Review: Operating a future UK national grid with increasing non-synchronous renewable energy generation

1 Introduction

Leading up to the UN Climate Conference COP26 in Scotland the UK government announced that they are to set in law an ambitious climate change target, cutting emissions by 78% by 2035 compared to 1990 levels, which would bring UK much closer to its goal of being net zero by 2050 [1].

However, such ambitious targets require drastic changes and will inevitably change the way we produce energy. Especially the development in offshore wind energy production is highly prioritized on the DECC's 'Renewable Energy Roadmap' [2] and in major urban areas like London the options for local renewable energy production is an important topic of research. In fact, a technical assessment by Greater London Authorities estimates that the technical potential of PVs in London (2031) is an annual production of 9083 GWh. This is of course an optimistic estimate, but in theory, this could cover up to 23.1% of London's electricity demand. Hence, PVs are likely to be an important contributor to achieving London's goals of supplying 15 per cent of its energy from renewable, local sources by 2030 [3].

There are many ways to reach net zero and it is hard to predict the pace of the green transition and how exactly the future energy system will take form. That being said, the tendency is that the energy system is moving towards a more decentralised model with wind, solar and storage having key-roles. And as both the number and diversity of those involved in the energy market increases, so too does the complexity of operating the system [4].

In the 'Operability Strategy Report 2021' [5], The Nation Grid ESO present what they believe will become the major challenges for operating a decentralized future energy system. They distinguish between five key areas: Frequency, Stability, Voltage, Restoration and Thermal.
To narrow the scope of this project, the frame for this paper will be limited to investigating the core challenges and solutions to the frequency regulation and stability of a more decentralized future energy system. This means that voltage control, system restoration and thermal constraints are not considered in this review paper.

Specifically, the paper addresses the following two research questions:

1. Which impacts does the decentralization and high penetration of non-synchronous renewable energy generation have on maintaining grid stability?
2. What are currently planned solutions to accommodate the expected operability challenges?

2 The development in UK frequency regulation

Prior to analyzing the impact that the increasing non-synchronous wind and solar generation has on grid stability, it is necessary to understand the main mechanisms in frequency regulation and how it has been done so far.

2.1 The fundamentals of the present UK frequency regulation

The grid frequency is the number of alternating current cycles per second of the power system. All synchronously connected generators and demand units rotate at this grid frequency, why it is crucial to maintain a stable frequency to ensure that all installations can operate under safe circumstances. When generation is greater than demand, the frequency rises and vice versa. Therefore, balancing the frequency can be seen as a matter of balancing the demand and supply of electricity [6].

The electricity system operators (ESOs) are responsible for maintaining a safe and stable grid. In the UK the grid frequency is balanced around the nominal frequency of 50.00 Hz. As shown on figure 1 the operational limits for the frequency are ±0.2 Hz and the statutory limits are ±0.5 Hz.

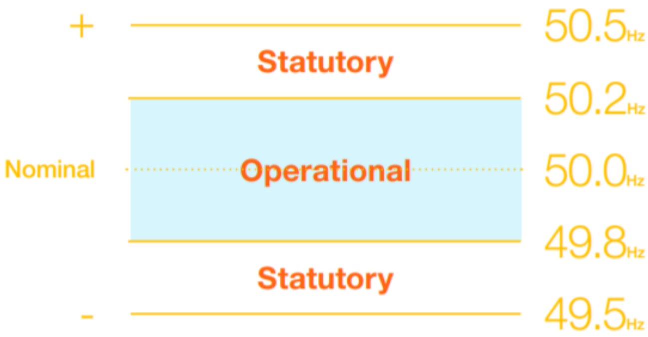

Figure 1: Frequency limits [7].

When balancing the grid frequency, the ESO's uses frequency regulation (FR) services. Briefly put, there are three types of FR ancillary service providers, which are paid for altering their power input or output in response to changes in the grid frequency [8]:

1. Transmission-connected generators.
2. Larger businesses with flexible demand, generation or energy storage.
3. Smaller demand side providers and other smaller parties.

Transmission-connected generators are generally obliged to offer 'Mandatory Frequency Response', receiving either holding payments or response energy payments. All approved providers can offer 'Firm Frequency Response', where payments are made on an availability basis, with additional payments for dispatch [8].

Both Mandatory and Firm FR are split into four categories: Primary, Secondary, High and Enhanced FR. As it can be seen on table 1 they have different characteristics and aims.

FR service	Speed	Duration	Aim
Primary	Within 10 s	30 s	Contain a falling f when f < 50 Hz
Secondary	Within 30 s	30 min	Restore f back to 50 Hz when f < 50 Hz
High	Within 10 s	Continuous	Contain and restore f back to 50 Hz when f > 50 Hz
Enhanced	Within 1 s	15 min	Provide fast response either side of 50 Hz

Table 1: The characteristics and aims of current UK frequency response services [9].

2.2 Transitioning from synchronous to non-synchronous generation and its effect on system inertia

2.2.1 Synchronous generation

The FR services shown in table 1 are designed to fit into a UK electricity system infrastructure that have traditionally been characterized by a small number of large fossil-fuel based and nuclear generators delivering energy to the national grid [10].

These generators are called *synchronous* generators, because their waveform of the generated voltage is synchronized with the rotation of the generator, which is connected directly to the grid [11]. The rotating mass in these generators are huge and weigh several tons, which make the generators able to store large amounts of energy in the rotating mass.

The sum of energy stored within the rotating mass of the generators is called the *inertia* and it presents a resistance to any change in angular velocity that may be triggered by a change in the electrical power balance of the transmission system.

The system inertia is defined by the total amount of kinetic energy available in the rotating masses of *all* directly connected synchronous generators, why the traditional fossil-based and nuclear generators are playing vital roles in achieving high system inertia in the present energy system [12].

The system inertia is inversely proportional to rate of change of frequency (RoCoF) after an imbalance between generation and demand. Therefore, system inertia can be understood as a key measure of how strong the electrical system is in response to changes in frequency [13]. So, when inertia is low, the frequency changes faster and is harder to balance and vice versa. The system inertia is therefore seen as one of the most important stabilising properties in frequency regulation as it provides the ESO's crucial seconds to manage sudden changes in frequency by using available FR services [9].

Up until now, the FR services shown in table 1 have been sufficient tools for the ESO's to balance the grid frequency. However, the general concern is that with the integration of more wind and solar energy, the existing FR services will no longer be responding fast enough for maintaining grid stability in the future [5].

In the following sections, the reasoning behind this concern is reviewed.

2.2.2 Non-synchronous generation

In the next decades, UK's energy mix is changing as the government looks to remove all coal from the system by 2025 and solar, wind and storage are expected to take up more of the mix [14].

Wind and solar energy production are non-synchronous generation (NSG), which means that they are decoupled from the system, as it uses power electronic devices to convert DC power to AC power in sync with the system frequency [12].

The converters that connects the NSG's to the grid do not naturally provide inertia, as they decouple any rotating masses involved in the generation from the system, unlike the traditional synchronous generators being directly connected to the system. Therefore, the decrease in traditional synchronous generators together with higher penetrations of non-synchronous renewable energy generation decreases the overall system inertia [15]. As a result, the system operator will have less time to respond to avoid the frequency deviating beyond the statutory limits shown in figure 1.

In the system operability framework document 'Operating a Low Inertia System (2020)' [13], national grid ESO gives four estimates for the future development of the system inertia, based on their own data.

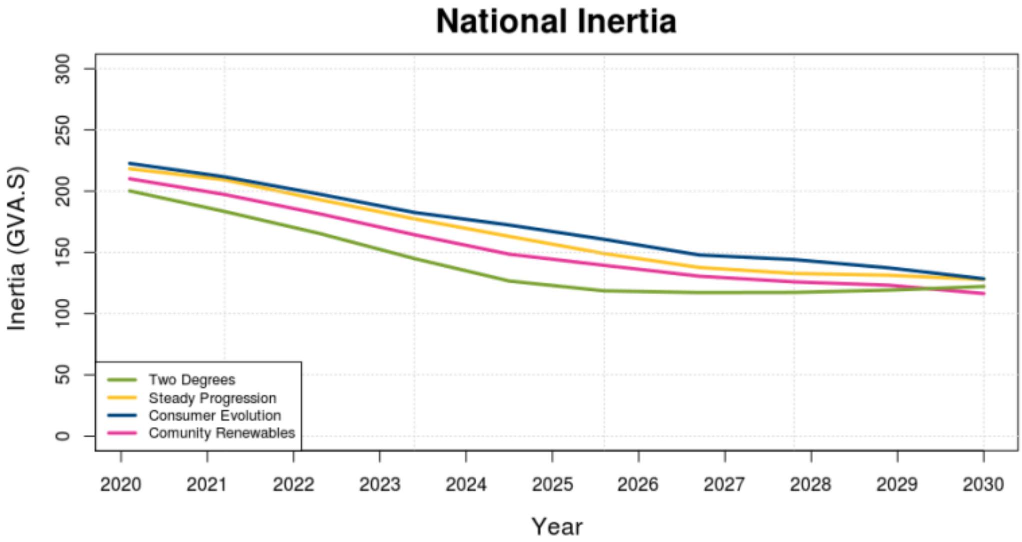

Figure 2: Inertia Trend to 2030 [13].

As it can be seen on figure 2, the trend is generally the same in all four cases. During the next decade the system inertia is expected to fall from above 200 GVAs to about 125 GVAs. These numbers are of course affected by uncertainties, but for illustrative intentions these are used in the forthcoming calculations.

By using the swing equation (1), it can be shown what influence the decreasing system inertia has on the systems ability to withstand large and sudden power losses.
The swing equation:

$$\Delta P = \frac{2H \cdot \text{RoCoF}}{f_0} \tag{1}$$

are widely used in frequency regulation because it linearly relates the RoCoF $[\text{Hz} \cdot \text{s}^{-1}]$, the system inertia H $[\text{GVA} \cdot \text{s}]$ and the grid frequency f_0 [50 Hz] to the maximum power loss ΔP [W] [16].

The upper limit of the RoCoF is by rule set to $0.125\text{Hz} \cdot \text{s}^{-1}$ [12]. By using the swing equation it can therefore be shown that if the existing FR services (table 1), are used in a future system with lower inertia, the power loss that the system can withstand is reduced from around 1000 MW to only 625 MW:

$$\Delta P_{2020} = \frac{2 \cdot 200[\text{GVAs}] \cdot 0.125[\text{Hz} \cdot \text{s}^{-1}]}{50[\text{Hz}]} = 1000[\text{MW}] \tag{2}$$

$$\Delta P_{2030} = \frac{2 \cdot 125[\text{GVAs}] \cdot 0.125[\text{Hz} \cdot \text{s}^{-1}]}{50[\text{Hz}]} = 625[\text{MW}] \tag{3}$$

System inertia is currently managed through limiting the largest system loss or increasing the system inertia [13]. This is done by contracting more conventional synchronous generation, which reduces the RoCoF with time.

There are two reasons why this is not a viable long term solution [17]. First of all, this is a *very* expensive solution, steadily increasing the cost of frequency control by millions of GBP as the inertia decreases. Secondly, the existing primary response services cannot react before two seconds, which means that as inertia decreases, they will be unable to react in time and prevent unacceptable frequency deviations, regardless of the volume of their response.

What this ultimately means, is that the existing FR services shown in table 1 are not responding fast enough for maintaining grid stability in the future [5]. In conclusion, a future lower inertia system demands new and faster frequency response.

2.3 Investigating the comparability of a faster frequency response service

The calculations provided in the previous section gave an overview of the effects that a decreasing system inertia have on the frequency regulation due to the penetration of non-synchronous generation. However, to shed light on potential solutions to accommodate these challenges, it is necessary to look into some of the research projects made in this field.

In 2018 a group of researchers [15], supported by the national grid ESO under Ofgem's Network Innovation Competition framework, investigated the potential of using a Fast Frequency Response (FFR) to enhance the frequency control in the future UK power systems with lower inertia. This research is relevant, because it uses simulation to compare the existing FR services in a low inertia setting with the performance of the FFR.

2.3.1 Outlining the design requirements of a new FFR

As concluded in the previous section, the FR ancillary services need to respond much faster. Using lithium-ion batteries for a new FFR would therefore be a feasible option since these can be very fast responding [17]. However, when using energy storage for FR services, the energy available is finite, why considering the energy capacity is just as important as considering the power.

Also, it is expected that there will soon be a much larger variation in the levels of inertia across the different regions in the UK. Therefore, it is possible that the thought of an overall system frequency may no longer apply [18].

Consequently, the fast response time of the system alone is not sufficient. Due to the different extent of regional renewable energy production and finite capacity of the batteries, the FR services need to be working dynamically. This means that the FR services should be able to change its delivery of power proportionally to system frequency.

The FFR used in the following research simulation is designed to meet these requirements. Its smart control system is more sophisticated and adaptive in order to accommodate daily and seasonal changes in inertia due to the intermittency of renewable energy generation. Having smart control and optimized coordination also makes this FFR tool a really cost effective solution to solving the decreasing inertia issues [17].

The conventional primary response shown in table 1 is required to be activated within 2 seconds following a frequency event and is expected to provide full response within 10 seconds and sustain it for 20 seconds. In comparison, the new FFR investigated in the following simulation can be triggered within 1 second to meet the balancing requirements in a low inertia system [15].

2.3.2 Simulation 1: Analyzing the performance of the conventional FR services in a low inertia environment

The starting point for the simulations, is the extreme event of a loss of 1.32 GW generation, which was in 2018 considered to be the largest possible generation loss in the UK energy system [15].

Through simulation, the researchers created four cases:

1. A high-inertia scenario (323 GVAs), where 80% of the generation is provided by synchronous generation, and with the primary response provided by 23.6% of the spinning reserve capacity.

2. A low-inertia scenario (212 GVAs), due to the higher penetration of NSG.

3. A low-inertia scenario (106 GVAs), due to the higher penetration of NSG *and* low demand condition.

4. A low-inertia scenario (106 GVAs), but with an economically expensive increase in reserve synchronous generation capacity for primary response from 23.6% to 43.2%.

In this first simulation, all four cases are based on the existing FR services to compare the performance of the current FR services in a low and high inertia setting. Also a number of assumptions have been made, based on a simplified GB transmission system model:

1. The average overall equivalent inertia constant of synchronous generators in seconds is assumed to be 5 seconds.

2. The loading factor and the power factor are assumed to be 0.8 and 0.85 respectively.

However, as they argue: "this case is still considered to be useful as a base case for investigating the impact of decreased inertia and the incorporation of FFR on the frequency profile".

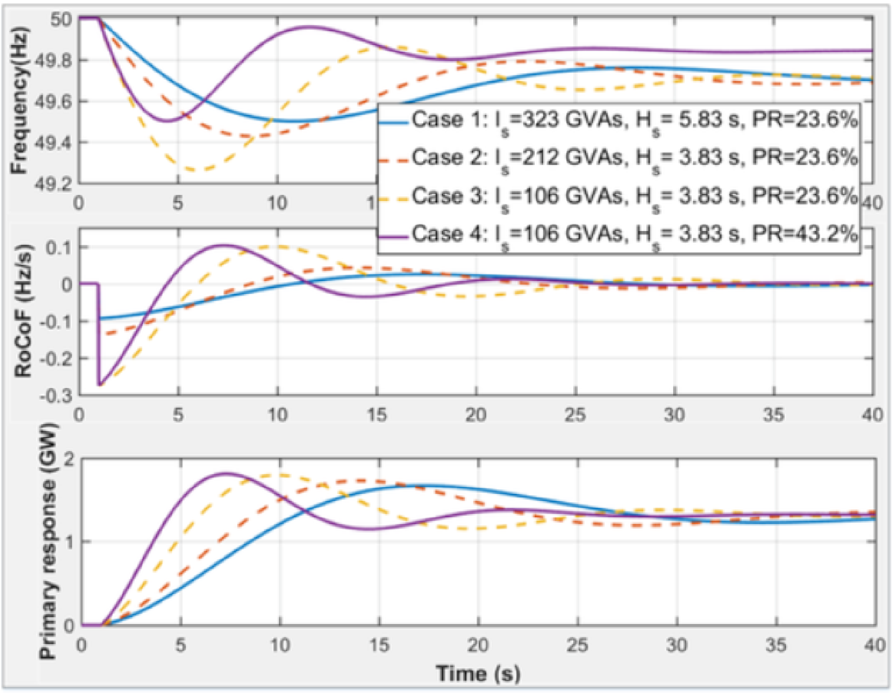

Figure 3: Simulation results demonstrating the impact of reduced inertia on frequency behaviour [15].

Simulating the four cases, as seen on figure 3, they found that only the energy system based on 80% traditional synchronous generation in case 1 and the costly increased reserve synchronous generation capacity for primary response in case 4, were able to maintain the frequency within the required frequency level. Conversely, as the inertia decreases in Case 2 and Case 3 due to the higher penetration of NSG and lower demand condition, the same event results in unacceptable low frequency levels below the statutory limit of 49.5 Hz.

These findings agree with was what deduced from the swing equation in the previous section, namely that the existing FR services are too slow in a low inertia environment and therefore unable to maintain a safe frequency in case of large infeed loss events.

2.3.3 Simulation 2: Comparing the new FFR to the conventional FR services in a low inertia environment

The next simulation compares the performance of the former FR services with a case where the new FFR service is integrated in the system.

Again, four cases is created:

1. A high-inertia scenario as before (323 GVAs), where 80% of the generation is provided by synchronous generation.
2. A low-inertia scenario (106 GVAs), due to the higher penetration of NSG *and* low demand condition.
3. Same as case 2, but with a costly increase in primary response to maintain proper frequency levels.
4. Same as case 2, but with 450 MW of the new FFR to maintain a proper frequency levels without having to increase the primary response.

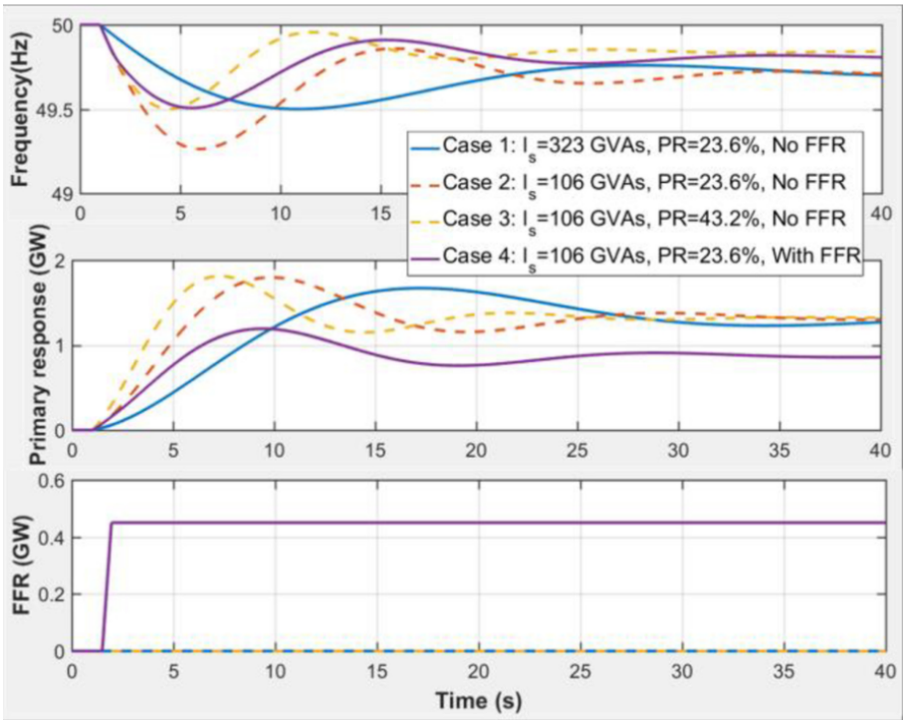

Figure 4: Simulation results illustrating the use of FFR to enhance frequency control [15].

Again, it can be seen on figure 4, that the high inertia system (case 1) is able to handle the large infeed loss, but when the inertia decreases the same amount of PR service is unable to maintain a proper grid frequency (case 2). Increasing the amount of PR service in the low inertia environment (case 3) can provide as good results as the high inertia system in case 1, but as described earlier, this solution is very expensive and not feasible in the long run. More interesting is the introduction of the new FFR shown in case 4. With this new faster response, the frequency is maintained within the statutory limits, while using much lower PR capacity than in case 3. So, with faster response the need of reserve capacity can be reduced, which is a very important result and conclusion from this analysis.

2.4 Introducing ESO's new dynamic FR services

Subsequent to the research described in the previous section, the national grid ESO is now working on three new FR services called Dynamic Containment (DC) [19], Dynamic Regulation (DR) [20] and Dynamic Moderation (DM) [21].
These FR services are highly relevant as they are meant to become the foundation of a more complex system for balancing the UK grid frequency in a lower inertia environment. They are designed to solve the issues outlined in this review paper by meeting the requirements described in section 2.3.1, which is briefly put that the new FR services must be much faster and dynamic while being cost effective.

The concept of the three new FR services are so new, that at this point in time (November 2021), only the DC has actually been launched into the UK energy system (October 2020) and is now still in its early phases [7]. This is mostly due to the fact that the national grid ESO is still in the process of fully defining the business details and technical requirements that firms must meet in order to provide acceptable DM and DR services [22]. Consequently, the amount of data and information publicly available are very limited.

2.4.1 Describing the different dynamic FR services

	Dynamic Containment	Dynamic Moderation	Dynamic Regulation
Speed of response	0.5 - 1 second	0.5 - 1 second	10 seconds
Delivery range	+/- 0.2 - 0.5 Hz	+/- 0.1 - 0.2 Hz	+/- 0.015 - 0.2 Hz
Performance metering	20 Hz	20 Hz	20 Hz
Duration	15 min for limited assets	30 min for limited assets	60 min for limited assets
LF/HF Split	Split	Split	Not split
Size	800-1400 MW	300-500 MW	400 - 600 MW

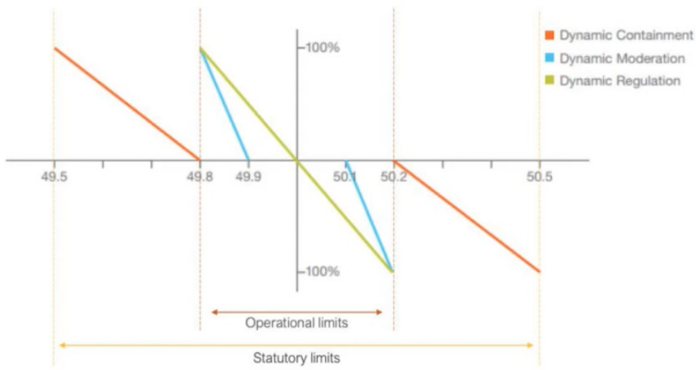

Figure 5: Specifications of DC, DM & DR [22].

As it can be seen on the above table, DR continuously operates within the delivery range of ±0.015-0.2 Hz. It is at its maximum output at ±0.1 Hz [23]. The DR is the main FR service slowly but steadily managing the constant small frequency deviations to keep the grid frequency near the nominal frequency of 50 Hz [20]. Therefore, the DR is very alike the traditional FR services and providers of DR have to provide both high and low FR, which makes DR a symmetrical service.

The purpose of DM is to assist DR in balancing the frequency within the operational limits if needed [21]. As well as DR, DM is also a symmetrical service. It rapidly provides additional FR within the delivery range of ±0.1-0.2 Hz to help manage sudden concerning imbalances, which could very likely be caused by the intermittency of wind and solar energy production.

In case of a huge unexpected frequency deviation that DR and DM cannot handle, the DC stands as a last resort. DC is designed to deliver very high power, as rapid as DM, but in the delivery range of ±0.2-0.5 Hz. Therefore, DC can be seen as the safety net, assuring that the statutory limit is never breached [9]. Also, DC actually constitutes two services. DC high and DC low. This means that a provider can choose to deliver either upwards (DC low), downwards (DC high) or both responses, which makes DC a non-symmetrical service [19]. This is suitable for wind and solar production, since these prefer to deliver high frequency response, while demand-side response are by nature suited to provide low frequency response [7]. Also, DC is very efficient per MW bought as it delivers 100% of its power within 1 second and starts responding after 0.5 second, as it can be seen in the table.

2.4.2 Analyzing the performance of DC, DR and DM

This year in May, a research [23] was made to study the influence that fully integrating DR, DM and DC services have on grid stability in a low inertia setting. The research did month-long simulations based on historical data and predictions from the national grid ESO.

It is important to mention that the case month (November 2018) for this study was chosen "due to it being a recent month where the frequency does not deviate outside of ±0.3 Hz" [23]. They then used national grid ESO's inertia prediction (shown in figure 2) to create a future low inertia case month (November 2030). As a result, the highest frequency deviations in the future case month are 50.372 Hz and 49.599 Hz.
The method is highly dependant on assumptions, why it could be expected that this method yields imprecise results, which is important to have in mind when interpreting the findings.

Nevertheless, the research provides a general picture of how the dynamic FR services perform in action, as the overall tendency can still be representative for their respective future performance.

As expected the researchers found that DR does the bulk of the work. DM had zero output for 89% of the time, while DC high and low combined had no output for 99.5% of the time. However, when DM was actually activated it had excellent performance in keeping the frequency within the operational limits, why the amount of time where DC had to be activated was very little. Yet when activated, DC was able to maintain frequency within the statutory limits and thereby satisfyingly playing its crucial role.

2.4.3 Main opportunities and challenges for the dynamic FR services

The analysis described in section 2.4.2 shows optimistic results for the proposed dynamic FR services and suggests that they will perform well in environments with substantially lower inertia than the UK's existing network. But which traits makes the dynamic FR services a superior alternative to the traditional FR services?

As mentioned several times, speed is one of many reasons. As it can be seen from the table in figure 5, the response service market for DR, DM and DC in total is only about 1.5 to 2.5 GW. In simulation 1 in section 2.3.2 we saw that the reserve capacity had to be increased for traditional primary response from 23.6% to 43.2% in order to cope with the decreasing inertia. In other words, decreasing the amount of system inertia pushes the market up. But logically, the opposite applies: If the FR services are faster, the response service market decreases. To the national grid ESO this is a very cost effective way of handling the low inertia environment.

A substantial change also worth mentioning, is that the business arrangements of providing dynamic FR have been innovatively rethought in comparison to the traditional way of providing FR. Because changes in the system condition is expected to happen on a daily basis, due to the intermittency of wind and solar energy production, the business behind providing FR services has been made much more flexible and adaptive than it has ever been before.

As an example, contracts for providing dynamic FR services will exclusively be made on a 24 hour basis. This makes it possible for FR service providers to choose and optimize on a daily basis which service or services they want to provide. The FR service providers have a lot to gain from this opportunity as they can change and even 'stack' FR services. This means that that they can divide their capacity into providing several FR services, such as 'X' MW of DC, 'Y' MW of DM and 'Z' MW of DR from day to day [7].

This is a very important change, because it allows the market to follow and adapt into the idea of creating of a 'smart' and dynamic frequency regulation system, which is a necessity for regulating the future intermittent energy system.

One of the concerns is however that batteries offering DR service will be required to deliver 3-5 cycles a day. This degrades the battery quite a lot, why it is likely that firms using batteries to offer FR services will find it unattractive to provide the DR service compared to the two other services [22].

Another challenge is shaping the long term future for DM, DR and DC in a network with massively increased presence of electric vehicles interacting with the grid and delivering FR services. Just having 20 Hz metering down to every single electric vehicle to confirm that they are responding properly is a huge task [22]. Connecting them all to the grid and making this work in compliance with the dynamic FR requires drastic system changes and expands into numerous areas not covered in this paper.

3 Conclusion

The effects of both the decentralization and higher penetration of NSG in the energy mix have been investigated and the following conclusions may be drawn.

A higher penetration of NSG and a lower fraction of traditional fossil-fuel based SG in the energy mix are causing significant operability challenges. Due to the lack of rotating elements in the system, the system inertia is inevitably decreased, why the RoCoF is inversely increased. Ultimately, the available time gap in which the system operators can react to a frequency change becomes so limited, that they are unable to maintain a safe frequency level within the statutory limits when using the traditional FR services.

Moving away from synchronous energy generation might therefore seem like an intangible task and it does indeed require drastic changes. Yet, as it has been shown in this paper, it also opens up for countless of opportunities.

Especially, the introduction of the new dynamic FR services looks very promising and will surely be a huge leap forward in the direction of a more sustainable UK energy production. The new dynamic FR services allow adding important renewable NSG into the energy mix, as it provides the national grid ESO with the necessary tools to regulate the frequency in a low inertia energy system. A low inertia system that the traditional FR services handle insufficiently.

Building upon the idea of a smarter and more dynamic energy system and integrating the dynamic FR services into this concept is an important task. It seems that the whole foundation of the future UK energy system is being created at this very moment, why the actions described in this paper are going to directly relate to how fast the UK are able to increase its proportions of renewable energy and ultimately reach its climate goals.

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