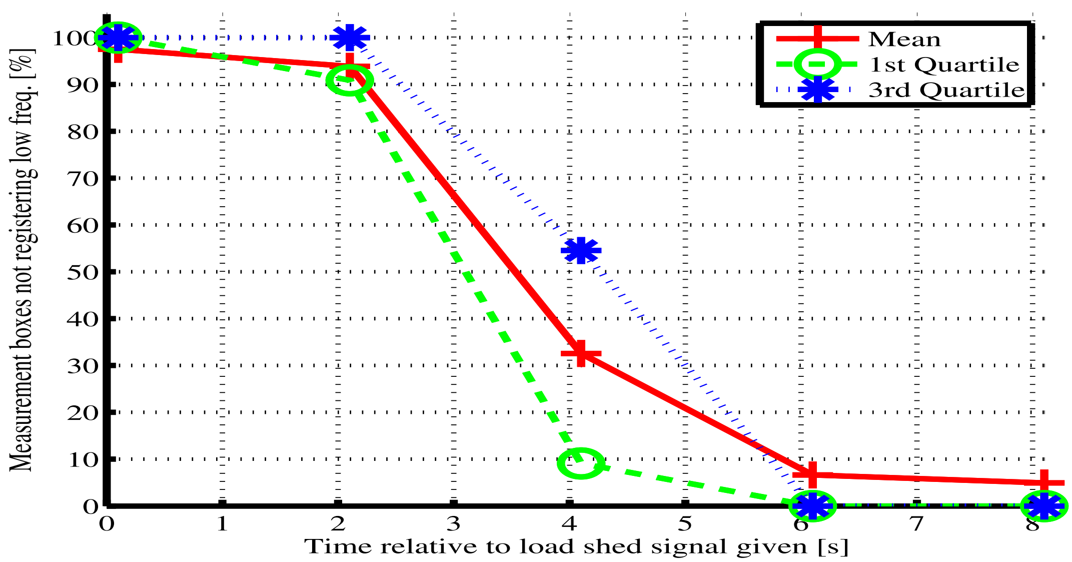

Figure 6. The response of the 11 measurement Smartboxes

are on average 70% curtailed, while the actual power measurements are only 60% curtailed.

Finally, the load profile upon restoring power was analyzed, shown in fig. 7. When the control Smartbox gave the restore signal, load returned to it's pre-curtailment level, though the 3rd quartile of events showed a short (5 s) transient increase of power consumption peaking at 140% the pre-curtailment power. The reason the spikes in power consumption apparent in fig. 3 are not more apparent in fig. 7 is that the spikes in power consumption that occurred each time load was restored were short (2 s), and spread out over a 30 s period, so that the average power consumption at each point in time was barely effected by the outliers.

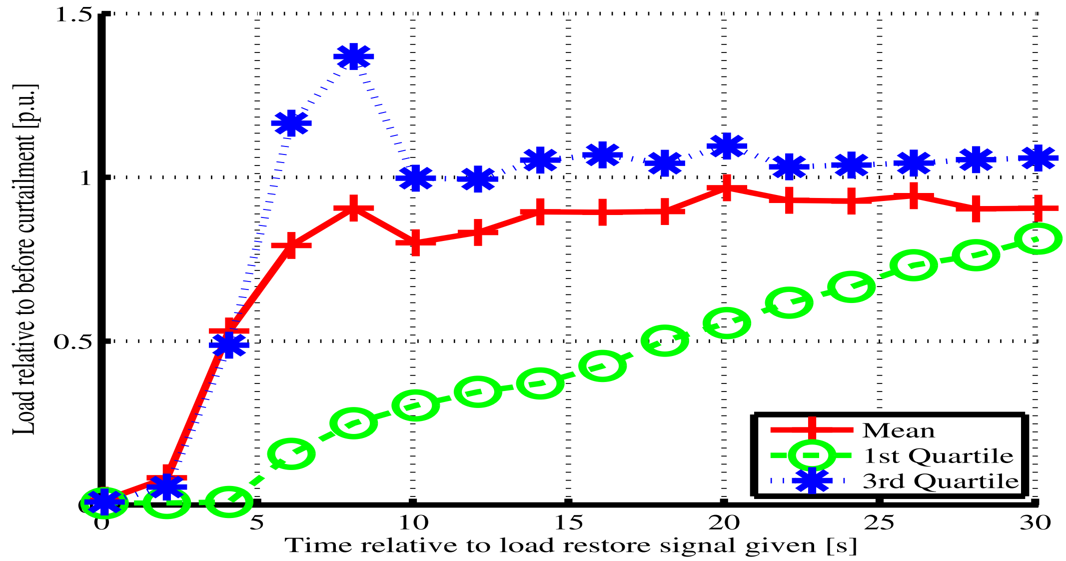

Figure 7. The response of water treatment plant to load restoration signal. Average, and quartiles of power consumption of 763 events. Normalized in time relative to the time when the control Smartbox gave the load restoration signal, normalized in power relative to the pre-curtailment load.

III. 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. Fig. 8 shows the time constraints graphically, a more detailed presentation of this algorithm can be found in [3].

The loads connected to this controller were diverse including pumps for circulating water, resistive heaters, and small refrigerators. These loads were located in educational institutions, offices and homes. A single configuration was used on this diverse population of loads, and as a results the time constraints were chosen conservatively. The configuration of the parameters was as follows:

Parameter	Value
f_{off}	49.90 Hz
$f_{restore}$	49.95 Hz
t_{min_off}	30 s
t_{max_off}	120 s
t_{min_on}	240 s

Data was collected from 9 controllers over a period of 12 weeks.

A. Results

During the experimental period, the frequency response of the relay-controlled showed a weak frequency response because of the strong influence of time constraints. A typical time series, where the maximum disconnect time and minimum reconnect time determine relay state, is shown in fig. 9. When the system frequency was below the cutoff value, more than 60% of the time the loads were energized because of the constraint on the maximum disconnect time and minimum reconnect

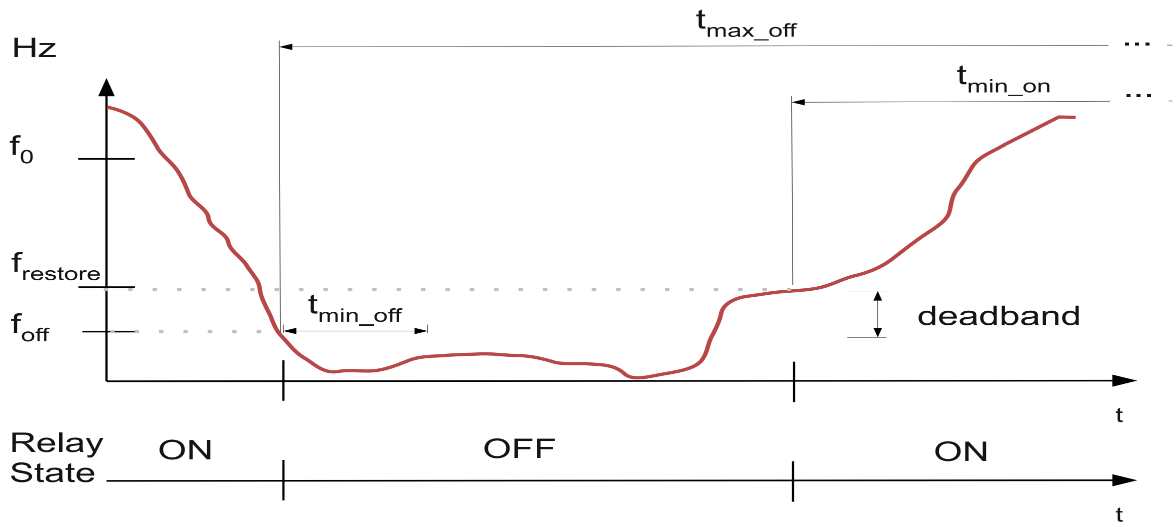

Figure 8. State of relay depends on system frequency and time constraints. Ideally, the relay is OFF when system frequency is below f_{off} and ON when system frequency is above $f_{restore}$. Time constraints take precedence over the ideal frequency response.

time, shown in fig. 10. A spike in power consumption occurs when the loads are reconnected because of an inrush current and rebound effect as the loads restore their desired state of operation. During normal operation, the average individual power consumption was 37.4 W. When the devices disconnected load, the average individual power consumption was 0.5 W. When the devices were in the Restore state, and the t_{min_on} constraint was active, the average individual power consumption was 43.5 W. The aggregate frequency response, shown in fig. 11, shows that power was curtailed on average from 310 W to 270 W, a reduction of 13 %.

These results show that 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 cutoff frequency could be lowered, so the reserve is active less often and for shorter time periods. Recent work by Beigel, et.al. [7] has addressed the problem of designing frequency threshold values by means of analyzing historical frequency data of a synchronous area, a method which could be applied to these devices.

IV. Christiansø

Christiansø is a decommissioned naval base that is a popular tourist destination. Around 100 people live permanently on the 0.22 km^2 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. Measurements are taken at high and low resolutions, meaning 2 second and 5 minute intervals. Data was collected in the summer of 2011 with DFCR disabled to establish a base-case, and in the autumn/winter of 2012 with DFCR enabled.

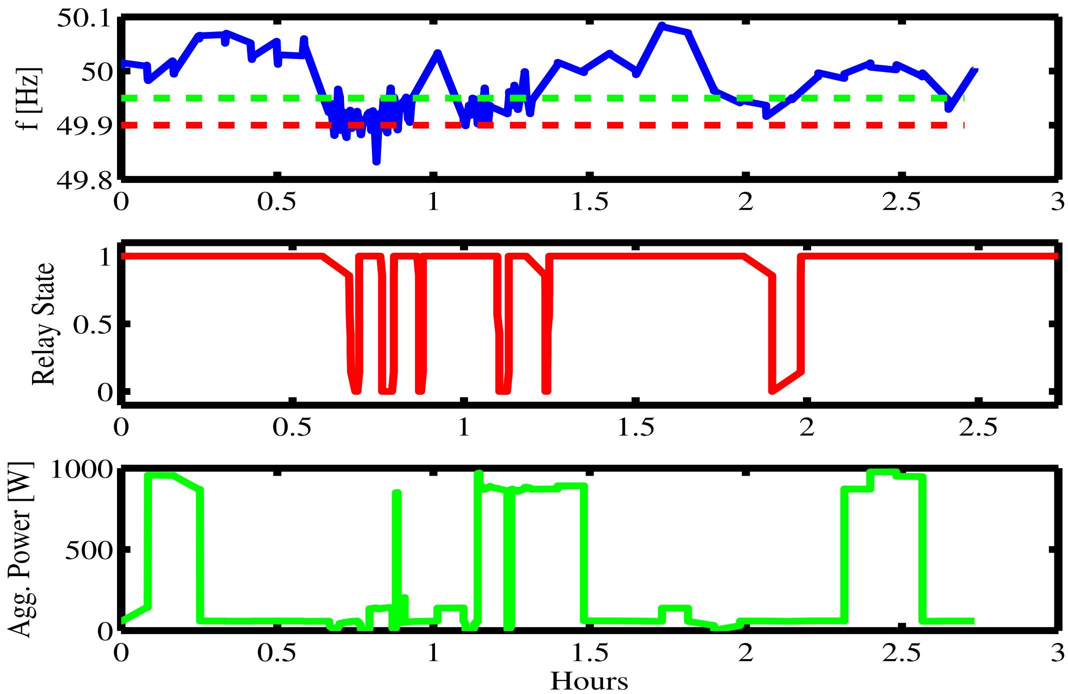

Figure 9. Typical time series of relay controlled loads with poorly configured time constraints. Frequency is shown at the top, aggregate power of all relay controlled loads in middle, and relay state at the bottom. When frequency declines, the loads are disconnected, but after the maximum disconnect time they are reconnected, with a spike in power consumption. When the loads are reconnected, the system frequency has declined to be lower than the initial cutoff frequency.

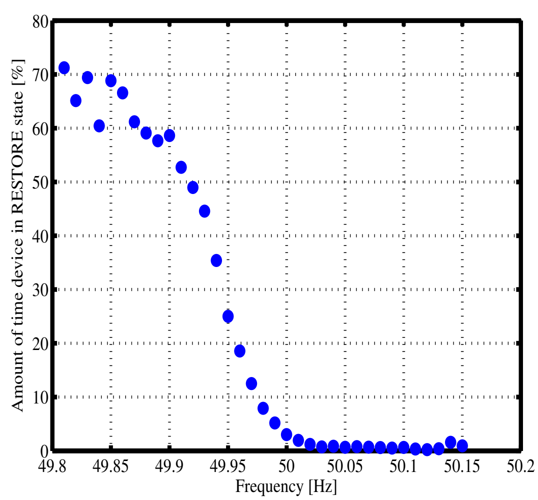

Figure 10. Amount of time where t_{min_on} constraint was active ("Restore" state) as a function of frequency. In this poorly configured example, time constraints dominate the frequency response, and the devices uses power when the system operates below the cutoff frequency.

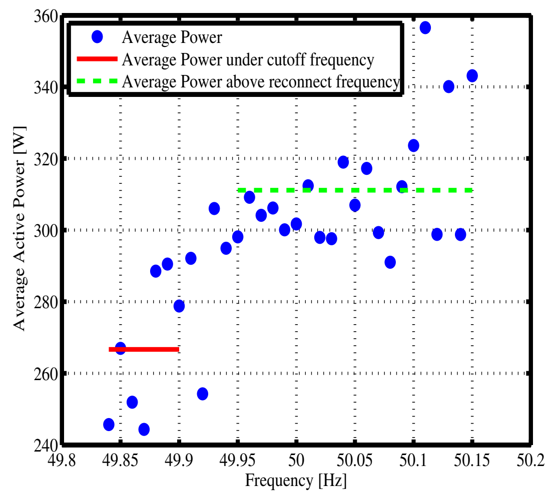

Figure 11. Average aggregate power consumption as a function of frequency. The frequency response is relatively small because of the predominance of time constraits.

A. *Results*

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, visible in fig. 12. Data was grouped accordingly: group one from June 30 to July 26 2011, and group two from October 1 to January 31 2013. Within each group, the frequency measurements fit well into a normal distribution, with the average value of 50.00Hz for group one and 50.12Hz for group two. The standard deviation for group 1 was 43.4 mHz, for group 2 was 62.1 mHz. For comparison, when Bornholm's power system is operated as an island, the average frequency is 50.00 Hz, and the standard deviation is 40 mHz.

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. The frequency response, shown in fig. 13, reveals a wide variation in power consumption at frequencies far from the mean because of the sparsity of the data set. In the 4 month data collection period, the system frequency was below 49.90 Hz, the frequency where the demand response began, for 0.2 % of the time, less than 6 hours. A least squares linear best fit of the frequency response region (49.80 Hz - 49.90 Hz) shows a slope of 144 W/Hz, with large residuals. Compared to identical refrigerators connected to the Nordic power grid [9], the response on Christiansø appears to be much weaker (558 W/Hz vs 144 W/Hz).

The statistical, rather than direct, relation between system frequency and fridge power consumption means the relatively small data set from Christiansø leaves a large margin for error as to what the true slope of the response is. 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). Today utility operators are reluctant to rely on autonomous or indirectly controlled demand response because of the difficulty of verifying the response, and our results confirm that verification of statistical responses of a few units to rare events is difficult.

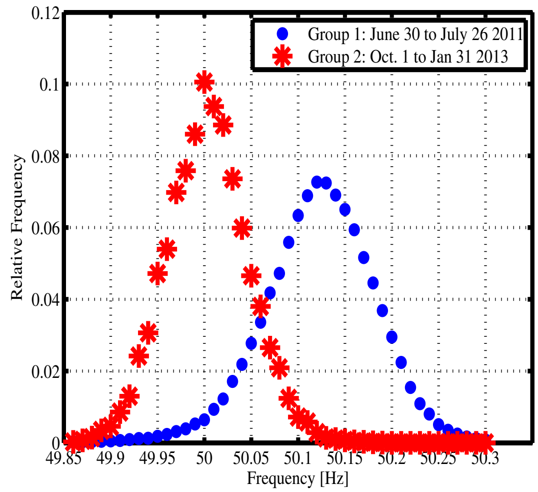

Figure 12. Frequency distribution on Christiansø in time periods June 20, 2011 to July 26, 2011 and October 1st, 2012 to January 31st, 2013.

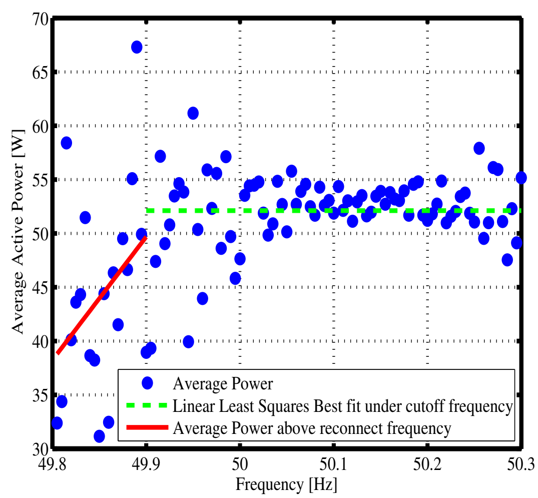

Figure 13. Frequency response of refrigerators on Christiansø configured according to Nordel's definition of disturbance reserve. The frequency response was rarely activated, and the variation of average power values at the low and high frequency extremes is explained by the relative sparsity of the data set.

V. Conclusion

This report has presented the behavior of frequency sensitive loads in three different contexts: a water treatment plant, general-purpose loads connected to a large power system, and refrigerators connected to a micro-grid.

The water treatment plant was a reliable source of frequency response, and the SCADA control layer introduced a delay smaller that the data sampling frequency of 2 s. The response of the general-purpose loads and refrigerators in the micro-grid was weak because the device parameters were not well aligned to the synchronous areas' respective frequency distributions.

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Appendix F Direct Load Control by AC frequency Modulation

Direct Load Control by AC Frequency Modulation

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Abstract

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 [1]. Micro-grids with a large portion of intermittent renewable generation will benefit greatly from this technology because their low inertia.

The paper proposes a operating procedure for utilizing DFCR loads for energy balancing, expanding DFCR's well known role as a power balancing resource. 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.

I Introduction

As photovoltaic (PV) module prices continue to fall and diesel prices rise, the penetration of PV generation is expected to increase in diesel fueled isolated power systems. The amount of PV generation in an isolated system is limited by the minimum forecast daytime load in the absence of battery storage systems or curtailment. To provide reliable electric power during periods of low renewable energy sources (RES) production, a dispatchable generator must have sufficient capacity to serve the peak load. If the system contained dispatchable loads, they could be activated during periods of high RES production adding to the minimum load, and they could be deactivated during periods of low RES production, lowering the capacity requirements of the dispatchable generator.

When frequency responsive DFCR loads were field tested in a small island power system, problems arose because the devices assumed the system's mean value for frequency was always the nominal frequency, but on the island, the system frequency was observed at off-nominal values for extended periods of time. It was clear from the sampled frequency data that the system was operated in two distinct frequency regimes and this observation lead us to investigate whether these frequency regime changes could be detected and utilized.

Loads suitable for DFCR operation will typically have constraints on the energy demanded over a given time period, but some loads may have additional time constraints on their operation. These time constraints have precedence over the frequency response, and have the potential to lead to undesirable system behavior.

Modulating AC system frequency has been used to curtail production in microgrid systems [2], and frequency responsive loads have been described in [1, 3, 4], but the authors are unaware of previous work describing the modulation of frequency for controlling loads with time constraints.

This paper is organized as follows. Section II describes the behavior of DFCR in micro-grids. The proposed system operation concept is described in detail in Section III, followed in Section IV by a case study of the island of Christiansø in the Baltic Sea. Finally, Section V is a discussion and Section VI concludes the paper.

II DFCR loads in Micro-grids

A micro-grid is modeled with 4 lumped entities: dispatchable generators with droop frequency controllers, stochastic RES generators (PV modules), DFCR load and finally residual (high priority) load, see Figure 1.

Typical automatically controlled loads (such as thermostat controlled loads) operate in two states, OFF and ON, with the duty cycle controlled to keep the energy level within desired bounds. A DFCR controller will alter the phase of the duty cycle to defer energy consumption away from time periods when the grid is overloaded. The only way to create

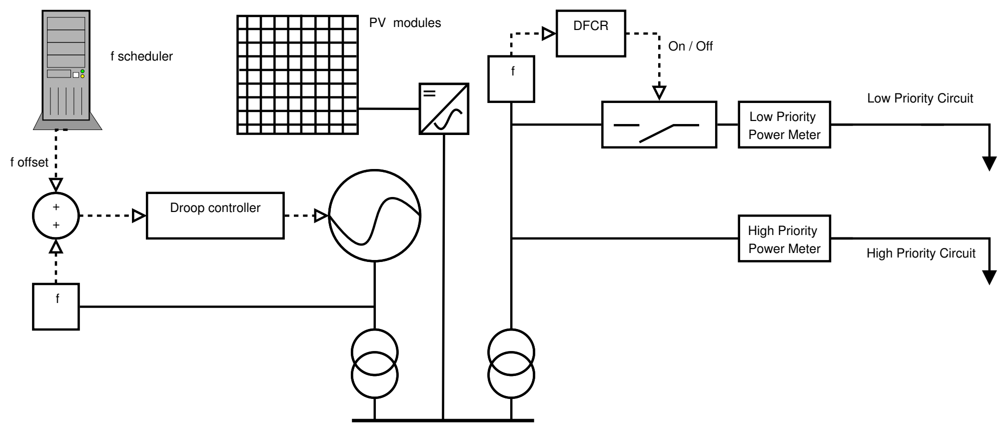

Figure 1: Oneline diagram showing relation between generator governor and DFCR. Solid lines represent electric conductors, dotted lines represent data transfer paths.

a smooth and reliable frequency response with OFF/ON loads is to have a population of devices with a diversifying parameter such as differing frequency thresholds. A small synchronous system will have a small population of DFCR loads, where each one may be a significant portion of the total load. Therefore, the diversity of a large population can not be counted on.

Energy constraints for loads are represented by the maximum time the device is allowed to be disconnected from the electric energy supply (t_{max_off}), and the minimum time it must remain reconnected after being disconnected (t_{min_on}). Processes with startup costs and shutdown costs, such as an induction motor's inrush current, will have additional constraints besides a minimum demand for electric energy over a given time period. The startup and shutdown costs are represented by the minimum ON time (t_{min_on}) and the minimum OFF time (t_{min_off}).

DFCR with time constraints is suitable to act as disturbance reserve, reducing load during large and infrequent drops in frequency, but is unsuitable to act as a continuous regulation resource within the normal frequency operating range. The problem with DFCR as a continuous regulation resources is acute both when RES production is high and the load low, and when RES production is low and the load is high.

When the RES production is more than the residual load, the droop controlled dispatchable generator cannot further reduce production, and the DFCR load is critical to absorbing the RES energy over-production. If the DFCR load is constrained by t_{min_off}, frequency will rise uncontrollably in the absence of alternative frequency regulation resources (i.e. dump load).

When RES production is low, the t_{min_on} constraint of DFCR can compromise the security of the system. In a scenario where the dispatchable generators do not have the capacity to supply the DFCR and the residual load simultaneously, DFCR load constrained by t_{min_on} can cause the system frequency to decline uncontrollably (until axillary frequency regulation resources such as shedding of high priority loads are activated), see Figure 2.

III Dispatch of DFCR loads

The control of distributed energy resources is typically classified as either direct or indirect [5]. Direct control corresponds to the architecture of existing utility SCADA systems where commands are issued from a centralized controller and remote terminals respond to the commands in a deterministic manner. Frequency controlled reserves are not usually considered as directly controlled because the control signal (system frequency) is not actively generated, but rather results from the intrinsic behavior of the power system. Dispatchable generators participating in frequency regulation are able to alter the system frequency by altering the parameters of their frequency controller, see Figure 4. When frequency measurements are averaged over long time periods to filter out the intrinsic volatility of the system power balance, changes in the generators' frequency regulation parameters can be detected by DFCR loads.

A droop controller will produce power proportional to the system frequency, with lower frequencies resulting in higher power output. Thus, at steady-state conditions, the frequency will indicate the amount of load on the droop controlled generator. In the presence of limited generation resources and a significant amount of frequency dependent demand, lowering the system frequency can be used as a proactive measure to balance load and generation by selective load shedding. Changing the system frequency target on some frequency regulation resources, but not others reallocates the energy production between the two groups of resources (ie. supply-side and demand-side).

The DFCR algorithm for relay-based devices described in [1] has a frequency threshold (f_{off}) below which the load is disconnected. Loads are reconnected when

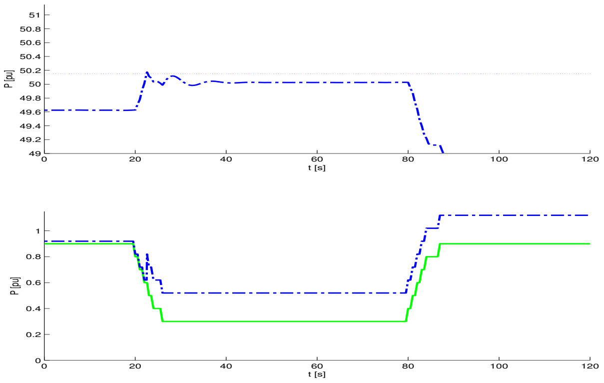

Figure 2: DFCR with t_{min_on} constraints during a transient spike in RES output. Top graph shows frequency with the black horizontal line $f_{restore}$. The bottom graphs show loads (minus RES production). The solid green line represents the residual load, the blue dashed line shows the addition of DFCR loads.

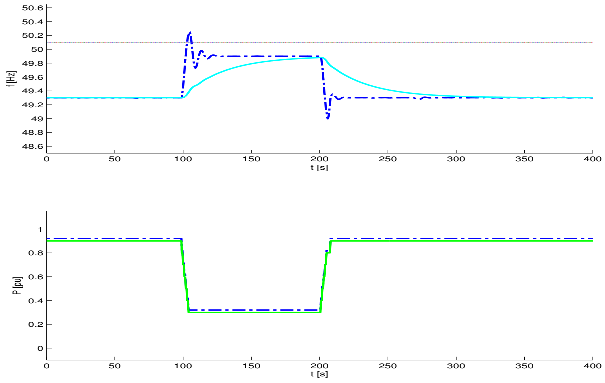

Figure 3: The top graph shows the system frequency (dark blue) and the frequency subjected to a low pass filter (light blue). $f_{restore}$ for the filtered frequency is the solid black line. The system frequency does not stay above the threshold long enough for the filtered value to cross the reconnect value, so the DFCR remains off.

system frequency is above a second, higher threshold frequency ($f_{restore}$), creating a simple deadband. A wide enough deadband would avoid spurious changes to DFCR state, but this has the disadvantage that when the system resides inside the deadband the DFCR state is uncertain because it depends on historical frequency deviations rather than the current frequency.

To narrow the deadband while avoid spurious switching DFCR state, the DFCR can pass the frequency samples through a low pass filter before comparing the value to preset thresholds. A moving average or exponentially-weighted moving average filter could be utilized.

A similar algorithm was described in [6], where different cutoff frequencies existed for short-term frequency deviations (i.e. 1s) and longer-term deviations (i.e. 5 min.). This algorithm is well suited for the proposed scheme because a small but consistent deviation from nominal frequency on a long time scale will force devices into either the ON or OFF state. Changes to the long-term average frequency are feasible to provoke, even when the frequency varies widely in the short-term.

Figure 3 shows how DFCR with a low pass filter will not change state when subject to steep ramps of RES generation.

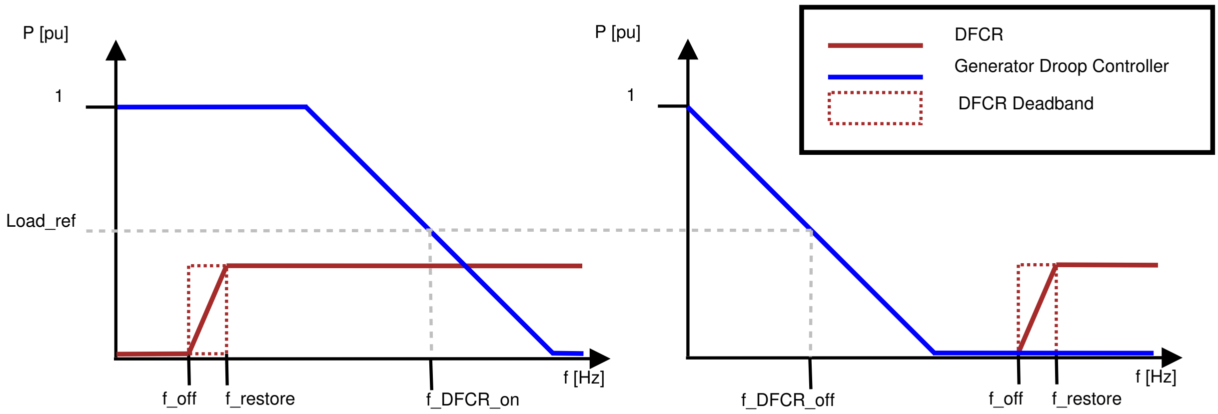

Figure 4: Left: DFCR devices dispatched in ON state by allocating droop controlled reserves to well above f_{off}. Right: DFCR devices dispatched in OFF state by operating droop controlled reserves well below $f_{restore}$.

IV Case Study: Christiansø

Christiansø is a decommissioned naval base which is a popular tourist destination. Around 100 people live permanently on the 0.22km^2 island. 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 as part of an ongoing experiment [7]. Frequency measurements were collected when the DFCR functionality was disabled to characterize the system.

Two modes of operation were observed, and within each mode, the frequency measurements fit well into a normal distribution, with the average value of 50.00Hz for group one and 50.11Hz for group two. The standard deviation for group one was 43.4mHz, for group two 137.3mHz. The moving average of high resolution frequency measurements from group two was found and the standard deviation of these filtered values was 48mHz.

The normal distribution of frequency samples implies that 99.9999% of the time the value will be within $\pm 5\sigma$ of the mean. Conversely, the system frequency will be farther than $\pm 5\sigma$ from the mean approximately 50 milliseconds per day. If the generators were set to produce at $f_{DFCR\_on} = f_{restore} + \sigma = f_{off} + 5\sigma$, then the filtered frequency would be above $f_{restore}$ 84% of the time, and below f_{off} 25ms per day.

With a deadband $4\sigma = 200mHz$, then the average frequency to dispatch DFCR in the ON state with high confidence would be $f_{DFCR\_on} = 50.150Hz$. To be highly certain that the DFCR devices are OFF, the average frequency would have to be $f_{DFCR\_off} = 49.850Hz$. This range of frequency offsets is slightly larger that that already observed during normal operation on Christiansø, but considered feasible without significantly effecting the functioning of conventional loads. Alternatively, if $f_{DFCR\_on} = f_o$, the $f_{DFCR\_off} = f_o - 6\sigma = 49.700Hz$.

The EN 50160 standard [8] used in Europe requires that island power system maintain their frequency at $50Hz \pm \%2$ ($49Hz$ to $51Hz$) for 95% of a week and $50Hz \pm 15\%$ ($42.5Hz$ to $57.5Hz$) for 100% of the time. A mean value of 49.700Hz gives a margin to the statutory minimum frequency of $700mHz$, which is acceptable during unfaulted operation.

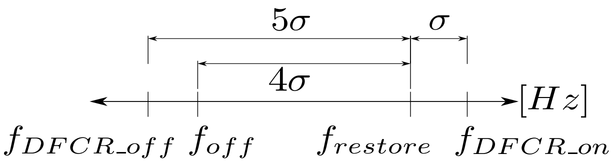

Figure 5: Relative placement of DFCR frequency thresholds and generator setpoints.

Parameter	Relative Value	Value
f_o		50Hz
σ		50mHz
f_{off}	$f_o - 2\sigma$	49.9Hz
$f_{restore}$	$f_o + 2\sigma$	50.1Hz
f_{DFCR_on}	$f_{restore} + \sigma$	50.150Hz
f_{DFCR_off}	$f_{off} - \sigma$	49.850Hz

Figure 6: Suggested parameter values for DFCR operation on Christiansø with thresholds symmetric to f_o

V Discussion

The difference between target frequency values would have to be larger than the typical variation of frequency (i.e. $> 5\sigma$) but if disturbances pushed the system frequency into a neighboring frequency band, the autonomous action of the DFCR would act to restore the frequency to the targeted value. The utility's load control performance would depend on how closely the autonomous action of the DFCR conformed to pre-established schedules. By designing the DFCR threshold levels and target frequencies, arbitrary levels of load control performance can be achieved. Metrics for measuring frequency quality would be redefined as deviations from the target frequency, not deviations from nominal.

VI Conclusion

The paper has proposed a new operating concept which utilizes DFCR, a highly distributed under frequency load shedding method, as part of direct load control scheme. 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 analyzing 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.

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Appendix G Broadcast Communication by System Frequency Modulation

Broadcast Communication by System Frequency Modulation

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***Abstract*—Load controllers available today can measure AC system frequency and react to frequency deviations. A system operator can communicate to frequency sensitive loads by changing the set-points of the system's dispatchable frequency regulation resources. Explicitly signaling system state by generating off-nominal system frequency values is a novel narrowband broadcast communications channel between system operators and frequency sensitive distributed energy resources (FS-DER). The feasibility of the proposed system is evaluated on an existing island power system in Denmark. This study shows that within standard frequency quality constraints, 4 distinct symbols are feasible on the island. However, the overarching imperative of system stability prevents the symbols from having arbitrary meanings. Higher frequency values must translate into greater consumption from loads, and vice versa. Within these constraints, the proposed system would allow operators to dispatch FS-DER in a robust manner, without using an external digital control channel. By dispatching FS-DER, their well known role as a power balancing resource can be expanded to include energy balancing services.**

I. INTRODUCTION

As non-dispatchable renewable power sources become more widely deployed, the power system as a whole must adapt to their stochastic production profile. Maintaining system stability by controlling loads to follow production is a new challenge for system operators. Loads are physically more dispersed than conventional generators, which means that existing technology for coordinating production from centralized generators is not feasible for controlling distributed energy resources (DER).

On short time scales (seconds to minutes) primary frequency regulation acts to reestablish the balance between generation and load. This made possible by high precision frequency measurements (± 1 mHz) of the AC waveform which can be done with low-cost microelectronics. Using loads to provide frequency regulation service has been previously described in [1]–[5].

Over longer time scales (5 minutes to hours to days), loads can also be controlled to match consumption to the available energy. Whether the loads respond to a direct signal from a central controller or indirectly to a price, all systems for energy balancing rely on a digital communication system to transmit information about the desired state of the loads.

While the availability of low-cost microcontrollers allows software control of even the smallest loads, creating a communications network that reaches out to highly dispersed units is a costly endeavor. Where such a communication system has been established, maintaining the N-1 protection criteria requires that failure of the communication system does not compromise system security, thus a fallback communication-less state must be defined.

The advantage of using system frequency to actuate highly distributed loads is that no digital communication channel is needed; the system frequency is inherently available to all buses in the synchronous system. Loads which can measure frequency for performing primary frequency control can be reprogrammed to detect different modes of operation of the power system, and in this way gain more knowledge about the system state.

Modulating AC system frequency has been used to curtail production in islanded microgrid systems with storage [6], [7]. These systems use inverters operating as voltage sources to generate a system frequency that indicates the battery state of charge. Previous work by the authors described the dispatch of frequency sensitive loads subject to time constraints [8], but the authors are unaware of previous work to analyze the feasibility of modulating frequency to convey information in an operating power system.

This paper is organized as follows. Section II analyzes the properties of system frequency when used for communicating to DER. The proposed communication system is described in detail in Section III, followed in Section IV by a case study of the island of Bornholm. Section V is a discussion and finally Section VI concludes the paper.

II. ANALYSIS OF AC SYSTEM FREQUENCY

There are constraints on the range of allowable system frequencies imposed by generators and FS-DER. These

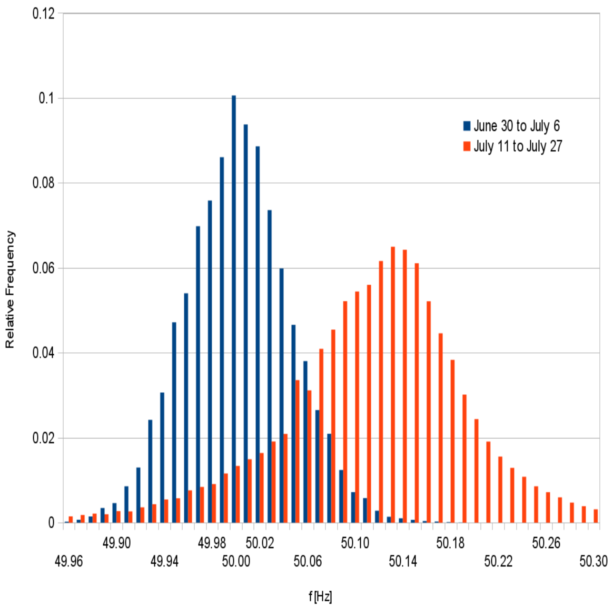

Figure 1. Relative frequency of system frequency samples a from small island power system divided into two time periods. The distinct frequency distributions were caused by two different diesel generators.

constraints will limit the number of symbols that can be encoded by modulating system frequency.

A field test of FS-DER providing primary frequency regulation is under way on the Danish islands of Bornholm (population $\approx 50,000$) and Christiansø (population $\approx$ 100) [9]. On Christiansø, a problem was observed with the experiment because the devices assumed the system's mean value for frequency was always the nominal frequency (50 Hz), like in the large interconnected Nordic power system, but on the island, the system frequency was observed at off-nominal values for extended periods of time. Fig. 1 shows the distribution of frequency data collected from Christiansø divided into two different time periods. It is clear from the data that the system was operated in two distinct frequency modes and this observation lead us to investigate whether these frequency mode changes could be detected by our controller and utilized to communicate information about the power system's state.

A. Generators

Large steam turbines are optimized to operate in a narrow range of frequencies and are vulnerable to frequency excursions. When electric energy is delivered from rotating machines, the swing equation dictates that system frequency will decline when the load exceeds production and frequency will rise when there is overproduction. Avoiding the upper limit on frequency is achieved by curtailing electricity production, an option that is always available. Avoiding the lower frequency limit is more costly to satisfy because it requires reserves. Grid codes in several countries allow generators operating at maximum output power to reduce output power in linear proportion to frequency when operating below a certain frequency (i.e. 49.5 Hz) [10]. In a system with inadequate generation capacity, when a power imbalance pushes the system frequency below this threshold, positive feedback exacerbates the imbalance until finally the frequency declines to a level (i.e. 47 Hz) where generator protection schemes are tripped. As a last resort to prevent total system collapse, load is shed at large granularity, causing widespread disruption.

In general, frequency regulation systems assume that changes in frequency are exogenous and that this a problem to be corrected as soon as possible, first with a droop response to stabilize the frequency and then a slower secondary control loop, such as an isochronous governor, responds to the integral of the frequency deviation to restore frequency to the set-point value. The proposed system would modify the settings of the droop to produce scheduled power at off-nominal frequencies and use the secondary control system to target off-nominal frequencies.

B. Loads

The EN 50160 standard [11] used in Europe specifies the physical characteristics of electric energy delivered to customers. Loads connected to a large interconnected power system must tolerate a frequency specified as:

50 Hz $\pm\%1$ for 99.5% of the year

Loads in a small island power system have a wider tolerance, and must be designed for frequency constraints:

50 Hz $\pm\%2$ for 95% of a week

Proposed grid codes from ENTSO-E [12] promote the deployment of FS-DER and relax the constraints on system frequency for large systems, allowing unlimited operation in the range 50 Hz $\pm\%2$.

C. Frequency Distribution

Observations of frequency measurements taken from several synchronous areas show that they conform to a Gaussian distribution, centered around the set-point value. The Gaussian distribution of frequency samples implies that with set-point frequency f_s and standard deviation σ, 99.7% of the time the frequency will be within $f_s \pm 3\sigma$.

To satisfy the requirements of [11] for residing between f_{min} and f_{max} for 99.5% of the time, assuming a Gaussian distribution of system frequency around f_s with standard deviation σ, the valid range of set-points satisfy:

$$(f_{min} + 3\sigma) < f_s < (f_{max} - 3\sigma) \qquad (1)$$

System frequency will always be subject to external disturbances when unpredictable imbalances between generation and load occur. The response of the system to these transient imbalances is dominated by the system's inertia and time constants on the primary and secondary reserves. The UCTE grid codes which apply to Western Denmark [13], specify that after a contingency, the system

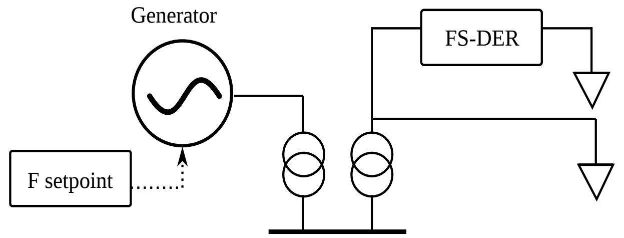

Figure 2. One-line system diagram. A lumped generator model is connected to FS-DER and conventional loads by a copper plate transmission system model. Frequency set point changes introduced to the generator are detected by the FS-DER.

frequency should be restored to ±20 mHz of the set-point frequency within 15 minutes. This time period corresponds to the time constants for increasing production from thermal power plants. During such a contingency, the system frequency will deviate widely from the set-point. While the system is operating outside of its normal, secure operating state, FS-DER will be unable to discern the set-point frequency. In this case, it is desirable that FS-DER contribute to restoring the system to a secure operating state.

III. Communicating System State to Frequency Sensitive Loads

While the different frequency modes shown in Fig. 1 were unintentional, this observation shows that a system operator has latitude to reprogram frequency governors to target off-nominal system frequencies without disturbing loads. Off-nominal set-points are used today in large interconnected systems in response to clock drift. In the Nordic power system, time correction is done on occasion by human intervention [14]. It is conceivable that a synchronous area would take active use of this degree of freedom to vary frequency set-points depending on the system state (i.e. based the predicted availability of stochastic energy sources).

The control of distributed energy resources is typically classified as either direct or indirect [15]. Direct control corresponds to the architecture of existing utility SCADA systems where commands are issued from a centralized controller and remote terminals respond to the commands in a deterministic manner. Frequency controlled reserves are not usually considered as directly controlled because the control signal (system frequency) is not actively generated, but rather results from the intrinsic behavior of the power system. A system operator with knowledge of FS-DER configuration parameters can directly control them by using existing generator governors to change the setpoint frequency to reflect the system state as shown in Fig. 2.

A. Generator Model

Previous work on FS-DER has focused on its role to supplement the generators performing primary frequency regulation [1]–[4]. Dispatchable generators perform primary frequency control with a droop controller which produces power proportional to the system frequency, with lower frequencies resulting in higher power output. The relationship between the system's primary droop response and FS-DER is shown in Fig. 3. Fig. 4 shows a block diagram of a droop controller augmented with a stream of inputs from the system operator which are encoded into frequency setpoints.

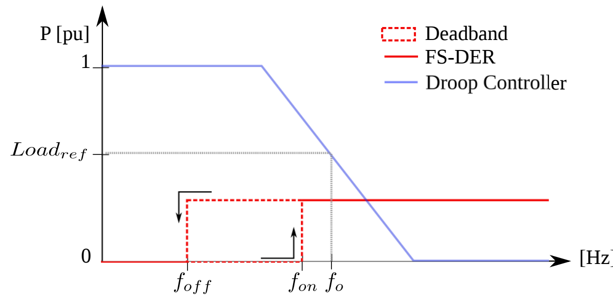

Figure 3. Deployment of FS-DER as frequency controlled reserve. Power output of dispatchable generation and power consumption of FS-DER with two states (OFF/ON) is shown as a function of system frequency. The generator delivers scheduled power ($Load_{ref}$) at the nominal frequency (f_o). The load is disconnected when the generator's capacity for up-regulation is exhausted.

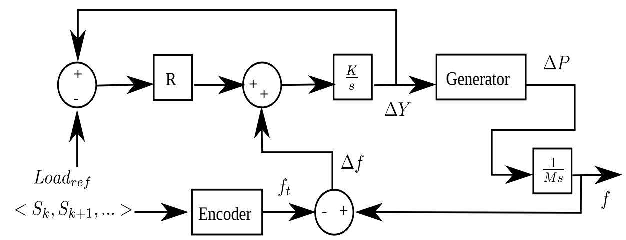

Figure 4. Simplified block diagram of a droop controller used as a transmitter, adapted from [16]. A series of symbols ($S_k, S_{k+1}, ...$) is encoded to frequency setpoint values (f_t) which are then given to the standard droop controller. The system's inertia (M) determines how quickly a power imbalance (ΔP) changes system frequency (f).

B. Load Model

The Demand as Frequency Controlled Reserve algorithm for discrete relay-based devices described in [3] has a frequency threshold (f_{off}) below which the load is disconnected. Loads are reconnected when system frequency is above a second, higher threshold frequency (f_{on}), creating a simple deadband. This concept can be generalized to more complex DER which have more than two states of operation. For FS-DER to identify a system frequency mode x, the sampled system frequency (f') must be between the lower frequency threshold (f_{x-}) and the upper frequency threshold (f_{x+}). The controller will transition to state x when:

$$f_{x-} \leq f' \leq f_{x+} \tag{2}$$

The thresholds would have to be chosen so that they were separated by enough distance to avoid spurious

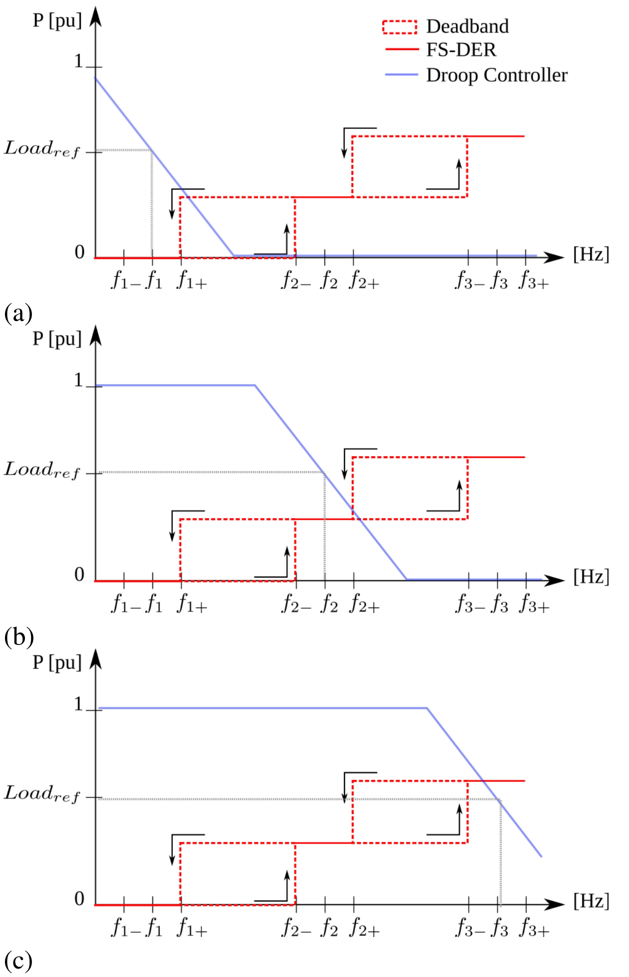

Figure 5. Power production from dispatchable generation with droop controller and consumption from FS-DER with three states. (a) Droop controller frequency setpoint at f_1. (b) Droop controller frequency setpoint at f_2. (c) Droop controller frequency setpoint at f_3.

unintended state changes. Fig. 5 shows how different frequency setpoints of a droop controlled generator can force FS-DER into one of 3 states.

To successfully communicate to DER, the system frequency should minimize the time it operates in the deadband, between two states. While the frequency is in the deadband, the probability of residing in an unintended state are higher because the FS-DER state is determined by hysteresis rather than the current frequency. A wide deadband is needed to avoid spurious changes to FS-DER state, but this forces frequency set-points to be farther from each other, reducing the number of symbols possible in a given bandwidth.

To narrow the deadband while avoiding spurious state changes, the DER can pass the frequency samples through a low pass filter before comparing the value to preset thresholds. In this way the variance of the Gaussian distribution is reduced. A similar algorithm was described in [17], where different cutoff frequencies existed for short-term frequency deviations (i.e. 1s) and longer-term

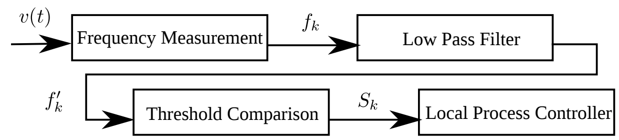

Figure 6. Block diagram of FS-DER load controller. In time period k, the frequency f_k of the incoming voltage waveform $v(t)$ is filtered and then compared to pre-set threshold values, resulting in state S_k which is given as input to the controller of the energy using process.

deviations (i.e. 5 min.). This algorithm is well suited for the proposed scheme because a small but consistent deviation from nominal frequency on a long time scale will force FS-DER into a known state. A block diagram of the full receiver is shown in Fig. 6.

C. Determining Frequency Threshold Values

Both the transmitter and receiver need to agree *a priori* on frequency setpoint and threshold values. To find appropriate frequency thresholds for the system states, the assumption of a Gaussian distribution of frequency measurements is used. If thresholds are chosen to be $f_s \pm 5\sigma$, the frequency value will be within this range 99.9999% of the time, implying that it will be outside this range 50 milliseconds per day. The frequency will be within $f_s \pm \sigma$ for 68% of the time. When the system operator wishes to communicate that the system is in state S_x, the encoder will set the generator's frequency set-point to f_x.

The distance from a given frequency set-point (f_x) to the next adjacent set-point (f_{x+1}) must be large enough to make spurious changes during normal operation rare. This is satisfied by ensuring

$$f_x + 5\sigma \leq f_{(x+1)-} \tag{3}$$

Fig. 7 shows the placement of set-points and state change thresholds for a system with 3 symbols.

When a state change is desired, the system frequency must be forced across the threshold values for long enough for the filtered value to cross the threshold. Filtering measurements over a longer time period reduces the maximum rate of change of symbols.

IV. Case Study: Bornholm

Bornholm, an island in the Baltic Sea, is normally connected to Sweden by means of a 60 kV AC cable. In April 2012, Bornholm operated as an electrical island, disconnected from Sweden. During this time, over a period of 4 days, high resolution frequency measurements were taken from a 60 kV substation. These frequency measurements were analyzed at 1 s intervals to characterize the system frequency when operating as an electrical island.

The frequency measurements conform well to a normal distribution, with a average of 50.002 Hz and $\sigma = 41$ mHz over the time period. The maximum frequency measurement was 50.200 Hz $= f_o + 4.87\sigma$, the minimum

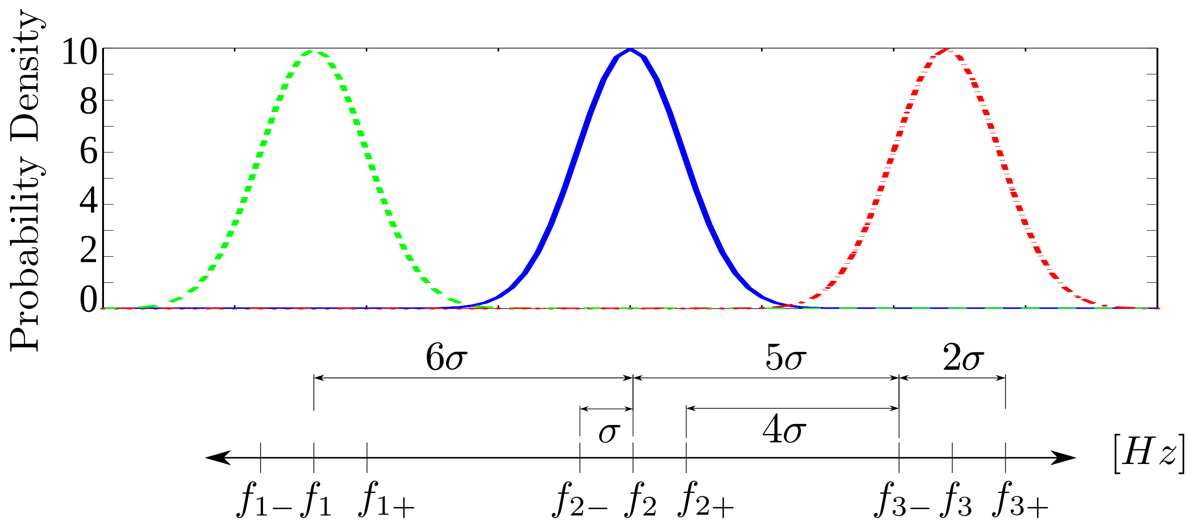

Figure 7. Top: Probability density of frequency samples for three system frequency setpoints: f_1, f_2, f_3. Below: The placement of set-points and the threshold values.

Table I
SUGGESTED PARAMETER VALUES FOR FREQUENCY SET-POINTS ON BORNHOLM WITH 4 SYMBOLS .

Parameter	Relative Value	Value
f_o		50 Hz
σ		40 mHz
f_1	$f_2 - 6\sigma(f_{min})$	49.64 Hz (49.62 Hz)
f_{1+}	$f_1 + \sigma$	49.68 Hz
f_{2-}	$f_2 - \sigma$	49.84 Hz
f_2	$f_o - 3\sigma$	49.88 Hz
f_{2+}	$f_2 + \sigma$	49.92 Hz
f_{3-}	$f_3 - \sigma$	50.08 Hz
f_3	$f_o + 3\sigma$	50.12 Hz
f_{3+}	$f_3 + \sigma$	50.16 Hz
f_{4-}	$f_4 - \sigma$	50.32 Hz
f_4	$f_3 + 6\sigma(f_{max})$	50.34 Hz (50.38 Hz)

measurement was 49.806 Hz $= f_o - 4.73\sigma$. Taking a moving average of samples over 1 minute marginally reduces the standard deviation to $\sigma = 38$ mHz (max: 50.163 Hz $= f_o + 4.29\sigma$, min: 49.846 Hz $= f_o - 4.05\sigma$), averaging over 10 minutes results in $\sigma = 35$ mHz (max: 50.135 Hz $= f_o + 3.86\sigma$, min: 49.87 Hz $= f_o - 3.23\sigma$). Averaging frequency samples smooths the extrema of the frequency distribution, but the reduction in standard deviation is not larger because the system exhibits off-nominal frequencies for long durations.

Assuming that Bornholm wished to live up to the requirements of an interconnected power system in [11], and with $\sigma = 40$ mHz, it follows from eq. (1) that the range of possible system frequency set-points is between $f_{min} = 49.62$ Hz, $f_{max} = 50.38$ Hz. The available bandwidth is:

$$50.38\,\text{Hz} - 49.62\,\text{Hz} = 0.76\,\text{Hz} = 18.5\sigma$$

Suggested values for frequency set-points and thresholds for 4 symbols are shown in table I.

If the system operator on Bornholm instead aimed for the more lenient requirements for a small power system, the available bandwidth would be:

$$50.88\,\text{Hz} - 49.12\,\text{Hz} = 1.76\,\text{Hz} = 44\sigma$$

In this case, a separation distance between symbols of 6σ would allow for 8 distinct states to be communicated from an operator to FS-DER.

V. DISCUSSION

Parameter values for the proposed AC frequency modulation system will vary greatly between synchronous systems. This operating method is most relevant for small synchronous systems because they already have a relatively wide range for their system frequency, and their generally smaller capacity margins motivate the use of energy management systems. Large synchronous systems have less available bandwidth but this is mitigated by larger inertia and smaller frequency variance, so the distance between symbols can be smaller.

The number of symbols that can be encoded with system frequency modulation is a trade-off between large off-nominal frequencies that reduce margins for frequency stability, and smaller spacing between set-point frequencies with an increased probability of communication errors to FS-DER. Low pass filtering of frequency samples can reduce the spacing between set-points without compromising error-rate, but results in slower transition time from one state to another. The maximum rate of change of frequency offsets, and hence the baud rate, will be constrained by the system's inertia and the dynamic properties of the rotating machines.

Analysis of a system's frequency stability will have to account for operation at off-nominal frequencies, which may result in the need for more frequency regulation resources. The operator's load control performance would depend on how closely the state received by FS-DER conformed to state intended by the operator.

The difference between frequency setpoint values would have to be larger than the typical variation of frequency (i.e. $> 5\sigma$) but if disturbances pushed the system frequency into a neighboring frequency band, the action of the FS-DER will act to restore the frequency to the targeted value. This means that the symbols can not have arbitrary meaning, higher frequencies must translate into higher consumption (and less production) in aggregate.

The frequency regulation function of FS-DER can co-exist with the proposed communication scheme if the FS-DER contained different cut-off thresholds: one threshold for fast response to serious disturbances, and another threshold for detecting system state changes using the low-pass filtered frequency samples.

Ideally, frequency set points would be adjusted equally above and below nominal to prevent clock drift, but if clocks are the only application which relies on this time service, it can be sacrificed because there are plenty of alternatives for finding the time of day.

Many loads are indifferent to variations in system frequency, but off-nominal frequency may lead to higher losses in machines optimized for a particular frequency (such as generators). This concept could have a negative effect on machine efficiency, however it is targeted towards applications where energy production capacity is the dominating constraint.

VI. Conclusion

The paper has described a new operating concept which broadcasts discrete system state information to frequency sensitive distributed energy resources (FS-DER). 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 analyzing 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.

Future work will seek to characterize the rate of change of frequency setpoints for different types of synchronous systems.

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Appendix H System Frequency as Information Carrier

System Frequency as Information Carrier in AC Power Systems

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Abstract

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 setpoint values are only rarely modified from nominal values. A system operator can communicate to frequency sensitive loads by changing the frequency setpoints of the system's frequency regulation resources. Explicitly signaling 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). This paper describes two protocols for utilizing off-nominal frequencies to carry information: Firstly, a protocol for dispatching blocks of FS-DER that is suitable for systems restricted to relatively slow rates of change of frequency (ROCOF). Secondly, for systems that allow higher ROCOF values, the feasibility of using power generation resources as a power frequency communication transmitter, such as for the TWACS system, is shown. Data gathered from operating island synchronous systems are analyzed to demonstrate the feasibility of the proposed communication system. By modulating system frequency from power generation sources the role of FS-DER as a power balancing resource can be expanded to include energy balancing services. In low-inertia systems, the control system for maintaining system frequency can be harnessed as a means of power frequency communication.

Index Terms

Power Frequency Communication; Ultra Narrow Band; Energy Management; Load Management; Voltage Source Inverters; Distributed Energy Resources; Frequency Control; ROCOF.

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I. INTRODUCTION

Transitioning electric energy systems to renewable power sources will increase the sustainability as well as the complexity of the power system. The diffuse nature of renewable primary energy favors distributed generation (DG), and as a result the number of entities actively participating in maintaining system stability will increase greatly. The stochastic production profile of renewable energy sources (RES) and scarcity of large-scale electric energy storage motivates the creation of energy management systems that include loads.

While the availability of low-cost microcontrollers allows software control of even the smallest loads, creating a communications network that reaches out to highly dispersed units is a costly endeavor. Real-time constraints on the control of power systems impose additional costs on communication systems. And where such a communication system has been established, maintaining the N-1 protection criteria requires that failure of the communication system does not compromise system security, thus a fallback communication-less state must be defined.

The physical characteristics of the voltage waveform (AC frequency and rms voltage) can be measured at the point of energy consumption, and can reveal valuable information about the state of the power system. Utilizing local measurements for autonomous control of DER was first proposed as "Homeostatic Utility Control" in [1]. The physical characteristics of the voltage waveform are subject to disturbances, but to the extent that system operators can maintain the parameters within known intervals, the system-based signal can be used for communication.

Power line communication has been in use since the pioneering days of public electric energy systems. This paper investigates the use of frequencies at and below the AC system frequency (50 Hz or 60 Hz) for transmitting information. Using the AC system frequency as a carrier for frequency modulation, called power frequency communication (PFC), was first introduced with the TWACS communication system [2]. The TWACS transmitters described in [2], [3] are intended for modifying frequency of a single radial in a large synchronous area, and previous work has not considered the design of TWACS transmitters for smaller synchronous systems.

This paper shows how operating at off-nominal frequencies can be used to dispatch FS-DER and where generator constraints allow fast frequency modulation act as a PFC transmitter . Common to both protocols is the use of power sources as modulators of system frequency. Section II describes frequency control of conventional large-scale power systems. Section III introduces new components with potential to disrupt conventional frequency control strategies. Section IV describes the system model that is applied in section Section V & VI to FS-DER dispatch and PFC transmission respectively. Section VII shows the feasibility of the proposed communication schemes with case studies from island power systems. Section VIII is a discussion and finally Section IX concludes the paper.

II. Conventional Frequency Control

Power systems must keep system frequency within a narrow range, and frequency stability can be a limiting factor for increasing penetrations of stochastic power sources [4]. Disturbances to system frequency are caused by imbalance between mechanical power provided to rotating generators (P_{m} [p.u.]) and electric power withdrawn by loads (P_{l} [p.u.]). The magnitude of change to system frequency is given by the swing equation [5]:

$$\Delta\dot{f} = \frac{f_{\mathrm{o}}}{2HS_{\mathrm{m}}}(P_{\mathrm{m}} - P_{\mathrm{l}}) \tag{1}$$

where f [Hz] is the system frequency, f_{o} [Hz] is the nominal frequency, S_{m} [MW] is the system's base power, and H [s] is the system inertia. The rate of change of frequency ($\Delta\dot{f}$) is abbreviated by the acronym ROCOF. When loads are uncontrollable, controlling generator input power is the only way to maintain power balance.

Primary frequency regulation acts to stabilize the frequency in the presence of disturbances on short time scales (milliseconds to minutes) by reestablishing the balance between generation and load. This is done by a droop response which makes generator input power inversely proportional to system frequency. The droop response results in a steady state error which indicates the amount of load on the droop controlled generators, and to restore system frequency to the setpoint frequency a slower secondary control loop, an isochronous governor, responds to the integral of the frequency deviation.

Observations of frequency measurements taken from several synchronous areas show that during normal operation, frequency samples conform to a Gaussian distribution, centered around the set-point value.

Systems operators perform simulation studies to determine the adequacy of primary and secondary frequency regulation resources [6]. These studies determine the frequency nadir after the largest expected contingency (typically a loss-of-generation event) and the distribution of frequency values during normal operation.

In addition to bounds on system frequency values, ROCOF must also be kept within well defined constraints. Events that provoke high ROCOF values place stress on synchronous machines, and

ROCOF relays are part of the generator protection schemes. Grid-connected DG will often have ROCOF relays to prevent island operation [7], [8].

A. Standards

The EN 50160 standard [9] used in Europe specifies the physical characteristics of electric energy delivered to customers. A large interconnected power system is required to deliver power with a frequency specified as:

50 Hz ± 1 % for 99.5 % of the year

50 Hz $+4$ %$/-6$ % for 100 % of the time.

Small island power systems have a wider tolerance, and must be designed for frequency constraints:

50 Hz ± 2 % for 95 % of a week

50 Hz ± 15 % for 100 % of the time.

Proposed grid codes from ENTSO-E [10] relax the constraints on system frequency for large systems, allowing unlimited operation in the range 50 Hz ± 2 %. The proposed grid codes require generators to remain online for ROCOF values less than 2 Hzs^{-1}. In general, interventions are not needed to meet the ROCOF requirement, but in synchronous areas with a growing penetration of non-synchronous generation, ROCOF values will increase to a level where mitigation efforts are needed. [11].

B. Rotating Machines

Large synchronous generators are characterized by relatively slow response times to operating point changes. When a change of output power is requested of a thermal power plant, time delays are introduced by the combustion of fuel, transfer of heat to steam, and the inertia of the turbine. The spinning mass of the rotor contributes inertia to the system (H in eq. 1), limiting the ROCOF during imbalances.

For the discussion that follows, we assume that the rate of change of power output of synchronous generation is limited by economic considerations to minimize fuel and maintenance costs. The part-loaded generators providing frequency regulation service generally have lower efficiency, and changes to power output put mechanical stress on machine components.

Induction motors are rotating machines that often compose a large part of system load (> 50 %) and contribute to system inertia [12].

C. Range of Frequency Setpoints

The use of off-nominal frequency setpoints is found on occasion in large interconnected systems to correct clock drift. In the continental European power system, frequency setpoints are adjusted to 50.01 Hz or 49.99 Hz for up to 24 hours [13]. It is conceivable that a synchronous area would take active use of the degree of freedom to vary frequency setpoints for communicating to FS-DER and as a consequence discard the time service.

The largest excursions away from frequency setpoints result from faults in central generators or high capacity transmission links. The response of the system to these transient imbalances is determined by magnitude of the power imbalance, the system's inertia and time constants on ramping up (or down) the primary and secondary frequency controlled reserves. Requirements for secondary frequency control in continental Europe [13] specify that after a contingency, the system frequency should be restored to ± 20 mHz of the set-point frequency within 15 minutes. This time period corresponds to the time needed to ramp up production from thermal power plants.

To maintain system integrity, the minimum frequency after an extreme disturbance must be above the trip thresholds of under-frequency protection relays. If the maximum frequency deviation after a disturbance in the negative/positive direction is given as $\Delta f_{\text{max-}}/\Delta f_{\text{max+}}$ [Hz], and the technical minimum/maximum frequencies are $f_{\text{limit-}}/f_{\text{limit+}}$ [Hz], the system operator can choose frequency setpoints f_{s} [Hz] that satisfy:

$$\forall f_{\text{s}} \in F \ s.t. : (f_{\text{limit-}} + \Delta f_{\text{max-}}) < f_{\text{s}} < (f_{\text{limit+}} - \Delta f_{\text{max+}}) \tag{2}$$

To satisfy the requirements that the probability of the system frequency residing between f_{min} and f_{max} is greater than an given value P_{ok}, assuming a Gaussian distribution of system frequency around the setpoint f_{s} with standard deviation σ, it is sufficient for the set of valid set-points to satisfy:

$$\forall f_{\text{s}} \in F \ s.t. : (f_{\text{min}} + f_{\text{margin}}) < f_{\text{s}} < (f_{\text{max}} - f_{\text{margin}}) \tag{3}$$

where f_{margin} is given by solving for the unknown quantity in:

$$P_{\text{ok}} = \text{erf}\left(\frac{f_{\text{margin}}}{\sigma\sqrt{2}}\right) \tag{4}$$

where $\text{erf}(x)$, the Gauss error function, gives the probability of a parameter falling within $\pm x$ of the expected value. Combining theses constraints gives the complete range of valid frequency setpoints:

$$\forall f_{\text{s}} \in F \ s.t.: \begin{cases} (f_{\text{limit-}} + \Delta f_{\text{max-}}) < f_{\text{s}} \\ f_{\text{s}} < (f_{\text{limit+}} - \Delta f_{\text{max+}}) \\ (f_{\text{min}} + f_{\text{margin}}) < f_{\text{s}} \\ f_{\text{s}} < (f_{\text{max}} - f_{\text{margin}}) \end{cases} \tag{5}$$

A system operator who chooses to vary system frequency setpoints, will have to maintain ROCOF constraints during the transition from one frequency setpoint to another. A ROCOF budget will subtract the maximum ROCOF seen during a contingency ($ROCOF_{\text{max}}$ [Hzs^{-1}]) from the technical limits ($ROCOF_{\text{limit}}$ [Hzs^{-1}]) , and the resulting difference will give the budget for additional $ROCOF_{\text{pfc}}$ [Hzs^{-1}] introduced when changing between frequency setpoints. $ROCOF_{\text{pfc}}$ my also be limited by the power available from frequency regulation resources (P_{reg}) relative to the system inertia.

$$ROCOF_{\text{pfc}} = \min(\frac{f_{\text{o}} P_{\text{reg}}}{2HS_{\text{m}}}, ROCOF_{\text{limit}} - ROCOF_{\text{max}}) \tag{6}$$

III. Unconventional Frequency Sensitive Components

Power systems are evolving rapidly as new environmental constraints are introduced and new technologies are diffused. Two changes that will affect system frequency regulation will be discussed here.

A. Inverter Dominated Systems

Inverters take a DC power source and apply power electronics to produce an AC waveform with low distortion. The architecture of a generic inverter is shown in Fig. 1. They are classified as either voltage source inverters (VSI) or current source inverters (CSI). Current source inverters (CSI) do not participate in generating system frequency, but instead follow the frequency of the incoming voltage and maintain phase synchronization via a phase locked loop (PLL). A system without rotating generators needs at least one VSI to produce a reference frequency to which CSI can synchronize. Any phase difference between inverters creates circulating currents, contributing to losses [14].

Synchronous areas dominated by VSI can be found in any island where the primary power sources or transmission links are realized with DC. For example, isolated mini-grids with storage

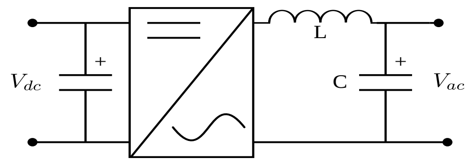

Figure 1. Inverter with LC output filter functions to convert DC primary energy source into AC.

will have a battery charge controller acting as a VSI. In [15], a synchronous system was dubbed an “empty network“ if all power sources and loads lacked inertia.

When primary energy sources are connected to an AC power system through voltage source inverters (VSI), the system frequency is controlled by software, without physical constraints tied to the swing equation. In a power system fed only by inverters, physical inertia will provided only by motors. While the fast response of power electronics to changes in power demand decouple system frequency from load changes, a $P(f)$ droop can be implemented to allow load sharing between generators (both inverter connected and rotating machines) [16]. If all rotating machines in a synchronous area are motors, or generators with constant power output, there will be no disturbances to the system frequency generated by the VSI, and frequency will be seen as constant on all busses.

In the context of using system frequency to carry information by changing frequency setpoint values, a low amount of physical inertia is an advantage because it allows rapid changes in system frequency (high ROCOF).

Grid codes for large synchronous areas require DG inverters to implement a $P(f)$ droop when system frequency is above a critical value (i.e. 50.2 Hz), thus providing emergency down regulation reserves. In an isolated mini-grid, VSI’s available today can utilize this emergency droop mode to curtail production from current source inverters (CSI). Modulating AC system frequency is used by VSI battery controllers indicate battery charge status, and to curtail production in islanded microgrid systems in the event that production exceeds load and energy storage devices are full [14], [17]–[19].

B. FS-DER for Primary Frequency Regulation

Previous work on FS-DER has focused on their role to supplement large generators performing primary frequency regulation [20]–[24]. The availability of low-cost microelectronics to accurately measure system frequency has made it feasible for loads as small as household appliances to act as FS-DER for primary frequency regulation. In [25] the value of primary frequency regulation services from FS-DER is cited to justify mandating their deployment on thermostat controlled loads.

Typical automatically controlled loads (such as thermostat controlled loads) operate in two states, OFF and ON, with the duty cycle controlled to keep the energy level within desired bounds. A FS-DER controller programmed for primary frequency regulator will alter the phase of the duty cycle to defer energy consumption away from periods when the grid is overloaded, as indicated by a low system frequency. If FS-DER is to mimic the primary frequency response of conventional generator governors, it should in aggregate provide a smooth response to small incremental changes in frequency. The only way to create a smooth and reliable frequency response with OFF/ON loads is to have a population of devices with a diversifying parameter such as differing frequency thresholds. Grouping FS-DER into discrete blocks would undermine the smooth response, but as shown in [24], large blocks still provide substantial improvement to the frequency nadir after a contingency.

The FS-DER algorithm for discrete relay-based devices described in [22] has a frequency threshold ($f_{\text{off+}}$) below which the load is disconnected. Loads are reconnected when system frequency is above a second, higher threshold frequency ($f_{\text{on-}}$), creating a simple hysteresis. This concept can be generalized to more complex (or aggregated) DER which have more than two states of operation. The controller will transition to state S when instantaneous measured system frequency f_{meas} [Hz] enters the decision region given by:

$$f_{S-} \leq f_{\text{meas}} \leq f_{S+} \tag{7}$$

System frequency (f_{meas}) must be between the lower frequency threshold (f_{S-} [Hz]) and the upper frequency threshold (f_{S+} [Hz]) to trigger a state change.

C. Two Way Automatic Communication System (TWACS)

Standard frequency band allocation of the powerline media gives utilities access to the lowest frequencies [26], but the standard stops at the lower limit of 3 kHz. The review in [27] reports of ultra narrow band systems using frequencies down to 300 Hz at speeds as low as 0.001 bps.

In contrast to power line communication which superimposes high frequency components onto the voltage waveform, power frequency communication (PFC) uses the AC system frequency as a carrier for frequency modulation. TWACS is the an implementation of PFC currently utilized for remote meter reading, distribution automation, and outage management [28]. Because the AC voltage signal must be continuous phase, frequency shift keying is used to encode symbols. TWACS encodes one data bit with 2 AC cycles [2].

While the system frequency can be assumed to be identical on all busses in a synchronous area, TWACS can modulate system frequency on a single radial by injecting current to distort the downstream voltage waveform. The protocol uses relative changes to the system frequency, and is robust in the presence of variations of system frequency.

A drawback of the TWACS frequency modulation technique [3] is reactive power losses. The advent of synchronous areas dominated by inverter connected generation introduces the possibility of modulating system frequency at the power source at no cost.

A TWACS receiver has equivalent frequency measurement capabilities as a FS-DER receiver.

IV. System Model

The following system model will be used to analyze how system frequency can be used as an information carrier. In a system with synchronous generators, system frequency is a noisy signal, subject to disturbances which follow from generation/load imbalances. Despite this noise, a system operator with *a priori* knowledge of FS-DER configuration parameters can communicate with FS-DER by using existing generator speed governors to change the setpoint. The load is composed of both FS-DER and conventional passive loads, including motors, as shown in Fig. 2.

A generic generator model is considered which covers all generation resources, both rotating machines and VSI. Fig. 3 shows a block diagram of a droop controlled generator that is augmented with a stream of inputs encoded into frequency setpoints by a 1-to-1 mapping. Decomposing the generator block in Fig. 3 of a rotating machine would reveal a transfer function from fuel delivery to turbine torque to electric power and the time delays involved in all sub-processes. Secondary frequency control is accomplished by changing $Load_{\text{ref}}$ [MW] values. The parameters of the generator block for a VSI has much smaller time delays, on the order of the input sampling rate, well within 20 ms.

The utilization of bandwidth can be maximized by narrowing the distribution of frequency samples. Without increasing the power and speed of frequency regulation resources, this can be achieved by passing frequency samples through a low pass filter before comparing the value to preset thresholds. A similar algorithm was described in [29], where different cutoff frequencies existed for short-term frequency deviations (i.e. 1 s) and longer-term deviations (i.e. 5 min.). A block diagram of the full receiver is shown in Fig. 4. The use of a low pass filter will decrease the effective $ROCOF_{\text{pfc}}$.

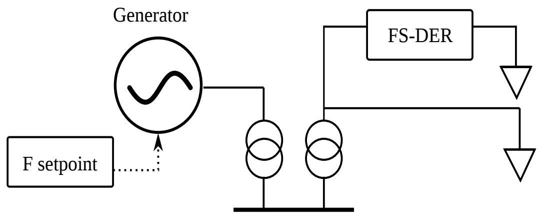

Figure 2. One-line system diagram. A lumped generator model is connected to FS-DER and conventional loads by a copper plate transmission system model. Frequency set point changes introduced to the generator are detected by the FS-DER.

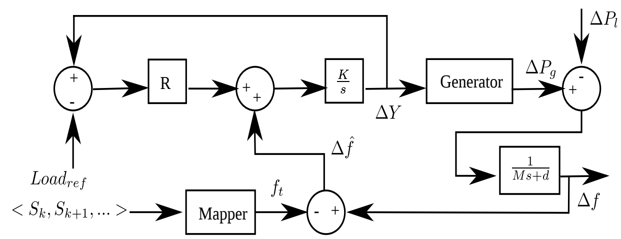

Figure 3. Simplified block diagram of a droop controller used as a transmitter, adapted from [5]. A series of symbols $< S_k, S_{k+1}, ... >$ is encoded to frequency setpoint values (f_t) by a simple 1-to-1 mapping which are then given to the standard droop controller. The system's inertia (M) determines how quickly a power imbalance ($\Delta P_{\mathrm{m}} - \Delta P_{\mathrm{l}}$) changes system frequency (Δf).

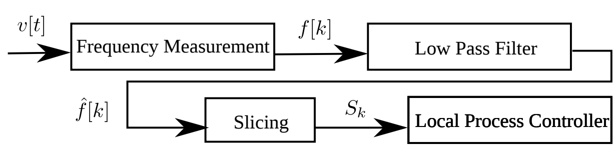

Figure 4. Block diagram of FS-DER load controller. In time period k, the frequency $f[k]$ of the incoming voltage waveform $v[t]$ is filtered and then compared to pre-set threshold values (slicing), resulting in state S_k which is given as input to the controller of the energy using process.

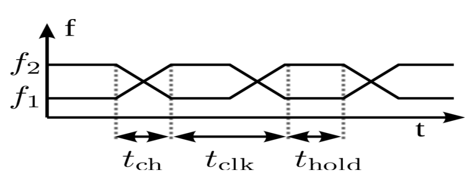

Figure 5. Timing diagram of PFC protocols. The time to change between symbols (t_{ch}). The hold time (t_{hold}) can be small.

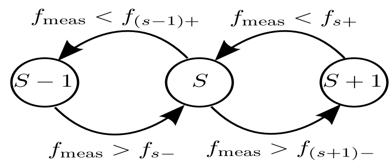

Figure 6. When dispatching FS-DER by modulating system frequency, state transitions only occur between neighboring states.

A timing diagram showing the transition between frequency setpoints is shown in Fig. 5. The hold time (t_{hold}) depends on the length of low pass filtering on the receiver, desired error rate, the size of the decision region, and where applicable, the accuracy of clock synchronization between sender and receiver.

The time taken for the system frequency to rise/fall (t_{ch}) is a function of the spacing between frequency setpoints($f_S - f_{S-1} = f_{\text{spacing}}$), and the $ROCOF_{\text{pfc}}$:

$$t_{\text{ch}} \geq \frac{f_{\text{spacing}}}{ROCOF_{\text{pfc}}} \tag{8}$$

The sum of the rise/fall time and hold time give the total time to transmit one symbol (t_{clk}):

$$t_{\text{clk}} = t_{\text{ch}} + t_{\text{hold}} \tag{9}$$

V. Dispatch of FS-DER

By relaxing the operational constraint that the frequency setpoint must always be the nominal frequency ($f_{\text{s}} \neq f_{\text{o}}$) during normal operation, system frequency can be modulated to communicate the value of a single discrete variable to FS-DER. In systems with low $ROCOF_{\text{pfc}}$, the time to transition between setpoints (t_{ch}) will be large, therefore it is only feasible to encode one symbol per time period, and decoding must be time-invariant. A further restriction with this protocol is that state changes only occur between adjacent states, as shown in Fig. 6. Finally, the design assumes the hold time t_{hold} is long enough to give a high probability of f_{meas} falling within the decision region of the intended state.

Fig. 7 shows how different frequency setpoints of a droop controlled generator can force FS-DER into one of 3 states.

A. Determining Frequency Threshold Values

Both the transmitter and receiver need to agree *a priori* on frequency setpoint and threshold values. Frequency thresholds must be chosen so that they are separated by enough distance to avoid

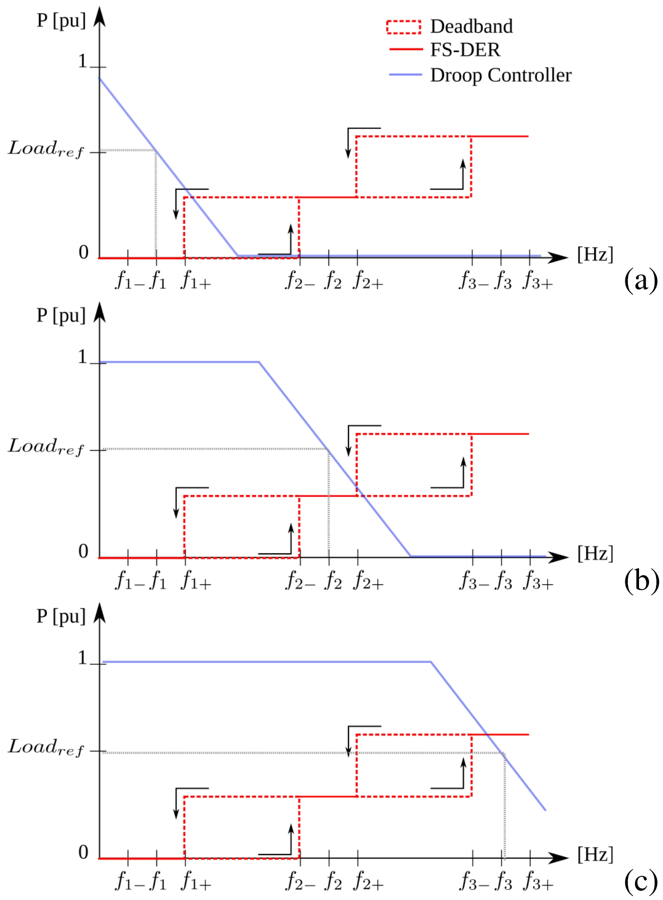

Figure 7. Power production from dispatchable generation with droop controller and consumption from FS-DER with three states. (a) Droop controller frequency setpoint at f_1. (b) Droop controller frequency setpoint at f_2. (c) Droop controller frequency setpoint at f_3.

spurious unintended state changes during t_{hold}. A wide spacing between setpoints (f_{spacing}) avoids spurious changes to FS-DER state, but simultaneously reduces the number of symbols feasible within in a given bandwidth. The hysteresis region between setpoints given by

$$f_{\text{hy}} = f_{S-} - f_{(S-1)+} \tag{10}$$

reduces f_{spacing}, while increasing the time needed to ensure f_{meas} lies within the decision region, and thus increasing t_{hold}.

To find appropriate frequency thresholds for encoding system states, the designer needs to be given a goal for the desired probability of a FS-DER residing in an unintended state (P_{e}), the standard deviation of the (Gaussian distributed) frequency values. The minimum distance between a frequency setpoint f_S, and the neighboring setpoints $f_{(S-1)}, f_{(S+1)}$ is found by solving for f_{spacing} in:

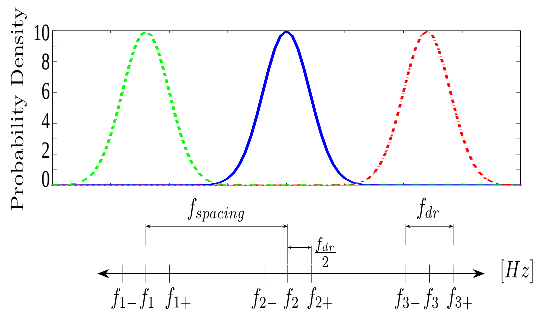

Figure 8. Top: Probability density of frequency samples for three system frequency setpoints: f_1, f_2, f_3. Below: The placement of set-points and the threshold values for dispatch of discrete blocks of FS-DER.

$$\text{erf}\left(\frac{f_{\text{spacing}} - \frac{f_{\text{dr}}}{2}}{\sigma\sqrt{2}}\right) = 1 - P_{\text{e}} \tag{11}$$

where erf is again the Gauss error function, and f_{dr} is the size of the decision region

$$f_{\text{dr}} = f_{S+} - f_{S-}$$

Eq. 11 assumes f_{dr} is the same for all setpoints and that setpoints are located is the center of the decision regions. For $P_{\text{e}} = 10^{-6}$ and $f_{\text{dr}} = 2\sigma$, $f_{\text{spacing}} = 5.89\sigma$. In the case studies, we assume $f_{\text{spacing}} = 6\sigma$ will give an acceptable error rate.

Fig. 8 shows the placement of set-points and state change thresholds for a system with 3 symbols and decision region of $f_{\text{dr}} = 2\sigma$.

For a given frequency bandwidth (f_{w}), the number of discrete symbols N encoded in that bandwidth is

$$N = \left\lfloor \frac{f_{\text{w}}}{f_{\text{spacing}}} \right\rfloor + 1 \tag{12}$$

VI. Generator Speed Governors as Transmitters for Power Frequency Communication

In synchronous areas that allow a high $ROCOF_{\text{pfc}}$, system frequency can be modulated fast enough to allow arbitrary digital information to be transmitted.

The transmitter (generator) and receiver (FS-DER) must be synchronized, so a data clock can be recovered and data packages delimited. Synchronization of clocks and package delimiters can be done with a preamble, as in TWACS [2]. The decoding of frequency measurements is time independent relative to the start of the data package.

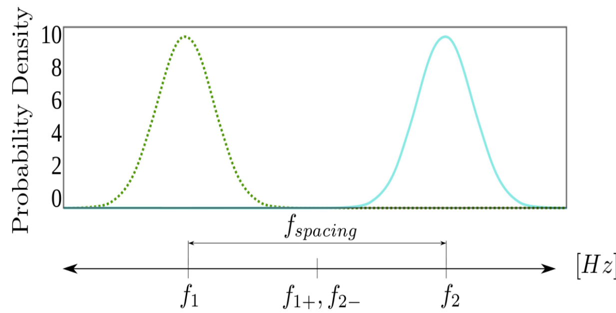

Figure 9. Top: Probability density of frequency samples for two system frequency setpoints: f_1, f_2. Below: The placement of set-points and the threshold values for PFC where $f_{1+} = f_{2-}$.

The placement of frequency setpoints for PFC uses the eq. 11 where the decision region is chosen to be $f_{\text{dr}} = f_{\text{spacing}}$, so there is no hysteresis region between adjacent symbols ($f_{\text{hy}} = 0$), as shown in Fig. 9. This wider decision region maps each frequency sample to the nearest setpoint value. The frequency during t_{ch} will be ignored, and only frequency samples taken during t_{hold} are decoded.

In the previous section it was shown how the available bandwidth can be divided into an alphabet of discrete symbols opening the option of multiple frequency shift keying. However, in general t_{hold} can be small compared to t_{ch} and the highest data rate is achieved by using only two frequencies for encoding data.

When the frequency of the data clock at or below the AC system frequency ($t_{\text{clk}}^{-1} \leq f_{\text{o}}$), dedicating cycles to rise/fall transition between frequencies is unnecessary ($t_{\text{ch}} = 0$). The transmitter is able independently modulate the frequency of each AC cycle, and thus act as a TWACS compatible transmitter.

VII. Case Studies

Using system frequency to encode information is most relevant for small synchronous systems because they already have a relatively wide range for their system frequency, and their generally smaller capacity margins motivate the use of energy management systems. Two island power systems in Denmark studied: one with thermal synchronous generation, and one migro-grid.

Bornholm, an island in the Baltic Sea, is normally connected to Sweden by means of a 60 kV AC cable. In April 2012, Bornholm operated as an electrical island, disconnected from Sweden. During this time, over a period of 4 days, power was provided by thermal generation and wind turbines, and high resolution frequency measurements were taken from a 60 kV substation. These frequency measurements were analyzed at 1 s intervals to characterize the system frequency when operating as an electrical island.

The second island, Christiansø, is a decommissioned naval base which is a popular tourist destination. Around 100 people live permanently on the 0.22 km^2 island. Their electric power system is composed of 4 diesel powered generators, two with a rating of 180 kW, one 130 kW and one 60 kW. At the moment, there is no renewable electricity generation, though wind and solar resources are available. Two bottle cooling refrigerators with FS-DER functionality have been installed as part of field experiment [30]. Frequency measurements were collected when the frequency response was disabled to characterize the system. These measurements are taken at both 1 min. intervals (low resolution) and 2 s intervals (high resolution). Two scenarios are considered on this island: first considering the present day generation portfolio, and second considering a future scenario where the rotating machines are replaced with inverter connected generation.

A. Bornholm

The frequency measurements conform well to a normal distribution, with a average of 50.00 Hz and $\sigma = 41$ mHz over the time period. Using a low pass filter on the frequency samples smooths the extrema of the frequency distribution, but the reduction in standard deviation small ($\sigma = 35$ mHz for 10 min. moving average) because the system exhibits off-nominal frequencies for long durations.

Assuming that Bornholm wished to live up to the requirements of an interconnected power system in [9], with $\sigma = 40$ mHz, $f_{\text{margin}} = 3\sigma$, and no danger of transient violations of frequency limits, it follows from eq. (5) that the range of possible system frequency set-points is between $f_{\text{min}} = 49.62$ Hz, $f_{\text{max}} = 50.38$ Hz. The available bandwidth is: $0.76\,\text{Hz} = 18.5\sigma$

With $f_{\text{spacing}} = 6\sigma$, 4 symbols are feasible. Suggested values for frequency set-points and thresholds for the 4 symbols are shown in table I.

If the system operator on Bornholm instead aimed for the more lenient requirements for a small power system, the available bandwidth would be: $1.76\,\text{Hz} = 44\sigma$. In this case, 8 distinct states to be communicated from an operator to FS-DER.

Estimating the $ROCOF_{\text{pfc}}$ is done by using a model of the island's power system from [31], and assuming $ROCOF_{\text{pfc}}$ is limited by P_{reg}. Simulations from [31] show that after a step change in load, the secondary frequency control restores system frequency from 48.75 Hz to 50 Hz in 75 s, giving a ROCOF of 16.7 mHzs^{-1}. The f_{spacing} = 240 mHz, from eq. 8 we get $t_{\text{ch}} = 14.4$ s. If we arbitrarily assume $t_{\text{hold}} = t_{\text{ch}}$, this gives a baud rate 125 symbols per hour.

Table I

SUGGESTED PARAMETER VALUES FOR FREQUENCY SET-POINTS ON BORNHOLM WITH 4 SYMBOLS.

Parameter	Relative Value	Value
f_o		50 Hz
σ		40 mHz
f_1	$f_2 - 6\sigma (f_{\text{min}})$	49.64 Hz (49.62 Hz)
f_{1+}	$f_1 + \sigma$	49.68 Hz
f_{2-}	$f_2 - \sigma$	49.84 Hz
f_2	$f_o - 3\sigma$	49.88 Hz
f_{2+}	$f_2 + \sigma$	49.92 Hz
f_{3-}	$f_3 - \sigma$	50.08 Hz
f_3	$f_o + 3\sigma$	50.12 Hz
f_{3+}	$f_3 + \sigma$	50.16 Hz
f_{4-}	$f_4 - \sigma$	50.32 Hz
f_4	$f_3 + 6\sigma (f_{\text{max}})$	50.34 Hz (50.38 Hz)

For PFC, $P_{\text{e}} = 10^{-6}$ gives

$$f_{\text{spacing}} = 9.8\sigma = 392\,\text{mHz}$$

From eq. 8 we get $t_{\text{ch}} = 23.5$ s. Again, if $t_{\text{hold}} = t_{\text{ch}}$, this gives a data rate 76 bits per hour, which is considered too low for practical applications.

B. Christiansø: Diesel Powered Mini-Grid

The following case study illustrates the use of AC system frequency modulation in the context of a mini-grid with synchronous generators. The following analysis assumes that the operator will live up to the requirements of small islands given in [9].

The system displayed distinct two modes of operation, and frequency measurements were placed into two groups: group 1 (June 20 - July 6) and group 2 (July 11 - July 27). In each group, measurements fit well into a normal distribution, with the average value of 50.00 Hz for group one and 50.11 Hz for group two. The standard deviation for group 1 was 43.4 mHz, for group 2 it was 137.3 mHz. The moving average over 5 minutes of high resolution frequency measurements from group 2 was found and the standard deviation of these filtered values was 50 mHz, as shown in Figure 10.

Assuming again that the range of frequency setpoints is constrained by the frequency distribution, and is given by eq. 3. The available bandwidth is 1.7 Hz $= 34\sigma$. By eq. 12 this allows for 6 discrete symbols to be encoded by frequency.

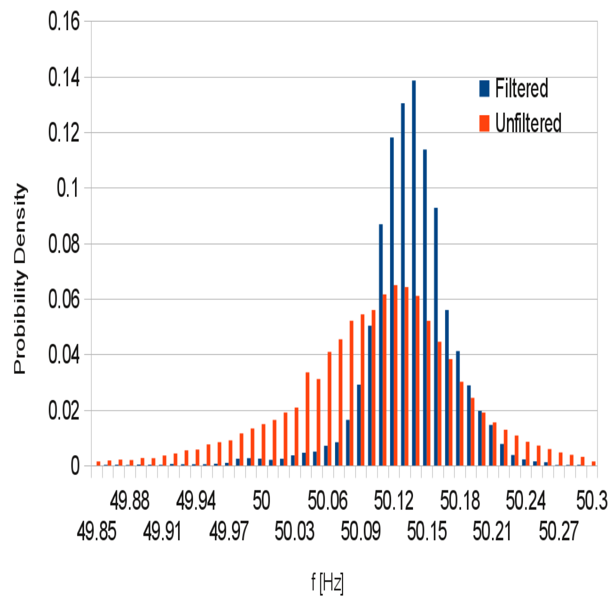

Figure 10. Relative frequency of data collected from group 2 (July 11 to July 27), raw data and after passing through a low pass filter (5-minute moving average). The wide distribution of the raw data is narrowed significantly by the low pass filter.

The length of the low pass filter (5 min.) fixes $t_{\text{ch}} = 300s$. If $t_{\text{hold}} = 0$, the baud rate be 12 symbols per hour. The feasible data rate of PFC is likewise 12 bits per hour because the increased spacing does not significantly influence t_{ch}.

C. Christiansø: Inverter Dominated Mini-Grid

The increasing cost of diesel fuel, and decreasing costs of RES, may one day motivate the operator on Christiansø to replace their current generation fleet with inverter connected energy sources. Without frequency data taken from an operational inverter dominated mini-grid, parameter values will be assumed. As discussed in section III, the VSI dominated synchronous areas are not subject frequency disturbances. The only variation in frequency measurements is therefore measurement noise. In one experimental setup of low-cost FS-DER, the measurement noise was found to have a standard deviation of $\sigma < 2$ mHz [30]. With the available bandwidth of 1.88 Hz $= 94\sigma$, and $f_{\text{spacing}} = 6\sigma$, eq. 12 indicates the bandwidth can accommodate 16 discrete symbols.

Estimating $ROCOF_{\text{pfc}}$ is assumes $ROCOF_{\text{limit}}$ constraints are from motors connected to the system, and $ROCOF_{\text{max}} = 0$. Induction motors, such as those typically found in smaller appliances, are robust machines not harmed by $ROCOF_{\text{limit}}$ values of 1 Hzs^{-1}.

As in the first case study, the frequency setpoints for PFC have $f_{\text{spacing}} = 9.8\sigma$, in this case 19.6 mHz. From eq. 8 $t_{\text{ch}} = 19.6$ ms. If t_{hold} can be kept under $400\,\mu\text{s}$, t_{clk} will be under one cycle time at 50 Hz. This indicates that it is safe to change frequency setpoints changes within one cycle and that the generator can produce TWACS compatible signals.

VIII. Discussion

This paper was not intended to present an optimal design, but rather to argue for feasibility of using generator speed governors as transmitters of discrete information. Compared to other power line communication protocols, the proposed protocol should be inexpensive to implement because it uses existing generator speed governors to encode data and allows decoding devices to be implemented with commodity low-cost microcontrollers. The use of low frequencies allow unlimited propagation distances.

Parameter values for the proposed AC frequency modulation system will vary greatly between synchronous systems. Large synchronous systems will have very low $ROCOF_{\text{plc}}$ values because of high inertia. This makes it infeasible to use generator speed governors for PFC, but this does not exclude using the limited available bandwidth for dispatching FS-DER. Inverter dominated synchronous areas have such high $ROCOF_{\text{plc}}$ values that enable TWACS compatible PFC to be implemented.

Detailed discussion of applications of these protocols is outside the scope of this paper, but to illustrate the difference between the two protocols, their application to price distribution is considered. Using the FS-DER dispatch protocol allows the current electricity price to be reflected by the system frequency, allowing marginal consumers to judge if the utility of their consumption exceeds the current price. However, future prices would be nothing but guesses, so long-term optimization is not possible. In contrast, with PFC and a bit rate high enough to send the price values not only for the current operation period , but also future time periods would give information to consumers allow them to optimize their consumption across a longer time horizon.

The frequency regulation function of FS-DER can co-exist with the proposed dispatch protocol if the FS-DER contained different thresholds: one threshold for fast response to serious disturbances, and another threshold for detecting system state changes using the low-pass filtered frequency samples.

Many loads are indifferent to variations in system frequency, but off-nominal frequency may lead to higher losses in machines optimized for a particular frequency (such as generators). This concept could have a negative effect on machine efficiency, however there will be many systems where the the benefit of distributing information for demand response outweighs these costs.

IX. Conclusion

The paper has shown how existing frequency regulation resources can be applied to transmitting discrete information. Systems that are restricted to slow changes in system frequency values can dispatch FS-DER into known states, while systems that allow fast changes to system frequency can implement one-way power frequency communication (PFC).

Data collected from small power systems shows that it is feasible to encode between 4 and 8 discrete symbols for FS-DER dispatch. Analysis of a small island supplied by power electronic interfaced generators showed that it is feasible to modulate system frequency cycle-by-cycle, and thus produce a signal compatible with first-generation TWACS receivers.

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