

2 Feb 2023

Charles Popple Reliability Panel Australian Energy Market Commission

Submitted online

Dear Charles

AEC Submission to Frequency Operating Standard Draft Determination

The Australian Energy Council (AEC) welcomes the opportunity to make a submission in response Frequency Operating Standard (FOS) Draft Determination.

The Australian Energy Council is the peak industry body for electricity and downstream natural gas businesses operating in the competitive wholesale and retail energy markets. AEC members generate and sell energy to over 10 million homes and businesses and are major investors in renewable energy generation. The AEC supports reaching net-zero by 2050 as well as a 55 per cent emissions reduction target by 2035 and is committed to delivering the energy transition for the benefit of consumers.

Our submission includes as an appendix some expert opinion from Provecta Consulting's Don Parker on matters in the Panel's advice by GHD Advisory that was relied upon by the Panel for its draft recommendation on Primary Frequency Control Band (PFCB).

The AEC broadly supports the Draft Determination's recommendations on Contingency Events and Time Error. The AEC does not support the leaving the present Normal Operating Frequency Band (NOFB) and Primary Frequency Control Band (PFCB) unchanged.

Frequency Performance During Normal Operation

Normal Operating Frequency Band standard

The AEC has engaged closely on NEM frequency control reform since 2018. The AEC then concurred with the general view that NOFB performance had become unacceptable and reform was required to tighten the normal condition frequency distribution including through the use of some Primary Frequency Response (PFR). However the AEC observed an evident paradox that this unacceptable distribution nevertheless remained compliant with the relevant standard of remaining within NOFB standard for 99% of the time.

Observing this paradox, the AEC <u>wrote</u> to the Panel that it required rectification through an urgent FOS review. This review would identify the new target NOFB outcome (through the Panel's role in identifying the optimal cost vs security trade-off), and, having developed a new target, work could begin on the best means to deliver it.

Instead reform has evolved in the reverse sequence to good regulatory practice. In 2020 a heavy-handed mandatory obligation was placed on a wide range of competitive equipment to achieve an undefined objective, and only then, having dramatically changed the frequency outcome, in 2022-23 is the Panel contemplating desired outcomes.

P +61 3 9205 3100 E info@energycouncil.com.au W energycouncil.com.au ABN 92 608 495 307 ©Australian Energy Council 2020 All rights reserved. Yet the Draft Determination has still not identified that desired outcome. Instead of determining a new economically based outcome standard for the NEM's acceptable frequency distribution, it has instead focused its work on one of the input tuning parameters associated with the mandatory obligation. Indeed it proposes perpetuating the inconsistency between this tuning parameter and the outcome standard.

The AEC considers that the cost-benefit analysis being performed by the Panel should instead target the output standard: the NOFB standard of 99% of the time being within +/-150mHz. This requires respecification. Like other Panel outcome standards, the NOFB should be set to the optimal trade-off between security and cost, and only then should the means to deliver it be determined.

An example of a such a form of delivery would be mandatory PFR and its associated input parameters, primarily the PFCB. The AEC therefore recommends that the work performed to date by the Panel be redirected into re-specifying the NOFB rather than the PFCB. Work on the PFCB (or any other means to deliver the NOFB) would come later, consequential on the new NOFB.

The draft determination did not engage with the four options for the NOFB suggested by AEMO and presented in the April 2022 Issues Paper. Of those options, the AEC does not support options 1 (qualitative criteria), 2 (additional frequency band within NOFB) nor 4 (mileage standard). It does support resetting the NOFB with adjustments to its width and/or time proportion (99%). Specifying a more sophisticated structure such as option 3 (frequency distribution standard deviation) may be useful.

Having set a clear outcome standard, the Panel could then lay out a process where input parameters, such as the PFCB, could be retuned regularly in order bring the system closer to that outcome. The AEC considers it incorrect to lock in this tuning parameter for five years at this time.

Primary Frequency Control Band

Noting the AEC disagrees with the Panel's approach in adjusting an input parameter without first determining an outcome objective, the AEC has the following comments on the Panel's work on PFCB.

The advice the panel commissioned from GHD appears to have been engaged to assess only PFCB, and in that manner considered only incremental changes to the existing +/-15mHz PFCB. It did this by attempting to balance costs of greater governor control at plant level with the greater resilience of having the system very close to 50Hz pre-contingency.

To assist it in interpreting the GHD report within that limited scope, the AEC sought advice from Provecta. Although only an initial view, Provecta identifies:

- Burdens placed on thermal plant by the narrow PFCB that were not fully identified by GHD; and
- System-wide frequency skew and wobble that appear worsened by the very tight PFCB.

Provecta consider these costs may materially reduce with even a very slight PFCB widening, to say +/-30mHz.

With respect to the benefits, the AEC agrees that, all else being equal, a system with a pre-contingent frequency close to 50Hz should be more resilient in the event of an extreme contingency. However in valuing resilience GHD contemplated extreme contingent excursions of the order 1000-2000 mHz. The loss of resilience resulting from a very small increase in the PFCB to, say, +/-30mHz would presumably be immaterial to this contemplation, and likely to be much less than the material savings that would come about through this relaxation.

Matters identified by Provecta

In relation to the benefits of a narrow PFCB, GHD has noted it should reduce costs associated with Regulation Frequency Control Ancillary Services (FCAS). The AEC objects to the description of an uncompensated mandatory service displacing a market mechanism as beneficial, but Provecta goes further in noting that the two are not technical equivalents in the way portrayed here, and do not substitute.

AEMO has provided considerable material on the system frequency distribution post the implementation of narrow deadband mandatory PFR. Whilst unquestionably a very tight distribution, there are two notable imperfections to the distribution for which we understand that AEMO is unsure of the cause:

- A "wobble" in terms of a slow frequency cycling with a period 18-24 seconds, and
- A "skew" in terms of an asymmetry in the distribution.

From its external perspective, Provecta observes that there are likely to be issues in:

- the setup and tuning of AEMO's AGC controller, and
- Regulation FCAS design and performance.

These issues require additional work that is clearly outside the Panel's role, but are unfortunately materially confusing the Panel's work. Provecta suspects the skew and wobble could be removed by

- Improving the AGC controller and FCAS design and performance, AND
- Either:
 - Slightly increasing the mandatory deadband e.g. +/-30mHz for all generators OR
 - $\circ~$ A more sophisticated deadband, e.g. a less severe, 10% droop, between +/-15 and +/- 30mHz, then 4% beyond +/-30mHz

With respect to the latter point, Provecta notes that in 2009, when PFR was widely provided on a voluntary basis, generators typically applied deadbands of +/-30 to +/-50mHz and resulted in a frequency distribution not observably wider than exists today with a +/-15mHz.

Steam turbines are experiencing considerable costs, wear and loss of thermal efficiency in caused by the numerous small movements required to support the current PFCB which Provecta consider to have been underestimated. Figure 7 (reproduced below) is real data drawn from a large NEM unit as it moves up from a minimum load point at the middle of the graph. Whilst at minimum load (a period when the frequency was above 50.00Hz) the unit was stable (as mandatory PFR does not require footroom). However upon moving up from minimum load, MW output varies continuously with frequency, and as a result, many mechanical parts of the unit are also moving.



Phone +61 3 9205 3100 Email info@energycouncil.com.au Website www.energycouncil.com.au

ABN 92 608 495 307 ©Australian Energy Council 2020 All rights reserved. Provecta is concerned that these real costs were not fully captured by GHD. Provecta took the view that even quite a small relaxation in deadband would likely materially lower them.

Settings for Contingency Events

Rate of Change of Frequency

As per its earlier submission, the AEC supports introduction of a ROCOF standard which may

- Assist connecting parties in understanding expected system performance against the resilience of their own equipment;
- Assist networks in determining acceptable Under Frequency Load Shedding (UFLS) speed;
- Assist in determining parameters for a future inertia market.

Maximum Contingency size

In its earlier submission, the AEC supported investigation of a maximum contingency size to simplify planning decisions and in doing so make the rejection of unacceptably large connection configurations appear less capricious. On consideration of the rationale presented in the Draft Determination, the AEC concurs that the FOS is not necessarily the best place to promulgate a maximum contingency size.

Nevertheless, the AEC considers greater predictability would be useful for investors, such as a published list of maximum acceptable contingency sizes in different locations of the NEM. Whilst this would not be a Panel responsibility, it could be a recommendation from the final determination.

Time Error

As per its earlier submission, the AEC agrees with the Panel that the customer justification for a time error standard is redundant. Attempting to correct for time error through an intentional set point bias seems inconsistent with mandatory narrow deadband PFR, and will confuse deviation payment settlement. For these reasons the AEC supports the Draft position.

However as stated in that submission, time error is a useful diagnostic tool with respect to demonstrating whether there is bias in normal operating frequency performance. The Draft Determination is silent on this matter. If the standard is simply withdrawn, it is likely that time error will no longer be monitored. It may be appropriate for the Panel to promulgate a reporting standard, say, based on exceedance of a delta time error in less than a specific period.

Any questions about this submission should be addressed to the writer, by e-mail to <u>ben.skinner@energycouncil.com.au</u> or by telephone on (03) 9205 3116.

Yours sincerely,

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Appendix: AE04-AECO-RPT001 Review of NEM Frequency Operating Standard GHD consultancy report by Provecta Rev 2 23/12/2022.

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AE04-AECO-RPT001 Review of NEM Frequency Operating Standard GHD consultancy report

Rev 2

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Reviewed: N Ronan 23/12/2022

1 Summary

Provecta Process Automation is a specialist electrical, industrial IT/OT and controls engineering company working in critical infrastructure, particularly in conventional and renewable generation, water and wastewater treatment in Australia and internationally. Mr Parker has been a specialist power plant controls engineer for 43 years and is recognised internationally, having provided services in NZ, Asia, UK and the USA, including a period of over 4 years managing the company's US branch.

Provecta was requested to consider particular aspects of the GHD report, particularly qualitative comments on:

- Impacts on thermal plants as a result of the PFCB that do not appear to have been fully captured by GHD;
- Qualitative postulations on the likely causes of the 'wobble' (system frequency cycling which is not always centred around 50Hz) and whether they are likely to be relieved by a slightly wider PFCB.

The following summarises observations made in this report.

1. Significance of PFR and difference to R-FCAS

It is recognised that PFR is essential to system security, and cannot be replaced by remote dispatch demands which are far too slow. PFR is fast, proportional, local and performs the function of arresting frequency deviations. In a generation loss event, frequency usually falls, initially at the rate determined physically by the quantity of synchronous rotating generation inertia and frequency-sensitive rotating loads, reaches a nadir as PFR responds and as RoCoF-related generation has returned to zero, and then 'bounces' back to a settled point determined by the speed of PFR response and total system droop.

PFR on conventional thermal generation plant responds with time constants (time to reach 63%) ranging from 10s to 30s depending on plant capability and control system design and tuning. Special functions are often applied to the boiler and governor controls to provide these fast steps in generation of up to 10% MCR. On the other hand, R-FCAS is rate-limited to the demand rate set locally and is typically 1-2%/minute. Thus, whereas PFR may generate a 10% MCR step in 30s, R-FCAS would achieve between 0.5 and 1% MW change in the same period and cannot respond quickly to frequency deviations.

Clearly, the cost upon boiler/turbine components is far greater with PFR than the ACE-based adjustments made by R-FCAS.

Nonetheless, even regular sawtooth-style R-FCAS demand changes introduce their own challenges to plant operation, albeit over a longer period and therefore affect slower processes in the boiler, particularly boiler steam pressure and temperature oscillations which can impact plant life. R-FCAS demand profiles should be optimised to minimise these effects on generating units.



2. System frequency cycling

The interconnected system is experiencing slow frequency cycling with a period of 18-24 secs, as reported by AEMO [1]. The peak-to-peak variation is around 20-40mHz and is not always centred around 50Hz, and therefore is not purely a function of limit-cycling around the deadband region, which can often occur in the control of integrating processes such as frequency when small deadbands are applied. This oscillation at times exhibits a 'beat' of about 5 minute period as shown in the AEMO white paper, which indicates the cycles may be initiated by resonances of slightly different base periods, which is surmised as coming from different MW response delays to R-FCAS commands.

One aspect of remote dispatch control in the past that has caused local MW instability was the operation of the AGC dispatch controller using generated MW as its process feedback, effectively creating a remote MW controller driving the setpoint to a local MW controller, which breaches fundamental control theory for cascade control structures. When local generation has a MW delay due, say, to governor hysteresis, the AGC demand would overshoot and had caused slow, cyclic MW variations as AGC 'chased' generation to the target. This was overcome at several stations by AGC switching to setpoint feedback. It is recommended that this arrangement, if not already done, be deployed at all stations in the NEM.

3. Impacts of cycling

While it is recognised that the narrow-band MPFR action generally holds the frequency to well within the NOFB, it is doing so in reaction to oscillations that are usually wider than the band and therefore generators are responding cyclically to what appear to be deviations caused by delays in either frequency response, R-FCAS MW following or regulation commands themselves, rather than random variations in generation/load imbalance.

As described in the report, the cyclic nature of the frequency deviations is causing excessive movement on many controlling devices, particularly in boiler components, as the boiler demand is 'kicked' by around twice as strongly as any change in MW demand during PFR activity, as required to help overcome the inherent boiler delay. Several boiler demand signals apply the rate of change of unit demand (including fast PFR bias) to form time-leading kicker elements, therefore cycling activity is amplified in the boiler controls and generates faster, more frequent actuator movements.

4. Frequency histogram 'skew' and R-FCAS operation

The source of this perceived skew away from being centred around 50Hz has not been investigated. However it is noted that the algorithm uses a deadband rate-limiter as described in the GHD report. When the rate limiter is active, a false deviation is being fed to the controller which can cause a longterm integration error. Instead, a low-gain region without rate limiting should be applied to the integrator. Any proportional component in the algorithm can have a pure deadband applied.

5. Notes on the current deadband setting

It is suggested that widening the deadband to +/- 30MHz would eliminate much of the PFR reaction to this cycle while still providing tighter control over frequency than before MPFR was introduced. Figure 2 shows the improvement in frequency spread since MPFR was introduced, but it also shows that in 2009 (and also the case earlier) that voluntary PFR, with deadbands on units ranging from 30mHz to 50mHz, was also narrow and close to the current profile.

One example quoted by AEMO of a system using narrow band is ERCOT (Texas) [2], set at +/- 17mHz. But the table from the ERCOT operating guide [2] provides two sets of bands; refer extract in Figure 1. Note that mechanical governor turbines have a wider band allowed. This appears



to be in recognition that there is a natural deadband in mechanical governors due to hysteresis (backlash) and the requirement to consistently provide PFR needs to begin outside that natural deadband. This is considered again with an example in Section 3. If applied to the NEM, in NSW this would affect eight large units. The wider band would also apply to some stations in other states.

6. Suggested alternative to single-deadband PFR

It is suggested that consideration should be given for a three-region PFR droop profile: 0-15mHz dead band; 15-30mHz 10% droop; over 30mHz 4% droop. These adjustments can be readily made in most DCS-based MW controllers and would reduce the impact on boiler-turbine processes while still providing support to hold frequency well within the NOFB.

Resource Type	Max. Deadband
Steam Turbines with Mechanical Governors	+/- 0.034 Hz
Hydro Turbines with Mechanical Governors	+/- 0.034 Hz
All Other Generating Units/Generating Facilities/ESRs	+/- 0.017 Hz



Figure 1 ERCOT PFR deadband settings [2]

Figure 2 Comparative annual frequency distributions in the NEM [1]

2 Comparing responses of R-FCAS and PFR and relative work burdens

The GHD report makes comment that increasing the PFR deadband requires a compensating effort by R-FCAS to manage frequency. This was done to enable cost comparisons to be made by using the AEMO values placed on the services. However there are several matters of concern with this approach:

a) R-FCAS performs a different function to PFR.

The following uses a low frequency event scenario by way of example.

Review of NEM Frequency Operating Standard GHD consultancy report



PFR is local, immediate and proportional. As it only responds to in direct proportion to a frequency deviation, the only way it can provide a change in MW to help re-balance the system is for there to be a residual, settled change in frequency that is in proportion to the original imbalance that has been restored.

R-FCAS, as secondary control acts to eliminate the residual frequency error through AGC by driving system generation up, causing frequency to rise, progressively reducing the frequency-biased generation and restoring rotating kinetic energy. The R-FCAS is by design a Proportional plus integral controller. The integral action continues to bias up the AGC demand until frequency deviation is eliminated. The proportional component is not required from deviation correction, but as frequency response is an integrating process, integral-only control of an integrating process in inherently unstable and proportional action is required to maintain phase margin for system stability.

During deviations around 50Hz, the R-FCAS proportional action can slightly assist with PFR if it is fast enough. Observations of some event trends have shown the 24-s period instability occurring, but also shows an R-FCAS signal driving MW demand with a phase delay of up to 90 Deg. The cause of the delay is unknown but may be related to communication, filtering and AGC demand processing delays (or possibly only a charting error).

During the restoration period after the frequency has settled, not only will PFR action be biasing MW down as the low frequency deviation reduces, but the proportional action of R-FCAS will be doing the same. A higher proportional gain in the R-FCAS controller could help keep frequency within PFCB, provided its output delay did not cause further instability, but in its role to *restore* frequency after an event, higher proportional gain will actually slow the recovery trajectory.

b) Questions exist on R-FCAS design and performance

The control design for R-FCAS provided in the GHD report, if representative of the actual implementation, appears simplistic for the complex system being controlled. It was surprising, for example that AEMO report on a need for manual bias to the controller to restore frequency error due to having a deadband in the controller. Since this is the overall 'trim' controller of an integrating process, basic control design mandates that the integrator must not have any deadband or there will be drift to the deadband edge, either remaining there or limit-cycling between limits. This can be overcome by either applying a deadband the proportional component only or including a low-gain region instead of a pure deadband.

There has been much activity in exploring improvements to regulation control of networks [6] lists around 300 relevant research papers with over 100 in the last 10 years, so it could be anticipated that R-FCAS would be further optimised over time.

c) R-FCAS work is not equivalent to PFR work

If R-FCAS could be adjusted to reduce the frequency histogram 'skew' and attenuate the slow frequency cycles in an optimised manner, PFR could be widened with minimal change to system risk, due to a naturally narrower bell curve. R-FCAS moves MW demand at the unit ramp rate, which does not 'overfire' the boiler as hard as PFR, and should be optimised to minimise load demand reversals by incorporating model-based control algorithms that place a cost on activity and direction reversals.



Review of NEM Frequency Operating Standard GHD consultancy report

3 PFR response dynamic variations – possibly contributing to the system cycling (control and mechanical factors)

Frequency response dynamics are not the same for all generators. Factors including MW controller cycle time (ranging from 0.1s to 1s in the NEM Interconnection), tuning and control structure (including pressure cross-influences), DCS protective overrides and governor rate limiting.

A simulation of frequency dynamics due to partial generation loss, with only synchronous thermal generation responding was constructed by the author in Simulink using an IEEEG1 turbine model (set for a 60Hz interconnection), and detailed unit co-ordinated controls. The simulation gave the results shown in Figure 3 by varying MW controller parameters and structure.



Figure 3 PFR MW controller design and tuning differences affecting the nadir

This is a reflection of the range of effects different PFR generation responses can have on frequency dynamics. While each generator is required to provide response models and confirm response performance, it is uncertain how the actual performance of each generator, or mix of generators at any point in time will affect overall frequency response and system deviations. Some combinations may contribute more to system cycling than others.

Another variation in PFR response in turbines with mechanical governors can arise from backlash or hysteresis as components wear. Of course some backlash is inherent to avoid stiction and allow for machining tolerances, but it is not uncommon to encounter 20mHz total hysteresis band, as demonstrated in Figure 4. This plot was taken from a period where a turbine governor that participates in the NEM was on manual for a set of tests, and during periods at two different positions the system frequency changed substantially. Since the linear HPCV position is derived from steam pressure ratios, there is some noise in the vertical axis but operation in the 49.95-49.98 region shows at least 20mHz hysteresis. This should not be considered abnormal as anecdotally, turbine manufacturers had expected 20-30mHz hysteresis in their systems.

This can affect PFR performance, depending on where the governor is in relation to the backlash at the time of action, and can also add a small delay (up to 30 secs) to R-FCAS response.



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Figure 4 Mechanical governor hysteresis, at least 20mHz total. (Governor on Manual at two base positions, during high frequency-droop activity)

4 Examples of effects on unit processes from frequent PFR activity

The following sections give some examples of boiler and turbine processes affected by PFR activity. Figure 5 shows some of the major processes affected. The focus here is on the effects of responding to the narrow-band frequency deviations, and particularly in response to regular PFR activity stemming from the frequency oscillation of 18-24s period that is occurring.



Figure 5 A frequency excursion disturbs around 30 control loops and 50 modulating devices

Some examples describe process effects on boiler operation and efficiency, some on the impact of operator adjustments to setpoints to raise unit security and others on the wear and tear of field devices.

To support the claim that PFR is more damaging to plant than R-FCAS for similar MW movement, we consider loops that are more affected by PFR than by R-FCAS. This is done by identifying



processes that have closed-loop time constants less than or equal to 25 secs and are therefore affected by the frequency cycling and constant fast activity occurring at the PCFB boundaries.

Process	Approx. <u>closed loop</u> response time constant (with typical	Control elements (typical)
	tuning) (Note 1)	
Air Flow	10s	FD Fan blades x2
Furnace Pressure	8-15s	ID Fan blades/vanes x2
PA Hot Bus Pressure	20s	PA Fan vanes x2
Mill air flow	15-25s	Mill air reg. dampers (multi-leaved),
		up to x6 at full load
Mill fuel flow (vertical spindle mills)	5s	Mill feeders (VFDs) up to x6 at full
		load
Superheater Spray desuperheater	25s	Spray water valves (between 4 and
temperature		14 per boiler)
Unit MW (DCS control including	8-20s (depending on design	Turbine Governor and CVs
frequency bias to Turbine master)	and tuning) (Note 2)	
Drum level (feedwater)	10s (feedwater response to	Boiler Feed pump
	steam flow change)	

Table 1 Boiler/Turbine processes with closed-loop time constants less than or equal to 25 secs

Note 1. The time for the process to reach 63% on a setpoint step change. Note 2. Open loop response is 3sec HP component (30%) plus 12sec RH/IP/LP component (70%) with slew-rate limiting to Governor, giving a complex MW control response with fast and slow components.

4.1 Steam temperature deviations

Increased PFR activity coinciding with ramp-related deviations can generate steam temperature exceedances. Steam temperature alarming will generally lead to temperature setpoint reduction. It is not expected this reduction would be great, but for a 660MW Rankin-cycle Reheat unit as an example, a 2°C reduction in main steam temperature would result in a 0.055% efficiency reduction, increasing CO_2 emissions by over 1,000 tons per unit per year and up to \$60-90,000/unit/year assuming 60% capacity factor [3].

4.2 Cycling causing material stresses

So long as cyclic frequency movement is being experienced on the system, PFR commands feeding directly to the Boiler and Turbine Masters, and the related fast process changes in steam flow and pressure, can lead to cyclic stresses in both boiler and turbine components. The impact of such factors is outside this study's scope, but effects of cycling, including thermal fatigue causing tube and header cracking and magnetite exfoliation are well researched and recorded phenomena [4]. The fast rates of change from the periodic PFR response will introduce high thermal change rates over relatively small temperature changes. Modern analysis tools are available to assess life consumption and stress-corrosion risk as a result. An extensive dynamic model study of the stress impact of PFR on boiler headers has been published in [5].





4.3 Excessive boiler control element activity

Boiler/turbine units operate in a Unit Co-ordinated mode, which operates on processes that are nonlinear, interactive and time-varying. In particular, by providing fast MW control with the turbine valves and controlling the boiler heat input to maintain steam pressure, the pressure responds as an *integrating* process, that is, unless heat input required for a particular generated power exactly matches the MW that the turbine controls are set to deliver, steam pressure will continue to rise or fall until a steam flow/MW balance is restored. The effect on steam pressure is therefore similar to system frequency requiring a constant generation/system load balance. Integrating processes are inherently unstable require control designs with stabilising components.

The slow response of thermal steam generators, including drum and supercritical once-through, means that any load demand change, whether for ramping or PFR, requires additional, leading fuel movement to 'get ahead' of the delays. these are in the form of various 'kickers' which are derived on the rates of change of load demand and steam pressure setpoint. Hence, the faster movement of PFR-based load change can result in greatly increased boiler response compared to ramping with R-FCAS.

For example, a 2% change up in MW demand from PFR (0.055Hz) would demand around a 4% change in fuel flow, air flow and induced draft extraction, and fast spray valve movements. Even small load changes generate sufficient drum shrink/swell to cause additional boiler feed pump movement above the normal load-demand and level control activity.

Figure 6 shows an example of this effect with the results from a frequency injection step response test at low load on a large drum-boiler unit. A frequency deviation calculated to generate 5% frequency bias action was injected in the DCS. Note the requirement to over-fire the boiler by 100% to recover steam pressure to the new load point, and also the need to drive the turbine governor well beyond what would have been a 5% "droop" movement of the CV in the event of a real frequency disturbance.



Figure 6 PFR step test by DCS injection (mechanical governor). Note large initial movement of Boiler Master and Governor compared with 'settled' value.



When all these small effects continue in a cyclic manner as frequency limit-cycles around either the upper or lower PFCB limit, continuous movement with a high level of reversals can cause excessive wear of control devices and affected materials.

Taking the 20s cycle effect as an example: well-optimised control actuators typically move at no more than 10 movements per minute under normal conditions, or more often during disturbances and fast ramps. Minimum positioning of electric actuators, for example, is around 0.3% of the range. If each 20sec PFR cycle at the deadband's edge requires 1% movement of a particular boiler actuator, this adds 6 ramps per minute with up to 3 movements per ramp, or an extra 18 movements per minute, increasing actuator activity by 180%, significantly reducing the life of gearboxes, linkage joints and valve glands. While the life reduction may not be seen for several years, even small levels of PFR activity should not be considered to have insignificant long-term cost.

An example of this increased process activity is shown in Figure 7 that trends recent data from a large unit in the NEM. Note increased activity of fuel flow, furnace pressure and damper movement when PFR is active. The periods shown with no PFR action are due to the unit being at minimum load and so 'lower' PFR is not available when frequency is high.



Figure 7 Trend showing comparative effect of small PFR influence on some boiler processes on a large unit in the NEM.

4.4 Control system resonances and effects on boiler combustion.

Several processes in Table 1 have fast time constants that can 'resonate' via the PFR response to cycling system frequency, or be 'kicked' by frequent random PFR demand changes. The most significant of these is Hot Primary Air duct pressure which supplies all mills with air. As a mill increases air flow in response to the PFR demand to the Boiler master (by opening its inlet damper), PA bus pressure falls and the PA fans respond, but with a delay. The two processes interact and can readily be sent into oscillation. The natural period of the coupled loop is similar to the grid frequency variations. Continued changes in mill air flow affects flame stability, a common issue particularly at the lower loads that units are now at for longer periods, and could increase carbon in dust (both efficiency and possibly loss of ash sales revenue) and NOx emissions.

The other combustion-related cost effect can come from concerns with flue gas O_2 (FGO2) which much remain well in excess of zero to ensure safe combustion. If due to fast, regular PFR movement an addition movement of FGO2 causes occasional reductions from setpoint that are of concern, the



FGO2 setpoint will be raised. 0.5% FGO2 translates to 2.5% higher air flow, raising auxiliary power to FD and ID fans by a similar amount.

4.5 Significant increase in Turbine CV activity

The increase in throttle valve activity can be vividly seen in a trend of a NEM unit taken at the time the deadband was switched from 150mHz to 15mHz. The position range of fast movement reversals on CV 3 increased by at least 300%. AEMO reports in the white paper [1] that already by 22/10/22 several generators had moved to 15mHz PFR deadband and a significant reduction in frequency spread had already occurred, so this movement increase was not a worst-case example which subsequently reduced significantly. Also, trends taken over long periods later showed similar increases in CV movement and MW variations.



Figure 8 Example of turbine valve movement change when +/-15mHz MPFR was activated



[1] AEMO, *Enduring primary frequency response requirements for the NEM*, Technical White Paper, August 2021

[2] ERCOT, *Nodal Operating Guide*, March 2021, at http://www.ercot.com/content/wcm/libraries/226349/March_1_2021_Nodal_Operating_Guide.pdf.

[3] Goble, S. Steam temperature control implementation at a coal-fired power station. Proceedings, *ICEX 95, IICA*.

[4] Electric Power Research Institute, *Effect of Operational Transients on Boiler Damage*, 1015649, March 2009.

[5] Hübel, Moritz, A. Berndt, S. Meinke, M. Richter, P. Mutschler, E. Hassel, H. Weber, M. Sander and J. Funkquist. "*Modelling a Lignite Power Plant in Modelica to Evaluate the Effects of Dynamic Operation and Offering Grid Services*." Proceedings of the 10th International Modelica Conference, Lund, Sweden, 2014

[6] Alhelou H. H. Golshan M. H. H. Zamani R. Forushani E. H. Siano P. (2018). "Challenges and opportunities of load frequency control in conventional, modern and future smart power systems: A comprehensive review". *Energies*, *11* (2497), *1–35*. doi:10.3390/en11102497 file:///C:/Users/dparker/Downloads/energies-11-02497.pdf accessed 08/20/21.