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 . 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, demonstration project, frequency control, 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 photovoltaics (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].

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 trademark 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 of 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.

Manuscript received June 08, 2012; revised January 02, 2013; accepted April 06, 2013. Date of publication July 12, 2013; date of current version August 21, 2013. Paper no. TSG-00349-2012.

P. J. Douglass, R. Garcia-Valle, and J. Østergaard are with the Centre for Electric Power and Energy, Technical University of Denmark, Elektrovej-Building 325, 2800 Kongens Lyngby, Denmark (e-mail: pjdo@elektro.dtu.dk; rgv@elektro.dtu.dk; joe@elektro.dtu.dk).

P. Nyeng is with Energinet.dk, 7000 Fredericia, Denmark (e-mail: pny@energinet.dk).

M. Togeby is with the EA Energy Analyses, 1220 Copenhagen, Denmark (e-mail: mt@eaea.dk).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TSG.2013.2259510

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.

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.

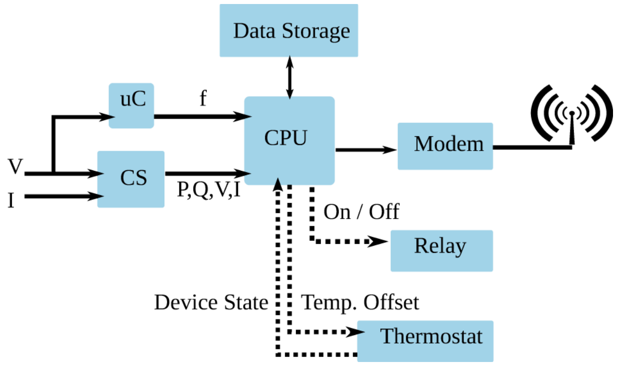

Fig. 1. DFCR block diagram. The CPU is a low cost micro-controller with 8 kB of RAM. The system frequency is measured by a secondary micro-controller (uC). Power consumption (real and reactive) is calculated by a dedicated component (CS). The measurements are buffered to an SD card (Data Storage), and 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 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 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.

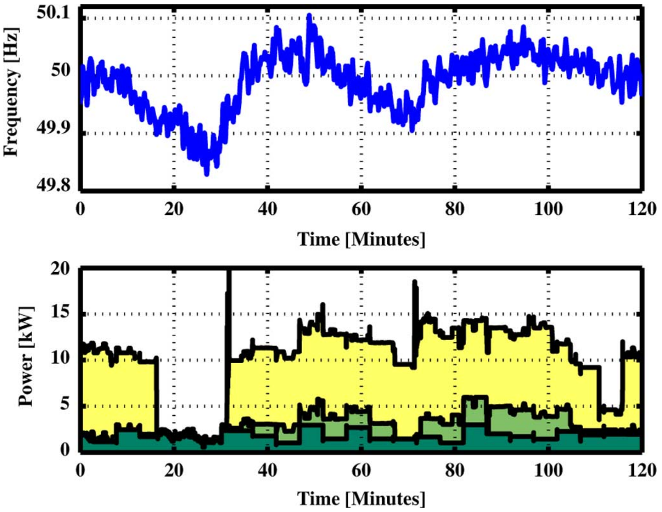

Fig. 2. Time series of system frequency (top) and aggregate response of DFCR loads (bottom) over a representative two hour period. In the bottom sub-figure the consumption of different devices is stacked, with the refrigerators is dark green at the bottom, heaters in light green in the middle, and the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

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 $50\ \mathrm{Hz} \pm 100\ \mathrm{mHz}$ for more than 2% of the time [14]. During periods when frequency was below the acceptable range, 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

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

normal reserve is active in the range 49.90 Hz—50.10 Hz, and requires a linear response from generators within 180 s. Generators that 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.

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 above 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° 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.

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 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 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

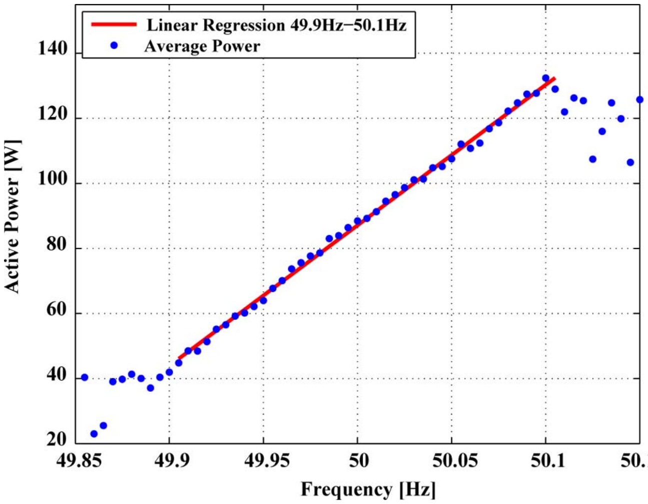

Fig. 3. Average frequency response of a refrigerator with least squares linear regression. Temperature offset varied linearly with ±2 °C in the range 49.90 Hz—50.10 Hz, with 0° offset at 50.00 Hz.

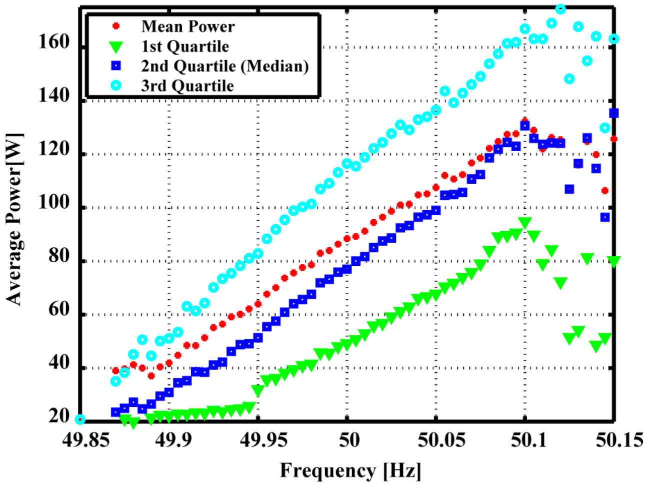

Fig. 4. For each frequency group, mean power is shown together with the median, 1st and 3rd quartiles.

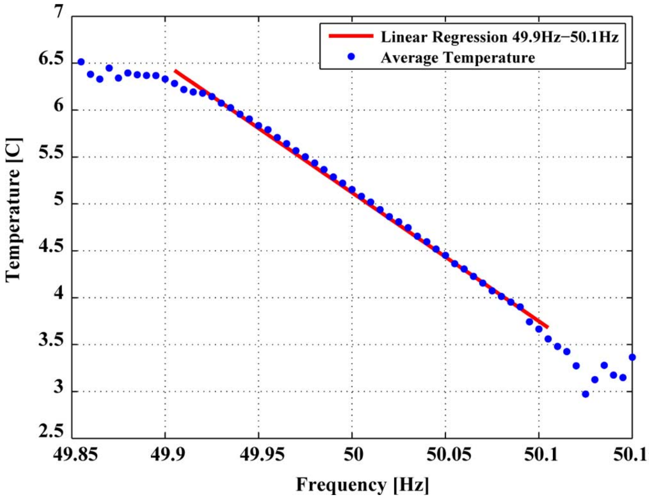

Fig. 5. Average internal air temperature of refrigerators vs frequency with least squares linear regression.

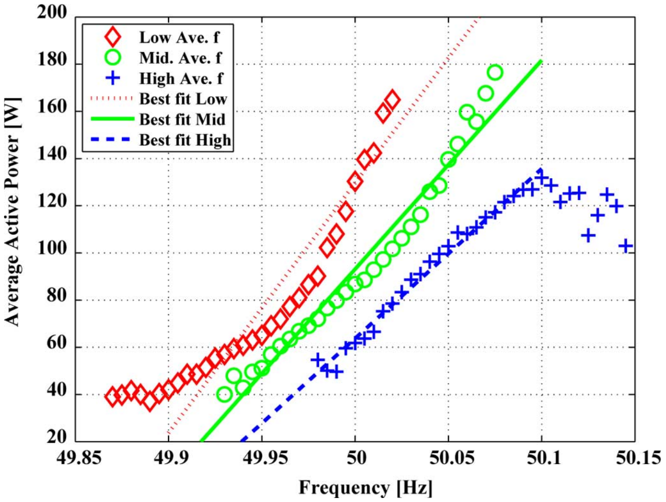

Fig. 6. Frequency response at low, middle, and high historical frequencies when calculating average frequency over 6 minutes, with best fit lines.

frequencies below 49.95 Hz, the first quartile is where all compressors in the population are off.

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 $\pm 1.3\ ^\circ\mathrm{C}$ from 49.90 Hz to 50.10 Hz, even though the thermostat setpoint has been offset by $\pm 2\ ^\circ\mathrm{C}$.

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 $\overline{f} < 49.975\ \mathrm{Hz}$, middle historical frequency ($49.975\ \mathrm{Hz} < \overline{f} < 50.025\ \mathrm{Hz}$ and high historical frequency $\overline{f} > 50.025\ \mathrm{Hz}$). The frequency 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 aggre-

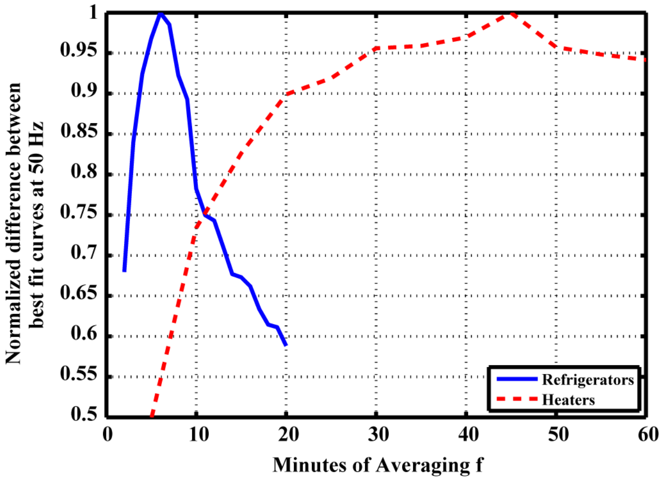

Fig. 7. The difference between low, middle, and high frequency best fit lines at nominal frequency for different sizes of time windows for calculating average frequency. The y-axis is normalized relative to the maximum difference observed for each device.

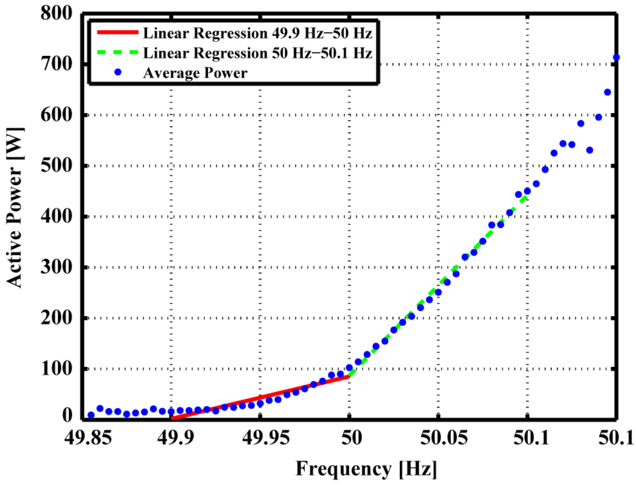

Fig. 8. Frequency response of electric heaters with piecewise linear regression. The average power consumption approached 0W before the thermostat's offset limit at 49.90 Hz was reached.

gated 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.

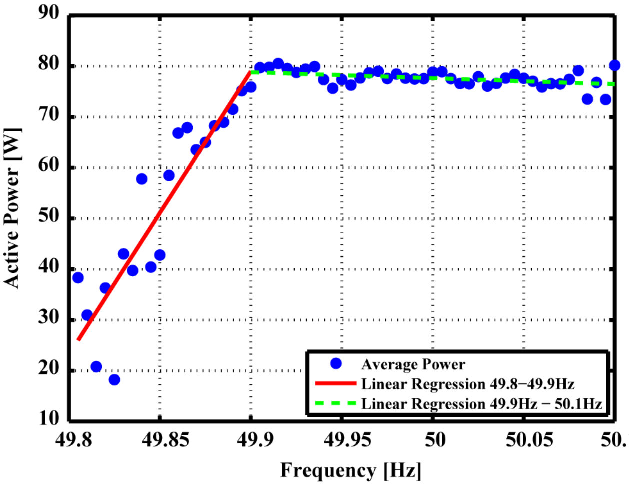

Fig. 9. Frequency response of refrigerators acting as a disturbance reserve, shown with piecewise least squares linear regression in regions above and below 49.90 Hz.

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 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° Hz is lower than in the normal reserve 20° 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

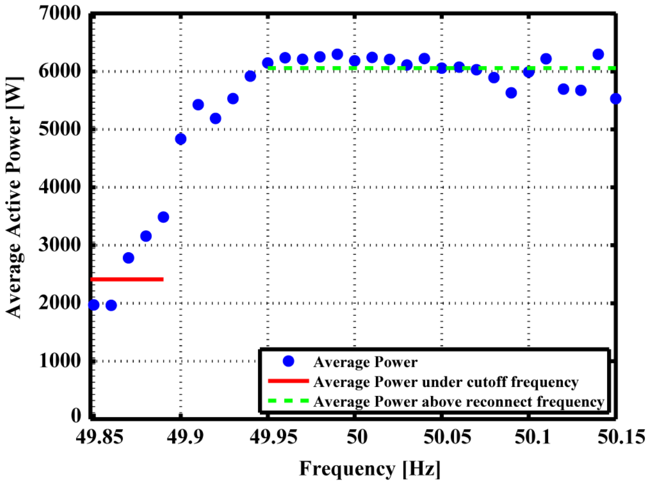

Fig. 10. Frequency response of water treatment plant configured with disconnect frequency 49.90 Hz and reconnect frequency 49.95 Hz. Solid line shows average power consumption below cutoff frequency, dashed line shows average power consumption about reconnect frequency.

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 below the reconnect frequency was 2.41 kW 6.05 kW, compared to an average above the cutoff frequency of 6.05 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].

VI. ACKNOWLEDGEMENTS

Special thanks to C. B. Rasmussen, R. Brus, N. M. Holmboe, and J. Hethey for their contributions.

REFERENCES

[1] Nordel, "System operation agreement," Apr. 27, 2012 [Online]. Available: https://www.entsoe.eu/

[2] Energy Information Administration, "Residential energy consumption survey," U.S. Dept. Energy, Washington, DC, USA, Tech. Rep, 2009.

[3] B. Hassan, *Robust Power System Frequency Control*. New York: Springer, 2009.

[4] Z. Xu, J. Østergaard, and M. Togeby, "Demand as frequency controlled reserve," *IEEE Trans. Power Syst.*, vol. 26, no. 3, pp. 1062–1071, Aug. 2011.

[5] F. Schweppe, R. Tabors, J. Kirtley, H. Outhred, F. Pickel, and A. Cox, "Homeostatic utility control," *IEEE Trans. Power App. Syst.* , vol. PAS-99, no. 3, pp. 1151–1163, May 1980.

[6] J. Short, D. Infield, and L. Freris, "Stabilization of grid frequency through dynamic demand control," *IEEE Trans. Power Syst.* , vol. 22, no. 3, pp. 1284–1293, Aug. 2007.

[7] N. Lu and D. Hammerstrom, "Design considerations for frequency responsive grid friendly(tm) appliances," in *Proc. IEEE PES Transm. Distrib. Conf. Exhib.* , May 2006, pp. 647–652.

[8] A. Molina-Garcia, F. Bouffard, and D. Kirschen, "Decentralized demand-side contribution to primary frequency control," *IEEE Trans. Power Syst.*, vol. 26, no. 1, pp. 411–419, Feb. 2011.

[9] Y. Chen, Z. Xu, and J. Østergaard, "Frequency analysis for planned islanding operation in the Danish distribution system—Bornholm," in *Proc. 43rd Int. Universities Power Eng. Conf. (UPEC)*, Sep. 2008, pp. 1–5.

[10] G. Tarnowski, P. Kjær, J. Østergaard, and P. SØrensen, in *Proc. 9th Int. Workshop Large-Scale Integr. Wind Power into Power Syst.*, 2010.

[11] P. Douglass, R. Garcia-Valle, P. Nyeng, J. Østergaard, and M. Togeby, "Demand as frequency controlled reserve: Implementation and practical demonstration," in *Proc. Innov. Smart Grid Technol.*, Europe, 2011.

[12] Danish Meteorological Institute, Weather Archive, Online Dec. 12, 2012.

[13] Danish Energy Association, Dansk Elforsyning Statistik, 2009.

[14] E-Bridge Analysis & Review of Requirements for Automatic Reserves in the Nordic Synchronous System, tech. Rep 2011.

[15] P. Nyeng, J. Østergaard, M. Togeby, and J. Hethey, "Design and implementation of frequency-responsive thermostat control," in *Proc. 2010 45th Int. Universities Power Eng. Conf. (UPEC)*, pp. 1–6.

[16] K. Burges, P. Zolotarev, and J. Lehner, "Impact of large-scale distributed generation on network stability during over-frequency events & development of mitigation measures," Sep. 2011 [Online]. Available: http://www.vde.com/en/fnn/pages/50-2-hz-study.aspx

[17] Entso-E Draft Demand Connection Codes, 2012.

[18] C. Bang, F. Fock, and M. Togeby, "Design of a real time market for regulating power," EA Energy Analyses, Tech. Rep., 2011.