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Payment Analysis for a BESS Providing Dynamic Frequency Response in the Irish Grid

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***Abstract*—The increased uptake of renewable energy generation has lead to a growing interest in the use of grid-connected energy storage systems, such as batteries and flywheels, for maintaining grid stability. A number of countries have developed schemes for managing the provision of frequency control services, with some grid operators, such as National Grid in Great Britain and Eiregrid in Ireland, having a range of static and dynamic services. For the provision of dynamic services, the use of tighter frequency margins, which results in the unit providing frequency response more regularly, may be incentivised through higher payments. One example of such a scheme is in Ireland under the Eiregrid DS3 programme, where a tariff system that incorporates both the performance and frequency margins of units providing dynamic response has been introduced. This paper examines how the choice of frequency margins affects overall payments for Battery Energy Storage Systems (BESS) operating in the Irish grid. Analysis is performed by simulating the BESS system using Irish grid frequency data. The results provide insights into how the frequency margins affect payments for different frequency response services, and show how payments to a BESS providing dynamic frequency response can be maximised.**

I. Introduction

The uptake of renewable energy generation has increased dramatically in recent years. Due to the intermittent and uncertain nature of renewable sources, such as wind and solar, grid operators must find ways to mitigate excessive frequency deviation and ensure that transmission and distribution networks remain stable at all times. Grid-connected Energy Storage Systems (ESS) are an efficient way to help regulate the grid frequency and voltage. ESS can provide a range of services to grid operators, including frequency response, load levelling, and peak shaving [1].

ESS can be realised with a number of technologies, including pumped hydro storage, flywheels, compressed air, superconducting inductors, and batteries [1]–[4]. Among these, Battery Energy Storage Systems (BESS) presents numerous advantages over some or all of the other technologies. These include high energy density, high charge/discharge rates, high efficiency, a relatively long lifetime, and low maintenance requirements. As a result, large-scale BESS systems have been installed in a number of countries for grid support [5].

The constant changes in supply and demand, as well as the large variety of generation sources and loads, mean that the frequency continually fluctuates about its nominal value, i.e. 50 or 60 Hz. Ensuring that the frequency remains as close to nominal as possible throughout the network is a key task for grid operators. In order to help manage the frequency of the grid, a number of grid operators, including National Grid (NG) in Great Britain and EireGrid (EG) in the Republic of Ireland, have introduced a variety of frequency response services [6], [7]. BESS are a strong candidate for providing these services, due to their high charge/discharge rates and high efficiency.

In Great Britain, a number of BESS have been contracted by NG to provide both static and dynamic frequency response. In 2016, 201 MW of BESS capacity was contracted for the provision of Enhanced Frequency Response (EFR) [8], with units of up to 40 MW capacity now being operational [9]. In Ireland, the use of BESS systems to provide frequency response services is less mature than in the UK, although in 2018, 358 MW of battery and battery/flywheel capacity were submitted to EG for consideration [10], with the individual proposals ranging in capacity from 3 to 60 MW. Furthermore, plans for a 100 MW BESS have been submitted for planning consideration [11].

An interesting feature of the EG frequency response services is the fact that the frequency margins of the dynamic response profile can be adjusted over continuous intervals, with tighter margins resulting in higher tariffs [12]. However, excessively tight frequency margins may result in the providing unit failing to respond fully to events, resulting in counteractive tariff deductions. This can be contrasted with the NG EFR scheme, which specifies only two services with fixed frequency response envelopes [13].

The motivation of the paper is to examine how the choice of frequency margins affects overall payments for a BESS operating in the Irish grid. Analysis is performed by simulating the BESS system using Irish grid frequency data. The results provide insights into how the frequency margins affect payments for different frequency response services, and show how payments to a BESS providing dynamic frequency response can be maximised. It is found that for a BESS with a maximum C-rate of 2, payments of up to € 72,000 per MW of available volume could be realised.

II. Dynamic Frequency Response Services

A. Background

In order to enable future renewable energy targets to be met, many grid operators have begun programmes which aim to enable the share of non-synchronous generation to increase without compromising the stability or security of the grid. In Ireland, this programme is called Delivering a Secure Sustainable Electricity System (DS3), one aspect of which is the management of grid frequency via a set of 14 system services, which range in speed-of-action and duration [14]. Two distinct processes are used by EG for procuring system services:

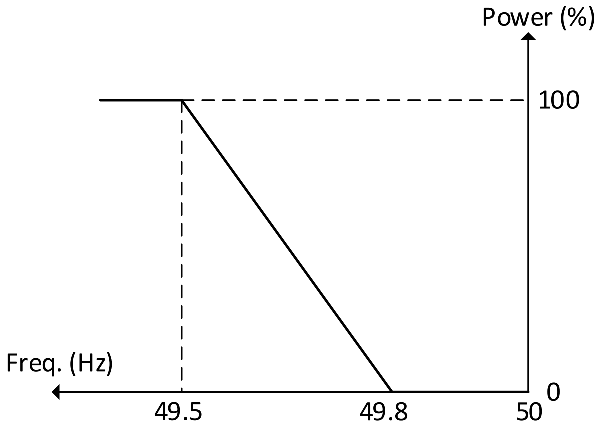


Fig. 1: Under-frequency dynamic response curve for the DS3 VC scheme. The output is zero above 49.8 Hz, before increasing in a linear fashion as the frequency drops between 49.8 Hz, until the output reaches full power at 49.5 Hz and below. The curve is mirrored and inverted for over-frequency response.

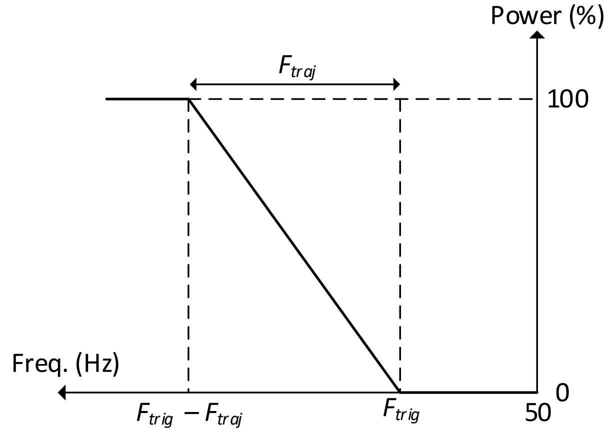


Fig. 2: Under-frequency dynamic response curve for the DS3 VU scheme. F_{trig} denotes the trigger frequency below which the unit must respond. F_{traj} denotes the width of the frequency 'trajectory' along which the unit increases its power output until reaching its maximum value at $F_{trig} - F_{traj}$. The curve is mirrored and inverted for over-frequency response.

1) Volume-Capped (VC): For VC, an upper limit to the volume of the applicable system services is applied, and for which the bidding parties offer a competitive price for each service in their tenders. Contracts are awarded based on technical capability and price. The VC scheme is intended for high-availability units, with a cap on the total MW capacity in order to mitigate excessive spending during the procurement process. The services provided under the VC scheme are fixed by EG, comprising Fast Frequency Response (FFR), Primary Operating Reserve (POR), Secondary Operating Reserve (SOR), and Tertiary Operating Reserve 1 and 2 (TOR1 and TOR2). The total duration of these five services is 20 minutes, with FFR being delivered within 2 seconds of a frequency event [14]. For units with dynamic capability, the trigger frequency margins are also fixed and are fairly wide, meaning that the units will only respond to frequency events a few dozen times per year on average [15]. Fig. 1 shows the dynamic response curve for the VC scheme.

2) Volume-Uncapped (VU): For VU, no volume limit applies and a fixed tariff scheme is used, meaning that the bidding parties do not offer a price for each service in their tenders. Contracts are awarded based on technical capability only [14]. Parties bidding under the VU scheme can include any of the 14 system services in their tenders. For units bidding to provide the services FFR - TOR1 with dynamic capability, the trigger frequency margins are set based on the technical capability of the unit and the requirements of the grid operator. Table I summarises the durations of these services. Fig. 2 shows the dynamic response curve for the VU scheme, which can be seen as a generalised version of the VC response curve. F_{trig} is the reserve trigger frequency, whilst F_{traj} denotes the width of the frequency 'trajectory' along which the unit increases its power output until reaching its maximum value at $F_{trig} - F_{traj}$. Note that in this paper, F_{trig} and F_{traj} are collectively referred to as the 'frequency margins'. For units operating in the VU scheme, the ability to operate with tighter frequency margins, as well as other advanced performance features, are incestivised through the payment scheme, as summarised next.

TABLE I: Summary of the DS3 volume-uncapped dynamic frequency response services [12].

Service	Response time [s]	End time [s]
FFR	2	10
POR	5	15
SOR	15	90
TOR1	90	300

B. Payments

Payment rates under the VU scheme are set by EG/SONI and are updated every twelve months [16]. The payment made in a month m, for each contracted service, s, over each half-hourly trading period, i, is given by

$$P(m,s,i) = V(i) \times R(s) \times S(m,s,i) \tag{1}$$

where $P(m,s,i)$ is the payment in €, $V(i)$ is the declared available volume of the unit in MW over the trading period i, $R(s)$ is the payment rate in €/MW for the service s, and $S(m,s,i)$ is the service scaling factor for month m for service s for the trading period i. Table II summarises the payment rates under the VU scheme for the services FFR - TOR1 as declared by EG/SONI [16].

1) Service Scaling Factor: The scaling factor $S(m,s,i)$ is a product of multiple individual scalars, which vary for the different services. For FFR, it is given by

$$S(m,FFR) = S_{EP} \times S_P \times S_C \times S_{FR} \times S_T \times S_L \tag{2}$$

where S_P is the performance scalar, S_{EP} is the enhanced provision (or product) scalar, S_C is the continuous scalar, S_{FR} is the fast response scalar, S_T is the temporal scarcity scalar, and S_L is the location scalar. For POR, SOR, and TOR1, the scaling factor is given by

$$S(m, s) = S_{EP} \times S_P \times S_T \times S_L \tag{3}$$

where the meanings of the individual scalars are the same.

For FFR, S_{EP} is calculated from two weighted components. The first component, S_{trig}, is calculated from the reserve trigger frequency F_{trig} and is given by

$$S_{trig} = 0.7 + \frac{3}{1.85}(F_{trig} - 49.8). \tag{4}$$

The second component, S_{traj}, is calculated from the frequency trajectory F_{traj} and is given by

$$S_{traj} = 0.5 + \frac{5}{6.5}(0.7 - F_{traj}) \tag{5}$$

if $F_{traj} \leq 0.7$. If $0.7 < F_{traj} \leq 2$, then $S_{traj} = 0.2$. The overall enhanced provision scalar, S_{EP}, is then given by

$$S_{EP} = 0.4S_{trig} + 0.6S_{traj}. \tag{6}$$

Note that (4) - (6) are derived from the information provided in [14]. For POR, SOR, and TOR1, S_{EP} is calculated from F_{trig}, and is given by [17]

$$S_{EP} = 1 - \frac{5}{6.85}(49.985 - F_{trig}) \tag{7}$$

It should be noted that POR, SOR, and TOR1 must follow the same dynamic response curve as FFR, meaning F_{trig} and F_{traj} are the same for all services [12].

For each service the performance scalar S_P is calculated based on the ratio of the actual to the expected response of the unit to frequency events, which for each month are denoted $j = 1...j_{tot}(m)$. $Q(m, s, j)$, which is the performance incident scaling factor during month m, for service s and frequency event j, is calculated based on the ratio of actual to expected response for each event; for FFR, Q is 0 if the FFR is adequately provided, and 1 otherwise. For POR - TOR1, Q varied between 0 and 1 based on the ration of actual to expected provision. Full details on the calculation of Q is found in [12], [17]. $Q(m, s, j)$ is used to determine a monthly scaling factor for each service $K(m, s)$, which is given by

$$K(m, s) = \frac{1}{j_{tot}(m)} \sum_{j=1}^{j_{tot(m)}} Q(m, s, j). \tag{8}$$

The monthly value of the performance scalar, $S_P(m, s)$, is given for each service by

$$S_P(m, s) = \max((1 - \sum_{n=1}^{5} V(n)K(m - n, s)),\ 0). \tag{9}$$

TABLE II: Payment rates for DS3 services for October 2018 - September 2019. Note that the rates in [16] have been converted from the €/MWh to €/MW, with (1) scaled accordingly.

Service	Payment rate [€/MW]
FFR	1.08
POR	1.62
SOR	0.98
TOR1	0.77

where $V(1) = 1$, $V(2) = 0.8$, ..., $V(5) = 0.2$. It can be seen from (9) that at month m, the value of S_P is actually based on the monthly scaling factor over the five previous months. For instance, for the payments in June, the performance scalar is based on performance in January - May, for payments in July is based on performance in February - June, and so on. This means that failure to respond fully to an event will lead to reduced payments over the subsequent five calendar months; the weighting $V(n)$ reducing with each successive month. Note that if $m - n \leq 0, n = 1...5$, then the terms where $m - n < 0$ are ignored. S_P has a maximum value of 1 and minimum of 0.

The continuous and fast response scalars, S_C and S_{FR} are only applicable to the FFR service. For each half-hourly trading period, S_C is 1.5 if the agreed output is provided for all of FFR, POR, SOR, and TOR1, and 1 otherwise [17]. S_{FR} varies between a minimum of 1, for a response time of 2s, to a maximum of 3, for a response time of 0.15s or less [12], [17]. The location and temporal scarcity scalars, S_L and S_{TS}, are detailed in [12], [17].

For a unit operating for months $m = m_{start}...m_{end}$, with the sequence of trading periods per month denoted $i = 1...i_{tot}(m)$, the total monthly payment per service, $P(s)$, is given by

$$P(s) = \sum_{m=m_{start}}^{m_{end}} \sum_{i=1}^{i_{tot}(m)} P(m, s, i). \tag{10}$$

The formulation of the payment scheme indicates an obvious trade-off between the enhanced provision scalar, S_{EP}, and the performance scalar, S_P. Tighter frequency margins lead to a higher value of S_{EP}, but also lead to more rapid charging and discharging of the BESS, which may result in some or all of the unit's services failing to respond to frequency events, reducing S_P. On the other hand, wider frequency margins will lead to a lower value of S_{EP}, but less rapid charging and discharging, a lower likelihood of failing to respond to frequency events, and a higher value of S_P. Consequently, it is important to understand how the values of F_{trig} and F_{traj} affect payments, and to develop an understanding of the revenue that a unit providing the services FFR - TOR1 could expect to earn.

III. Case Study and Example Operation

A. Case Study

The case study consists of a lithium-titanate BESS connected to the low-voltage grid through a power converter, as illustrated in Fig. 3. The BESS model is based on the 1 MWh, 2 MW system that is currently installed for grid support at Willenhall, UK. The BESS consists of 40 parallel racks, each rack being made of 22 series-connected modules. Each module contains 24 cells. The Toshiba SCiB cell is used [18], which has a nominal cycle life of 20,000 charge/discharge cycles with a C-rate of 3 [19]. The bi-directional power converter acts as an interface between the DC voltage provided by the BESS

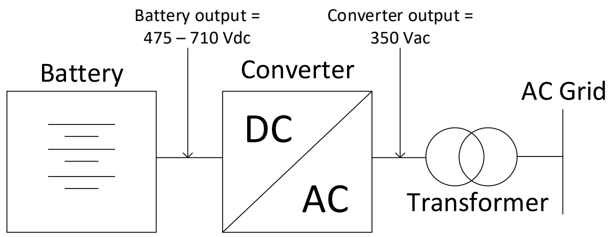


Fig. 3: Block diagram showing the structure of the system under consideration.

and the AC grid. More details on the system can be found in [20].

The analysis is performed with the unit providing four services - FFR, POR, SOR, and TOR1, meaning that the maximum response time of the unit is 5 minutes. It is further assumed that the unit provides both over- and under-frequency service response, and as such the State-of-Charge (SoC) is assumed to balance naturally in response to frequency fluctuation, meaning that no additional recharging policy is used to maintain the SoC. Note, however, that a low level of recharging is necessary to compensate for the static losses in the BESS.

B. Example Operation

In order to demonstrate the performance of the BESS whilst providing the DS3 services, the system is simulated over the 2016 calendar year, using real frequency data measured at Rhode, Republic of Ireland. For this example, the maximum power delivery of the unit is 2 MVA. Two sets of frequency margins are used. Case 1 uses $f_{trig} = 49.945$ Hz and $f_{traj} = 0.35$ Hz. Case 2 uses $f_{trig} = 49.905$ Hz and $f_{traj} = 0.7$ Hz. Table III shows the enhanced provision scalar, S_{EP}, and the average values of the event performance and overall scalars, $\overline{S_P}$ and $\overline{S}$, for each of the four services. The average values are taken over the final seven months of the year, such that full performance information is available when calculating S_P, as per (8).

For Case 1, which has narrow frequency margins and higher S_{EP} values, the averaged performance scalar $\overline{S_P}$ ranges from 0.863 for TOR1, to 0.886 for FFR. The resulting average overall scalar $\overline{S}$ ranges from 0.741 for FFR to 0.851 for POR and SOR. For Case 2, which has wider frequency margins and lower S_{EP} values, $\overline{S_P}$ is 1 for all services. $\overline{S}$ ranges from 0.648, for FFR, to 1 for POR, SOR, and TOR1. Case 2 gives a higher value of $\overline{S}$ for each of the services, except for FFR, which is higher for Case 1. To further illustrate, Fig. 4 shows the grid frequency, power delivery, and state-of-charge of the BESS for the two cases over December 2016. Fig. 4(a) shows the frequency over the month. Fig. 4(b) shows that the narrow frequency margins for Case 1 result in the SoC regularly hitting its lower limit, which results in the unit not being able to respond fully to all under-frequency events, reducing the average performance scalar $\overline{S_P}$ for all services. On the other hand, the wide frequency margins for Case 2 means that the unit delivers power less frequently and in lower volumes, with the SoC remaining balanced at around 50% throughout the month, as seen in Fig. 4(c). The results clearly demonstrate the trade-off between the the enhanced provision and performance scalars, and illustrates the need to understand how the values of f_{trig} and f_{traj} affect the trade-off between S_{EP} and S_P, and consequently the payments for the different services.

TABLE III: Comparison of performance for the two different sets of frequency margins.

	Case 1			Case 2		
Service	S_{EP}	$\overline{S_P}$	$\overline{S}$	S_{EP}	$\overline{S_P}$	$\overline{S}$
FFR	0.836	0.886	0.741	0.648	1.000	0.648
POR	0.971	0.876	0.851	0.942	1.000	0.942
SOR	0.971	0.876	0.851	0.942	1.000	0.942
TOR1	0.971	0.863	0.838	0.942	1.000	0.942

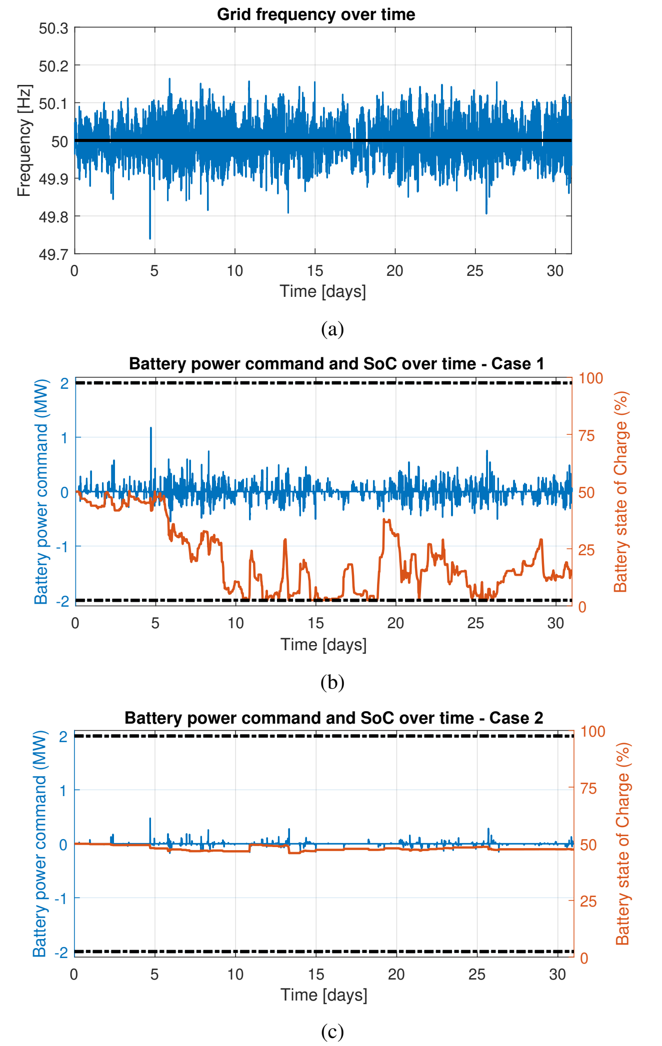
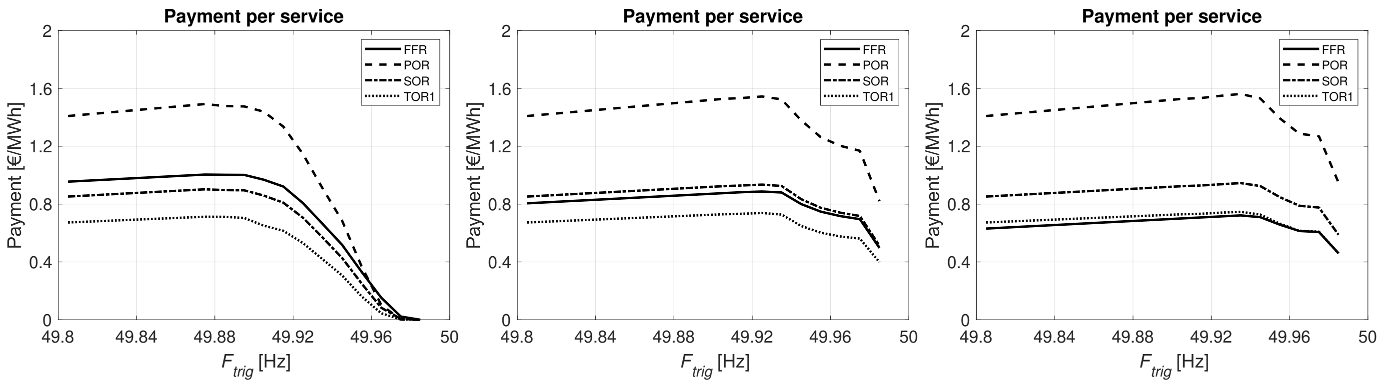


Fig. 4: Grid frequency (a) and battery dynamic response and SoC for Case 1 (b) and Case 2 (c).



(a) F_{traj} = 0.05 Hz. (b) F_{traj} = 0.35 Hz. (c) F_{traj} = 0.70 Hz.

Fig. 5: Payments for each of the services FFR, POR, SOR, and TOR1 for different values of F_{traj}.

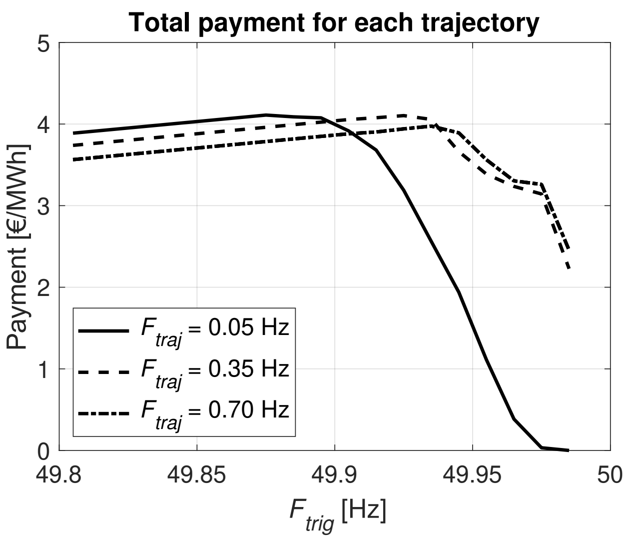


Fig. 6: Average combined payment per trading period per MW for the three frequency trajectories that are considered.

IV. Simulation and Analysis

A. Formulation of the Sensitivity Analysis

The sensitivity analysis is carried out by varying the value of f_{trig} on the interval $[49.805, 49.985]$ Hz, and f_{traj} over the values $\{0.05, 0.35, 0.7\}$ Hz. For each combination of f_{trig} and f_{traj}, the system is simulated over a year, using the 2016 grid frequency data. For each service the total payment over the final seven months of the year, $P(s)$, is calculated as per (1). In order to generalise the presentation of the results, the payment for each service $P(s)$ is normalised to an average payment per trading period per MW of available volume using the equation

$$\overline{P}(s) = \frac{P(s)}{\sum_{m=6}^{12} \sum_{i=1}^{i_{tot}(m)} V(m,i)} \tag{11}$$

where $\overline{P}(s)$ has a unit of €/MWh.

In performing the analysis several assumptions are made, the main ones being as follows:

- The available volume $V(m,i)$ is assumed to be fixed at the maximum output of the BESS over the year.
- The unit does not provide any system services other than FFR, POR, SOR, and TOR1.
- The unit operates continuously without interruption for e.g. maintenance.
- The temporal scarcity and location scalars are fixed at 1 for all services.

B. Results and Discussion

Fig. 5 shows the average payment per trading period per MW, $\overline{P}(s)$, against the reserve trigger frequency, F_{trig}, for each of the four services. Fig. 5(a) shows the results with the frequency trajectory F_{traj} = 0.05 Hz. As F_{trig} increases from 49.805 Hz, the payments increase linearly for each of the services. In this range, S_P = 1 for all services, and the increase is a result of the value of S_{EP} increasing as the trigger frequency is gradually tightened. At 49.875 Hz, payment for each service reaches a peak before dropping off significantly. When F_{trig} is above 49.9 Hz, the SoC limitations of the BESS begin to significantly limit the response of the unit, this effect increasing as F_{trig} moves closer to 50 Hz. With F_{trig} at its highest value of 49.985 Hz, payments for all services are zero.

Fig. 5(b) shows the same results, with the frequency trajectory increased to F_{traj} = 0.35 Hz. The trend is similar as with the F_{traj} = 0.05 Hz, although the payments do not begin to drop until F_{trig} is above 49.93 Hz. Further, the payments do not drop away to 0, indicating that S_P remains above zero for all services. Fig. 5(c) shows the results with the frequency trajectory increased to F_{traj} = 0.7 Hz. The trend is very similar to that seen in Fig. 5(b), with the payments beginning to drop when F_{trig} is above 49.94 Hz. Notably, the payment for FFR is substantially lower with F_{traj} = 0.7 Hz than with 0.35 Hz, due to the relatively high weight that is placed on F_{traj} when calculating S_{EP} for FFR, as per (6).

Fig. 6 shows the combined payment for the services FFR, POR, SOR and TOR1 for the different frequency trajectories. It can be seen that the maximum payment for the three trajectories is almost the same with each value of F_{traj}, which indicates that the maximum achievable payment is not linked to on a single value, or narrow range of values, of F_{traj}. This is summarised in Table IV, which shows the maximum combined payment and corresponding value of F_{trig} for each value of F_{traj}. Although not shown on the graphs, an important point to note is the fact that for each of the three values of F_{traj}, the combined payment is maximised at the highest value of F_{trig} for which $S_P = 1$ for all services; beyond that point, the reduction in S_P exceeds the increase in S_{EP}.

The payment rate for Case 1 in Table IV results in a theoretical maximum annual payment of around € 72,000 per MW, assuming that the available volume is fixed and equal to the maximum output of the BESS over the year. In reality, the actual payments would be lower for several reasons - the BESS would not always be available, due to planned and unplanned outages, and the temporal scarcity scalar, which has been assumed to be fixed at 1 in this paper, would at times be 0 due to the percentage of non-synchronous generation falling below 50%, which would reduce payments to 0 during some trading periods [12]. Additionally, the grid operator has authority over setting the frequency margins, and it is likely that the margins that are optimal from an operational perspective would differ from those which maximise payments to the providing unit.

V. Conclusions

Under the Eiregrid DS3 programme, a tariff system that incorporates both the performance and frequency margins of units providing dynamic response has been introduced. This paper examines how the choice of frequency margins affects overall payments for Battery Energy Storage Systems (BESS) operating in the Irish grid. The case study comprised a BESS operating in the Irish grid providing dynamic frequency response four services - FFR, POR, SOR, and TOR1. Analysis was performed by simulating the BESS system using Irish grid frequency data. The results indicate that annual payments of up to € 72,000 per MW of available volume could be realised for a BESS with a C-rate of 2, which can be achieved with a reserve trigger frequency of 49.875 Hz (or 50.125 Hz for over-frequency response) and a frequency trajectory of 0.05 Hz. Future work may investigate the optimal sizing of BESS units for the provision of volume-uncapped grid services in Ireland, by considering capital and operating costs, as well as the effects of changing the services provided, which could include adding longer-acting system services such as TOR2.

TABLE IV: The maximum combined payment and corresponding trigger frequency for the three different frequency trajectories.

	Case 1 F_{traj} = 0.05 Hz	Case 2 F_{traj} = 0.35 Hz	Case 3 F_{traj} = 0.7 Hz
$\overline{P}_{max}$ [€/MWh]	4.11	4.10	3.97
F_{trig} [Hz]	49.875	49.925	49.935

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