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SCOPE FOR DOMESTIC APPLIANCE DYNAMIC DEMAND SIDE MANAGEMENT

Tinashe Chinyemba¹, Farhad Anvari-Azar², Dani Strickland^{1}*

¹*Wolfson School, Loughborough University, Loughborough, UK*

²*Green Frog Power, Gorsey Lane, Birmingham, UK*

**d.strickland@lboro.ac.uk*

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Abstract

It is expected that the future UK's grid inertia will reduce as the UK moves towards decarbonisation. The consequence is that National Grid may have to increase its spending on primary frequency responses, to keep the frequency within limits. There is however, potential for National Grid to reduce this cost with the assistance of a dynamic domestic Demand Side Management schemes. This paper considers how domestic appliances may be utilised to help with frequency response. This paper looks at the potential size of a domestic appliance service using a droop based scheme to participate in dynamic Demand Side Management for frequency response and determines the impact of this on frequency response costs.

1. Introduction

The control of the grid frequency is a balancing act between generation and demand. Generators have an inherent inertia associated with their operation which assists with this. Rotating load also helps to contribute to grid inertia albeit on a much smaller scale which may be typically modelled as a change in load with frequency as shown in equation (1). The increase in power electronic converters have acted to reduce the grid inertia of both generation and loads. This has an impact on the market for frequency control services.

$$D = \frac{\Delta P_{L(freq)}}{\Delta \omega} \quad (1)$$

In the UK, National Grid use a variety of balancing services to control the frequency including STOR and Firm Frequency Response (FFR) also known as Primary, Secondary and High response modes [1]. This FFR response can be static (the generator is either on or off based on a threshold and must respond within 30s) or dynamic – the generator continually changes output to follow the frequency and must respond within 10s. The minimum participation size of a holding is currently 1MW which may be met through an aggregated service [2]. Some of the frequency response service is undertaken using Demand Side Response (DSR) also sometimes referred to as Demand Side Management (DSM). The majority of DSR is done by switching loads on and off in response to the frequency. In addition to turning the load on and off (similar to a static response), some attempts have been proposed in previously published literature to control loads in a dynamic response mode.

Control attempts have been made to directly control water heaters by using “ripple” control technology, such as turning water heaters on and off with frequency [3]. An alternative control strategy has been proposed in [4], based on a house with multiple controllable loads that have a priority rating. The control scheme considers preference settings and the

loads are turned on and off in order such that there are marked setpoints with frequency deviation rather than an on/off approach. Reference [5] proposes a control strategy for DSM that temporarily prohibits the turn on of high power appliances that are not already in use. This reduces the number peaks on the load profile. In addition to turning the devices on and off, some research has looked at changing the setpoints. Ciapessoni et al [6] undertook peak clipping with domestic fridges and heaters, by temporarily changing their setpoints. Reference [7] explored the different variations of controller's configurations of commercial Heating, Ventilation and Air-Conditioning (HVAC) loads, for the purposes of frequency regulation. The power consumptions of HVAC systems can be modified by either adjusting fan speed by controlling the variable frequency drive and/or applying a mass/pressure flow offset and applying a thermostat set offset.

Reference [8] - [9] have published simulations undertaken for the use of DSM to provide FFR. [8] investigated the impact of DSR in FFR, the methodology proposed the use of domestic thermostatic devices such as domestic water heaters and cooling loads. They are considered flexible due to their inert thermal inertia. The thermostat set point changes in response to the frequency. Reference [9] looked into reducing load to be used within FFR, this used a droop-based demand response on a DC load. The PWM controlled synchronous rectifier allowed for the load to be adjusted appropriately rather than just turning this load on/off. The PWM controlled rectifier allowed for more flexibility in load. The Pacific Northwest National Laboratory in America conducted a demonstration project for an autonomous underfrequency controller called the Grid Friendly Appliance (GFA) [10]. The controller was configured to observe the frequency (nominal value 60Hz) and when the frequency fell below 59.95Hz. The GFA controller would then request for the connected appliance to reduce its load. The project used residential clothes dryers that were manufactured for the project and retro fitted water heaters. The cost of the GFA

was approximately \$44. This is a significant cost to implement across a range of domestic products and would be unlikely to be feasible in practice.

This paper also looks at reducing load in a domestic consumer environment as a method of reducing the costs of balancing to National Grid and ultimately the consumer. The paper uses an alternative approach to those already published. This paper investigates if there is sufficient scope of magnitude to adjust ac loads dynamically in a similar manner to reference [9] by experimentally testing appliances to understand what change in power is possible with a change in frequency. Historically it has been assumed that a 3% variation in voltage on the grid produces a 5% demand reduction. However, operation Juniper in the UK in 2013 showed that reducing the voltage at the primary substations only showed a load reduction of 1.5% [11]. As some of these loads are constant power, reducing the voltage acts to increase the current and so the split between loads which can be used for response and those that can't results in figures that are lower than expected. This paper splits out the constant power loads and targets only those loads that show reduced power with voltage which can then be used to reduce power consumption with frequency.

Section 2 presents the methodology used to understand the available load reduction that might be available. Section 3 presents the results from a range of load types. Section 4 quantifies what this might mean for National Grid in terms of cost reduction of FFR services.

2. Experimental methodology

To work out the scope for reducing domestic load with decreasing frequency to help meet dynamic response services it is necessary to understand what level of power variation is available from different loads at different voltage and frequency levels. Only those loads that offer the chance to manipulate the power with frequency in the correct manner will be potentially available as a service. The most practical means of adjusting the load with frequency is to choose loads that have an operational envelop independent of frequency but that then offer the chance to reduce the power drawn by manipulating the input voltage. It was decided not to use an appliance which would need to operate at a higher power level in order to provide these services as this would increase electricity consumption and negatively impact the customer. Fig. 1 shows the single line diagram of the setup used to investigate how load changes with respect to voltage and frequency, while Fig. 2 shows a photo of the test set up.

Fig. 1. Test Schematic Set Up

Fig. 2. Test Rig photo

In the UK, the voltage standard is 230 volts -6%, +10%. This gives an allowed voltage range of 216.2 volts to 253.0 volts. There is therefore more scope to provide frequency response when the voltage is 253.0V than when it is 216.2V. At the nominal value of 230V, the scope for droop control is approximately:

$$droop = \frac{\Delta P}{P_r} \times 100 \quad (2)$$

Where

$droop$ is the % of power available for frequency response

ΔP is the change in power between nominal voltage and -6%

P_r is the rated power of the device

3. Experimental Results

The domestic devices that were tested included a kettle, toaster, iron and sandwich press, along with fridges, washing machines and other more complex loads. As part of this testing overall performance was compared in conjunction with the voltage, current and power measurements.

3.1 Kettle

A Cookworks 12106 kettle was tested between 45Hz and 55Hz, for a voltage range between 220V and 240V. The kettle operates at unity power factor and is on continuously. During the course of the experiments the power factor remained at unity. Results in Fig. 3 indicate that as the voltage drops so does the power consumption, this makes the kettle a viable domestic appliance for DSM. However the time for the kettle to boil increased. 7% droop is available at nominal voltage.

Fig. 3. Kettle Power Variation with Frequency and Voltage

3.2 Iron

A 043269 Sainsbury's own brand iron was tested between 45Hz and 55Hz with a voltage range between 220V and 240V. The iron operates in conjunction with a thermostatic switch which turns the heating element on and off with temperature. The iron is unaffected by the variations in frequency. The iron is active approximately 20% of the time when the iron is on. The power consumption variation when the iron is on is shown in Fig. 4. At nominal voltage 8% droop in power is available.

Fig. 4. Iron Power Variation with Frequency and Voltage

3.3 Sandwich Toastie

A SM09 Tesco own brand sandwich toastie maker was tested between 45Hz and 55Hz, for a voltage range between 220V and 240V. The sandwich toastie maker operated at unity power factor and operates in conjunction with a thermal switch which turns the heating element on and off with temperature. During the course of the experiments the power factor remained at unity. Results in Fig. 5 indicate that as voltage reduces, so does power and is independent of frequency. The droop available at 230V nominal is around 12%.

Fig. 5. Sandwich Toastie Power Variation with Frequency and Voltage

3.4 Toaster

A WMTTW4S002 Wm Morrisons own brand toaster was tested between 45Hz and 55Hz. Each frequency was tested with a range of voltages between 220V and 245V. Results shown in Fig. 6 indicate that as the voltage decreased so did the power consumption. The frequency did not have an effect on the power consumption of the toaster.

Fig. 6. Toaster Power Variation with Frequency and Voltage
A control test used was to look at the impact on the toast colour for a fixed setting under the different conditions. These showed that frequency had little impact, but the reduction in voltage resulted in less power to the toaster and therefore a lighter toast as seen in Fig. 7. There is approximately 11% droop at nominal frequency.

Fig. 7. Toast produced under different conditions

3.5 Load Availability for DSR

The experimental results show that the kettle, iron, toaster and sandwich toaster, have scope to participate in a droop-based DSM scheme. Motor based appliances such as fridges and washing machines were not suitable. Table 1 lists other domestic loads that can be used for DSM within the UK. In all these devices, power consumption varies with voltage and performance is independent of frequency.

However, it is not just a case of what power is available to participate, but also when it is available. Data from the National Statistics in Fig. 8 shows the approximate number of houses in the UK [12]. Fig. 9 uses the CREST load model [13] which calculates the probability that an appliance is on based on results from a time of use study to estimate resistive load. The probability that a resistive based load is on is multiplied by the number of houses and average power consumption to get a minute resolution of the total resistive based load in the system in each minute. As expected, the highest peak occurs during the evening period. If it is assumed that this load has a droop capability of 8% available, based on the experimental values, this equates to a theoretical peak load reduction of 1120 MW.

Table 1 Domestic Loads

Appliance	Typical Ratings W	Time	Appliance	Typical Ratings W	Time
Kettle	2200-3000	Min	Steam Cleaner	2000	Hr
Toasters	700-1500	Min	Laptop Charger	45-85	Hr
Deep fryer	1200	Min	Electric Hob	1000-2000	Hr
Oil filled Radiator	1500-2500	Hr	Electric Shower	7000-10500	Min
Instant Hot Tap	1430	Min	Power Shower	8500-10500	Min
Dish washer	1050-1500	Hr	Slow Cooker	250	Hr
Iron	1000-1800	Min	Electric Oven	2000-2200	Hr
Towel Rail	250-400	Hr	Rice Cooker	700	Hr
Air Fryer	1400	Min	Deep Fryer	1800	Min
Sandwich and Panni Press	1000-2000	Min	Crepe Maker	1000	Min

Fig. 8. Total Number of Houses in The UK

Fig. 9. Power Probability Distribution of Resistive based Domestic Appliances

4. Frequency Response Services

FFR frequency services are expensive and total expenditure on commercial frequency response was estimated as >£70 million in 2018 found by checking the contracted frequency each month. The faster the response the more expensive it is to purchase. Fig. 10 shows the accepted, availability prices for dynamic and non-dynamic years between APR-15 and JAN-21 from ELEXON[14]. In general, dynamic services were about four times more expensive. FFR dynamic services are expected to detect a frequency event within 2s and ramp up to full output within 10s, while the figure for non-dynamic is 30s. The prices indicate that it is around 5 times more expensive to purchase dynamic response compared to static response. The contracted dynamic service is larger than the non-dynamic service as shown in Fig. 11. If the proportion of dynamic to non-dynamic service can be altered or reduced there could be good financial savings.

Fig. 10. Average accepted FFR weighted average availability price 2015

Fig. 11. Contracted volume of dynamic and non-dynamic frequency response since 2015

This paper modifies the methodology presented in references [15-16] and calculates the change in frequency at different inertias for a 1GW step change in load to understand the effect of loss of infeed due to a significant event. Equation (3) is used to model the frequency:

$$\frac{df}{dt} = \frac{P_{in} - P_{out}}{2SH} f = \frac{\Delta P}{2I} f \quad (3)$$

Where

P_{in} is the active power input to the power system (MW)
 P_{out} is the active power output to the power system (MW)
 ΔP is the active power imbalance (MW)
 S is the apparent power rating of the machines connected to the power system (MVA)
 H is the inertia constant connected to the power system (s)
 I is the system Inertia (MVA.s)
 f is the system frequency (Hz)

Equation (3) is a differential equation describing the change in frequency with time which can be solved using numerical techniques, in this case Euler's Forward method implemented in Matlab 2018b using the method in Fig. 12. The key difference in this paper compared to previous work is the change in power that would result from the use of an aggregated dynamically responsive load that is represented with a frequency droop characteristic, D, as defined in equation (1).

Fig. 12. Functional Frequency Calculation Model

The objectives of the simulations are to analyse and quantify the required level of primary response for four different scenarios of load response for a range of grid inertias from 160,000 MVA.s to 360,000 MVA.s. The following assumptions have been made.

1. Primary Response occurs with a 2s detection and ramping to full power within 10s.
2. An event of a 1000MW interconnector trip
3. The frequency does not fall below 49.2Hz and the calculated ROCOF does not exceed 0.5Hz/s

Four different scenarios for load response have been considered;

The load is reduced at a fixed droop rate of 4% or 8% if the frequency drops below 50Hz and the load is reduced at 4% or 8% if the frequency is below 50.5Hz as shown in Fig. 13.

Fig. 13 Load Response Scenarios

Fig. 14 shows the frequency in the event of a 1GW loss of generation at peak load with a low inertia and 300MW of primary response. The response from the demand at 8% droop is sufficient to significantly limit the frequency drop, while that at 4% shows a reduction of frequency and highlights the need to maintain some additional primary response. The minimum primary response required at each inertia for each scenario is shown in Fig. 15. To guarantee that the frequency won't drop below 49.2Hz with an extremely low grid inertia, 410 MW of holding reserve is required with a 4% droop.

Fig. 14 Frequency Response for an inertia of 160000 MVA.s

Fig. 15. Primary Holding under two different scenarios

The implementation of a DSR scheme would reduce the requirement to operate at current levels of primary reserve opening the door to slower responding services which could be potentially cheaper. Cost indications indicate that (excluding mandatory FFR) reducing the commercial primary dynamic response by 400MW and increasing the level of secondary response to compensate for this would result in savings of around £7.30 per MW/h availability payment (average dynamic – non-dynamic weighted average cost from Fig. 10) giving a potential saving of £25m per year.

If these savings could be extended for a period of 10 years, National Grid will save a total of £250m. If a droop-based scheme was to be implemented in every household on up to 4 devices. Then a load reduction strategy would have to cost < £2.50 per device to be effective.

5. Conclusion

As the UK moves towards decarbonisation, the inertia of the UK grid is likely to decrease. Consequently, if nothing else changes, National Grid may have to procure more primary dynamic response to keep the frequency within the limits. This paper has established that by using a droop based DSR scheme for controlling resistive based domestic devices such as a toaster, iron, sandwich toastie maker and kettle, there could be a potential of up to 1120 MW of power that could be used as a buffer to alleviate the need for primary FFR services, opening the door to slower and cheaper secondary FFR services. This scheme has shown that it can adequately curtail the frequency for at least 30 seconds, until the secondary FFR is available. Initially costing has resulted in a target figure of £2.50 per load controlling device in order to be cost effective. This is significantly lower than previously published schemes and will be challenging to meet.

Future work will aim to implement such a device in hardware at the cost target price.

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