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Suitability Assessment of Flywheel Energy Storage Systems for providing new Frequency Response Services in the UK

1st Andrew. J. Hutchinson
Dept. of Electrical and Electronic Engineering
University of Sheffield
Sheffield, United Kingdom
ahutchinson1@sheffield.ac.uk

2nd Daniel. T. Gladwin
Dept. of Electrical and Electronic Engineering
University of Sheffield
Sheffield, United Kingdom
d.gladwin@sheffield.ac.uk

***Abstract*—National Grid ESO has recently introduced three new frequency response services to the UK electricity market. The three services are Dynamic Containment (DC), Dynamic Regulation (DR) and Dynamic Moderation (DM). Each service has individual performance requirements and restrictions. This paper looks for the first time at how Flywheel Energy Storage Systems (FESSs) can be used to supply these services. Sensitivity analyses have been performed for each service to assess the suitability of FESSs of differing C-Rates to participate. It has been demonstrated that a FESS rated up to 18C is able to provide an average availability above 95% when performing high and low DC simultaneously, with the same threshold being reached up to 4C for DM. None of the C-Rates analysed were able to reach this threshold when performing DR. Hybridisation is shown to introduce performance benefits to the systems, allowing higher C-Rate systems to reach the 95% threshold than when performing individually.**

***Index Terms*—Energy storage, Flywheels, Frequency Response, control schemes**

I. Introduction

RECORD levels of renewable generation are currently being produced in the GB grid, with 19.6GW of wind generation being produced on 29th January 2022 [1]. This ever increasing penetration of renewable generation is leading to increased instability within the grid, as the intermittent nature of the generation combined with a changing landscape of electricity consumption causes wider gaps between demand and generation than ever before.

The introduction of a new suite of frequency response services in 2021 was brought about due to this increasing instability in the GB electricity grid, with frequency deviations away from 50Hz becoming more common and more severe. New frequency response services aim to provide a more flexible range of faster acting mechanisms that will stabilise the grid frequency and allow a greater range of energy providers to participate [2].

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The new services, either already launched or awaiting deployment, consist of Dynamic Containment (DC), Dynamic Regulation (DR) and Dynamic Moderation (DM). The introduction of these new services represents an opportunity for different energy storage mediums to participate in the frequency response market compared to the existing service of Dynamic Frequency Response (DFR) which, in recent years, has been dominated by Battery Energy Storage Systems (BESSs) [3].

Energy storage systems (ESSs) have long been used to provide these frequency response services. Whilst BESSs dominate the deployed mediums of energy storage in the UK, other types of energy storage have also been deployed for this application including hydro-power stations [4]. This study will focus on BESS and Flywheel Energy Storage Systems (FESSs). Table I compares the key characteristics between the two energy storage mediums.

In this study, the services are represented as 24/7 delivery without considering partial-day block tendering or baseline energy management that would be required when providing the service in real-world conditions. This study instead focuses on the suitability of the response envelopes for delivery by Flywheels and shows for the first time how FESSs of varying C-Rates could provide these services. The response envelope is one of the key defining characteristics of a frequency response service, and directly effects the flow of energy to and from the storage system. It is therefore important to consider how a certain storage medium operates under each response envelope without operational restrictions as this study does in order

TABLE I
Selected Li-ion BESS and FESS Characteristics

	Li-Ion Battery	Flywheel
Timescale	Hours-Days	Seconds-Minutes
Cycle lifetime	1,000-10,000	100,000-1,000,000
Efficiency	∼90%	∼95%
Self-dischare	∼1.5% per month	10-20% per hour

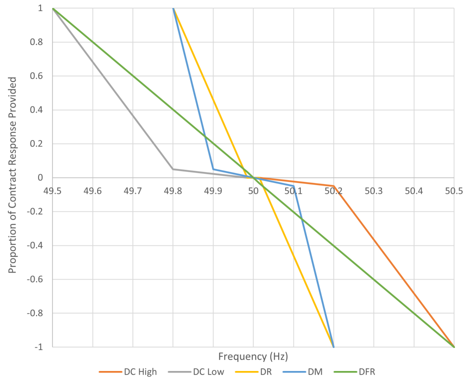

Fig. 1. Response envelope for Dynamic Containment High and Low, Dynamic Moderation, Dynamic Regulation and Dynamic Frequency Response

TABLE II
SELECTION OF FLYWHEEL ENERGY STORAGE SYSTEMS EITHER COMMERCIALLY AVAILABLE OR IN DEVELOPMENT

Manufacturer	Specifications		
	C-Rate	Energy Capacity per flywheel	Power Capacity per flywheel
Amber Kinetics	0.25	32kWh	8kW
OXTO Energy	13C	5kWh	65kW
Stornetic	23-65C	2-2.3kWh	60-120kW
Vycon	240C	0.52kWh	125kW

to determine it's overall potential at providing said service. Figure 1 shows the response envelope of the services being discussed in this paper.

A. Flywheel Energy Storage Systems

Flywheels are a short-duration energy storage medium, typically storing energy for only seconds or minutes at a time. One of the reasons they are most commonly used in this way is the high self-discharge rate [5]. However, they are also highly resilient to cycle based degradation, meaning that they can be charged and discharged multiple times in a short time span without effect upon the lifespan of the system [6]. Flywheels are often characterised by their high C-Rates and low energy individual units. C-Rate is defined as in Equation 1.

$$\text{C-Rate} = \frac{\text{ESS Power (MW)}}{\text{ESS Energy Capacity (MWh)}} \tag{1}$$

The majority of energy storage systems that are either already available or being commercially developed have a high C-Rate and low energy capacity per unit. However, there are some instances of more energy centric systems being developed suggesting potential for them to be deployed in energy intensive application such as frequency response. Table II shows a selection of commercial available or in development FESSs.

FESSs have been studied in a wide range of different applications [7] [8]. The high cycle life and high power means that there are many power based applications highly suited for deploying flywheels in, such as meeting short-duration very high power demands [9], responding to voltage drops and variations in a system [10] or being hybridised with other systems to extend operational lifetimes [11].

The Flywheel Energy Storage system presented in this paper has been developed in MATLAB/Simulink in partnership with a Flywheel Manufacturing company using the specifications of their system.

TABLE III
DYNAMIC CONTAINMENT SERVICE PARAMETERS

Service Specification	Detail
Dead-band	49.985Hz to 50.015Hz
Dead-band delivery	0%
Initial delivery	Between 0.015Hz and 0.2Hz up to 5% of rated power at 0.2Hz
Knee point	+/- 0.2Hz
Full delivery	+- 0.5Hz

B. Dynamic Containment

Dynamic Containment was introduced in 2021 primarily as a post-fault service designed to react more quickly to frequency deviations [2]. The key operational feature of this service is that it only provides up to 5% of the rated power when the frequency is +/-0.2Hz from 50Hz hence the overall power output is considerably lower. This means there is a comparatively large 'dead-band' compared with DFR. Additionally, no charge management is allowed within the dead-band, with any charge management required being managed by submitting a baseline power for the following 1 hour delivery period. However, this baseline power must not take away from the available contracted power. For instance, a 10MW ESS would only be able to provide 9MW of contracted power should the asset need to reserve 1MW for baseline power charge management. Reducing the contracted power available for service delivery reduces the revenue potential of the asset and is therefore not desirable. Full details of the Dynamic Containment service specification are shown in Table III.

A sensitivity analysis for varying levels of energy capacity and C-Rates delivering Dynamic Containment was conducted in [12]. This paper determined that DC is generally a less demanding service than DFR, and that higher C-Rates (up to 10C) could be utilised effectively to provide the service. This suggests that there is a significant opportunity for short term energy storage such as Flywheels to provide this service. However, when considering the contract service delivery terms of Dynamic Containment the paper suggests that the higher c-rate systems struggle with maintaining compliance due to long duration frequency events where there is not enough energy in the ESS. This paper develops this work to analyse the terms of service to determine under what conditions a FESS could provide a standalone service.

C. Dynamic Moderation

This service is designed to operate pre-fault managing larger imbalances in demand and generation when the frequency

TABLE IV
DYNAMIC MODERATION SERVICE PARAMETERS

Service Specification	Detail
Dead-band	49.985Hz to 50.015Hz
Dead-band delivery	0%
Initial delivery	Between 0.015Hz and 0.1Hz up to 5% of rated power at 0.2Hz
Knee point	+/- 0.1Hz
Full delivery	+- 0.2Hz

TABLE V
DYNAMIC REGULATION SERVICE PARAMETERS

Service Specification	Detail
Dead-band	49.985Hz to 50.015Hz
Dead-band delivery	0%
Knee point	+/- 0.015Hz
Full delivery	+- 0.2Hz

trends towards the limits of operational range and was introduced in May 2022 [13]. The ESS is required to deliver 30-minutes of service at any one time without the need to recharge. For instance, a 10MW service may be contracted to deliver a low frequency response service and hence must have a minimum energy requirement of 5MWh.The service parameters are shown in Table IV

Dynamic Moderation has the potential to suit the high dynamic power capability of a FESS, however, the high minimum duration of 30-minutes will likley result in periods of non-compliance due to insufficient energy storage.

D. Dynamic Regulation

Dynamic Regulation is also designed to operate as a pre-fault service continuously correcting smaller deviations in frequency and was introduced in April 2023 [14]. The ESS is required to provide 1 hour of continuous service without the need to recharge in any given direction. For instance, a 10MW service may be contracted to deliver a low frequency response service and hence must have a minimum energy requirement of 10MWh. All systems are obliged to recover at least 20% of the total energy requirement in a following settlement period. The service parameters are shown in Table III.

Due to the 1 hour requirement of continuous service, along with a minimum 1C energy capacity, it is unlikely that Flywheels will be able to provide this category of service as it has been proposed. Higher energy capacity assets such as BESSs would be best suited to provide this service. This study will consider under what specification of Flywheel would be required when using this response envelope to provide a viable level of availability and energy throughput.

II. SERVICE ANALYSIS

For the purposes of this study, the services will be viewed as operating on a 24/7 basis. This will give a solid foundation upon which to determine the potential effectiveness of FESSs providing each service. This has been used previously in studies [12] [15] [16] to produce reliable results on system performance. The main metrics to be assessed will be as follows;

- Availability - The total duration of time where the ESS output matches the request as a proportion of operational time, as shown in Equation 2. This metric plays a key role in existing services, in determining whether an ESS installation will be paid for it's operation. The targeted average availability is 95%. An ESS may become 'unavailable' due to reaching high or low state of charge (SOC) limits and hence being unable to charge or discharge any further.
- Energy Throughput - The total amount of energy that passes through the ESS. This is an important metric to track when considering energy limited storage such as Flywheels, as it gives insight into how often the ESS is asked to operate.
- Energy Delivery Proportion (EDP) - The total energy throughput of the ESS as a proportion of the overall energy requested by the service as given in Equation 3.

$$\text{Availability (\%)} = (1 - \frac{\text{Non-available time}}{\text{Total simulation time}}) \times 100 \quad (2)$$

$$\text{EDP (\%)} = (1 - \frac{\text{ESS Energy Throughput}}{\text{Requested Energy Throughput}}) \times 100 \quad (3)$$

The analysis has been carried out in MATLAB/Simulink using a bucket model of a FESS that includes both the efficiencies throughout the system and the mechanical spinning losses of the flywheel. . The model used has been previously presented in more depth in multiple papers [17] [15]. The simulation uses frequency data from November 2020 to October 2021 [18]. The system has been studied providing a 1MW service under each response envelope, with the FESS maximum power set as 1MW and the C-Rate subsequently varied between 1C and 20C.

The average availability for varying C-Rates of FESS under the different service parameters is shown in Figure 2. For all services, the average availability peaks when being provided by a 1C system before falling as the C-Rate is increased. The 1C FESS achieves the best average availability when performing DM, reaching 98.69% availability, whilst once the C-Rate is increased beyond this the FESS is best at performing DC. The FESS can provide an average availability above 95% for C-Rates up to and including 18C when performing DC, up to and including 4C for DM, and fails to reach that threshold under any C-Rate for DR.

Figure 3 can be used to inform the results from Figure 2. It shows that the energy throughput for DR is significantly higher than for either DM or DC, which is a key reason for the lowered average availability, especially at the higher C-Rates (which have lower energy capacity). It can also be seen that there is a significant drop off in overall EDP as the C-Rate is increased, representing the FESS no longer having enough energy capacity to handle the requests of the service.

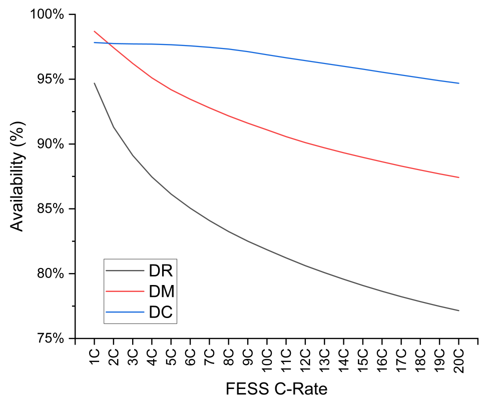

Fig. 2. Average availability of a year long simulation for varying FESS C-Rates performing DC, DR and DM

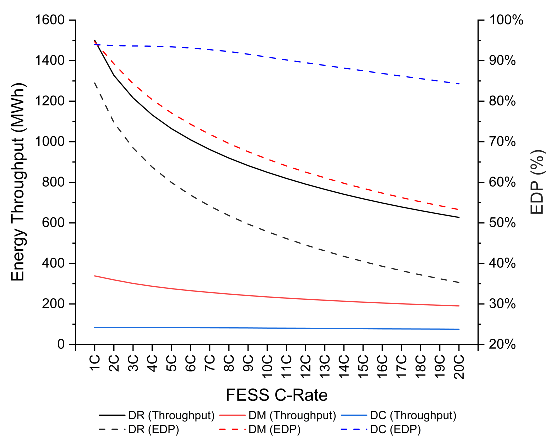

Fig. 3. Energy Throughput (MWh) and EDP (%) from a year long simulation for varying FESS C-Rates performing DC, DR and DM

A key takeaway from this graph is that at the higher FESS C-Rates, the FESS is unable to deliver high power responses for extended periods but is able to respond adequately when the frequency deviations are small, thus reducing the energy throughput and EDP severely whilst only resulting in a modest reduction in average availability. For instance, at 20C, a FESS provides only 35.3% EDP over the year, but the availability is significantly higher at 77.1%, suggesting that the system is only managing to respond when the deviations are small and subsequently highlighting that whilst the availability remains high, the system is not providing the service required of it by the response envelope. The EDP suggests that for DC, the FESS is able to provide a significant portion of the requested energy regardless of C-Rate as the EDP starts at 94.0% for 1C and only falls to 84.3% for 20C. This is in contrast to the rapid decreases in EDP for DR and to a lesser extent DM.

III. Hybridisation with a BESS

In order to achieve a higher level of average availability, a small amount of Battery Energy Storage

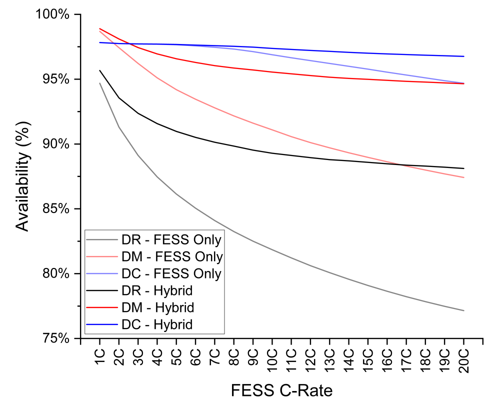

Fig. 4. Average availability during a year long simulation for varying FESS C-Rates performing DC, DR and DM both alone and hybridised with a 0.1MWh/0.1MW/1C BESS

(0.1MWh/0.1MW/1C) was introduced to hybridise the system. The control was set to exclusively use the FESS to respond to the power demands, with the BESS only being requested to provide power if the FESS was not able to. The BESS will therefore only cover requests where it can either 'top-up' the FESS delivery by 0.1MW to deliver the requested power, or where the FESS cannot provide any power, the request must be 0.1MW of either charging or discharging power for the BESS to be able to meet it. For this study, average availability and EDP will be considered as the primary metrics of if and how the addition of a BESS improves the service.

In Figure 4 it can be seen that for all services there is an increase in availability when a BESS is introduced, as is to be expected. For some services this increase is more significant than others. For example, when DR is considered, at the low C-Rate end of the analysis there is a minimal increase in average availability with an increase of 0.98% being seen at 1C, whilst a peak increase of 10.97% is seen at 20C. For DC however, the impact is minimal, suggesting that hybridising for this service would not be worthwhile as the increase to availability only reaches a peak of 2.1% at 20C. The effect for DM falls between the two other services, with a moderate increase being achieved across the C-Rates by introducing the BESS, peaking at an increase of 7.3% at 20C.

Following on from this, Figure 5 shows how the energy throughput is changed by introducing a BESS for each service. Again taking into consider the previous Figure 4, this provides context for the availability statistics, showing that as the overall energy throughput increases there is a correspondingly larger increase in availability. Looking again at DR, it is clear that the increases in energy throughput at the higher C-Rates are the primary driver for the increase in availability, with the additional energy capacity of the BESS becoming more important as the energy capacity of the FESS is reduced. For DM and DC there is a smaller increase in energy throughput by introducing the BESS, resulting in smaller increases to average

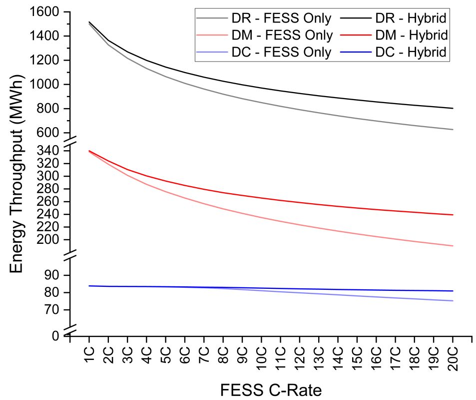

Fig. 5. Energy throughput experienced during a year long simulation for varying FESS C-Rates performing DC, DR and DM both alone and hybridised with a 0.1MWh/0.1MW/1C BESS

availability.

It should be noted that the effectiveness of introducing this size of BESS is closely linked to the response envelope being tested. For DC, there is a very shallow incline in required power response meaning only a small amount of energy throughout occurs in the area where a 0.1MW BESS would be able to deliver the service (i.e when the power request is between 0-10%, which is the range the 0.1MW BESS can cover). However, for DR, there is a much steeper incline in required power response as the frequency deviates further from 50Hz, meaning the 0.1MW BESS will have more instances where it can utilise its full capabilities.

With the two graphs taken together, it is clear that there is potential to use hybridisation to provide greater security in deploying FESSs to participate in the new suite of services, with further work required to assess how this configuration can be controlled and optimised using methodologies used in previous studies that have been conducted for DFR [16].

IV. Conclusion

In this paper, the suite of new services from National Grid ESO have been presented and discussed along with their suitability for provision by FESSs. The contractual service parameters for all three new services represent challenges for provision by energy-limited assets such as FESSs. In order to encourage a wider range of energy storage medium participation, modifications would need to be made to aspects such as minimum delivery time. To assess the suitability for a FESS to deliver the response envelope associated with each service, a C-Rate sensitivity analysis was undertaken. The results of this analysis showed that the most suitable response envelope for a FESS to deliver effectively is DC delivering both high and low services simultaneously, where the average availability >95% up to and including an 18C system. Conversely, for the DR response envelope, the FESS will never achieve >95% which has been shown to be due to the high levels of energy throughput required by the service which even the lower C-Rate FESSs cannot cope with. Subsequently, a hybridisation exercise was undertaken to assess how the performance of the system could be improved by introducing a 0.1MWh/0.1MW/1C BESS. It was shown that for DR a significant improvement could be achieved in the average availability of the system, although for the majority of C-Rates the 95% threshold could not be reached. For the other two services, DM and DC, more moderate improvements were achieved. Future work should concentrate on looking at how a frequency response service could be set up to extract the most value out of short-duration energy storage technologies.

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