Dynamic Ancillary Service Provided By Loads With Inherent Energy Storage

Katie Bloor[(1)], Andrew Howe[(1)], Alessandra Suardi[(2)], Stefano Frattesi[(2)]

RLtec[(1)]

75-76 Shoe Lane, London EC4A 3BQ, UK

katie.bloor@rltec.com, andrew.howe@rltec.com.

Indesit Company[(2)]

Viale A. Merloni 47 - 60044 Fabriano (AN), Italy

alessandra.suardi@indesit.com, stefano.frattesi@indesit.com

Keywords: Dynamic Demand; Demand-side management (DSM); Frequency regulation; Demand response

Abstract

Electrical load devices with inherent energy storage can be used to provide a loss-less energy storage service to an electricity grid without any noticeable effect to the load owner. Populations of such loads can autonomously provide distributed response regulation, displacing large generation regulation services. This leads to a significant saving in emissions (including CO_2) in the electricity supply industry.

The authors have run a laboratory trial of refrigerators, where the refrigerator's electronic control board has been modified to provide the autonomous "Energy Balancing Controller" (EBC) function. The laboratory test rig allows the grid service response level to be determined, mirroring standard practice in the UK for large generator set response (regulation service) testing.

In a field-scale deployment of EBC-enabled refrigerators, examples of grid Smart Appliances, the authors have designed an instrumentation system interfacing smart appliances with an in-line home energy monitor device, and connecting to a central data server. The server provides real-time monitoring of the grid response (ancillary) service by collecting certain physical variables measured in each individual Smart Appliance.

This paper describes the methodology of the laboratory trials and presents results on the response service provided by the laboratory refrigerators, together with early data and forecasts for the response service expected from field tested appliances. Early information on the carbon savings potential and field measurement methodology will be presented. Indesit Company, the 2nd largest household appliance manufacturer in Europe, is RLtec's development partner and will provide the refrigerators implementing this innovative control technique for the field trial.

1. BACKGROUND

1.1. UK Grid

1.1.1. System Operation of the UK Grid

The UK Grid is operated differently to those in the US and Europe and in the UK there are no area balancing requirements. The UK System Operator, National Grid plc, provides a monopoly system operation service, which is operated under a license from the government regulator (Ofgem). Globally, grid System Operators, whether independent ISOs or otherwise, face the requirement to ensure a net balances in energy, second by second. This typically requires large generation assets to change their electrical output in response to load changes. Electricity cannot be easily stored on the electricity grid and production and consumption must remain matched.

The System Operator is required to control the generation fleet, usually with a suite of energy balancing services that are designed to maintain energy balance and security of supply. Major black-out events, which do occur both in US, Europe and UK, inevitably result from loss of control of energy balance, usually leading to mandatory load shedding (aka black-outs). Geographically the terminology and specification of these grid energy balancing services vary. The physics behind grids is universal although grid scale in total MW consumed and generation set size does influence grid operational characteristics.

Grid energy balancing services can be segmented by the time taken to respond: response time. This is illustrated in Figure 1. With energy balancing services, there is no difference between decreasing load and increasing generation; load may therefore participate in providing balancing services.

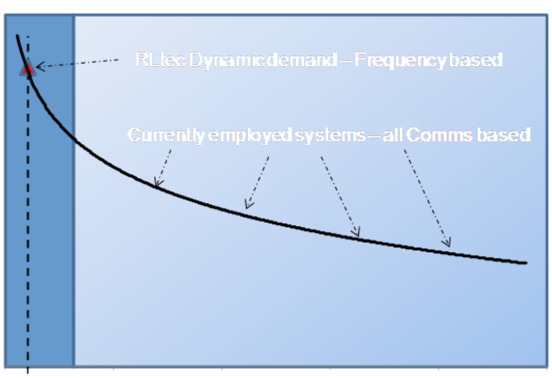


Figure 1.

1.1.2. UK Grid Services

In the UK, National Grid purchases a variety of energy balancing services from suppliers, usually generation owners, but also load and generation aggregators. These services allow National Grid to operate the UK grid to the specified requirements: (1) specified fault tolerance conditions; (2) maintain frequency within specified tolerances and (3) high availability requirements. The balancing services are categorized by the time to respond as given in Table 1.

Table 1.

Service	Time to respond	Hold
Primary	2 seconds	30 seconds
Secondary	30 seconds	30 minutes
Tertiary	As required	As required

The primary based service is today provided by operating generation plant partially loaded and with the generator set electrical output depending on the instantaneous grid frequency and under "throttle control" with a closed loop control system. Primary service provides an "insurance" against fault conditions such as plant failures and transmission line disconnects. In the US, this is referred to as regulation service. There is a requirement to both increase and decrease the generation plant output with regulating services. Operation of thermal generation plant in such regulation modes leads to loss of thermal plant efficiency.

Secondary service provides to restore the primary regulation service back to its set-point, while net energy increase or decrease can be dispatched from the remainder of the generation fleet. The System Operator is continually monitoring and changing the generation fleet configuration to maintain the grid operation to specified requirements while minimizing the balancing costs charged to the consumer.

1.1.3. Short Term Energy Storage Versus Renewable Integration

In de-carbonizing electricity generation and reducing dependence on imported primary fuels, governments provide incentives for the deployment of renewable generation resources such as wind, solar and wave generation. Unlike conventional plants, renewable generation output is less controllable, and predictable, and its use requires that higher volumes of energy balancing services are available to maintain grid operation within the specified parameters.

Many groups are computing the scenarios for high volumes of renewable (usually wind) generation introduced on the grid. One study from SKM[1] commissioned by the UK Government indicates that the cost of energy balancing services will increase by a factor greater than five as more volume is required.

This increase in total volume of energy balancing service is one part of the Smart Grid campaign. These services will come from several technology sources which include those seen in Table 2.

Table 2.

Technology	Service	Comment
Conventional generation plant	Primary, secondary and tertiary.	Traditional.
Demand Response	Load shedding, turning down or off service is response to dispatch requests.	Requires communications, peak shaving technique, affects the end user. Typically secondary low side response
Energy Storage	A grid capacitor / battery consuming power at times of excess generation and providing energy at times of grid stress	Pumped hydro storage is common solution, high capital cost / kW. Round trip energy losses. Carbon may be used to pump water or cause energy to be stored. Flywheels, compressed air, batteries etc. being trialed. Primary and secondary response.
Dynamic Demand	Short to medium term energy balancing provided by loads	Load side service, low capital cost, can both increase and decrease consumption with no detriment to load operation. Carbonless. Primary and secondary.

1.2. Dynamic Demand

National Grid distinguishes between "static" and "dynamic" balancing services; also demand and supply (generation) sources. Static refers to on / off services such as demand response, while generation throttle controlled service is dynamic and proportional to the grid frequency. Dynamic demand is therefore a frequency (or AGC[2]) dependent service provided by loads. The instantaneous consumption of a *population* of loads can be configured to vary and depend on the instantaneous value of grid frequency, providing a bi-directional (regulated up and down) modulated service identical to AGC or throttle controlled generation.

By using the inherent energy that may be stored in loads, for example refrigeration loads, hot water, heat pumps and water tanks, it is possible to use (or not use) the stored work to provide a grid-based loss-less, carbon free, autonomous, primary energy balancing service. Further it is possible to ensure that the load is operated inside its normal operational parameters so that there is no noticeable detriment to the end use service.

The UK Government has written two reports[3] on dynamic demand which describe the features and benefits of this service to the UK Grid and identify the potential to save approximately 2% of the carbon emissions associated with the UK generation fleet.

The following illustrates how the work stored in a load may be used to provide an energy balancing service and is a simplified description referring to refrigeration.

Refrigerator devices have a duty ratio and typically cycle temperature during cooling (uses electricity to run the compressor) and warming (compressor motor is off). Assuming the duty ratio is 20%, then across an example population of 1,000,000 fridges, at any one time, 200,000 will have compressors running and 800,000 will be off and warming. The work stored is reflected in both fridge temperature and compressed coolant liquid volume.

By arranging for proportionally more fridges to switch off as grid frequency reduces, until at the lowest grid frequency ALL available fridges are turned off; and vice versa. It then becomes possible for a population of refrigerators to provide a "modulated" (i.e. service magnitude depends on frequency excursion) and bi-directional service. See Figure 2.

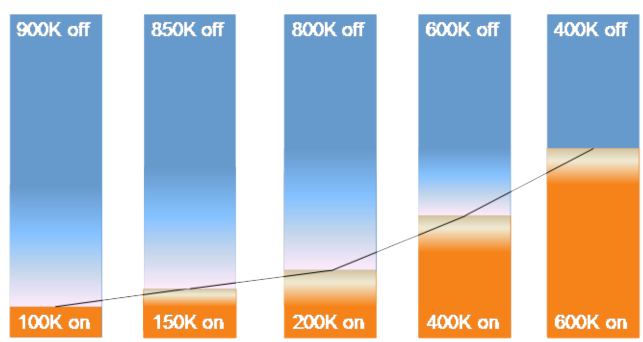


Figure 2.

[1] SKM
[2] AGC = automatic generation control
[3] Reports 1 and 2

The average net temperature of the population depends on the total energy state of the population and clearly it is possible to deplete the total energy storage or – alternatively - fully charge it. The population acts as a grid battery; however, it is lossless.
Energy storage characteristics depend on the load type. For example refrigerators have short (tens of minutes) of energy storage, while freezers have longer storage times. Similarly, buildings display considerable thermal inertia (large energy time constant).

1.3. Measurement and Validation of Response-Regulation

The dynamic demand service comprises a population of autonomous independent and distributed loads. In the UK the service can be delivered based on grid frequency measured at the load point and hence no communications are necessary to provide the service. This has useful implications regarding cyber security, fault tolerance and self-healing properties on the grid, as well as cost.

1.4. Carbon Saving

In providing fast response (regulation) services to the grid, a large generation plant is operated below peak thermal capacity. By removing the requirement for this plant to provide regulation, it is possible to improve the operational efficiency of the "grid machine". DOE commissioned a report[4] by Kema showing the emission reductions obtained by replacing large plant regulation service by flywheel based energy storage systems. Similar UK studies[5] indicate that using load side response services will reduce the total stack CO_2 emissions of the generation fleet by some 2,000,000 tons annually (in the region of 2%).

1.5. US Grid

The US Grid(s) operate using automatic generation control (AGC). This provides for energy balancing to be accomplished within a geographical area and avoids some problems with transmission constraints / overload across area borders. While a plant failure will instantaneously reconfigure transmission energy flows, the AGC signal strives to re-balance the energy within the area and maintain the cross area border energy flows.
Examination of the AGC signal from PJM's territory shows the strong correlation of the AGC signal and grid frequency. While the grid frequency is identical across a synchronous grid (excepting instantaneous phase) and an energy balancing service can be provided, in the US it may be necessary to provide area balancing control.

[4] DOE Beacon Emission Report
[5] Second DECC DD Report

2. OVERVIEW AND INTRODUCTION

2.1. Overview

In this paper the authors show results from RLtec's patented dynamic demand control algorithm "RL++", implemented in domestic refrigeration via the Energy Balancing Controller (EBC). RL++ is a development of the original FAPER[6] control algorithm and incorporates a probabilistic approach to the response triggering mechanism. For proprietary reasons full details of the algorithm are not given here.
The paper is divided into three parts. In the first, an approach to measuring response-regulation performance of an individual appliance is introduced, based on results from simulating the behavior of large-scale fridge populations and generator-style tests of response performance. In the second, first laboratory results and performance indicators from a real fridge-freezer implementation of the controller are shown. In the third part a prototype device and data system developed by the authors for field trial studies of such 'smart appliances' is described.

2.2. Introduction

An issue in providing dynamic demand from small-load appliances is the value attendant in such a process. A natural question concerns how two similar appliances compare in the response-regulation service offered by populations, and how such a comparison may be made. The UK grid operator, National Grid, has defined a test protocol for generators which may be applied to laboratory-scale (but "large enough") populations of frequency response-enabled appliances, and measures expected population performance under a range of frequency inputs. Laboratory requirements for this process of testing are extensive.
In simulation work with refrigerators, the authors introduce the concept of a per-unit "response capacity" rating, simply obtained from fridge cycle data under normal operation, and demonstrate that it corresponds to the expected population response in laboratory testing designed for generator assessment. The novelty of the work here is to examine how a response regulation service provided by a population may be quantified by examining the thermal behaviors of a single device. Projected results on how the response capacity is altered by day-to-day variation of grid frequency (a "lab-to-field factor") are given.
The authors have successfully implemented dynamic demand in a popular fridge-freezer model currently on sale in the UK and are working with the UK grid operator to bring the technology into the response regulation market. In

[6] Schweppe, F.C., Tabors, R.D., Kirtley, J.L.,Outhred, H.R., Pickel, F.H., Cox, A.J., "Homeostatic Utility Control", *IEEE Transactions on Power Apparatus and Systems*, vol PAS-99, no.3, pp 1151-1163, May 1980

implementing the technology in a real fridge controller (the Energy Balancing Controller, or EBC), initial measurements of the response capacity are reported, and implementation issues discussed. Further results in this direction are planned in a large-scale field trial of domestic refrigerators in the UK.

A challenge in conducting field trials for smart appliances is the requirement for a communications interface to the appliance, and for an extensive data network. Any communications interface should be CE-approved and relevant service data should be taken unobtrusively from the home, without interfering with normal usage patterns. The authors describe their development of a unique monitoring product and data collection service for the purpose of trialing smart grid appliances.

3. A SIMPLE FRIDGE MODEL

RLtec's dynamic demand controller (DDC) is modeled in a static, two-compressor fridge-freezer implementation. This is the simplest implementation of the technology and provides a solid starting point for an investigation into service provision from domestic refrigeration. Two outcomes of the modeling work are

- characterization of fridge population load response to standardized UK grid library "events" in the same style as for generators
- identification of individual fridge time constants for a-priori "name-plate response capacity".

3.1. Fridge Model Description

The cooler and the freezer are each modeled as two thermal blocks, with heat extracted from the evaporator block when the compressor is on. There is thermal contact between the evaporator block and the cavity block; and between the cavity block and ambient surrounding. Any heat transfer from the cavity takes place by conduction to and from the evaporator and ambient surroundings.

Control of the cavity temperatures (cooler and freezer) is performed by a hysteresis loop associated with each compressor. For the cooler and for the freezer there are therefore two threshold temperatures: cut-in > cut-out; the difference between cut-in – cut-out is 1˚C. See Figures 3 and 4 for model output.

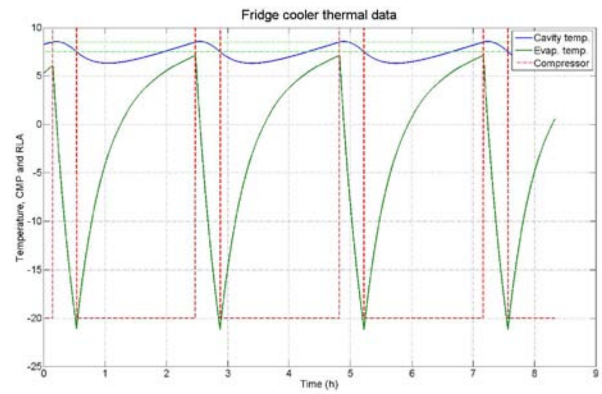


Figure 3. Thermal model of temperature curves for fridge cooler cavity and evaporator box.

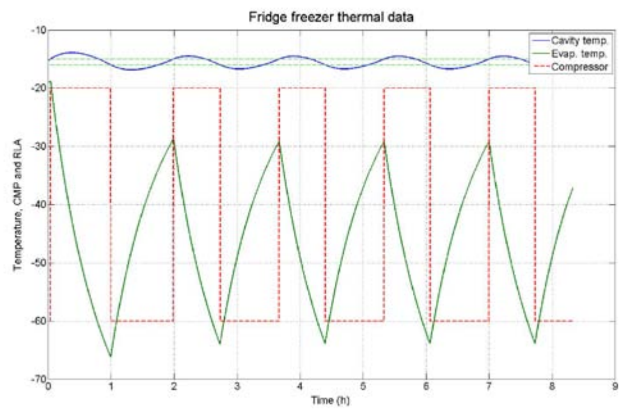


Figure 4. Thermal model of temperature curves for fridge freezer cavity and evaporator box.

3.2. Dynamic Demand Control

RLtec's implementation of dynamic demand, the Energy Balancing Controller (EBC), features a control algorithm, RL++, designed to work alongside the existing fridge controller, providing as output a *switch recommendation* to the controller when the grid demands it. The switch recommendation is the output of a logic which compares grid frequency to an internal, dynamically-defined *trigger frequency*; it is a Boolean variable which requests (or not) a change of state in the compressor: from on to off, or off to on. If grid frequency exceeds the trigger-on frequency of any fridge that is off, or – conversely - if grid frequency falls below the trigger-off frequency of any fridge that is on, the RL++ control will recommend a change of compressor state. Trigger frequencies are spread in a range around the nominal frequency of the grid (50 Hz in the UK) and are defined by a probability density over the range of definition. An illustration of the interaction is given in Figure 3.2. The algorithm receives as input the instantaneous grid frequency in Hz; the current compressor state of the fridge and the % responsive load availability, RLA.

In the model the control algorithm is represented by a Simulink block, where frequency input is a user-defined workspace variable. Its output switch recommendation is fed directly to the existing compressor control from the previous section.

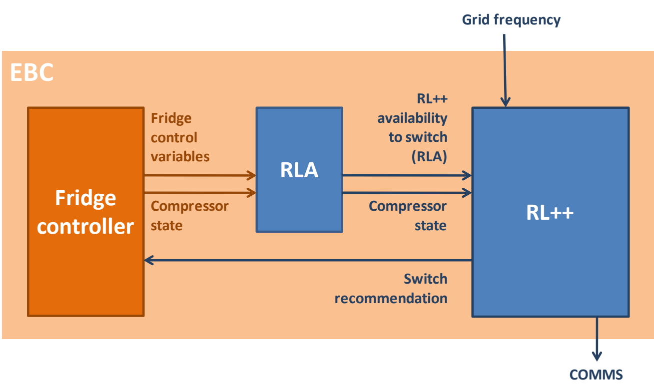


Figure 5. The Energy Balancing Controller (EBC) as an interaction between fridge thermostat control and responsive load algorithm RL++.

3.3. Responsive Load Availability (RLA)

The DDC algorithm receives a signal from the fridge indicating its percentage willingness to switch: the responsive load availability, (RLA). If the fridge is warm, the compressor is unwilling to switch off but very willing to switch on, although only one 'willingness' is relevant, depending on the state of the compressor.

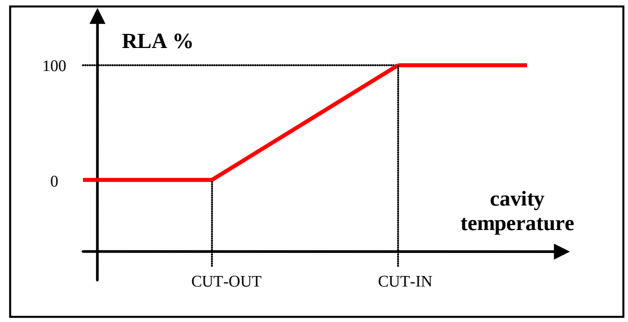


Figure 6. Responsive Load Availability calculated from temperature in hysteresis control.

In the example of the simple hysteresis control loop, the fridge cooler / freezer RLA is given by a linear interpolation of the cavity temperature between its cut-in and cut-out thresholds.

In this implementation the meaning of the RLA % reverses orientation when the compressor is on:

RLA_ON	=	RLA	when CMP = 0
	=	0	otherwise.
RLA_OFF	=	1 – RLA	when CMP = 1
	=	0	otherwise.

The availability signal is designed so that there is no contradiction between DDC switch recommendations and the fridge temperature protection: where there is zero availability to switch, no recommendation to change compressor state is made.

4. MEASURING RESPONSE IN FRIDGE POPULATIONS

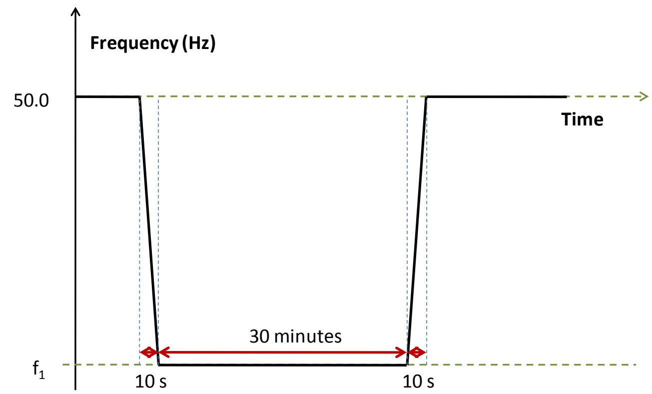
The behavior of a population is obtained in simulation by running many individuals in parallel, subject to the same frequency input. The aggregate total load is summed in output. The model is “open loop”: the assumption is that the number of fridges is small enough for the effect of fridge load variation on the grid frequency signal itself to be negligible; this form of model is also more suited for generator testing methods and for calibration against fridge laboratory population data.

4.1. UK Grid Frequency Injection Tests for Generators

The UK grid operator, National Grid, has defined a series of standard frequency inputs for the purpose of generator testing. The frequency inputs are designed to test the *speed* and *duration* of response regulation service provided, as well as the *absolute amount* (in kW) delivered over the period of regulation. An ideal response regulation “engine” will start responding to frequency events within 2 seconds, attain maximum response provision within 10 seconds and maintain the response provision (in decrease or increase of generation / load) for 30 minutes. Treating fridge populations as generators, response capabilities are assessed by examining total fridge load responding to grid frequency; the sign of the power-to-frequency relationship is inverted to reflect the demand vs supply nature of service provision.

4.1.1. Generator Tests and Response Matrix

Frequency input profiles are as shown in Figure 7.



f_1 (Hz)
50 ± 0.5
50 ± 0.4
50 ± 0.3
50 ± 0.2

Figure 7. Frequency input profiles for generator response testing.

Change in population load is measured from time zero – the instant the frequency begins to move away from 50 Hz.

4.1.2. Maximum High Regulation

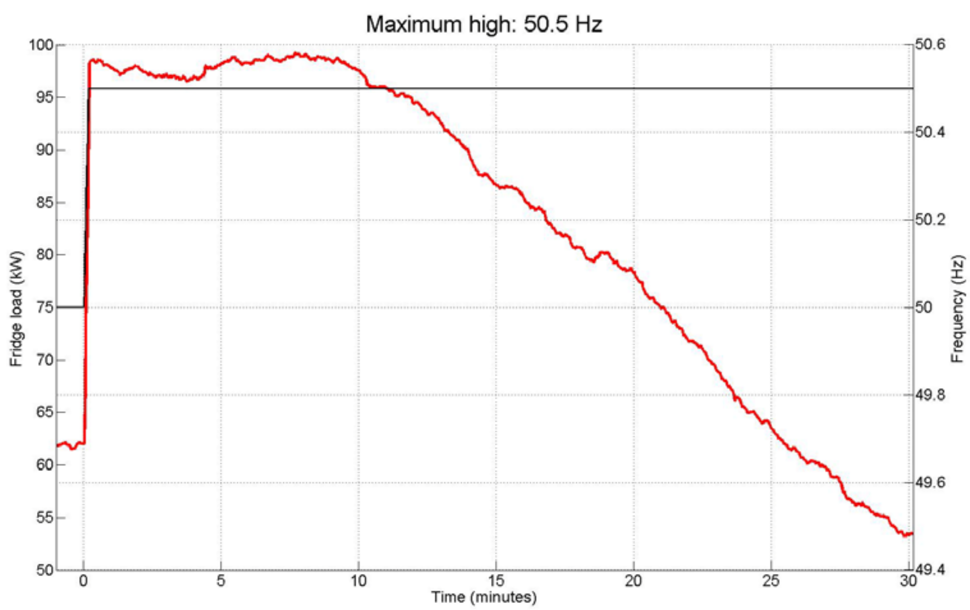


Figure 8(a). Maximum high regulation.

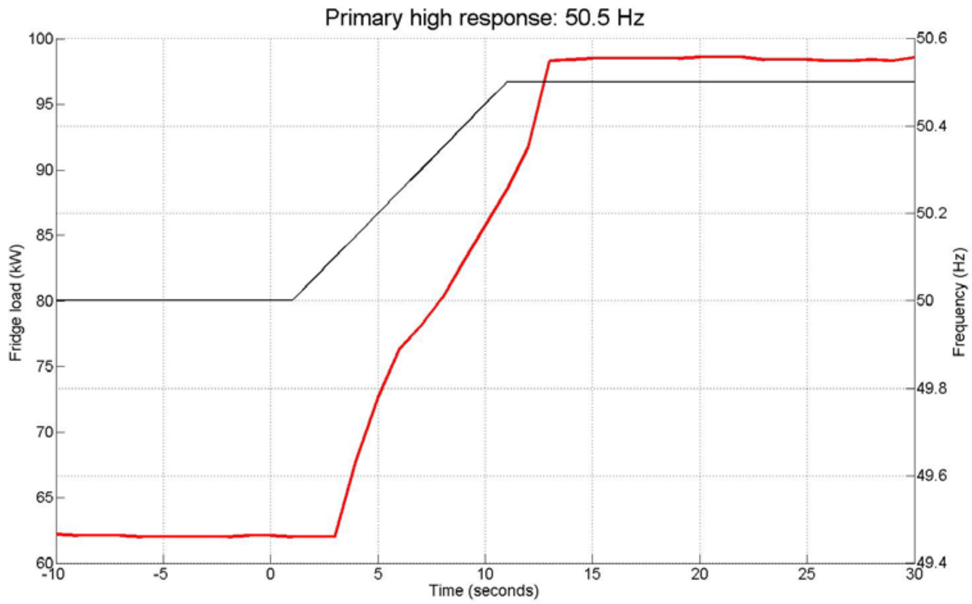


Figure 8(b). Maximum high regulation.

4.1.3. Maximum Low Regulation

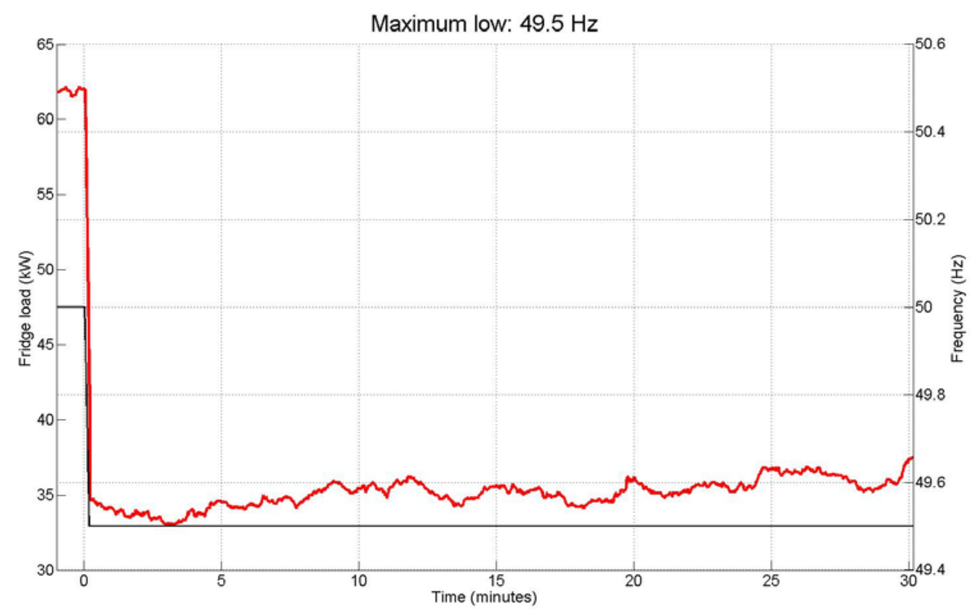


Figure 9(a). Maximum low regulation.

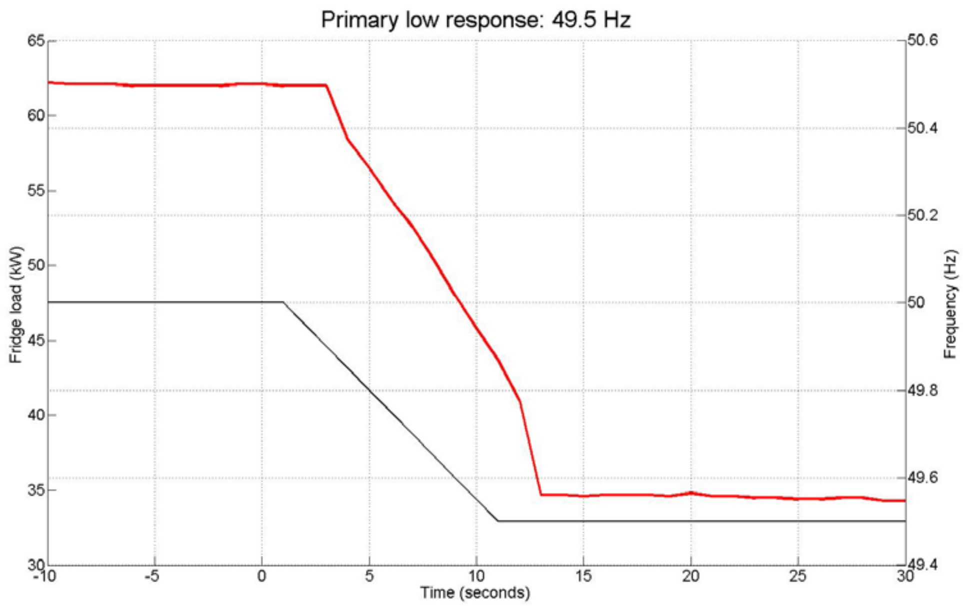


Figure 9(b). Maximum low regulation.

4.2. Forty-year "Worst Case"

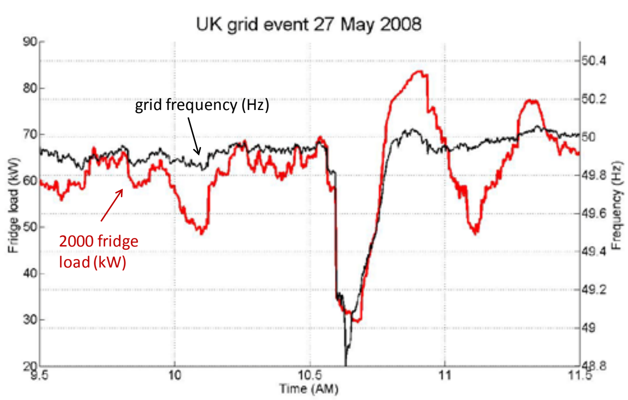


Figure 10. Response regulation provided by 2,000 fridges, simulated against a worst case

The frequency injection profiles defined as test cases by National Grid are zero probability events on the grid. A theoretical fridge response to the worst case in forty years of UK grid operation is attached.

2000 fridge-freezers with two 50kW compressors are modeled with inertial temperature dynamic (much of the temperature cycle is outside of the 'available' range) provide a proportionate response, dropping from a characteristic population load level of around 60 kW to a level of 30kW: approximately half of the fridges that are on are available to switch off, or 15% of the total population. This is in line with the results seen in the generator testing profiles, where approximately 13-14% respond (see Figure 9).

Note that fridges are modeled in an "open-loop" situation. The algorithm is designed to recover energy once the grid frequency is within limits. Any energy storage system (including batteries) is required to recover its net energy position. Closed loop grid modeling with National Grid is in progress.

5. RESPONSE CAPACITY IN A SINGLE FRIDGE

To assess the response regulation provided by any given brand of fridges using the standard generator testing procedure outlined in 4.1., it is necessary first of all to work with a manufacturer to implement the technology in a lab-scale population of production-line refrigerators; to isolate the fridge population from the mains and supply power via a frequency inverter or otherwise simulate the frequency that the lab population receives as input 'grid frequency'; finally to measure power on the circuit over standardized frequency injection profiles in order to generate results as shown in simulation in Figures 4.1.2 (a) – (d).

Here a simple method of examining the thermal characteristics of operation for a single fridge is proposed as an alternative way to measure response. The method is valid for response estimation under identical lab test conditions as the generator tests: i.e. the test frequency 'event' follows a period of operation at nominal frequency where fridges are cycling normally, and requires the same level of lab-testing as a standard energy efficiency rating.

The statistical properties of the RLA 'availability' signal calculated from temperature data are characterized to obtain a *response capacity* rating. It will be shown that, via a linear response model, the response capacity rating is a per-fridge equivalent of the generator tests described above. A-priori response capacity estimation is particularly useful for manufacturers, as an assessment may be carried out and a relative value attached before the main work of implementation.

5.1. Availability Time Averages and Response Capacity

Each load-bearing device fitted with RLtec's dynamic demand control technology, RL++, reports a load availability signal, RLA, to the RL++ controller. The RLA signal is a percentage value and indicates the willingness to switch on/off of the device, as described in 3.2.1. In general, a device will have an ON period followed by an OFF period as part of its normal operation. For some part of the ON period the device will be willing / available to switch OFF. Conversely, for some part of the OFF period, the device will be available to switch ON. For a static fridge controlled by a hysteresis over temperature thresholds a typical RLA signal is as given below.

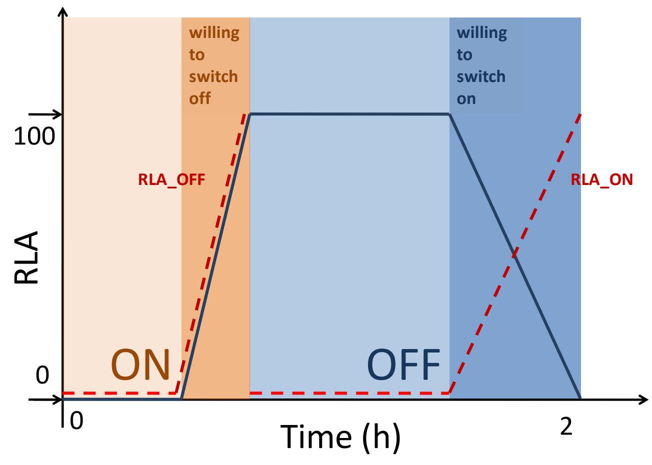


Figure 11. Responsive Load Availability.

From the RLA signal the following two time average quantities are defined:

Proportion of time available to switch ON	$\alpha = \frac{TIME(compressorOFF \ \& \ RLA\_ON > 0)}{TIME(compressorOFF + compressorON)}$
Proportion of time available to switch OFF	$\beta = \frac{TIME(compressorON \ \& \ RLA\_OFF > 0)}{TIME(compressorOFF + compressorON)}$

With the ergodic assumption that the fridge population is spread uniformly throughout possible temperature states, the available proportions will determine the expected maximum response regulation provision in a population of fridges. Assuming that the fridge has an average load rating of X Watts, define the *maximum response capacity*, $\mathbf{RCAP_{HIGH/LOW}}$, for a single fridge as the expected change in power consumption, measured in Watts, due to high or low frequency response regulation:

$RCAP_{HIGH} = \alpha X$ Watts
$RCAP_{LOW} = \beta X$ Watts.

Over a population of N fridges, the maximum expected high (low) response, $R^{HIGH}{}_{max}(N)$ ($R^{LOW}{}_{max}(N)$), when grid frequency moves from nominal to the upper (respectively lower) limit of the trigger frequency range, is given by

$R^{HIGH}{}_{max}(N) = RCAP_{HIGH} N$ Watts
$R^{LOW}{}_{max}(N) = RCAP_{LOW} N$ Watts.

Under standardized environmental conditions (in the lack of any other environmental perturbation, α and β will depend on ambient temperature and the thermal mass of fridge contents) $RCAP_{HIGH/LOW}$ can serve as nameplate response regulation ratings.

5.2. RL++ Linear Response Model

For frequency events of intermediate size, the response of the N-fridge population is given proportionately from the maximum expected response defined in the previous section.

E.g. if trigger-frequencies are spread ±0.5 Hz (above and below nominal), and $|\Delta f| \leq 0.5$, the expected response of the population is given as follows:

$$R^{HIGH}{}_{\Delta f}(N) = R^{HIGH}{}_{max}(N)\ \ (\Delta f / 0.5)$$
$$R^{LOW}{}_{\Delta f}(N) = R^{LOW}{}_{max}(N)\ \ (|\Delta f| / 0.5).$$

The fridge model detailed in Section 4. is run for a single fridge at an ambient temperature setting of 21˚C (as an assumed average UK room temperature) to estimate response capacities α and β. The linear model of response is shown in Figure 5.2.1. Against the linear model, simulated response is shown for a population of 1000 fridge-freezers.

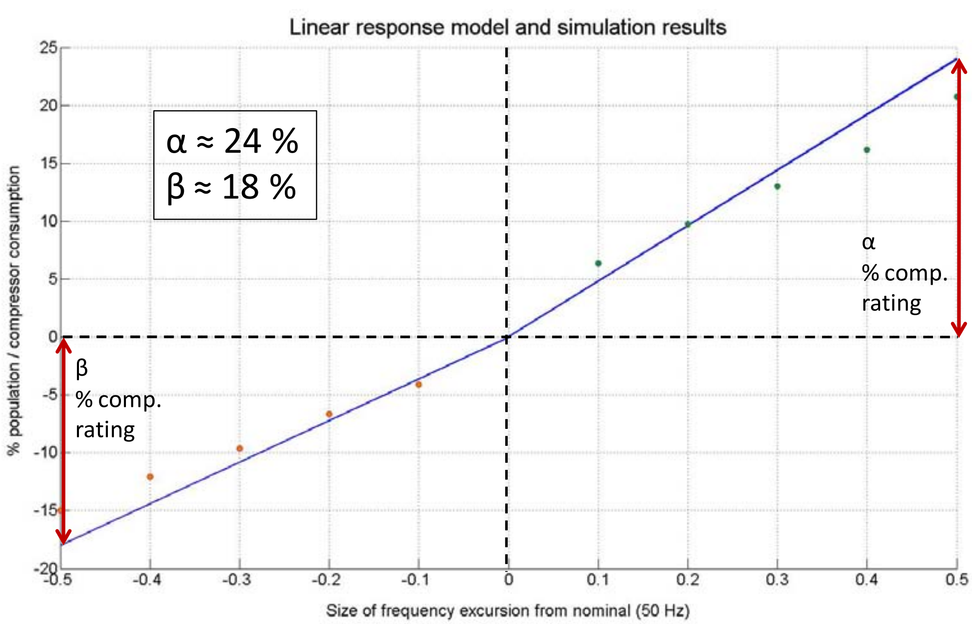


Figure 12. Linear model of response regulation.

6. UK MARKET FRIDGE

Indesit is the market leader in supplying fridges in the UK, with a share of 37% at Q2/2009 (GSK source). They are supplying RLtec with frost free fridges implementing the EBC controller. The fridge is fitted with an enhanced controller board which has been engineered to allow measurement of grid frequency to better than 1 mHz resolution; the EBC function is programmed into the existing firmware. The appliance is fully approved and qualified with CE marking and is manufactured alongside normal appliances in the Indesit manufacturing plant.

A "frost free" refrigerator is composed of 2 cavities (fridge and freezer) and its main components are:

- an on/off compressor and evaporator which represent the thermodynamic circuit;
- a fan blowing air from evaporator both to fridge and freezer cavities;
- a damper, i.e. a valve controlling air flow to the fridge cavity;
- a heater to defrost the evaporator as soon as the frost amount becomes critical for cooling efficiency.

This kind of machine has improved performance in terms of food quality, preservation and energy efficiency but - from the technical point of view of this project - they are more complex: the freezer is coupled with the fridge and a single compressor is used to reach two independent temperature targets.

The responsive load availability (RLA) signal in the case of the simply-modeled, single compressor-single cavity fridge described in the last section is computed as a percentage of probe temperature between the extreme limits given by the thermostatic thresholds. For this reason it can be interpreted as a measure of the thermodynamic state and used as an estimator of the availability of the fridge to switch on or off the compressor.

In the case of the real, no-frost appliance, the overall principle is still valid. Nevertheless, specific design has been provided to cope with coupling effects between fridge and freezer cavities which prevent the single compressor-single cavity relationship to be always true. Questions like: which temperature represents the current thermal state of the frost free appliance? is it always true that maximum temperature corresponds to a reasonable availability to switch on the compressor? are rising temperatures always connected with compressor off states? Many others have also been faced and addressed during the design, additionally taking into account the two main control modes of the appliance (Eco and Normal); and setting up logic for enabling dynamic demand control while ensuring correct thermostatic behavior of the fridge.

6.1. Lab Set-Up

The algorithm has been designed and tested experimentally both during the control logic design phase by means of an Hardware In the Loop (HIL) architecture and during the firmware design and validation by the A.I.D.A. Indesit software tool.

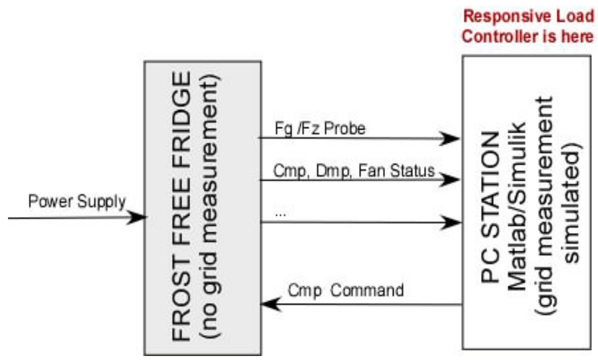


Figure 13(a). HIL set-up schematic.

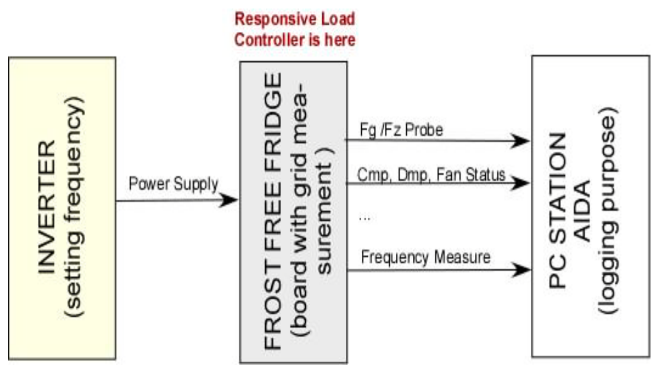


Figure 13(b). AIDA set-up.

The Hardware In the Loop architecture (see Figure 13(a)) has been set up by interfacing a PC to a standard fridge power control board via Indesit communication dlls. The fridge in this case has been powered by grid and the frequency patterns have been simulated. A Matlab/Simulink control algorithm implementation running on the PC reads the temperatures for both fridge and freezer cavities, the loads status (compressor, fan, dampers, heaters) along with other needed variables (like door status). It then computes the responsive load availability (RLA) and the requests to switch ON/OFF the compressor and actuates them according to the main thermostatic control algorithm too.

Once the new power board with the frequency measurement circuit and EBC have been designed, the A.I.D.A. Indesit software tool (see Figure 13(b)) has been used to log data useful for response analysis. An inverter has been used in order set the prefixed frequency patterns power supply to the fridge.

During tests performed in both set-ups, RLA computation has been tested and fridge response analysis has been addressed in several environmental conditions. In order to analyze responsiveness, a baseline at 50.000Hz has been used with 5 minutes injections at 49.500 Hz (LF injection) and 50.500 Hz (HF injection).

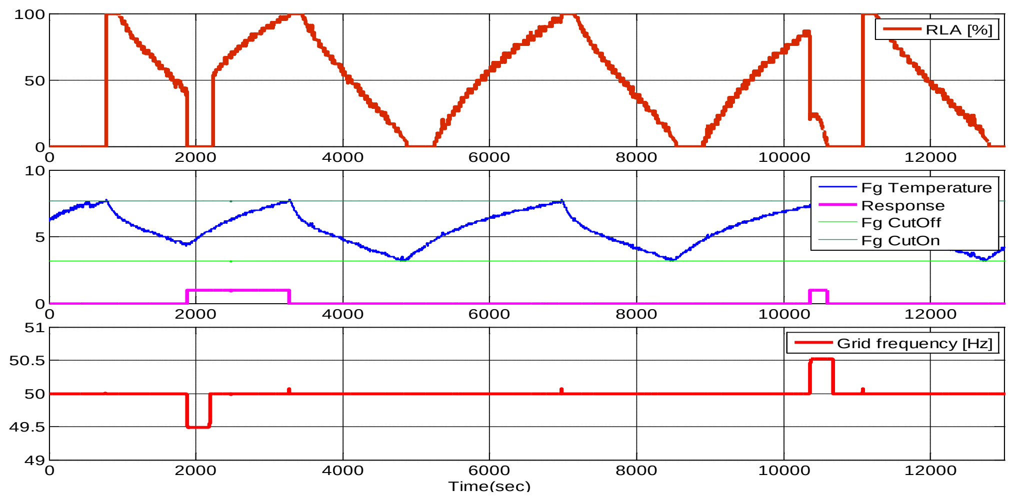


Figure 14(a). Response over cooling phase.

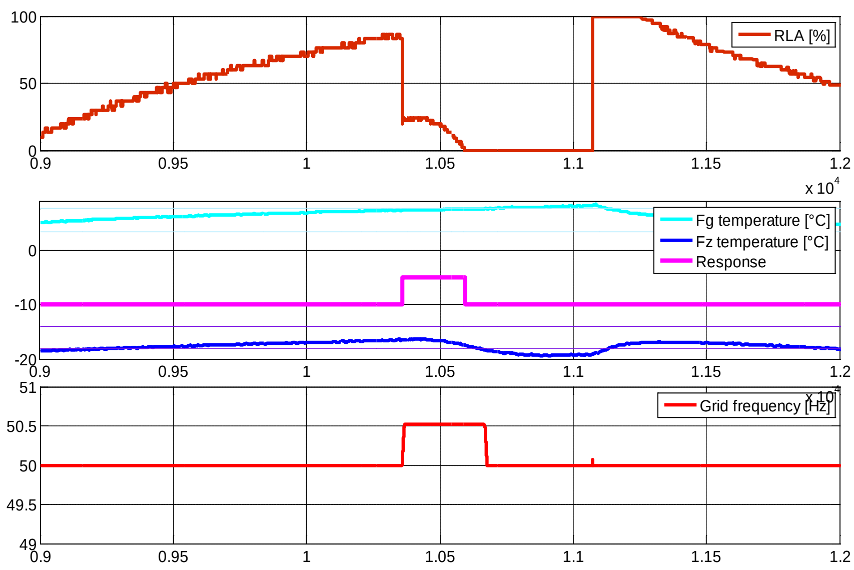


Figure 14(b). Response over warming phase.

In Figure 14(a), a LF injection is applied. As consequence the fridge responses switching off the compressor earlier if compared to the thermostatic needs. As shown in 3 indeed the compressor is switched off before the fridge temperature reaches the Fridge CutOff threshold.
In Figure 14(b) a HF injection is applied. As consequence the fridge responses switching on the compressor earlier if compared to the thermostatic needs. Please note that in this case both fridge and freezer temperatures have been plotted. As shown in Figure 6.1.4 indeed the compressor is switched on before the fridge or the freezer temperature reaches their relevant Cut On thresholds. In the case of freezer the effect of switching on the compressor reflects immediately on temperature (indeed freezer temperature decreases) whereas the damper close state prevent fridge from cooling, even if the compressor has changed state.
In both cases the response is at a high value till the compressor change state due to the thermostatic controller.

6.2. Response Capacity Values

Response capacity is estimated from laboratory data over normal fridge cycling (with the frequency response function disabled). The purpose is to estimate initially the response capacity of a real fridge under laboratory conditions as a reference value for later comparison with field measurements (see later discussion of the field trial).
It should be stressed that laboratory response capacity values are deeply connected with appliance thermodynamic behavior and depend directly on the operation condition selected (such as control mode, temperature set point, ambient temperature surround, load condition of the fridge etc).
In order to identify reference values, a study has been done in both cases of Eco and Normal modes, with set temperatures of +5°C for the fridge and -18°C for the freezer.

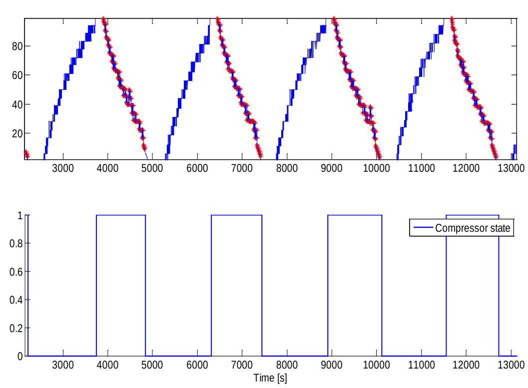


Figure 15(a). Regulation capacity to switch OFF.

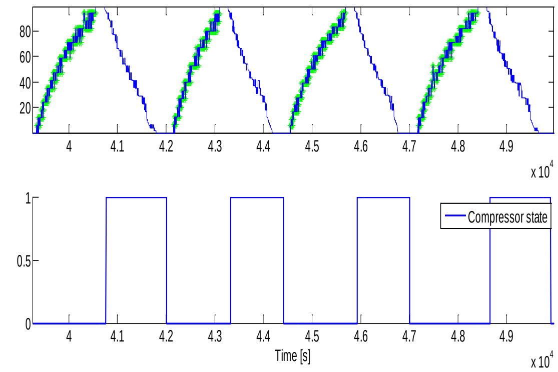


Figure 15(b). Regulation capacity to switch ON.

Figure 15 shows the capability for response regulation in the case of Eco Mode, delivering a low response capacity β = 40% (a) while the high response capacity α = 38% (b). Similar computations have been performed for Normal mode with a low response capacity β = 38% and high response capacity α = 30%.

7. UK FIELD TRIAL SYSTEMS ARCHITECTURE

With the Indesit frost-free EBC-enabled refrigerator described in Section 7, RLtec is conducting a large-scale trial of dynamic demand response provided by refrigerators installed in homes across the UK. The purpose of the trial is to

- demonstrate that in-house appliances can provide a fast frequency based balancing service to grids;
- measure the "in-field" service levels;
- calculate the carbon saving benefits achievable in the UK.

The trial partners are RWE npower, a large European utility whose customers are hosting the trial equipment; Indesit, an Italian appliance manufacturer with the largest refrigeration volumes in greater Europe; and RLtec as system integrator, metering and database provider. The UK's energy regulator OFGEM is acting as a customer for the test data, supported by KEMA providing technical overview.

The programme is being conducted in two phases. The first stage is a deployment of 300, single model, fridge freezer appliances, together with instrumentation. The second will roll-out the technology in additional model types to test service variability in differing model and configuration types.

As part of the trial, RLtec is instrumenting the fridges in order to conduct large-scale data analysis. This instrumentation is not necessary for service provision (frequency regulation) but will provide all the necessary information to measure the "in-field" service levels and associate a carbon-saving value to each fridge.

7.1. Remote Energy and Data Monitor (READ^{m})

RLtec has designed a platform product which is able to interface to internal data on the fridge control electronics, measure the fridge power consumption and communicate this data via the internet to a server-based database. READ^{m} is effectively a Smart Meter product and can support a variety of interfaces and protocols as necessary to enable effective and accurate real time monitoring of appliance sample population. The control electronics is a platform product across the Indesit PRIME appliance range and hence it will be possible to deploy the techniques across a variety of appliances.

For the initial trials, the READ^{m} uses mains signaling to communicate via a home plug into the household router. Wireless communications using any Smart Meter protocol is also possible.

7.2. End-to-end System

The physical disposition and functional decomposition of the system is shown below and the main elements comprise:

1. Appliance with hardware key
2. READ^{m} – Remote Energy and Data Monitor
3. HTTPS Data Collection Server
4. SQL Database Service
5. RLtec Custom Analysis Tools

7.3. Recorded Data and Analysis

The data available internally within the fridge is comprehensive and Table lists the data available. The data is sent via two services: (1) event driven, for example compressor motor state changes and (2) polled, for example every minute. This allows for real-time monitoring of important parameters and allows for second by second measurement of availability information and power consumption. The data set recorded for the trial will have a total size greater than one terabyte. The main analysis will be to ascertain the energy balancing service provided to the grid from the appliance population, as a function of seasonal factors, fridge usage patterns and/or time of day. Using this information the carbon savings potential of an EBC-fitted domestic fridge population will be quantified.

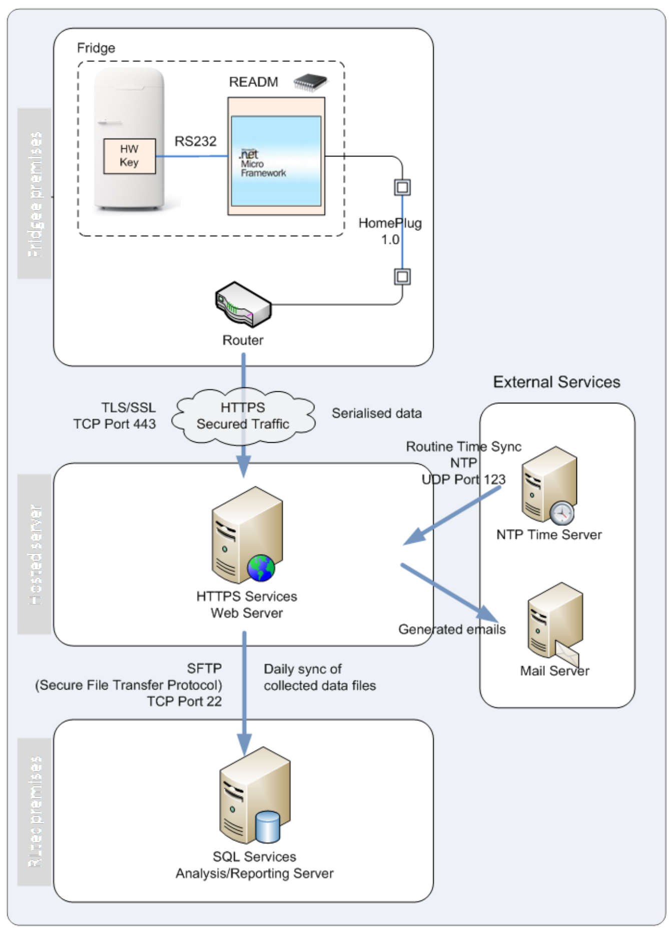


Figure 16. Data system architecture.

Table 3.

name	description	units	data min.	data max.	resolution	accuracy	Mirror buffer displacement (bytes)	Microcontroller Data Type
Fridge variables								
Cooler								
CoTCa	Cooler cavity temperature	˚C	0	40	0.1	tbd	0	**signed word (16 bits)**
CoDmp	Damper state	true/false	0	1	N/A	N/A	8	**unsigned char (8 bits)**
CoSpvCa	Cooler cavity Supervisor	none	0	2^{16} - 1	n.a.	n.a.	10	**unsigned word (16 bits)**
CoDS	Cooler door state	true/false	0	1	N/A	N/A	16	**unsigned char (8 bits)**
CoTLev	Cooler temperature level	˚C	0	255	1	n.a.	17	**unsigned char (8 bits)**
Freezer								
FrTCa	Freezer cavity temperature	˚C	-30.0	40.0	0.1	**tbd**	**2**	**signed word (16 bits)**
FrTEv	Freezer evaporator temperature	˚C	-50.0	40.0	0.1	**tbd**	**4**	**signed word (16 bits)**
FrCS	Compressor state	true/false	0	1	N/A	N/A	6	**unsigned char (8 bits)**
FrFan	Fan State	true/false	0	1	N/A	N/A	9	**unsigned char (8 bits)**
Heater	Heater State	true/false	0	1	N/A	N/A	7	**unsigned char (8 bits)**
FrSpvCa	Freezer cavity Supervisor	none	0	2^{16} - 1	n.a.	n.a.	12	**unsigned word (16 bits)**
FrTLev	Freezer temperature level	none	0	255	1	n.a.	18	**unsigned char (8 bits)**
Global								
VrSpvCa	Virtual cavity Supervisor	none	0	2^{16} - 1	n.a.	n.a.	14	**unsigned word (16 bits)**
PrbWarn	Probe warnings	none	0	255	n.a.	n.a.	19	**unsigned char (8 bits)**
LoadsWarn	Load warnings	none	0	2^{32} - 1	n.a.	n.a.	20	**unsigned long (32 bits)**
ACLine	Line Voltage (RMS)	V	0	32767	tbd	tbd	24	**signed word (16 bits)**
RL++ variables								
RLA	RLA	%	0.0	100.0	1.00	0.50	36	**unsigned word (16 bits)**
CoRLA	Cooler RLA	%	0.0	100.0	1.00	0.50	38	**unsigned word (16 bits)**
FrRLA	Freezer RLA	%	0.0	100.0	1.00	0.50	40	**unsigned word (16 bits)**
GF	Grid frequency	Hz	49.0	51.0	0.001	0.001	28	**unsigned word (16 bits)**
CF	Central frequency	Hz	49.0	51.0	0.001	0.001	26	**unsigned word (16 bits)**
HD	High dice	none					32	**unsigned word (16 bits)**
LD	Low dice	none					30	**unsigned word (16 bits)**
TrigF	Trigger frequency	Hz	49.0	51.0	0.01	0.01	34	**unsigned word (16 bits)**
External variables								
Cl	Real time clock	s	0.0	62899200.0	1	0.1		
TAmb	Ambient temperature	˚C	-10.0	40.0	1	1		

7.4. Interoperability Challenges

A number of choices presented themselves in the construction of the comms interface and the development of the READ^{m} solution. These choices are listed below.

7.4.1. Home gateway to database

- household ADSL modem *RLtec choice*
- electric meter
- specific home energy box
- radio modem to mast and then internet (e.g. Sensus Flexnet)

RLtec judged that a large proportion of homes available for participation would have an ADSL or other modem with wired internet input and the use of homeplug device provided very reliable high speed low cost comms. We note that some ADSL modems now have mains signalling built in (BT in the UK has this for their BT Vision product for home video delivery) and the desire of Telcos to offer video media into the home may represent a future data pipe for our industry.

7.4.2. Energy monitor to gateway

- Radio (e.g. .Zigbee)
- Mains signaling (e.g. homeAV) *Rltec choice*

RLtec selected mains signalling, HomeAV, primarily for certainty and avoiding multipoint relays that may be necessary with home installations. For the trial speed and risk were main drivers and cost not so important.

7.4.3. Energy monitor to Smart Appliance

- Radio
- Wires (e.g. RS232) *RLtec choice*
- Other (e.g. Infrared)

Indesit already supported RS232, as a platform interface across ALL their controllers in many appliance types, as part of the field maintenance and development debug, with much invested in the support tools and software.

7.4.4. Other issues

1. There is much debate on security. Clearly RLtec needs to secure this energy service for cyber security and some simple preventative measures have been taken. Security is expected to harden as standards develop and RLtec welcomes the focus in the US on this important component of Smart Grid.

2. We note that work is being done in Europe to standardise appliance interfaces and encourage further development of international standards to allow delivery of energy and other services with appliances.

3. READ^{m} is essentially a home energy monitor device and the development team in RLtec have cross industry and continent experience of electricity meter design issues. READ^{m} was developed as a platform product with expansion capability to support other interface options. It is clearly a Smart Meter as it does not have a display! We have chosen to use Microsof primarily driven by the data handling aspects required and ease of re-using type definitions across READ^{m} and database. There have been issues with these tools requiring large memory processors and we suspect that either Microsoft will improve their tools to allow targeting of smaller memory devices, or silicon geometries shrinkage (Moore) will allow the chip vendors to offer increasingly more capable processor products at low pricing.

4. Our database is complex and has many more variables than normal metering data.We note standardisation of the meter information e.g. ANSI C12, and this will be an interesting area for development of standardisation to support energy services.

We should congratulate all the design teams involved in the delivery of this cross disciplinary project who made it possible: (1) Indesit design team, Fabriano, Italy; (2) Sentec Ltd, Cambridge UK; (3) dotNetsolutions Ltd, Windsor, UK; (4) Design Edge, Cambridge UK; (5) Effekta, Luton, UK...and not least the in-house RLtec team.

We'd like to thank RWE nPower for their support; together with Department for Energy and Climate Change, Ofgem, the UK Energy Regulator and Kema providing carbon consulting support.

8. CONCLUSIONS AND FURTHER WORK

8.1. Summary

In simulation and in the laboratory the authors have shown that autonomous EBC-fitted smart appliances can provide the response-regulation service of generators, with frequency response measured and verified in the same way. Extensive laboratory requirements for generator-type testing of appliance populations, and manufacturers' need for a-priori assessment of relative value in EBC implementation mean that it is beneficial to use the response capacity rating developed here as a generator-test equivalent. A linear model or "rule of thumb" from measured response capacity ratings can be used to estimate or predict response to frequency events of any given size and complete the response matrix required by the UK grid operator.

Field trials of domestic smart appliances require extensive data networks and appliance-targeted communications devices. The READm and data system architecture developed for the EBC-fridge trial provide a valuable tool for future work both in instrumentation but also control of load applications.

8.2. Further Work

8.2.1. Lab-to-field factor in response capacity measurement

Initial estimates from simulation data with input day-to-day grid frequency indicate a 1-2 % increase in availability time averages α and β when moving from the lab to the field. This doesn't take account of field effects such as population distributions in fridge content, door openings over time and ambient temperatures.

Using the data gathered in the field trial, analysis will be carried out on the availability data to estimate lab-to-field effect on response capacity. The inclusion of different fridge models in the trial will permit a comparison of response performance in devices with different lab-measured response capacities.

8.2.2. Verification of linear model in the field

The improvement in availability time averages α and β over a varying frequency signal may be at the expense of the RLA distribution: one might expect the 'very available' fridges, with RLA_ON, RLA_OFF > 50%, to be eroded from the population, and a corresponding over-population of the less-available fridges (RLA_ON, RLA_OFF < 50%) to occur. The linear response model using estimations of α and β depends to some extent on a uniform distribution of fridge availability (RLA) signals.

Recorded grid events will be used to assess the validity of the linear response model of RL++ in the field.

8.2.3. Other applications of READ^{m} and data system

The data set being logged over the course of the field trial, and the system architecture itself will be of use in other applications. For example, it will be possible to measure the true in-home energy efficiency of an appliance. It may also be possible to test behavioral warnings and messaging. For example, specific services can be run on the data collection server that would provide the appliance user warnings regarding door opening or perhaps general energy use, or misuse of the appliance settings. For example the in-home energy use could be measured and a warning with recommendation sent when abnormal or high energy use patterns detected.