A Comprehensive Approach to Evaluate Frequency Control Strength of Power Systems

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***Abstract*—This paper introduces the concept of "frequency control strength" as a novel approach to understand how different real-world power systems compare to each other in terms of effectiveness and performance of system-wide frequency control. It presents a comprehensive comparison, based on measurement data, of the frequency control strength of four real-world, renewable-based, synchronous islands power systems, namely Great Britain (GB), All-Island power system (AIPS) of Ireland, and Australia (AUS) mainland and Tasmania (TAS). The strength is evaluated by means of different frequency quality metrics. The common understanding is that the bigger the capacity of a power system, the bigger its robustness with respect to events and contingencies. Here we show that this is not always the case in the context of frequency control. In fact, our study shows that mainland AUS shows the highest frequency control strength during normal operating conditions, whereas the AIPS shows the highest relative frequency control strength for abnormal system conditions. The strength is, in particular, greatly influenced by different regulatory requirements and different system/ancillary services arrangements in each jurisdiction. The paper also provides possible mitigations to improve frequency control strength through grid codes and market rules.**

***Index Terms*—Frequency control, strength, metrics, primary frequency control, RoCoF, deadband.**

I. Overview

Frequency control of power systems is an emerging area of research due to the increasing penetration of variable Renewable Energy Sources (RES) such as wind and solar Photovoltaic (PV) generation [1], [2]. For example, as the inertia decreases with the displacement of conventional synchronous generators there is a concern that frequency excursions become faster, and therefore the likelihood of instability occurring earlier increases [3]. While there are significant ongoing efforts from both academia and industry on how to best deal with the frequency control challenges (during both normal and abnormal system conditions), it is not clear how different real-world RES-dominated power systems compare in terms of the "strength" of frequency control. This paper fills this gap by comparing the strength of frequency control of four real-world synchronous islands power systems namely the Great Britain (GB), All-Island Power System (AIPS), and Australia (AUS) mainland,[1] and Tasmania (TAS). The frequency control strength of each system is evaluated by means of various metrics of frequency quality.

It is generally understood that small (islanded) synchronous power systems exhibit rapid and substantial frequency excursions compared to large power systems following typical generation loss [5], [6]. For instance, when comparing the different frequency control of GB, AIPS, and AUS power system, reference [7] states: *Ireland is chosen because its power system has, arguably, greater challenges than GB's, owing to its small size, limited interconnection and high penetration of wind. AUS was chosen because of its National Electricity Market's comparable size and renewable penetration to the GB grid.* The measurement data discussed in this paper, however, demonstrate that size may not necessarily mean greater or lower frequency control challenges. Specifically, despite GB being bigger/much bigger than AIPS, AUS, and TAS systems (see next section), it appears, based on this study, to face greater frequency regulation challenges. We elaborate on these differences by means of the concept of *frequency control strength*.

There is currently no commonly accepted definition of "frequency strength" and how it may relate and overlap with system strength definition(s) [8]. For instance, reference [9] suggests that frequency strength exhibits its meaning in two dimensions, namely the inertia support capability, which defines the initial Rate of Change of Frequency (RoCoF) (see equation (1) below) after an active power disturbance, and the Primary Frequency Control (PFC) capability, which defines the amount of active power that the power system can absorb or release during the frequency deviation. However, this definition is incomplete as it assumes that frequency strength only deals with contingency events and does not include the ability of power systems to counteract frequency deviations during normal operating conditions.

Motivated by this confusion and gap in the literature we propose the following definition of frequency strength:

> **Frequency strength** is the ability of power systems to resist and control changes in frequency during normal and abnormal operating conditions.

In this context, references [10], [11] propose real-time frequency strength evaluation indices based on a unified transfer function structure to theoretically quantify the frequency strength in terms of nadir and the average RoCoF. In the same vein, a frequency security index to evaluate power system frequency performance is proposed in [12]. These metrics, however, aim at quantifying frequency strength only during

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This work was partially supported by Research Ireland by funding Taulant Kërçi under NexSys project, Grant No. 21/SPP/3756; and by the Sustainable Energy Authority of Ireland (SEAI) by funding Federico Milano through FRESLIPS project, Grant No. RDD/00681.

[1] In the reminder of this work AUS indicates the combined transmission system of Queensland, New South Wales, Victoria, and South Australia [4].

abnormal operating conditions. On the other hand, reference [13] focuses only on normal system conditions and proposes frequency regulation performance requirement constraints into a generation planning model to ensure frequency quality. Frequency quality is also studied in [14] with a focus on sub-15-min and sub-1-hr time scales and the highest data resolution used is 10 s.

References [15], [16] provide an overview of frequency control challenges in the GB and AUS power systems, respectively. Reference [17] discusses the efficacy of the proposed new frequency response services in GB using a month-long case study. Similarly, references [18], [19] study the volatility of GB frequency using 1 s frequency resolution data and demonstrate the existence of the relationship between increased frequency events and RES penetration, and rate of change of demand, respectively. Reference [20] utilizes real-world frequency data of different countries in Asia, AUS, and Europe and compares the statistical properties of the frequency, that is, asymmetry of Frequency Probability Distribution (FPD).

This paper compares the strength of frequency control under normal and abnormal operating conditions of four power systems that are at the forefront of the integration of RES, namely, GB, AIPS, AUS and TAS. Novel contributions of this work are as follows.

- A comprehensive review of the main characteristics of GB, AIPS, AUS and TAS systems and an overview of their frequency control.
- Novel metrics to evaluate and enable a systematic comparison of frequency control strength on actual historical frequency measurements/events.
- It highlights that, overall, the AUS power system shows higher frequency regulation strength, while the AIPS power system shows the "strongest" frequency performance when it comes to arresting frequency and RoCoF relative to its size.
- A set of possible mitigations to improve frequency performance (i.e., grid codes and market rules).

II. System Characteristics and Frequency Control

This section provides a detailed comparison, from the frequency control point of view, of the main characteristics of the GB, AIPS, AUS, and TAS power systems. These systems are at the forefront internationally to integrate pioneering levels of RES. Table I compiles all the relevant information. Note the different sizes of the systems in terms of peak demand and inertia floors. Specifically, the GB system is, from a peak demand and inertia perspective, between 5.2-6.3, 1.3-3.3, and 22-37 times bigger than AIPS, AUS and TAS systems, respectively.

On the other hand, the four power systems are very similar in terms of instantaneous RES penetration and electricity met by RES. Concerning the PFC provision, the GB system differs from AIPS, AUS, and TAS systems as it procures/pays units to reserve headroom (but PFC bids are mandatory) [7]. Motivated by a decline in the frequency control performance under normal conditions, in 2020 the Australian Energy Market Commission made a final (mandatory) rule to require all generators (scheduled and semi-scheduled) in the National Electricity Market (NEM) to provide PFC response (droop-based) with narrow dead-band (± 15 mHz) and thus support the secure operation of the power system. This change led to a significant improvement in frequency quality in the NEM which will be discussed in detail in the case study section. Next, all four systems have similar requirements for dead-band (± 15 mHz) and droop (3-5%). Regarding other relevant services, AIPS includes an Synchronous Inertial Response (SIR) service while the rest do not. This is not the case for the Fast Frequency Response (FFR) service where all four systems have recently introduced it with a Full Activation Time (FAT) between 0.15-2 s. Note that FFR is a class of PFC that is more needed at low levels of synchronous inertia [21]. Battery Energy Storage Systems (BESS) are one of the most favorable candidates to provide the FFR service due to their fast responsive time and flexibility of operation [22]. With respect to Automatic Generation Control (AGC), both GB and AIPS do not currently implement it while AUS and TAS do.

With regard to RoCoF ride-through requirement, all systems have a limit ranging from 0.125 Hz/s in GB (the most sensitive RoCoF protection on the GB system) to 3 Hz/s in TAS. This makes sense since TAS is a much smaller system and thus needs to deal with higher RoCoFs. In terms of LSI and LSO loss, National Energy System Operator (NESO) operates and designs the system assuming a 1400 MW loss (the capacity of an IC) to ensure the resulting RoCoF would not exceed 0.5 Hz/s while AIPS a 500 MW and TAS a 144 MW loss (AUS does not include this criterion). There is also a significant difference in the number of ac and dc ICs. Specifically, this number ranges from 10 for GB to just 1 for TAS. Note that while more ICs between countries mean better market integration, it could also have the negative effect on frequency control if several ICs ramp at the same time. In this context, GB has a much higher IC ramp rate (100 MW/min) compared to AIPS (5 MW/min), and AUS/TAS (40 MW/min). For comparison, the AIPS system expects to have a combined IC ramp rate of 40 MW/min by 2030 which has to be compared to the current limit of 15 MW/min. These aspects are critical to frequency variations and are discussed below.

Table II summarizes all the relevant frequency control products of the selected jurisdictions. More specifically, Table II suggests that reserve products in AIPS namely Primary Operating Reserve (POR), Secondary Operating Reserve (SOR), Tertiary Operating Reserve 1 (TOR1), Tertiary Operating Reserve 2 (TOR2), and Replacement Reserve (RR) are designed and procured to deal with Under-frequency (UF) events (i.e, upward reserves), while in GB and AUS/TAS reserves are procured to deal with both under and Over-frequency (OF) events (PFC-based upward/downward reserves). Note that Dynamic Containment (DC)/Dynamic Regulation (DR)/Dynamic Moderation (DM) services (all with a ± 15 mHz dead-band and predominately being provided by BESS) are faster than the two legacy response products mandatory frequency response and static firm frequency response services.

One may argue, and we certainly agree, that there is no need

TABLE I: Main characteristics of GB, AIPS, AUS and TAS power systems.

Item	GB	AIPS	AUS	TAS
Peak demand [GW]	44	7.5	34	2
Inertia floor [GWs]	120	23	35.8	3.2
Instantaneous RES [%]	87.6	75	72.1	100
Electricity from RES [%]	51	42	39.4	93.4
PFC provision	Market/Mandatory	Mandatory	Mandatory	Mandatory
dead-band [mHz]	$\leq \pm 15$	$\leq \pm 15$	$\leq \pm 15$	$\leq \pm 15$
Droop [%]	3-5	3-5	≤ 5	≤ 5
SIR	No	Yes	No	No
FFR	Yes (1 s)	Yes (0.15-2 s)	Yes (0.5-1 s)	Yes (0.5-1 s)
AGC	No	No	Yes	Yes
RoCoF ride-through requirement [Hz/s]	0.125 - 1	1	1	3
Largest Single Infeed (LSI) loss [MW]	1400	500	-	144
Largest Single Outfeed (LSO) loss [MW]	1400	500	-	144
Number of Interconnectors (ICs) (ac/High Voltage Direct Current (HVDC))	10	3	6	1
IC (ac/HVDC) ramp rate [MW/min]	100	5	40	40
Dispatch model	Self	Central	Central	Central
Flexibility markets	Mature	Early stage	Early stage	Early stage

TABLE II: Comparison of frequency services of GB, AIPS and AUS/TAS systems.

Jurisdiction	Service	Direction (Upward/Downward)	FAT [s]	Purpose
AIPS	FFR	Upward	0.15-2	Post-fault contingency
AIPS	POR	Upward	5	Post-fault contingency
AIPS	SOR	Upward	15	Post-fault contingency
AIPS	TOR1	Upward	90	Post-fault contingency
AIPS	TOR2	Upward	300	Post-fault contingency
AIPS	RR	Upward	1200	Post-fault contingency
GB	DC	Upward/Downward	1	Post-fault contingency
GB	DM	Upward/Downward	1	Pre-fault continuous
GB	DR	Upward/Downward	10	Pre-fault continuous
GB	Mandatory frequency response	Upward/Downward	$<$ DC/DM/DR	Post-fault continuous
GB	Static firm frequency response	Upward	10-30	Post-fault contingency
GB	Commercial frequency response	Varies	Varies	Post-fault contingency
GB	Slow reserve	Upward/Downward	900	Post-fault contingency
GB	Quick reserve	Upward/Downward	60	Pre-fault continuous
GB	Fast reserve	Upward/Downward	120	Pre-fault continuous
GB	Balancing reserve	Upward/Downward	600	Pre-fault continuous
AUS/TAS	FFR	Upward/Downward	0.1-1	Post-fault contingency
AUS/TAS	Fast reserve	Upward/Downward	6	Post-fault contingency
AUS/TAS	Slow reserve	Upward/Downward	60	Post-fault contingency
AUS/TAS	Delayed reserve	Upward/Downward	300	Post-fault contingency
AUS/TAS	AGC	Upward/Downward	300	Pre-fault continuous

for so many frequency reserve products. For instance, European Network of TSOs for Electricity (ENTSO-E) has defined and recommended the use of four standard reserve products namely Frequency Containment Reserve (FCR), Automatic Frequency Restoration Reserve (aFRR), Manual Frequency Restoration Reserve (mFRR), and RR [23]. In addition to these products, Transmission System Operators (TSOs) operating low-inertia grids might need to introduce an FFR product.

III. Frequency Control Strength Metrics

A. *Nadir/Zenith and Minutes-based Metrics*

Minutes-based metrics such as "minutes outside the normal operating band" are, more often than not, used by ENTSO-E as a measure of long-term/annual frequency quality. Table III presents various frequency quality parameters for the four power systems. TSOs continuously monitor and periodically report on these indices [4]. In particular, it is worth pointing out that the standard frequency range in GB and AIPS is ± 200 mHz while in AUS and TAS is ± 150 mHz. In addition, AIPS and GB have a target to maintain frequency within an even tighter range namely ± 100 mHz for $\geq 98\%$ of the time, while AUS and TAS have a target to keep frequency within ± 150 mHz for $\geq 99\%$ of the time. We apply these metrics to operational data to evaluate and quantify the strength of frequency control under both normal and abnormal system conditions.

Similarly, TSOs operate and design power systems based on predefined maximum instantaneous frequency deviations namely nadir and zenith, and if these limits are exceeded then defense measures may be in place (for example, load/generation shedding) to avoid system blackouts.

B. *Δf and RoCoF-based Metrics*

Frequency stability is generally evaluated based on three key metrics namely RoCoF, nadir and zenith [24]. RoCoF measures how fast frequency changes following imbalances between generation and demand. RoCoF is important during frequency transients as it is used by protections such as, for example, loss-of-mains protection settings by generators.

The initial RoCoF is calculated as follows:

$$\mathrm{RoCoF}|_{t=0_+} = \frac{\Delta p_{\mathrm{imbalance}}}{p_{\mathrm{load}}} \frac{w_o}{4\pi H_{\mathrm{agg}}}\,, \tag{1}$$

where $\Delta p_{\mathrm{imbalance}}$ is the size of the infeed/outfeed outage event, p_{load} is the current system load consumption; H_{agg} is the system aggregated inertia constant; ω_o is the synchronous reference frequency. $\mathrm{RoCoF}|_{t=0_+}$ is used by the four TSOs that we examine in this paper to determine the minimum inertia floors to maintain RoCoF within limits [16], [25], [26].

This way to calculate the RoCoF is motivated by the swing equation of synchronous machines but gives only a snapshot and only at the initial instant after a major event. Moreover,

TABLE III: Relevant frequency quality parameters of the Continental Europe (CE), GB, AIPS, AUS and TAS power systems.

Parameter	CE	GB	AIPS	AUS (mainland)	TAS
Standard frequency range [mHz]	±50	±200	±200	±150	±150
Frequency key performance indicator [mHz]	-	±100 (≥ 98%)	±100 (≥ 98%)	±150 (≥ 99%)	±150 (≥ 99%)
Maximum instantaneous frequency deviation [mHz]	800	800	1000	1000	2000
Maximum steady-state frequency deviation [mHz]	200	500	500	500	500/1000
Time to restore frequency [min]	15	15	15	-	-
Frequency restoration range [mHz]	not used	±200	±200	-	-
Maximum number of minutes outside the standard frequency range	15,000	15,000	15,000	-	-
Minutes outside normal operating frequency band during normal (abnormal) system conditions	-	-	-	≤ 5 (5)	≤ 5 (10)

$\mathrm{RoCoF}|_{t=0_+}$ is a conservative calculation as it neglects the FFR being provided in the inertial time frame. Thus, it appears useful to have additional information over a mobile window in the seconds after the event. With this aim, we define first the frequency window of interest as:

$$\Delta f_i(t) = \big|f(t) - f(t-i)\big| \,, \tag{2}$$

where $f(t)$ is a suitable estimation of the instantaneous frequency at time t. As it stands, Δf_i is a useful metric for normal operating conditions and we will use it in the remainder of this paper to compare long-term frequency deviations of real-world power systems.

We are now ready to define RoCoF-based metrics that are complementary to (1), as follows:

$$\mathrm{RoCoF}_i(t) = \frac{\Delta f_i(t)}{i} \,, \tag{3}$$

$$\overline{\mathrm{RoCoF}_i}(t) = \frac{1}{N}\sum_{h=0}^{N-1} \mathrm{RoCoF}_i(t - h\Delta t) \,, \tag{4}$$

$$\mathrm{RoCoF}_{\max,i}(t) = \max_{h=0,\dots,N-1} \big\{\mathrm{RoCoF}_i(t-h\Delta t)\big\} \,. \tag{5}$$

Equation (3) is RoCoF calculated for a given period i, whereas equations (4) and (5) are the average and maximum RoCoFs, respectively, calculated over the time period i with $\Delta t = i/N$. While these RoCoF-based metrics can be applied during both normal and abnormal system conditions, these three metrics best characterize abnormal operating conditions.

The metrics above are "absolute." To be able to compare the strength of frequency control of different power systems it is also useful to consider "relative" RoCoF-based calculations that can take into account the size of the power systems. With this aim, we propose two relative metrics, as follows:

$$\mathrm{RoCoF}_{\mathrm{r1}} = \mathrm{RoCoF}_{\max,i}\,\frac{p_{\mathrm{total}}}{\Delta p_{\mathrm{imbalance}}} \,, \tag{6}$$

$$\mathrm{RoCoF}_{\mathrm{r2}} = \mathrm{RoCoF}_{\max,i}\,\frac{p_{\mathrm{conv}}}{\Delta p_{\mathrm{imbalance}}} \,, \tag{7}$$

where p_{total} is the total active power in the system; and p_{conv} is the amount of conventional generation in the system. These metrics can be interpreted as follows. Two systems should have same $\mathrm{RoCoF}_{\mathrm{r1}}$ ($\mathrm{RoCoF}_{\mathrm{r2}}$) if their inertia and control are equally proportional to p_{total} (p_{conv}). For example, the product $\mathrm{RoCoF}_{\max,i} \cdot p_{\mathrm{total}}$ should be the same for two systems controlled in the same way. On the other hand, a weak system will show a higher $\mathrm{RoCoF}_{\mathrm{r1}}$ than a strong one.

C. *Frequency Standard Deviation-based Metrics*

Frequency standard deviation-based metrics are widely and for a long-time used in power systems. For instance, the TSOs in the US utilize the standard deviation of the frequency, say, σ_f (calculated based on 1-minute frequency deviation averages over a year), as a long-term frequency Control Performance Standard (CPS)1 [27]. In the case of Electric Reliability Council of Texas (ERCOT), CPS1 compliance is assumed if σ_f(year) $\leq$ 30 mHz [27].

In this context, we recently proposed a new metric based on σ_f to calculate and measure the asymmetry of the frequency distribution ($\Delta\sigma_f$) in power systems [28].

In an ideal scenario $\Delta\sigma_f$=0. However, this is impossible in practice due to losses and nonlinearity. It makes sense thus to use the asymmetry index as a measure of strength of frequency control as a perfect frequency control would lead to $\Delta\sigma_f = 0$.

IV. Real-world System Data

In this section, we apply the metrics described in the previous section to real-world data of the four power systems for both normal and abnormal (contingency) operating conditions. These have been made publicly available by the relevant TSOs. In particular, and if not otherwise stated, we use 1 s frequency resolution time series data for GB and AIPS and 4 s for AUS and TAS power systems. For this reason, and where possible, we calculate the relevant frequency control strength metrics at 4 s resolution for GB and AIPS to allow a direct comparison with AUS and TAS systems.

A. *Normal System Conditions*

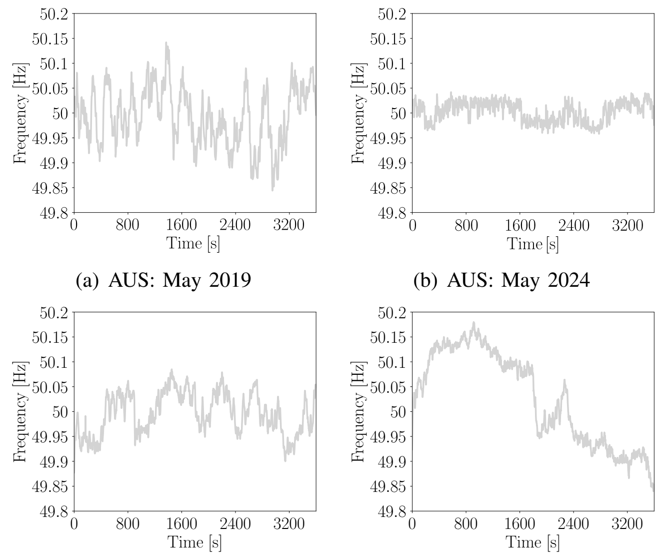
This section focuses on normal operating conditions and applies various minutes-based, Δf_i-based and σ_f-based metrics to quantify and evaluate frequency strength of the GB, AIPS, AUS and TAS power systems.

1) Minutes-based comparison: The first comparison that we look at are the minutes outside the relevant standard frequency ranges. For this, we select year 2023 and present all the results in Table III. For illustration and comparison purposes, we present these minutes for the CE power system as well which has a peak demand of around 440 GW and thus approximately ten times bigger than GB. While the standard frequency range for GB and AIPS is ±200 mHz, we calculate the minutes outside ±100 mHz as well as this is an even tighter frequency band that the TSOs of GB and AIPS systems aim at maintaining and reporting on a continuous basis. On the other hand, while the standard frequency range for AUS and TAS is ±150 mHz, we calculate the minutes outside ±100 mHz as well to allow a direct comparison with GB and AIPS power systems. Regarding the CE statistics, we show the minutes outside ±50 mHz.

Table IV suggests that despite CE being the biggest power system, it is the one that has exceeded, for the first time, its annual frequency quality target, namely, frequency outside the ±50 mHz range for more than 15,000 minutes. Table IV also suggests that, by far, frequency in GB is spending much more minutes outside the ±200 mHz (710.6) and ±100 mHz (80,131.36) ranges compared to the AIPS, AUS and TAS power systems. It should be noted, however, that GB is still within frequency quality limits in terms of minutes outside standard frequency range (±200 mHz) in Table III (15,000 minutes). As a matter of fact, in 2014 frequency was inside the ±100 mHz range for 94% of the time (or approximately 534 hours outside) compared with 90% in 2021 (or approximately 832 hours outside) [29]. It seems, though, that frequency spent even more hours outside limits during 2023 (approximately 1335) compared to 2014 (534) and 2021 (832). This is interesting considering that GB recently launched two new Primary Frequency Regulation (PFR) products namely DR and DM to tackle the challenge of frequency regulation. It appears, though, that frequency regulation is, as expected by NESO, still a major challenge to be addressed [29]. In fact, NESO anticipates *"this exposure to increase in the future as the system is getting more volatile (more renewable connected, low inertia, large uncertainty)*, and suggests *the need for faster response and reserve products"* [29].

Looking at the AIPS, AUS and TAS statistics in Table IV, one can see that AUS outperforms the rest of power systems (only 3.4 minutes outside ±150 mHz and 134.26 minutes outside ±100 mHz in 2023). This could be explained by the much bigger size of the AUS system compared to the AIPS and TAS systems and the fact that the AUS system utilizes an AGC compared to the AIPS system. What is interesting, though, is that despite being slightly a smaller system than GB, the AUS system shows a significant better frequency performance during normal operating conditions. One of the main differences with GB relate to the fact that the PFC provision (±15 mHz dead-band and droop/proportional response) is fully mandatory in the AUS system whereas that is not the case in GB (see Table I). This can be seen as the frequency regulation task is distributed among many units in AUS while in GB it is concentrated onto a few units. In this context, it has been shown in the literature that the former approach leads to a better frequency performance [30]. Another key reason why AUS shows a better frequency regulation performance is that AUS utilizes and AGC whereas GB does not.

The AUS system, in fact, was showing a decline in frequency control performance under normal conditions (similar to GB) before 2020 where frequency regulation was predominantly managed through AGC and relatively wide dead-band (for example, ±150 mHz). However, managing frequency regulation only through AGC seemed a hard task for Australian Energy Market Operator (AEMO). For this reason, in 2020 the Australian Energy Market Commission introduced mandatory PFC rule for all generators, including from Inverter-Based Resources (IBRs) such as wind power but excluding Distributed Energy Resources (DERs) such as roof-top PV [31]. The mandatory PFC provision with narrow dead-band (±15 mHz) and proportional droop response led to a significant improvement of frequency performance in AUS. This is illustrated in Figure 1 where frequency traces of the GB and AUS systems are compared for the same hour and day (May 21, 2019 and 2024). Frequency variations in AUS have dramatically improved compared to 2019 but that is not the case in GB. This suggests that a potential solution for GB is to impose PFC with narrow dead-band, even though this might be difficult to implement in practice by all generators as narrow dead-band increases wear and tear. For instance, large dead-bands may be preferred for nuclear units to avoid movement in active power output from scheduled values caused by changes in frequency [32].



(a) AUS: May 2019 (b) AUS: May 2024

(c) GB: May 2019 (d) GB: May 2024

Fig. 1: Comparison of frequency traces of GB and AUS power systems for 1 hour on May 21, 2019 and 2024, respectively.

If the mandatory PFC rule with narrow dead-band is not possible, then implementing an AGC (well-proven frequency regulation capability) should be another viable solution for GB to consider.[2] We believe this is important considering the fact that the IC ramp rates in GB are significantly higher than in AIPS (100 MW/min vs 5 MW/min). In other words, several ICs ramping at the same time exacerbates the control of system frequency [34] and, thus, an AGC may be best to deal with it. In addition, despite PFC being a fast-acting and continuous method of control, it is not perfect tracking and thus will not bring the frequency error to zero in steady-state in contrast to AGC (includes an integrator term) [35]. Another solution to better manage the real-time power imbalance could be fast generation dispatch but it has been shown in the literature

[2]For instance, the Nordic TSOs identified aFRR/AGC as one of the main measures to stop the weakening trend of the frequency quality and introduced it back in 2013 [33].

TABLE IV: Frequency quality in 2023 for the power systems of CE, GB, AIPS, AUS and TAS.

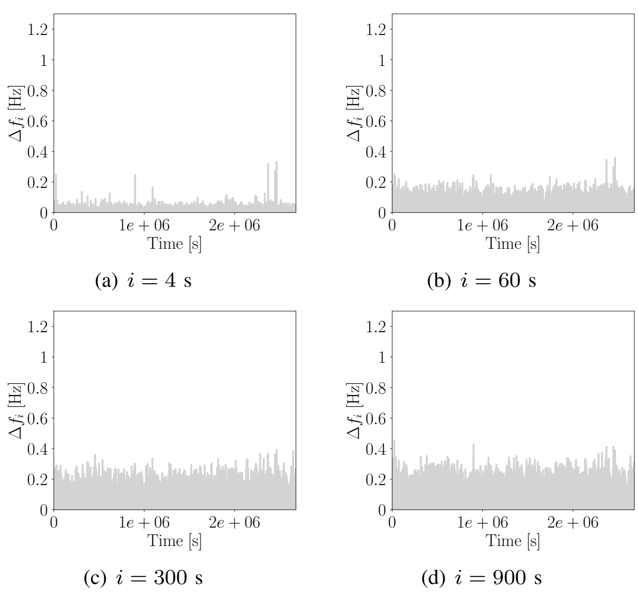
Minutes outside	CE	GB	AIPS	AUS	TAS
± 50 mHz	15,389	-	-	-	-
± 200 (± 100) mHz	-	710.6 (80,131.36)	(3.56) 6,796	-	-
± 150 (± 100) mHz	-	-	-	3.4 (134.26)	2,074.6 (7,157.66)

that AGC outperforms it in terms of frequency regulation performance [36]. The GB might also consider increasing the volumes of DR and DM products. As a matter of fact, in February 2025, NESO increased these volumes to better manage significant MW movements observed in recent weeks, see Table V [37]. However, these new volume requirements will lead to additional costs.

TABLE V: DR & DM requirements increase.

	DR-Low [MW]	DR-High [MW]	DM-Low [MW]	DM-High [MW]
Before February 2, 2025	330	330	170	200
Since February 2, 2025	480	480	300	300

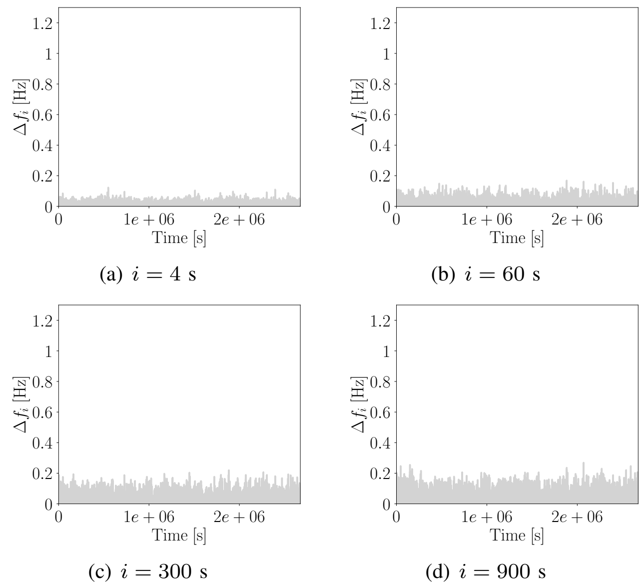
2) Δf-based comparison: To get a better insight into the dynamics of frequency variations under normal conditions of the four power systems, we calculate Δf_i over different time periods. With this aim, we select March 2024 as the reference month. Specifically, Figures 2, 3, 4 and 5 show Δf_i calculated for $i = 4$ s, $i = 60$ s, $i = 300$ s and $i = 900$ s time periods. As expected, considering its small size, TAS system shows the highest Δf_i across all the considered time periods compared to GB, AIPS and AUS systems.



(a) $i = 4$ s (b) $i = 60$ s (c) $i = 300$ s (d) $i = 900$ s

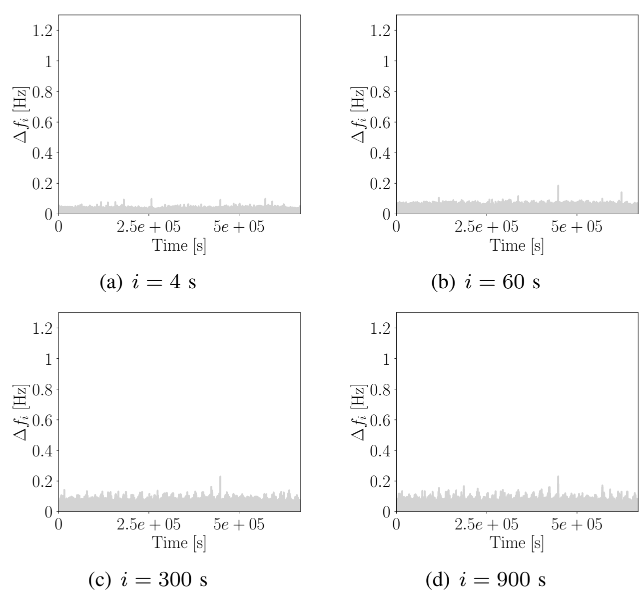
Fig. 2: Δf_i variations in the GB power system.

GB follows TAS with the second highest Δf_i experienced across 4 s, 60 s, 300 s and 900 s, respectively. While this is a counter intuitive result from the system size point of view, it is somehow expected following the frequency quality deterioration of GB discussed in the previous section. Figure 2 shows another insightful result, that is, it appears that Δf_i gets higher for higher time periods, for example, Δf_{300} higher than Δf_{60}. These results are consistent with the observation from NESO that states that during 2021 around 65% of the total time outside ± 100 mHz is due to events lasting 60 s or more, and only around 15% of the total time outside ± 100 mHz is due to events lasting 5 minutes or more [29]. This observation is not as obvious for AIPS and AUS systems. This means that events that lead to frequency variations in AIPS and AUS last less time and are compensated more quickly than in GB.



(a) $i = 4$ s (b) $i = 60$ s (c) $i = 300$ s (d) $i = 900$ s

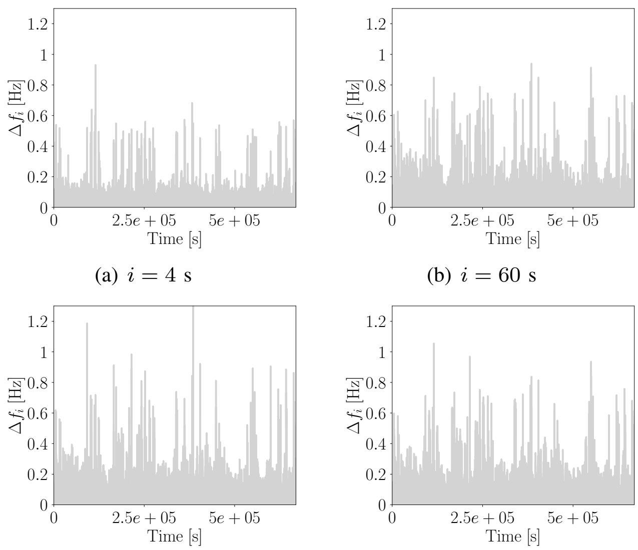
Fig. 3: Δf_i variations in the AIPS.



(a) $i = 4$ s (b) $i = 60$ s (c) $i = 300$ s (d) $i = 900$ s

Fig. 4: Δf_i variations in the AUS power system.

While one might argue that Δf_i in the AUS system are lower compared to GB due to AGC in AUS, that is not the case when comparing GB with AIPS system. Specifically, since



(a) $i = 4$ s (b) $i = 60$ s

(c) $i = 300$ s (d) $i = 900$ s

Fig. 5: Δf_i variations in the TAS power system.

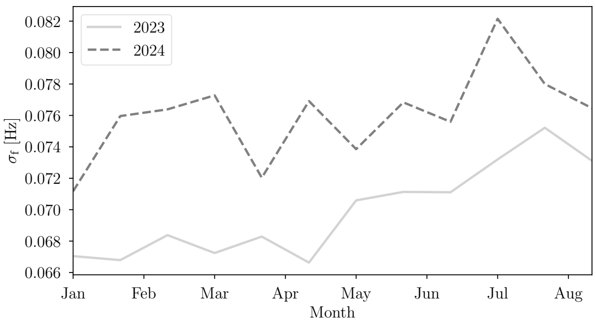


Fig. 6: Evolution of σ_f in the GB power system in 2023 and 2024.

both AIPS and GB systems have a manual AGC, then the main difference between the two systems is the PFC rule, that is, mandatory in AIPS and non-mandatory in GB. Another potential reason (difference) why frequency variations last more in GB could be related to market-driven variations that might be significantly higher in GB due to, for example, higher IC ramp rates and more demand volatility due to GW level flexibility services being procured by NESO and Distribution System Operators (DSOs) in GB [38]. For example, reference [19] suggest that one of the causes of frequency events in GB is a high rate of change of demand. In fact, if one looks at the flexibility service volumes contracted in GB in Table VI, in particular, post-fault products ("Dynamic" and "Restore") that have response times in time scale of minutes, it might be concluded that demand response has increased significantly in recent years [39].

3) Frequency standard deviation-based comparison: We conclude the frequency control strength comparison for normal system conditions by comparing the various σ-based metrics presented in Section III-C. Results are presented in Table VII. Similar to the frequency quality and Δf_i-based results, GB has the highest σ_f (0.076 Hz) compared to AIPS (0.042 Hz), AUS (0.025 Hz), and TAS (0.042 Hz) systems. These different σ_f in March 2024 match quite well the σ_f in 2023 for the four power systems. Specifically, the σ_f in 2023 for GB, AIPS, AUS and TAS are 0.069 Hz, 0.042 Hz, 0.025 Hz, and 0.040 Hz, respectively. These results support the idea that one month frequency analysis/data (March 2024) is representative enough of the overall frequency performance of the selected power systems. In fact, σ_f has recently constantly increased in the GB power system as shown in Figure 6. As mentioned above, because of this increased frequency volatility, NESO increased the volumes of procured PFR reserves namely DM and DR reserve volumes.

Regarding the asymmetry of the FPD, $\Delta\sigma_f$, it is probably non-intuitive to see that AIPS shows lower asymmetry compared to AUS, GB, and TAS systems. This is despite TAS and AUS systems having an AGC installed.

Figure 7 shows the FPDs of the frequency of the four systems for March 2024. Arguably, the source of asymmetry might come from IBRs providing mandatory PFC with ± 15 mHz dead-band in AUS and TAS similar to what is reported in AIPS in [28]. As mentioned in [28], AEMO recognizes that the observed asymmetry in the NEM's frequency characteristic could be due to the application of narrow dead-bands in some power plants [40].

Note that in GB 50 Hz is not the most common frequency. For this reason, NESO procures frequency response assuming a pre-fault frequency different from 50 Hz [29]. This approach is not common among other TSOs that instead assume nominal frequency. In any case, NESO maintains frequency within operational limits mainly because of the large size, that is, aggregated inertia, of its power system. For example, it has been shown in the literature that the size of the grid serves as a controlling factor to make grid dynamics more robust [41], [42]. In other words, "size" can be seen as part of the frequency control and, in this case, might "hide" the strength, or lack thereof, of control. This aspect is further discussed in the next section.

B. Abnormal System Conditions

We now discuss the frequency control strength for abnormal operating conditions. Tables VIII and IX compare: (i) information on recent relevant trips of the four systems; (ii) operating conditions, namely, inertia, total demand at the time and power imbalance due to the outage; and (iii) various frequency strength metrics as well as the five RoCoF-based metrics described above.

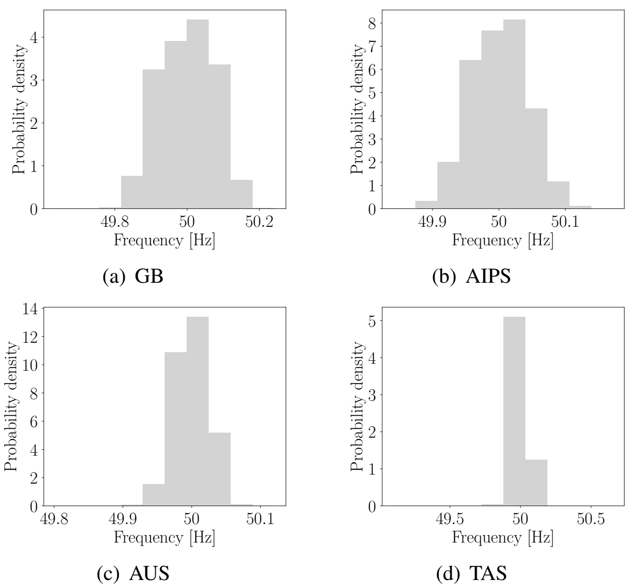
a) GB and AIPS trips on May 14, 2024: On May 14, 2024, at around 1 am, the two HVDC ICs that connect AIPS with GB tripped one 20 s after the other with a total import (AIPS) / export (GB) capacity lost of 912 MW (530 MW and 382 MW). This allows an excellent frequency control strength comparison, as it represents the same contingency for the two systems. Tables VIII and IX show system conditions and all relevant results for the AIPS 2024 and GB 2024 cases, while Figure 9 shows the relevant frequency transients following the ICs trips. In particular, note that the inertia level in GB was just above the limit (121 GWs) while in AIPS was quite above

TABLE VI: Evolution of service products contracted across all GB utilities.

Flexibility Service	2018 [MW, %]	2019 [MW, %]	2020 [MW, %]	2021 [MW, %]	2021/2022 [MW, %]
Sustain	0, 0	0, 0	2, 0	13.3, 1	28.1, 2
Secure	23.8, 20	10.3, 4	105.1, 9	262.6, 16	375.2, 20
Dynamic	33.8, 29	120.8, 47	555.9, 48	729.7, 45	925.7, 50
Restore	58.5, 50	125.1, 49	502.5, 43	603, 37	538, 29
Total	116.1, 100	256.2, 100	1165.5, 100	1608.5, 100	1867, 100

TABLE VII: Summary of standard deviation-based results in March 2024.

Power System	σ_f [Hz]	σ_{f-} [Hz]	σ_{f+} [Hz]	$\Delta\sigma_f$ [Hz]
GB	0.076	0.078	0.074	0.0043
AIPS	0.042	0.0423	0.0433	0.0010
AUS	0.025	0.0267	0.024	0.0026
TAS	0.042	0.0458	0.0386	0.0072



(a) GB (b) AIPS

(c) AUS (d) TAS

Fig. 7: Comparison of FPD of GB, AIPS, AUS and TAS power systems in March 2024.

the limit (32.3 GWs) as wind levels were particularly low (534 MW) which means many conventional units online (2153 MW) to meet demand (3699 MW). Also, note that only the MW trip of the first IC ($\Delta p = 530$ MW) is shown in the table as that is important for the different RoCoFs calculations. The second IC, in fact, trips 20 s later and less active power is lost.

Tables VIII and IX show that frequency zenith/nadir for the GB/AIPS systems reached 50.154 Hz and 49.593 Hz, respectively. The difference in the maximum frequency deviations is expected as the total active power trip represented around 25% of total demand for AIPS system while only around 4% for GB. Also, nadir happens quickly in AIPS (2 s for the first trip and 26 s for the second trip) than zenith in GB (4 s and 27 s, respectively) due to much lower inertia. Frequency took around 969 s to recover within ± 100 mHz for AIPS system while for GB only 393 s. Results also show that the maximum calculated RoCoFs ($\mathrm{RoCoF}_{\max,i}$) based on 1 s (4 s) resolutions are 0.066 Hz/s (0.034 Hz/s) and 0.16 Hz/s (0.06) Hz/s for GB and AIPS systems, respectively. These absolute values are expected considering the different inertia levels for both systems namely 121 GWs and 32.3 GWs for GB and AIPS, respectively. What is interesting, though, is the fact that the $\mathrm{RoCoF}_{\max,i}$ for GB (0.066 Hz/s) almost matches the initial $\mathrm{RoCoF}|_{t=0_+} = 0.063$ Hz/s. This suggest that the inertial level of GB appears to be a good indication of the $\mathrm{RoCoF}_{\max,i}$ experienced even when using 1 s resolution data.

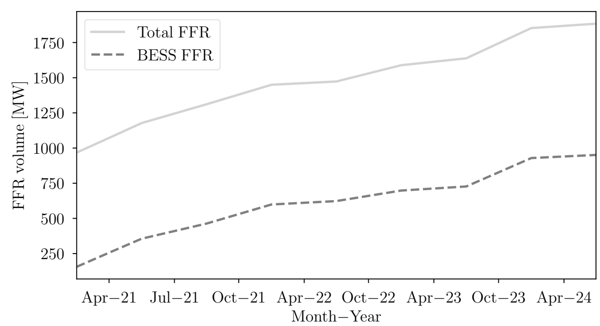


Fig. 8: Evolution of FFR contracted volumes in the AIPS.

For the AIPS system, on the other hand, $\mathrm{RoCoF}_{\max,i} = 0.16$ Hz/s (while the one calculated from 20 ms resolution data and over a rolling 500 ms period is higher namely 0.27 Hz/s, as expected). The initial RoCoF calculated with (1) equals $\mathrm{RoCoF}|_{t=0_+} = 0.41$ Hz/s (still higher than 0.27 Hz/s from 20 ms resolution data). The fact that $\mathrm{RoCoF}|_{t=0_+} > \mathrm{RoCoF}_{\max,i}$ means that there is more frequency support in the inertial time frame in the AIPS than in GB. This can be explained by significant volumes of FFR being provided in less than a second in the AIPS system and thus helping with addressing RoCoF as well (instead GB has a full FFR delivery requirement of 1 s). For example, Table X and Figure 8 show that the AIPS system has around 1,800 MW of upward FFR available (tariff-based procurement) to deal with UF events. This volume is significantly higher compared to its size and the rest of the power systems and thus comes with a significant cost. In this context, NESO has developed a clear and transparent methodology to determine the right balance between the two competing objectives of reliability and cost, focusing on the risks, impacts and controls for managing the frequency [25].

For instance, the 2025 Frequency Risk and Control Report (FRCR) from NESO recommends reducing the inertia floor from 120 GWs to 102 GWs due to significant cost savings (see Table XI [43]). To improve system risk, NESO recommends procuring 200 MW additional DC-Low (or upward FFR) as the most cost-effective solution.

In fact, because of high reserve costs, the AIPS system is introducing more competitive arrangements to procure reserves (auction-based) in the future including FFR [44]. Another factor could be that there might be slightly more inertia available

TABLE VIII: Frequency strength for contingency events in GB, AIPS, AUS and TAS.

Power system Year		GB 2024	AIPS 2024	GB 2019	AIPS 2022	AUS 2024	TAS 2024
Inertia	[GWs]	121	32.3	201	34.7	90	6
p_{conv}	[MW]	9,649	2,153	15,980	3,077	–	–
p_{total}	[MW]	21,773	3,699	28,029	4,847	23,122	1,111
$\Delta p_{\mathrm{imbalance}}$	[MW]	530	530	1,000	530	660	114
Nadir/zenith	[Hz]	50.154	49.593	49.62	49.674	49.8	49.3
Time to nadir/zenith	[s]	4/27	2/26	6	3	8	8
Time to recover within $\pm$100 mHz	[s]	393	969	255	780	64	48

TABLE IX: RoCoF-based metrics for contingency events in GB, AIPS, AUS and TAS.

Power system Year			GB 2024			AIPS 2024			GB 2019	
i	[s]	1	4	0.02	1	4	0.02	1	4	0.02
$\mathrm{RoCoF}\|_{t=0_+}$	[Hz/s]		0.063			0.41			0.124	
$\overline{\mathrm{RoCoF}_i}$	[Hz/s]	0.0021	0.0012	–	0.0012	0.0010	–	0.0026	0.0022	–
$\mathrm{RoCoF}_{\mathrm{max},i}$	[Hz/s]	0.066	0.034	–	0.16	0.06	0.27	0.118	0.085	–
$\mathrm{RoCoF}_{\mathrm{r1}}$	[Hz/s]	2.71	1.39	–	1.11	0.42	1.88	3.30	2.38	–
$\mathrm{RoCoF}_{\mathrm{r2}}$	[Hz/s]	1.20	0.62	–	0.65	0.24	1.09	1.88	1.36	–

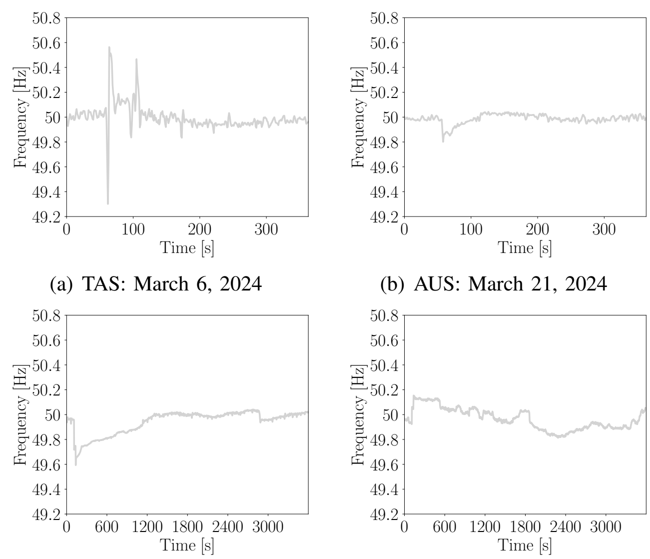
Power System Year			AIPS 2022			AUS 2024			TAS 2024	
i	[s]	1	4	0.02	1	4	0.02	1	4	0.02
$\mathrm{RoCoF}\|_{t=0_+}$	[Hz/s]		0.38			0.18			0.47	
$\overline{\mathrm{RoCoF}_i}$	[Hz/s]	0.0018	0.0012	–	–	0.0024	–	–	0.0072	–
$\mathrm{RoCoF}_{\mathrm{max},i}$	[Hz/s]	0.242	0.086	–	–	0.023	0.14	–	0.23	0.46
$\mathrm{RoCoF}_{\mathrm{r1}}$	[Hz/s]	2.21	0.78	–	–	0.80	4.90	–	2.24	4.48
$\mathrm{RoCoF}_{\mathrm{r2}}$	[Hz/s]	1.40	0.50	–	–	–	–	–	–	–

TABLE X: FFR volumes in GB, AIPS and AUS systems.

Direction	Units	GB (DC)	AIPS (FFR)	AUS/TAS (FFR)
Upward	[MW]	$\sim$ 1,300	$\sim$ 1,800	250
Downward	[MW]	$\sim$ 1,300	$<$ 100	125

TABLE XI: Assessment of minimum inertia requirements in GB.

Inertia floor [GWs]	140	120	110	102
Cost [£m]	524	266	198	170



(a) TAS: March 6, 2024 (b) AUS: March 21, 2024

(c) AIPS: May 14, 2024 (d) GB: May 14, 2024

Fig. 9: Comparison of frequency traces of the GB, AIPS, AUS, and TAS power systems for relevant contingencies in 2024.

in the AIPS system than the 32.3 GWs figure (assumed coming only from conventional generators and neglecting inertia from demand, for example), while for GB the 121 GWs figure might be representing better the actual inertia in the system.

Based on the discussion above and the considered metrics, it appears that the GB power system is stronger than the AIPS system in absolute terms. However, if we calculate the relative frequency strength of the two power systems using equations (6) and (7) the situation changes. Specifically, $\mathrm{RoCoF}_{\mathrm{r1}}$ values for GB and AIPS systems are 2.71 Hz/s (1.39 Hz/s) and 1.11 Hz/s (0.42 Hz/s), respectively, and thus lower for AIPS. Note that the values before (within) brackets are calculated using $\mathrm{RoCoF}_{\mathrm{max},i}$ from 1 s (4 s) data resolution. Similarly, the $\mathrm{RoCoF}_{\mathrm{r2}}$ values are lower for AIPS than GB namely 0.65 Hz/s (0.24 Hz/s) and 1.20 Hz/s (0.62 Hz/s).

b) GB trip on July 1, 2019 and AIPS trip on August 9, 2022: To further validate the above results and conclusions, we select two more relevant contingencies for GB (GB_{2019}) and AIPS (AIPS_{2022}) namely IC trip (1,000 MW import) on July 1, 2019 at 08:27 in GB and IC trip (530 MW import) on August 9, 2022 in AIPS [45]. The respective system operating conditions and results are given in Table VIII. It can be seen that the results are very similar to the previous comparison. Specifically, the nadir happens quicker in AIPS than in GB and similarly the frequency restoration in AIPS takes much more time. The GB system performs better than the AIPS system in terms of frequency recovery following contingencies.

Next, notice again that $\mathrm{RoCoF}_{\mathrm{max},i}$ and $\mathrm{RoCoF}|_{t=0_+}$ for GB are very similar (0.118 Hz/s and 0.124 Hz/s, respectively) while that is not the case for AIPS (0.242 Hz/s and 0.38 Hz/s, respectively). As mentioned above, two contributing factors here are the bigger support from FFR in the AIPS system (response time down to 150 ms) and potentially more inertia available than the calculated inertia from conventional units in AIPS (34.7 GWs inertia figure might be higher in reality) compared to GB (201 GWs seems to be close to actual inertia). It is also fascinating to see that the difference between $\mathrm{RoCoF}_{\mathrm{max},i}$ and $\mathrm{RoCoF}|_{t=0_+}$ has increased for AIPS over the last years (0.138 Hz/s in 2019 and 0.25 Hz/s in 2024).

Basically, this means that the frequency support in the inertial time frame has increased steadily (see Figure 8). This, in turn, has led to significant frequency stability improvement in recent years in the AIPS system [46].

With regard to the relative RoCoF calculations, again, AIPS shows lower values than GB. Specifically, $\mathrm{RoCoF_{r1}}$ values for GB and AIPS systems are 3.30 Hz/s (2.38 Hz/s) and 2.21 Hz/s (0.78 Hz/s), respectively. $\mathrm{RoCoF_{r2}}$ values are also lower for AIPS (1.40 Hz/s (0.50 Hz/s)) than GB (1.88 Hz/s (1.36 Hz/s)). This lead to confirm that the AIPS is stronger than the GB system relative to its size. Considering both jurisdictions are moving towards lower levels of inertia (Table XI) and competitive procurement of reserves, it would be interesting to perform a similar comparison in a few year's time to see whether the above conclusion will still hold.

c) AUS trip on March 21, 2024 and TAS trip on March 6, 2024: We conclude the comparison for abnormal operating conditions by selecting two relevant trips for AUS and TAS systems namely March 21, 2024 (trip of Bayswater Power Station Unit 1 at 660 MW at 18:00) and March 6, 2024 (trip of Comalco at 114 MW at 8:07), respectively [4]. It is important to note that the frequency measurements for these two events are provided in 4 s resolution and the inertia values are guessed based on time series graphs provided in [4]. While these minor limitations in data might lead to small discrepancies, we note that it does not affect the main conclusions drawn.

The system operating conditions and results are provided in Table VIII, while Figure 9 illustrates the relevant frequency transients. Due to the size of the TAS system (around 6 GWs compared to 90 GWs of AUS) and the size of the contingency at the time of incident (114 MW representing approximately 10% of demand), frequency nadir reached the lowest value (49.3 Hz). Regarding the time to nadir, both the AUS and TAS systems show a similar value of 8 s. Note, however, that since only 4 s data is available these times may be slightly lower and thus similar to AUS and AIPS systems. On the other hand, in contrast to GB and AIPS, the AUS and TAS power systems show a much better frequency recovery, namely, tens of seconds vs hundreds of seconds for GB and AIPS. This could be explained by the fact that both AUS and TAS systems employ an AGC while that is not the case for GB and AIPS systems (see Table I).

Regarding different RoCoFs calculations, one can see that the average $\overline{\mathrm{RoCoF}_i}$ ($i = 4$) shows a higher value for AUS (0.0024 Hz/s) and TAS (0.0072 Hz/s) systems as compared to the GB (0.0012 Hz/s and 0.0022 Hz/s) and AIPS (0.0010 Hz/s and 0.0012) systems. This makes sense considering that both the AUS and TAS systems recover their frequency quite quickly to ± 100 mHz (see Figure 9). With regard to the maximum $\mathrm{RoCoF}_{\max,i}$, since there is no 1 s resolution data, we utilize the value provided in [4] by AEMO (0.14 Hz/s and 0.46 Hz/s for AUS and TAS, respectively). AEMO calculates these from high-resolution data (20 ms) and 500 ms rolling window and filtering short-term transients [4]. But if we are to calculate $\mathrm{RoCoF}_{\max,i}$ from 4 s resolution data then these values are 0.023 Hz/s and 0.23 Hz/s for AUS and TAS, respectively. This means that the TAS system experiences the worst $\mathrm{RoCoF}_{\max,i}$ (0.23 Hz/s) compared to GB (0.034 Hz/s and 0.085 Hz/s), AIPS (0.06 Hz/s and 0.086 Hz/s), and AUS (0.023 Hz/s) systems. Similar to the nadir explanation above, this is to be expected considering the size of the TAS system and contingency.

Looking at the $\mathrm{RoCoF}|_{t=0_+}$ calculations, we can see that they are very similar to those calculated using 20 ms data and 500 ms rolling window namely 0.14 Hz/s and 0.18 Hz/s for AUS, and 0.46 Hz/s and 0.47 Hz/s for TAS system. Similar to the GB cases (GB_{2024} and GB_{2019}), the similarity in the values of $\mathrm{RoCoF}|_{t=0_+}$ and $\mathrm{RoCoF}_{\max,i}$ indicate that the inertial levels of the AUS and TAS systems are a good indication of the actual experienced RoCoF and that there is little FFR being provided in the inertial time frame. Note that even if the inertia values of the AUS and TAS systems might be slightly different than the current values (90 GWs for AUS and 6 GWs for TAS), the value of the $\mathrm{RoCoF}|_{t=0_+}$ will not change significantly and thus will not affect the main conclusions.

The $\mathrm{RoCoF_{r1}}$ results mean that the AUS (0.80 Hz/s) shows higher relative frequency control strength compared to GB (1.39 Hz/s and 2.38 Hz/s) and TAS (2.24 Hz/s) systems and lower strength compared to the AIPS (0.42 Hz/s and 0.78 Hz/s) system. Therefore, it can be concluded that based on the relative RoCoFs comparisons namely $\mathrm{RoCoF_{r1}}$ and $\mathrm{RoCoF_{r2}}$, the AIPS system shows a higher relative frequency control strength than GB, AUS and TAS systems, in fact, relative $\mathrm{RoCoF_{r1}}$ and $\mathrm{RoCoF_{r2}}$ are lower for AIPS. Note that if one considers other frequency strength metrics such time to recover within ± 100 mHz, then the above conclusion may completely change. However, we think that since RoCoF-based results, in particular, $\mathrm{RoCoF_{r1}}$ and $\mathrm{RoCoF_{r2}}$, are more critical/important than the recovery period in terms of frequency stability, it makes sense to reach the conclusion based on those results.

V. Conclusions

The common understanding is that the bigger the capacity of a power system, the bigger its robustness with respect to events and contingencies. Data discussed in this paper show that this is not always the case in the context of frequency control. Specifically, the key findings of this paper are summarized below.

A. Normal operating conditions

Our analysis indicates that despite being the second-biggest power system, AUS performs better in frequency regulation during normal system conditions. This is a counterintuitive result from a system size point of view [41] and, in particular, because NESO has recently introduced two new dynamic frequency regulation products (but DC also helps slightly in normal conditions by having ± 15 mHz dead-band [29]). A possible mitigation for GB is to consider a similar path to AUS regarding mandatory PFC provision with a narrow dead-band. If this is the case, it is suggested to focus on a potential increase in the asymmetry of frequency distribution like in AUS. Alternative solutions include implementing an AGC and revising frequency regulation products. Despite the AUS system showing, overall, the best frequency regulation performance, it appears that frequency asymmetry ($\Delta\sigma_f$) is higher than in AIPS. It is suggested to study more in detail $\Delta\sigma_f$ and its sources in the AUS system.

B. Abnormal operating conditions

The frequency control strength comparison is more complex during contingency events due to the different stages of frequency control such as FFR/PFC and AGC. The AIPS power system appears the "strongest" to arrest frequency and RoCoF relative to its size. This is mainly due to the significant procurement of FFR volumes and thus comes to a higher cost compared to the rest of the power systems. The AUS and TAS show better frequency recovery compared to the AIPS and GB power systems. A possible solution to this problem could be that GB and AIPS consider implementation of automatic secondary frequnecy control such as AGC similar to AUS and TAS.

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