A dynamically-controlled refrigerator

Results of a preliminary test-run

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Summary

- A refrigerator operating under "dynamic demand control" was found to operate satisfactorily, keeping food cool during hot weather in a busy office.
- The fridge used most power during periods of excess power on the electricity grid, and least power during periods of deficit.
- The relationship between refrigerator power demand and the grid's "AC frequency" was encouraging, indicating that many such appliances acting together could provide valuable balancing services to the National Grid.

Figure 1: Context of the refrigerator under test: the kitchen area of The Hub, a busy 4th-floor shared office in North London.

1 Introduction

Dynamic demand control is a low-cost technology that uses the properties of a specific group of electrical appliances to provide an energy storage system on the electricity grid. Such technology has the potential to replace certain back-up generation, increasing the efficiency of the electricity system and reducing greenhouse gas emissions. It could also smooth out short-term fluctuations caused by variable sources of energy such as wind power.

The technology involves incorporating microcontrollers into appliances so that they are biased to consumer power at times when there is an excess of it on the grid. It works by sensing the "system frequency" of the National Grid which is a direct result of the speed of rotation of all the generators on the system. The frequency fluctuates continuously around the nominal value of 50Hz (50 cycles each second). When demand exceeds supply, generators slow down slightly causing the frequency to fall. Conversely, when there is an excess of supply over demand, the frequency rises.

The frequency can be measured, using simple low-cost electronics, from any power outlet on the grid (i.e. any outlet in the UK). A dynamic controller uses the grid frequency to alter the timing of electricity consumption of time-flexible appliances such as industrial or commercial refrigerators, air conditioners, heat-pumps and water heaters. Such equipment uses power intermittently in "duty cycles", the timing of which can be altered to coincide, whenever possible, with periods of high frequency (i.e. excess generation).

This report outlines the results of a short test of a single fridge-freezer operating under dynamic demand control.

2 Set-up

The refrigerator (a modified Zanussi under-the-counter fridge-freezer) was tested for a 30-hour period. The set-up of the experiment is described in Appendix A. The location is pictured in Figure 1.

Usually, refrigerators operate under thermostatic control, whereby they are switched *on* if temperature rises above the top switching temperature, say T_{high}, and *off* if it falls below T_{low}. (This fridge is controlled using the freezer box temperature, though some use cabinet air temperature.)

Normally the switching temperatures are constant, but under dynamic demand control, T_{high} and T_{low}, are continually modified according to the current grid frequency. If the frequency is high (i.e. there is too much generation) then the switching temperatures are lowered, and vice-versa.

The result is that at times of power shortage (low frequency) a dynamic demand appliance is more likely to be *off*. With many such appliances on the grid, the collective behaviour has been predicted by simulation studies to resist changes in frequency, hence providing stability to the grid. As frequency falls, for example, the switching temperatures will rise. This will cause a progressive shedding of load as the appliances begin switching *off* early (starting with the coolest first) and will help prevent the frequency-fall.

3 Results

Figure 2 shows the internal temperatures (right-hand scale) inside the refrigerator, along with the system frequency (left-hand scale). Shown in grey are the two switching temperatures, which can be seen to vary inversely to the system frequency (shown in red).

As can be seen, the freezer box temperature (blue) “bounces” between the ceiling and floor created by the two switching temperatures. During times of low frequency, the switching temperatures were high. This increased the likelihood that the fridge switched *off* earlier (or remained *off* for longer). Conversely, high frequencies caused the fridge to switch *on* early or stay *on* for longer.

The green line shows the cabinet air temperature. The various sudden increases are caused by the fridge door being opened. The purple line shows the temperature of food inside the freezer. As can be seen, in this test, controlling the refrigerator dynamically has minimal effect on the food temperature.

Some idea of the effect of aggregating many such appliances can be seen by looking at the behaviour of this one appliance over a longer period, covering many different grid frequencies, temperatures and on/off states.

Figure 3 shows that the likelihood of the refrigerator being *on* was very dependent on the frequency of the grid. Each point on the chart represents all the times when the grid frequency was at or near a certain value (shown by the point’s position on the x-axis). A point’s height shows how often the fridge was *on* during those times. It is evident that the fridge preferred to be *off* when the grid frequency was low.

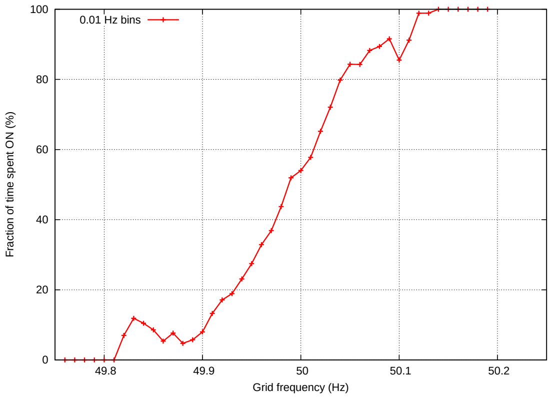

Figure 3: Demand-frequency dependence for a refrigerator under dynamic demand control for a 30 hour period. The chart shows that the fridge used most power during times of high grid frequency, i.e. during times of excess power on the grid.

Figure 3 also indicates how an aggregation of many such appliances might behave, with the left axis showing the percentage of appliances that would be *on* (hence the total refrigeration demand) for any particular grid frequency.

Clearly this assumes that the devices act independently of each other and do not become synchronised, or ‘clumped’ by the continually changing frequency. (Although this assumption is backed up by a separate simulation study conducted by Dynamic Demand, we recommend that a pilot involving a large number of devices be carried out to test that it holds in practice.)

As might be expected, there was a strong inverse relationship between freezer box temperature and grid frequency. Figure 4 shows that during low frequency periods, the temperature was, on average, higher than normal.

Figure 5 shows the distribution of grid frequencies measured throughout the test. During this period, the average (mean) frequency was found to be slightly lower than nominal. Frequency excursions below 49.85 Hz or above 50.15 Hz were extremely rare.

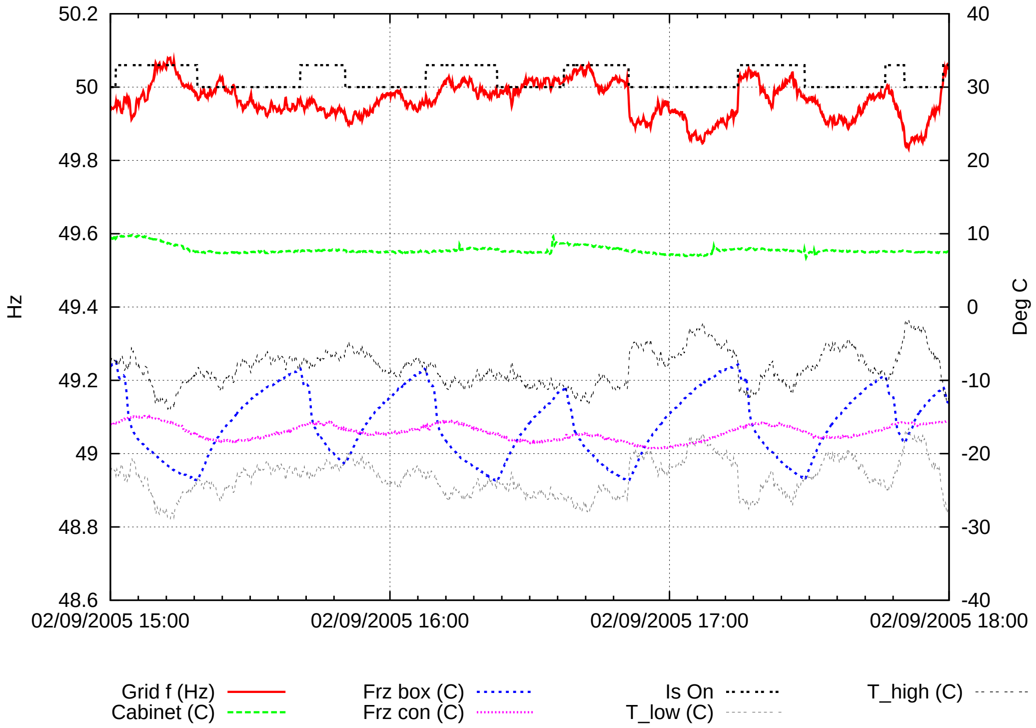

Figure 2: Grid frequency (left axis) and temperatures (right axis) as measured for a fridge running under dynamic demand control for a three hour period. Because the switching temperatures vary with grid frequency, the fridge tends to avoid using power during periods of low grid frequency, i.e. periods of generation deficit.

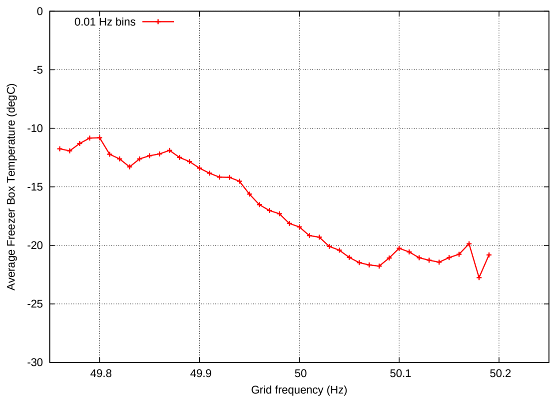

Figure 4: Relationship between average freezer box temperature and grid frequency. As expected, the fridge tended to be warmer when the grid is short of power.

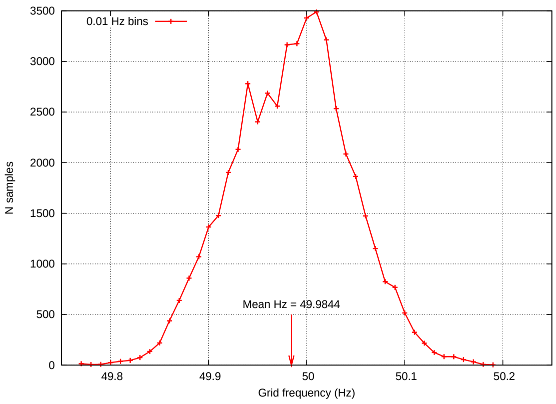

Figure 5: Distribution of grid frequency for a 30 hour period starting 31/08/2005 18:54:00. The mean frequency was slightly lower than nominal.

4 Conclusion

During this limited test, no adverse affects on the normal operation of the refrigerator were found. Despite regular opening of the door, and high ambient temperatures, the refrigerator operated satisfactorily under dynamic demand control.

The test showed that during low-frequency periods, i.e. during periods of power shortage on the grid, the refrigerator was more likely to be *off*. In fact, there was a positive near-linear relationship between the likelihood of being *on* and the grid frequency. This is encouraging as it indicates that the aggregated demand of many such devices acting together would also vary positively with frequency. This is necessary if many such devices are to be used to provide balancing services to the National Grid.

A pilot study using many such appliances is recommended in order to test the assumption that the temperatures and on/off states do not become synchronised over time.

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Appendices

A Methodology

A.1 Measurement

A typical under-the-counter fridge-freezer (Zanussi) was tested for how it performs under dynamic demand control. The refrigerator was in a busy shared office environment (The Hub in Islington, North London) and was under normal use throughout the test.

Thermocouples were used to measure three separate temperatures inside the refrigerator:

1. The freezer box (placed in direct contact with the metal base of the box and insulated from above using foam)
2. The freezer contents (inside a plastic cup of ice sitting on the base of the freezer box)
3. The air temperature (towards the top of the main fridge compartment).

The temperatures, accurate to within $\pm 2^o$C, were smoothed using a moving average over 200 samples and stored every 5 seconds.

An industrial transducer was used to measure the frequency of the mains.

The connection between the thermostat and the compressor was broken and a relay used to control the compressor directly.

All signals were connected to a PC via a standard interface board.

A.2 Control

The control algorithm involved altering the top and bottom switching temperatures (T_{high} and T_{low}) according to the current excursion in mains frequency, ΔF. So that:

$$T'_{high} = T_{high} - k\Delta F \tag{1}$$

and

$$T'_{low} = T_{low} - k\Delta F \tag{2}$$

Where k is a constant (50 $^oC/Hz$ in this test) that can be changed to control the sensitivity to changes in mains frequency.