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].

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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).

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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 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.

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

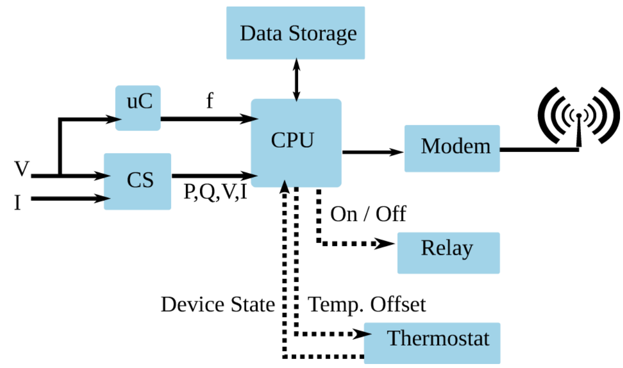

Fig. 1. DFCR block diagram. The CPU is a low cost micro-controller with 8 kB of RAM. The system frequency is measured by a secondary micro-controller (uC). Power consumption (real and reactive) is calculated by a dedicated component (CS). The measurements are buffered to an SD card (Data Storage), and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

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