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A Bespoke Frequency Response Service suitable for delivery by Flywheel Energy Storage Systems

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***Abstract*—With National Grid ESO introducing a suite of new Frequency Response Services for the GB electricity market, there is an opportunity to allow alternative energy storage systems to participate in the frequency response market on a level they have previously been able to do due to lack of energy capacity, degradation effects or other characteristics that restrict their ability to provide such services. In this study, the effects of varying the response envelope of the frequency response service on the performance of a standalone Flywheel Energy Storage System is assessed through year-long simulations in MATLAB/Simulink. In doing so, a new Frequency Response Service that would allow Flywheels and other high power, low energy storage devices to participate in the frequency response market as standalone systems is designed. This results in a 20C FESS achieving a 95% availability over the course of a year of operation, representing a excellent level of performance under existing market conditions. This work shows that a far wider range of energy storage mediums have the capability to provide meaningful contributions to grid frequency control than previously assumed.**

***Index Terms*—frequency control, flywheels, energy storage, grid services**

I. Introduction

Due to the intermittent nature of most renewable energy, the balance between demand and generation is becoming more difficult to manage. Many countries offer contracts for energy storage installations to participate in where they will either charge or discharge in relation to frequency deviations. In the UK, multiple frequency response services have been introduced to help keep the grid frequency within operational limits by National Grid ESO who operate the GB electricity grid.

Of the currently operating services, Dynamic Frequency Response (DFR) is one of the longest-standing [1]. It is a well established frequency response service aimed at continuously correcting any deviations from 50Hz that occur. A significant amount of Energy Storage has already been deployed and participated in this service.

Despite the service now being phased out to make way for a new suite of services, the extensive publicly available data provides an excellent basis to perform suitability assessments on the ability of energy storage to provide these services [2] [3]. There has been extensive research conducted using DFR as a benchmark, mainly using Battery Energy Storage Systems (BESSs) [4] [5] but less commonly exploring different technologies or distributed resources [6] [7]. In [6] it was determined that a standalone Flywheel Energy Storage System (FESS) could be economically viable in the 2.5C-5C range when costing no more than £400/kW.

To replace DFR, National Grid ESO are introducing a suite of three new frequency response services, namely Dynamic Containment (DC), Dynamic Regulation (DR) and Dynamic Moderation (DM) [8]. These three services are being introduced with different approaches to the objective of stabilising the frequency at 50Hz.

Some studies have already looked into the suitability of various energy storage systems to provide Dynamic Containment [9] [10]. In [11] the author presents an analysis of C-Rate (Equation 2) sensitivity on both availability (the total proportion of operational time that the ESS is able to provide the requested power) and non-compliance (the total proportion of operational time that the ESS falls outside of contract requirements such as state of energy). It was shown that for DC, a 5C generic energy storage system could deliver the service with average availability (Equation 1) in excess of 95% with a significant reduction in average availability when using C-Rates higher than this.

$$\text{Availability (\%)} = (1 - \frac{\text{Non-available time}}{\text{Total simulation time}}) \times 100 \quad (1)$$

$$\text{C-Rate} = \frac{\text{ESS Power (MW)}}{\text{ESS Energy Capacity (MWh)}} \quad (2)$$

BESSs are the most widely deployed energy storage medium that provides these services with BESSs either operational, under construction or planned totalling more than 16GW of capacity [12]. Crucially, they generally have a high energy capacity enabling them to provide the services for extended periods of time, therefore generating income over greater durations [13]. Additionally, for the new response services, there are stringent state of energy (SOE) requirements that must be met in order to participate, meaning shorter term

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energy storage is now unlikely to be able to participate in the frequency service market.

FESSs are generally high power and low energy storage systems, with low degradation and low maintenance requirements [14] but suffer from high self-discharge rates (spinning losses) relative to a BESS. For this reason, they are usually unsuitable to provide energy intensive services such as those discussed above. They have been extensively studied for use in hybrid systems [15] [16] where they can provide benefits such as longer BESS lifetime and additional economic value. Whilst studies have often looked at standalone or hybrid FESSs providing frequency response services, tailoring such a service to the characteristics of a FESS has not yet been presented.

This work presents for the first time an investigation into designing a bespoke frequency response service for FESSs to perform. The service is represented as a continuous 24/7 service and the effectiveness is determined by the average availability over a year of the service being provided. Availability is defined as in Equation 2 where it represents the total amount of time where the grid request is met as a proportion of overall operational time. Additionally, the energy throughput of the service has been assessed and compared with that provided by the existing frequency response services offered by National Grid ESO in order to verify that the system is operating for a sufficient amount of time to be worthwhile. The initial analysis is performed on a 1MW/1MWh/1C FESS system providing a 1MW service. Finally, a C-Rate sensitivity analysis has been performed to assess the effects of varying the C-Rate on the performance of the system.

II. Creating a Bespoke Response Envelope

In order to assess the suitability of a FESS to provide the frequency response services designed in this study, a MATLAB/Simulink model was used as outlined in previous works [17] [5]. GB grid frequency data consists of publicly available 1HZ sampled data from November 2020 to October 2021 [2]. The target for an effective service is that it should be available for a minimum of 95% of the operational time. However, the service should also be able to be reach this availability at higher C-Rates with many of the existing or in-development FESSs having C-Rates in the region of 4-20C. It should also provide a total energy throughput in the same order of magnitude as that which would be provided by existing services, which has been chosen as a design criteria to ensure that the service is operating frequently enough to contribute meaningfully to the balancing mechanism.

A baseline of how a 1MW/1MWh/1C FESS providing a 24/7 1MW service would perform delivering existing response profiles is shown in Table I. Of the existing service profiles Dynamic Moderation would provide the most suitable envelope to be delivered by the FESS, whilst also providing the lowest total energy throughput over the year of operation. Dynamic Regulation is the worst performing as the only service below 95% average availability. It should be noted that 24/7 delivery of these services is not practical under current market and service contract conditions, but it is included here as a representative benchmark for how the FESS can perform for different response profiles.

TABLE I
Baseline results from a 1MWh/1MW/1C FESS providing 1MW of the existing frequency response services

	Metrics	
Service	***Availability***	***Energy Throughput (MWh)***
DFR	97.4%	627.4
DC	97.8%	83.9
DR	94.7%	1545.8
DM	98.7%	338.4

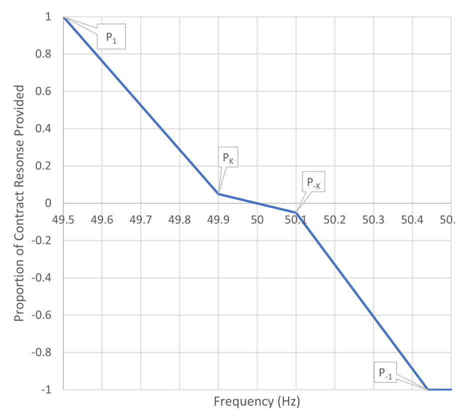

Fig. 1. Response envelope example showing the points in the envelope that are varied for the initial and knee-point analysis

Additionally, DC is represented as performing both DC high and DC low concurrently for the same reason. The services designed in this study are proposed as 24/7 services as for FESSs, it is undesirable for it to be inactive for long periods of time due to spinning losses incurred and would therefore be more beneficial for it to be continuously operating. Finally, a deadband (zone where no power is imported or exported) between 49.985Hz and 50.015Hz is present at all times to mimic the most common approach taken by existing response envelopes and prevent excessive low power cycling.

The initial analysis of a bespoke frequency response envelope consisted of varying the 100% power point (P_1 and P_{-1} on Fig 1) for both the low and high frequency ends of the spectrum with a 1MWh/1MW/1C system providing a 1MW service. Both Dynamic Containment and Dynamic Moderation have 'Knee Points' where up to a certain frequency the power delivery is a small proportion of the overall contracted service, followed by a linear rise to the maximum power point. The knee-point analysis section of the study focuses on placing a knee point into the response envelope and how this effects the average availability. For this analysis, the points P_K and P_{-K} on Fig. 1 are varied in a similar manner to the initial analysis.

A. Initial Analysis

A year long simulation was conducted for each combination of P_1 and P_{-1} between 49.5-49.9Hz and 50.1-50.5Hz respec-

TABLE II

AVERAGE AVAILABILITY FOR VARYING HIGH AND LOW FREQUENCY 100% POWER POINTS WITH THE 10 COMBINATIONS RESULTING IN THE HIGHEST AVERAGE AVAILABILITY HIGHLIGHTED BY A BLACK OUTLINE

Average Availability		Higher Frequency 100% Power Point (Hz)																				
		50.1	50.12	50.14	50.16	50.18	50.2	50.22	50.24	50.26	50.28	50.3	50.32	50.34	50.36	50.38	50.4	50.42	50.44	50.46	50.48	50.5
Lower Frequency 100% Power Point (Hz)	49.9	91.2%	91.0%	90.5%	89.8%	89.0%	88.3%	87.6%	86.9%	86.4%	85.9%	85.4%	85.0%	84.7%	84.4%	84.1%	83.8%	83.6%	83.4%	83.2%	83.0%	82.8%
	49.88	92.0%	92.1%	91.8%	91.3%	90.6%	89.9%	89.1%	88.4%	87.8%	87.2%	86.7%	86.2%	85.8%	85.5%	85.1%	84.8%	84.6%	84.3%	84.1%	83.9%	83.7%
	49.86	92.2%	92.8%	92.9%	92.6%	92.0%	91.4%	90.6%	89.8%	89.1%	88.5%	87.9%	87.4%	87.0%	86.5%	86.2%	85.8%	85.5%	85.2%	85.0%	84.7%	84.5%
	49.84	92.2%	93.1%	93.5%	93.6%	93.3%	92.7%	92.0%	91.2%	90.5%	89.8%	89.2%	88.6%	88.1%	87.6%	87.2%	86.8%	86.5%	86.1%	85.9%	85.6%	85.3%
	49.82	91.9%	93.0%	93.8%	94.2%	94.2%	93.8%	93.3%	92.5%	91.8%	91.1%	90.4%	89.8%	89.2%	88.7%	88.2%	87.8%	87.4%	87.0%	86.7%	86.4%	86.1%
	49.8	91.5%	92.8%	93.8%	94.5%	94.8%	94.7%	94.3%	93.7%	92.9%	92.2%	91.5%	90.9%	90.3%	89.7%	89.2%	88.7%	88.3%	87.9%	87.5%	87.2%	86.9%
	49.78	90.9%	92.3%	93.5%	94.5%	95.0%	95.2%	95.1%	94.7%	94.1%	93.3%	92.6%	92.0%	91.3%	90.7%	90.2%	89.6%	89.2%	88.8%	88.4%	88.0%	87.7%
	49.76	90.4%	91.8%	93.1%	94.2%	95.0%	95.5%	95.6%	95.5%	95.0%	94.4%	93.7%	93.0%	92.3%	91.7%	91.1%	90.6%	90.1%	89.6%	89.2%	88.8%	88.4%
	49.74	89.9%	91.3%	92.6%	93.8%	94.8%	95.5%	95.9%	96.0%	95.8%	95.3%	94.7%	94.0%	93.3%	92.7%	92.0%	91.5%	90.9%	90.5%	90.0%	89.6%	89.2%
	49.72	89.4%	90.7%	92.1%	93.3%	94.4%	95.3%	95.9%	96.3%	96.3%	96.0%	95.5%	94.9%	94.2%	93.6%	93.0%	92.3%	91.8%	91.3%	90.8%	90.3%	89.9%
	49.7	88.9%	90.3%	91.5%	92.8%	93.9%	94.9%	95.7%	96.3%	96.6%	96.6%	96.2%	95.7%	95.1%	94.5%	93.8%	93.2%	92.6%	92.1%	91.6%	91.1%	90.7%
	49.68	88.5%	89.8%	91.0%	92.3%	93.4%	94.5%	95.4%	96.1%	96.7%	96.9%	96.8%	96.4%	95.9%	95.3%	94.7%	94.1%	93.4%	92.9%	92.3%	91.8%	91.4%
	49.66	88.2%	89.4%	90.6%	91.7%	92.9%	94.0%	94.9%	95.8%	96.5%	97.0%	97.2%	97.0%	97.0%	96.1%	95.5%	94.9%	94.3%	93.6%	93.1%	92.6%	92.1%
	49.64	87.8%	89.0%	90.2%	91.3%	92.4%	93.4%	94.5%	95.4%	96.1%	96.8%	97.3%	97.4%	97.2%	96.8%	96.2%	95.6%	95.0%	94.4%	93.8%	93.3%	92.8%
	49.62	87.5%	88.6%	89.8%	90.9%	91.9%	93.0%	94.0%	94.9%	95.7%	96.5%	97.1%	97.6%	97.6%	97.3%	96.9%	96.4%	95.8%	95.2%	94.6%	94.0%	93.5%
	49.6	87.2%	88.3%	89.4%	90.4%	91.5%	92.5%	93.5%	94.4%	95.3%	96.1%	96.8%	97.4%	97.8%	97.8%	97.4%	97.0%	96.5%	95.9%	95.3%	94.7%	94.2%
	49.58	86.9%	88.0%	89.1%	90.1%	91.1%	92.0%	93.0%	93.9%	94.8%	95.6%	96.4%	97.0%	97.6%	98.0%	97.9%	97.6%	97.1%	96.6%	96.0%	95.4%	94.9%
	49.56	86.7%	87.7%	88.8%	89.7%	90.7%	91.6%	92.6%	93.4%	94.4%	95.2%	96.0%	96.6%	97.3%	97.8%	98.1%	98.0%	97.7%	97.2%	96.7%	96.1%	95.5%
	49.54	86.5%	87.5%	88.5%	89.4%	90.3%	91.3%	92.2%	93.0%	93.9%	94.7%	95.5%	96.2%	96.9%	97.5%	97.9%	98.3%	98.1%	97.8%	97.3%	96.7%	96.2%
	49.52	86.3%	87.2%	88.2%	89.1%	90.0%	90.9%	91.8%	92.6%	93.4%	94.3%	95.1%	95.8%	96.5%	97.1%	97.7%	98.2%	98.4%	98.2%	97.8%	97.4%	96.8%
	49.5	86.1%	87.0%	88.0%	88.8%	89.7%	90.6%	91.4%	92.2%	93.0%	93.8%	94.6%	95.4%	96.1%	96.8%	97.4%	97.9%	98.4%	98.5%	98.3%	97.9%	97.4%

tively. The results of this simulation are shown in Table II.

It is immediately apparent that as the 100% power point is moved further from 50Hz in both directions the average availability steadily increases. From a symmetrical 49.9/50.1Hz combination giving an average availability of 91.2%, the combination of 49.5/50.5Hz provides an average availability of 97.4% showing a significant improvement.

There is also a degree of asymmetry to the results, with a higher availability produced when the high frequency 100% power point is reached sooner than the low frequency 100% power point. This leads to the maximum availability of 98.5% being achieved with a combination of 49.5Hz and 50.44Hz. However, if the asymmetry is increased too far then the average availability experiences a rapid reduction.

This asymmetry is due to the FESS experiencing spinning losses. By having a steeper charging curve, the spinning losses are constantly being countered with more energy being taken from the grid than discharged back. In this manner, the response envelope being slightly asymmetric uses the spinning losses to its advantage.

Taking this assessment as a baseline, the best performing 100% power point combination was used to perform a C-Rate sensitivity analysis. The C-Rate was increased incrementally up to a value of 20C with the results of this analysis shown in Figure 2. There is a significant drop in average availability as the C-Rate is increased, with only a 1C and 2C system achieving average availability in excess of the required 95%. This suggests that the suitability of the envelope to more common FESS system characteristics like high power and low energy is poor and needs further tuning to enable it to perform at higher C-Rates.

B. Knee Point Analysis

The maximum power points are set as 49.5Hz and 50.44Hz (points P_1 and P_{-1} respectively on Figure 1) as determined in the previous section, with the power level of the knee-point set as 0.05% of the overall contracted service, replicating the setting used by DC and DM. The low and high knee-point frequencies (points P_K and P_{-K} on Fig. 1) are then varied between 49.85-49.95Hz and 50.05-50.15Hz respectively

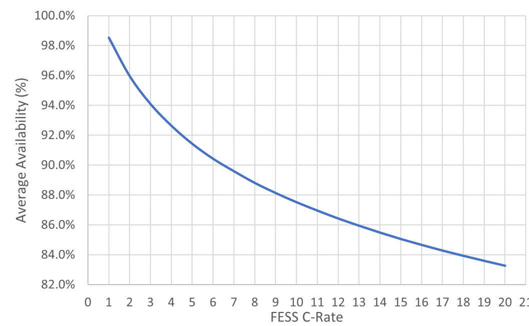

Fig. 2. C-Rate sensitivity analysis when utilising 100% power points of 49.5/50.44Hz with a 1MW/1MWh/1C FESS providing a 1MW service

in increments of 0.01Hz. The results of this analysis are shown in Table III.

The average availability once again increases as the knee-point is moved further away from 50Hz before decreasing again after a peak at 49.91/50.09Hz. In 90.08% of simulated combinations the average availability was reduced by adding in a knee point. Despite this, some of the combinations represent a significant increase in average availability, peaking with the combination of knee points at 49.87Hz and 50.12Hz which provides an average availability of 99.89% across the year, meaning it will fail to meet the requested power of the grid for less than 10 hours over the course of the year. This combination shows again the benefits of small asymmetry within the response envelope, causing the FESS to charge slightly more often than it discharges.

The total energy throughput for the year was also monitored during this assessment, with the values ranging from 518.4MWh (49.95/50.05Hz knee points) to 118.1MWh (49.95/50.15Hz knee points). For the combination that provided the highest average availability (49.87/50.12Hz), the total energy throughput was 160.9MWh, which would place it between the levels of energy provided by Dynamic Moderation (83.9MWh) and Dynamic Containment (371.0MWh). This suggests that it operates sufficiently over the course of a year to be providing a worthwhile service to the GB Grid. Figure

TABLE III

AVERAGE AVAILABILITY FOR VARYING HIGH AND LOW FREQUENCY KNEE POINTS WITH THE 10 COMBINATIONS RESULTING IN THE HIGHEST AVERAGE AVAILABILITY HIGHLIGHTED BY A BLACK OUTLINE

Average Availability		High Frequency Knee Point (Hz)										
		50.05	50.06	50.07	50.08	50.09	50.10	50.11	50.12	50.13	50.14	50.15
Low Frequency Knee Point (Hz)	49.95	97.65%	95.90%	93.32%	91.17%	89.40%	87.96%	86.82%	85.80%	85.12%	84.58%	84.13%
	49.94	97.99%	98.71%	95.99%	93.48%	91.42%	89.78%	88.45%	87.25%	86.46%	85.83%	85.30%
	49.93	95.73%	98.12%	98.82%	96.11%	93.69%	91.75%	90.22%	88.84%	87.92%	87.15%	86.55%
	49.92	93.70%	95.93%	98.31%	98.85%	96.22%	93.96%	92.14%	90.53%	89.48%	88.61%	87.88%
	49.91	92.03%	94.01%	96.22%	98.54%	98.86%	96.33%	94.25%	92.33%	91.08%	90.11%	89.31%
	49.9	91.18%	92.51%	94.46%	96.59%	98.80%	98.81%	96.05%	94.27%	92.81%	91.66%	90.72%
	49.89	90.10%	91.31%	93.05%	94.98%	96.99%	99.09%	98.24%	96.22%	94.61%	93.27%	92.20%
	49.88	89.22%	90.37%	91.95%	93.66%	95.55%	97.87%	99.43%	98.17%	96.35%	94.91%	93.69%
	49.87	88.54%	89.62%	91.10%	92.67%	94.37%	96.48%	97.99%	99.89%	98.10%	96.46%	95.18%
	49.86	87.97%	89.02%	90.39%	91.87%	93.40%	95.37%	97.05%	98.71%	99.79%	98.01%	96.55%
	49.85	87.50%	88.75%	89.81%	91.19%	92.64%	94.16%	95.77%	97.38%	98.93%	99.69%	98.06%

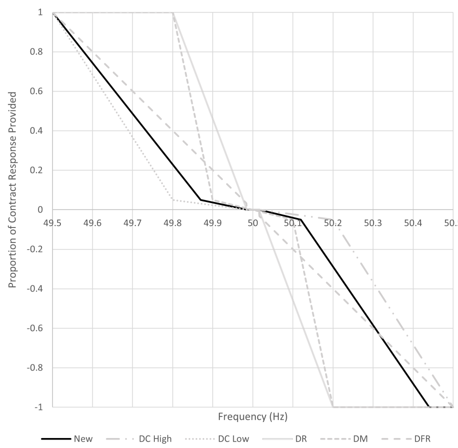

Fig. 3. New frequency response envelope most suitable for provision by a 1MW/1MWh/1C FESS providing a 1MW service with existing frequency response service envelopes shown for reference

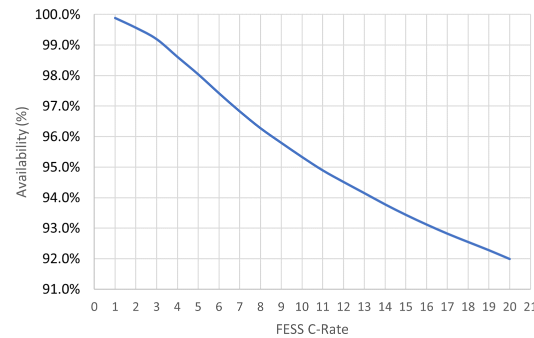

Fig. 4. C-Rate sensitivity analysis when utilising the response envelope shown in Figure 5 with a 1MW/1MWh/1C FESS providing a 1MW service

3 shows the resulting response envelope with the existing services shown for reference.

From Figure 3, it can be seen that the response envelope created falls somewhere in the middle of existing services, showing that it could operate in a region where there is not currently a comparable service.

Following on from introducing a knee point, a second C-Rate sensitivity analysis was conducted with the results of this shown in Figure 4. Compared with the analysis shown in Fig.2 there is a much more shallow reduction in availability as the C-Rate is increased. At 10C (0.1MWh/1MW) there is still an average availability above 95% whilst still providing 138.54MWh of energy throughput across the year, showing that it is possible to have a high power, low energy FESS that can provide an effective frequency response service.

C. Higher C-Rate Analysis

A final study was conducted to optimise the response envelope for different FESS C-Rates. The key criteria was achieving the highest availability possible whilst attempting to match, or improve upon, the lowest energy throughput provided by an existing service (83.9MWh - Dynamic Containment). An example of how this was conducted for a 5C system is shown in Table IV and Table V. In Table IV, the cells are highlighted to show the highest average availability in green, trending downwards to the lowest availability in red. In Table V, the green cells are highlighted as achieving a higher overall energy throughput than the equivalent Dynamic Moderation service whilst the cells highlighted in red fall short of achieving this.

TABLE IV

EXCERPT OF AVERAGE AVAILABILITY BASED KNEE-POINT OPTIMISATION FOR A 5C SYSTEM

Average Availability for 5C System		Specifications			
		50.18	50.19	50.2	50.21
Low Frequency Knee Point (Hz)	49.81	98.57%	97.66%	96.77%	95.98%
	49.8	99.24%	98.51%	97.66%	96.83%
	49.79	99.21%	99.25%	98.50%	97.69%
	49.78	98.63%	99.34%	99.21%	98.47%
	49.77	98.01%	98.81%	99.47%	99.18%

This analysis showed that whilst the average availability can be increased further, the energy throughput would then be decreased further. The combinations where the energy throughput falls below the desired level are discounted, with the highest availability from the remaining combinations taken as the best option. This optimisation balances the two to provide the most suitable overall service for each C-Rate.

TABLE V
EXCERPT OF ENERGY THROUGHPUT BASED OPTIMISATION OF A 5C SYSTEM

Energy Throughput (MWh) for 5C System		High Frequency Knee Point (Hz)			
		50.18	50.19	50.2	50.21
Low Frequency Knee Point (Hz)	49.81	93.55	88.33	83.50	79.17
	49.8	92.44	87.92	83.36	79.14
	49.79	89.65	87.30	83.20	79.11
	49.78	85.67	85.20	82.67	78.90
	49.77	81.85	81.66	81.17	78.57

TABLE VI
RESULTS OF C-RATE BASED OPTIMISATION OF THE RESPONSE ENVELOPE KNEE POINTS

C-Rate	Metrics			
	Low Knee Point (Hz)	***High Knee Point (Hz)***	***Availability***	***Energy (MWh)***
1	49.87	50.12	99.89%	143.88
5	49.78	50.19	99.34%	85.20
10	49.79	50.18	97.80%	85.63
15	49.80	50.17	95.93%	85.68
20	49.78	50.18	95.00%	76.05

It should be noted however that if energy throughput was removed as a constraint then further increases in average availability could be achieved, albeit with the system providing less energy to and from the grid. For instance, in Table IV and Table V, a higher average availability could be achieved using the combination of 49.77/50.2Hz but would result in a loss of 4.03MWh of energy throughput across the year, for just a 0.13% increase in average availability. The results of the study for a 5C, 10C, 15C and 20C system are shown in Table VI, with the 1C results determined previously included for reference.

These results show that for different C-Rates slight variations on the high and low knee points are required to extract the best combination of average availability and energy throughput. By tailoring the knee points to the C-Rate being considered, a 20C system was able to achieve a 95% availability, albeit with a slightly lower energy throughput than desired. The outcome of this study shows that with a small amount of versatility in response envelope, much higher C-Rate systems can provide standalone frequency response services.

III. CONCLUSIONS

In this paper, a bespoke frequency response service has been designed and analysed. When considering a baseline 1MW/1MWh/1C system providing a 1MW service, a peak average availability of 99.89% can be achieved when operating the service 24/7 delivering the response envelope shown in Fig. 3. Subsequently, this response envelope has been investigated for different FESS C-Rates. It has been shown that different FESS C-Rates require slightly different response profiles in order to extract maximum performance benefits. By using these small modifications to the response profile, a 20C FESS can achieve a average availability of 95%. The research presented in this paper has the potential to open up the frequency response market to a much wider range of energy storage mediums such as FESSs and Super-capacitors than has been previously been suggested. Future work should further consider the C-Rate based optimisation of the response envelopes and assess the economic case.

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