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Analysing the Impact of Large-scale Decentralised Demand Side Response on Frequency Stability

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ABSTRACT

Advances in communications technology, higher penetration rates of renewable energy and an evolution towards smarter electrical grids are enabling a greater role from demand side response (DSR) in maintaining power system security and reliability. The provision of primary operating reserve (POR) from domestic loads through a decentralised, system frequency based approach is discussed. By considering a range of system configurations (generation mix, system generation and load) and control strategies, this paper endeavours to answer critical questions concerning the large-scale roll out of decentralised DSR, including the following: what are the implications of DSR resource seasonal variability on system operation and performance following the loss of a large infeed/load? Do increased load coincidence and energy payback phenomena have the potential to significantly impact system frequency recovery? How do DSR controller hardware characteristics influence the provision and effectiveness of reserve delivery? What are the repercussions of a “fit & forget” approach to decentralised control from flexible load on frequency stability as the technology penetration increases? Can DSR be directly substituted for conventional reserve sources while recognising its post-event recovery period? Residential customer behaviour, seasonal effects and the diversity of individual device characteristics are recognised in a detailed thermodynamic flexible load model which is integrated with a detailed power system model to perform the analysis.

1. INTRODUCTION

Technological advancements, coupled with a global drive towards utilising natural energy resources, have encouraged the exploitation of flexibility in the demand resource. Historically, the role of demand in system operation has been limited to the provision of emergency static reserve, whereby a contracted fraction of load was disconnected as a measure to arrest system frequency decline following a generator contingency. However, with higher penetrations of renewable energy sources, particularly wind and solar, there are increased opportunities and benefits from demand playing a greater role in system balancing. An increasing number of jurisdictions around the world are utilising flexible load for system ancillary services e.g PJM and ERCOT, with flexible load providing 50% of ERCOT's spinning reserve requirement [1].

A demand/generation imbalance resulting from a contingency (loss of generation or load) manifests itself as a variation in the system frequency. In the absence of flexible loads, part-loaded generators under droop control increase/decrease their output to counter any imbalance. Depending on the size and configuration of a power system, other resources such as storage units and interconnection may be activated. Flexible loads offer an alternative as they can quickly increase/decrease their output [2], thus acting as virtual generation. However, it is important to recognise differences between flexible load and conventional generators in terms of their available capacity and sustained response. For thermostatically controlled appliances (TCAs), variations in ambient temperature as well as user interaction affect the demand resource as a function of time of day and year [3]. Cooling TCAs (fridge/freezers, air conditioners) will tend to have a higher flexible resource during the summer and daytime hours, while heating TCAs (space heating, water heating) will tend to offer a higher resource during the winter, morning and evening hours. User activity, e.g. fridge door openings for cooling TCAs, coupled with ambient temperature variations will also affect the intra-day resource variability. It should be noted that the rated output of certain generation technologies will also be affected by variations in ambient conditions, e.g. gas turbine plant, but the variations are less dramatic [4]. Domestic electricity consumption makes up almost 30% of electricity consumption in the EU-27 countries [5], and is largely responsible for creating the peaks and troughs in the system load profile, further leading to increased system ramping requirements. Thermal loads from the residential sector can be considered flexible as they are mostly non-critical and discretionary. However, each individual load is small, and therefore many such loads need to be controlled in concert to yield the desired aggregate demand.

Control schemes and infrastructure requirements for deploying flexible demand generally vary with the nature of the service envisaged: flexible load has been suggested for load shifting [6], frequency regulation [7], [8] and load following [9] [10]. However, displacement of part-loaded conventional generation at higher wind penetration levels restricts a system’s ability to cope with the loss of a major infeed [11], making provision of primary reserve a key area of concern. The concept of altering thermostat setpoints of TCAs in proportion to the system frequency deviation, thus utilising the least energy deficient appliances first was presented in [12], to provide primary operating reserve (POR) from a homogenous fleet of cooling appliances. Switching multiple load types (refrigerators, space and water heating) based on the magnitude and duration of a disturbance was demonstrated in [13]. For the Great Britain system, [14] simulates the impact of switching flexible appliances using frequency measurements from smart meters to determine the amount of flexible load required to maintain the system frequency within required levels (for a single large infeed loss). In [15], all appliances have been assumed to be switched at a uniform frequency threshold for providing system frequency control. However the above studies [14-17] ignore the flexible load daily/seasonal variability which impacts the magnitude of the available DSR based reserve, while considering only loss of generation scenarios and therefore not catering for the asymmetric nature of DSR reserve for an upward/downward response. These studies also assume fixed decentralised control settings, ignoring the impact of a change in parameters on the improvement/deterioration of the frequency nadir. As opposed to previous studies, [16] and [17] propose a semi-decentralised mechanism involving two-way communication, whereby an aggregator pre-configures the DSR based POR for local frequency based triggering, maximising the aggregator's profit [17] and customer welfare through load utility functions [16]. All of the mentioned studies [14-19] however, adopt a simplified lumped representation of conventional generation, thus ignoring the impact of static reserves on the frequency nadir, while considering only a single set of system operating conditions (generation mix, system demand, flexible load level). These studies consider only the short-term (several seconds after a contingency) impact of DSR on the system frequency, but not considering phenomenon such as the energy payback, and its impact on system frequency as the load resumes normal operation after providing the requested response.

The provision of reserve from frequency dependent flexible load (specifically thermostatically controlled appliances) in a completely decentralised manner is being considered by a number of TSOs, including ENTSO-E (European Network of Transmission System Operators for Electricity) for large-scale implementation [18]. Analysing the performance of such a resource over a range of future system scenarios (particularly if the volume of appliances increases in magnitude), while considering the effects of seasonal resource variability, the lack of real-time controllability and observability, and a subsequent loss of load diversity is essential to identify potential operational issues and to evaluate possible mitigating measures. Moreover, the underlying controllers for such appliances are likely to be low cost [12], and since the resolution and response time of the hardware is likely to be affected, the impact of both attributes on DSR performance must be analysed. In this work, domestic fridge/freezers are considered as a representative TCA, as unlike other flexible loads, e.g. air conditioning and space heating, the cold load resource sees a smaller daily and seasonal variation, making it a dependable source of primary reserve. Considering the recent industry developments mentioned above and previously carried out research, the main contributions of this work are the following:

Using detailed models for the responsive load and the underlying power system (Section 2), for various system operating points (generation mix, system demand and responsive demand magnitudes) this study highlights the system impacts of utilising large-scale decentralised DSR based POR, on short and longer-term frequency stability. The impact of DSR resource seasonal and diurnal variability on the system frequency profile is demonstrated, and the unsymmetrical nature of an under & over-frequency demand resource, and the implications of decentralised "fit & forget" control are shown (Section 3.1). The analysis is extended to post-DSR event frequency stability by evaluating the impact of loss of aggregated load diversity and the associated energy payback (Section 3.2). Large-scale implementation issues are highlighted by quantifying the impact of the DSR response time and input resolution (controller hardware) on the system frequency response following a contingency (Section 3.3). Various response triggering and restoration strategies are considered to highlight phenomena such as the relationship between the frequency nadir improvement and resource over-responsiveness, with control mechanisms proposed to address the identified trade-off (Section 3.4). Potential issues regarding post-contingency DSR resource recovery, such as a second frequency nadir, and flexible load profile uncertainty due to sustained response provision, are demonstrated (Section 3.5) and changes to system operation policy for wide-scale implementation of decentralised DSR are proposed. The paper is concluded in Section 4.

2. MODELLING APPROACH

Individual fridge/freezer appliances have been stochastically modelled and aggregated to represent system-level power consumption. Fridge/freezer load has been chosen as being representative of TCAs owing to their high penetration levels and availability throughout the year. The aggregate flexible load model (fridge/freezers) has been integrated into a detailed power system model [19] for further analysis.

2.1 Aggregate load model

Many different refrigerator models have been developed from a thermal performance point of view, which tend to be very detailed and computationally intensive [20], [21]. Here, however, analysis is focused on a load resource for system services: a model is required that can accurately predict the energy consumption of individual appliances while providing reasonably fast computation, so that a sufficiently large and diverse fleet of such devices can be simulated individually and aggregated to system level. Modelling individual appliances has the advantage of greater transparency into the load states, which is particularly relevant for the deployment of a demand resource scheme, as respect for individual appliance (thermal) limits can be ensured, as part of any governing control strategy. An individual appliance model has been adopted from [12], with the additional modelling of fridge openings to represent consumer behaviour. Individual appliance components, such as the freezer box, freezer contents, fridge air space, fridge contents and the room in which the appliance is placed are modelled as separate components that exchange heat with all the adjacent components. The heat exchange $dE_{l,i}$ in an appliance i through a heat link l between two components n and $n+1$ with initial temperatures $T_{n,i}$ and $T_{n+1,i}$, during a time interval dT is calculated as

$$dE_{l,i} = U_{l,i}A_{l.i}\left(T_{n,i} - T_{n+1,i}\right)dT \tag{1}$$

with $U_{l,i}$ and $A_{l,i}$ being the thermal conductivity and cross sectional area of link l. The temperature of each component is calculated by subtracting the sum of heat exchanged with all adjacent links n_l from the initial stored energy $E_{n,i}$, with $S_{n,i}$ and $m_{n.i}$ being the specific heat capacity and mass of the n^{th} component

$$T_{n,i} = \frac{E_{n,i} - \sum_{l=a}^{n_l} dE_{l,i}}{S_{n,i}m_{n.i}} \tag{2}$$

The appliance cavity temperature is maintained within the thermostat limits by a compressor. Each fridge opening is assumed to replace a fraction of the appliance cavity airspace with ambient air in accordance with experimental studies [22]. The heat energy corresponding to each fridge opening is represented as

$$E_{op,i} = S_{air}\rho_{air}T_{amb,i}V_{cav,i}\emptyset_i \tag{3}$$

where S_{air} and ρ_{air} are the specific heat capacity and density of air, $T_{amb,i}$ represents the ambient temperature, $V_{cav,i}$ is the volume of appliance cavity and $\emptyset_i$ is the fraction of the appliance cavity volume which is replaced by air at ambient temperature.

The aggregate flexible load from a system-wide fleet of fridge/freezers has been estimated by simulating individual stochastic devices, formed from 10 base categories. Gross capacity, power rating and coefficient of performance (COP) of each appliance in the aggregate fleet are varied depending on the appliance base categorie. Individual heat link U-values were varied within $\pm 10\%$ of the experimentally recorded values mentioned in [12]. It was observed that the variability of the aggregated power demand was not noticeably affected by simulating more than 4500 individual appliances. The frequency with which fridge openings occur for each appliance, as a function of time of day, has been determined from a probability distribution based on survey data [23]. The (local) ambient temperature also forms an input to the individual appliance models, Fig. 1, recognising that the fridge load will tend to be higher during summer days over winter days, and during day

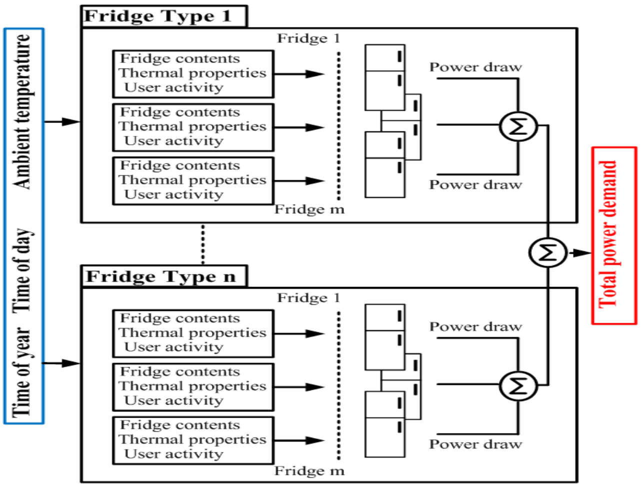

Fig. 1 Appliance modelling overview

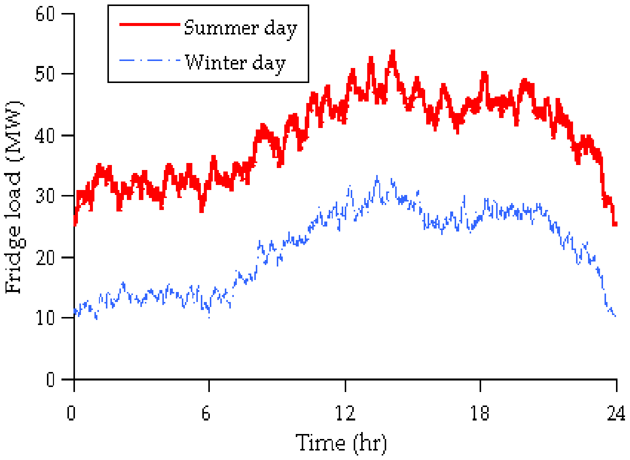

Fig. 2 Seasonal variation of aggregate power consumption

time periods over night time periods. The night time load will be further reduced by lower user activity, i.e. fewer fridge openings. Although the local ambient temperature will be different for each appliance, it has been considered as a global variable here for better illustration of the impact of seasonal variation on the demand resource. An aggregate demand model of the Irish domestic cold load has been developed as a test case. There are ≈1.65 million households in Ireland [24], with a cold device penetration level exceeding 99% in the country. Fig. 2 shows the aggregate power consumption of the fridge/freezer population for both summer and winter days, with the average ambient temperature on the summer day assumed to be 7 °C higher than for the winter day. A 20-25 MW difference, depending on the time of day, can be seen between the two responses, with the demand reducing during the night and early morning due to lower ambient temperatures and reduced user activity.

2.2 Power system model

As opposed to the majority of studies, a detailed power system model has been utilised to characterise the effects of flexible load on the system frequency. The detailed model offers the advantage of modeling static sources of reserve such as HVDC interconnectors and large scale storage. The detailed representation of individual generator dynamics provides a more realistic estimation of the system frequency, particularly for small systems. The future (2020) Irish system has been used as the representative power system. It is a relatively small system with limited DC connection (1000 MW) to Great Britain through two interconnectors, and consists of combined cycle gas turbines (4292 MW capacity), coal-fired plant (1323 MW), open cycle gas turbines (1192 MW), pumped storage hydro plant (292 MW), combined heat and power plant (161 MW), and wind farms (5 GW installed). The system model is based on a feedback loop whereby the system frequency is calculated based on the active power imbalance between demand and generation, and the stored energy of the rotating masses in the system, while the fed back frequency determines the power output from individual generators. All generation units are assumed to be grid code compliant with a 4% droop setting and individual plant characteristics such as plant inertia are based on data provided by the manufacturers. The steam turbines, combustions turbines and hydroelectric units have been modelled based on [25], [26] and [27] respectively. Wind generation output is considered to be invariant during the POR provision time frame, while the potential for emulated inertia provision and governor droop control on wind generators have been neglected to clearly observe the impact of demand resource provision on the system frequency. Both flexible and inflexible loads are represented. Flexible load modelling is highlighted in Section 2.1. Inflexible loads incorporate inherent frequency sensitivity, but are assumed not to change their operating cycles depending on the system frequency deviation, not contributing to DR. The frequency sensitivity of the inflexible load is based on experimental data. Frequency traces from various system contingencies provided by the transmission system operator have been used to validate the model over a number of years [4], [19], [28].

3. RESULTS AND DISCUSSION

Considering domestic fridge/freezer load as being representative of thermostatically controlled appliances, the flexible load and system models described in Section 2 are used to evaluate the impact of load flexibility following the loss of the largest generator/load. It has been assumed initially, for ease of comparison, that the reserve available from flexible demand has not been recognised during the system dispatch. The influence of seasonality, hardware controller characteristics (resolution and response time) and post-event load behaviour, along with the system implications of load triggering and load energy recovery, are examined**.**

3.1 Variation of system reserve

The daily/seasonal variability of the DSR resource is one of the most important characteristics that distinguish it from conventional generation reserve response. Failure to recognise the variability of DSR based reserve can result in an under or over-responsive system. The magnitude of flexible load available for a loss of generation (appliances consuming power) and a loss of load (appliances not consuming power) contingency is asymmetrical, while the available demand resource is autonomous and non-dispatchable in a “fit & forget” control approach. A number of representative system configurations for the Irish power system, corresponding to varying levels of system demand, wind generation and HVDC import/exports, which have been obtained using the WILMAR stochastic unit commitment tool [29] are shown in Table 1. For each case, loss of the largest

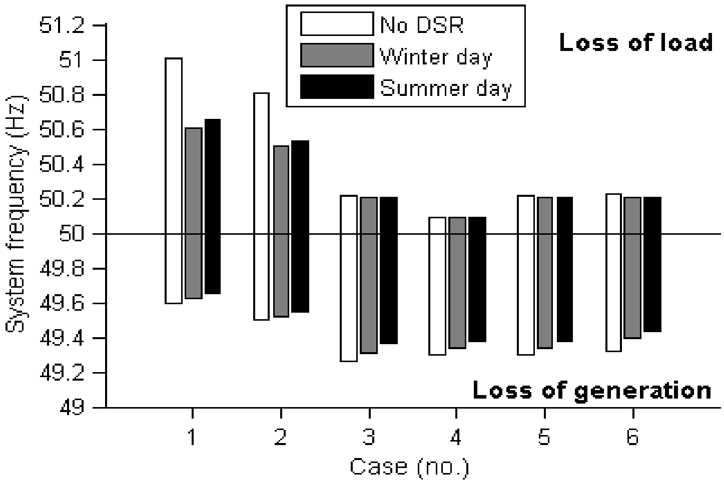

Fig. 3 Impact of seasonal DSR resource variation

Table 1: Representative system scenarios

Case	Total demand (MW)	Wind gen. (MW)	Conv. gen. (MW)	Total import (MW)	Total export (MW)
1	3658	3038	1620	-	1000
2	5431	4343	2088	-	1000
3	4840	1462	3572	-	194
4	5514	308	4531	675	-
5	6166	3315	2251	600	-
6	3873	1641	2017	215	-

generation/load infeed is considered, and the frequency response of the system is simulated, with the frequency nadir (generation loss) and zenith (load loss) recorded. Two levels of flexible load (domestic fridge/freezers) are considered for each case, representing summer (25 °C internal average temperature) and winter (18 °C) days, as shown in Fig. 2. For clarity, it is assumed that all of the available demand side resource is triggered for an observed frequency deviation of ± 0.2 Hz from nominal. It can be seen in Fig. 3 that as wind generation supplies a higher proportion of the demand requirement (cases 1 and 2), it displaces conventional generation, thus tending to reduce the size of the largest infeed, and resulting in an improved frequency nadir, following the loss of the largest infeed. The addition of DSR improves the system performance in each case, by raising the frequency nadir. In all cases of loss of the largest infeed, the summer response is improved over the winter response, which is unsurprising given the increased flexible load at this time. Fig. 3 also considers the DSR capability for loss of load scenarios. For cases 1, 2 and 3, in which the Irish system is exporting power to the GB system, the loss of a HVDC interconnector is considered, while for cases with no export (4, 5 and 6), loss of a 100 MW load is assumed. A loss of interconnection/loss of load may lead to a high frequency event: flexible load responds by increasing consumption to absorb the imbalance, whereby fridges in an off state switch on (compressor). Since on a winter day it is likely that more appliances will be in an off state, as compared to a summer day, the winter day DSR resource has more capacity to provide over-frequency reserve. The loss of load considered for cases 3, 5 and 6 is very small, such that a minimal increase in flexible load arrests the frequency deviation, leading to similar responses on a summer and a winter day. In case 4, the loss of load does not result in the system frequency rising beyond the threshold (50.2 Hz), thus the flexible load does not respond. The results in Fig. 3 show that the magnitude of the under-frequency and over-frequency POR available from flexible load are inversely correlated for each case. Moreover, an identical loss of generation/load for a specific system configuration results in two different frequency nadirs/zeniths on a summer vs winter day, highlighting the impact of DSR resource variability.

3.2 Loss of load diversity

Thermostatically controlled appliances tend to be cyclical in operation, so that a widespread interruption in their *on* cycle will result in short-term cycle synchronism across the appliance fleet, leading to a loss of natural load diversity. The resulting load coincidence can impact the generation-demand balance, and may also have implications at distribution system level, where residential networks are designed recognising a certain level of load diversity. Post-event load coincidence, if not recognised, prevents the flexible load from behaving in a manner similar to conventional plant, i.e. an increased and sustained response, and challenges the scheduling of DSR as system reserve.

With the flexible load fleet pre-set to be responsive (not drawing power) for intervals ranging from 5 to 25 minutes, the post-DSR peak and trough values, as a percentage of pre-DSR consumption, have been calculated, Table 2. The analysis has been performed for a sample summer and winter day. For ease of comparison the ambient temperature on a sample day has been assumed constant, whereas in reality it may well vary. With an increase in the response time, the post-DSR peak magnitude tends to increase, while the post-DSR trough becomes deeper, indicating a higher level of (on-off) synchronism across the appliance fleet. The summer day values exhibit higher peaks and deeper troughs, as compared to the winter day, owing to the higher pre-DSR steady-state power draw. It can be seen in Fig. 4 that extending the response time (from 5 to 20 minutes) results in a higher coincident load, while the seasonal variation in temperature also has an effect. Since the aggregate appliance power consumption is stochastic, the average steady-state power consumption and associated standard deviation are calculated for the simulated cases (Fig. 4) to ascertain the boundaries of the normal operating zone (± 5 standard deviations from the mean has been considered here). An aggregated demand excursion beyond these limits implies an increased (not normal) load coincidence. Fig. 4 demonstrates how switching load off for 5 and 20 minutes affects the load coincidence for a summer and winter day. The area bounded by the horizontal lines represents the normal operating zone, with the coincidence duration considered as the time period from the first excursion beyond the normal operating zone to the final return within limits. The load coincidence magnitude depends on seasonality (pre-DSR event power consumption), appliance type and the duration of the response provided. The loss of load diversity and energy payback are the major factors which limit the customisation of the TCA response, thereby complicating the participation of demand response in ancillary services.

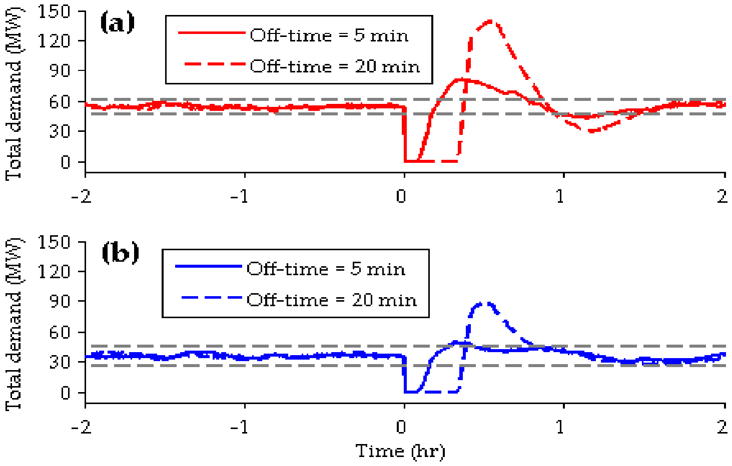

Fig. 4 Loss of load diversity (a) summer day (b) winter day

Table 2: Post DSR peak & trough magnitudes

Summer day			Winter day	
Response time (min)	Peak* (%)	Trough (%)	Peak (%)	Trough (%)
5	150	79.74	138.1	84.72
10	185.5	73.31	163.6	83.01
15	249.5	60.21	211.0	75.67
20	257.0	54.48	249.9	75.53
25	296.6	50.00	290.0	65.75

*% values based on pre-DSR power consumption

3.3 Required controller hardware characteristics

The response of flexible appliances in a decentralised control mechanism is primarily dependent on the hardware implementation. Since large-scale roll out of frequency responsive load in the domestic sector entails the addition of a controller to each appliance, its cost is likely to be a small fraction of the appliance itself, which for white goods such as a fridge/freezer is likely to be moderate. The cost of the hardware may have knock-on impacts, e.g. controller response time and resolution, which influence the aggregate DSR and subsequently the system frequency nadir or zenith. Appliance controller attributes that influence the provision of DSR are:

a) Controller response time: the time interval (s) between frequency measurement and appliance response activation

b) Controller resolution: the smallest frequency deviation (Hz) value that can be detected by the controller

One of the main technical benefits of utilising a DSR resource for reserve provision, in place of conventional generation, is an improved speed of response. This, however, may be nullified by the use of hardware controllers with an unsuitable response time and resolution. It is, therefore, important to determine which controller characteristics have the potential to offset this benefit and significantly impact an improvement in the frequency nadir. Considering a 230 MW trip for case 1, as before, it is assumed that all flexible appliances switch off at 49.8 Hz. Fig. 5 shows how the controller resolution and response time impact the system frequency nadir. It can be observed that a short response time coupled with a small resolution value (< 0.05 Hz) provides the best frequency nadir. For response times beyond 0.4 s and a frequency resolution greater than 0.25 Hz the demand resource has limited effect on the frequency nadir. It must be noted that these limits apply to the particular system configuration and loss of largest infeed considered, however similar trends can be expected for larger systems as well. It is also noteworthy that the frequency encountered by *local* frequency controllers will not be uniform across the system during a contingency due to oscillations originating from the loss of generation.

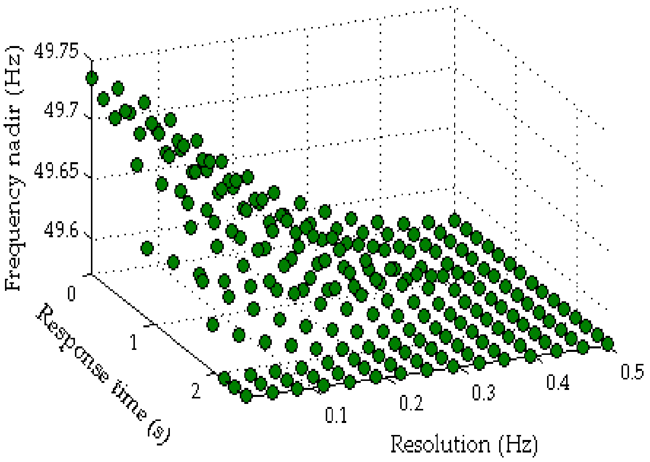

Fig. 5 Impact of controller resolution and response time

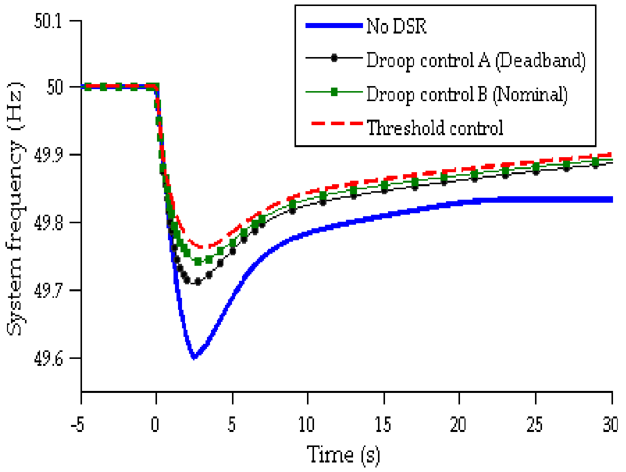

Fig. 6 System frequency for a 230 MW infeed trip (Case 1)

From the results presented in Fig. 5, it can be concluded that the controller characteristics noticeably influence the system frequency nadir (a difference of ≈0.2 Hz between best and worst case) following loss of the largest infeed. The hardware response times combined with controller resolution determine the speed of response.

3.4 System implications of DSR triggering

Maximising the inherent benefits of the demand resource for contingency reserve (speed of response), as compared to conventional plant, can be achieved using local on-board frequency measurement and control. However, a “fit & forget” approach to control parameter tuning neglects the seasonal and diurnal variation of the resource, as well as the volume of the installed resource. For a future case with a large-scale penetration of frequency responsive load, this can lead to DSR under-utilisation or, in contrast, frequency oscillations, leading to additional stress on conventional units and risking system security. It has been assumed so far that all appliances are triggered beyond a frequency deviation (4) threshold.

$$\Delta f = f_{nom} - f \tag{4}$$

Such a triggering mechanism ensures the delivery of the entire DSR resource resulting in maximum improvement in frequency nadir/zenith. This triggering mechanism can be summarised as follows:

- *T1 − Threshold control:* frequency deviation from nominal, beyond a threshold value, triggers 100% of the available demand resource.

Assuming a generation trip of 230 MW occurs in case 1 (Table 1) with an available flexible load magnitude of 100 MW and a frequency deviation threshold of 0.1 Hz, Fig. 6 shows the improvement in frequency nadir by DSR under the threshold control mechanism. Reducing the deadband or raising the trigger frequency will improve the response further, but may also increase the likelihood of false triggering or a frequency overshoot. If instead a smaller trip occurs, e.g. 80 MW, as seen in Fig. 7, threshold control results in an over-frequency

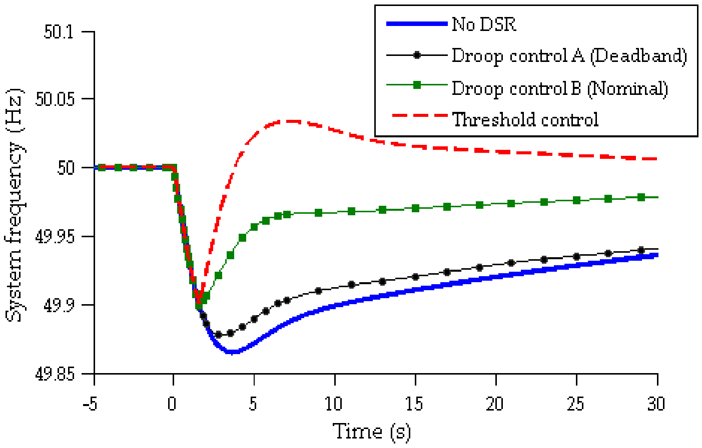

Fig. 7 System frequency for a 80 MW infeed trip

Table 3: Comparison of nadir improvement

	Frequency nadir improvement (Hz)		
Case	T1-Threshold control	T2- Droop control A (deadband)	T3- Droop control B (nominal)
1	0.164	0.110	0.132
2	0.101	0.101	0.101
3	0.150	0.136	0.145
4	0.103	0.077	0.079
5	0.187	0.158	0.170
6	0.177	0.176	0.177

event, suggesting that a staggered (multiple frequency) deployment might instead be appropriate for the available flexible load magnitude. In order to ensure DSR provision in proportion to frequency deviation in a manner akin to generator droop, the following triggering mechanism is considered:

- *T2 − Droop control A (deadband):* frequency deviation beyond a deadband D_b results in the thermostat setpoints of the TCAs being increased/decreased in proportion to the frequency deviation Δf beyond the deadband (5).

$$\tau_i^{new} = \begin{cases} \left(\dfrac{\Delta f \mp D_b}{O_r} \times \Delta\tau_i^{max}\right) + \tau_i^{old}, & if\ D_b \le |\Delta f| \le D_b + O_r \\ \Delta\tau_i^{max} \pm \tau_i^{old}, & if\ D_b + O_r \le |\Delta f| \\ \tau_i^{old}, & Otherwise \end{cases} \qquad (5)$$

where O_r represent the operating range, $\Delta\tau_i^{max}$ is the maximum allowable change in thermostat setpoints for the i^{th} appliance (to ensure food safety), considered 1 °C in this case, and τ_i^{old} represent the original and new thermostat setpoints for i^{th} appliance. The upper and lower thermostat setpoints of an appliance change by the same magnitude in response to a frequency deviation from nominal. The change in both the upper and lower thermostat setpoints is represented by (5). Using the T2 approach results in a smaller improvement in the frequency nadir for a 230 MW trip, Fig. 6; however, for a 80 MW trip, DSR over-responsiveness is avoided, Fig. 7. It is also noteworthy that strategy T2 results in a significantly smaller improvement in the frequency nadir, compared to T1 which highlights a trade-off between nadir improvement and DSR over-responsiveness. In order to overcome the slowness of the DSR provision resulting from T2, while avoiding the inherent over-responsiveness of T1, a new triggering mechanism is proposed, which can be summarised as:

- *T3 − Droop control B (nominal):* frequency deviation beyond a deadband results in the thermostat setpoints of the TCAs being increased/decreased in proportion to the frequency deviation from the *nominal* value (6)

$$\tau_i^{new} = \begin{cases} \left(\dfrac{\Delta f}{O_r + D_b} \times \Delta\tau_i^{max}\right) + \tau_i^{old}, & if\ D_b \leq |\Delta f| \leq D_b + O_r \\ \Delta\tau_i^{max} \pm \tau_i^{old}, & if\ D_b + O_r \leq |\Delta f| \\ \tau_i^{old}, & Otherwise \end{cases} \tag{6}$$

Mechanism T3 provides a portion of the available DSR capability immediately as soon as the frequency exceeds the deadband, which is similar to T1 where 100% of the available DSR resource is provided at a frequency threshold. The remaining DSR resource is provided in proportion to the frequency deviation beyond the deadband in a manner similar to T2. It can be seen in Fig. 6 that strategy T3 results in an improved frequency nadir, as compared to T2, while DSR over-responsiveness is avoided, Fig. 7. All the system configurations mentioned in Table 1 are simulated for the respective loss of the largest infeed considering the three control strategies. It can be seen (Table 3) that threshold control, T1, provides the best improvement in the frequency nadir compared to no DSR. However, as demonstrated in Fig. 7, a change in the size of the contingency or the magnitude of the available DSR resource can lead to over-responsiveness under the T1 control mechanism. T2 eliminates the over-responsiveness for the considered cases, but results in a smaller improvement in the frequency nadir, while T3 provides a better improvement in the nadir while avoiding DSR over-responsiveness. Those cases with identical improvements for all triggering mechanisms in Table 3 follow from the system configurations (generation mix and contingency magnitude), whereby a fast rate of change of frequency due to low inertia contributes towards mitigating the inherent triggering delay differences between the mechanisms

It is clear that a DSR triggering strategy should not aim solely at maximising the improvement in the frequency nadir/zenith since it can potentially lead to a frequency overshoot, and the controller settings must be chosen with care. It is noteworthy that using a “fit & forget” approach aimed at maximising the improvement in frequency nadir, even for the frequency dependent triggering mechanisms (T2 & T3) in an over-frequency followed by an under-frequency (or vice versa) and oscillations in the system frequency may yet result in a frequency overshoot. This can happen due to the variability of the available demand resource, with time of day and time of year (dependent on ambient temperature), coupled with a very tight operating range. It may therefore be necessary to dynamically tune the control parameters depending on the system configuration and the flexible load magnitude.

3.5 System implications of DSR energy recovery

In order for DSR to represent a suitable replacement for POR from conventional generation, it should ideally be able to directly substitute for each MW of conventional generation. Conventional plant exhibit certain characteristics such as a sustained and frequency dependent response during POR provision. System operational

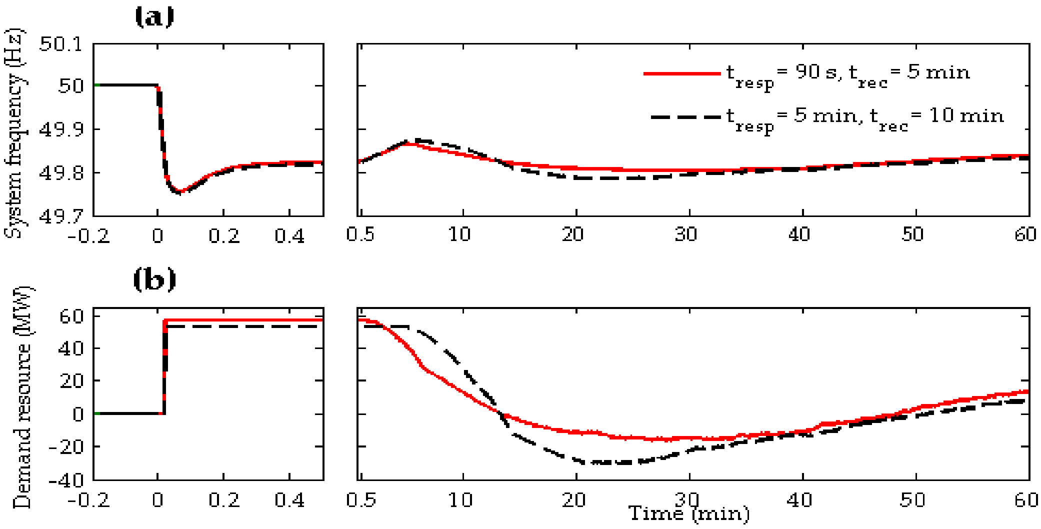

Fig. 8 Impact of DSR load coincidence (b) on frequency profile (a) (fixed response-time strategy – Case 3)

reserves are typically divided into categories (primary, secondary, tertiary, etc.) and are scheduled based on these characteristics. It is therefore critical to highlight differences between the behaviour of flexible load and conventional generation sources during the system recovery to a post-contingency state, and the associated implications for power system scheduling and operation. Flexible demand can be configured to provide a sustained response following the loss of a large infeed, similar to conventional plant, by following recovery strategy R1:

- *R1 – Fixed response time:* forced curtailment of flexible load for a fixed interval (fixed response time), followed by a random recovery period (recovery time)

Power draw from the appliances is disabled for a fixed period following a system contingency: longer *off* times result in an improved post-contingency frequency, but they also increase the load coincidence and individual appliance energy deficiency. Appliance recovery must be managed to avoid a sharp post-event increase in power draw, achieved by randomly restoring appliance normal operation within an activation window following a fixed off time called “recovery time”. Normal operation does not mean that an appliance will be on, merely that if temperature limits are exceeded then it can switch on. Fig. 8 illustrates the system frequency and load response for a fixed response time of 90 s (secondary reserve duration limit for the Irish power system) and 5 minutes (tertiary reserve duration), and with different recovery times when a 230 MW (not the largest infeed) generation trip occurs for case 3 (Table 1). Due to the stochastic nature of load, the available demand resource magnitude is slightly different in each case.

It can be observed in Fig. 8 that a longer fixed response time results in an improved (initial) frequency recovery, but this is followed by a deeper load recovery due to the impact of load coincidence and energy payback. This highlights the need for a revision of the secondary reserve targets to cater for the load recovery. Conventional plant reserve therefore cannot be directly substituted (without revision of secondary reserve

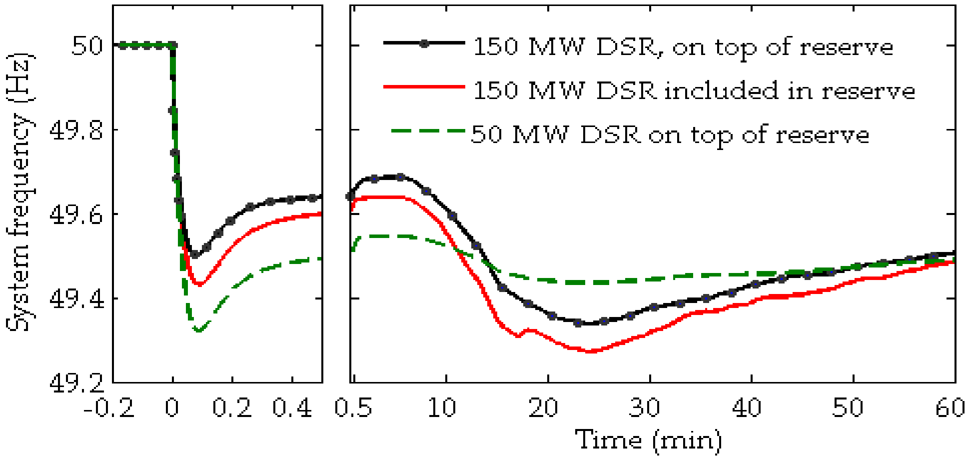

Fig. 9 Effect of “fit & forget” approach and DSR direct substitution (fixed response-time strategy – Case 3)

targets) with DSR. In addition, the fixed response time and activation window settings must recognise the available demand response: consider a 480 MW trip for the same case with a 5 minute fixed response time and a 10 minute activation window, for both a 50 MW (1.65 million appliances, 25 °C ambient temperature) and 150 MW (4.95 million appliances, 25 °C ambient temperature) resource, Fig. 9. In the latter case, during the recovery window, the frequency falls to 49.34 Hz which is lower than the initial nadir, 49.5 Hz (assuming no fast-starting generation is activated). The combination of fixed response time and activation window considered is clearly sub-optimal for the managing 150 MW of DSR. If, instead, the DSR is pre-scheduled (included in system reserve contribution), the frequency drops even further as the DSR displaces conventional sources of contingency reserve, triggering static load shedding of 25 MW after ≈16 min. This example serves to demonstrate the repercussions of directly substituting DSR for POR from conventional generation, without scheduling additional secondary reserves.

A sustained response is provided through R1 for a fixed period of time, without any regard to the system frequency and therefore falls short of effective restoration of the frequency following a contingency. Flexible load recovery can be linked to frequency, in a manner similar to conventional generation, using the following recovery mechanisms:

- *R2 – Droop control A (deadband):* appliance thermostat setpoint adjustment in proportion to the frequency deviation beyond a deadband (5).
- *R3 – Droop control B (nominal):* appliance thermostat setpoint adjustment in proportion to the frequency deviation from the *nominal* value (6).

The R2 & R3 load recovery options represent system frequency dependent mechanisms: droop control A (deadband) alters the appliance setpoints in proportion to the (local) frequency deviation beyond the deadband, resulting in a smaller initial flexible load magnitude (assuming tripping mechanism T2) as compared to droop

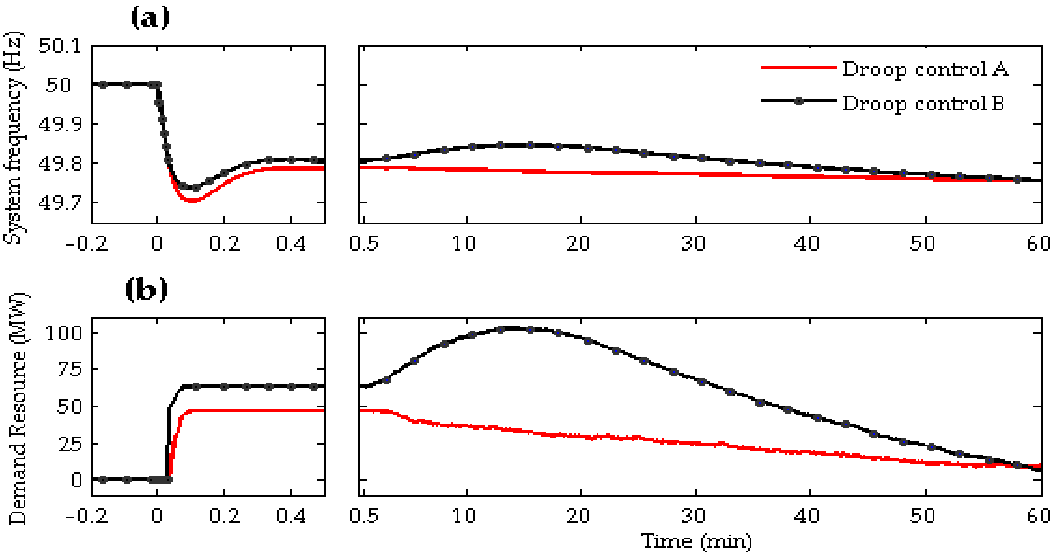

Fig. 10 (a) Frequency profile, (b) DSR resource (frequency dependent mechanisms – Case 4)

control B (nominal). Droop control A recovers the system frequency towards the deadband setting, while droop control B strives to recover the frequency to nominal. Consequently, droop control A provides a smaller response from the flexible load, both in terms of duration and magnitude.

Fig. 10(a) shows the frequency profile for a 250 MW trip (not the largest infeed) for case 4, with the deadband and operating range set at ± 0.2 Hz. Droop control B recovers the system to a higher frequency (49.85 Hz) as the thermostat setpoints in this case are raised to higher values. The thermostat settings do not recover back to their initial values as the system frequency does not reach its nominal value within the time period shown. In contrast, the thermostat setpoints for droop control A recover very close to their initial values when the system frequency reaches 49.8 Hz. The flexible load response for droop control B increases after about 5 minutes, although the corresponding thermostat setpoints remain almost the same, which occurs because, in the case of fridge/freezers, the *on* cooling down rate is higher than the *off* warming up rate. So, consequently, as the frequency falls and thermostat setpoints are raised *on* devices are switched *off*, but as the high setpoints persist increasingly more appliances switch *off*. The energy payback in this case is being deferred for longer as compared to R1, however as the system frequency recovers to nominal, thermostat limits return to normal, and increasingly more appliances switch *on*, which may need to be recognised as part of (secondary and) tertiary reserve targets. It can be seen in the R3 case, that although the post-event frequency restoration is adequate, Fig. 10(b), owing to the frequency dependent nature of the response, the magnitude of reserve provided is not governed entirely by the frequency but also depends on the appliance(s) internal dynamics. This introduces additional unpredictability in the flexible load profile, as opposed to the higher certainty of frequency dependent conventional generation reserve.

For all the recovery mechanisms, DSR resource seasonal variability impacts the system recovery due to load coincidence. Direct substitution of reserve from conventional sources by flexible load reserve can lead to undesirable frequency profiles in the form of double frequency nadirs, although revising secondary and tertiary reserve targets can mitigate this issue. Frequency dependent recovery mechanisms (R2 & R3) can provide a sustained and predictable flexible load response akin to conventional generation provided flexible load variability is recognised through control parameter updates, while secondary and tertiary reserve targets are revised recognising subsequent load coincidence and TCA setpoints are restored relatively quickly.

4. CONCLUSIONS

Utilisation of flexible demand for the provision of decentralised primary operating reserve has been considered using detailed thermodynamic models of fridge/freezers, being representative of thermostatically controlled appliances, and the Irish power system as a test system. Frequency based decentralised control of DSR using a “fit & forget” control approach is considered in this paper. Considering the non-dispatchable nature of decentralised DSR, this study highlights the effects of flexible TCA load variability on power system operation, while also quantifying the magnitude of the loss of load diversity, and the effect of controller hardware characteristics on the frequency nadir improvement. As opposed to previous studies, potential issues associated with using a “fit & forget”' DSR control approach using a number of system load, generation mix, contingency, flexible load magnitude scenarios and control strategies, following a contingency are highlighted.

The seasonal variation of the DSR resource significantly impacts the system nadir/zenith following a contingency. For the cases considered (Table I), on a summer day the nadir was improved, on average, by an additional 60% as compared to a winter day. The magnitude of the available DSR for a loss of load vs generation is inversely correlated. Therefore, the winter day improvement in the frequency zenith, on average was 18% more compared to a summer day, highlighting the need for asymmetrical DSR control for under & over-frequency events

Post-DSR load coincidence entails a consumption peak (for loss of generation contingencies), with the magnitude depending on flexible demand seasonality, appliance type and the duration of the response provided. The coincidence peak varies from ≈150% (5 min duration -- winter day) to 300% (25 min duration -- summer day) of the pre-event consumption, for the cases considered, indicating a significant impact on the system frequency profile in the post-contingency state. Direct substitution of reserve from conventional sources by flexible load reserve can lead to undesirable frequency profiles (such as a second “energy recovery”' nadir), due to an increased load coincidence and energy recovery. Effective utilisation of DSR for POR, therefore, requires a revision of secondary and tertiary reserve targets to cater for increased post-DSR load coincidence, along with recognition of the DSR based primary reserves in system reserve scheduling.

Triggering the entire demand resource at a particular frequency threshold, and so aiming to maximise the improvement in frequency nadir, can potentially lead to a subsequent over-frequency event which becomes particularly important at higher levels of technology penetration. A balance needs to be maintained between the improvement in the frequency nadir and flexible load responsiveness, possibly by staggering the demand response provision, akin to a conventional generator droop. The proposed triggering mechanism droop control B successfully provides a balance between an improvement in the frequency nadir and DSR responsiveness, by altering thermostat setpoints for individual appliances in proportion to the frequency deviation from the nominal value, beyond a deadband. It provides a 10% nadir improvement on average, compared to triggering mechanism droop control A, while avoiding an over-frequency result.

Failure to update DSR control parameters (deadband & operating range) as a result of flexible load variability, owing to its seasonal and diurnal variation, or an increase in the available response volume in the longer term, can lead to DSR under-responsiveness or frequency oscillations during the event and “double dip” nadir scenarios during the recovery period. Seamless integration of DSR for reserve provision, while maximising its inherent benefits, is possible by periodically updating the control parameters, if such a capability is available. These issues are more likely to appear at higher levels of technology penetration.

The DSR controller hardware characteristics significantly influence the system frequency nadir (difference of ≈0.2 Hz between the best and worst case). The improvement in the frequency nadir is dependent on the controller hardware response time as well as its resolution.

The results obtained in this work are generally scalable to other TCAs such as space heaters, water heaters and stand alone freezers. The test cases are conservative, as most temperature controlled loads will have a larger thermal inertia as compared to fridge/freezers, and so the recovery period and increased load coincidence will be less significant. Future work will look at the optimal balance between DSR based and conventional generation based reserve and a reconsideration of long-term system reserve targets, while considering DSR variability, post-DSR load coincidence and any energy recovery using co-ordinated tuning of flexible load control parameters, and the subsequent impact on system operational procedures.

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