ARENA INSIGHTS WEBINAR

Advanced Inverters

27 MAY 2021

Today's Agenda

Opening remarks

- Darren Miller, CEO, ARENA

Session 1: Market Body Context

- Chris Mock, Principal Engineer – Future Energy Systems, AEMO

- Christiaan Zuur, Energy Policy Director, AEMC

Q&A Facilitated by Dan Sturrock

Session 2: Project Knowledge

- Sachin Goyal, Power System Engineer, Powerlink

- Garth Heron, Head of Development (Australia), Neoen

- Dr Behrooz Bahrani, Senior Lecturer and Director of Grid Innovation Hub, Monash University

- Malithi Gunawardana - Principal Engineer, Network Planning and Operations, Transgrid

Q&A Facilitated by Carl Tidemann

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- **ARENAWIRE** is our virtual newsroom with news and analysis about ARENA funded projects, as well as videos and other content. Subscribe at arena.gov.au/blog.
- ARENA's **Knowledge Bank** is an open-source library of reports, studies and tools. Subscribe to our industry newsletter, **Insights**, arena.gov.au/knowledge-bank
- Our **podcast** looks at the pieces of Australia's energy puzzle and how they might come together in a future powered by renewables. Subscribe wherever you get your podcasts.

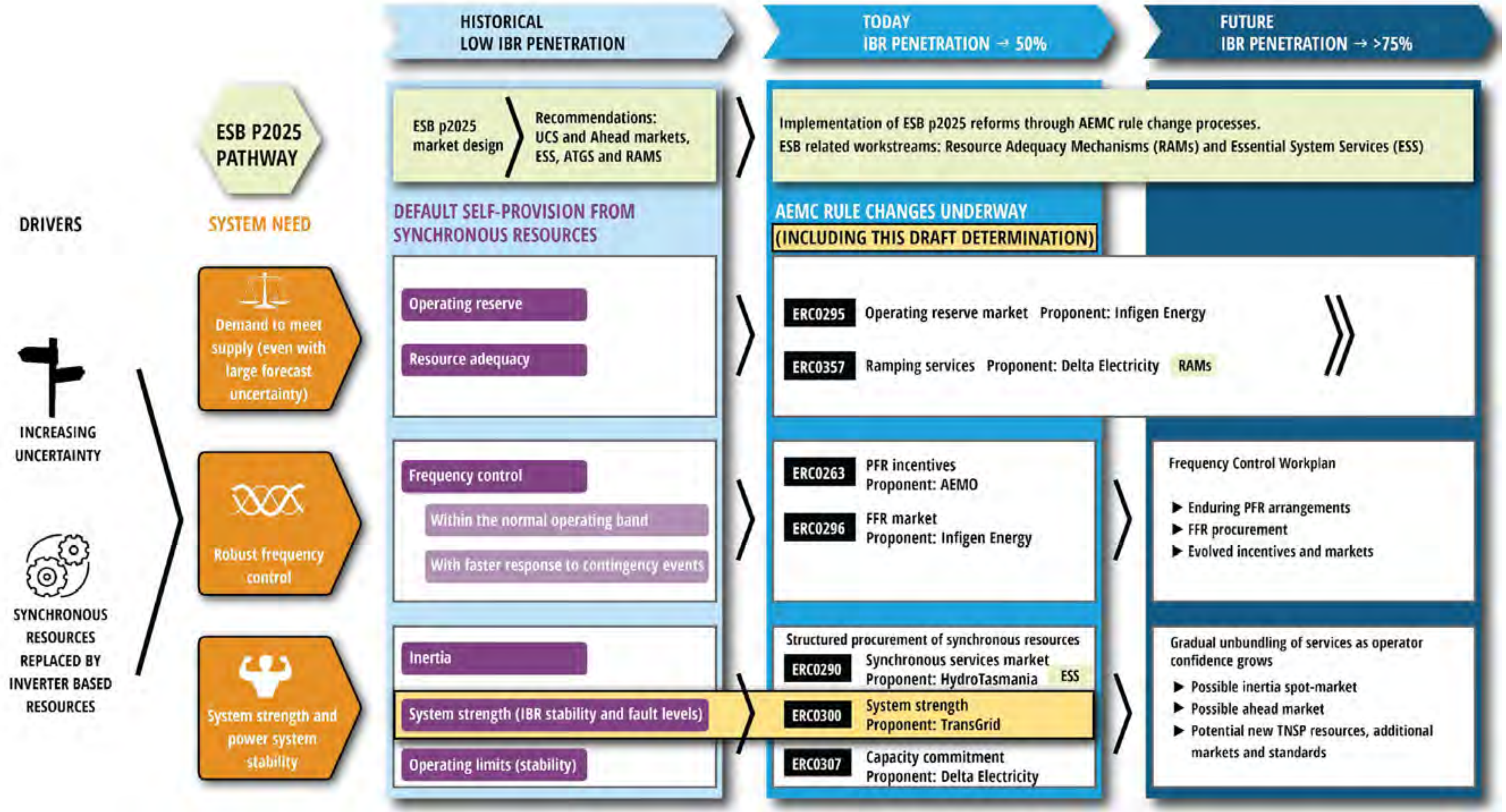
EFFICIENT MANAGEMENT OF SYSTEM STRENGTH ON THE POWER SYSTEM DRAFT DETERMINATION

ERC0300 – TRANSGRID RULE CHANGE

STAKEHOLDER BRIEFING,

MAY 2020

Interaction between AEMC & ESB work



OVERVIEW OF THE DRAFT RULE

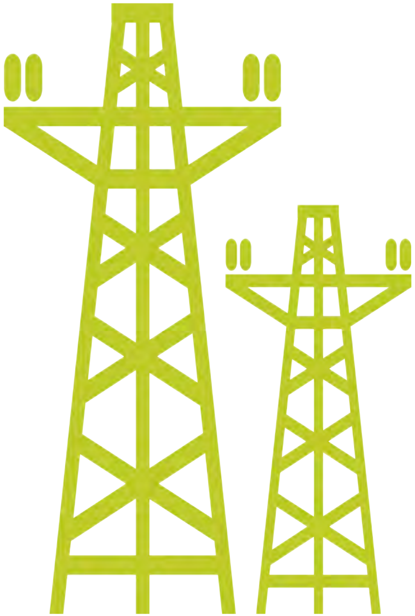
Overview of draft rule determination

Consistent with our recommendations from the *Investigation* there are three elements:

1. **Supply side:** A TNSP led procurement of system strength. TNSPs working closely with AEMO, would be responsible for providing efficient levels of system strength on a forward looking basis over the given timeframe. This would be a prescribed transmission service, with the TNSP required to meet a system strength standard at certain locations on its transmission network.

2. **Demand side:** New access standards, to ensure that connecting parties with IBR would only use the efficient volumes of this valuable common pool resource.

3. **Coordination:** The system strength mitigation requirement, which would provide connecting parties with IBR a choice between paying to use the system strength provided by the TNSP, or providing their own system strength by remediating their impact. This means that connecting parties will pay for some of the provision of system strength

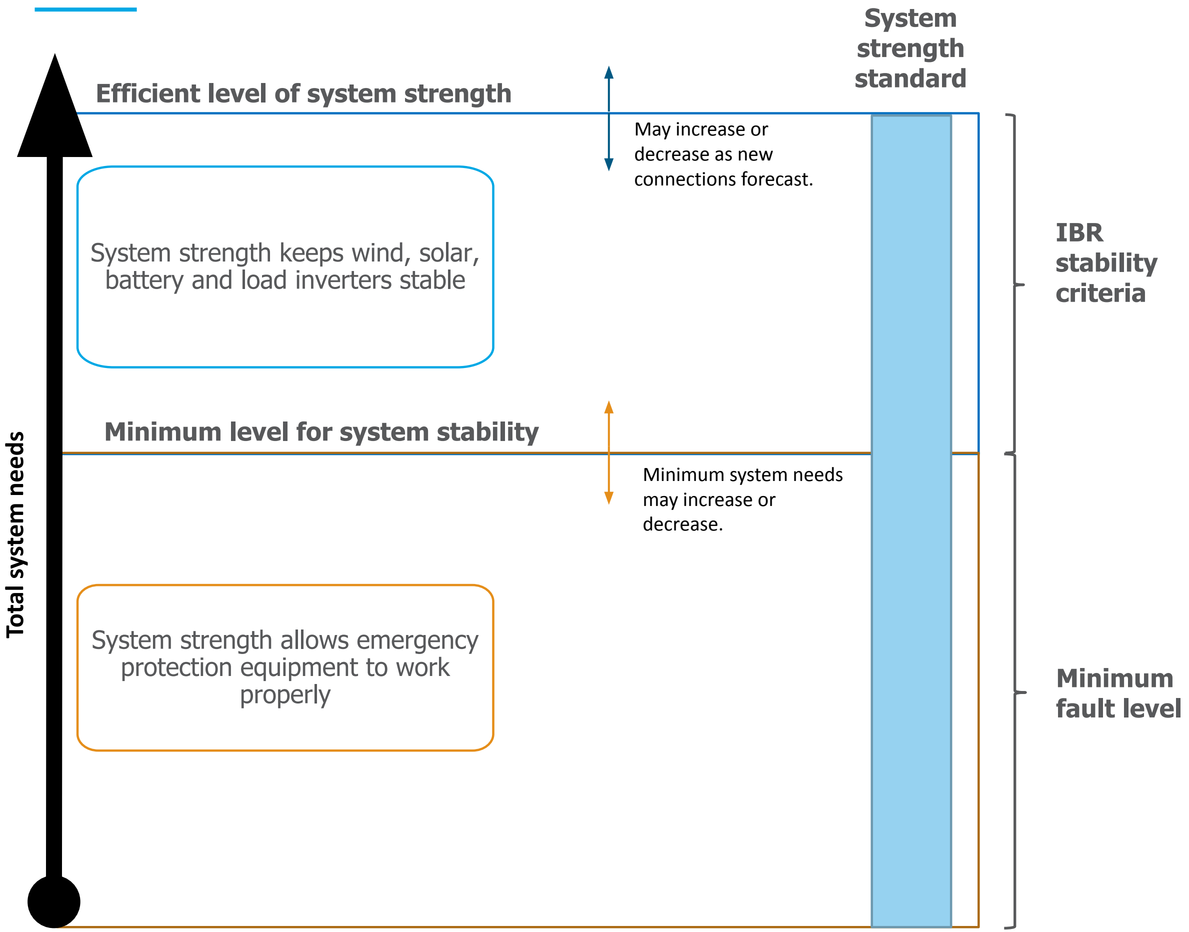


Benefits expected from the proposed draft rule

We consider that the proposed framework would address the key issues with the current frameworks and promote the long-term interests of consumers:

- **Reduce investment and connection costs, which flow through to consumers:**
  - Connecting parties can choose between paying the charge or undertaking own remediation
  - Connecting parties would have greater certainty over the connection process – reducing investment costs and making the connection process faster
- **Enhance scale, scope and operational efficiencies,** by making TNSPs responsible for delivery of the efficient amount of system strength.
  - TNSPs can leverage significant economies of scale and scope to deliver system strength at lowest cost – coordinating with their other responsibilities
- **Address the reactivity of the current frameworks**, by requiring AEMO and TNSPs to actively plan ahead for the provision of the efficient volumes of system strength; and making clear standards required for connecting parties.
  - System strength would be provided when and where it is needed, which would help to address the bottlenecks in new connections, and curtailment of existing generation

The new system strength planning standard



'Reasonable endeavours' obligations on networks

Keep the voltage stable, so that wind, solar battery and load inverters can operate properly: *Achieve stable voltage waveforms such that the efficient amount of IBR and market network service facilities projected to be connected by AEMO will remain stable in steady state conditions and remain synchronised following credible contingency events.*

Provide enough system strength so emergency equipment can operate properly and keep the system safe: *Maintain the minimum three phase fault levels specified by AEMO in the system strength requirements required for plant and network protection systems.*

The system strength charge

Price ($/MVA)

Total generator charge ($) = { System strength price (SSP) ($/MVA) **X** System strength locational factor (SSL) } **X** System strength quantity (SSQ) (MVA)

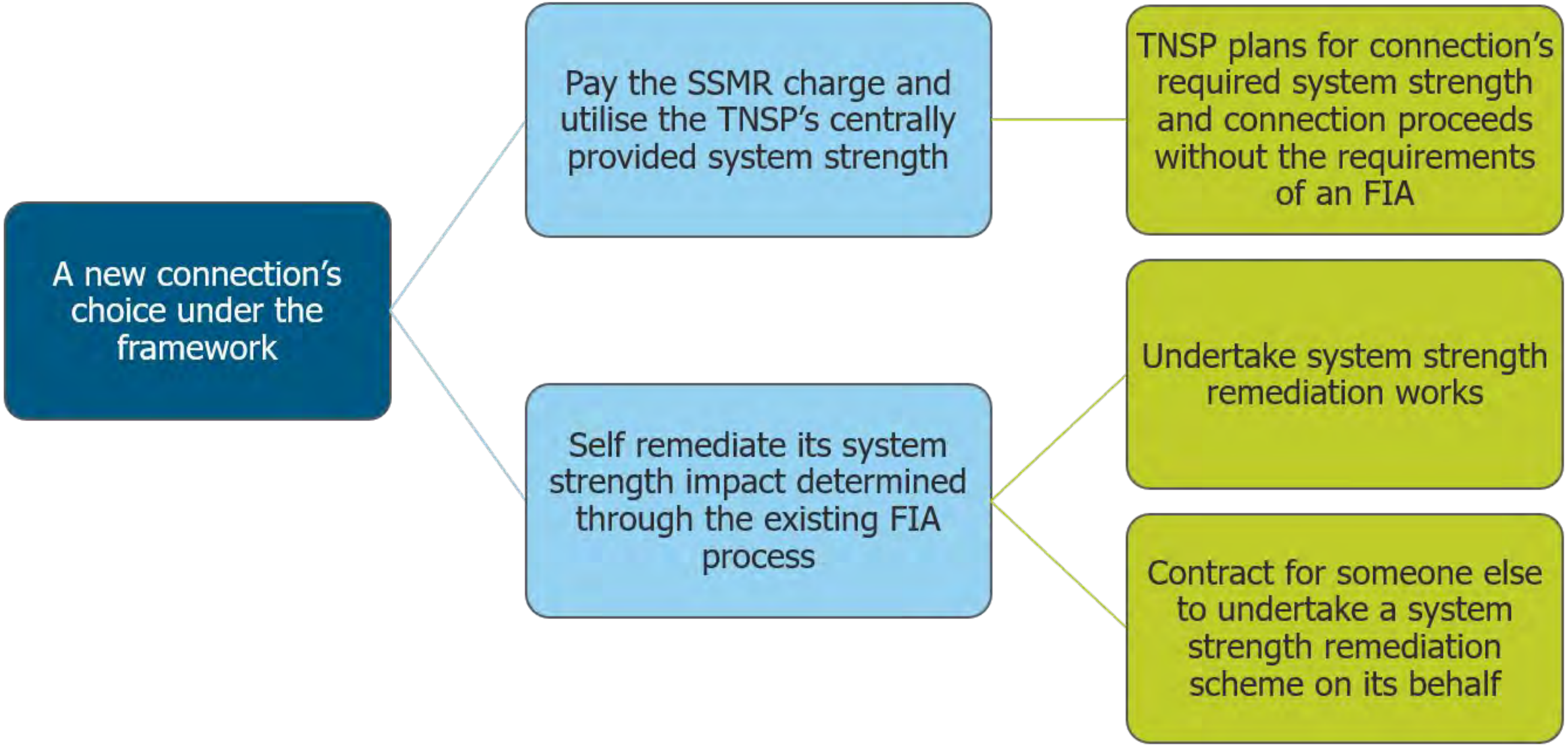
The charge is made up of three components, which, when multiplied together, equal the charge a connecting party would pay:

1. **The system strength unit price** component of the system strength charge reflects the change in **forward-looking** cost of the SSS Provider supplying system strength at each system strength node as a result of a change in demand for the service. **Fixed (indexed) for each 5 year period, recalculated by SSSPs.**

2. **The system strength locational factor** component reflects the localised nature of system strength. This component changes the magnitude of the charge a particular connection would face depending on its approximate electrical distance (or impedance) from the closest system strength node. **Fixed (indexed) for each 5 year period, recalculated by SSSPs.**

3. **The system strength quantity** component of the charge reflects the amount of the service used by the connection. The component is estimated from: the size of the connecting party's plant in megawatts (MW) and its short circuit ratio (SCR) (MVA/MW) requirements. **Fixed at time of connection, can be updated by plant through alterations.**

The system strength choice for connecting parties



The draft access standards

These new access standards are:

1. Minimum short circuit ratio (SCR), requiring new connecting inverter based resources (asynchronous generating units and inverter based loads) and market network service providers (MNSPs) to be capable of meeting all of their agreed performance standards at a SCR level of 3.0.
   - Forms basis of system strength charge
   - To allow parties to reduce their exposure to the system strength charge over time, the draft rule allows relevant inverter based plants to renegotiate technical performance in respect of SCR if they alter their plant in future
2. Generating systems comprising partly or fully of asynchronous generating units to not include a vector shift or similar protection relay that would operate for a voltage phase angle shift less than or equal to 20 degrees, as measured at the connection point. **(Only applies to asynchronous generators)**

- Note that these standards only place obligations to have equipment with capabilities sufficient to allow them to perform to set standard(s), but not to be tuned to those settings at the time of connection. Rather, the connection will still have to have setting required to meet its performance standards suitable for the network conditions at its

Grid forming inverters – system strength some other implications

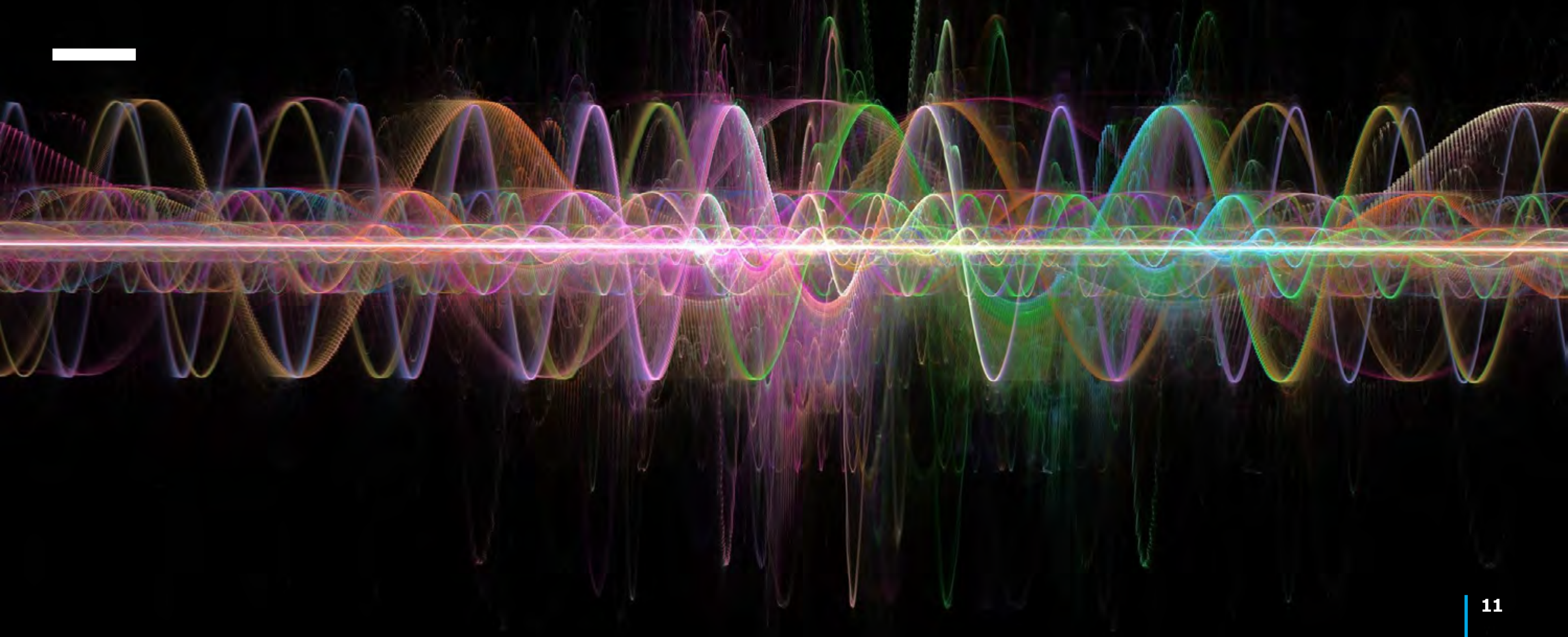
Main applications for grid forming inverters under new system strength framework

- Reduce SSMR charge to zero
- Provide opportunities for generators to offer network support agreements to NSPs, to meet either part of the standard

There are other areas where the regulatory frameworks can be developed to account for grid forming inverters

1. **Access standards**
2. **System operation / security obligations**
3. **System restoration and restart services**
4. **System security mechanism (ESB)**

WRAP UP



Next steps

- **Submissions to the draft determination are due 17 June 2021.**
- We welcome any interested stakeholders to contact us to discuss your thoughts on the proposal ahead of providing a submission.
- We will continue to work closely with the ESB, AEMO and AER on this rule change and its interaction with related work, given this work is being coordinated with the Post 2025 work.
- The final determination of the TransGrid's *Efficient management of system strength on the power system* (ERC0300) rule change is currently expected on 29 July 2021.
- I can be contacted at christiaan.zuur@aemc.gov.au

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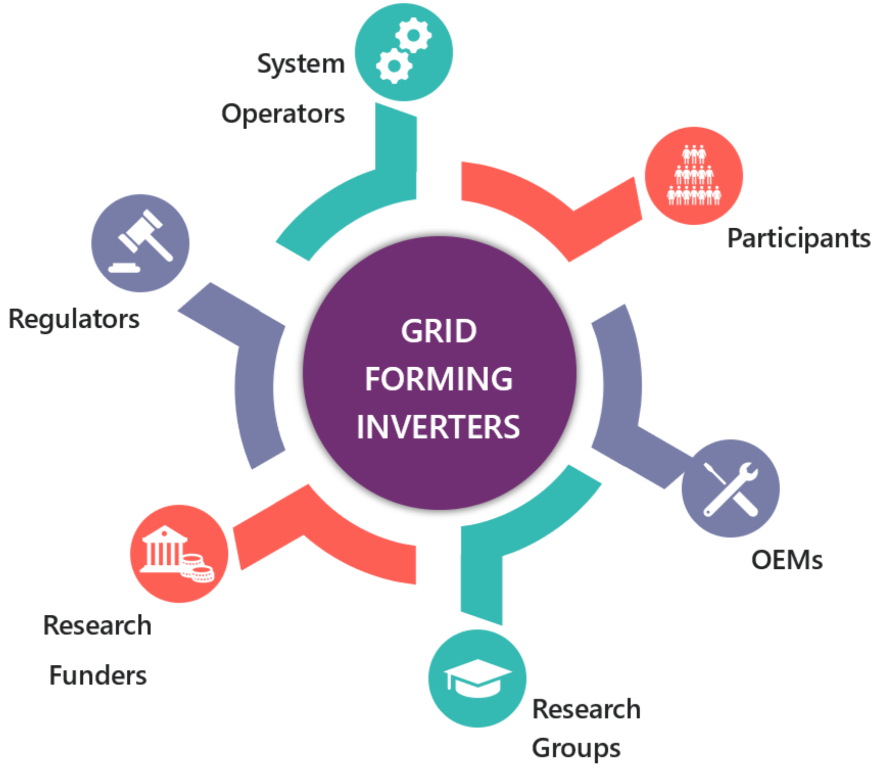
Engineering Framework – Advanced Inverters White Paper

ARENA Webinar – 27 May 2021

AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

Introduction

- Advanced Inverters will play a role in supporting the power system as it transitions toward operation with fewer synchronous generating units online
- Demonstration of Advanced Inverter technology at scale is needed to develop, characterise and prove its operation in applications supporting gigawatt-scale power systems
- Pathways toward a capable fleet of Advanced Inverters are needed if this technology is to support the future grid
- A cross-sector effort is required to overcome barriers and capture opportunities



Applications

Connecting IBR in weak grid areas	Supporting synchronous grid operation	Island / system split	System restart
• Manage local system strength and stability requirements for new connections • Potential alternative to synchronous condensers	• Services currently provided by synchronous machines • Inertia, frequency control, fault current, disturbance performance • Interaction with and support for other generating units	• Microgrid vs. interconnected system • Surviving vs. forming	• Restoring a black power system requires significant fault current and capability to operate under adverse conditions

Increasing capability

Barriers and Enablers

Capability specification

- Requirements definition
- Future specifications and standards
- Connections requirements and processes

Capability demonstration

- Operation at scale
- Ability to operate within standards
- Ability to achieve simulated results for rare events

Costs

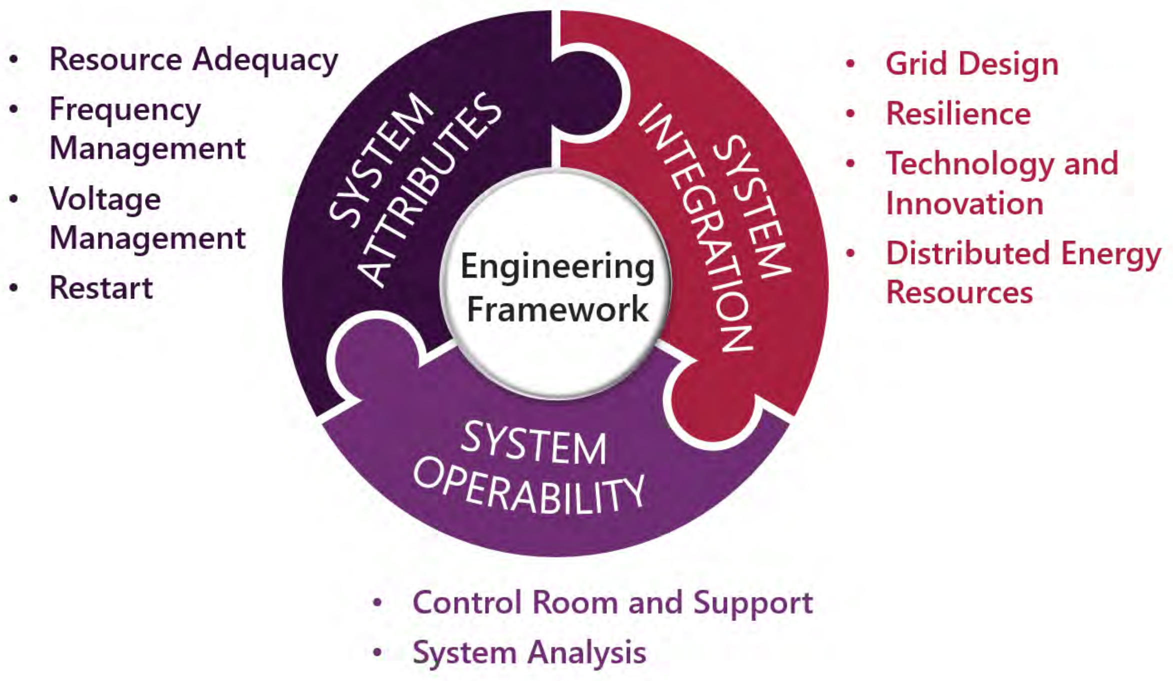
- Uprated components
- Service delivery dependent on stored energy
- Compliance and connection

Revenue

- Many potentially valuable services do not have established revenue streams
- Impact on uptake rate

Next Steps

- AEMO is preparing a white paper on Advanced Inverters for publication July 2021.
- The Engineering Framework will identify gaps and opportunities relating to future operational conditions. The Advanced Inverter work will be continued under this banner.
- Question: How can the energy sector ensure that the large batteries being developed and installed today have the capability of serving the applications detailed in this presentation? What can AEMO and others do (both near-term and long-term) to help make this a reality?



PSCAD assessment of the effectiveness of Grid Forming Inverter

Powerlink Queensland

Sachin Goyal
Yi Zhou
Daniel Andersen
Jonathan Dennis

Forward

- Powerlink has completed this ARENA funded project in conjunction with project partners, Pacific Hydro and Sun Metals.

- Our goal is to help promote a better understanding of system strength throughout the industry while reducing the time, cost and risk of renewable connections.

- The project consists of three reports available on the ARENA website.

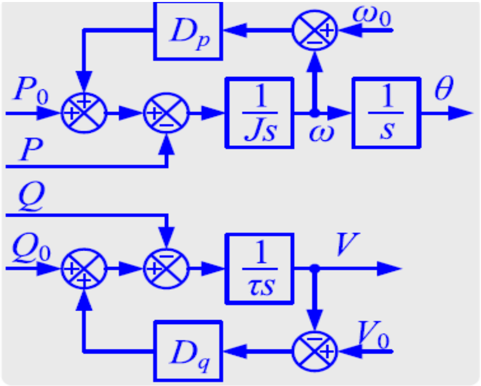
- This presentation covers the third report and examines the effectiveness of a battery connected grid forming inverter in a weak grid context.

- Grid Forming Inverter
- Study Case
- Results
- Challenges

Grid Forming Inverter

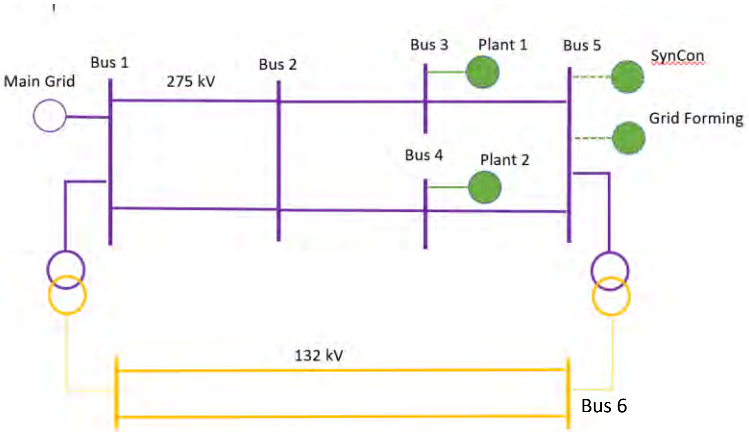
- High penetration level of Inverter Based Renewable (IBR) generation
  - Weak grid connection
  - Control resonance causes sub and super synchronous oscillations
  - Low inertia

- Grid Forming Inverter (GFMI) emulating synchronous generator
  - Do not need Phase Locked Loop (PLL) to synchronize with grid
  - Provide inertia and grid voltage support
  - Provide damping



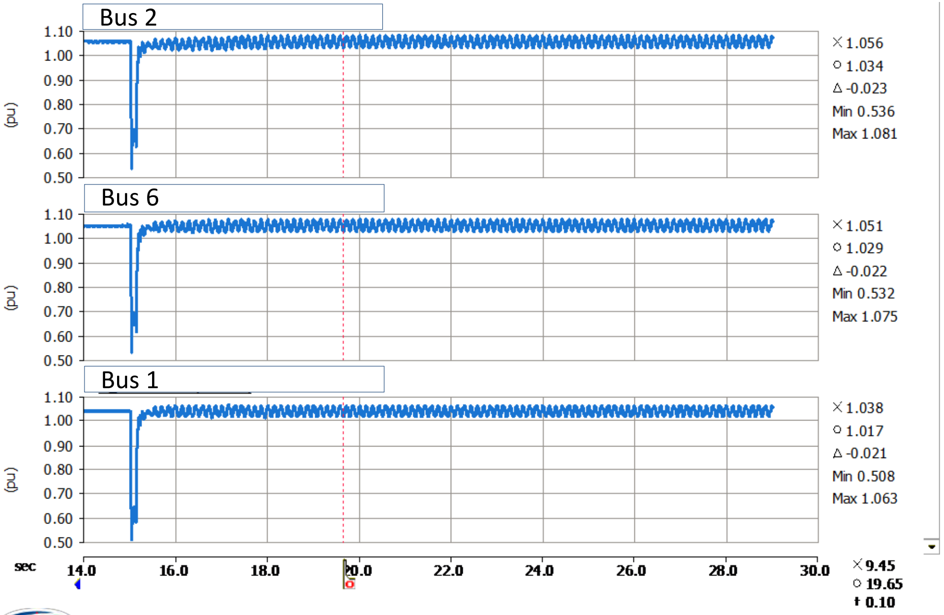
Study Case

- Challenges of the grid under analysis:
  - Sub-synchronous oscillations
  - Voltage and transient stability
- Studied case
  - Case 1 - base case with only inverter based renewable generators, Plant 1 and 2
  - Case 2 - add Synchronous Condenser (SynCon) at Bus 5
  - Case 3 - add Grid Forming Inverter at Bus 5



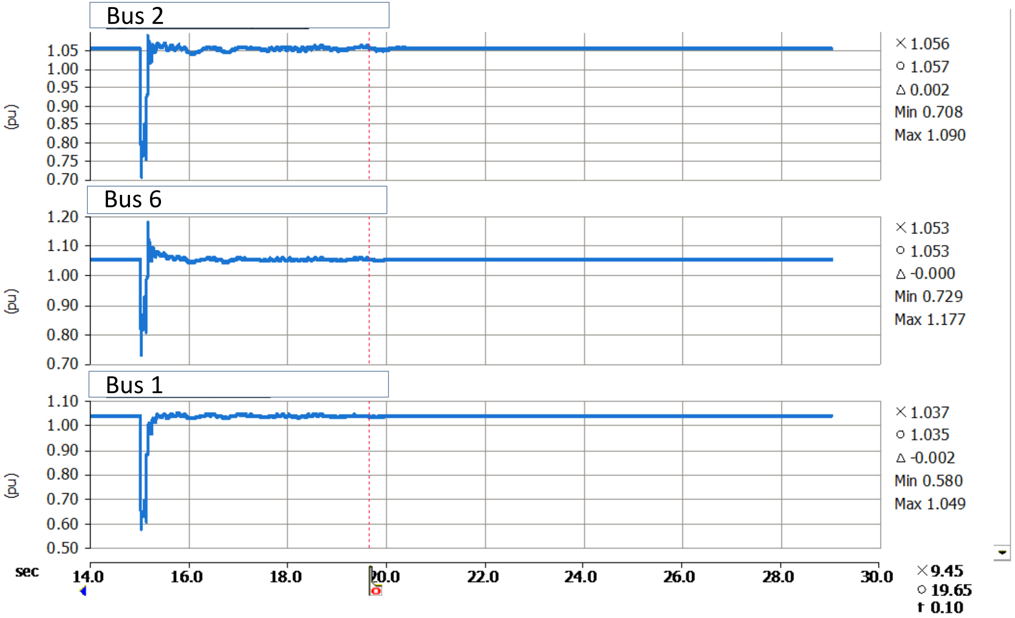
Simulation Results – Sub Synchronous Oscillations

- Base Case



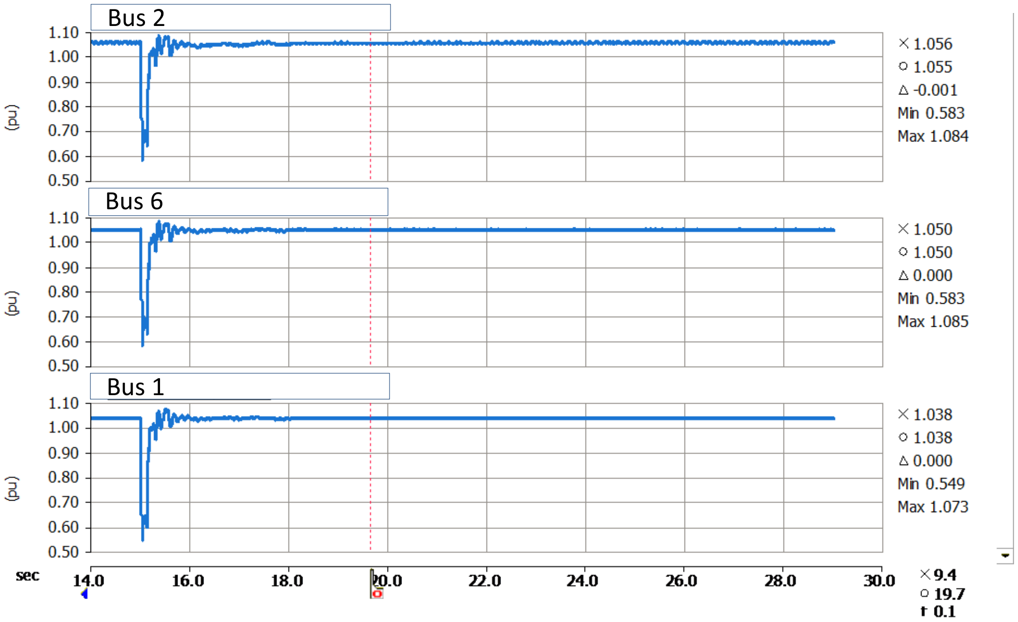
Simulation Results – Sub Synchronous Oscillations

- With synchronous condenser providing damping



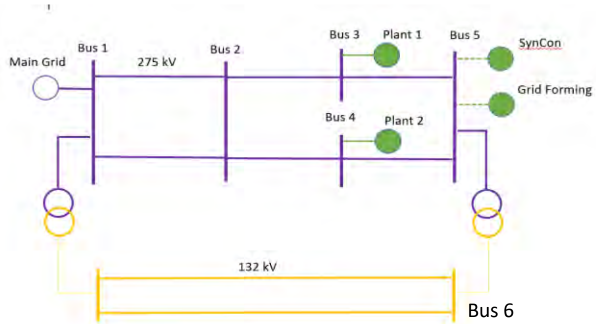
Simulation Results – Sub Synchronous Oscillations

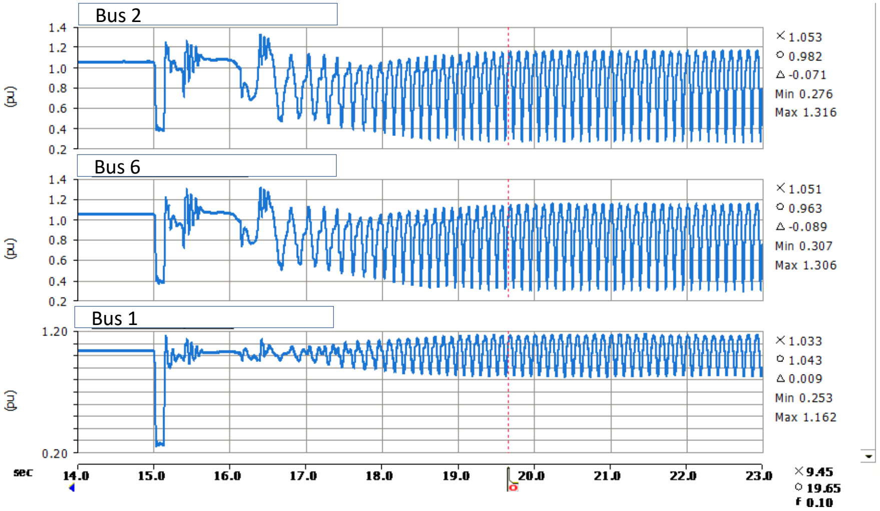
- With proper tuning of controller, a grid forming inverter can provide similar damping at half the size.



Simulation Results – Voltage and Transient Stability

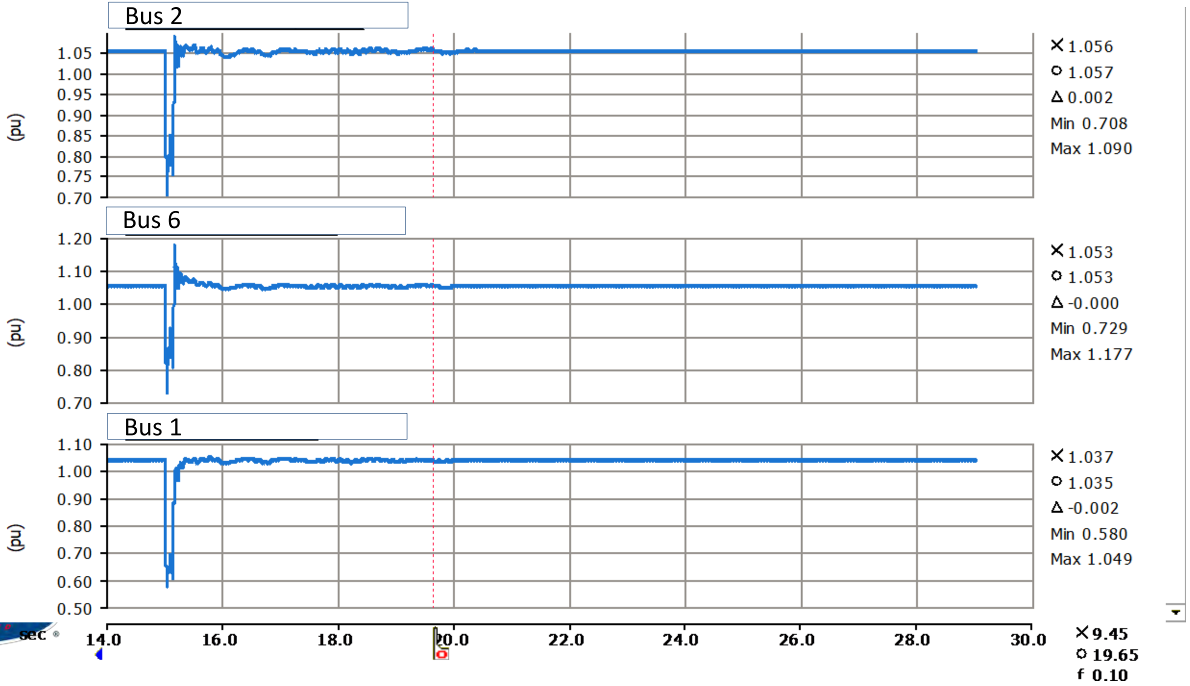
- Base Case
  - The system becomes unstable after tripping double 275kV lines, if both inverter based renewables are not tripped fast.
  - If the inverter based renewables' plant level voltage controller is too slow, the voltage becomes unstable during the inverter based renewable generators recovery after the fault.
  - Small synchronous generator is out of step.
  - To maintain system stability, it is required to reduce the inverter based renewable generators to at least to 80% before disturbance and trip both extremely fast after the fault.





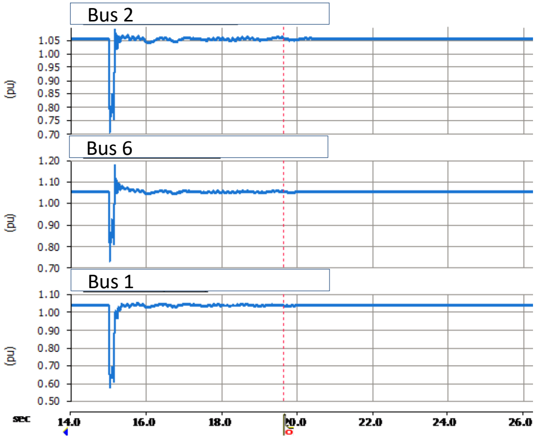
Simulation Results – Voltage and Transient Stability

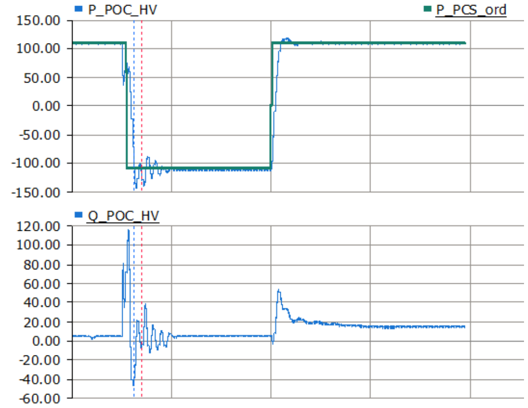
- With fast reactive power support from a synchronous condenser, the system is stable if one or more inverter based generators is tripped after the fault.



Simulation Results – Voltage and Transient Stability

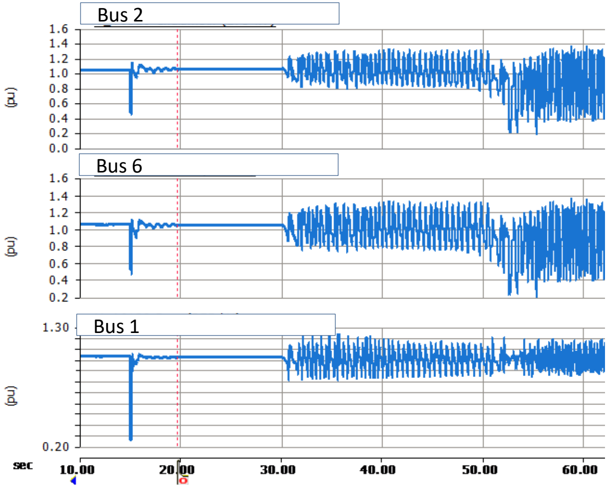
- Grid Forming Inverter with Battery Energy Storage System (BESS)
  - With a grid forming inverter BESS, there is no need to trip any inverter based renewable generators if the grid forming inverter BESS and inverter based renewable generators are co-ordinated.
  - The grid forming inverters provide fast reactive power support similar to a synchronous condenser.
  - The grid forming inverter BESS can change from discharging mode to charging mode after the fault, to give time for the inverter based renewable generators to ramp down instead of tripping, thus inverter based renewable generators can still provide slow voltage control for the grid.
  - Inverter based renewable generators ramp down to 50% with their maximum allowable ramp rate.

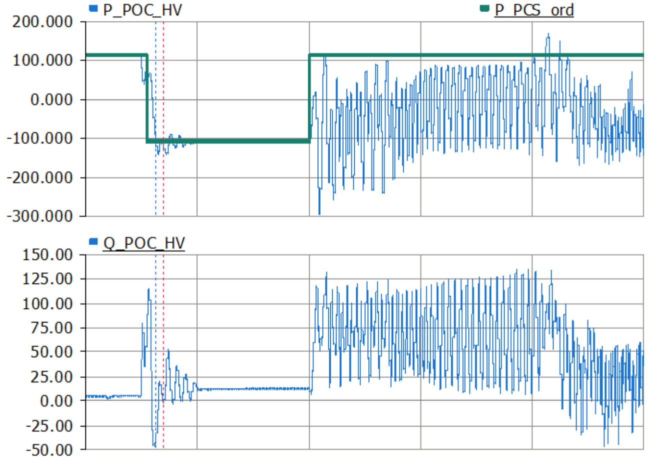




Simulation Results – Voltage and Transient Stability

- The system can still be unstable, if the grid forming inverter BESS is not co-ordinated well with inverter based renewable generators.
- For example, if the grid forming inverter BESS is ramped up before the inverter based generators are ramped down, the system could become unstable.





Challenges of Grid Forming Inverters

- Increased cost due to inverter oversizing and required BESS.
- Supplementary controller design and parameters require tuning for different grid conditions and to solve different grid challenges.
- To manage typical implementation of fault current limitation, either have to switch to a standby current control loop or clamp the current by hardware or software.
- May be prone to small signal instability.

Conclusions and Recommendations

- Grid forming batteries can play a very constructive role enabling renewables and supporting the operation of the power system.
- In this example, this study has shown that a 100MW battery can support the connection of 300MW of inverter based generation. Thus they are a welcome addition to the toolkit of possible responses.
- The thoughtful deployment of grid forming batteries alongside other technologies and techniques will be critical to managing the transition to renewables.
- Given the positive findings of the study, the logical next step is to install a Grid Forming Inverter with battery in a weak grid context in the NEM, and validate the results through field trials.

Questions and Thank you!

Synthetic inertia trial at the Hornsdale Power Reserve

27th May 2021

Key Project Stakeholders and Supporters

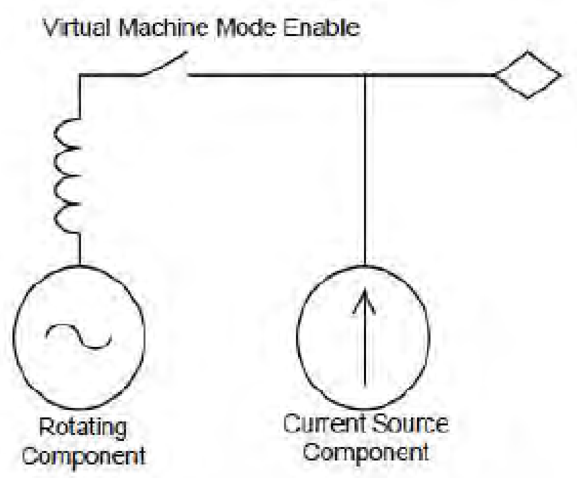
- Australian Renewable Energy Agency
- Government of South Australia
- Hornsdale Power Reserve Pty Ltd
- Neoen
- Tesla

1. Background
2. Traditional Inertia versus Synthetic Inertia
3. Modelling and Test Bed Results
4. Dual inverter trial (results and challenges)
5. Next Steps

Background

Virtual Machine Mode (VMM) / Synthetic Inertia

- VMM is a feature implemented on Tesla inverters that mimics the behaviour of a synchronous machine
- The virtual machine component runs in parallel with the conventional current source component as represented in the figure below.
- Under stable system conditions, the inverter's behaviour is driven by the current source component. The inverter charges and discharges in accordance with the real and reactive power commands received from the operator.
- If there is a grid disturbance, the rotating component responds by:
  - Producing an active power response proportional to the rate of change of frequency (ROCOF)
  - Producing a reactive current in response to changes in voltage



Traditional Inertia versus Synthetic Inertia

- The power exchange between the generator rotor and electrical grid due to the rotor acceleration and deceleration is called the inertial response.
- The inertial constant, “H” represents the ratio of the synchronous machine’s rotor inertia (kinetic energy) to the machine’s apparent power rating.
- Tesla inverters implement an inertial response synthetically via microprocessor-based control. This allows selection of inertial parameters to suit the grid conditions in which it is installed.
- The transient response to a grid disturbance for an inverter operating with VMM, compared with a synchronous machine with the same inertial constant, will differ primarily due to the typically lower overload rating of the inverter.
- Transient current will saturate at a lower value during the inverter’s response.
- Excluding saturation, the response shape will be very similar.
- This means that inverters could feasibly be set with much higher inertial constants than those typically observed for synchronous machines. The advantage being that it would facilitate a prolonged response to grid disturbances, without excessive overshoot.

Modelling and Test Bed Results

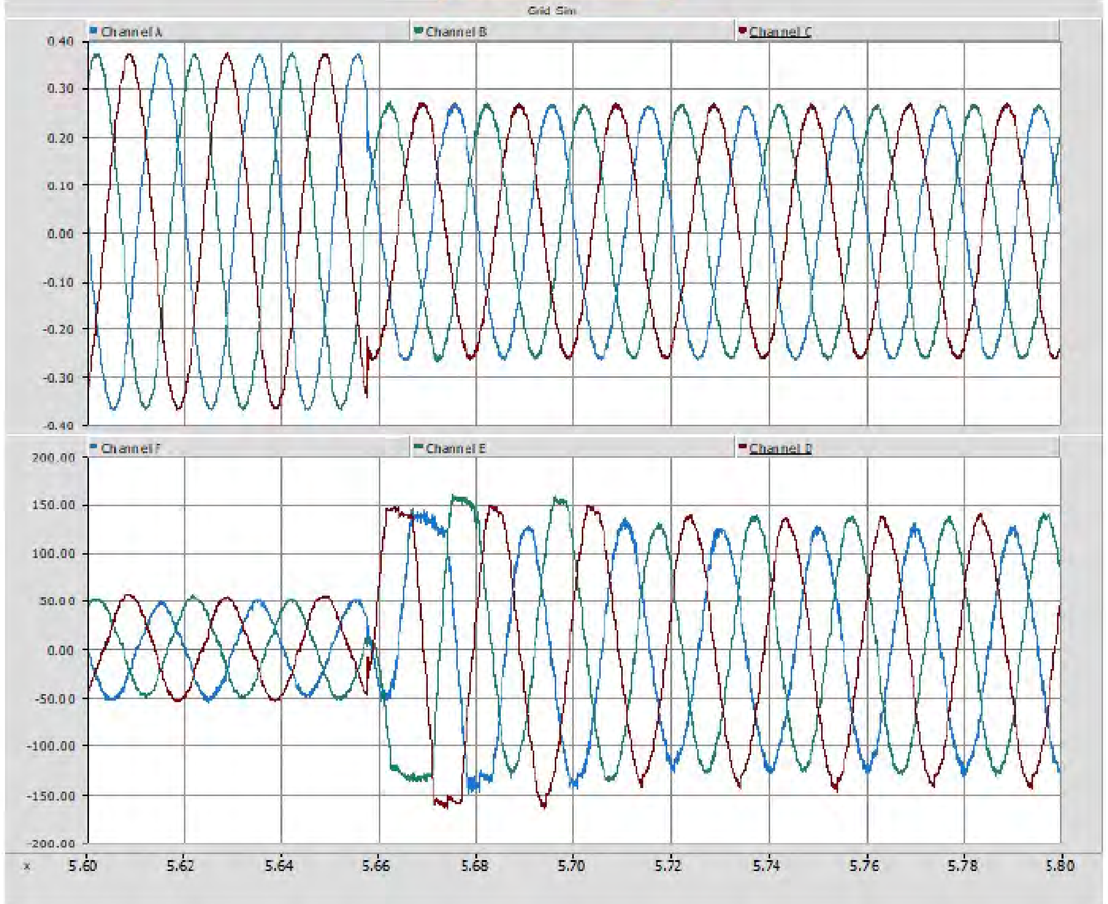
- PSCAD and GridSim Validation Testing was completed at Tesla's facilities.
- The aim was to verify that PSCAD VMM model is representative of actual operation, to give confidence that it will not pose a risk to site operation during two inverter trial at Hornsdale.
- A 90kVA Chroma Amplifier Grid Simulator located at a Tesla USA facility is utilized.
- The Grid Simulator (GridSim) is a full 4-quadrant AC power source that emulates characteristics of a stiff grid. The GridSim is set to nominal 415V, 50Hz. Voltage and frequency deviations are induced, and inverter response waveform captured via a PicoScope Oscilloscope. The PSCAD model is set up with a stiff grid source, to mimic GridSim operation.
- Numerous frequency and voltage tests were performed.

Modelling and Test Bed Results

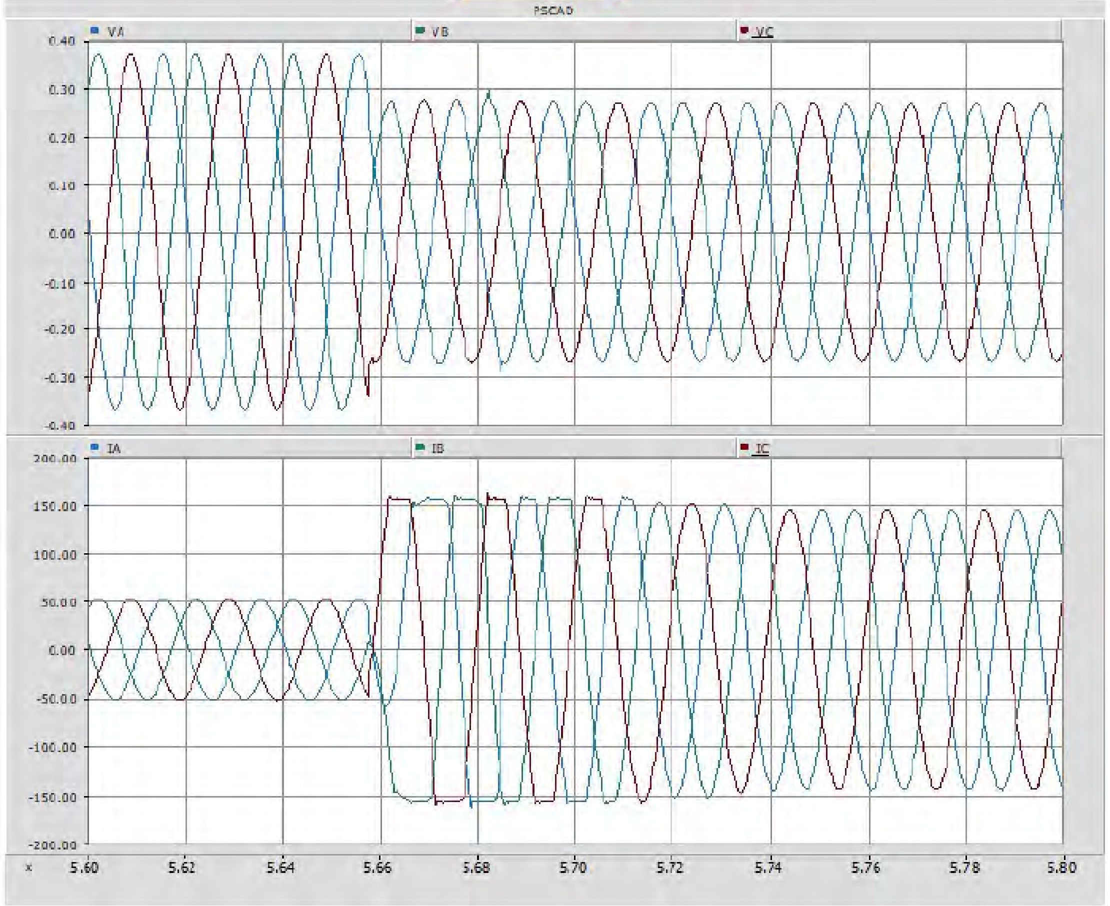
System Test vs PSCAD: VMM + F/W + Iq

Voltage Step – 0.7pu – start

System Test



PSCAD

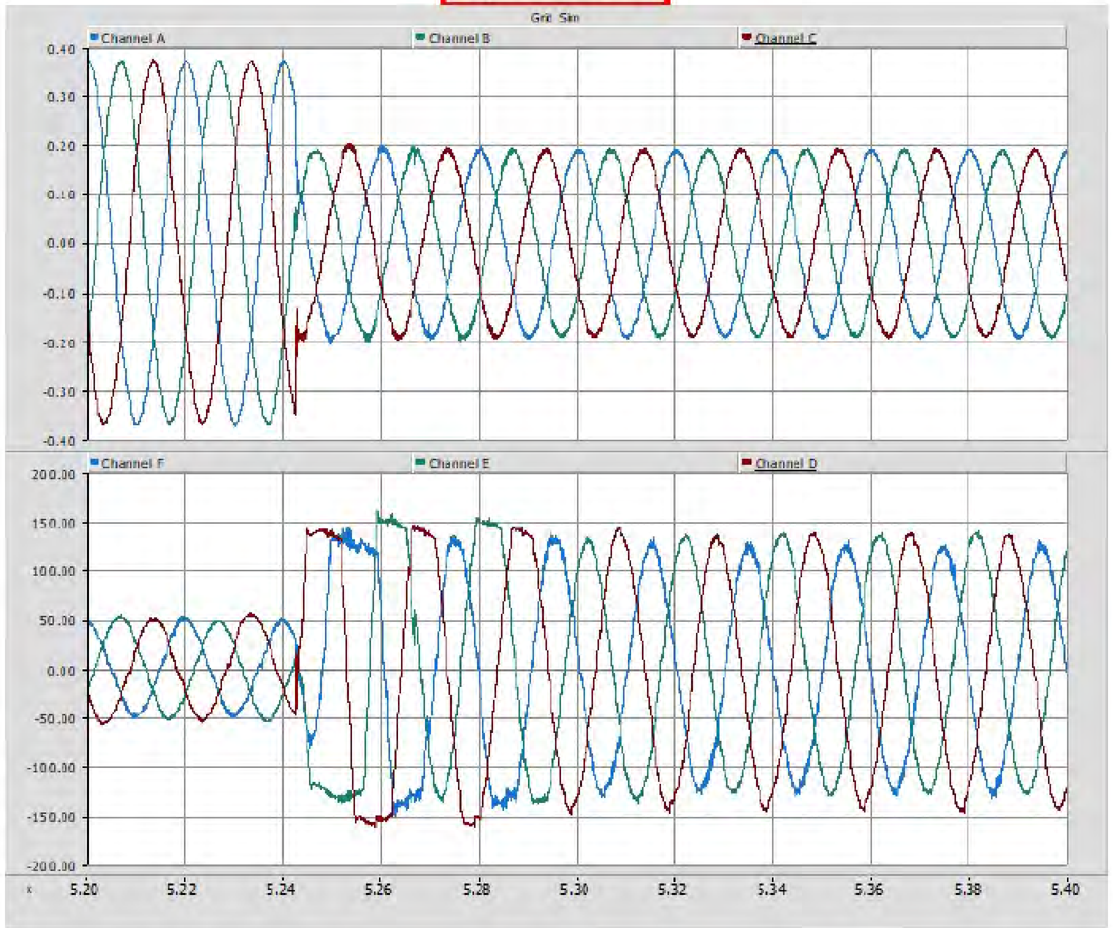


Modelling and Test Bed Results

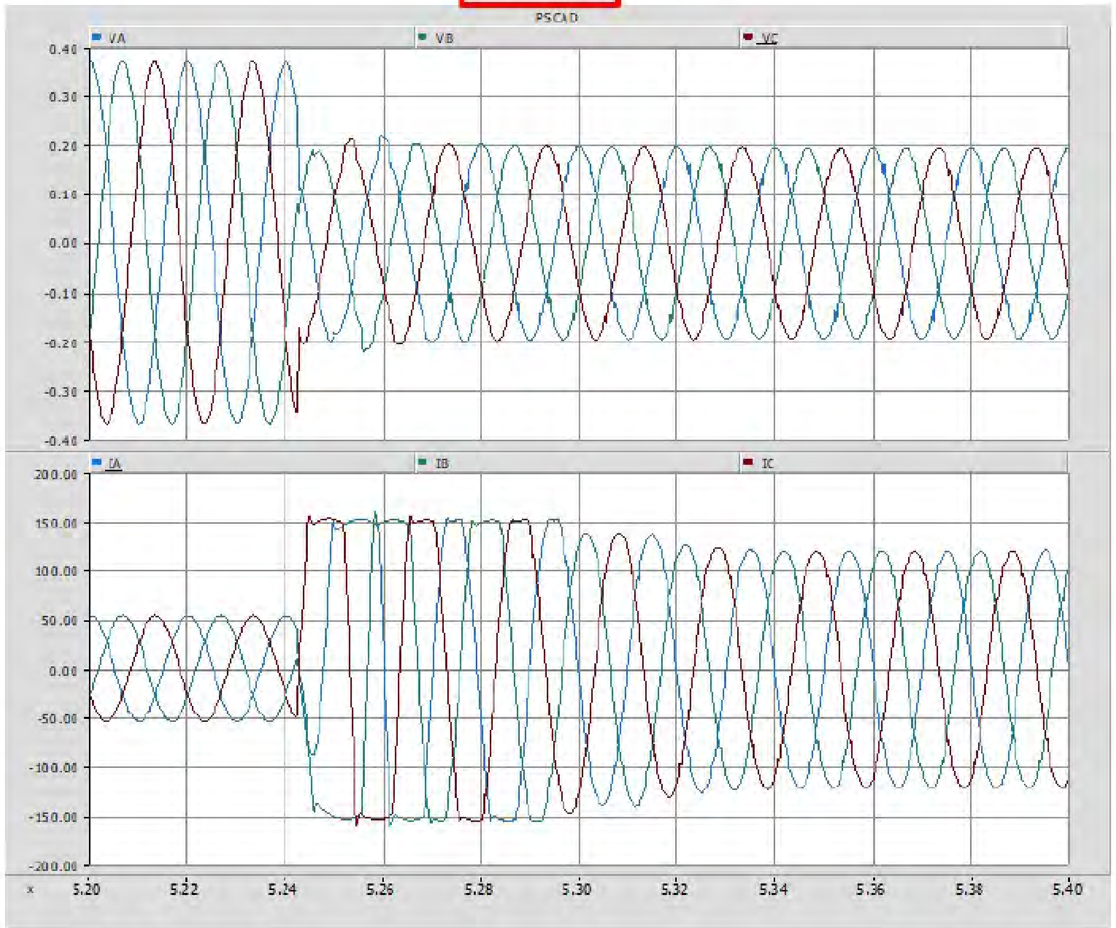
System Test vs PSCAD: VMM + F/W + Iq

Voltage Step – 0.5pu – start

System Test



PSCAD



Dual Inverter Trial

Seeking approval:

- Meetings with AEMO/ENET to work through remaining impediments for approval
- Submitted a test plan specific to the trial
- Provided VMM model to AEMO and updated RUG's
- Approval was granted on Friday 12/2/2021
- Software was implemented on Monday 15/02/2021

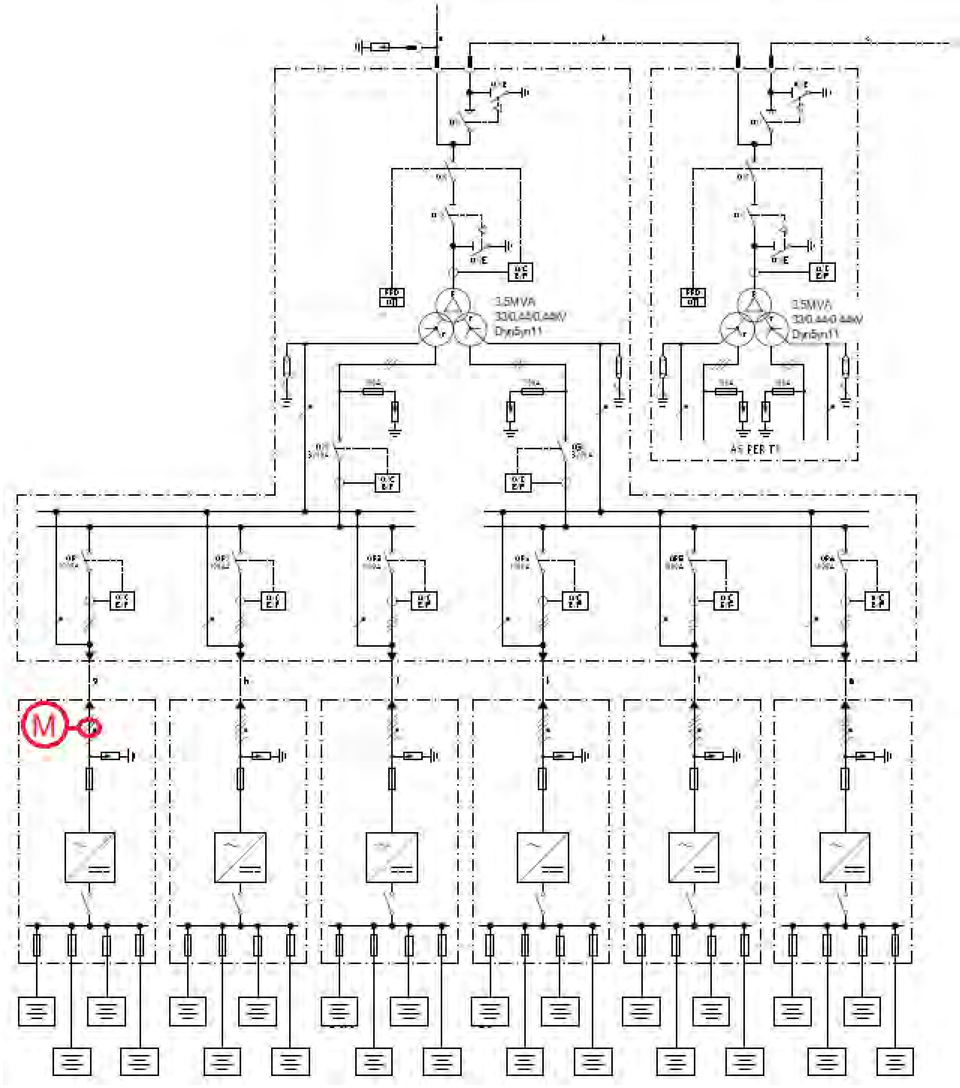
Inverter settings:

parameter	Existing HPRX Inverters	Trial Inverter #1	Trial Inverter #2
inertia_constant_H	NA	5	50
rotor_k_damp	NA	67.08	212
on_grid_machine_enable	0	1	1

Dual Inverter Trial

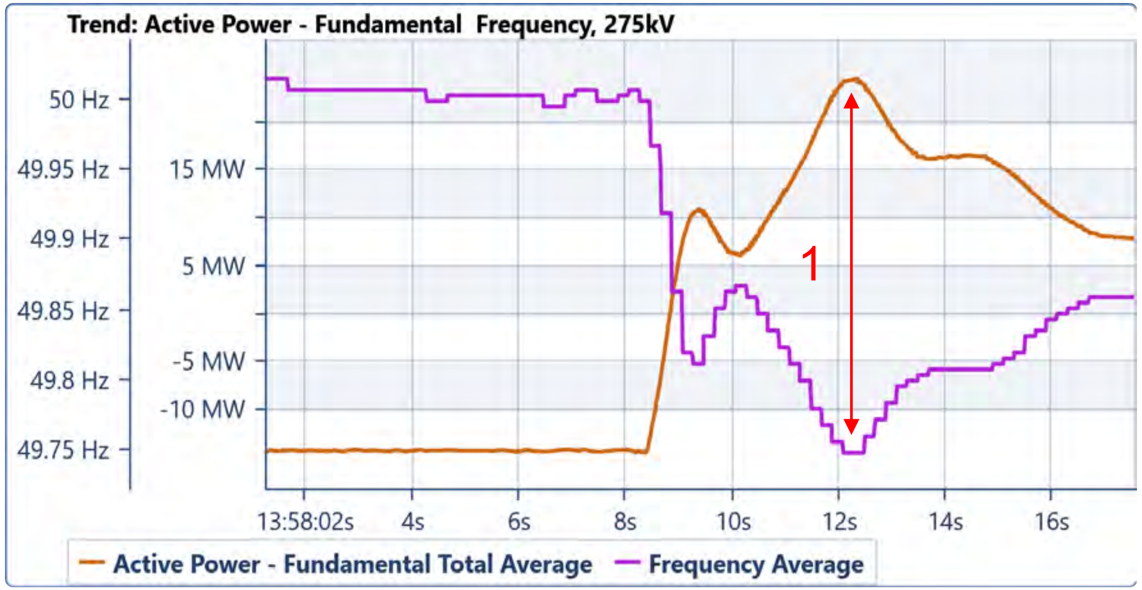
Results:

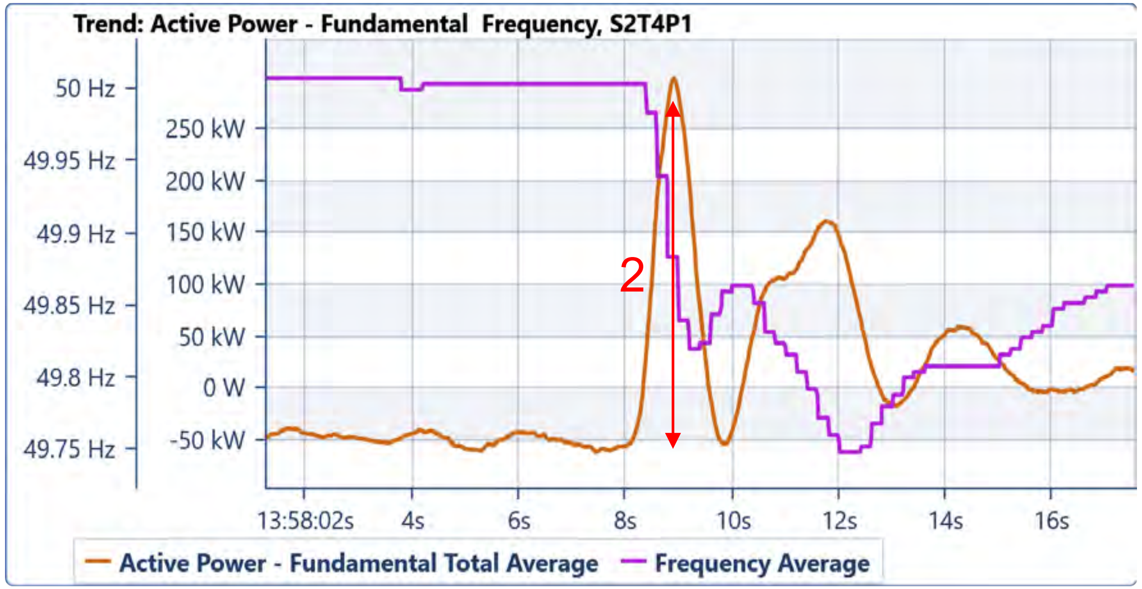
- Meter Manufacturer: Schweitzer Engineering Labs
- Meter Model: SEL-735 Power Quality and Revenue Meter
- Type of Monitoring: Event Triggering
- Event Recording:
  - 128 sample per cycle
  - 600 cycles event length
  - 50 cycle pre-fault length
- Additionally, one of the trial inverters had a permanent Elspec Power Quality Meter already installed



Dual Inverter Trial - Results

- VMM event captured 21/5/2021
- “H” Constant = 50
- Clear response of VMM responding to ROCOF





Site Response

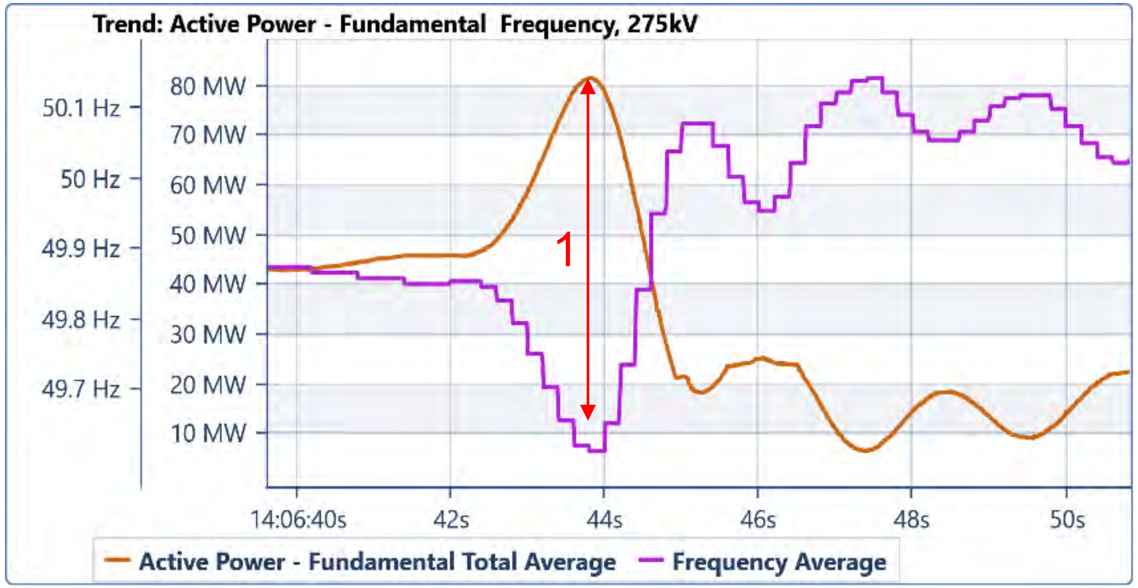
[1] Max active power response at max frequency deviation

VMM Enabled Inverter Response

[2] Max active power response at max RoCoF

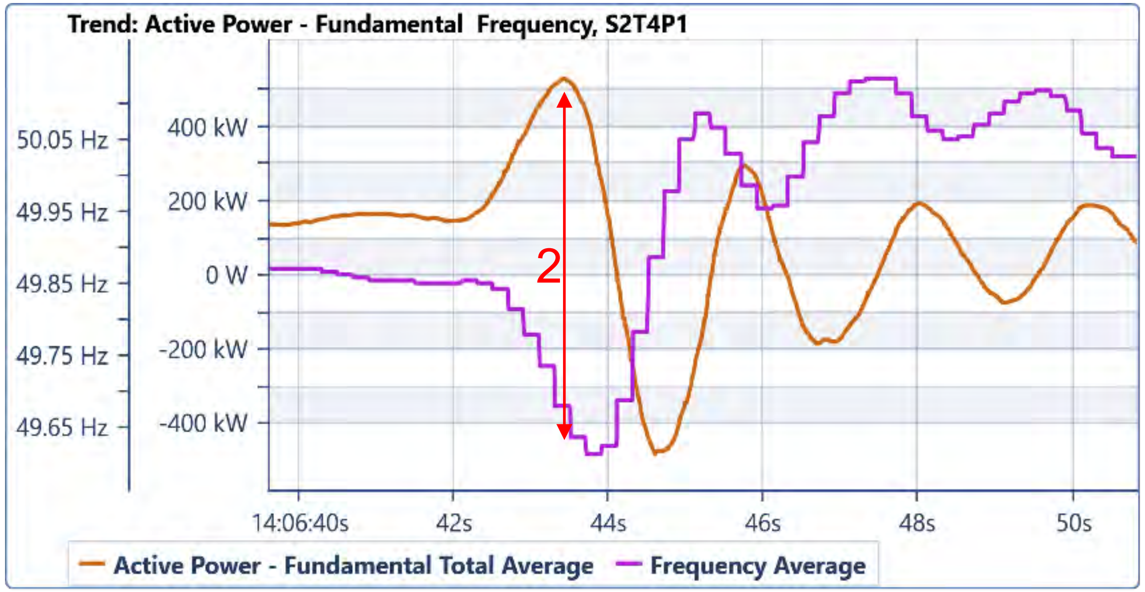
Dual Inverter Trial - Results

- VMM event captured 25/5/2021
- “H” Constant = 50
- Clear response of VMM responding to ROCOF



Site Response

[1] Max active power response at max frequency deviation



VMM Enabled Inverter Response

[2] Max active power response at max RoCoF

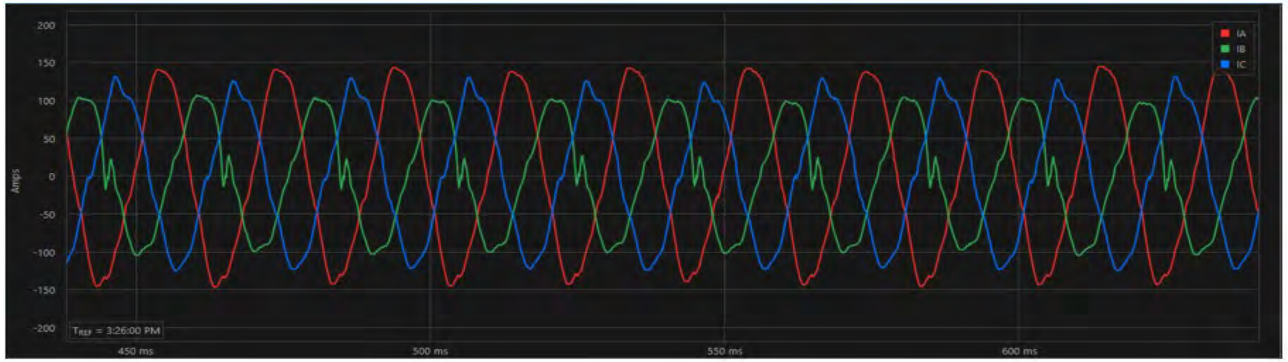
Dual Inverter Trial – Challenges

The dual inverter trial has faced numerous challenges

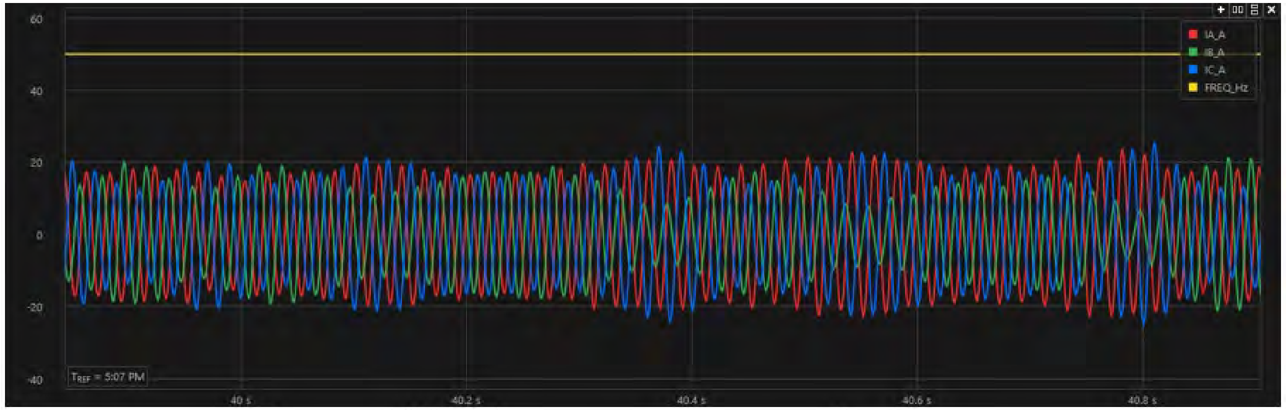
- SEL meters are set to trigger on high rate of change of frequency or current. The observed reality is that this method of triggering is not reliable. Either the settings are not sensitive enough, and events are missed, or settings are too sensitive, over triggering which results in filling up the data cache.
- A more robust event triggering system is in development. It utilizes internal Powerpack signal to recognize that VMM event has occurred and trigger event capture. This requires work from design and test validation team to understand latency. This work is currently in progress.
- The rationale behind this approach is to capture valuable real-world data and better support the benchmarking process, ultimately justifying the perseverance with the trial, as opposed to relying entirely on the US GridSim testing facility.

Dual Inverter Trial – Challenges

- Data manually captured from the trial inverters have revealed harmonics on the inverter's current waveform. This may be regular harmonic filtering, though one potential theory is that VMM operation is increasing the inverter's active harmonic filtering.



- Additionally, a ~5Hz envelope (frequency wobble) was also observed on the inverters output current waveform. The leading theory is that this is driven by the Sandia Frequency Shift (SFS) anti-islanding technique.



Dual Inverter Trial – Challenges

A test plan has been developed by Tesla to better understand the harmonic distortion and frequency wobble:

- Aim is to isolate the cause of the anomalies by conducting 3 tests:
  - Current settings
  - VMM disabled
  - VMM enabled, SFS off

- Procedure:
  - Command P = 250 kW and Q = 0 kVAR to each Trial Inverter (repeat for each test)
  - Run test with current settings
  - Disable VMM on Trial Inverters by changing ‘on_grid_machine_enable’ parameter to ‘0’ via grid code override and command P & Q
  - Re-enable VMM and disable SFS on Trial Inverters and command P & Q
  - Retrieve data and analyze results

- Testing will proceed in the very near future.

Next steps

Dual inverter trial:

- Complete test to understand harmonics and frequency wobble
- Finalize and implement new trigger methodology
- Continue to analyze Elspec data (frequency and voltage disturbances)
- Capture high-resolution data using SEL-735 meters
- Conclude trial and report findings

5.3.9:

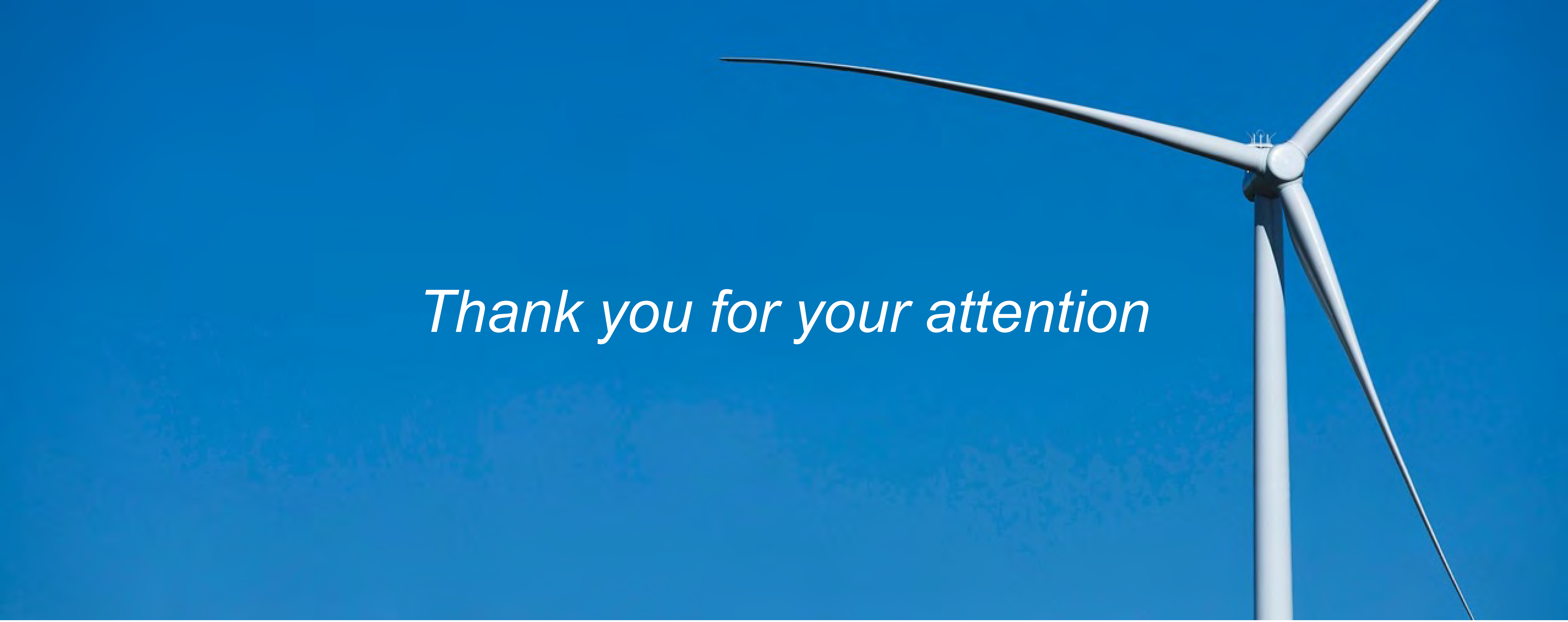
- Continue studies
- Engage with stakeholders to review preliminary results, settings, assumptions and ensure we are aligned
- Commence detailed studies
- Submission timing of package TBC (separate discussions underway)

Bench testing (GridSim):

- Prove trigger methodology
- Bench tests where there is no adequate events from inverter trial (discussions with AEMO/ENET to review trial results)

NEOEN

Questions?



NEOEN

ARGENTINA AUSTRALIA CROATIA ECUADOR EL SALVADOR FINLAND FRANCE IRELAND JAMAICA MEXICO MOZAMBIQUE PORTUGAL SWEDEN USA ZAMBIA

Stability enhancing measures for weak grids study

Dr Behrooz Bahrani

Senior Lecturer & Director of Grid Innovation Hub
Department of Electrical & Computer Systems Engineering
Monash University

Presentation outline

- ☐ **Project description**
- ☐ **Stability margin of grid following inverters (GFLIs)**
- ☐ **Grid Forming Inverter Control**
- ☐ **Grid forming inverter transient stability improvement**
- ☐ **SynCon Control and Allocation**
- ☐ **Next Steps**

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MONASH University
Power Engineering Advanced Research Laboratory [PEARL]

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Project Tasks & Timeframe

Monash University
Power Engineering Advanced Research Laboratory [PEARL]

Task1 - Grid Classification & Test-Bed

- ☐ Weak Grid Classification
- ☐ Quantification of Stability Conditions for Wind/Solar Farms
- ☐ Test-bed Development based on Northwestern Victorian Grid

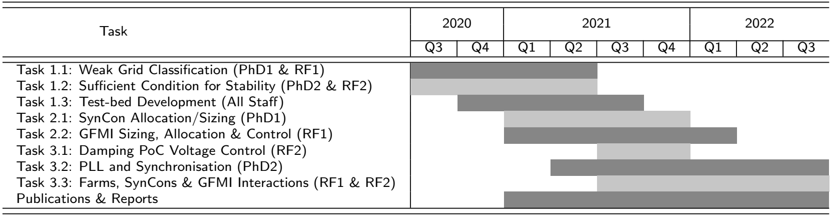
Task2 - Grid-Strengthening Solutions

- ☐ Synchronous Condensers: Allocation and Sizing
- ☐ Grid Forming Inverters: Control, Allocation, Sizing, and Black-start Capability

Task3 - Internal Controllers & Interactions

- ☐ Farm Voltage Control for Damping Northwestern Victoria Oscillations
- ☐ Farm Synchronisation with Weak Grids
- ☐ Interaction of Wind/Solar Farms, HVDC Converters, SynCons and Grid Forming Inverters

Two research fellows (RFs) for two year, funded by ARENA, and four PhD students, funded by Monash University, will be collaboratively working on this project as per timeline below.



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Grid-Following Inverters (GFLIs) in Weak Grids

- GFLI's dynamics are important in the stability.
- The main issue is coming form the synchronization unit (PLL).
- Both the grid and PLL must be considered in the stability analysis.
- A grid strength index considering both sides in required.
- Lyapunov direct method is employed to fulfill these requirements.

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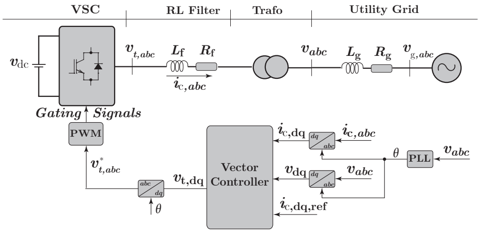

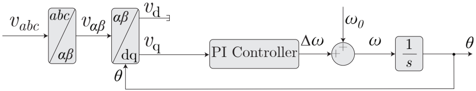

- A Laypunov function is proposed for the system.
- Using this function, a domain of attraction can be found for the system.
- The normalized radius of this domain of attraction is chosen as a grid strength index.
- This index is absolute, and hence, lets a comparison between to inverters in terms of stability.

Stability analysis of GFLIs

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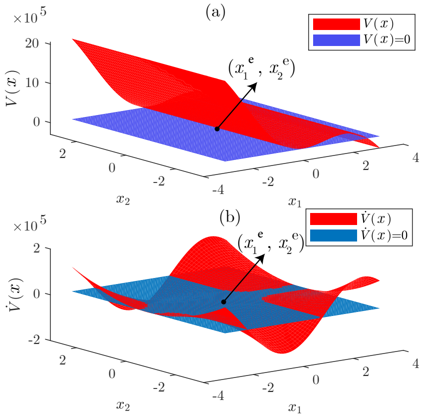

[1] M. Z. Mansour, S. P. Me, S. Hadavi, B. Badrazadeh, A. Karimi and B. Bahrani, "Nonlinear Transient Stability Analysis of Phased-Locked Loop Based Grid-Following Voltage Source Converters Using Lyapunov's Direct Method," in IEEE Journal of Emerging and Selected Topics in Power Electronics, doi: 10.1109/JESTPE.2021.3057639.

Stability margin improvement of GFLIs

- A compensator for the PLL is designed that extends the domain of attraction to the whole plane.
- Doing so results into a particularly robust system.
- Hence, the system works in very weak grids.
- Phase portrait of the conventional and compensated systems are shown for SCR$= 0.25$.

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Power Engineering Advanced Research Laboratory [PEARL]

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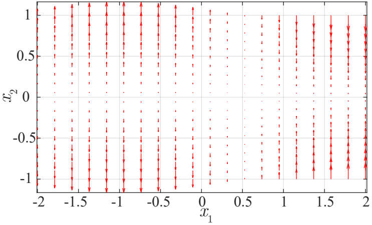
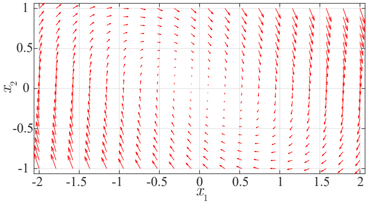




Presentation outline

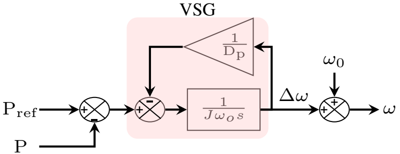
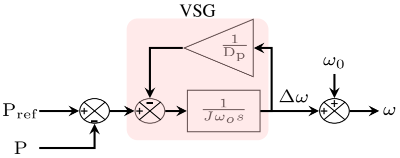


Figure 1: Virtual synchronous generator.

$$G_{\mathrm{cl,vsg}}(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2},$$

where $\omega_n = \sqrt{\mathrm{D_p k_g}/J\omega_0}$ and $\zeta = \sqrt{1/4\mathrm{D_p k_g}J\omega_0}$



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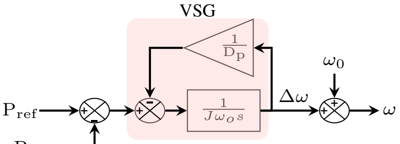
- Damping ratio and bandwidth both depend on $\mathrm{D_p}$ and J.



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- Damping ratio and bandwidth both depend on $\mathrm{D_p}$ and J.
- For a given $\mathrm{D_p}$ as J is reduced the overshoot is reduced and bandwidth is increased. Power references are tracked well.

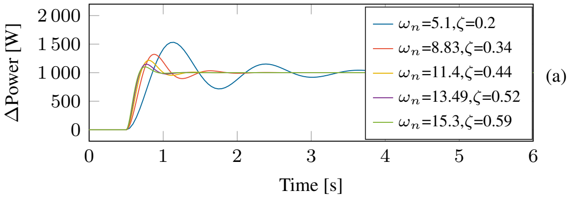
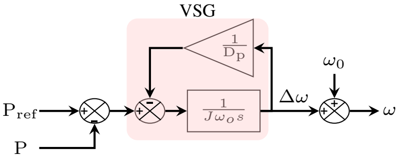


Figure 2: Power reference change in grid-connected mode.



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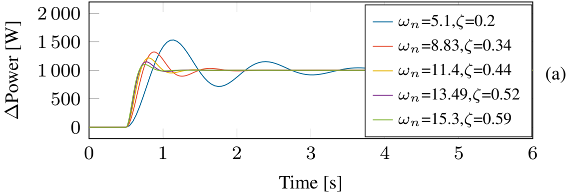
- Damping ratio and bandwidth both depend on D_p and J.
- For a given D_p as J is reduced the overshoot is reduced and bandwidth is increased. Power references are tracked well.
- However, this reduces virtual inertia provision and results in a very high initial RoCoF.



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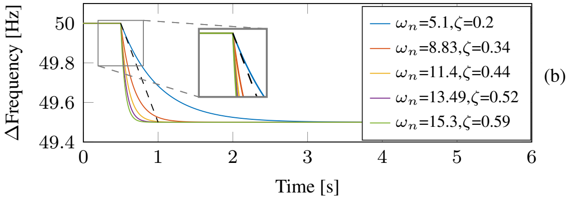


Figure 3: Frequency change in standalone mode.

Proposed $\mathcal{H}_\infty$-based controller

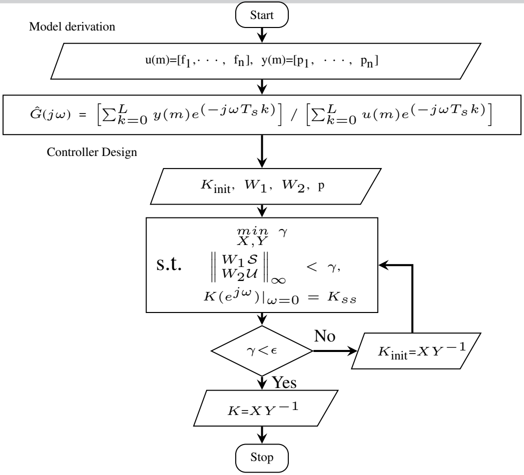
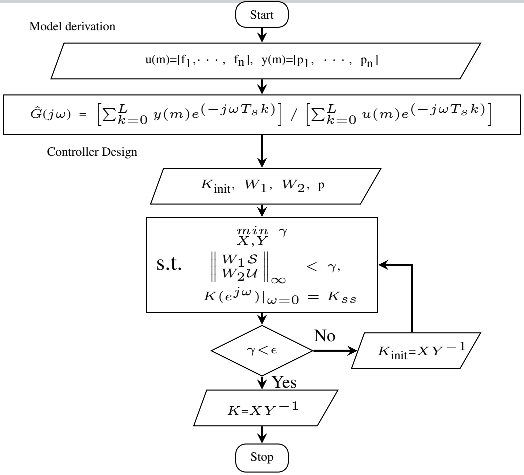


Figure 4: Proposed $\mathcal{H}_\infty$ control design.

Proposed $\mathcal{H}_\infty$-based controller



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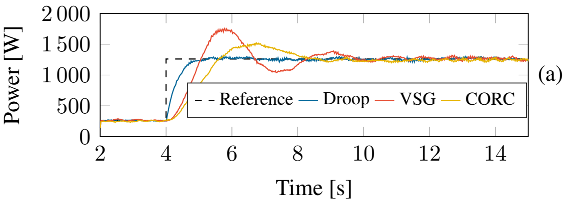
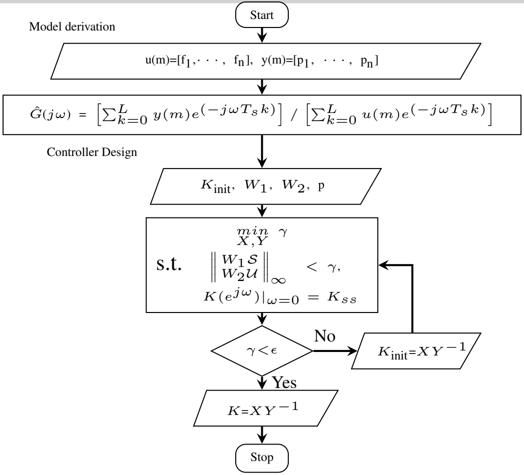


Figure 5: Power reference change in grid-connected mode.

Proposed $\mathcal{H}_\infty$-based controller



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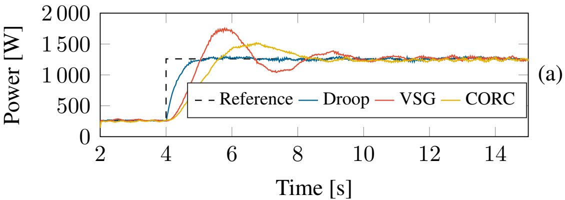

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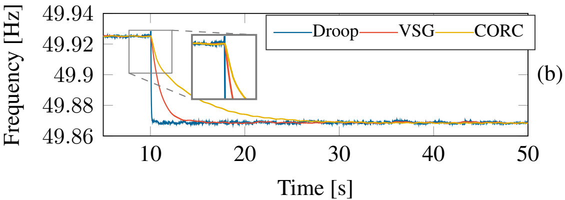


Figure 6: Frequency change in standalone mode.

- Since $\mathcal{H}_\infty$ and optimization-based methods are highly technical and difficult to implement an analytical approach is considered to tune the proposed controller.

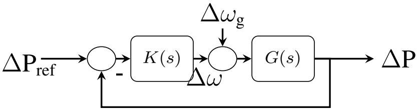
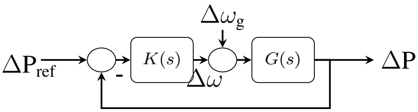


Figure 7: Control block diagram of the proposed controller.

$$K = \frac{D_p(as+1)}{(bs+1)(cs+1)}$$

Control design: analytical approach

- Since $\mathcal{H}_\infty$ and optimization-based methods are highly technical and difficult to implement an analytical approach is considered to tune the proposed controller.
- The RoCoF constraint in standalone mode is guaranteed by shaping the frequency response of the controller.



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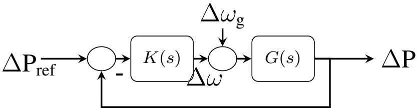
- The RoCoF constraint in standalone mode is guaranteed by shaping the frequency response of the controller.
- Accurate power reference tracking in grid-connected mode is achieved by shaping the open-loop frequency response.



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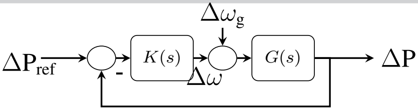
- The RoCoF constraint in standalone mode is guaranteed by shaping the frequency response of the controller.
- Accurate power reference tracking in grid-connected mode is achieved by shaping the open-loop frequency response.
- The overshoot is further minimized by designing a compensator.



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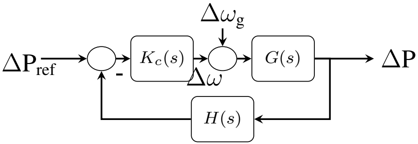

Figure 8: Control block diagram of the proposed controller with a compensator.

$$K_c = \frac{D_p}{(bs+1)(cs+1)}$$

$$H = (as+1)$$

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- ☐ Next Steps

Post-fault oscillations in weak grids

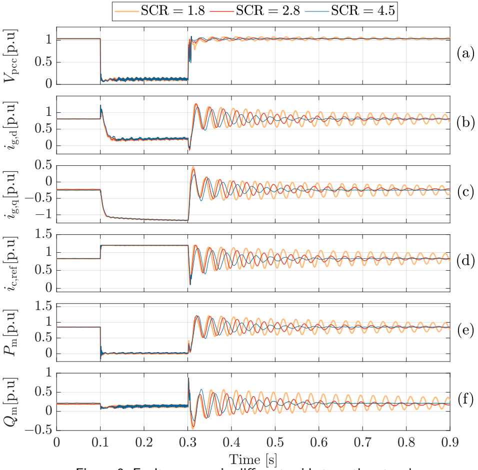


Figure 9: Fault recovery in different grid-strength networks

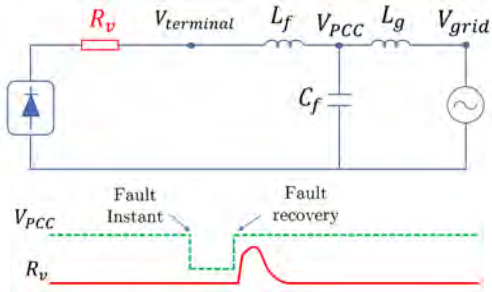
- Caused by:
  - Poorly-tuned controllers in cascaded loops.
  - Wind-up due to current limitation.
  - Weak grids.
- Result in unnecessary disconnections of GFMIs.

⇒ Virtual resistance (VR) can be used to dampen the post-fault oscillations.

- Post-fault oscillations are more severe in weak grids, hence requiring more VR to dampen the oscillations.

⇒ Oscillation magnitude can be used to determine how much VR should be integrated to dampen the post-fault oscillation.

Adaptive virtual resistance for post-fault oscillation damping



- A dynamic VR is only added in the fault-recovery process.
- Value of the VR is adaptive to the oscillation magnitude in different grid-strength networks to avoid degrading the fault recovery.
- Operation of the adaptive VR (AVR) is governed by a state machine.

Improvement brought by the AVR

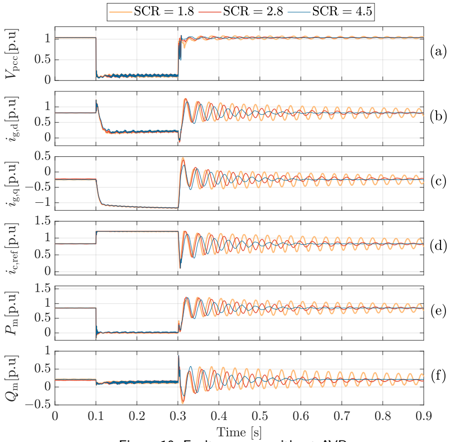


Figure 10: Fault recovery without AVR.

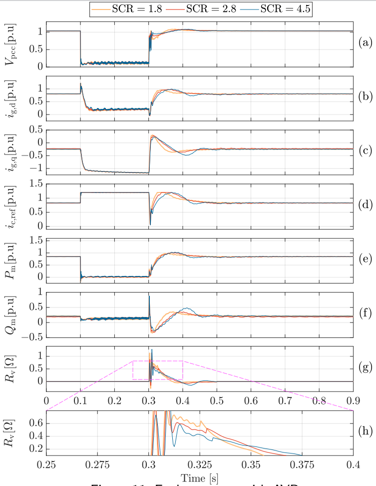


Figure 11: Fault recovery with AVR.

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MONASH University
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Synchronous Condenser (SynCon) is a synchronous machine without a prime mover.

Figure 12: https://new.siemens.com/

Advantages

- Contribution of short-circuit power
- Voltage support (exciter)
- Providing inertia

Drawbacks

- Installation/operation costs
- Lead-time

Overall Research Aim

- Utilizing SynCons for weak grid connection and their impacts on weak power systems dynamic in presence of wind and solar farms.
- Framework for analyzing interaction between wind and solar farms and SynCons.

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- Utilizing SynCons for weak grid connection and their impacts on weak power systems dynamic in presence of wind and solar farms.
- Framework for analyzing interaction between wind and solar farms and SynCons.

Research Questions

- How to install SynCons?
- What is the imapct of SynCons exciter controller?
- How to analyse the interaction between farms and Syncons?

Optimal Allocation and Sizing of SynCons

- Using heuristic algorithm:
  - Link with the simulation software
  - It does not give the best result sets
- Using convex optimization:
  - Difficult to formulate
  - Give the global optimal results

Designing an Exciter

- Apply identification method to identify a system
- Apply the H_∞ robust controller design
- Design an exciter to stabilize a weak system

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Next Steps

In the next few months, we will focus on:

- Optimal allocation of grid forming inverters
- Transient stability of grid forming inverters
- Interaction analysis of inverter-based resources based on impedance-based analysis
- Alternative, PLL-less grid following inverters

For updates and more details, please visit our website:
https://www.monash.edu/energy-institute/grid-innovation-hub/home/stability-enhancing-project

Questions

TransGrid

Wallgrove Grid Battery Project

Presenting to ARENA Insights Webinar: Advanced Inverters

May 2021

Energy Transition Challenges

NSW system inertia (typical) reduction due to synchronous generator retirement

- Over 30% of the coal-fired generation capacity in NSW scheduled to retire over the next decade.
- Emerging energy security and power system security issues.
- Power system security challenges come in the form of both system strength and inertia.
- Declining inertia in NSW and the NEM as coal generators retire.

Battery Storage as a Solution

- TNSP's have the responsibility under the NER to source solutions for inertia at the time AEMO declares an inertia gap in the region.
- TransGrid is investigating emerging technologies to meet these challenges.
- Compared to traditional technologies, batteries offer significant cost saving for customers.
- Pilot projects demonstrating both technical and contracting requirements will ensure least cost solution for customers.

	Capital Cost Projections	
Inertia Retired from System	Batteries	Synchronous Condensers
Liddell (6500 MWs)	<$100m ✔	$200-300m
Liddell & Vales Point (11,500 MWs)	<$200m ✔	$500-600m

TransGrid

Wallgrove Grid Battery: Objectives

Installation of a 50MW / 75MWh Battery Energy Storage System (BESS)

- Joint funding from ARENA and NSW government
- To provide fast frequency response (FFR) and synthetic inertia services to NSW
- Demonstrates the scale-efficient technical solution and future contractual requirements

Supporting technical innovation

> Improved understanding of the ability of batteries to address an emerging inertia gap with transferable learnings across the NEM.

Pathway to commercialisation

> Utilising batteries for both network and market uses offers a pathway to commercialising the technology through multiple revenue sources where applications are complementary.

Supporting power system modeling for BESS

> This will be the first grid scale battery in NSW and will provide TransGrid's planning team with better data to support future battery projects connecting to the NSW network.

TransGrid

Wallgrove Grid Battery: Overview

- Nameplate capacity 50MW / 75MWh.
- Connected to the 132 kV bus at TransGrid's Wallgrove substation in Western Sydney.
- Designed and constructed by Tesla using 36 Tesla Megapack units.
- Synthetic inertia capabilities can be enabled using Tesla's Virtual Machine Mode (VMM)
- TransGrid is appointing a market intermediary – Infigen – who will undertake all market functions.

Indicative image of Tesla battery pack (Source: Tesla)

TransGrid

Tesla Virtual Machine Mode (VMM)

- The synthetic inertia capability of the Tesla battery inverters can be enabled using Tesla's Virtual Machine Mode (VMM).
- Tesla inverters with VMM are capable of emulating dynamics of a rotating machine.
- As the VMM inertial response is governed by software, its parameters such as the inertia constant are configurable based on grid requirements.
- For the Wallgrove BESS, VMM will be enabled as part of the Stage 2 of this project.

TransGrid

Project Timeline

October 2020
Contracts signed

March 2021
Design completion

May 2021
AEMO 5.3.4A
5.3.7g issued

July 2021
Delivery of major equipment

Aug – Sept 2021
Registration, compliance and performance tests

October 2021
Full operation in grid following mode (Stage 1)

~ Nov – Dec 2021
Tesla's Virtual Machine Mode tested and enabled (Stage 2)

Battery deployment

Proposed Testing Methodology - Summary

Key Testing Plan Objectives

Objective 1: To test the hypothesis that a BESS can provide a useful inertia service to the power system

Objective 2: To demonstrate the above whilst the BESS is in normal commercial operation

On-going performance monitoring, and analysis, over and above the normal generator connection and commissioning process:

- Wait for a “trigger event”
  - Loss of single large generator (or multiple small generators)
  - Loss of large load
  - System separation
- Measure the Wallgrove BESS response
- Capture network data at the time of the trigger event
- Replicate network model at time of trigger event, simulate BESS response operating in VMM
- Compare modelled response with actual BESS VMM response

Thank You

Malithi Gunawardana, Network Planning and Operations
May 2021