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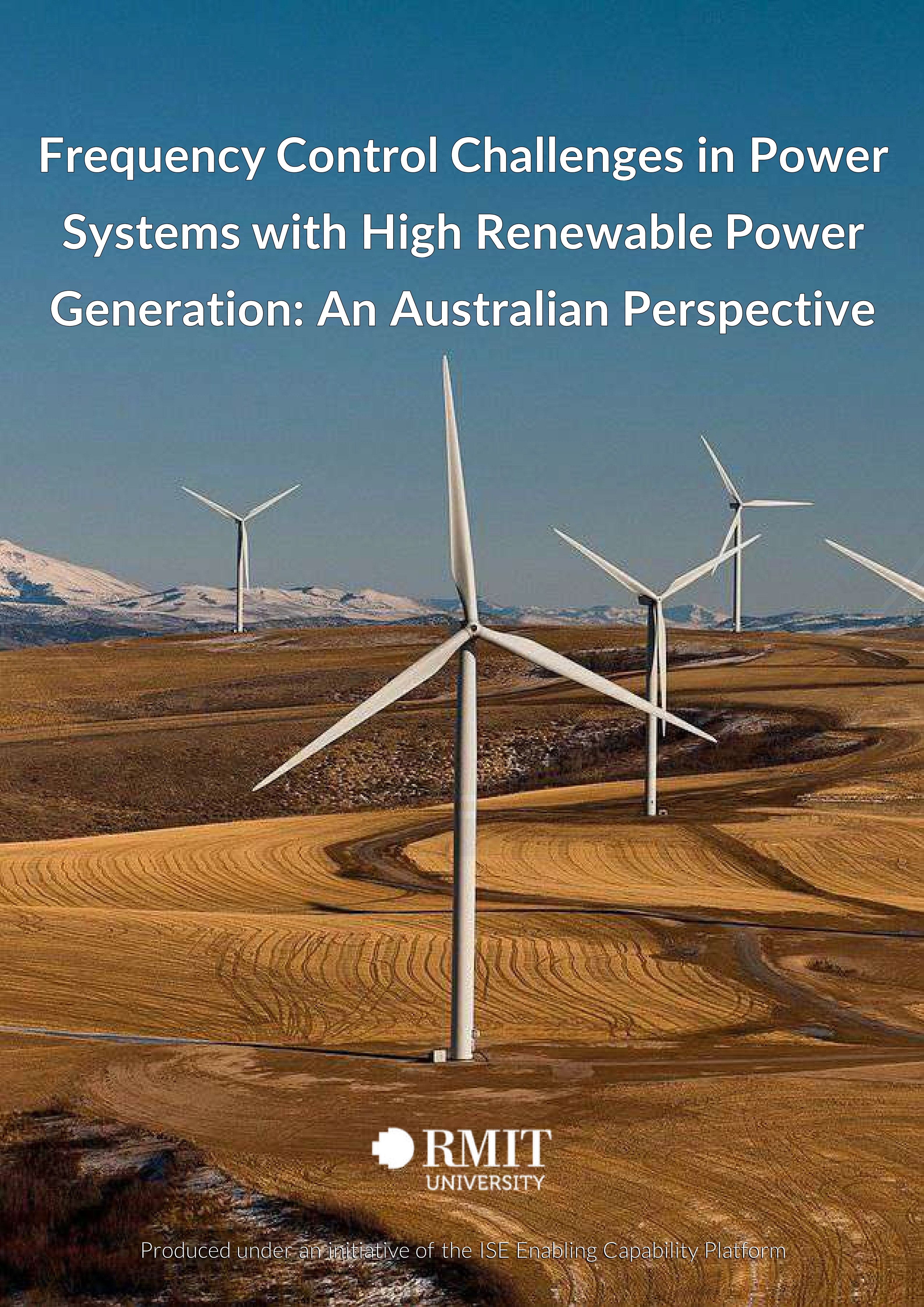

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Frequency Control Challenges in Power Systems with High Renewable Power Generation: An Australian Perspective

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Executive Summary

Frequency control within Australia's power system has become increasingly challenged over the past few years. This paper examines some of the current topical issues and associated literature, which poses four open questions:

1. Are large governor deadbands and inactive governors on synchronous generating units contributing to frequency control issues?
2. Are market frameworks overriding the technical design of the system resulting in deterioration of frequency control?
3. What changes are necessary for the future to overcome the effects of reduced system inertia?
4. How can renewable energy generation be better utilised to participate in the provision of frequency control ancillary services?

To improve frequency control in the Australian power system recommendations are made to both mandate governor response and ensure governor deadbands do not exceed 100 mHz (±50 mHz).

Background

The control of frequency in power systems deals with the instantaneous balance of active power demand and generation. If generation exceeds demand, frequency increases, conversely, if demand exceeds generation, frequency decreases.

Traditionally, power systems have contained large amounts of synchronous generators found within fossil-fuelled power stations. Such equipment is directly coupled to the grid and contains inertia stored within the rotating masses.

However, modern-day power systems (and those of the future) contain increasing amounts of renewable energy sources connected through power electronic converter (PEC) interfaces, owing to the need for cleaner generation to tackle the issue of climate change.

PEC interfaced renewable energy sources present a range of challenges when compared to traditional synchronous generators such as different dynamics, stochastic generation profiles, and a lack of inertia.

For example, PEC interfaces effectively decouple renewable generators from the system, which contributes to reduced system inertia. Consequently, new control methods will increasingly be required in the future to overcome this issue. Moreover, when compared to traditional, large synchronous generators, PEC interfaced sources have faster dynamics.

The provision of ancillary services, such as voltage and frequency control, is also challenged as synchronous generators are displaced. Therefore, new ways to utilise renewable power generation and power electronic converter technologies will be required to ensure system stability and security is maintained or improved. Changes to the vertically integrated structure of the power system, as well as market dynamics further challenges power system operation.

Having an unstable power system containing predominantly synchronous generation will also challenge the transition towards a cleaner, PEC dominated system. Power system frequency control is crucial to the quality and security of electrical power systems [1]. Therefore, such issues require examination in the Australian context - a system which is currently undergoing rapid change while grappling with control issues concerning its fleet of traditional synchronous generators.

Frequency Control in Power Systems

Three frequency control responses are typically applied within a system to maintain and restore active power balance, each with varying operational timescales, which forms what is known as frequency control. The frequency of a system will vary from its equilibrium if an imbalance in active power occurs as a result of a system event — for example, a sudden change in load or a loss of generation.

Primary Frequency Control

Given a decline in frequency, such as that shown in Figure 1, a primary control response acts to arrest the frequency drop and stabilise the system. Primary frequency control is composed of a natural inertial response followed by a primary control action.

The inertial response acts to limit the rate of change of frequency (RoCoF) by releasing the kinetic energy stored within the rotating masses into the network. Following this, the primary control action acts to arrest the frequency decline.

Frequency is sensed locally at the machine, and the steam valve of the turbine is actuated in proportion to the frequency error (measured frequency versus nominal value) to change the mechanical power input to the machine, thus altering its active power output.

However, the frequency is not returned to its nominal value as the control action is in proportion to the error (called proportional control). In summary, primary frequency control is imperative for power system stability.

Secondary and Tertiary Control

Within 30 seconds, the secondary control response takes over. Secondary control uses a proportional-integral (PI) control action to provide time-error correction of frequency. Therefore, system frequency is returned to its nominal value, typically over minutes. On the other hand, tertiary responses refer to manual variations in unit commitment.

In 2001, the *Reliability Panel* reported that "frequency must be managed on a second-by-second basis, far faster than any market mechanisms can deliver" [1]. As will be shown in the following sections of this document, the frequency profile of the Australian system has progressively flattened over the past few years, which indicates that the control philosophy of the system requires reform.

As we transition to a power system centred around the use of PEC interfaced renewable energy sources, the need for new types of technologies to participate in frequency control will increase. Furthermore, tapping into renewable energy generation to provide ancillary services will be essential to ensure power system security and stability.

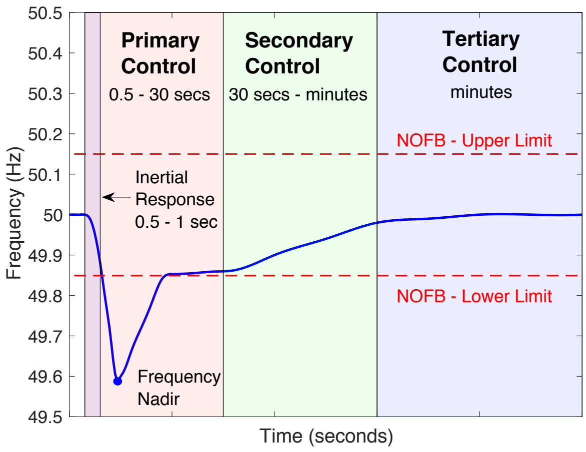

Figure 1: Fundamental frequency control principle.

Open Questions

The adequacy of Australia's FCAS market has been called into question owing to the continued, evidenced degradation of frequency control, coupled with an increase in FCAS recovery costs. The *Independent Review into the Future Security of the National Electricity Market - Blueprint for the Future* highlighted that a deadband similar to international jurisdictions might be necessary [2].

The Engineers Australia submission to the *Frequency Control Frameworks Review* illustrated the contribution of synchronous generators to power system oscillations in the National Electricity Market (NEM) and presented potential challenges of reduced inertia on system stability [3]. A reduction in the provision of primary frequency control within the NEM is cited as a being a catalyst for the deterioration of frequency control owing to the widening of governor deadbands and use of digital control systems [4].

Engineering studies have demonstrated the importance of governor deadbands and governor activity for power system stability [5]. Moreover, recent rule change requests submitted to the Australian Energy Market Commission (AEMC) have all highlighted the current frequency control issues in Australia's NEM [6], [7], [8]. Consequently, four key questions currently exist concerning current and future issues:

1. Are large governor deadbands and inactive governors on synchronous generating units contributing to frequency control issues?
2. Are market frameworks overriding the technical design of the system resulting in deterioration of frequency control?
3. What changes are necessary for the future to overcome the effects of reduced system inertia?
4. How can renewable energy generation be better utilised to participate in the provision of frequency control ancillary services?

Evolution of Australia's National Electricity Market

Australia's National Electricity Market (NEM) was created in 1998 and runs on one of the world's longest interconnected power systems [9]. The system is radial in nature, which presents unique stability attributes when compared to other tightly meshed power systems across the world. Figure 2 illustrates the transmission system as well as selected interconnectors.

Figure 2: The Australian power system with selected interconnectors.

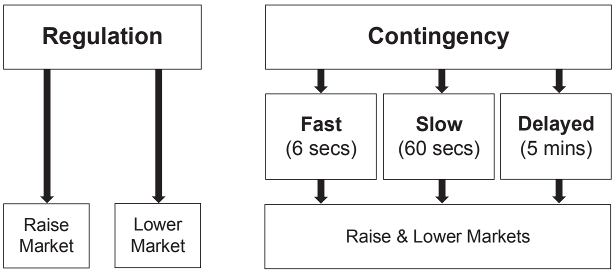

Figure 3: Regulation and contingency FCAS markets.

In 2001, the Frequency Control Ancillary Services (FCAS) market was introduced and is still in effect today. Eight (8) markets exist for regulation and contingency services. Raise, and lower markets are provided for fast (6 seconds), slow (60 seconds) and delayed (5 minutes) contingency responses [10]. Further to this, raise, and lower markets also exist for regulation services. Figure 3 provides a diagrammatic representation of the eight FCAS markets. The adequacy of the system is increasingly called into question following an evidenced deterioration of frequency control.

The creation of the NEM and subsequent implementation of a market-based ancillary services scheme saw substantial changes to established practice, including, but not limited to [11]:

1. Multiple areas of control aggregated into a single control area.
2. Removal of mandatory governor control.
3. Alteration of the Frequency Operating Standards (FOS), including widening of the Normal Operating Frequency Band (NOFB).

Before implementation of the FCAS markets, governor deadbands on synchronous generating units were no greater than 100 mHz ($\pm$50 mHz) [11].

Figure 4 illustrates the progressive deterioration in frequency control within the NEM from 2011 to 2019. Observe that the system frequency is tightly concentrated around (nominal) 50 Hz between 2011 and 2014, which is indicative of good frequency control. However, from 2014 onwards degradation in frequency control is evidenced - characterised by a flatter frequency profile (frequency is less concentrated around nominal 50 Hz).

A severe power system event which occurred in August 2018 also raised further questions regarding performance [12]. Much debate currently exists as to why the deterioration in frequency control has occurred, and how the problem should be addressed. Therefore, four open questions are examined in the remainder of this paper.

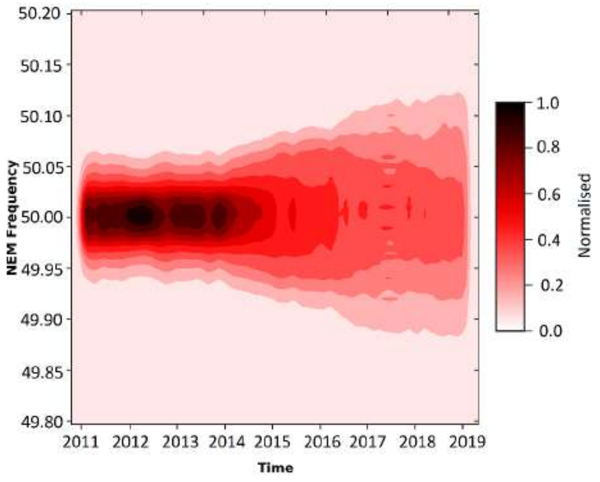

Figure 4: **Frequency (Hz) control deterioration in the NEM from 2011 to 2019 [6].**

Open Question 1

Are Large Governor Deadbands and Governor Inactivity Contributing to Frequency Control Issues?

Issues in Australian Frequency Control Practice

The Australian system currently utilises wide governor deadbands, typically around 300 mHz (±150 mHz), which is an order of magnitude higher when compared to other international jurisdictions. Figure 5 presents the absolute governor deadband range for different power systems across the world.

Governor deadbands are areas in which the governors of synchronous machines do not respond to changes in speed (and therefore frequency). Typically, governor deadbands are small and centred about the operating point of a machine to reduce wear and tear.

Having wide governor deadbands results in a delayed primary control action, and thus a more significant frequency excursion requiring more secondary response to correct.

Recommendations have been made to improve frequency control within the NEM, such as reducing governor deadbands to 100 mHz (±50 mHz) - the size used before the implementation of the FCAS markets [5].

A lack of mandatory governor response is also another issue within Australia's NEM. Only 15% of generating systems (by capacity) always operate in frequency response mode [8].

In the event of a fault, the system's frequency response cannot be guaranteed, which threatens system security. Mandating governor response is beneficial in this respect, as it ensures a uniform system response to an event.

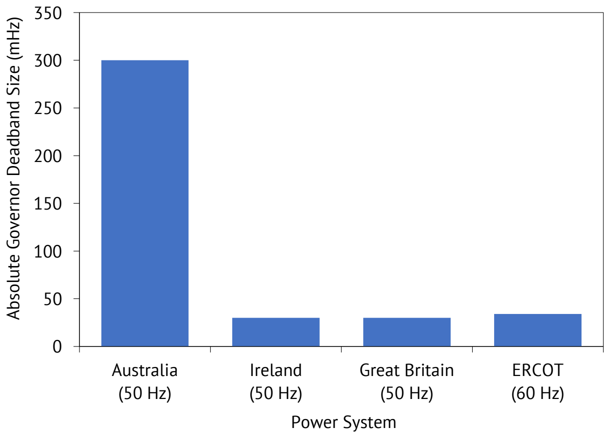

Figure 5: **Comparison of absolute governor deadband sizes by region [13], [14], [15].**

Open Question 2

Are Market Frameworks Overriding the Technical Design of the System?

Frequency Control under a Market Environment

The area of power systems has been tumultuous in recent times. Significant power system events have occurred within Australia's National Electricity Market (2018), as well as Great Britain and Argentina (both in 2019).

These issues have reinforced the importance of power system security and resilience. Resilience relates to the capability of a system to remain in operation while subjected to disruptions [16].

The market-based provision of frequency response in Australia's NEM differs considerably from many other

Jurisdiction	**Providers of PFR**	**Frequency response**	**Procurement of response reserves**
NEM	Generation	Market	Market, with voluntary offering
Brazil	Thermal, hydro	Mandatory	Not managed
Great Britain	Generation, load	Mandatory	Market, with mandatory offering
Finland	Synchronous, wind, load	Market	Market
Ireland	Synchronous, wind	Mandatory	Market
Spain	Generation	Mandatory	Mandatory headroom

Table 1: Provision of primary response in selected power systems [7].

power systems across the world, as shown in Table 1. Therefore, when coupled with the previously mentioned frequency control issues which are challenging the system, the adequacy of the market frameworks are increasingly questioned.

In addition to the degradation in frequency control, FCAS costs for both contingency and regulation services have risen rapidly in recent times, signalling that the market is insufficient. Figure 6 presents the FCAS costs from 2014 to 2018.

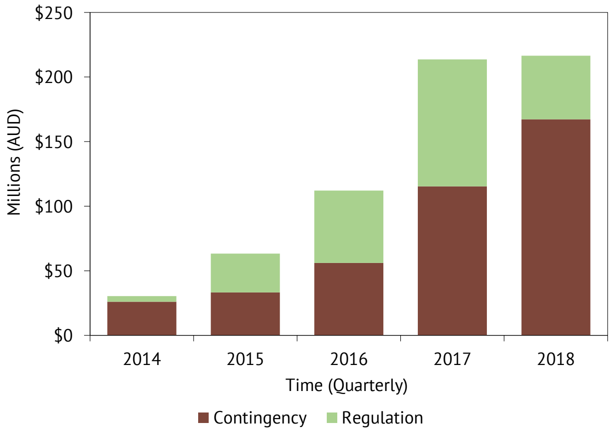

Figure 6: Frequency Control Ancillary Services (FCAS) costs in the NEM [8].

The costs associated with maintaining system frequency within the existing normal operating frequency band were considered in 2001, as were the cost savings available from reducing system requirements for regulating ancillary services [1]. However, the costs associated with poor frequency control have not.

NEM System Separation Event on 25th August 2018

On 25th August 2018, a single lightning strike occurred on a supporting structure of the Queensland-New South Wales Interconnector (QNI) which resulted in the tripping of both its circuits [12].

An 835 MW power mismatch between Queensland (QLD) and New South Wales (NSW) followed the event causing QLD's frequency to rise and the collective frequencies of the rest of the NEM to fall. South Australia later disconnected from Victoria.

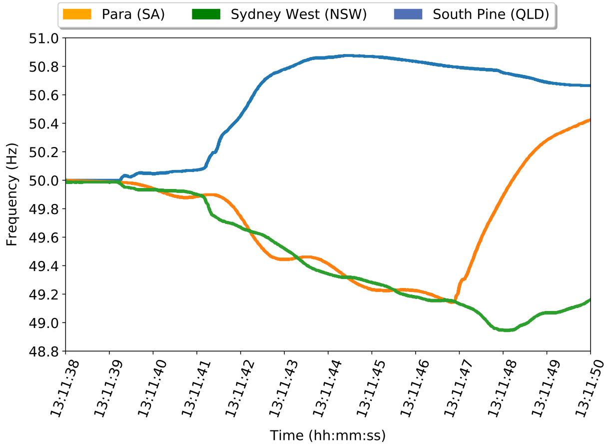

Figure 7: Selected NEM frequencies during 25th August 2018 system separation event [12].

The event highlighted the inadequate provision of primary frequency control. Figure 7 presents the system frequencies.

In such instances, the uniform provision of primary frequency control is essential. System stability is challenged owing to the use of digital governors and a lack of mandatory governor response as the system's frequency response to such an event cannot be guaranteed. Additionally, system modelling is complicated as the response of governors is unknown.

Blackout in Great Britain on 9th August 2019

On 9th August 2019, Great Britain experienced sporadic blackouts following a lightning strike on a transmission circuit which affected approximately one million people [17]. Subsequently, Hornsea offshore wind farm and Little Barford gas power station reduced their outputs, which resulted in a loss of 1,378 MW of generation. Consequently, frequency declined quickly and went outside the normal range of 49.50 Hz – 50.50 Hz. In total, 5% (1 GW) of demand was shed to protect the system. Figure 8 provides a graphical analysis of the event.

The event highlighted the importance of power system control, especially in the presence of more significant rates of change of frequency (RoCoF).

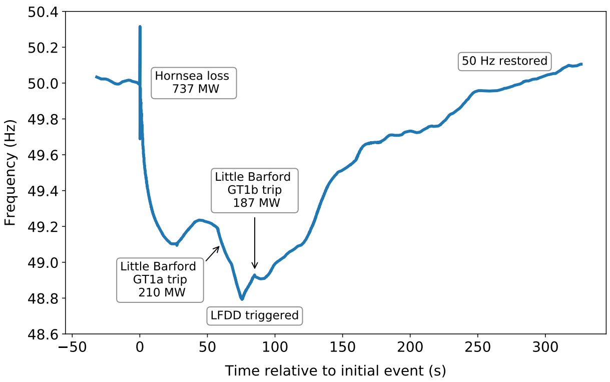

Figure 8: System frequency during Great Britain's blackout on 9th August 2019 [17].

Contemporary Overview

In the future, more considerable amounts of PEC interfaced renewable energy sources are expected to be integrated within power systems, displacing traditional synchronous generators. Furthermore, extreme weather events may become more frequent and severe [18], potentially challenging power system resilience.

Sound power system governance and energy policy will be critical to improving the resilience of the network.

Open Question 3

What changes are necessary for the future to overcome the effects of reduced system inertia?

Increasing Renewable Energy Penetration

In Australia's NEM, integration of PEC interfaced generation is occurring rapidly within both the distribution (solar PV) and transmission networks (solar PV, wind and battery storage). Between 2012 and 2018, there was a 155% increase in the installed PEC interfaced generation within the transmission system, as illustrated in Figure 9.

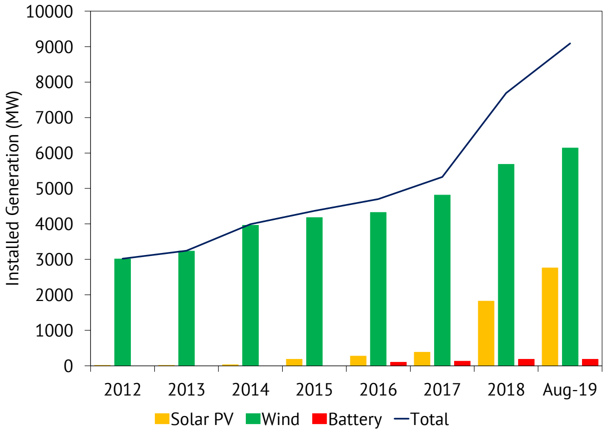

Figure 9: Installed power electronic converter (PEC) interfaced renewable energy generation in the NEM [19], [20].

Moreover, within the distribution network, behind-the-meter solar PV is installed in significant amounts. The rapid increase in solar PV systems (<100 kW) is demonstrated within Figure 10.

The large amount of rooftop solar PV has augmented the traditional system demand profile and provided new challenges to system operation owing to the current lack of real-time control [21].

Improved control and coordination of rooftop solar PV will become increasingly important as capacity continues to increase. As of August 2019, installation of significant amounts of solar PV, wind and battery energy storage will occur within the transmission system in the future. Figure 11 illustrates the proposed generation capacity for PEC interfaced sources.

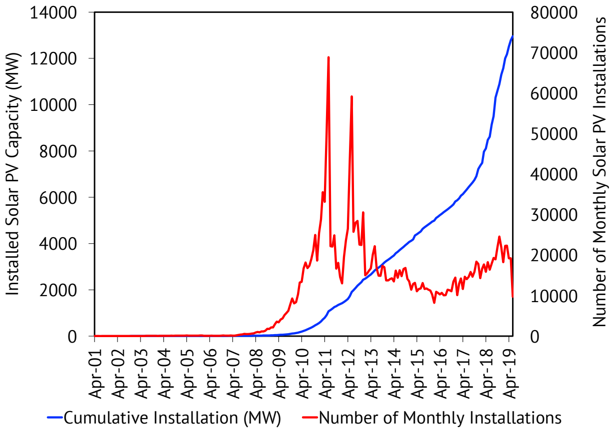

Figure 10: Installed solar PV capacity and number of monthly installations in the NEM [22].

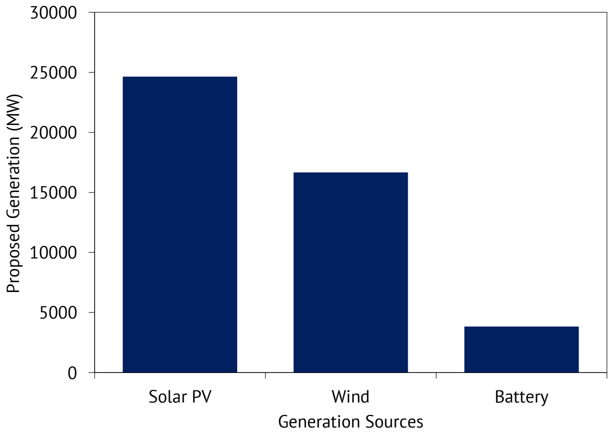

Figure 11: Proposed PEC interfaced renewable energy generation capacity to be installed within the NEM [20].

As the integration of PEC interfaced renewable energy sources increases, power system security and stability will become increasingly challenged. System inertia opposes changes in frequency and is abundant in networks with large amounts of synchronous machines owing to the direct connection of the rotating masses to the system.

The use of power electronic converters decouples renewable generation sources, such as wind and solar PV, from the network. Consequently, inertia is low within systems containing large amounts of renewable energy, resulting in a greater RoCoF and more dynamic behaviour during system events.

Figure 12 illustrates the effect of the reduced system inertia on frequency. Observe that halving the amount of system inertia results in a larger RoCoF and a less damped response.

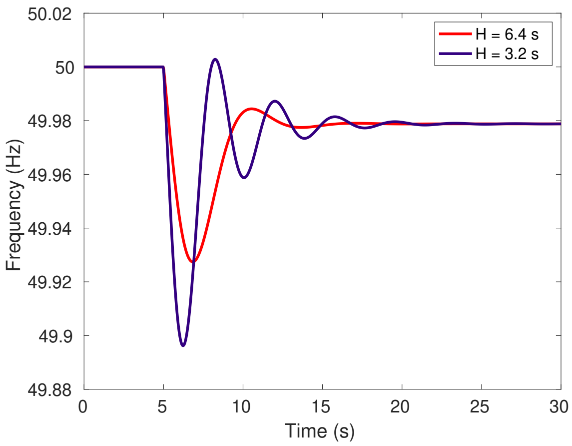

Figure 12: Effect of reduced inertia on system frequency.

From a system perspective, the integration of large amounts of PEC interfaced renewable energy generation will introduce a range of challenges, such as intermittency of generation, power quality issues and provision of reactive power support [23] (and, in general, provision of ancillary services). Consequently, large bodies of work now exist, attempting to overcome such issues.

Battery energy storage systems are increasingly used within power systems to overcome more significant rates of change of frequency owing to their fast dynamics. The question remains, what other considerations need to be made to overcome the effects of reduced system inertia in the future?

Open Question 4

How Can Renewable Energy Generation Be Better Utilised?

Utilising Power Electronic Converters and Renewable Energy Generation

In power systems of the future, the utilisation of power electronic converters will be imperative to ensure renewable energy sources contribute to the provision of ancillary services. While less inertia results in more dynamic behaviour, power electronic converters can respond much faster than traditional synchronous generators which have the potential to mitigate the issue of more significant rates of change of frequency. Furthermore, tapping into renewable power generation will be a necessity to ensure system stability.

Provision of Ancillary Services by Wind

Emulated inertial response is one strategy used to improve the stability of power systems containing wind farms, whereby the behaviour of traditional directly-coupled synchronous generators is imitated [24]. The implementation of such a control strategy allows turbine power output to be increased by approximately 5-10% of rated power in response to a decline in frequency [25]. Such a response assists in stabilising systems following frequency excursions.

Emulated inertial control strategies are broadly classified into three main categories [26]. These are:

(i) $\triangle F$ *response* which is dependent on the frequency deviation.
(ii) *Fixed trajectory response* which is triggered by a specific threshold of frequency deviation.
(iii) $\frac{df}{dt}$ *response* which is triggered by RoCoF.

Long-term deloading methods are another strategy for the provision of frequency support from wind resources, where the wind turbine is operated in a non-optimal state to provide a power margin for frequency reserves [27]. Using such a scheme results in generators incurring costs owing to reductions in energy market revenue. The optimal control of a coordinated wind and energy storage scheme has been investigated to reduce the economic burden associated with the deloading scheme [28].

Power Electronic Converter Technology

Grid-following converters are currently widely used within power systems to interface renewable energy sources to existing transmission infrastructure. Such converters are operated as current sources and provide active and reactive power with reference to the grid voltage [29] using a phase-locked loop (PLL). Therefore, the operation of such devices requires synchronous machines to provide a stiff voltage to the system. Consequently, a 100% penetration level of grid-following converters is theoretically not possible as a frequency reference for the system would not exist.

On the other hand, grid-forming converters control the voltage magnitude and frequency [30], and operate as a controllable voltage source. Given these characteristics, a 100% penetration level is feasible with grid-forming control. Such devices can be used to improve frequency dynamics and stability [29]. Table 2 provides a comparison of the grid-following and grid-forming control schemes.

Table 2: **Grid-following and grid-forming inverter comparison.**

Grid Following Converters	**Grid Forming Converters**
Controls current and phase angle	Controls voltage magnitude and frequency
No standalone operation	Standalone operation
100% penetration not possible	100% penetration possible

Increasing Use of Energy Storage Systems

Energy storage solutions are increasingly utilised in power systems to deal with more significant rates of change of frequency. Within Australia, the Hornsdale Power Reserve (HPR) was the first battery installed in the NEM [31]. The energy storage system has a speedy response to system frequency declines and is registered for participation in all eight FCAS markets (regulation and contingency responses).

ElectraNet's 30 MW / 8 MWh grid-scale battery [32] has also recently been connected to Australia's NEM, as has the 30 MW / 30 MWh Ballarat Battery Storage System [33]. Other storage technologies examined within the research domain include supercapacitors [34] to complement traditional energy storage technology. In the future, supercapacitors could be widely used within the industry.

Frequency Control in the NEM

Effect of Poor Frequency Control in Power Systems

Poor control of frequency within a power system can result in a broad range of issues. These include [3]:

Safety and reliability issues

- blades on synchronous turbines may be damaged;

Reliability issues

- wear and tear on generating governing equipment;
- inefficient operation of generators resulting in increased emissions;
- stable control of synchronous machines may be compromised;

Security issues

- system stability may be compromised;
- impedance measurement may affect stable control of voltage;
- feedback through stabilisers may affect voltage;
- interconnectors may deviate away from their dispatch targets and during a contingency may lead to cascading failure;
- measurements of quantities that require a certain level of accuracy may be compromised;

Price issues

- dispatch of energy and interregional loads may no longer be optimised owing to measurement error;
- local measurement and its billing may be affected;

Quality issues

- harmonic dependent measurement devices may be affected; and
- harmonic filter efficiency.

What Best Suits the NEM?

The system separation event on 25th August 2018 briefly detailed within this document highlighted the need for improvements in the provision of primary frequency control within Australia's NEM.

The current practice of not mandating primary frequency response within the Australian system results in system vulnerabilities which have the potential to be detrimental to system security and stability.

Therefore, mandatory governor response is recommended to improve frequency control within the Australian system.

Figure 13 compares the effect of having no governor deadbands versus a large governor deadband on system frequency. Observe that a large governor deadband size results in a worse frequency nadir and more significant steady-state frequency error. As the frequency settles further away from 50 Hz, more secondary reserves are required to return the frequency to its nominal value.

Thus, it is also recommended that governor deadbands do not exceed 100 mHz (±50 mHz).

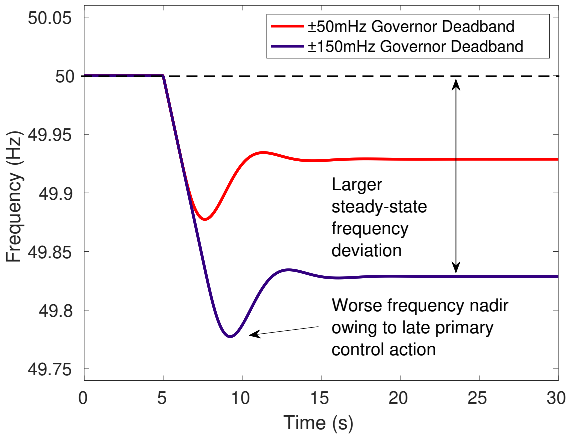

Figure 13: **Effect of governor deadband size on system frequency.**

Concluding Remarks

This paper has examined some of the current and future issues concerning frequency control within the Australian power system. The system employs large governor deadbands when compared to other international jurisdictions. Moreover, a lack of mandatory governor response and market frameworks also presents potential complications.

The frequency profile of the system has progressively flattened over the past few years, and oscillatory behaviour is evident within the normal operating frequency band. A severe power system separation event on 25 August 2018 raised further questions surrounding frequency control within the Australian system. In the future, further integration of PEC interfaced renewable energy generation could complicate the control issues owing to their different dynamics and reduced ability to participate in the provision of frequency control.

From an operational perspective, engineering principles rather than economic principles must govern the control of system frequency.

Consequently, it is recommended that governor deadband sizes do not exceed 50 mHz and that mandatory governor response is reintroduced to the system. Such changes will provide good control of system frequency, which is essential for system stability and security. Moreover, as renewable energy generation will displace traditional synchronous generators in the future, utilisation of power electronic converters and renewable energy sources to provide ancillary services will also be essential to maintaining and improving stability.

Acknowledgments

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