THE FUTURE POWER SYSTEM SECURITY PROGRAM

FREQUENCY CONTROL

August 2016

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AUSTRALIAN ENERGY MARKET OPERATOR

AGENDA:

1. Secure operating envelope for RoCoF (~15min)
2. Options for managing high RoCoF (~30min)
3. Supply-demand balance for FCAS (~15min)
4. Review of FCAS Specifications (~5min)

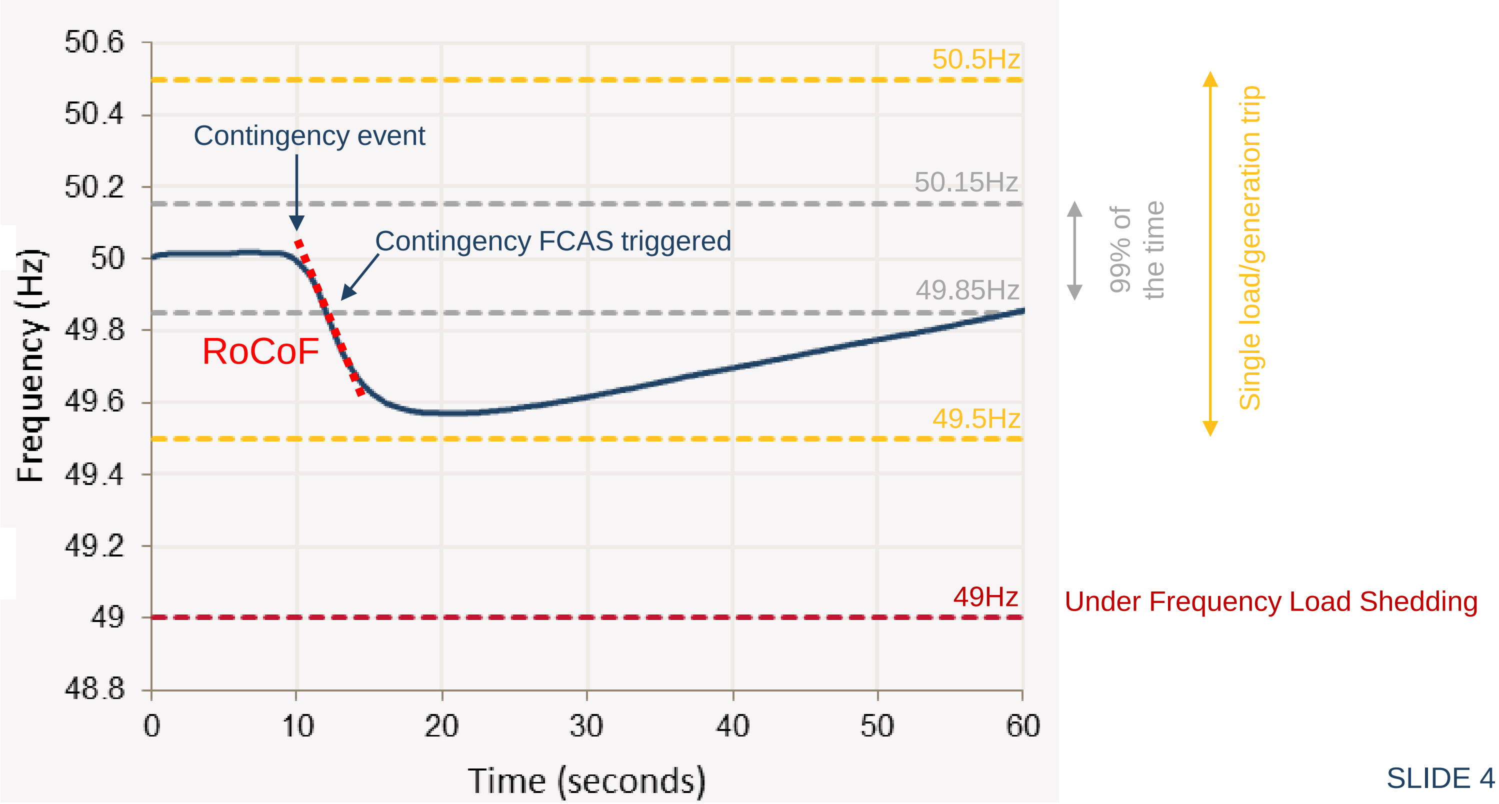
Aim of this session: To share our “hot off the press” results on frequency control, and seek your feedback and suggestions.

Work in progress!

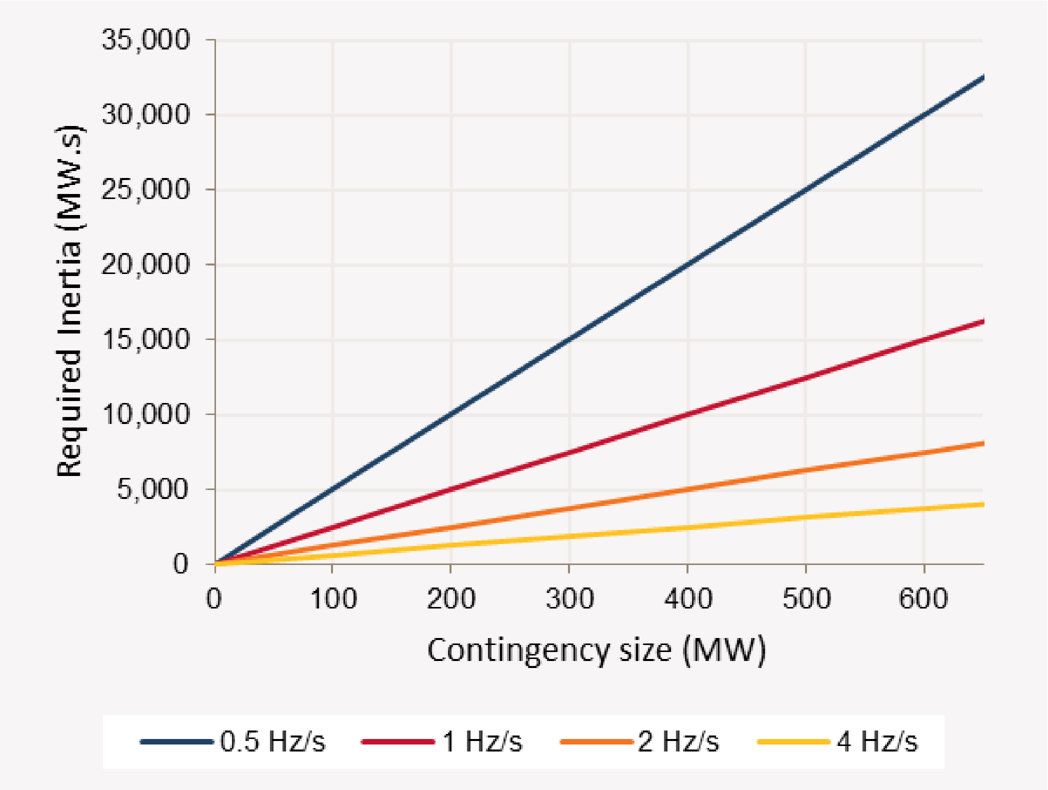
SECURE OPERATING ENVELOPE FOR RATE OF CHANGE OF FREQUENCY (ROCOF)

RATE OF CHANGE OF FREQUENCY

- Following a contingency event (unexpected loss of generation/load)
  - Imbalance in supply-demand causes system frequency to rise/fall
- If “Rate of change of Frequency” (RoCoF) is too high:
  - Could result in cascading trip of load or generation
  - Emergency control schemes may not prevent system collapse



RATE OF CHANGE OF FREQUENCY



Initial RoCoF depends upon:

$$\text{RoCoF} = \frac{50\text{Hz}}{2} \times \left(\frac{\text{Contingency size (MW)}}{\text{System inertia (MW.s)}}\right)$$

System RoCoF withstand capability + Contingency size → Amount of inertia required

HOW HIGH IS TOO HIGH?

- There is no system standard for RoCoF at present
- Generation access standards introduced in 2007:

	Access Standard
Automatic	4 Hz/s for 0.25 seconds
Minimum	1 Hz/s for 1 second

HOW HIGH IS TOO HIGH?

Historical events:

Historical contingency event	Maximum RoCoF (measured over 200ms)
2004 SA separation (08/03/2004)	-2.5 Hz/s (-2.1 Hz/s measured over 500ms) (-1.7 Hz/s measured over 1s)
2005 SA separation (14/03/2005)	-1.9 Hz/s (-1.6 Hz/s measured over 500ms) (-1.3 Hz/s measured over 1s)
2007 SA separation (16/01/2007)	+ 0.3 Hz/s
2009 contingency event (02/07/2009)	- 0.3 Hz/s
2012 contingency event (19/06/2012)	- 0.4 Hz/s
2015 SA separation (1/11/2015)	- 0.4 Hz/s

RoCoF withstand capabilities of the system highly uncertain

INERTIA IN SOUTH AUSTRALIA

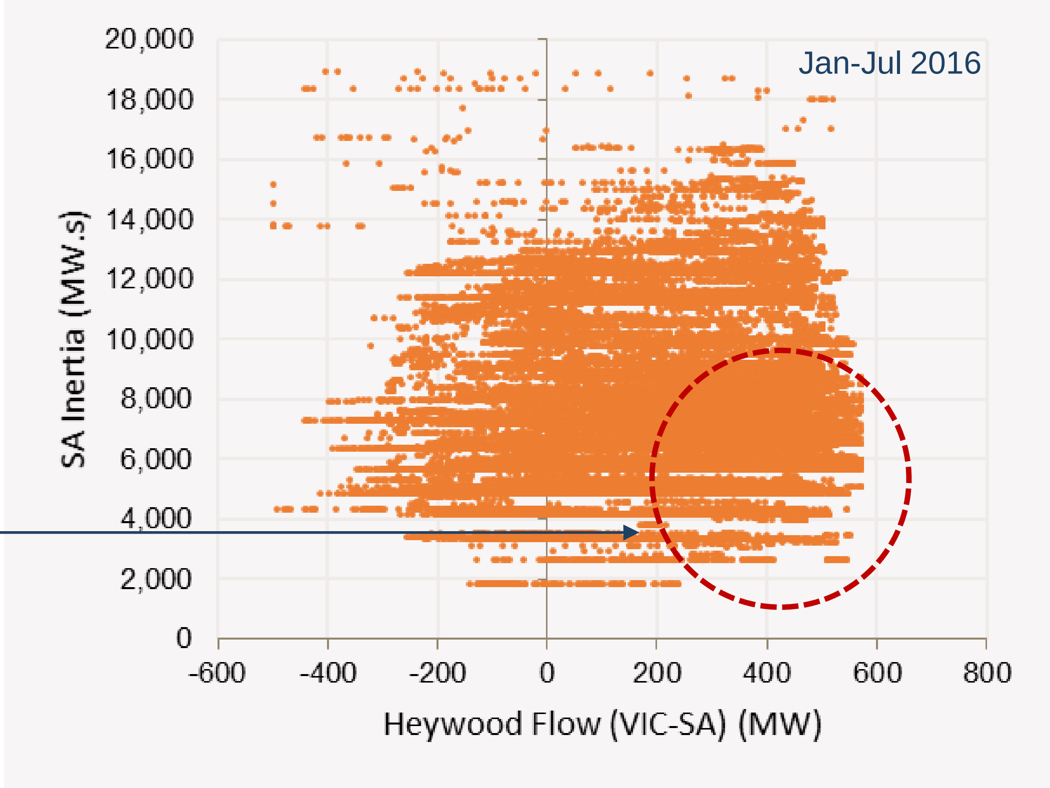
- Total inertia available in SA: ~**19,000 MW.s**
  - However, synchronous units must be operating to contribute inertia
- SA inertia now observed below **2,000 MW.s** in some periods

Low inertia

+

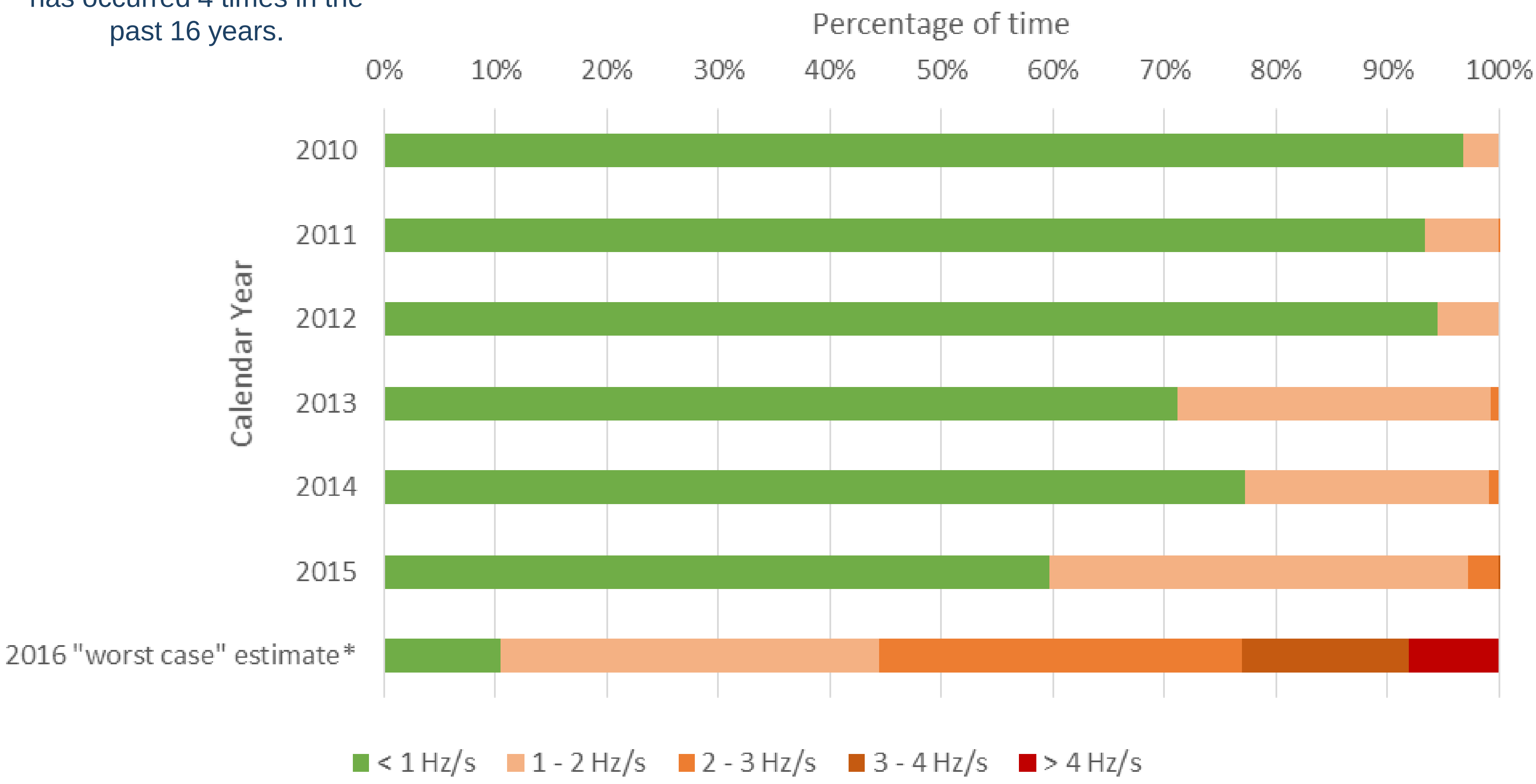
Large potential contingency size

High RoCoF exposure
(upon rare "non-credible" separation)



ROCOF EXPOSURE UPON **NON-CREDIBLE** SEPARATION IN SOUTH AUSTRALIA

Non credible separation of SA has occurred 4 times in the past 16 years.



* 2015 data, with Northern generation replaced by increased Heywood flows up to 650MW limit

INTERNATIONAL EXPERIENCE

- Ireland provides an analogue for South Australia:

	South Australia	Ireland
Demand	1 – 3.4 GW	2.3 – 6.8 GW
% of energy from non-synchronous sources (2015)	**42.5%** (1.5 GW wind, 600 MW PV)	**23%** (wind)
Interconnectors	1 AC 1 HVDC	2 HVDC

- EirGrid work program since 2010 to identify secure operating envelope for RoCoF
  - Progressed slowly (breaking new ground)

	Present RoCoF System Limit	Targeted future RoCoF Limit
Ireland (EirGrid/SONI)	**0.5 Hz/s**	**1 Hz/s** (measured over 500ms)
UK (National Grid)	**0.125 Hz/s**	**0.5 Hz/s** for synchronous generators, **1 Hz/s** for non-synchronous generators

- Very little other international experience with high RoCoF in **large** power systems

POSSIBLE FAILURE MECHANISMS

Mechanical stress

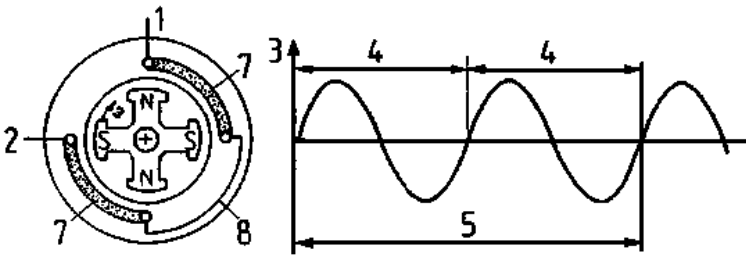
- High torque (wear and tear), eventually leading to pole slipping

Protective relays

- Some types of relays may maloperate during periods of extreme RoCoF

Controls

- May introduce additional vulnerabilities (related to control settings or structure)



Pole slipping: A synchronous generator "falls out of step" with the rest of the AC network

(rotor goes beyond a critical angle, at which the magnetic coupling fails).

POSSIBLE FAILURE MECHANISMS

- What do we know so far?

Synchronous units

- EirGrid analysis shows signs of instability for 1.5 - 2 Hz/s
- Depends upon leading or lagging power factor
- Gas turbines may be more sensitive to positive RoCoF (rising frequency) because of risk of combustion instability

Wind turbines

- Type 3 & 4 wind turbines typically very insensitive to RoCoF (but may experience issues with control / protection systems)
- Type 1 & 2 wind turbines may experience impacts on the mechanical drive train

Embedded generation

- Anti-islanding protection (preventing operation of electrical islands, fed by embedded generation) can be very sensitive to high RoCoF

Demand

- EirGrid is conducting analysis (DNV-GL)

WORK PACKAGES: ROCOF

Advising on RoCoF System Limits	RoCoF Withstand Capabilities of South Australian Generators
• What are the possible RoCoF failure mechanisms? • What is the secure operating envelope for RoCoF in the NEM, based upon the best available knowledge and tools at present? • Develop a plan for reducing uncertainty.	• What are the RoCoF withstand capabilities of South Australian generating units? • Modelling each individual unit • Wind & synchronous

Will not be conclusive (breaking new ground), but will provide significant insights, and clarify the path forward.

DISCUSSION:

- **What are your experiences with high RoCoF?**
  - Are you aware of system elements that are sensitive to, or will not operate properly at, high RoCoF?
  - What is the mechanism by which that element fails?
  - At what RoCoF level is this likely to occur?
  - Can this response be adjusted?
- **Should a system limit for RoCoF be maintained in the NEM?**
  - If so, what RoCoF limit would be suitable, and why?

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OPTIONS FOR MANAGING HIGH ROCOF

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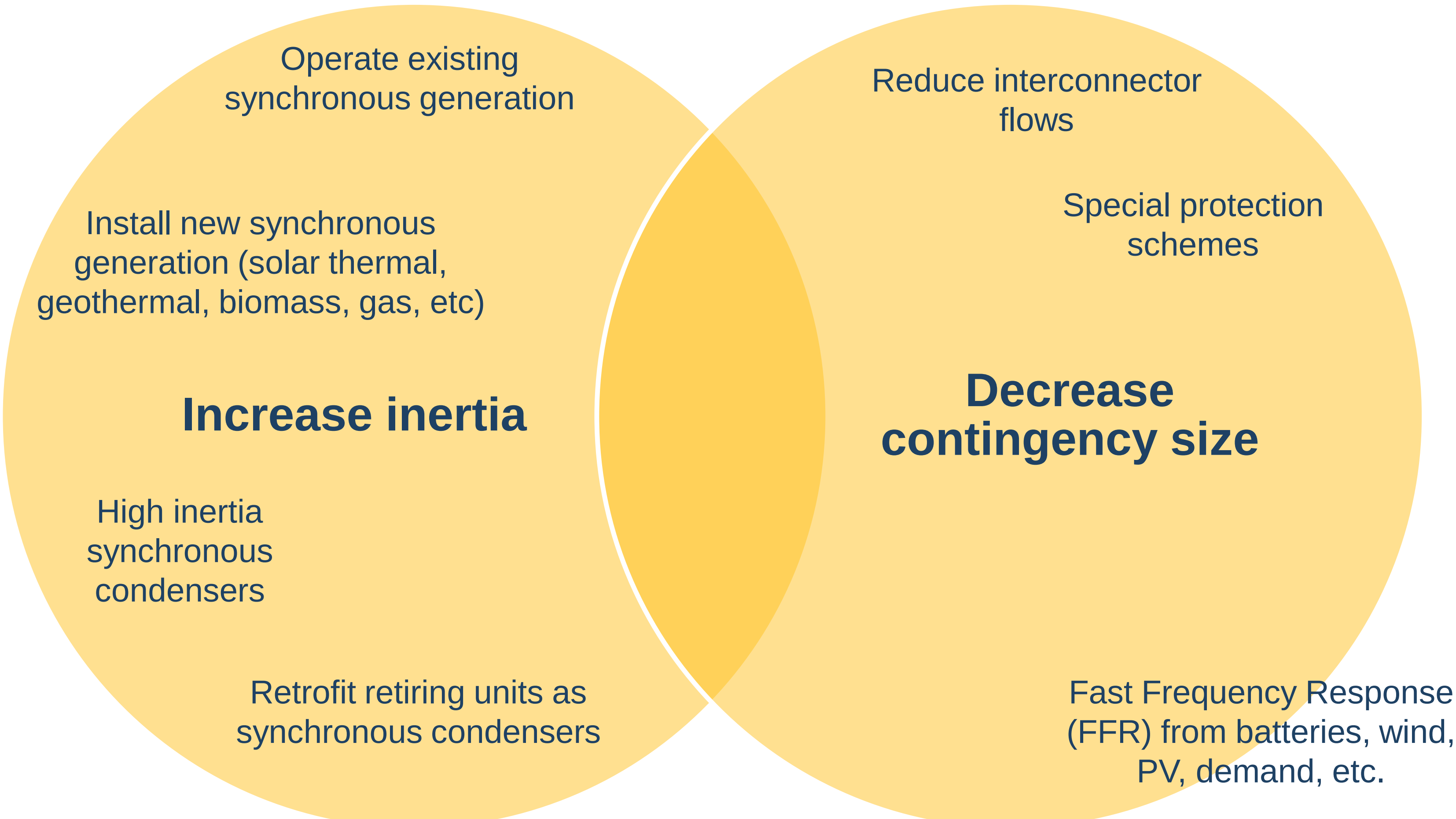
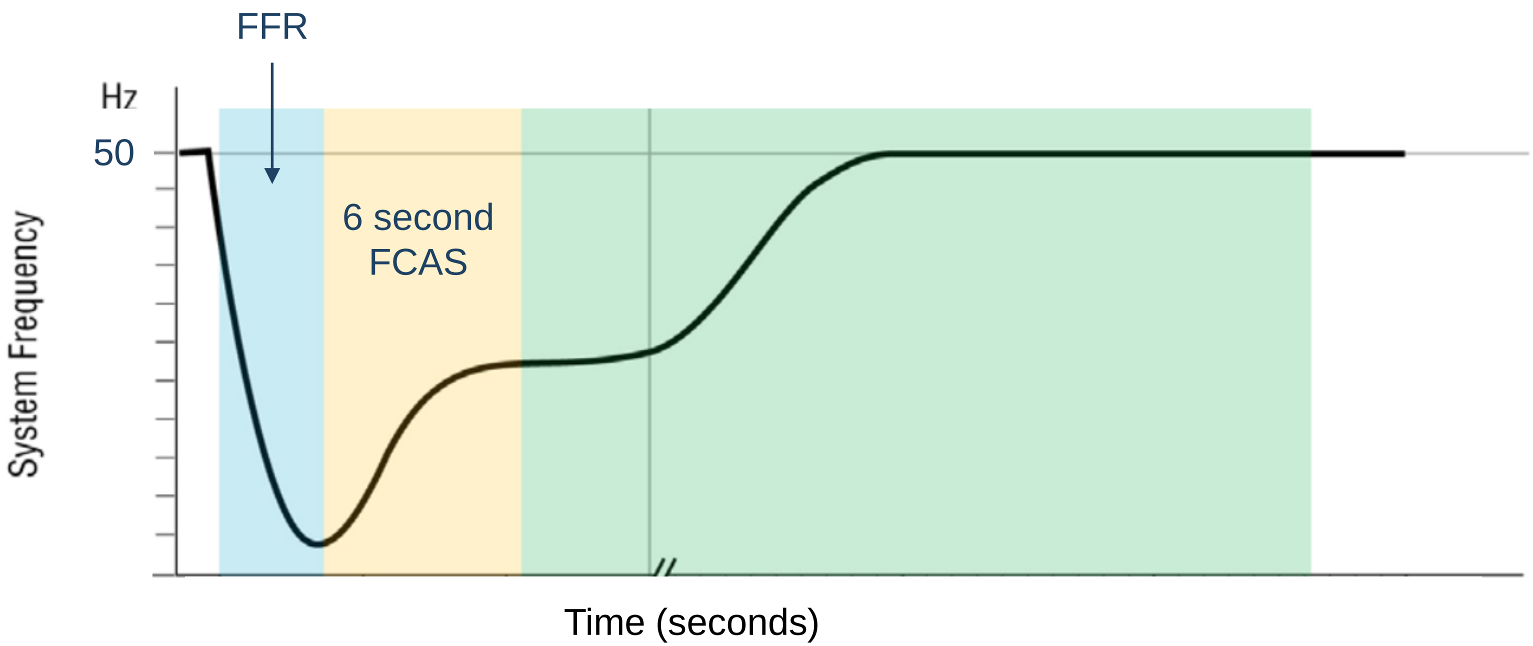


Other possible “partial” solutions:

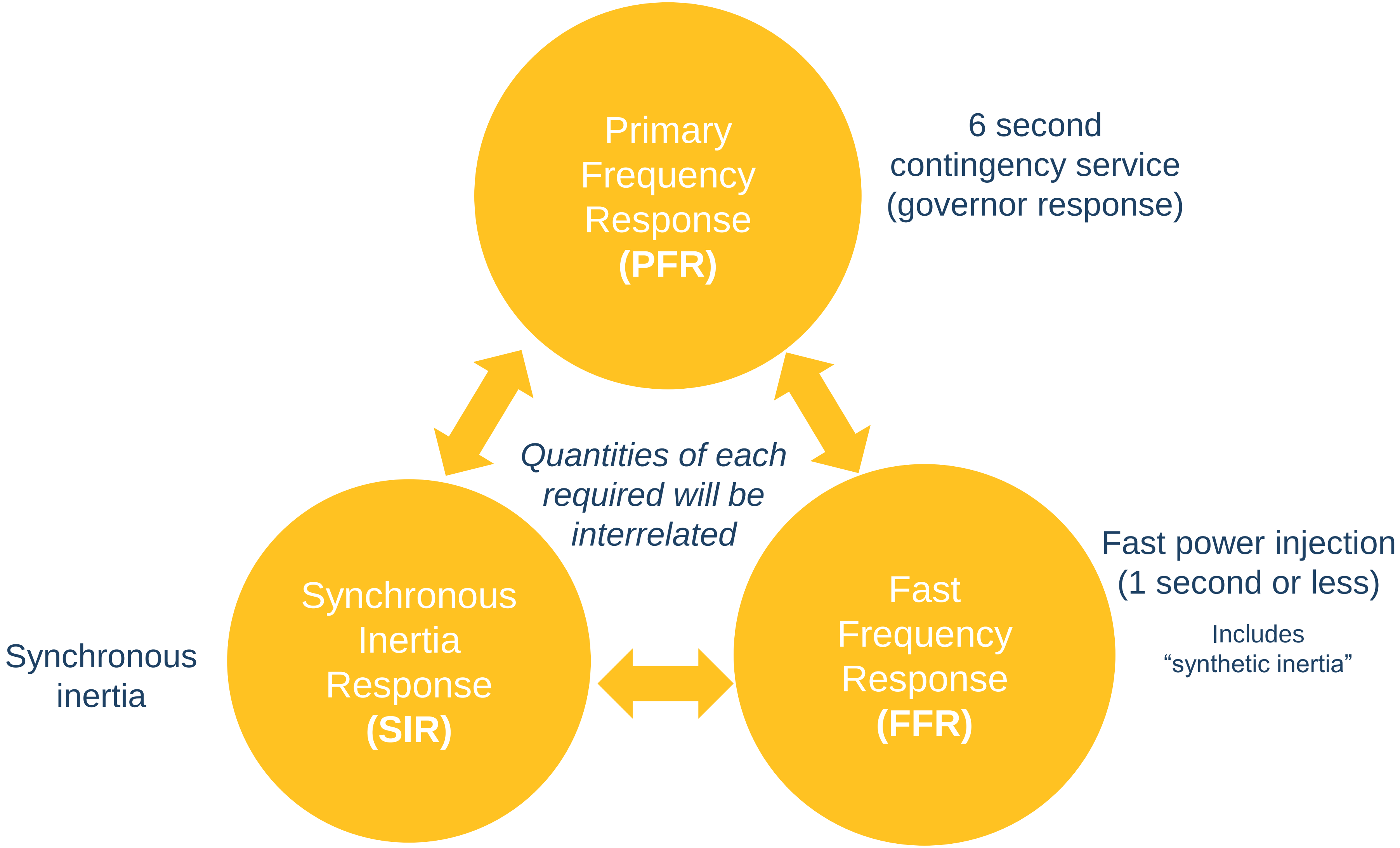
- Improve UFLS / OFGS
- New AC interconnectors

FAST FREQUENCY RESPONSE (FFR)

- Fast power injection, to arrest the initial fall in frequency
- Gives governors (6 second contingency FCAS) time to act



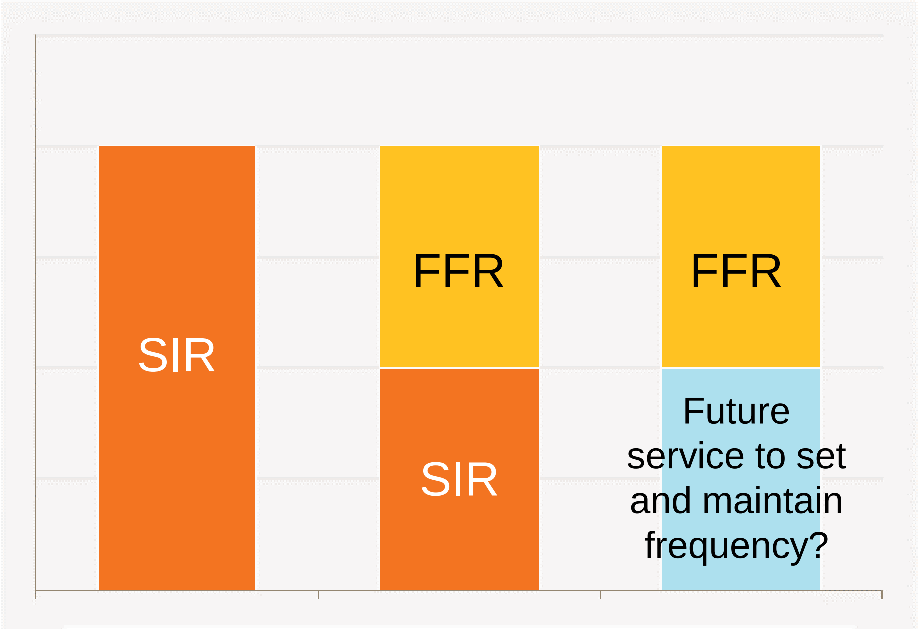
THREE DISTINCT SERVICES



NO SYNCHRONOUS INERTIA?

- Is it possible to operate a large power system with no synchronous inertia?
  - Would require new technology to set and maintain frequency
  - Not possible in a **large** power system at present, but may be in future
    - "Sharing duty" and coordinated frequency setting remains challenging

- FFR alone (or "synthetic inertia") is not sufficient
    - Will always be a delay for detection and response
  - But FFR can probably reduce the amount of synchronous inertia required
- For now, some minimum amount of synchronous inertia is required to manage **large** power systems



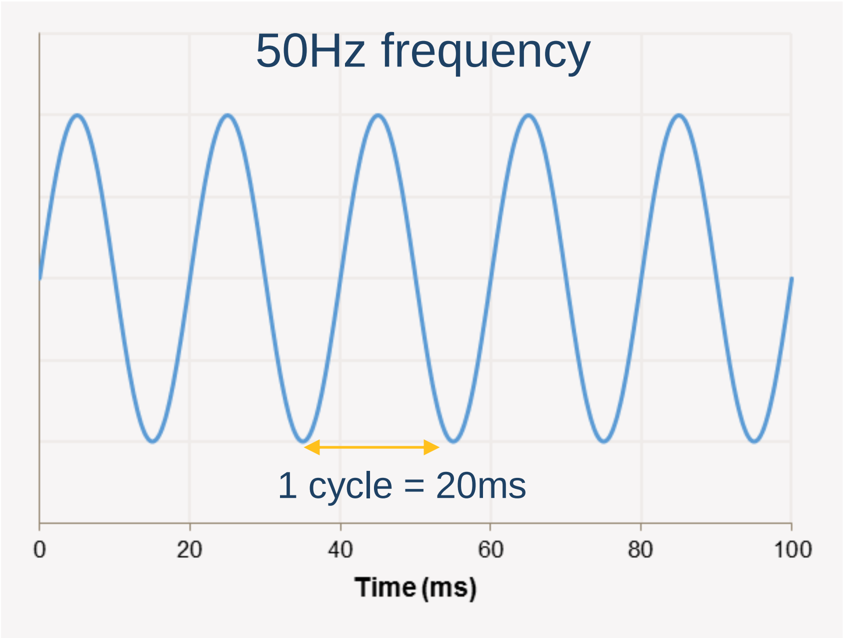
INTERNATIONAL EXPERIENCES

- Only a few international jurisdictions have introduced or considered FFR services

	Response time	**Sustain duration**	**Notes**
Ireland (EirGrid/SONI)	**2 seconds**	8 seconds	-
UK (National Grid)	**1 second**	15 minutes	Tendering process (July 2016)
Texas (ERCOT)	**0.5 seconds**	10 minutes	Rejected (June 2016)

FAST FREQUENCY RESPONSE (FFR)

- How fast does it need to be?

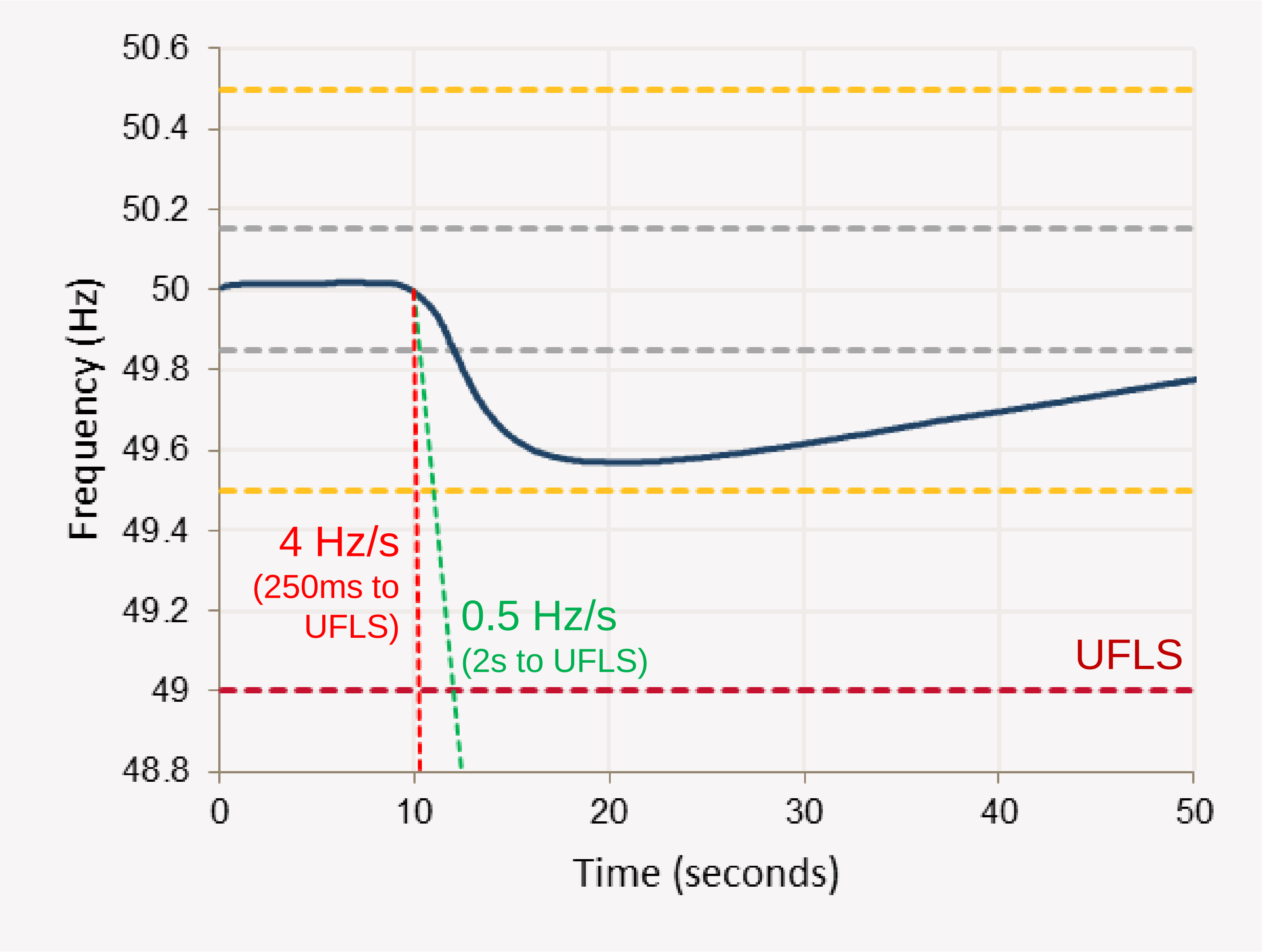


More inertia ↓

RoCoF	Time to 49Hz (UFLS)	Number of cycles
4Hz/s	250ms	12.5
2Hz/s	500ms	25
1Hz/s	1s	50
0.5Hz/s	2s	100

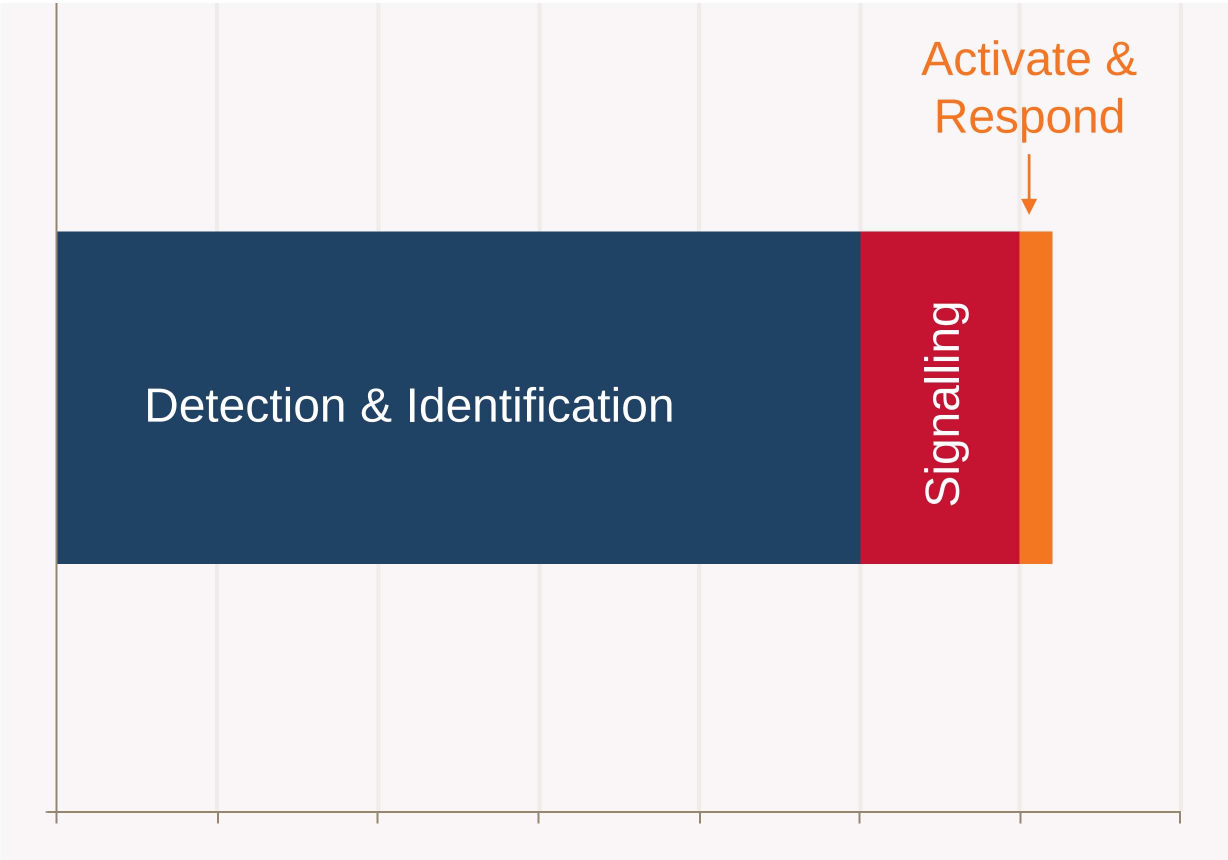
More inertia means FFR can be slower

VISUALISING ROCOF



FAST FREQUENCY RESPONSE (FFR)

- How fast *can* it be?



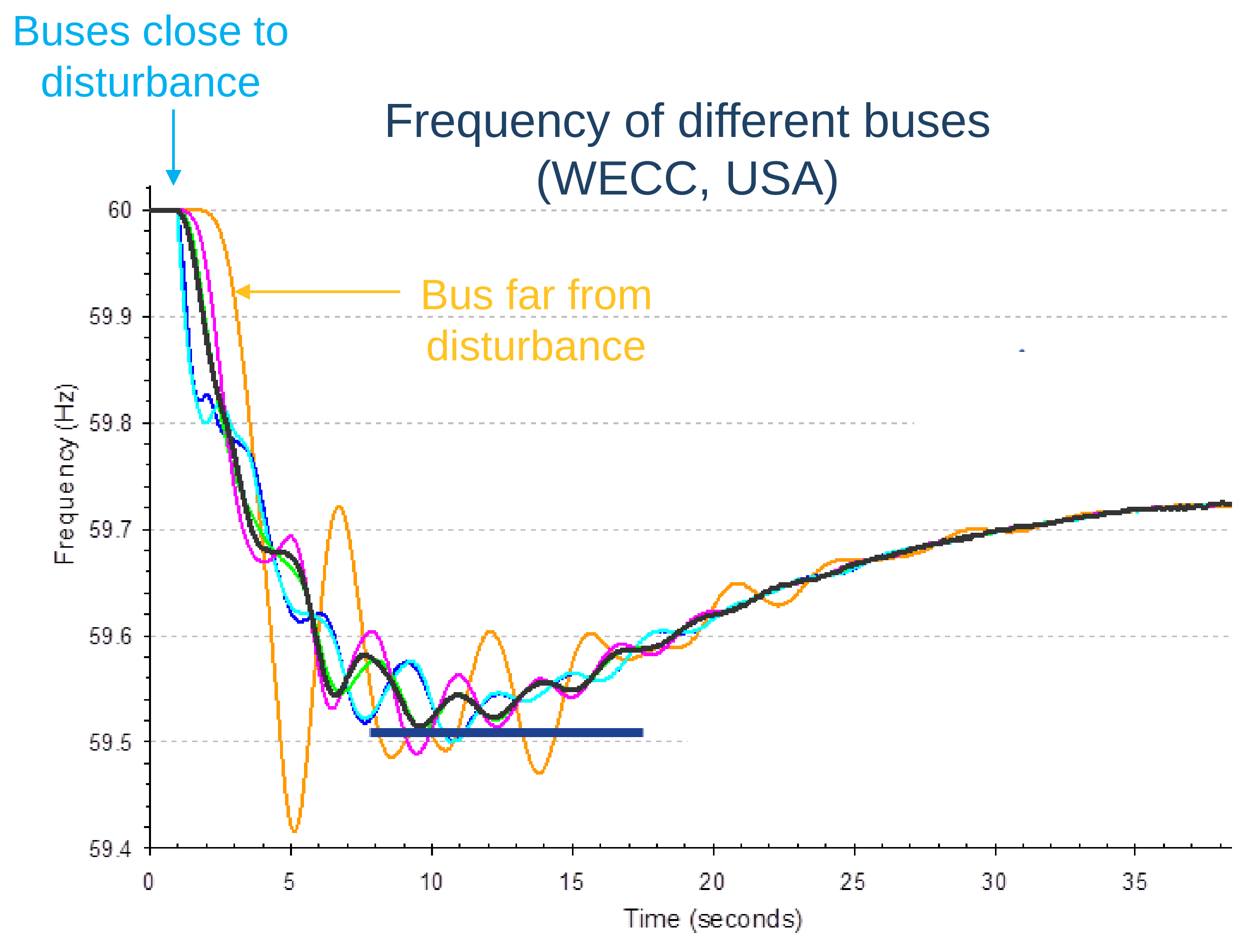
DETECTION

- Very fast detection devices do exist
  - Eg. PMUs: RoCoF detection in 1.2 – 3.25 cycles (24-65ms)
  - But…

Super fast detection may not be a good idea, from a system perspective…

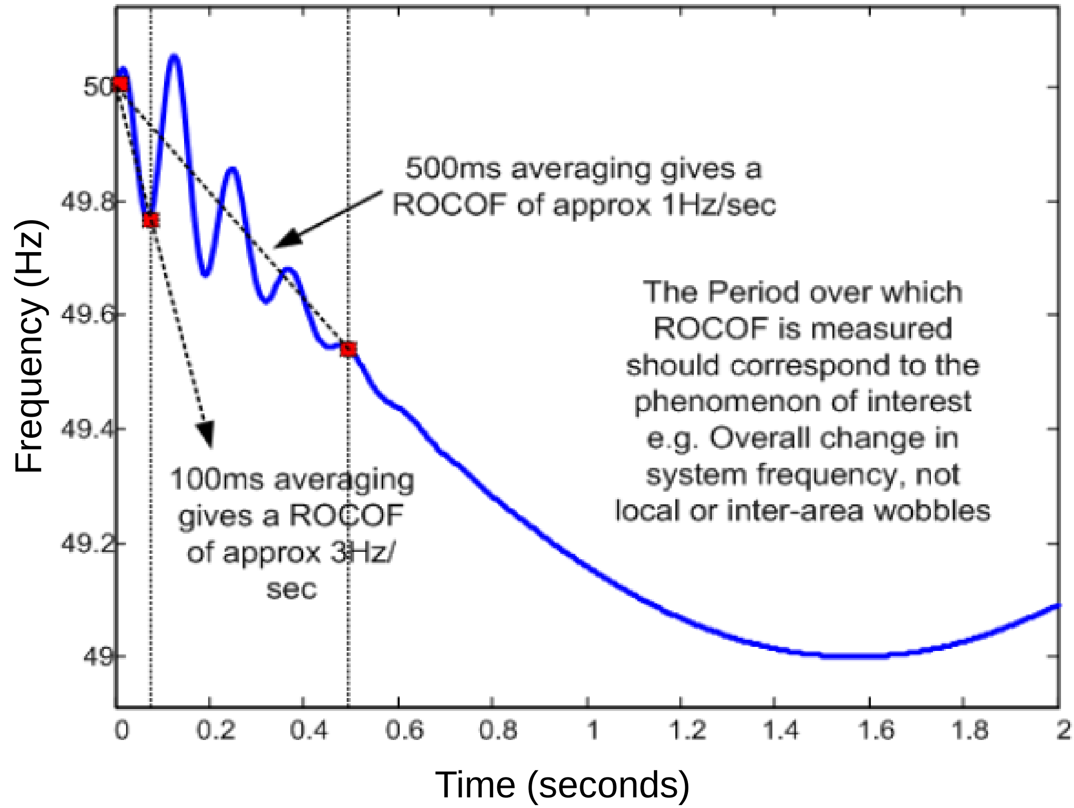
LOCAL FREQUENCY VARIATION

- In the initial period following a large disturbance, system dynamics result in multi-modal swings.
- Until inter-area swings damp out, frequency varies with location.
- Could cause false triggering of local detection.



OSCILLATORY PHENOMENON

Sufficient sampling window important to distinguish between overall grid frequency, and local dynamic effects following a disturbance



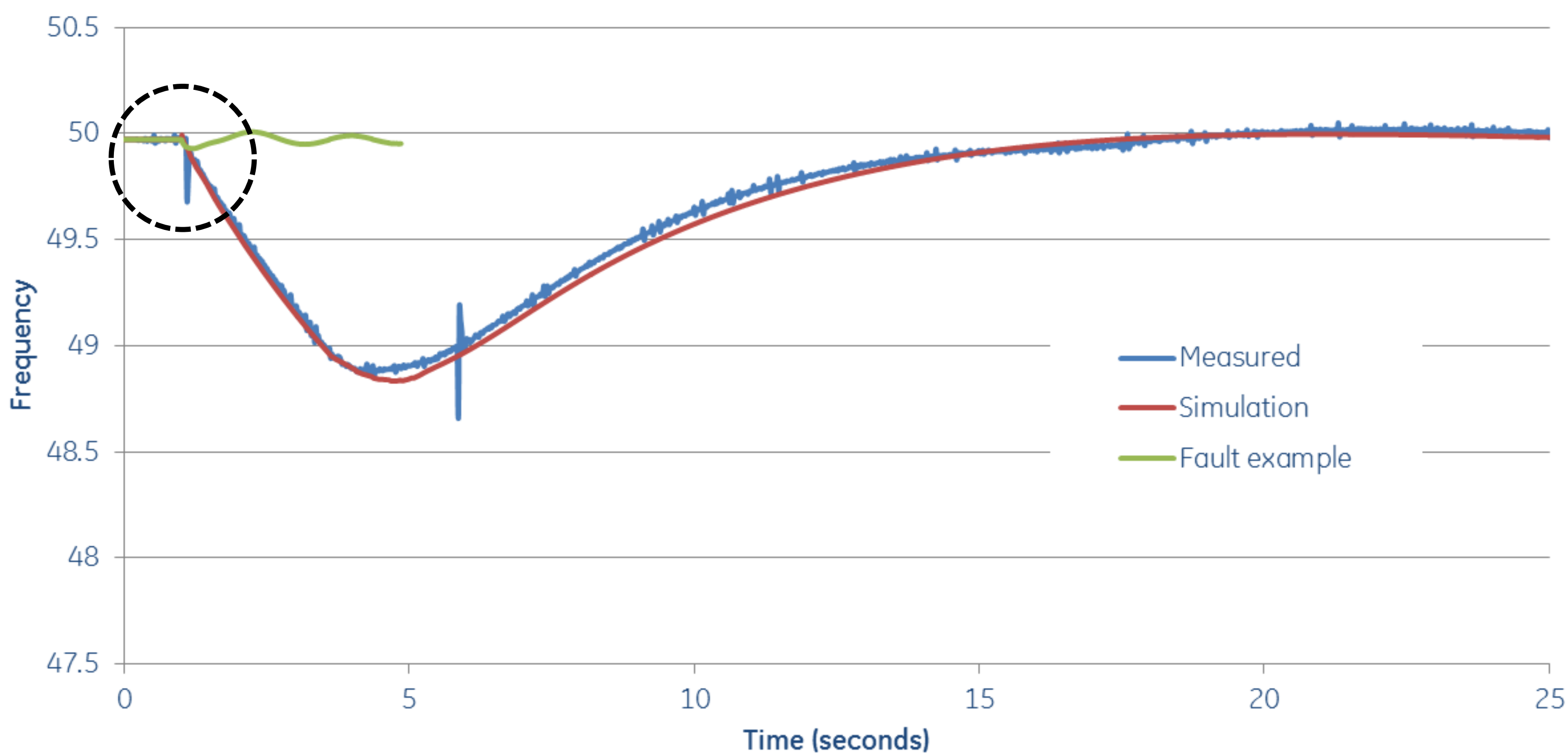
Source: *EirGrid & SONI Position Paper, Sept 2012*

DISTINGUISHING BETWEEN EVENTS

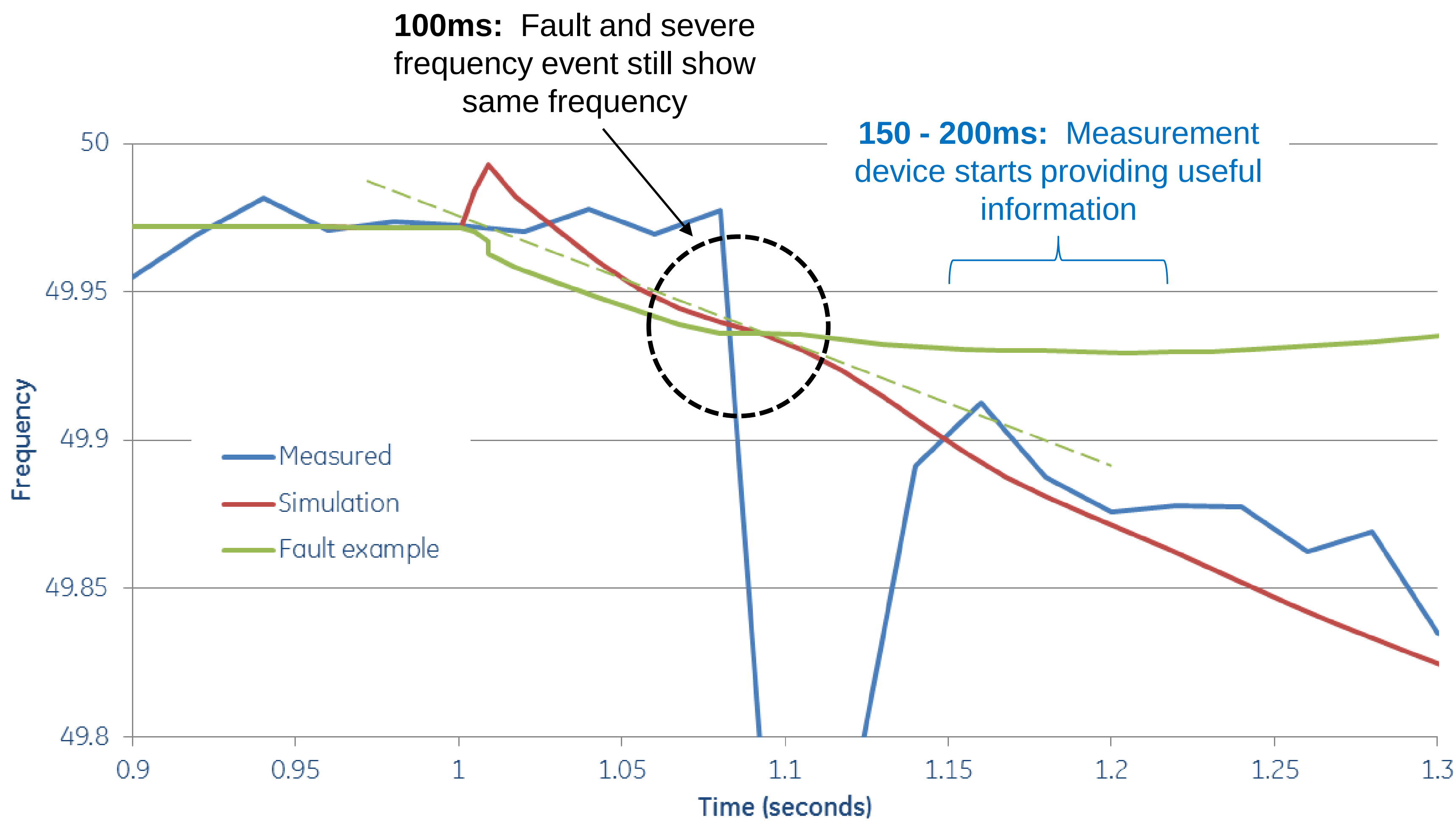
Severe frequency event
(Needs FFR)

Difficult to distinguish

Fault on interconnector that clears
(Doesn't need FFR)



DISTINGUISHING BETWEEN EVENTS



Problematic to distinguish between these two very different events in <100ms

DIRECT EVENT DETECTION

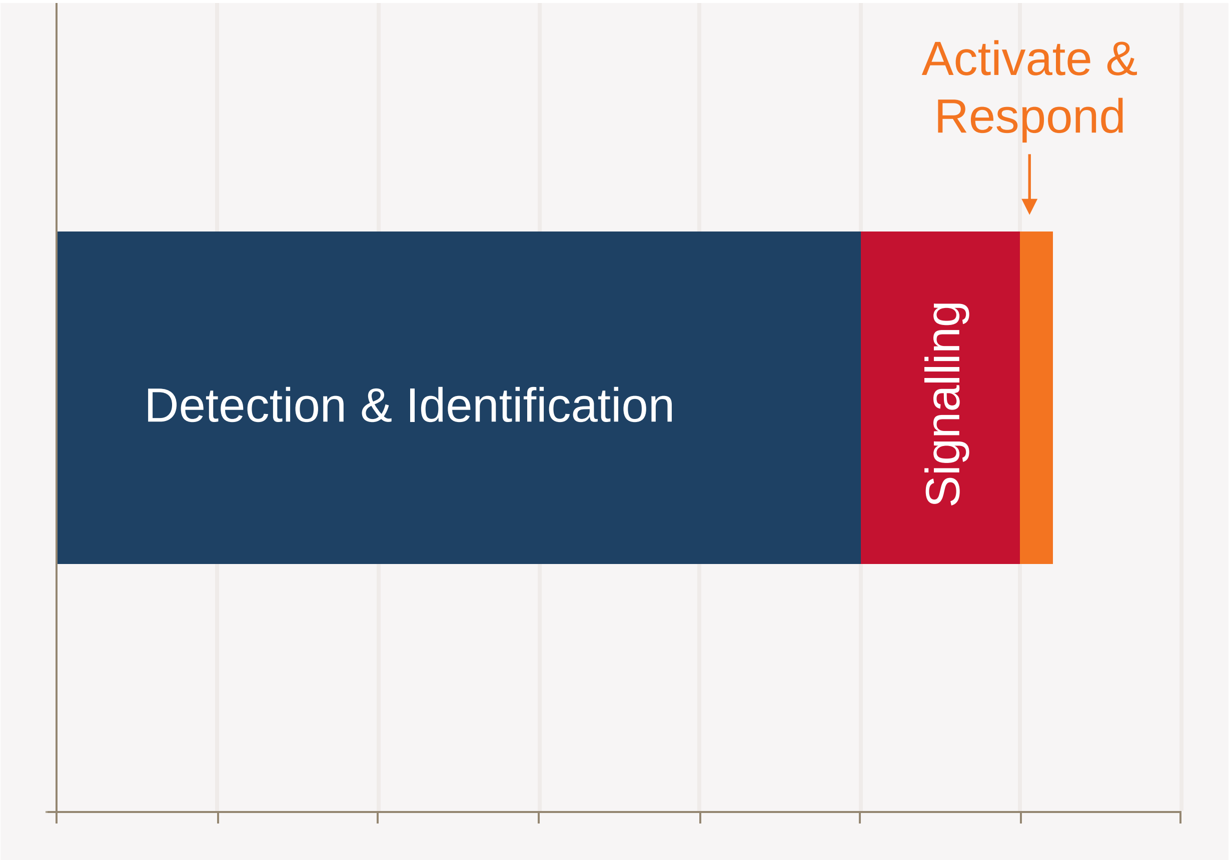
- **Direct event detection** offers an alternative for managing specific events
  - Bypass need to wait to measure RoCoF/Frequency

Directly detect when a specific event has occurred → Rapid signal to FFR devices → Trigger FFR

- Suitable for managing separation events
  - Constantly monitor interconnector flows, and pre-calculate & “arm” FFR response
  - Communication latencies are the key limitation
    - Proximity of FFR resources may be important

FAST FREQUENCY RESPONSE (FFR)

- What technologies can provide FFR?



WIND TURBINES

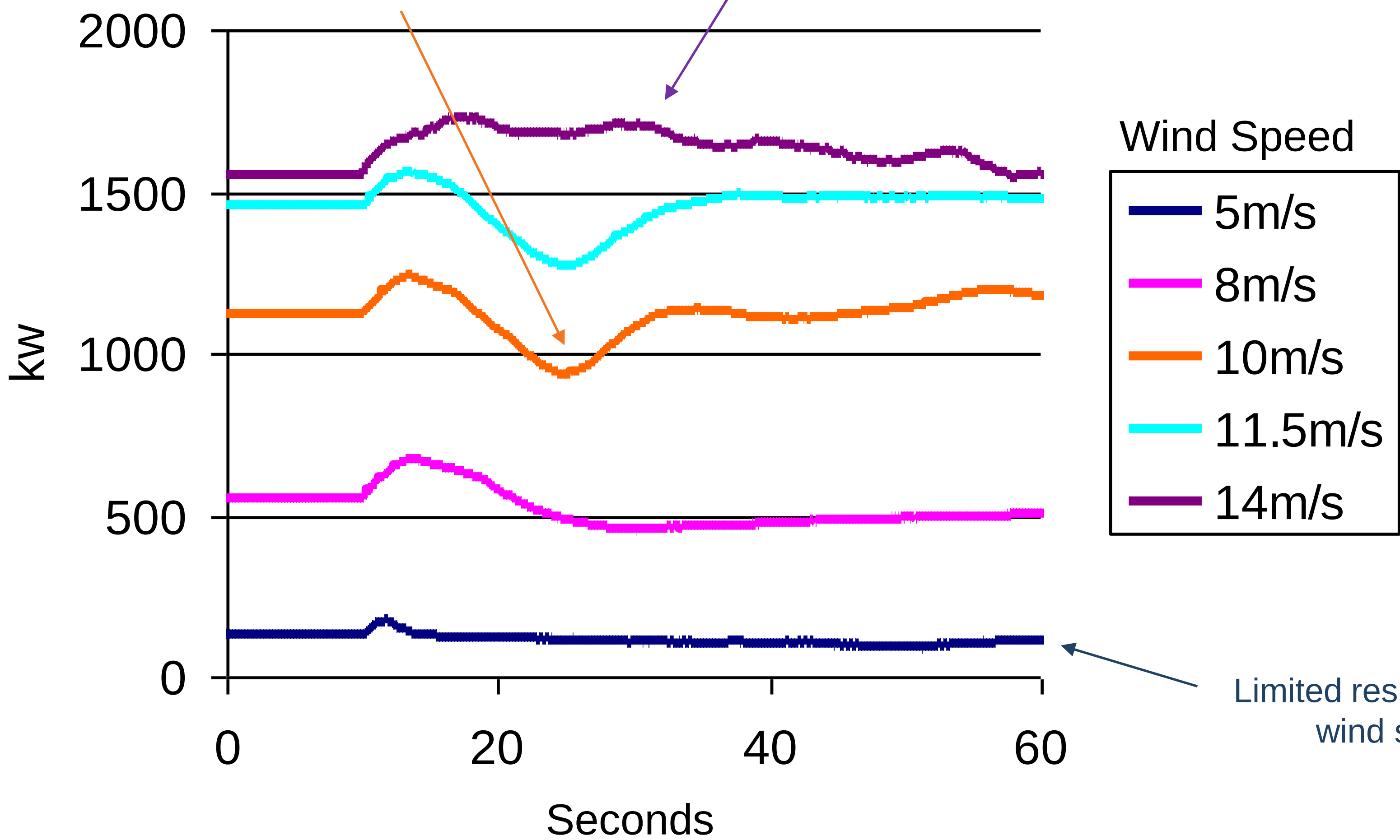
- Two types of fast active power response from wind turbines:

Pitch Control	"Inertia-based FFR" (Synthetic inertia)
• Adjust blade pitch to vary active power • In order to provide more active power, **plant must be pre-curtailed** • Usually controlled through plant supervisory control system (communication latencies 200-500ms)	• Accesses stored rotational energy in the turbine rotor and drive-train • Energy available is limited, and active power must be reduced again afterwards (to prevent stalling) • **Does not require pre-curtailment** • Usually controlled at individual turbines (minimises latencies)

WIND – INERTIA-BASED FFR

When operating above rated wind speed, pitch control can provide additional power (no recovery deficit)

Need for power recovery at moderate wind speeds

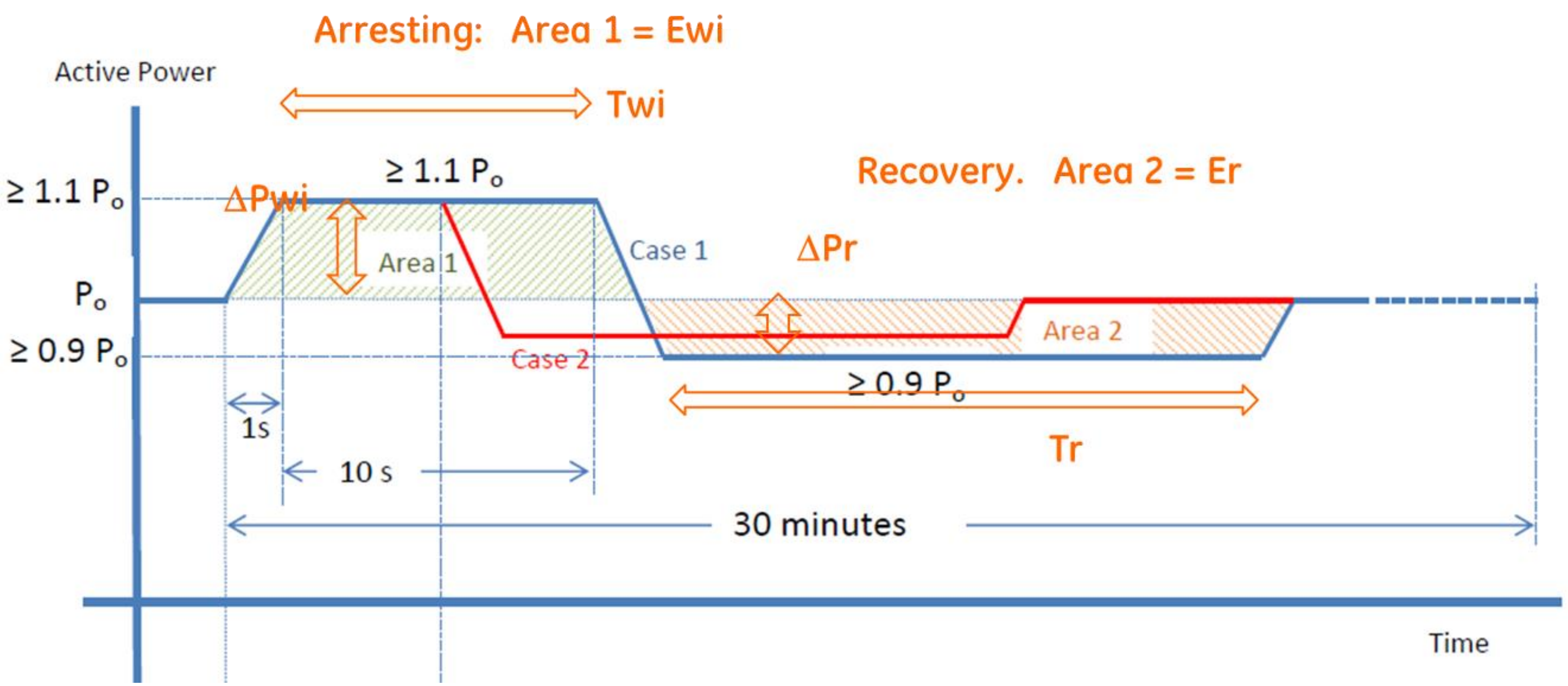


Turbines can typically provide ~10% of rated power, with full response in ~500ms (once control is activated)

Limited response at low wind speeds

SPECIFICATION CHALLENGES

IESO (Ontario) – minimum performance requirement for wind plants (June 2016)

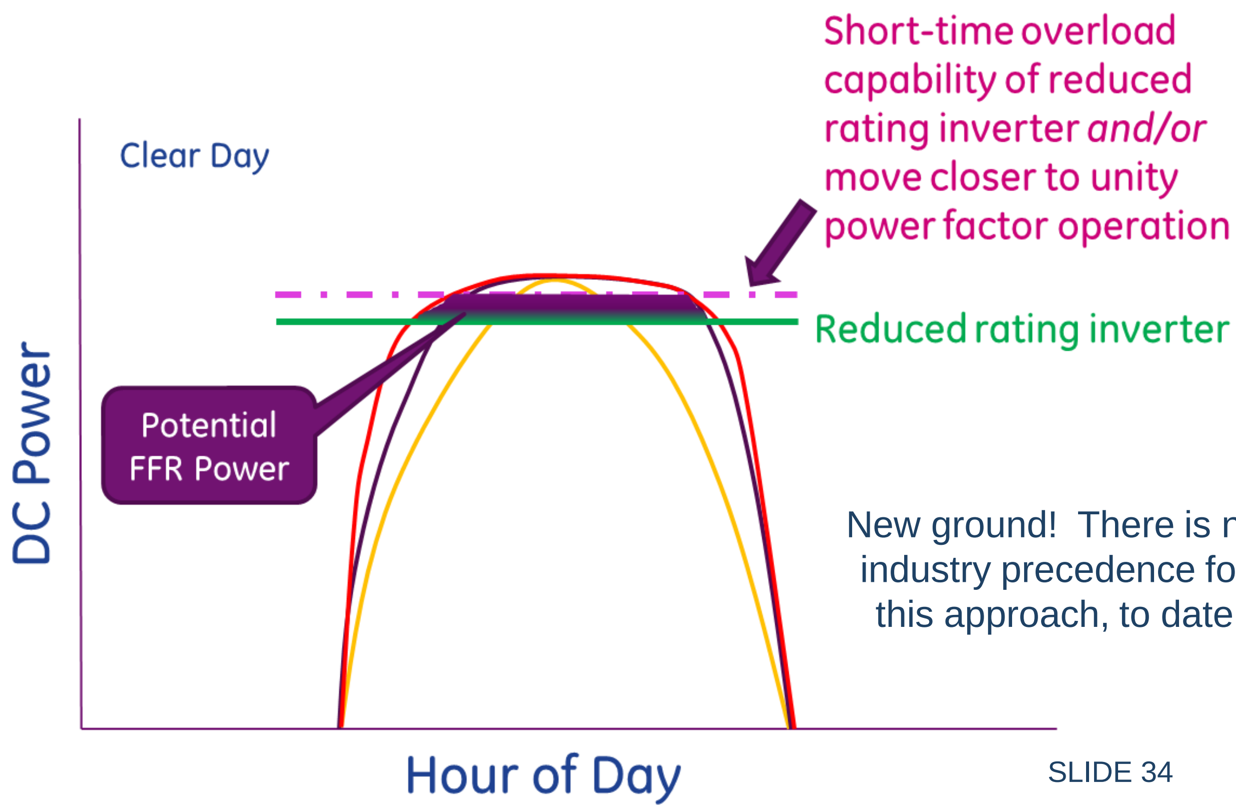


Instead of a prescribed shape, specify an amount of energy to be delivered over a prescribed time?

SOLAR PV

- Unlike wind, no physical inertia
  - Would typically need to pre-curtail to provide FFR
- However:

- Now common to size inverters to be less than power of the panels
- Excess PV energy available for FFR
- **Option 1:** Utilise short-term overload capability of inverter, and/or
- **Option 2:** allow active power priority over reactive power (temporarily)



New ground! There is no industry precedence for this approach, to date

OTHER TECHNOLOGIES

- A range of other technologies that can respond very quickly (following detection & identification) – 10-100ms

Lithium batteries	Flow batteries	Lead acid batteries	Super capacitors
Flywheels	Loads	HVDC	

- Main limitation is inverter and controls response times
  - Location of controls is important, to minimise latencies

OVER-FREQUENCY VS UNDER-FREQUENCY EVENTS

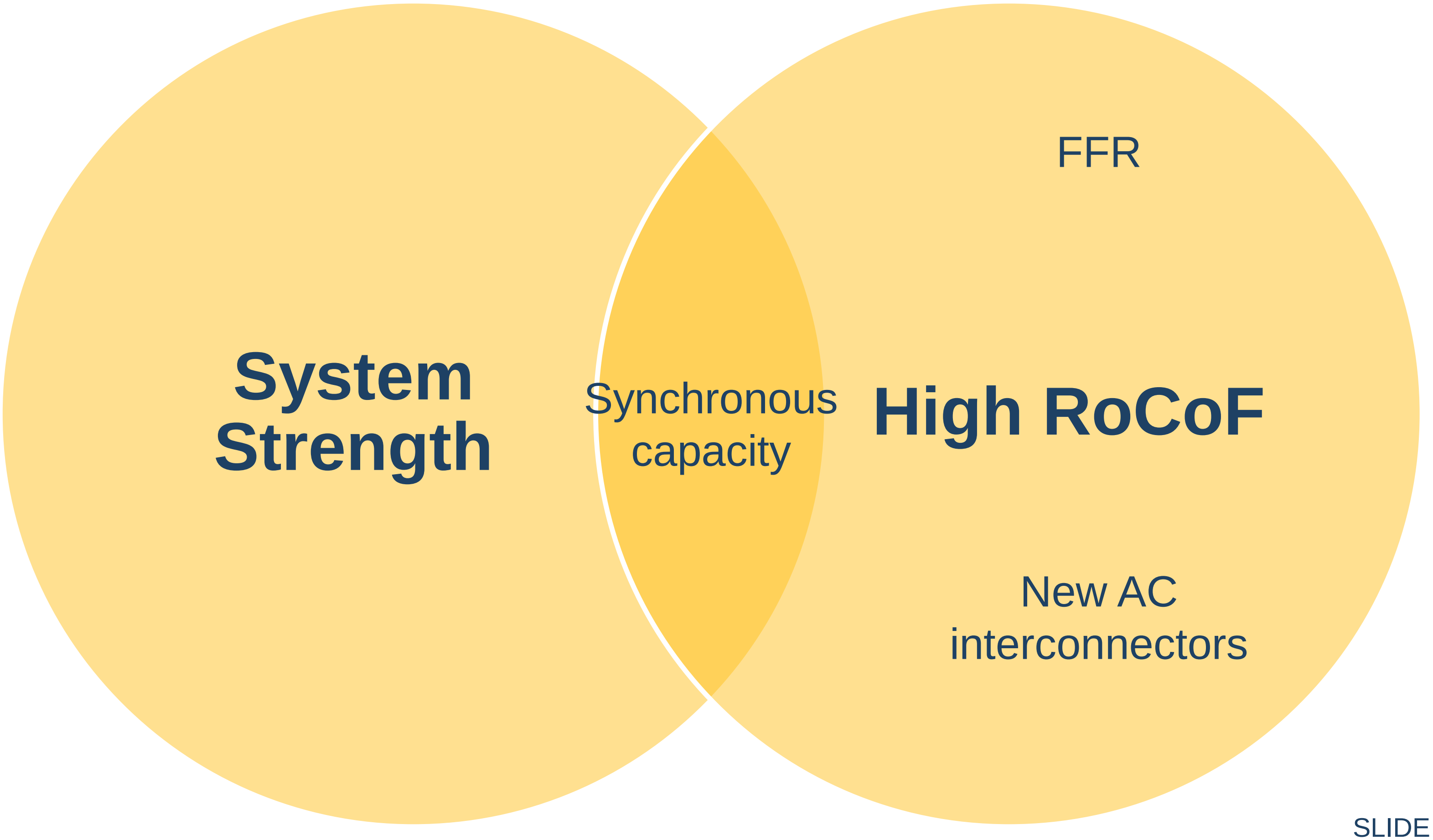
- FFR is not symmetric
  - Different costs and implications for raise and lower services
- For some emerging FFR resources, cost to provide FFR lower services is likely to be small
  - Can reduce power output quickly, to low levels, with little risk of tripping
  - No need to pre-curtail
  - Some additional control systems required
- Mandated response in some jurisdictions
  - EirGrid, ERCOT, South Africa
- Have focused this discussion on raise services, but lower services will also be required.

FAULTS AND WEAK SYSTEM ISSUES

- **Faults:**
  - Large frequency excursions are often triggered by faults
  - Power electronics nearby experience active power disruptions (during and following the fault)
  - May make it difficult to provide FFR following a fault
- **Weak systems:**
  - Voltage must be restored following a fault before active power can be evacuated – reactive power given priority
  - In weak systems, active power recovery tends to be slower, FFR is delayed

SOLUTIONS OVERLAP

- Important to consider the overlap between different challenges, for efficient holistic solutions



DISCUSSION:

Work Package:

- What are the capabilities and limitations of technologies that can provide a FFR service?
- To what degree can FFR substitute for synchronous inertia?
- How should new ancillary services be specified?
- What further insights can we draw from international experiences?

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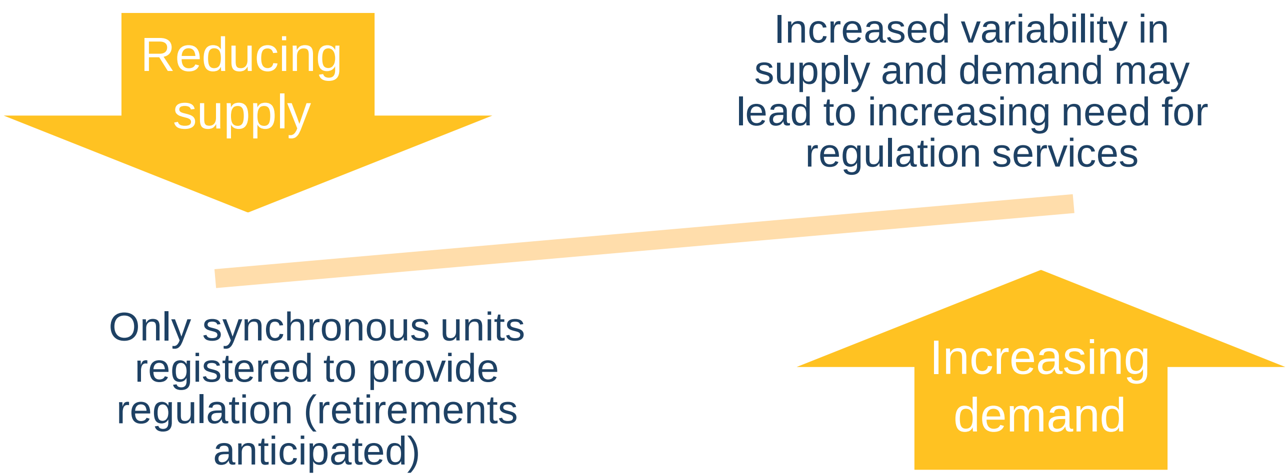
SUPPLY-DEMAND BALANCE FOR FCAS

FREQUENCY CONTROL ANCILLARY SERVICES

Contingency FCAS	Regulation FCAS
• Corrects the generation / demand imbalance following **major contingency events**	• Continually corrects the generation / demand imbalance in response to **minor deviations** in load or generation

OBJECTIVES

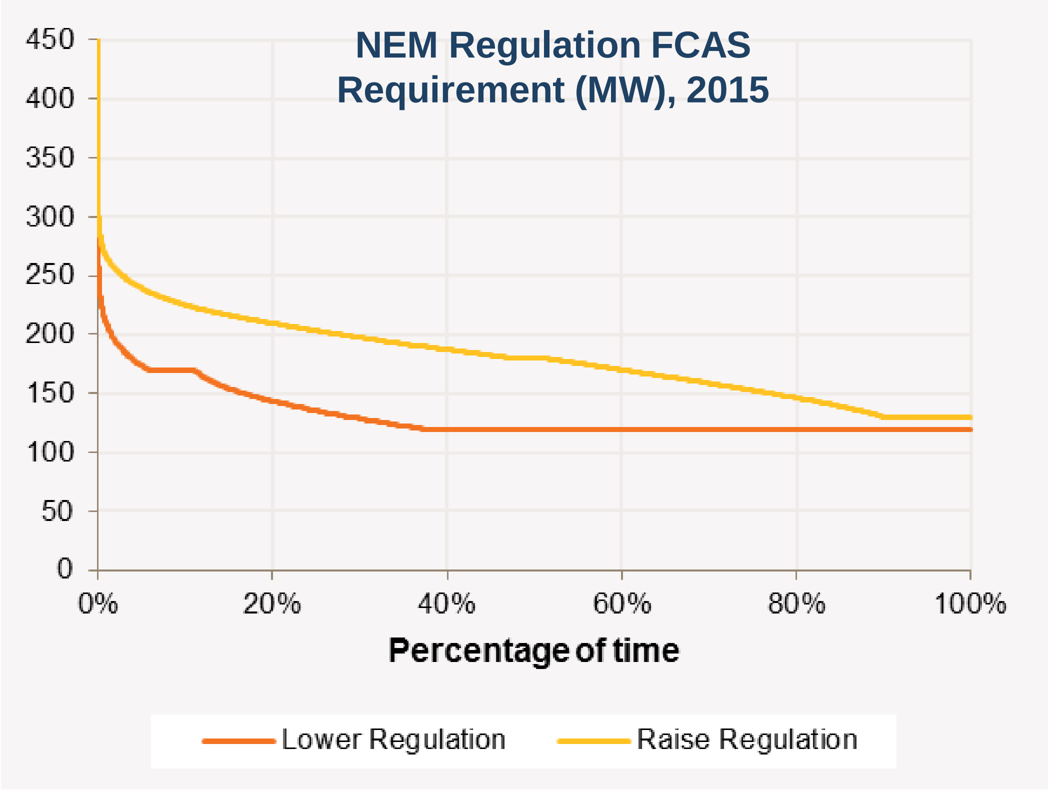
- Will there be sufficient regulation FCAS in future?



- Develop a first principles methodology for projecting regulation FCAS requirements
- Work in progress!
  - Suggestions welcome

METHODOLOGY

- Minimum quantities of regulation enabled have been determined empirically, by operational experience



- No methodology for determining regulation requirements from first principles
  - Need to develop this to project forward

METHODOLOGY

NEM Mainland Frequency Operating Standards – interconnected system

Condition	Containment	Stabilisation	Recovery
Accumulated time error	5 seconds		
no *contingency event* or *load event*	49.75 to 50.25 Hz, 49.85 to 50.15 Hz 99% of the time	49.85 to 50.15 Hz within 5 minutes	
generation event or *load event*	49.5 to 50.5 Hz	49.85 to 50.15 Hz within 5 minutes	
network event	49 to 51 Hz	49.5 to 50.5 Hz within 1 minute	49.85 to 50.15 Hz within 5 minutes
separation event	49 to 51 Hz	49.5 to 50.5 Hz within 2 minutes	49.85 to 50.15 Hz within 10 minutes
multiple contingency event	47 to 52 Hz	49.5 to 50.5 Hz within 2 minutes	49.85 to 50.15 Hz within 10 minutes

Broad indication that regulation should be sufficient to manage ~99% of supply-demand imbalance events, under normal conditions

METHODOLOGY

- If regulation is intended to cover 99% of imbalances, might expect a **1% Probability of Exceedence (POE) measure** to broadly equate to empirically determined regulation requirements
- At present, one of the main drivers of regulation needs is demand forecast errors
- Calculate 1% POE for 5min demand forecast errors:

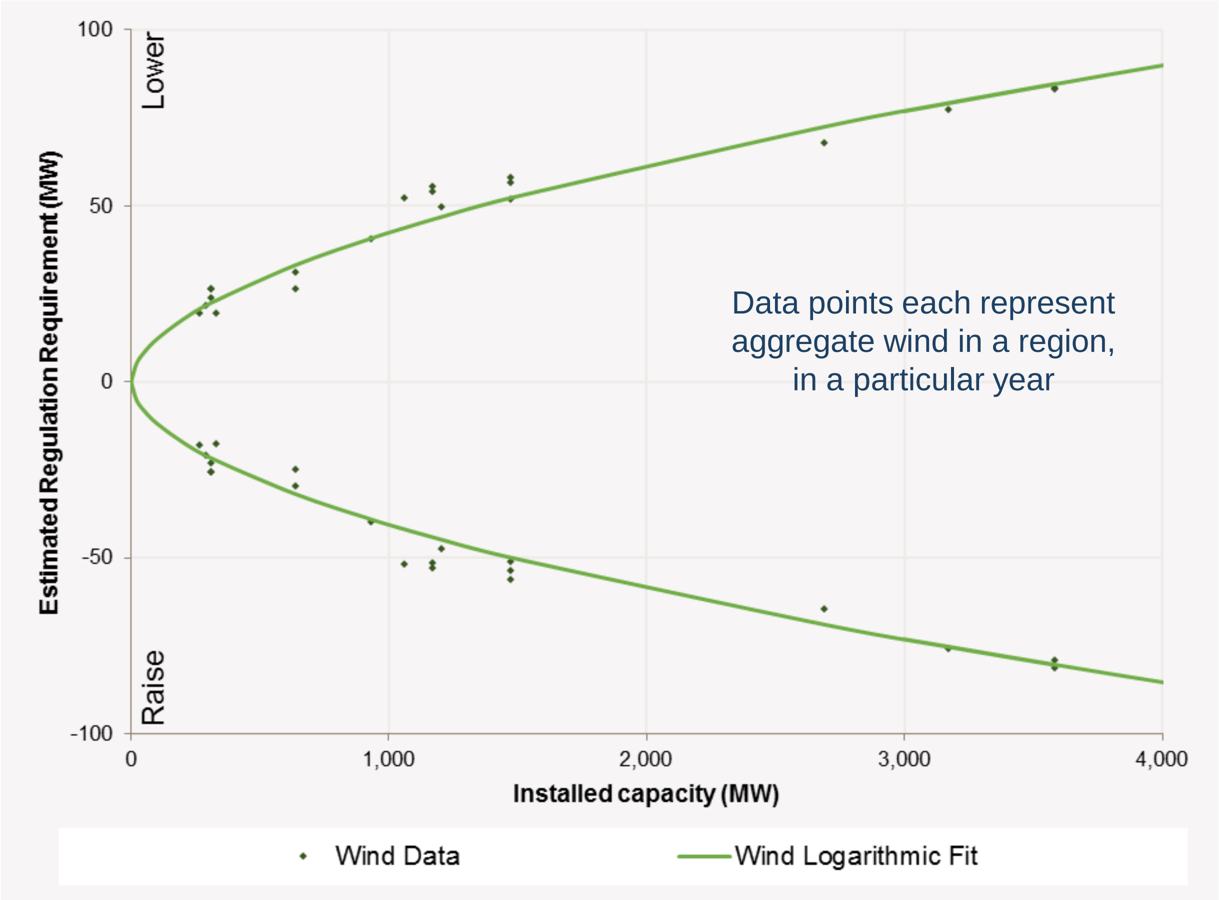
- Suggests that a 1% POE measure does provide an indication of regulation needs

	Regulation Raise / Lower (MW)	Demand forecast error (5 min) 1%POE (MW)
		2012 – 2015 average
NEM	130 / 120	190
QLD	110	130
SA	70 / 35	43
TAS	50	31

WIND VARIABILITY

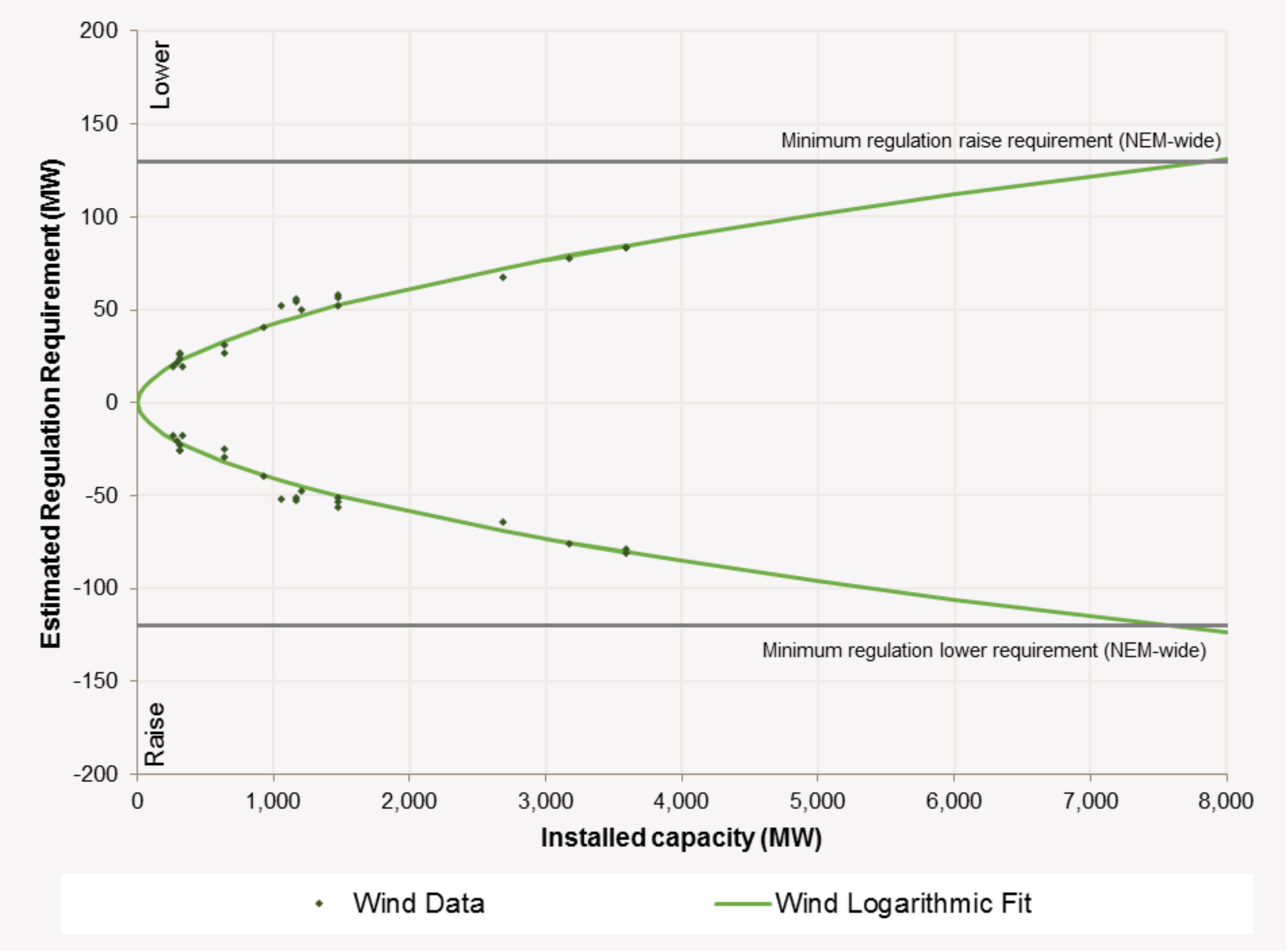
Applied the 1% POE metric to NEM wind generation (change in 5min), to provide an estimate of regulation requirement related to wind generation.

Geographic smoothing leads to reduced marginal increase in regulation needs, as installed capacity increases.



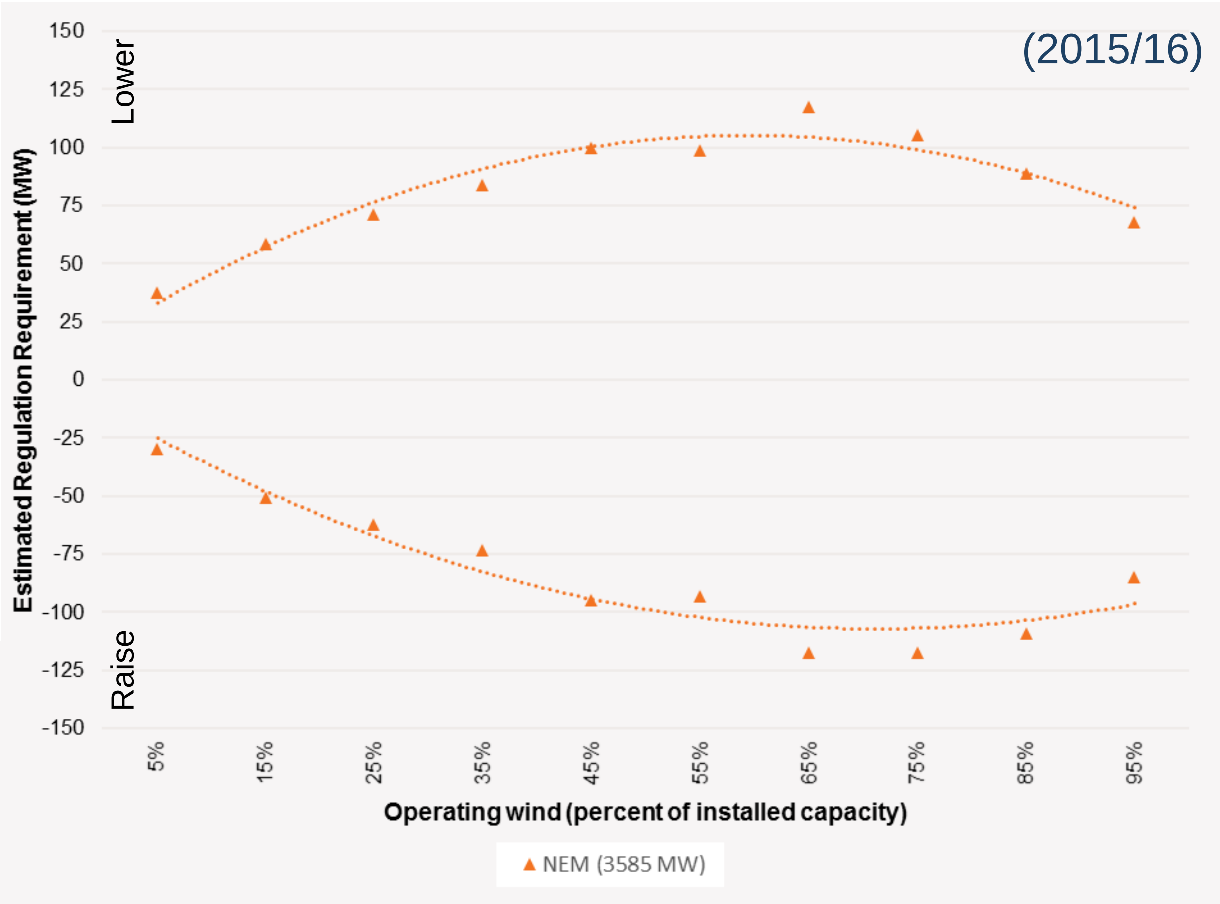
PROJECTING WIND VARIABILITY

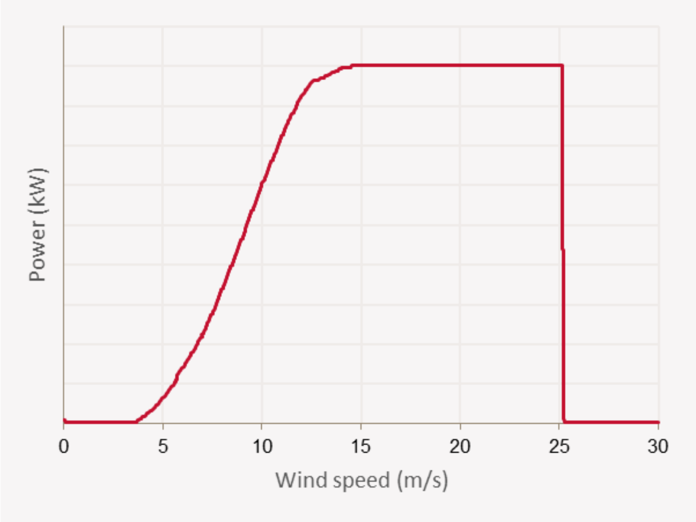
- Project forward (based upon logarithmic fit).
- Variability of wind remains within minimum NEM regulation requirement until ~6-10GW of installed wind capacity
- Beyond this point, wind variability may cause enablement of more regulation FCAS in some periods.
- Can be managed under present frameworks.



WIND VARIABILITY

- Wind variability is lower when operating at low or high levels





UTILITY PV

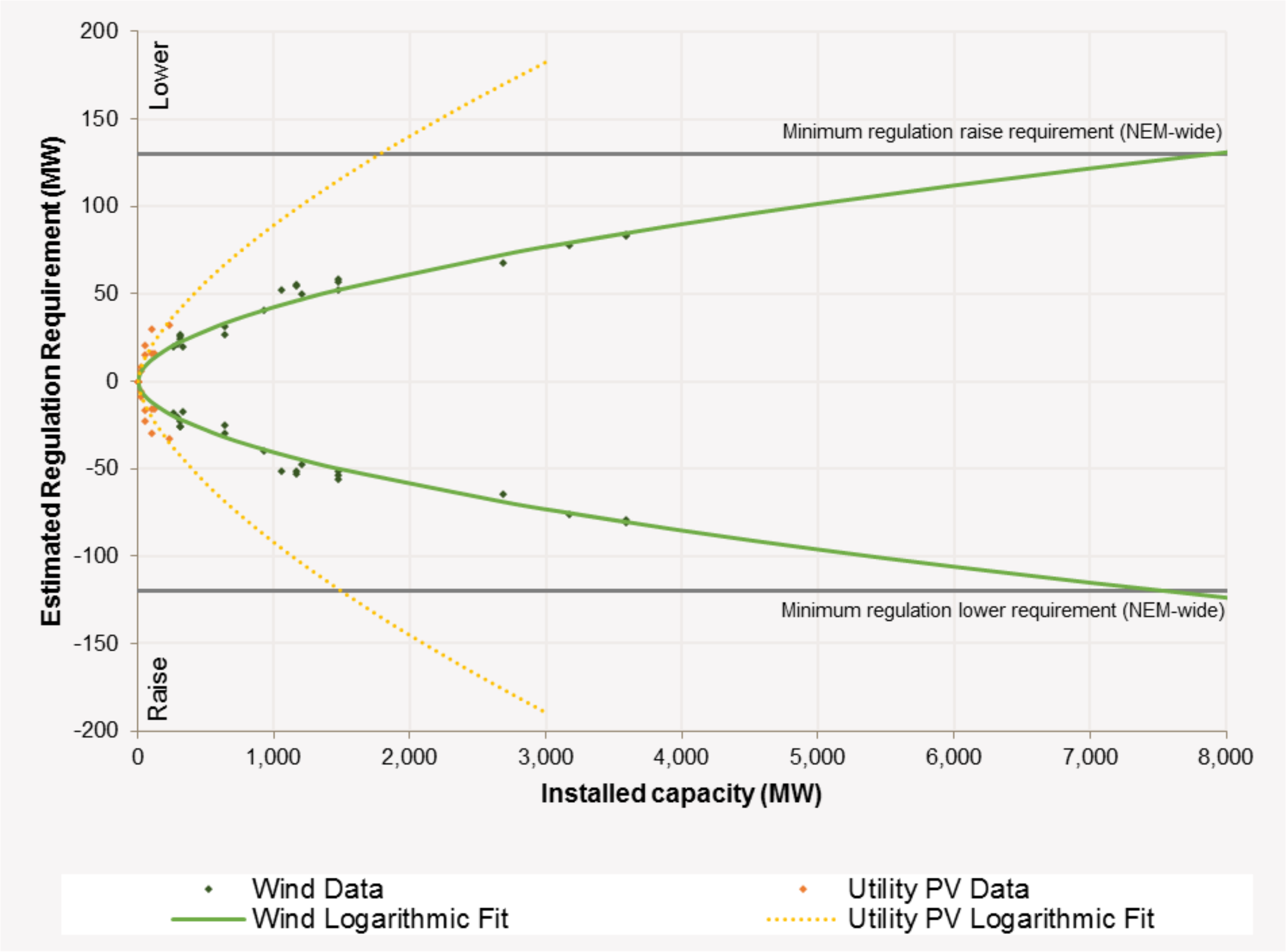
- Consider utility-scale PV first
  - Distributed PV analysis to come later
- Very limited utility PV data available

Utility PV	Installed Capacity (MW)	Commissioning
Nyngan	102	Mar-June 2015
Moree	55	Feb-Mar 2016
Broken Hill	53	Sept-Oct 2015
Royalla	21	Apr 2015

- Only possible to do an initial preliminary assessment
  - Will improve as more units are installed, for a longer duration

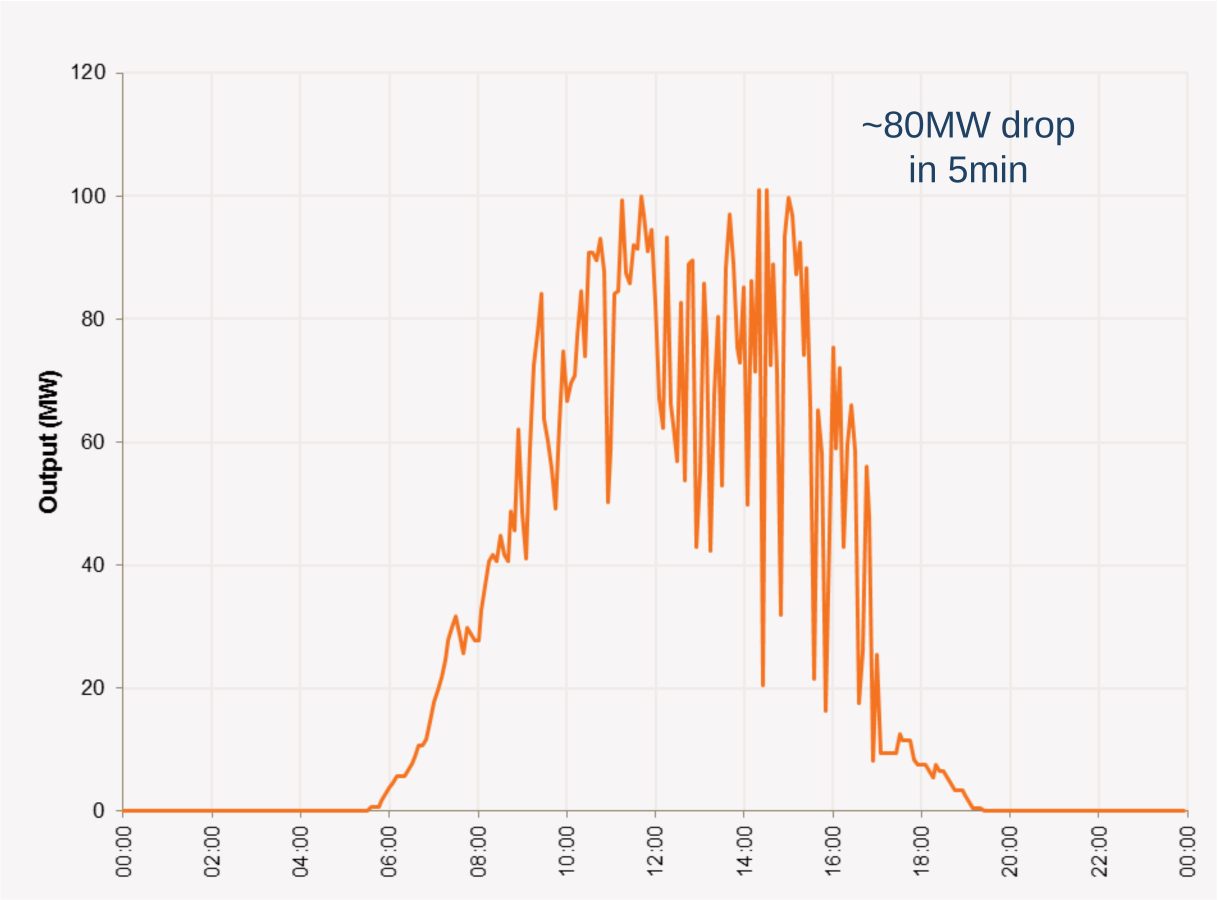
PROJECTING UTILITY PV VARIABILITY

- **Very limited utility-PV data available –** preliminary assessment only!
- Variability of utility PV remains within minimum NEM regulation requirement until ~1-2GW of installed capacity.
- Beyond this point, PV variability may cause enablement of more regulation FCAS in some periods.
- Can be managed under present frameworks.

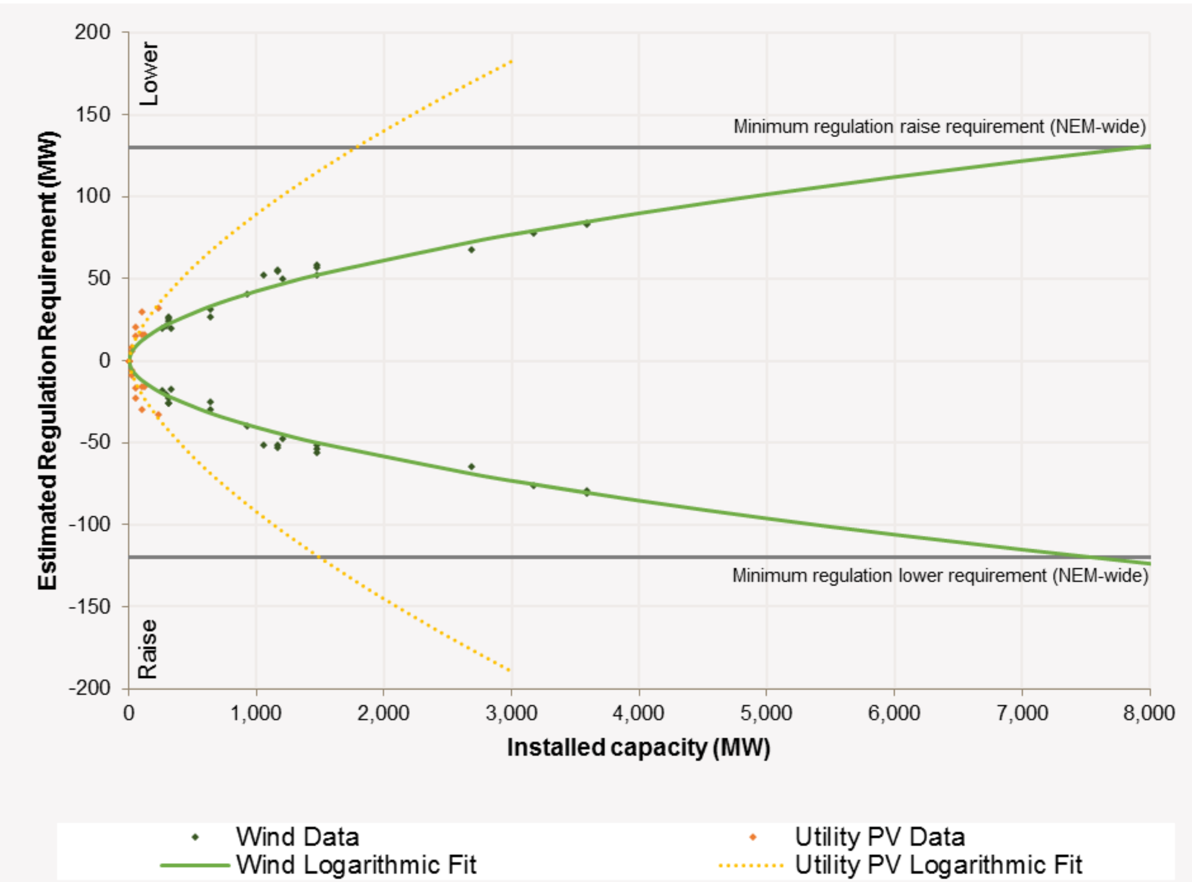


UTILITY PV VARIABILITY

- Utility PV appears to be generally more variable than wind generation, on short timescales
- Likely to be a more significant driver of regulation needs, in the absence of smoothing measures
- However, no additional variability *overnight*, regardless of installed capacity



SUPPLY-DEMAND BALANCE



Registered capacity:

	Regulation Raise (MW)	Regulation Lower (MW)
NEM	**7,055**	**7,023**
QLD	1,026	1,054
SA	380	320
TAS	2,141	2,141

No shortfall in regulation supply anticipated soon, unless:

- Significant growth in utility PV/wind, particularly if concentrated in one region
- Significant retirement of regulation providers, without new entrants

NEXT STEPS & DISCUSSION POINTS:

- Explore opportunities for more efficient regulation
  - Suggestions?
- Distributed PV variability assessment
  - Sources of distributed PV generation data, 1-5min resolution, NEM-wide?
- Further insights on utility-scale PV generation
  - International data? (1-5min resolution)
- Contingency FCAS services supply-demand balance
  - What factors may influence the demand for contingency services in future?

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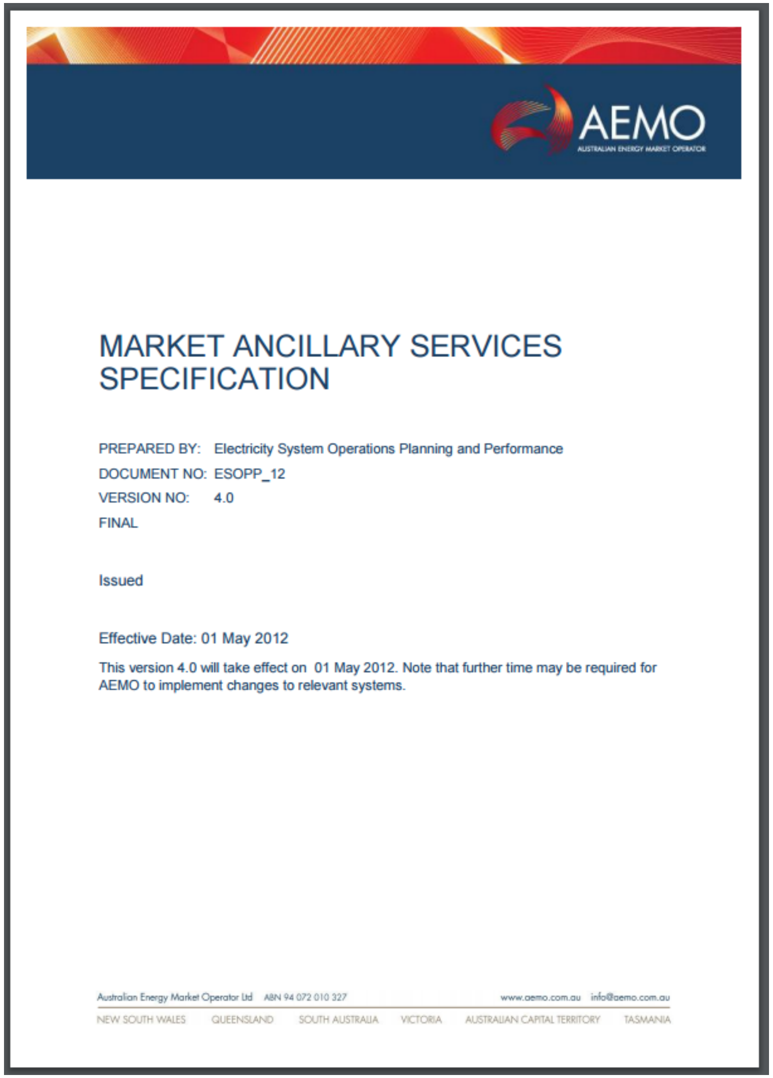
REVIEW OF FCAS SPECIFICATIONS

REVIEW OF FCAS SPECIFICATIONS

- To date, no emerging technologies registered to provide FCAS
  - Is this simply a lack of economic incentives? Or are there technical barriers?
- Program of work to:

Identify & remove unnecessary technical barriers, to facilitate broadest possible participation in FCAS	Ensure specifications adequately describe power system needs

- Specifications currently defined in the MASS (Market Ancillary Services Specification)



AEMO

AUSTRALIAN ENERGY MARKET OPERATOR

MARKET ANCILLARY SERVICES SPECIFICATION

PREPARED BY: Electricity System Operations Planning and Performance

DOCUMENT NO: ESOPP_12

VERSION NO: 4.0

FINAL

Issued

Effective Date: 01 May 2012

This version 4.0 will take effect on 01 May 2012. Note that further time may be required for AEMO to implement changes to relevant systems.

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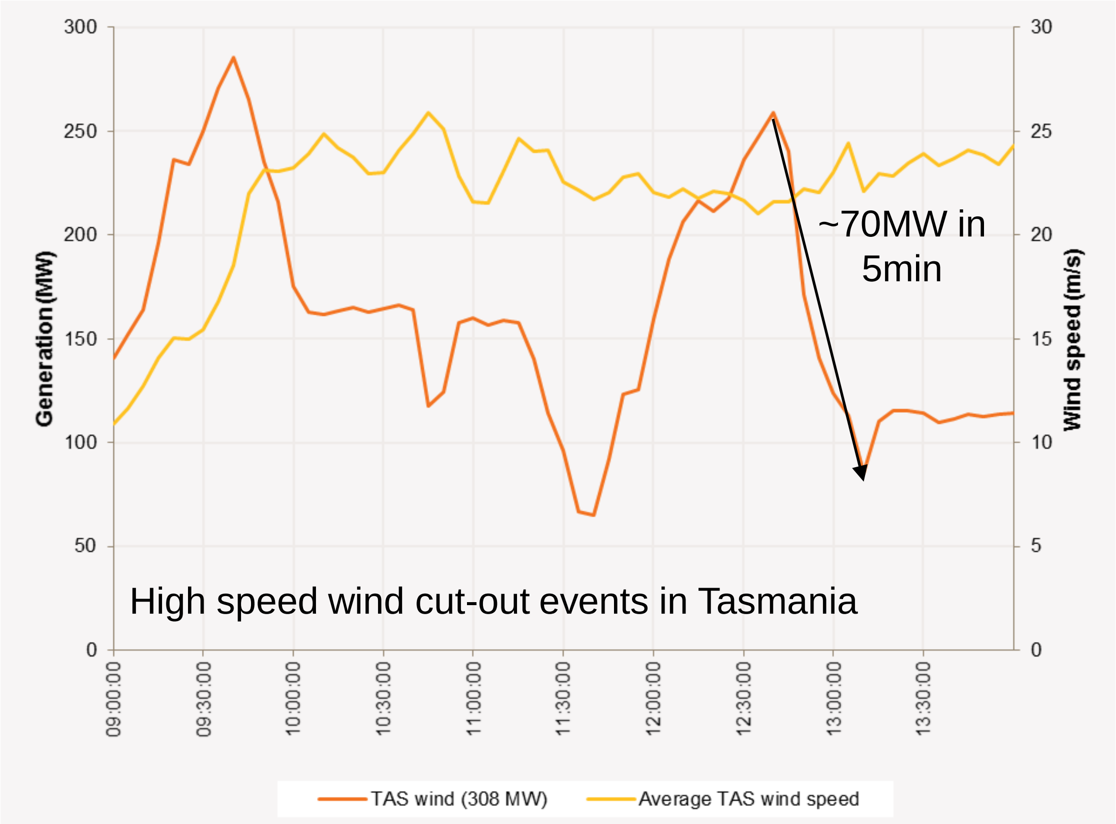
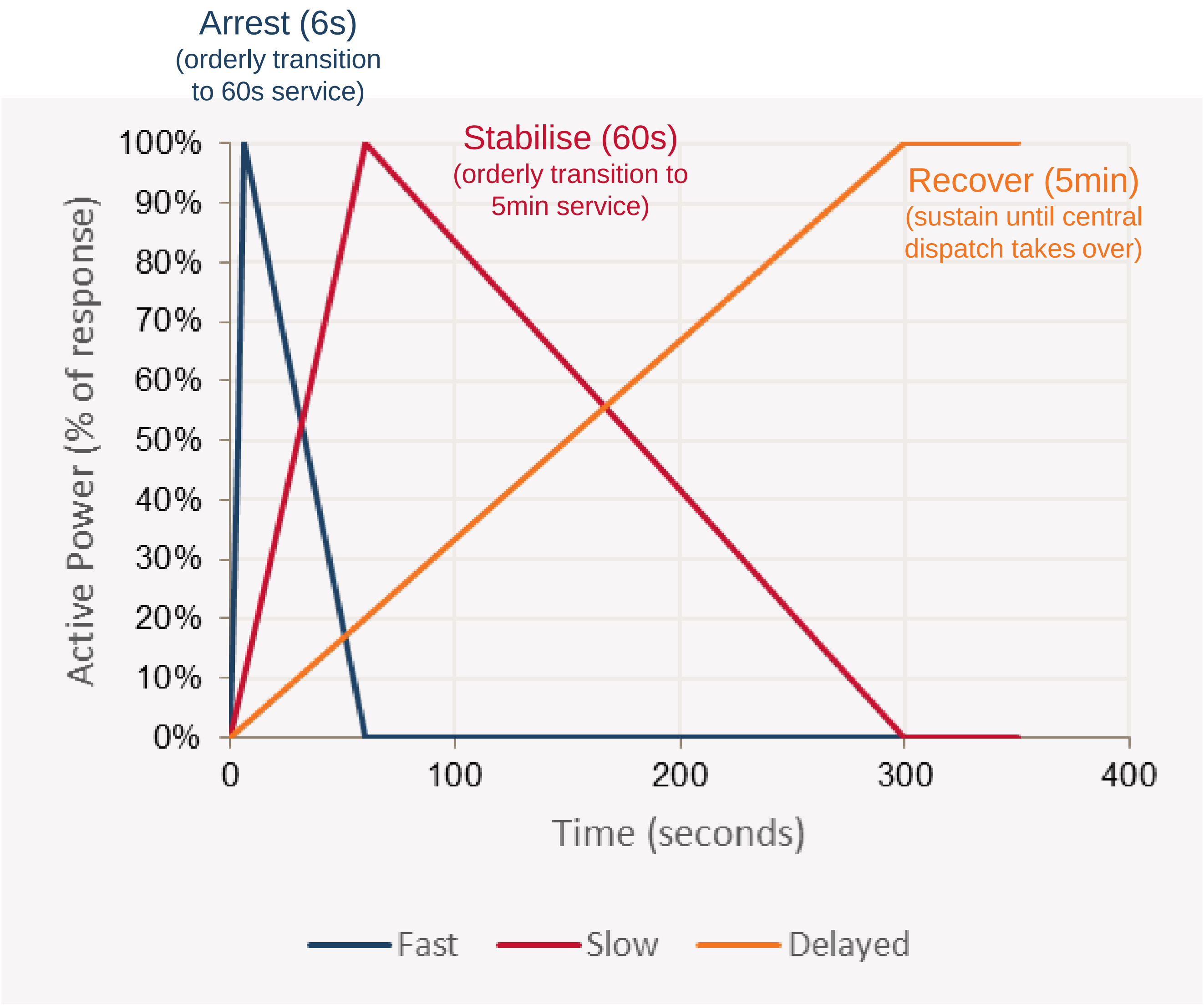
NEW SOUTH WALES QUEENSLAND SOUTH AUSTRALIA VICTORIA AUSTRALIAN CAPITAL TERRITORY TASMANIA

REGULATION FCAS

- Efficient management of new types of events, eg:
  - High speed cut-out events (wind)
  - Utility PV intermittent cloud cover days
  - EV/battery switching
- Is regulation appropriate for managing these new types of events?
- Are there benefits to subdividing further?
  - Eg. “everyday” regulation for normal variability, and “occasional” regulation for larger, rarer events?



CONTINGENCY SERVICES



- Response times originally selected to allow all participants with a useful response to contribute
- May not be optimal for emerging technologies
- Would further subdivision of these timeframes allow broader participation?
- Do we need to specify any aspects of the response more precisely?

DISCUSSION:

Work package:

- Can emerging technologies provide all existing FCAS services?
- Are there any technical barriers to participation of emerging technologies in FCAS?
- Does the specification adequately define power system needs?
- How can FCAS frameworks be adapted for broader participation?

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