Grid Forming Energy Storage: Provides Virtual Inertia, Interconnects Renewables and Unlocks Revenue

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POWERING GOOD FOR SUSTAINABLE ENERGY

2020-07-06

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This meeting will be recorded and made available.

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Do not put yourself or others at risk by attending a meeting – even in listen-only mode – while driving. **If you are driving, please drop off the meeting now.**

Outline

1. Introduction
2. Converter Technology
3. Case Study – ESCRI Dalrymple Grid Forming BESS
4. Virtual Inertia vs Fast Frequency Response
5. Real World Results
6. Supporting Renewable Interconnections
7. Economics & Commercial Models
8. Key Takeaways

The presenters

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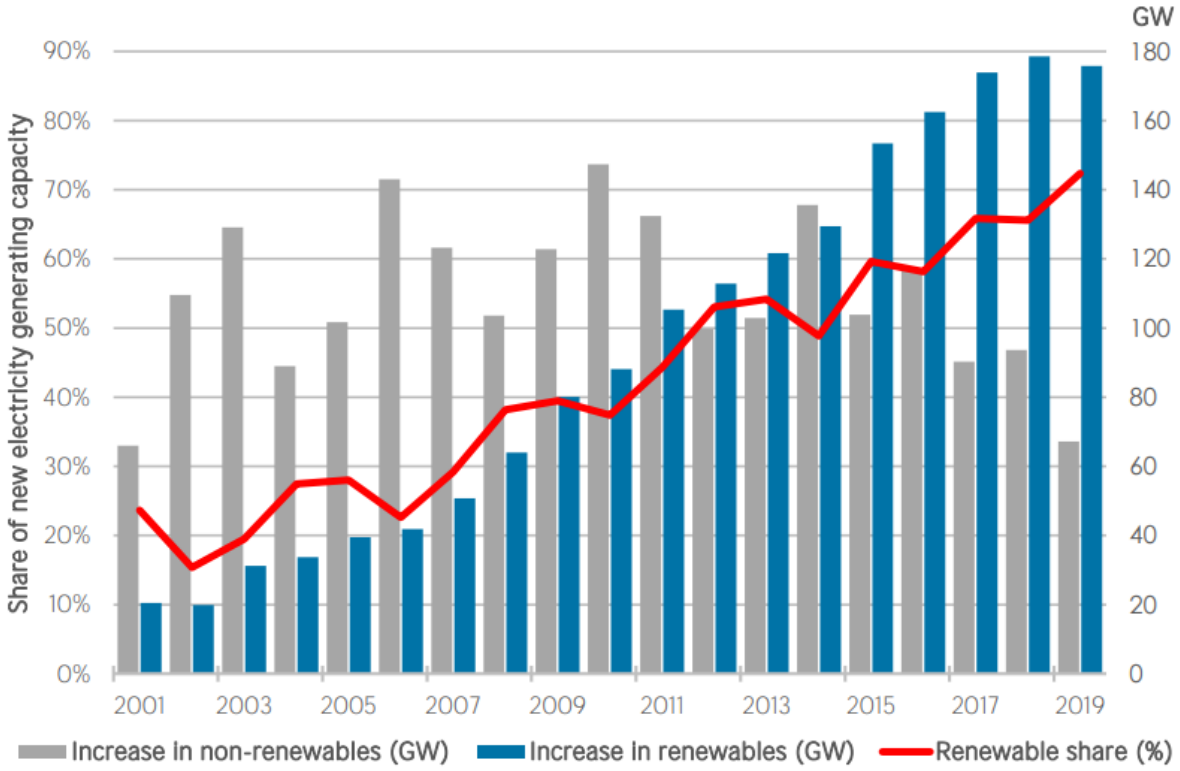
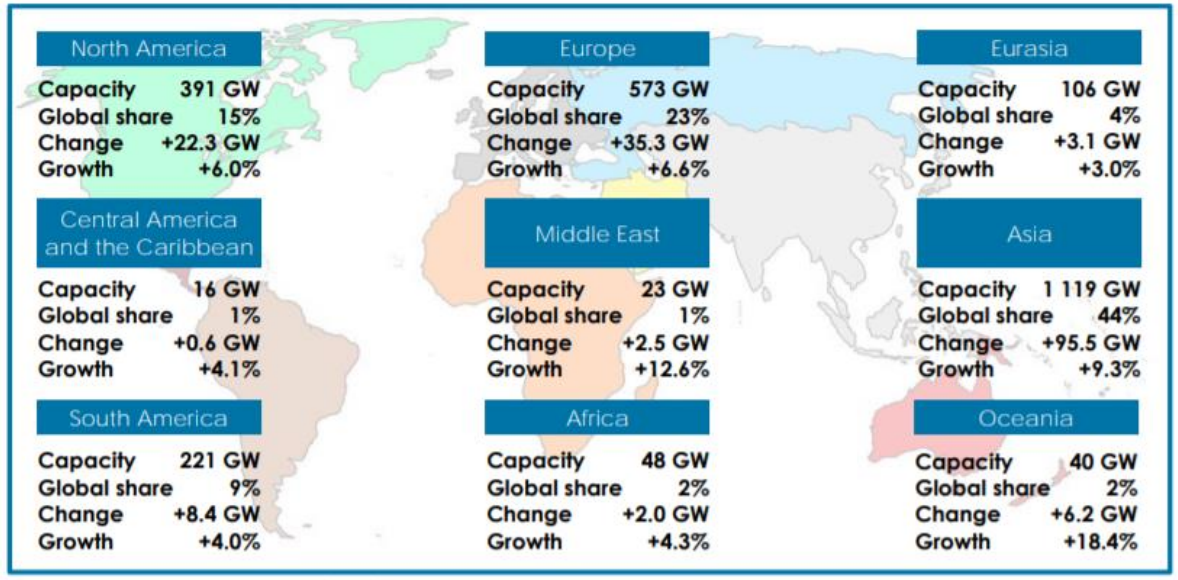
Introduction

The changing power system

Globally, almost 75% of new electricity capacity was renewable in 2019

New global capacity additions over the past two decades; 90% of this is solar and wind





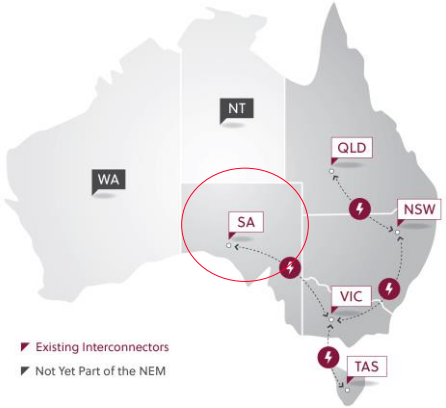
Source: IRENA, Renewable Capacity Statistics 2020, https://www.irena.org/publications/2020/Mar/Renewable-Capacity-Statistics-2020

South Australia – a view to the future compared to other major power systems

A comparison to other high penetration major power systems

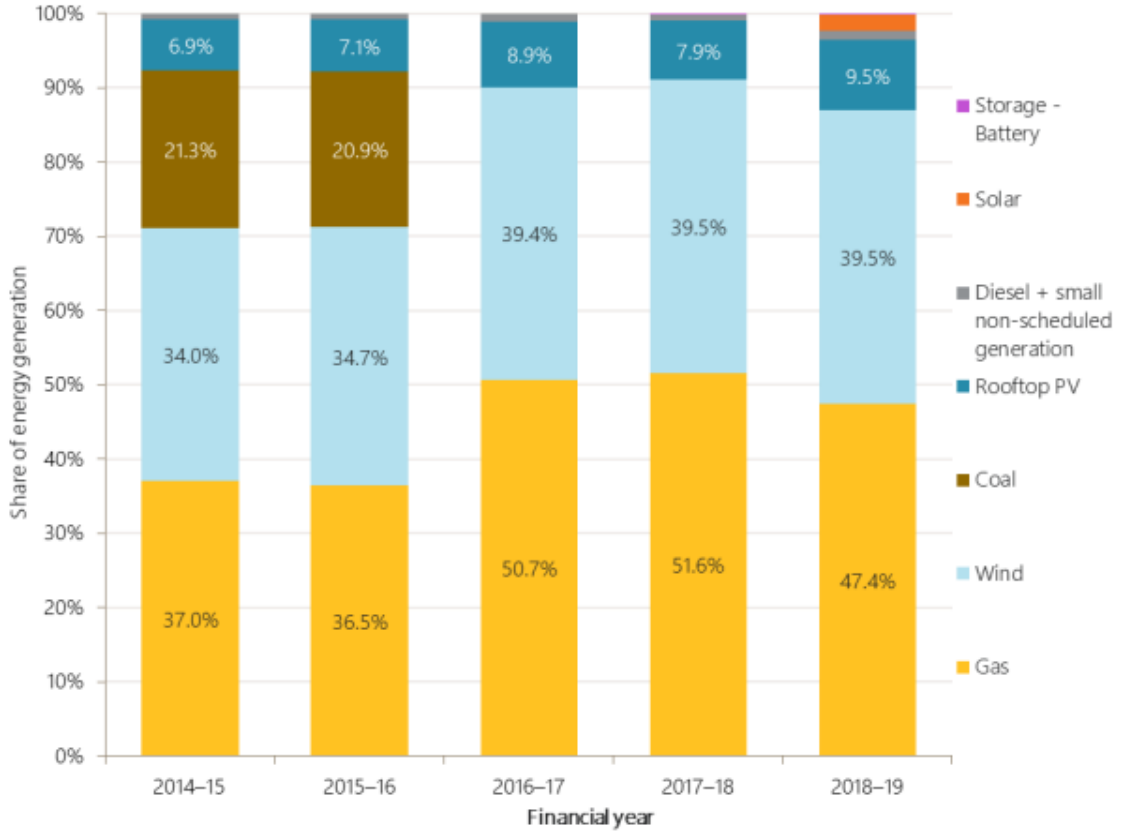
High penetration of non-synchronous generation

- Similar renewable penetration trends are observed worldwide
- However, South Australia is in a unique position:
  - Ireland: imposes a maximum penetration limit to non-synchronous generation (65% since 2017)
  - Texas: relatively low non-synchronous generation compared to load (54% peak in 2017)
  - Denmark: has strong interconnections to nearby countries
- South Australia has had instantaneous wind penetration of 170% (generation/load)
- South Australia has experienced periods with insufficient synchronous generation online
- Number of synchronous generators in decline, as are inertia and system strength



Generation mix in South Australia 2014 - 2019

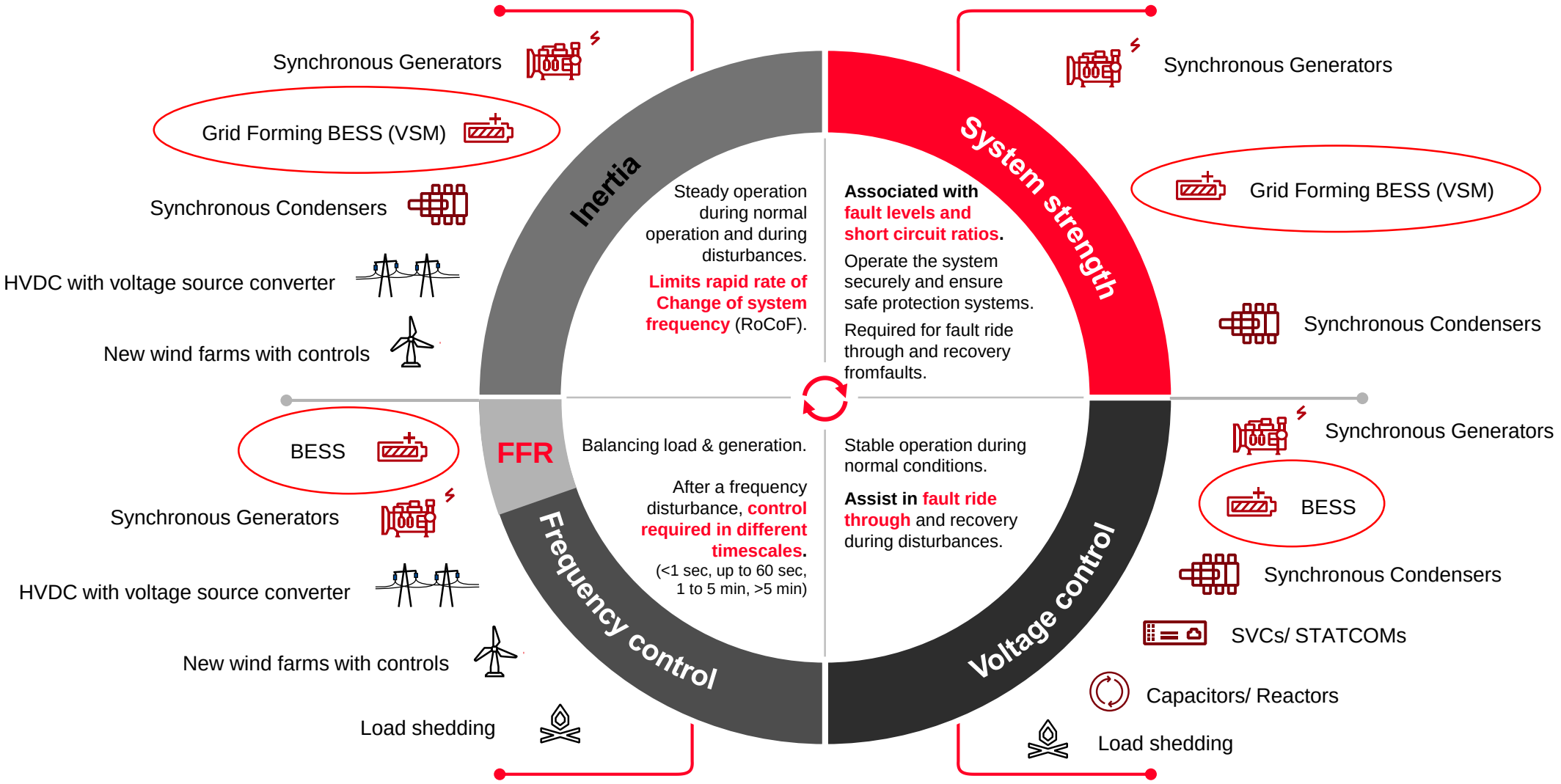
Figure 15 South Australian energy generation by fuel type



Sources: AEMO, ERCOT

What services are required to operate a stable and secure grid?

Ancillary services required in an “energy only” market for a viable electricity system



Source: www.escri-sa.com.au, adapted BESS = Battery Energy Storage System VSM = Virtual Synchronous Machine

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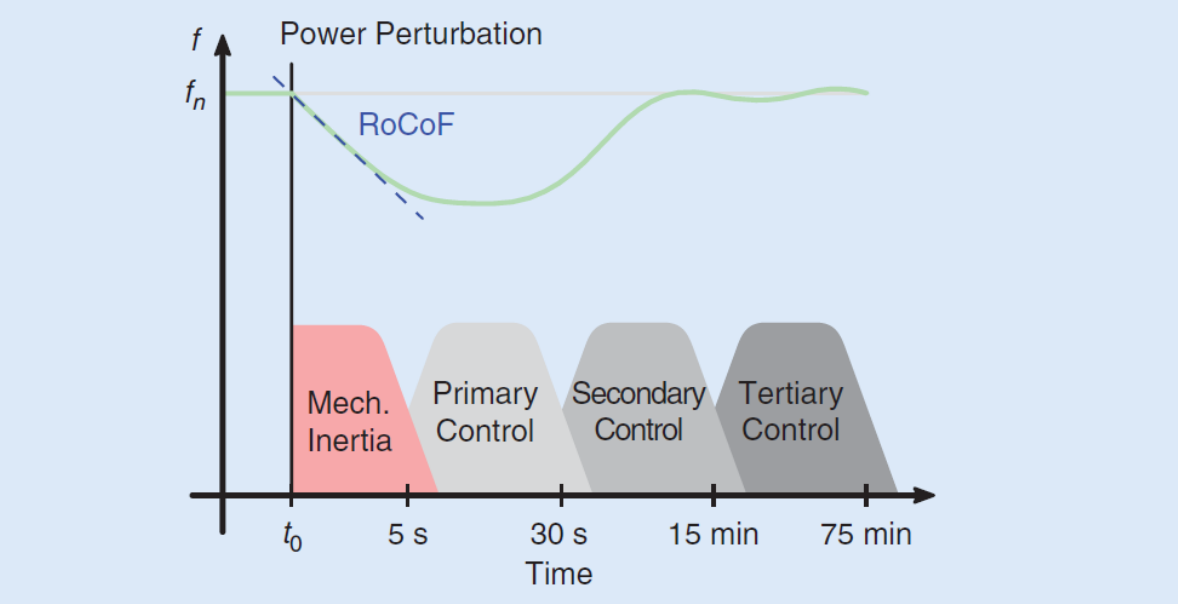
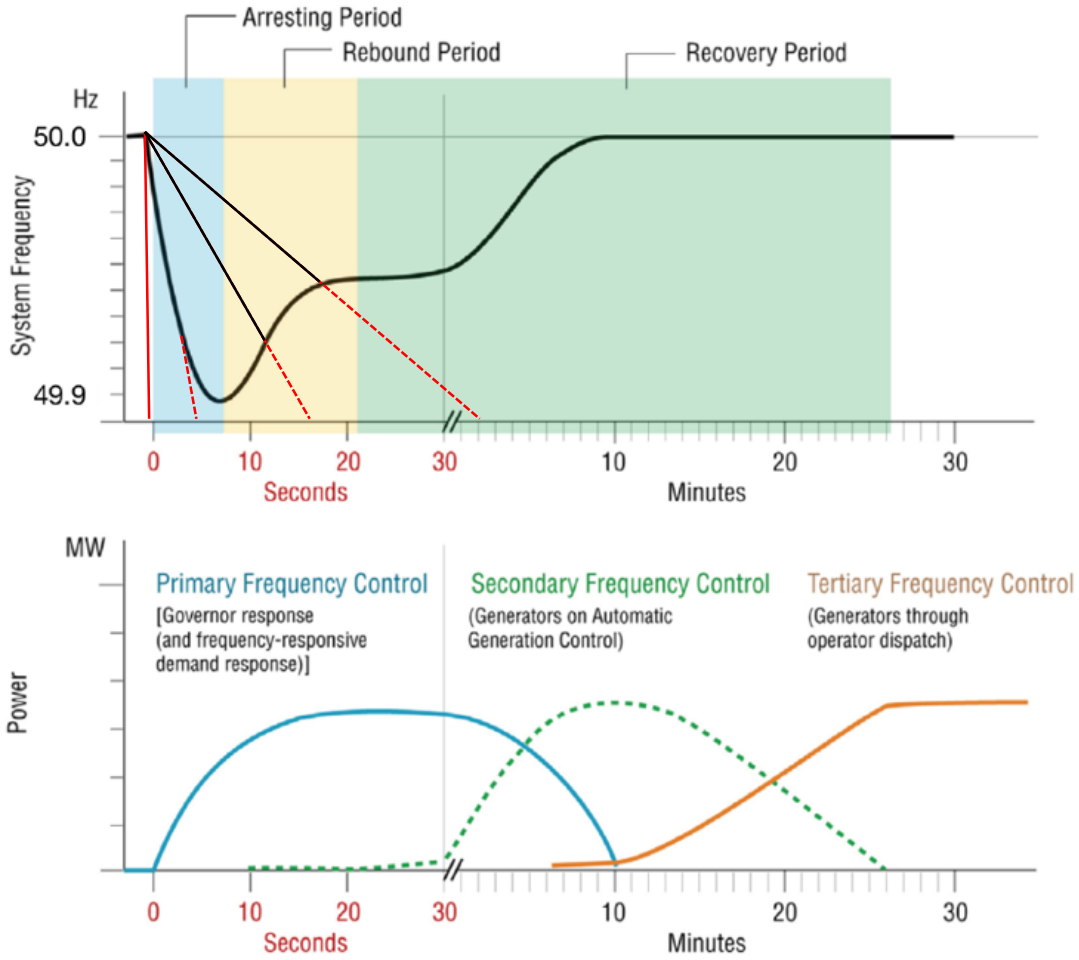
What is inertia?

Capability of the power system to resist changes in frequency by means of an inertial response from a generating unit, network element or other equipment that is electro-magnetically coupled with the power system and synchronised to the frequency of the power system.

*Inertial response from synchronous generators is **inherent**, **uncontrolled**, and independent of output level.*





Source: E. Unamuno, J. Paniagua, J.A. Barrena "Unified Virtual Inertia for ac and dc Microgrids. And the role of interlinking converters.", IEEE Electrification Magazine, December 2019
Source: CAISO, Source: NER , Source: https://www.nrel.gov/docs/fy20osti/73856.pdf

What is system strength?

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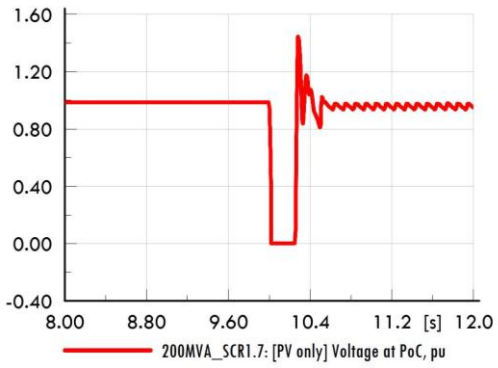
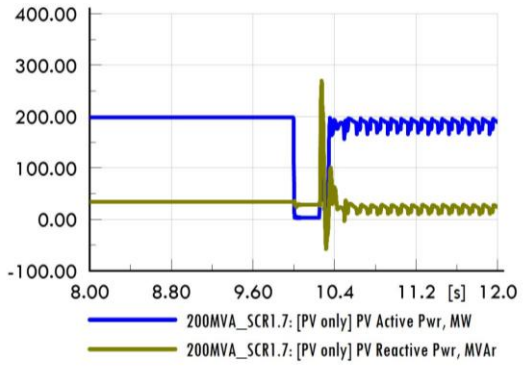
Definition

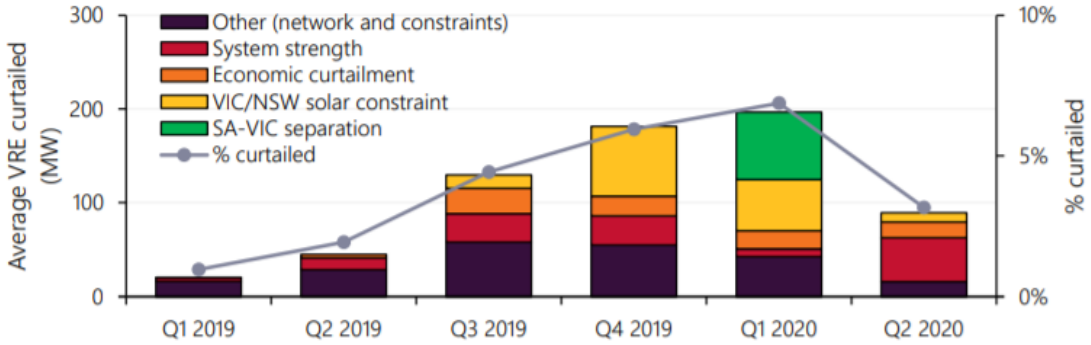
"System strength is the ability of the power system to maintain the voltage waveform at any given location, with or without a disturbance."

- High fault levels = high system strength
- Short Circuit Ratio (SCR) associated with system strength
- Phase Lock Loop (PLL) of grid following plants require high system strength for stable operation
- PV plants may not recover post fault on low SCR network; oscillatory behavior post fault
- Fast response doesn't cut it, needs to provide fault current and inertia (high inverter overload important)

Lack of system strength prevents interconnection and increases renewable curtailment







Grid Forming inverters do not need a PLL – they generate their own waveform

Source: https://aemo.com.au/-/media/files/electricity/nem/system-strength-explained.pdf?la=en, https://aemo.com.au/-/media/files/major-publications/qed/2020/qed-q2-2020.pdf?la=en&hash=D1A82334D16E915FCB1B628640A05223
Source: https://aemo.com.au/-/media/files/major-publications/qed/2020/qed-q2-2020.pdf?la=en&hash=D1A82334D16E915FCB1B628640A05223

Converter Technology

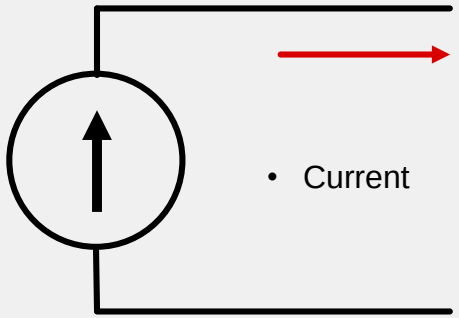
Grid Following, Grid Forming & Virtual Synchronous Machines

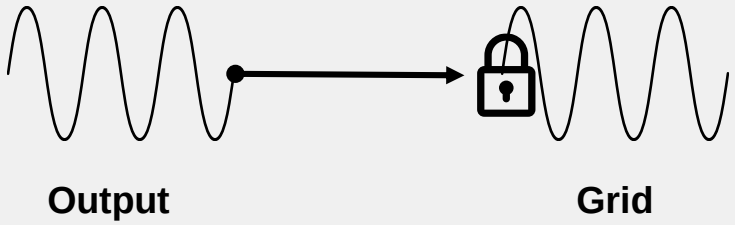
Converter technology

Grid Following, Grid Forming and Virtual Synchronous Machine

Grid Following - CSI

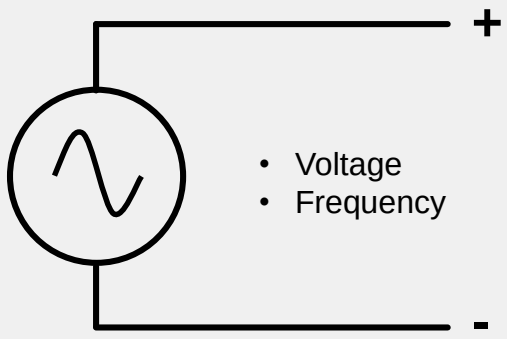
Current Source Inverter

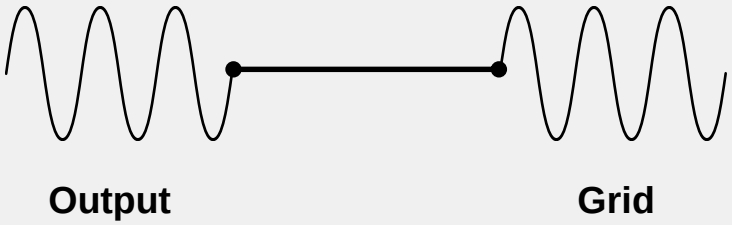




Grid Forming - VSI

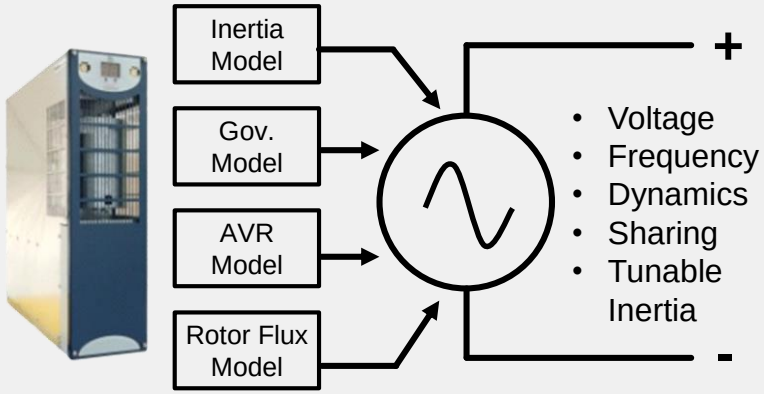
Voltage Source Inverter

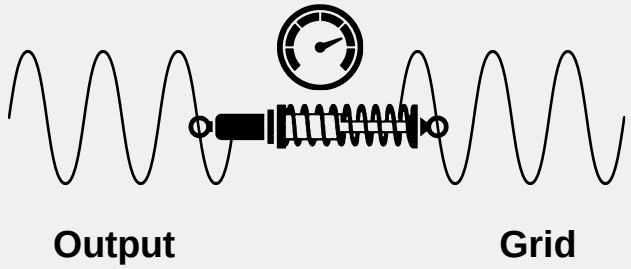




Virtual Synchronous Machine - VSM

Hitachi ABB PowerStore™





CSI = Current Source Inverter (Current controlled)
VSI = Voltage Source Inverter (Voltage controlled)

Alinta Newman 30MW / 8MWh PowerStore™

How do we switch off the last generator?

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Single Line Diagram

AUSTRALIAN ENGINEERING EXCELLENCE AWARDS

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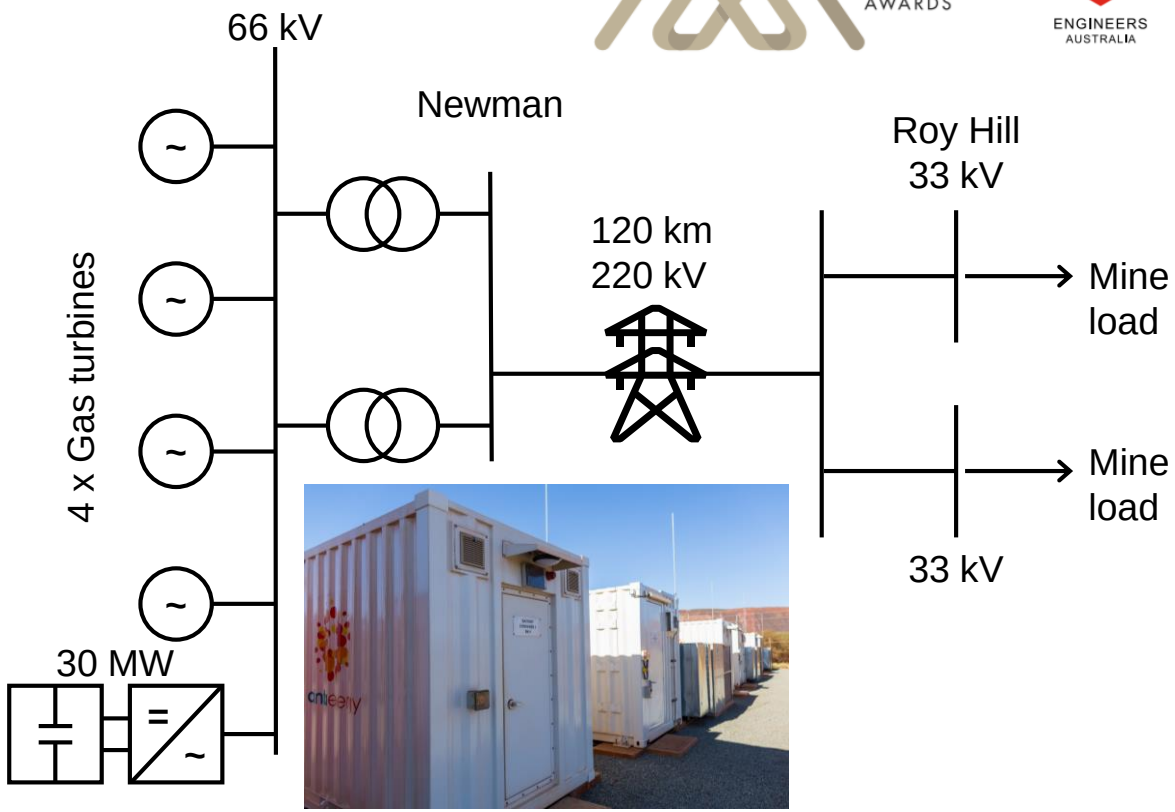
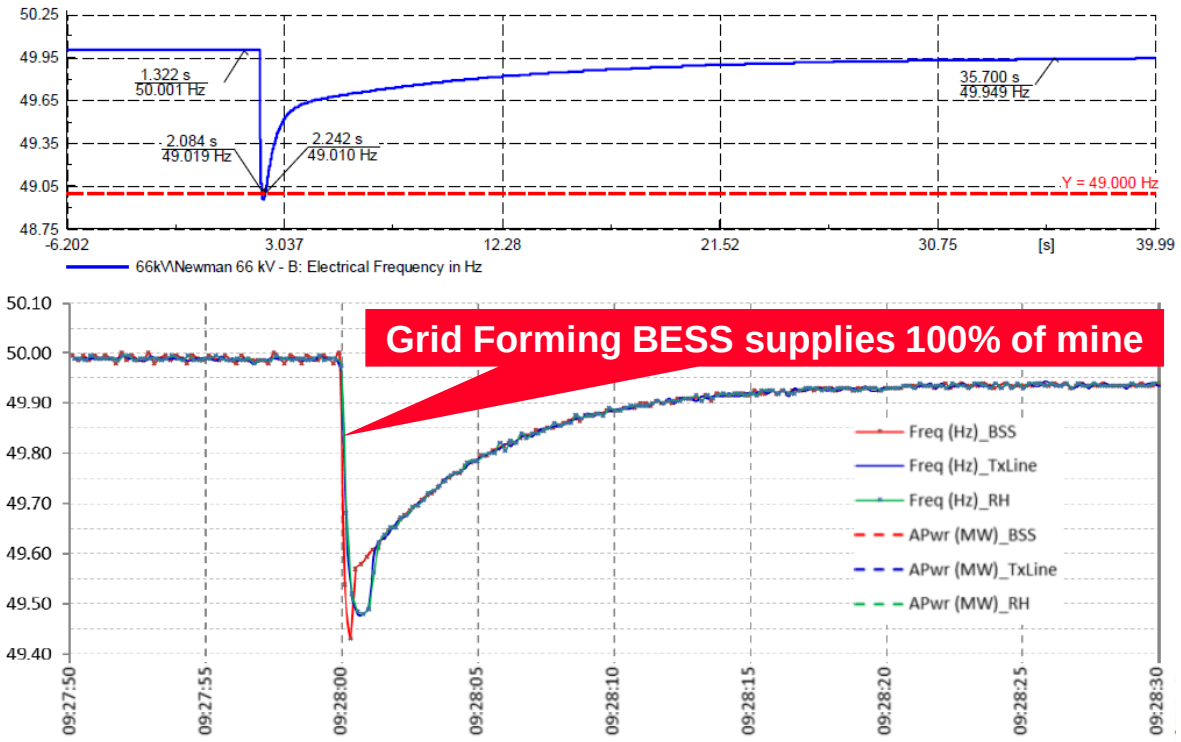


Last gas turbine trips off – simulated vs. actual response



Virtual Synchronous Machines are critical to allow Synchronous Machines to switch off

ESCRI Dalrymple Grid Forming BESS

ESCRI is the first and currently only VSM connected to the Australian NEM

Australian Renewable Energy Agency (ARENA):

"The ESCRI-SA project is the first Large Scale BESS in Australia to operate as a virtual synchronous generator while grid connected (grid-forming). Benefits include:

- **Simulated [virtual] inertia** and **improved voltage stability** through the very fast response capability of voltage source inverters;
- **system strength** through provision of fault current."

Grid forming inverters, unlike grid following inverters, **do not suffer instabilities** during disturbance events → this can enable their fault current contribution to be recognised as contributing to system strength.

Source: ARENA "Large-Scale Battery Storage Knowledge Sharing Report", adapted

Case Study

ESCRI Dalrymple – World's first large scale utility connected Grid Forming BESS

Dalrymple ESCRI-SA BESS
Business Case & Commercial Arrangements

Innovation Awards

Energy Networks Australia:
2019 Industry Innovation Award

South Australia Premier's Award:
2019 Energy Sector - Transformational Innovation

Project scope and objectives

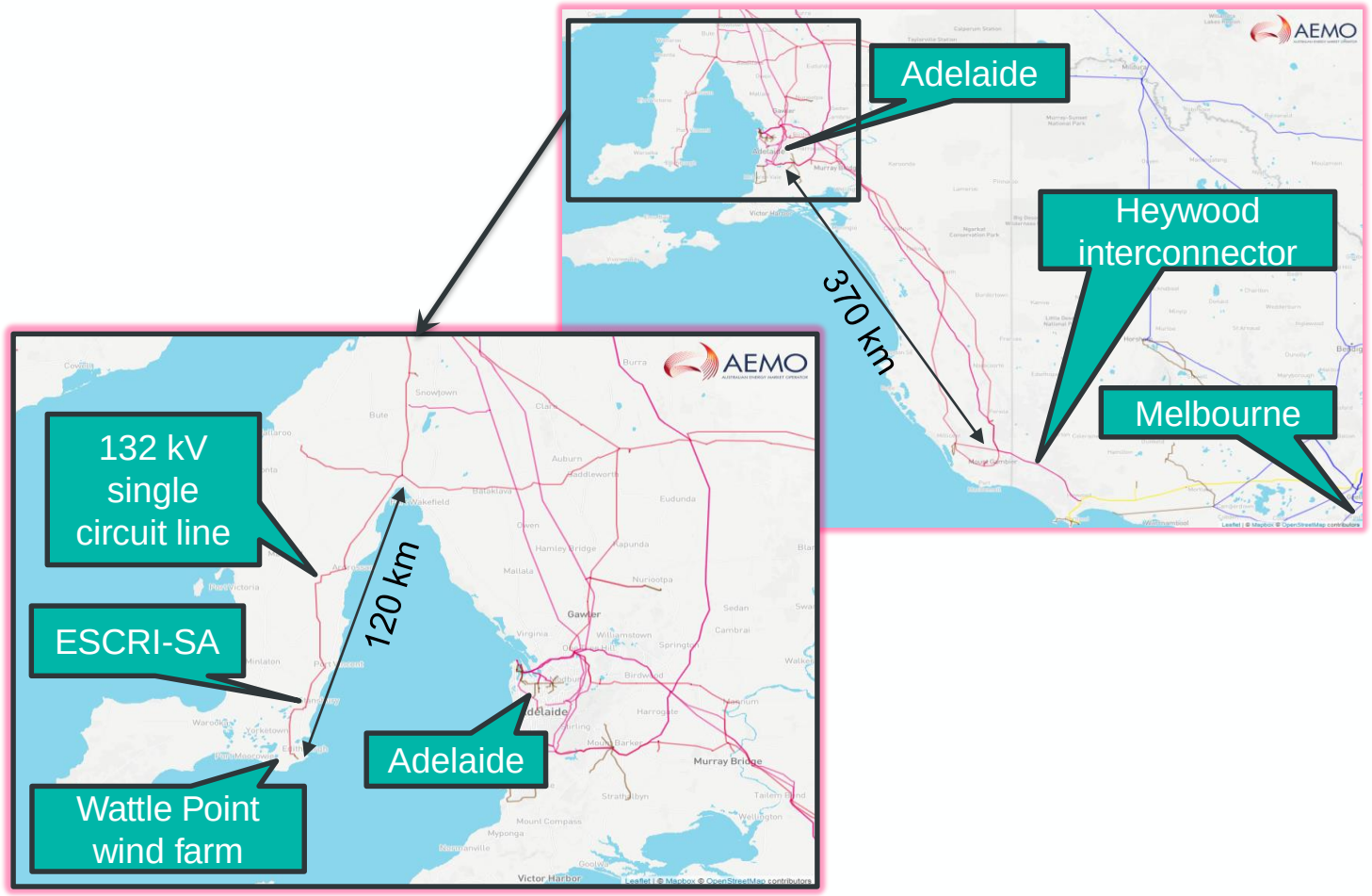
Scope: Nominal 30 MW, 8 MWh lithium-ion battery

1. Gain practical experience and learnings from the application of grid connected utility scale battery storage as an enabler of large scale intermittent renewable energy on an interconnected system
2. Demonstrate that utility scale battery storage can effectively provide network reliability and security services alongside market services
3. Demonstrate network ownership of battery storage and commercial appropriate separation of provision of regulated services and competitive energy market services
4. Demonstrate “seamless” islanded operation with 100% renewable generation following transmission outages

ESCRI BESS: location at the edge of NEM

Utility scale 30MW/8MWh BESS near the end of a long radial line in proximity to a wind farm

- Connection at 33 kV at Dalrymple substation on Yorke Peninsula – land available
- Opportunity to reduce expected unserved energy under islanding conditions (max demand is about 8 MW but on average need about 3 MW for 2 hours)
- Site is close to the 91 MW Wattle Point Wind Farm – provides opportunity for battery to support islanded operation with the wind farm and 2 MW of local rooftop solar, following network outages



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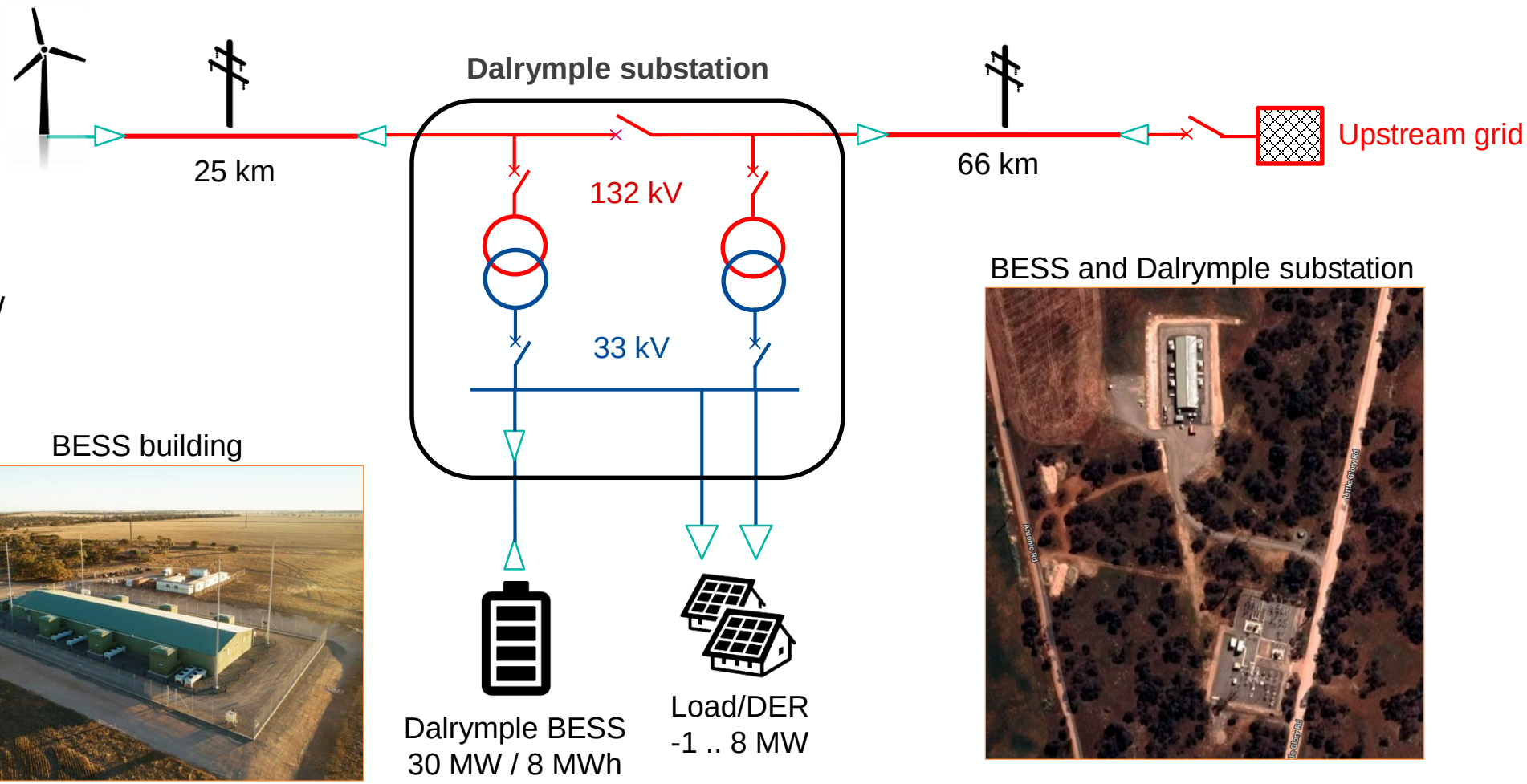
Integration at ElectraNet's Dalrymple substation

Wattle Point Wind Farm 91 MW
(55 x Vestas V82 directly coupled induction generators)



BESS building

BESS and Dalrymple substation

Images (left to right): Wind farm: Flickr https://www.flickr.com/photos/daveclarkecb/
BESS: Courtesy ElectraNet
BESS and substation: Courtesy Google Maps

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Benefits / Revenue streams

Providing both regulated and competitive market services

Regulated services[1] (ElectraNet)	**Competitive market services (AGL Energy)**
Fast frequency response Heywood Interconnector benefit	Ancillary services revenue (FCAS)
Reduced unserved energy benefit	Energy trading

1. During project implementation the BESS was incorporated in the System Integrity Protection Scheme (SIPS), providing additional regulated benefits. The SIPS is an important emergency control scheme that significantly enhances power system security in South Australia (SA) for the non-credible loss of multiple generators in SA.

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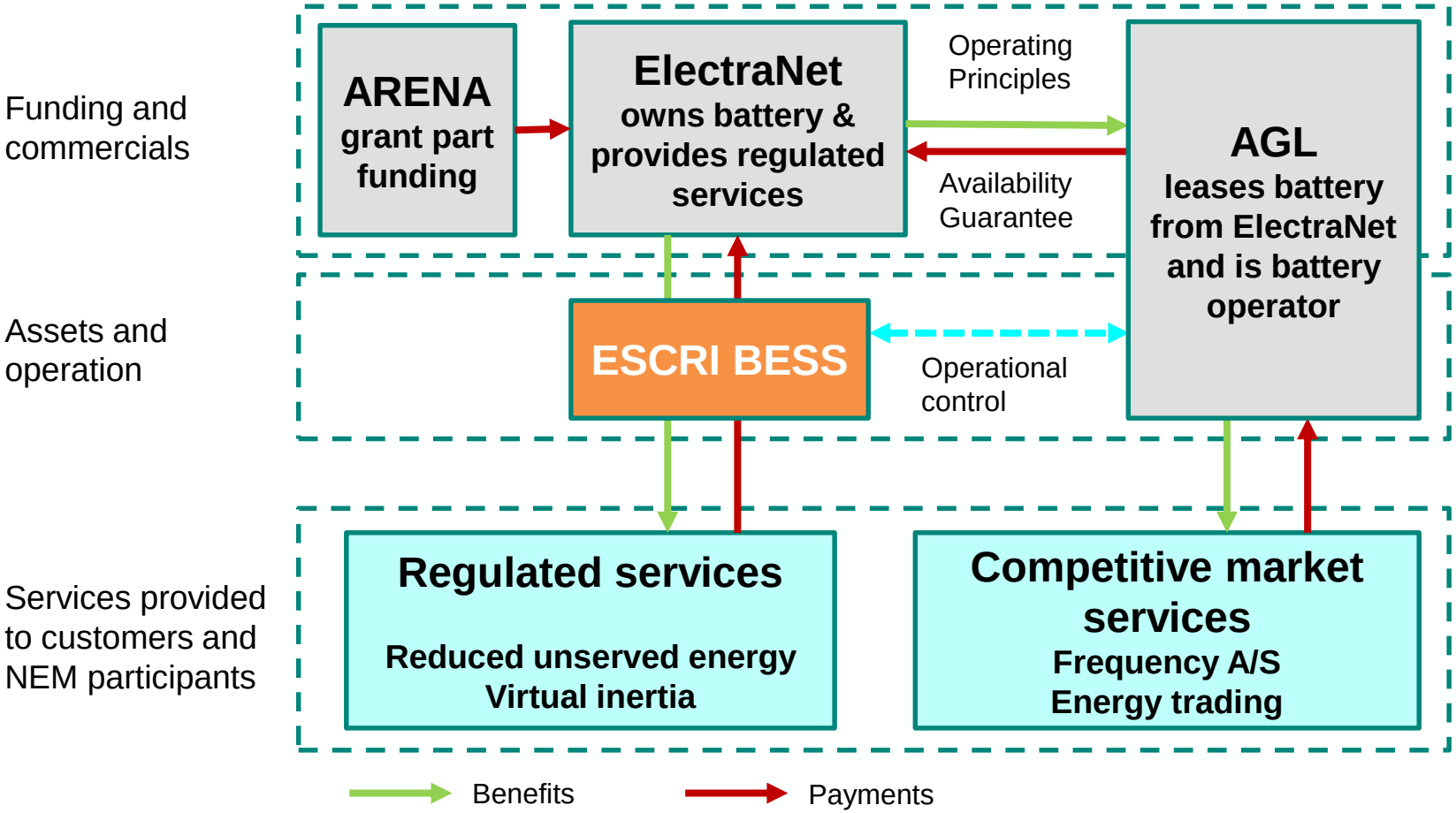
Commercial arrangements

Providing both regulated and competitive market services



EPC/ D&C contract and 12-year maintenance agreement awarded to Consolidated Power Projects (CPP) following extensive procurement process

ElectraNet

Key Metrics – First 12 months of operation

Key Performance Metric	H1 2019	H2 2019	2019
Average BESS Availability	98.01%	97.35%	97.68%
BESS Charging Cost	AUD 120,000	AUD 101,000	AUD 221,000
BESS Discharge Revenue	AUD 116,000	AUD 97,000	AUD 213,000
FCAS Revenue	AUD 1.33M	AUD 3.73M	AUD 5.06M

H1: (14-12-2018 to 14-06-2019)
H2: (14-06-2019 to 14-12-2019)

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Industry innovation

A number of firsts

- Largest (30 MW BESS) indoor and climate-controlled BESS installation in Australia
- Largest autonomous regional microgrid development to-date. All-in-one control design co-optimised for both grid-connected and islanded operation, allowing seamless transition between the two operating states
- Grid-forming capability implies ability to operate conceptually at very low Short Circuit Ratios (<<1.5)
- Islanded grid master control including WF generation MW dispatch / curtailment
- Black-start capability for 8 MW island
- Topology-based Islanding Detection Scheme (IDS)

Knowledge Sharing Portal

- ARENA knowledge sharing commitments
  - Project delivering substantial knowledge sharing benefits to stakeholders
- Real-time data
- Data downloads
- Reports
- Presentations
- Knowledge Sharing Reference Group
  - Agendas
  - Minutes

www.escri-sa.com.au

ElectraNet

Virtual Inertia vs FFR

What is the difference and why does it matter?

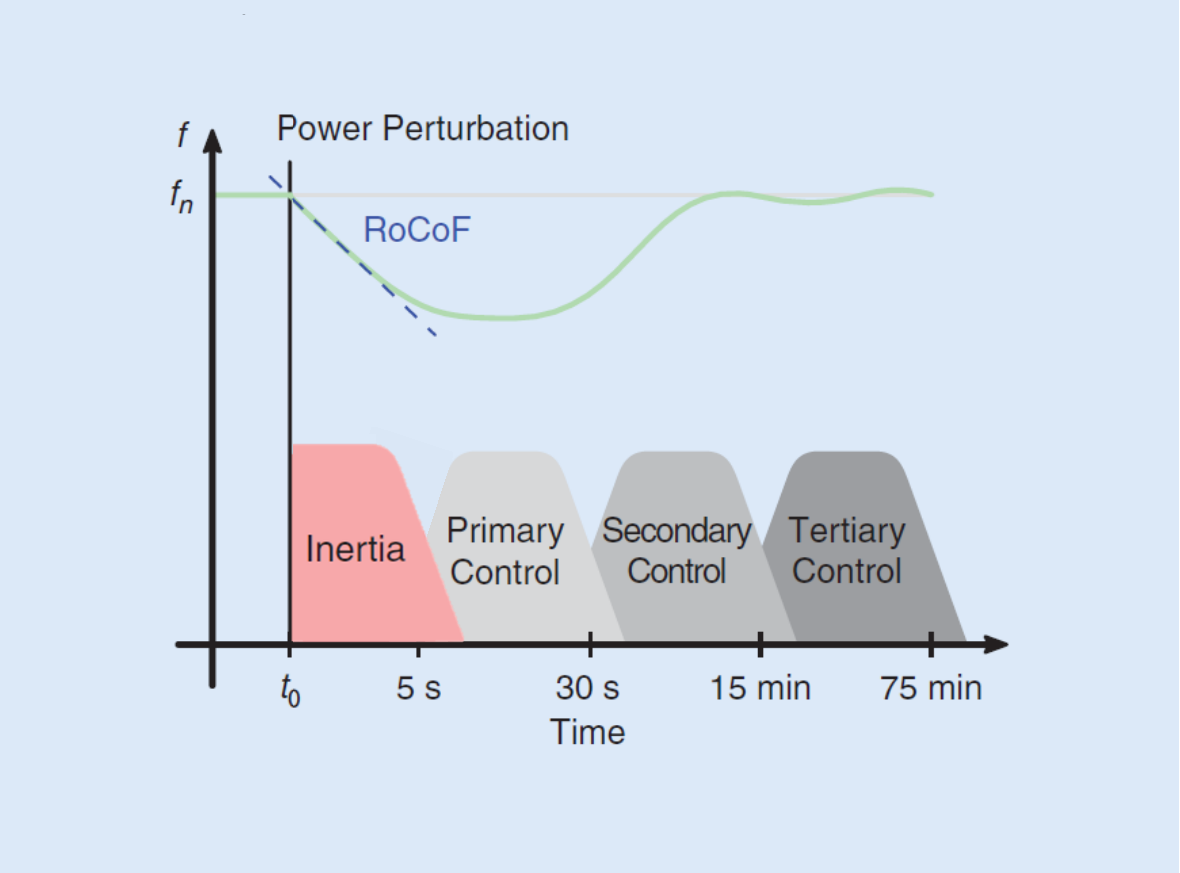
Fast Frequency Response (FFR)

Fast frequency response is not inertia, but an important service

FFR and inertia are technically different services:

- FFR is a response in 2 seconds or less but does not have a single definition globally
- FFR isn't an inherent response
- FFR requires measurement, detection, processing, filtering and activation – inertia does not
- FFR is an important service to compensate for less inertia in the power system but is does not replace inertia
- FFR can falsely trigger or fail to trigger when attempting to measure frequency and RoCoF very quickly after a major power system fault
- FFR can be provided by grid following and grid forming inverters; inertia only by grid forming inverters

Inertia and FFR in the context of frequency support:



RoCoF = Rate of change of frequency

E. Unamuno, J. Paniagua, J.A. Barrena "Unified Virtual Inertia for ac and dc Microgrids. And the role of interlinking converters.", IEEE Electrification Magazine, December 2019
AEMO: (Fast Frequency Response in the NEM Working Paper, Future Power System Program, 2017) (Inertia requirements methodology)

Virtual Inertia is driven by same physics as synchronous inertia

Response equivalent but tunable

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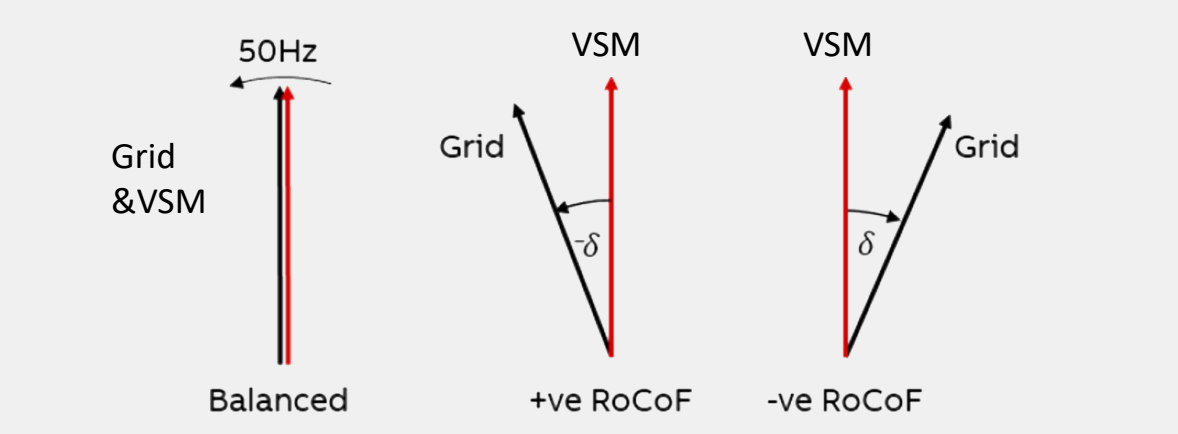
Power transfer equation:

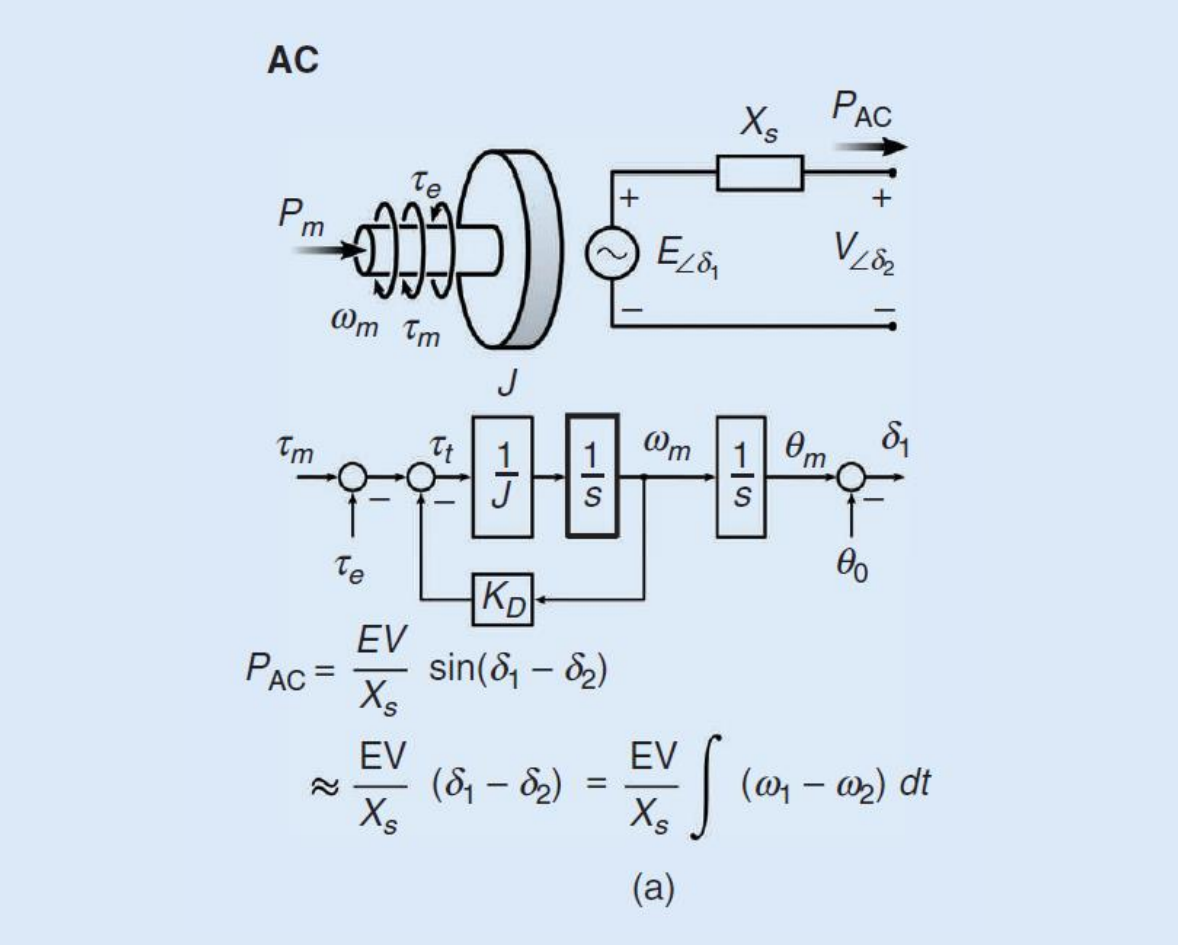
$$P = \frac{V_s V_r}{X} sin\Delta\delta \quad \propto \quad \Delta\delta$$

where:

- Vs is the sending end voltage (BESS internal voltage)
- Vr is the receiving end voltage (Grid voltage at coupling terminals)
- X is the coupling impedance
- $\Delta\delta$ is the phase angle between the two voltage sources (internal BESS voltage and voltage at the coupling terminals)



Dynamic model of Synchronous machine:



E. Unamuno, J. Paniagua, J.A. Barrena "Unified Virtual Inertia for ac and dc Microgrids. And the role of interlinking converters.", IEEE Electrification Magazine, December 2019

Virtual Inertia – Tunable inertia

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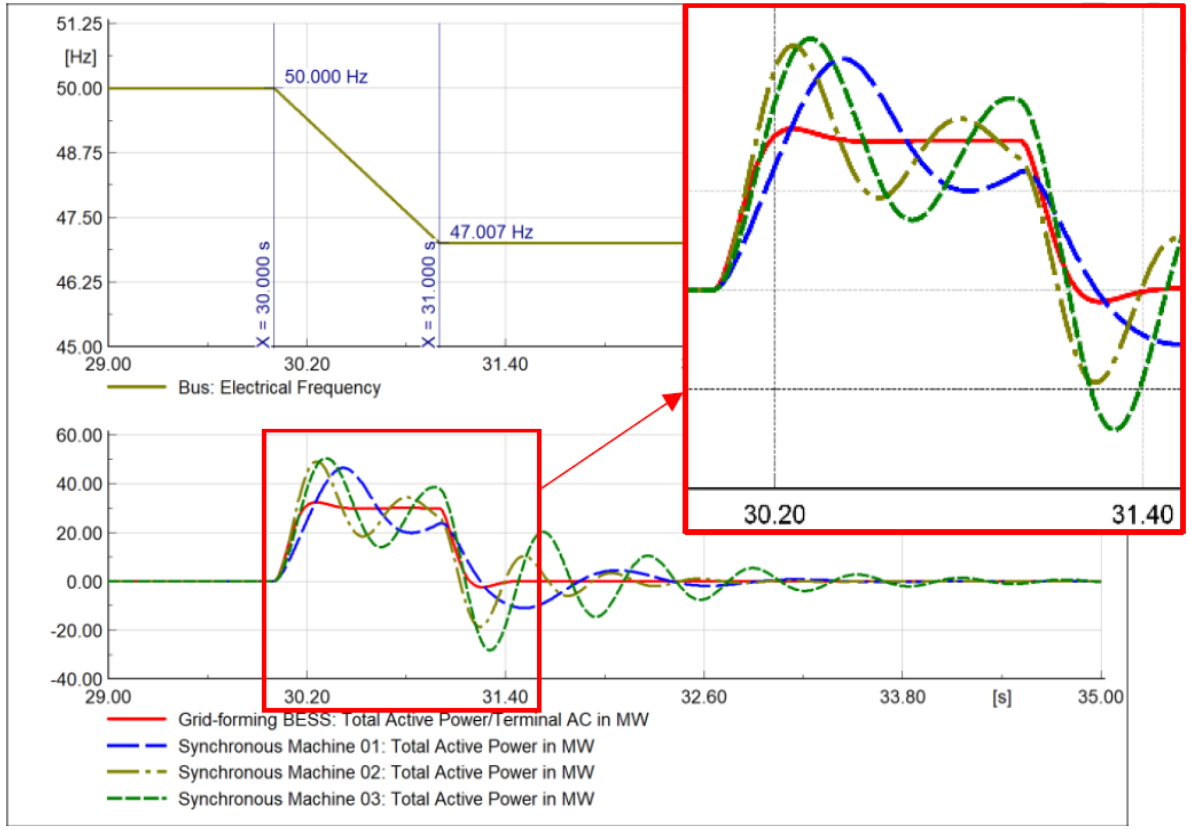
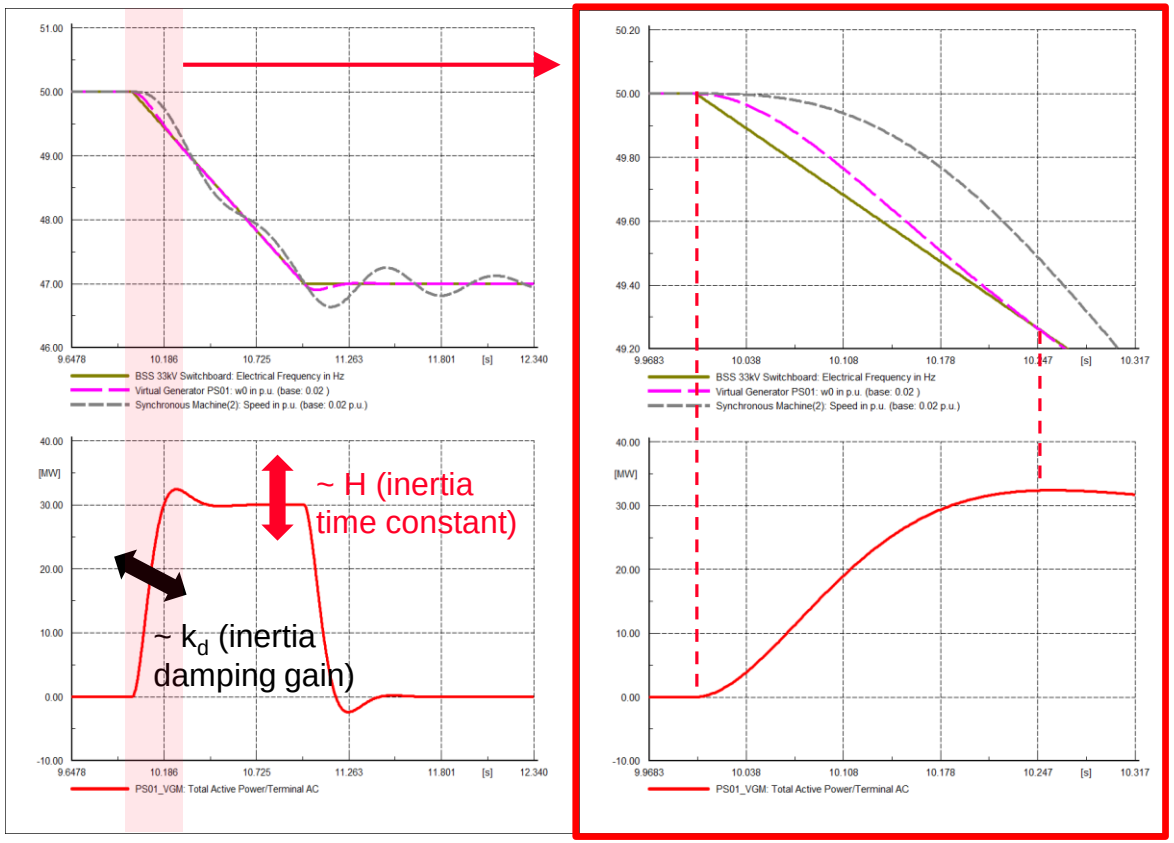
RoCoF response of VSM vs Synchronous Machines:



The difference between the internal speed & grid frequency drives response:



RoCoF = Rate of Change of Frequency; VSM = Virtual Synchronous Machine

Real World Results

ESCRI Dalrymple – World's first large scale utility connected Grid Forming BESS

Unplanned islanding without the wind farm

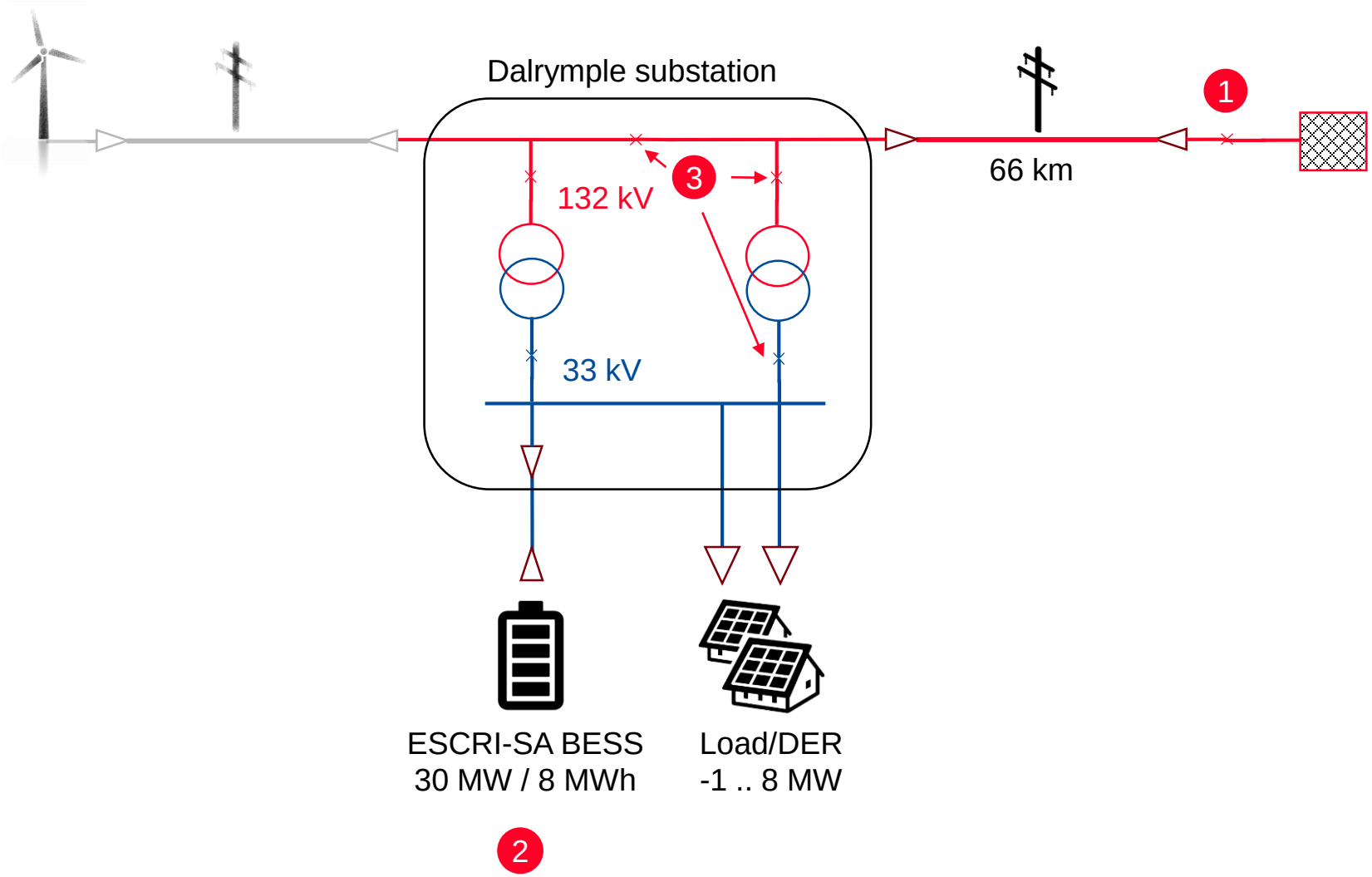
Sequence of events

Pre-event conditions

- Wind farm offline
- BESS running unloaded on the NEM
- Local load ~ 4 MW
- All breakers closed

Event

1. 132 kV breaker at the upstream substation opens
2. BESS becomes the only grid forming source in the now islanded microgrid and instantaneously supplies the area
3. Some 80 msec later the protection system at Darlymple disconnects the upstream line

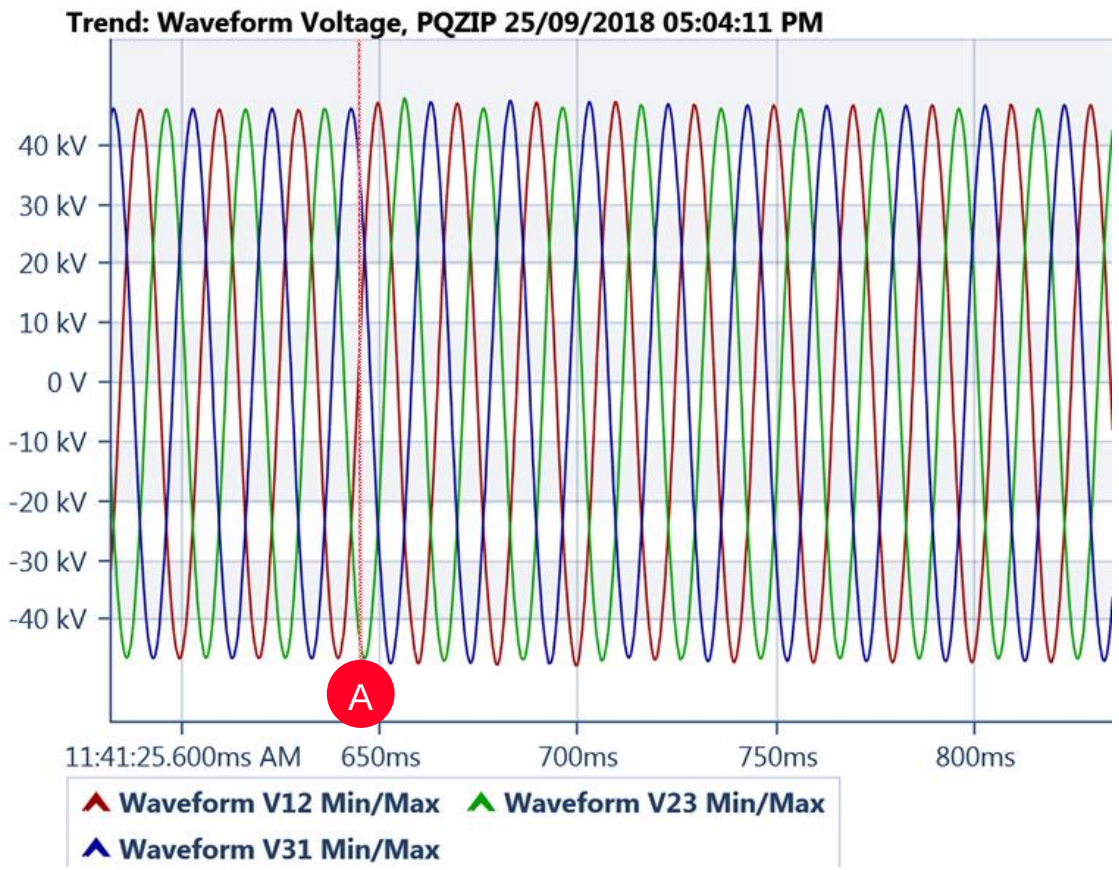


NEM = National Electricity Market

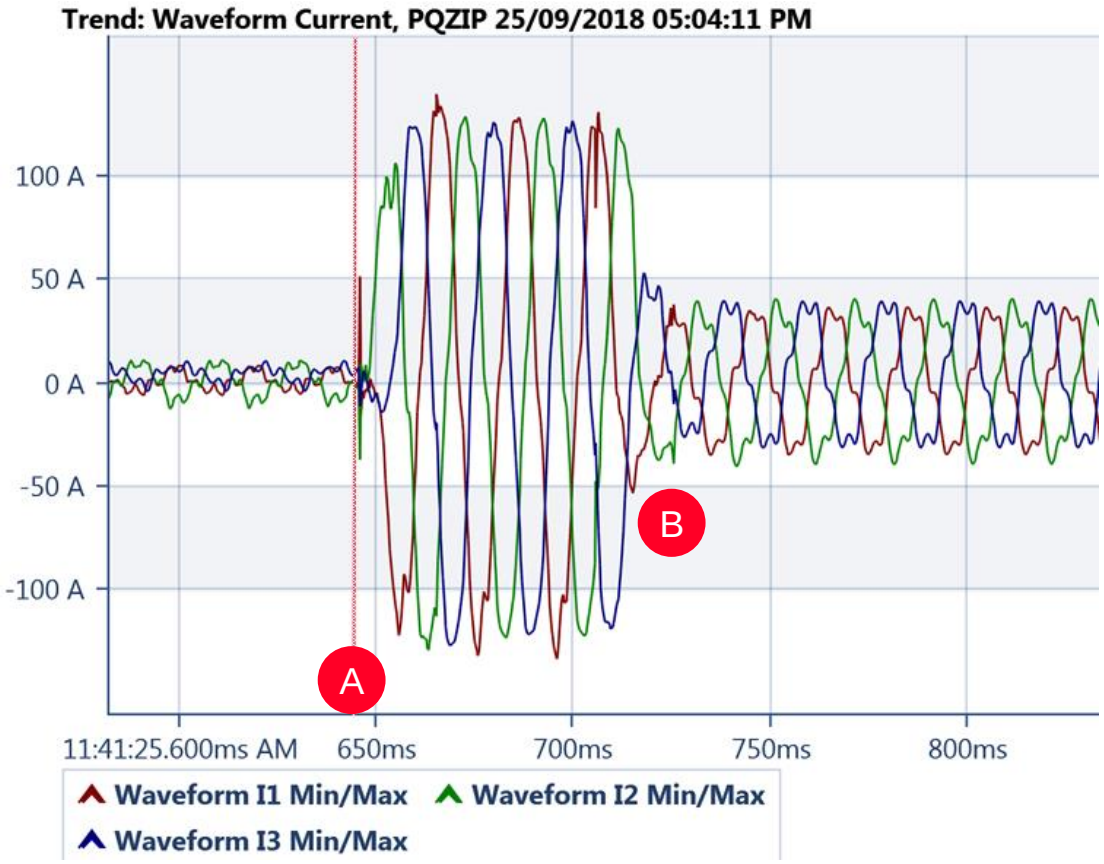
Unplanned islanding without the wind farm

The islanding instant – BESS voltage and current waveforms

A 132 kV breaker at upstream substation opens = islanding takes place



B Upstream line is disconnected



Misconception: Dalrymple BESS does not switch modes from grid connected to islanded – it is always Grid Forming

Unplanned islanding with the wind farm

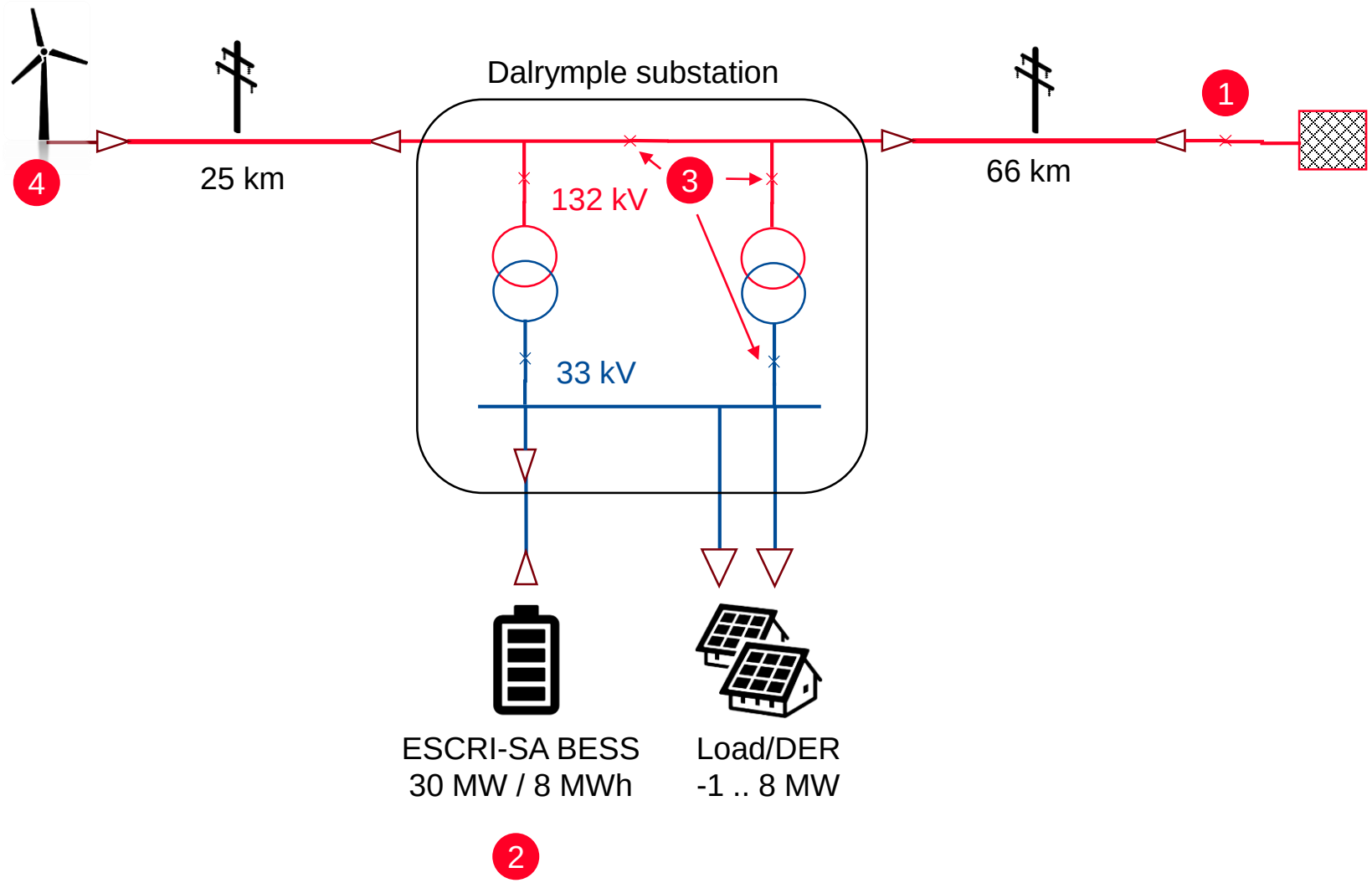
Sequence of events

Pre-event conditions

- Wind farm output ~ 80 MW
- BESS running unloaded on the NEM
- Local load ~ 4 MW
- All breakers closed

Event

1. 132 kV breaker at the upstream substation opens
2. BESS becomes the only grid forming source in the now islanded microgrid and instantaneously supplies the area
3. Some 80 msec later the protection system at Dalrymple substation disconnects the upstream line
4. At about the same time protection at the wind farm trips 4 out of 5 collector groups (~80% of capacity)



NEM = National Electricity Market

Unplanned islanding with the wind farm

The islanding instant – virtual inertia in action

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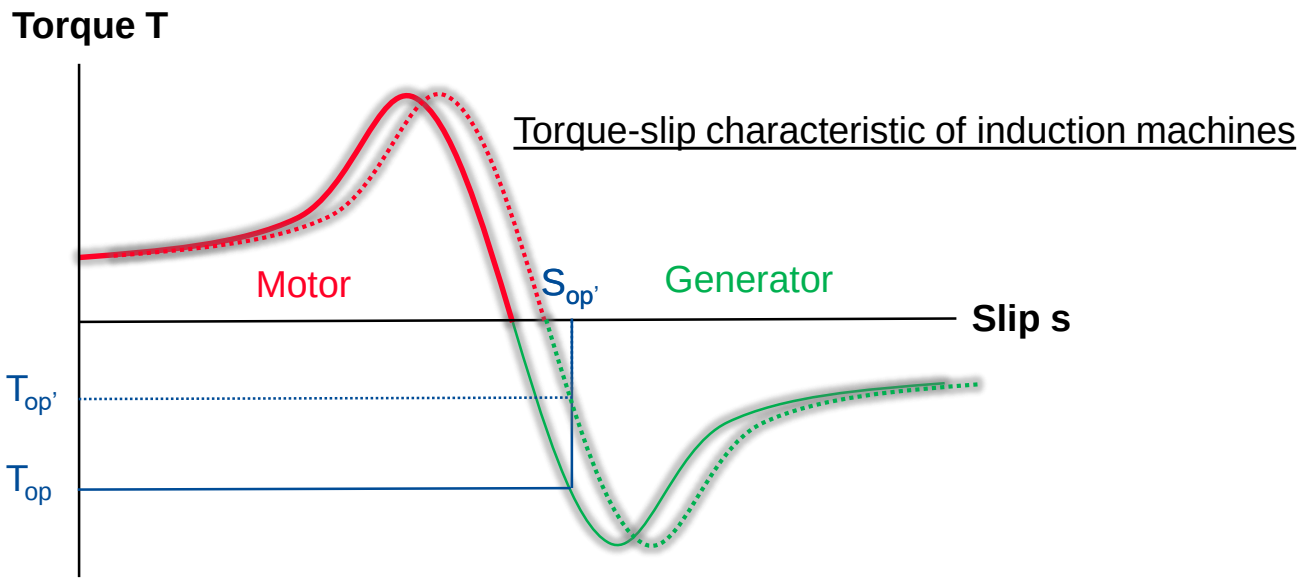
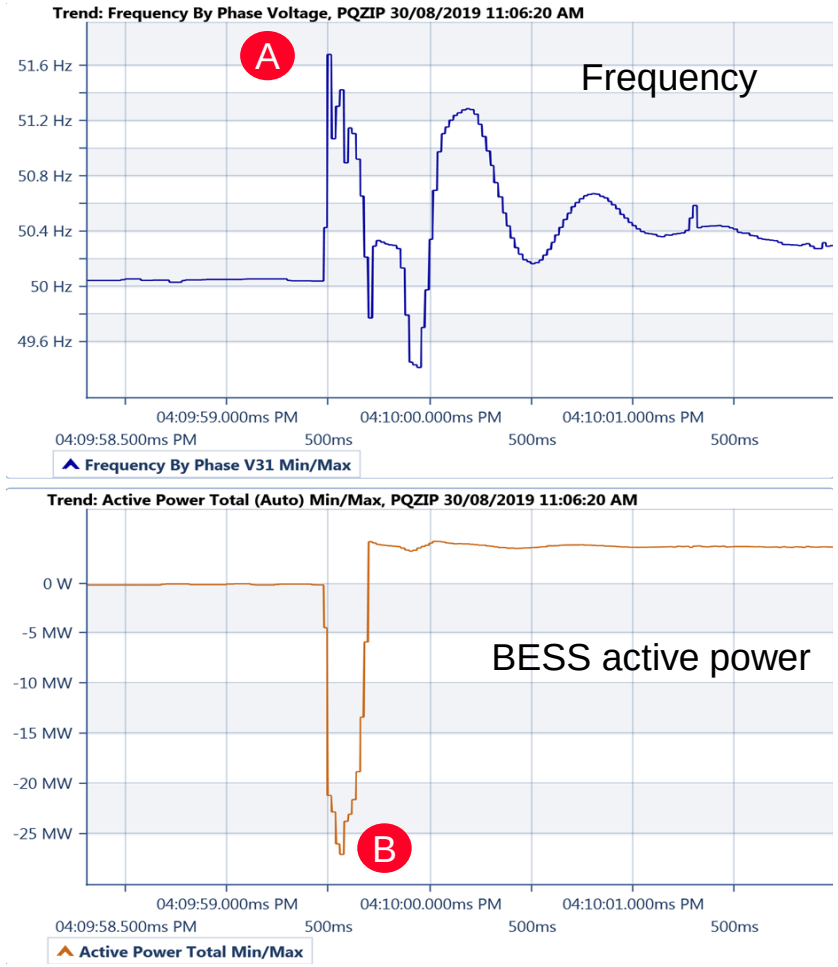
A Upstream breaker opens B 80% of WTGs disconnected





➡ Upon islanding, frequency is pushed up by the virtual inertia of the BESS reducing slip, electric torque and power output from the WTGs

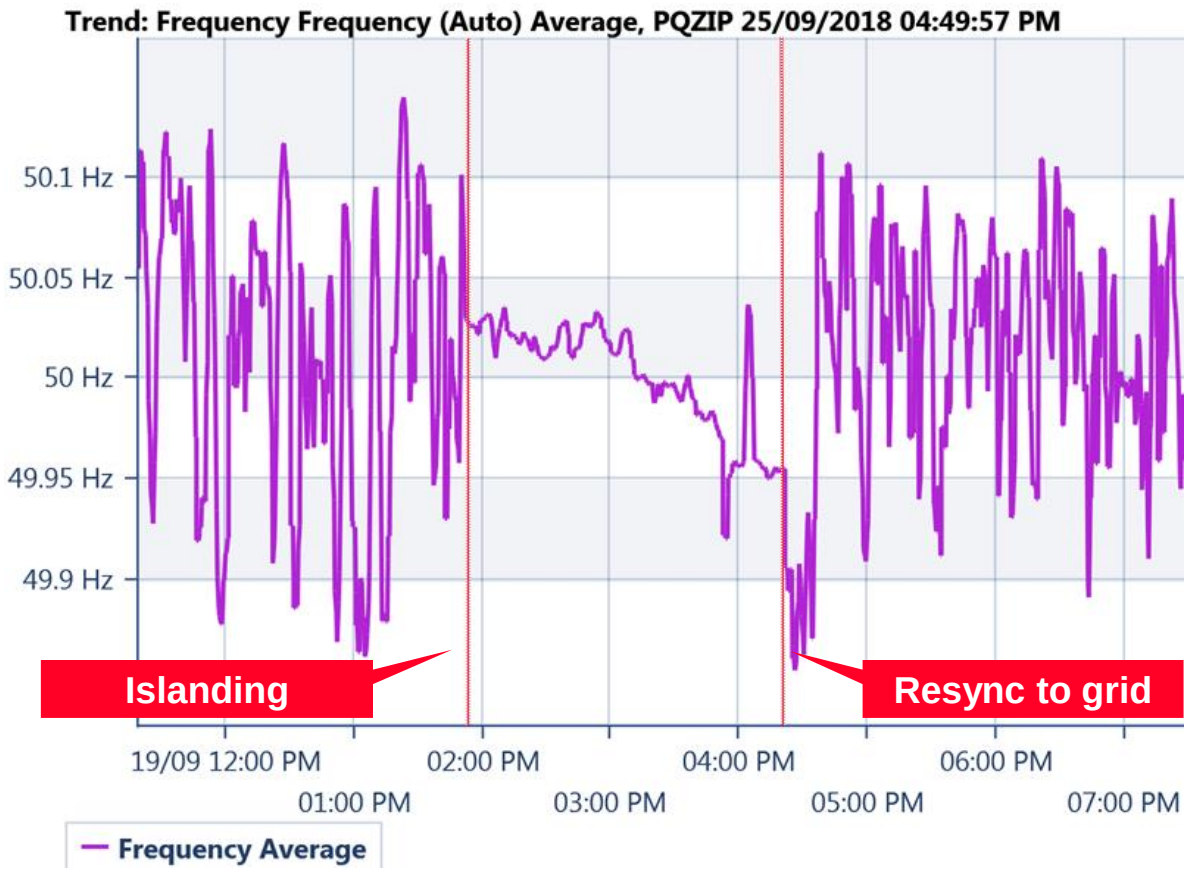
Wind farm's output is momentarily reduced from ~80 MW to ~27 MW

WTG = Wind Turbine Generator

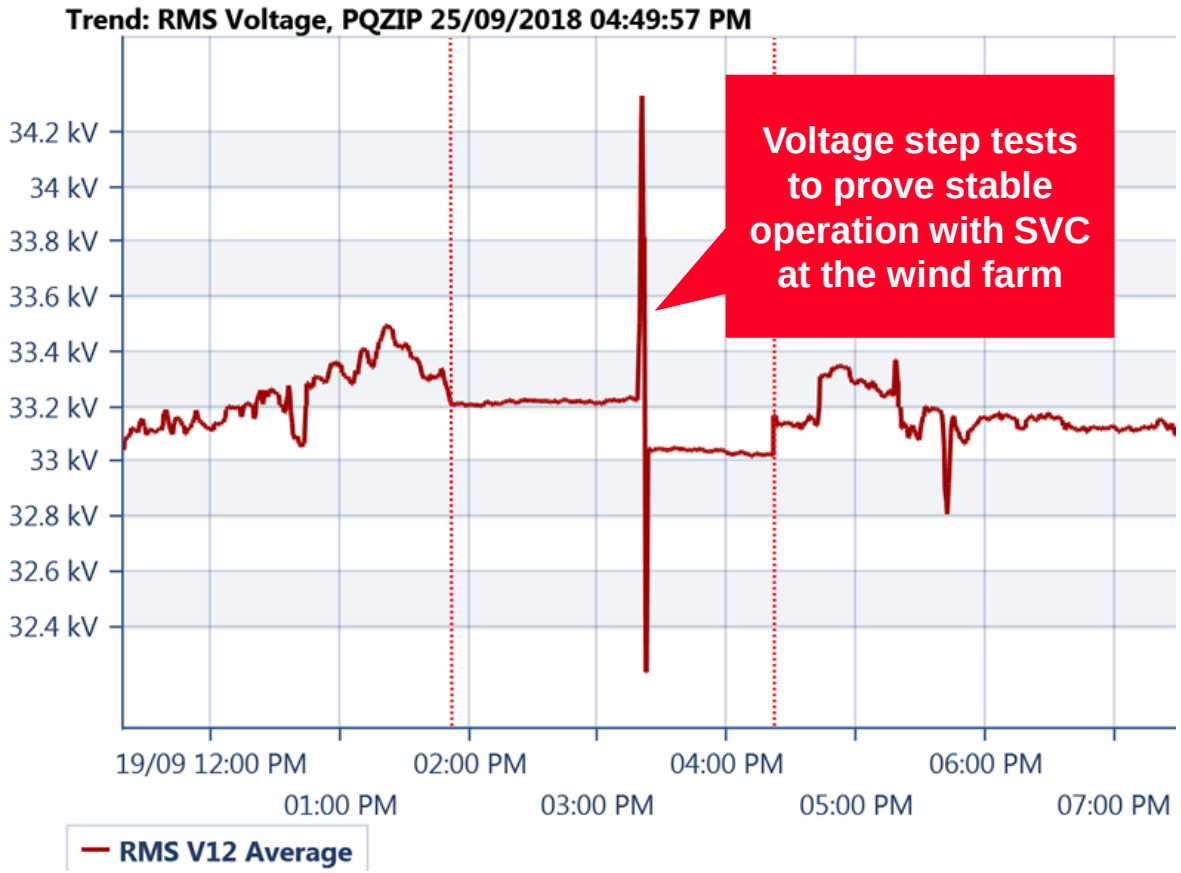
Islanded operation

BESS regulates frequency and voltage

Frequency performance: grid-parallel vs islanded



Voltage performance: grid-parallel vs islanded



SVC = Static VAR Compensation

South Australia Islanding Event: Inertia Response

Grid forming inverter responds to frequency change in the network – 8-second view

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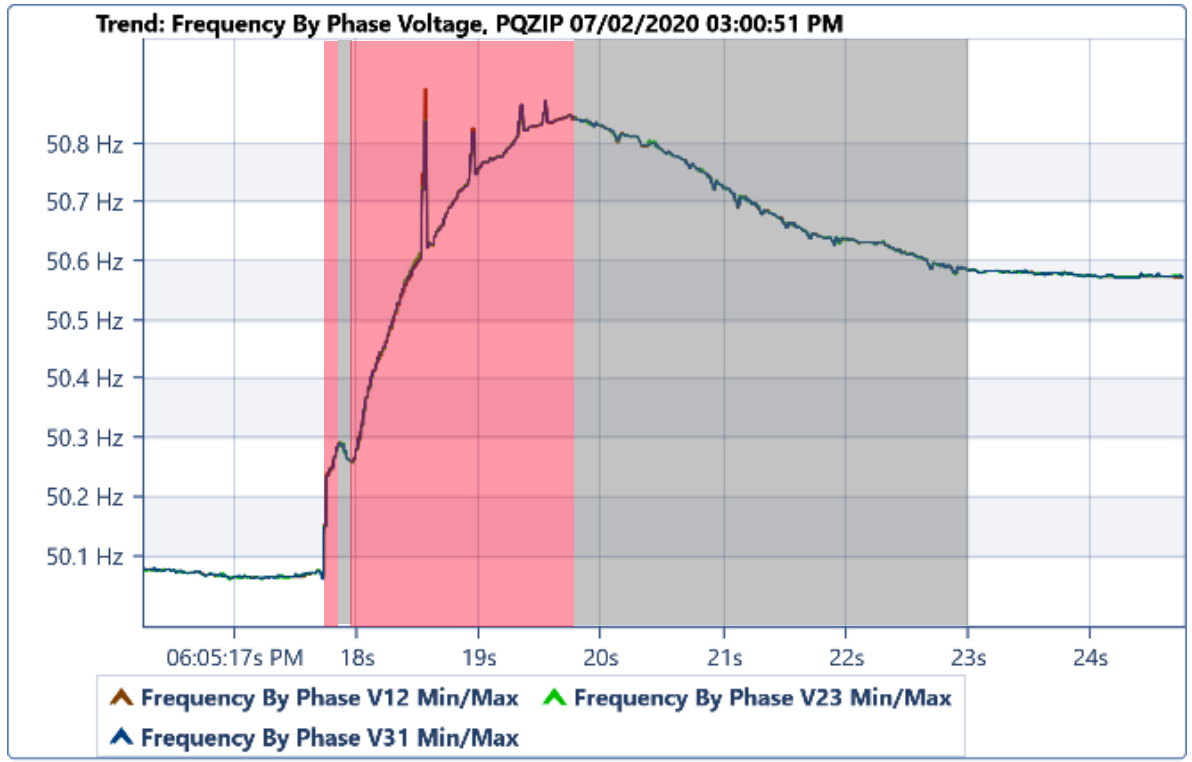
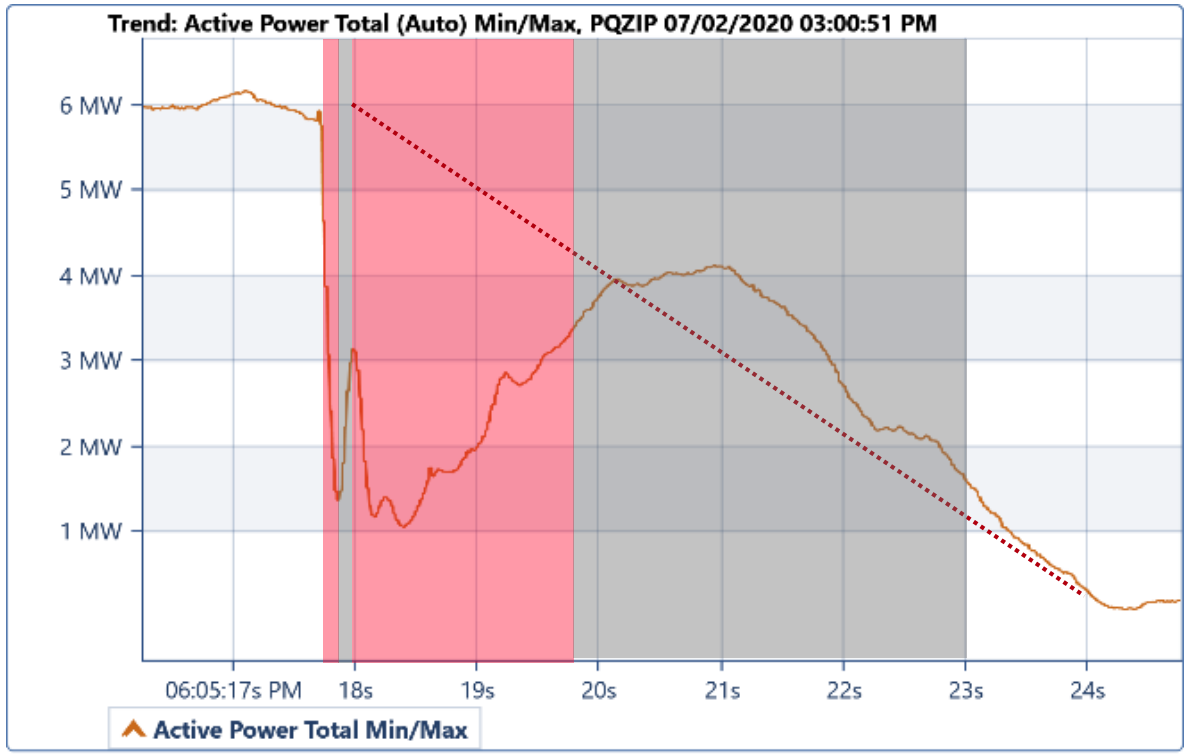
RoCoF event in South Australia over 8s (red positive RoCoF, grey negative RoCoF)



Active Power response over 8s – Inertial response initially to grid frequency (left) prior to FCAS setpoint (red dotted line) on secondary controller driving 6 second FCAS market response as per bid 6MW bid



RoCoF = Rate of change of frequency

South Australia Islanding Event: Inertia Response

Grid forming inverter responds to frequency change prior to high speed data recorder

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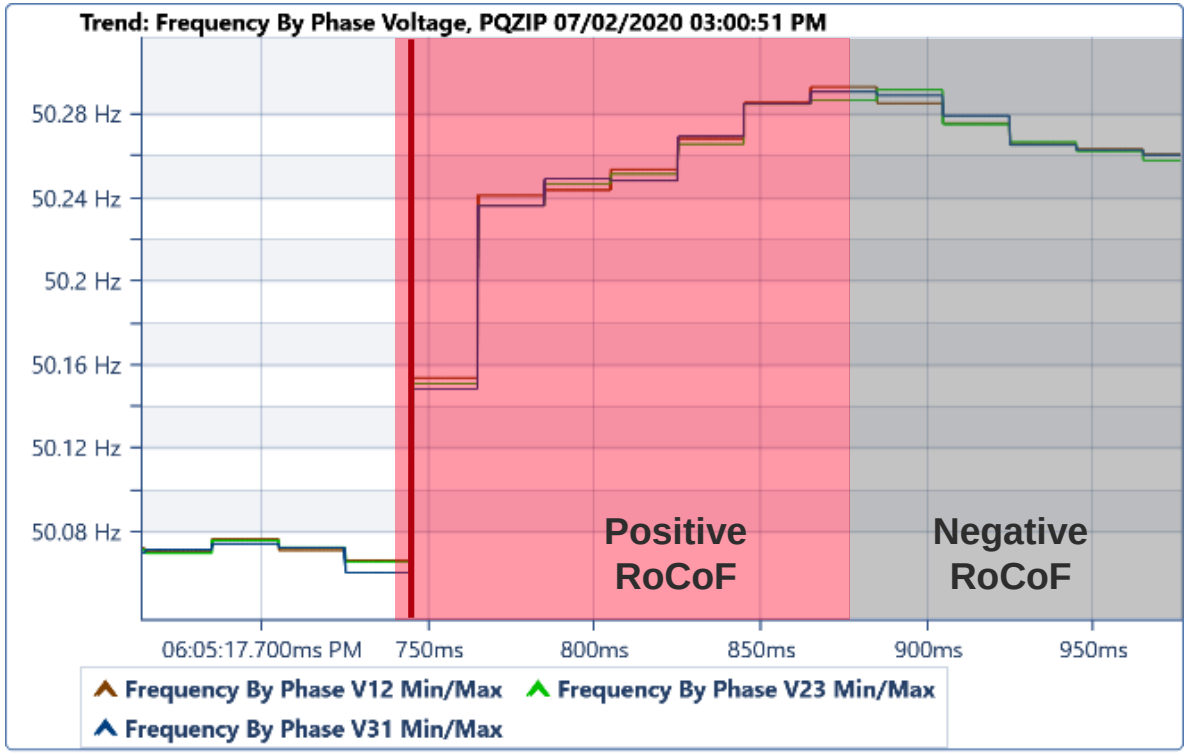
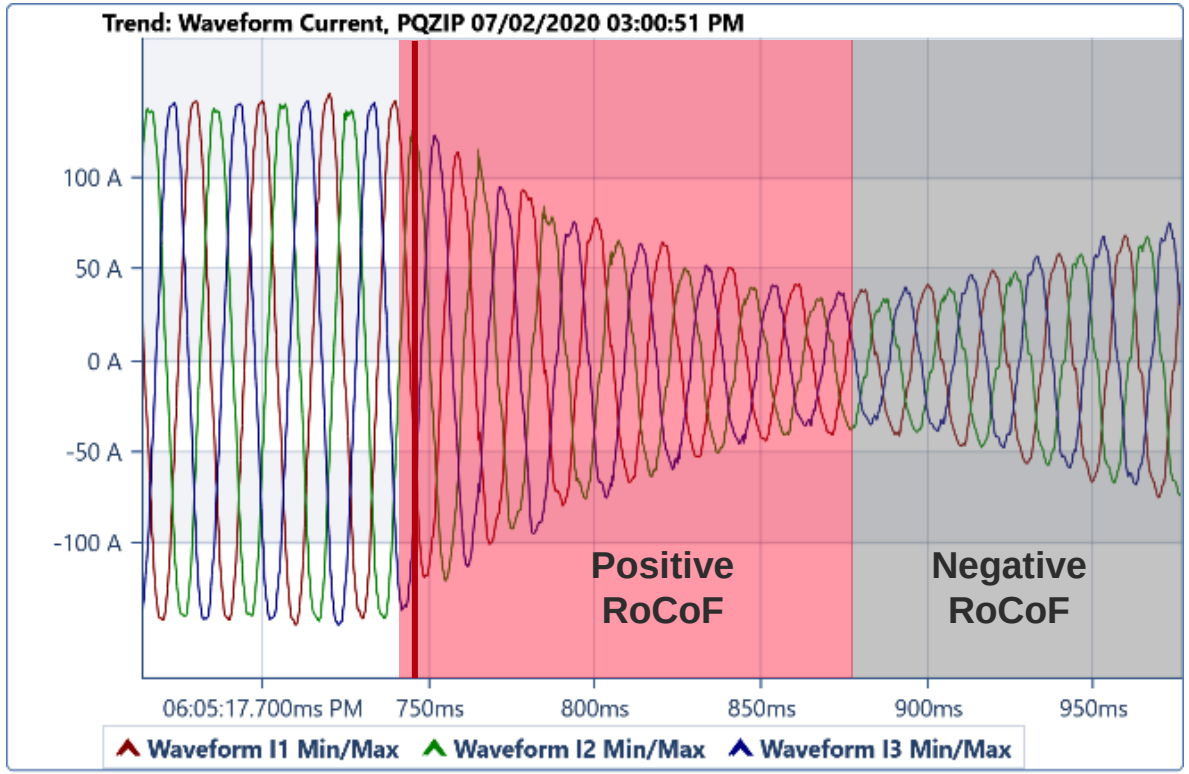
Frequency Measurement by high speed data recorder over 300ms



VSM Response – Current responds prior to frequency measurement (red vertical line) and the output (below) mirrors the grid frequency (left) as it resists the change in frequency with its purely inertial response in this timeframe



RoCoF = Rate of Change of Frequency

HITACHI ABB POWER GRIDS

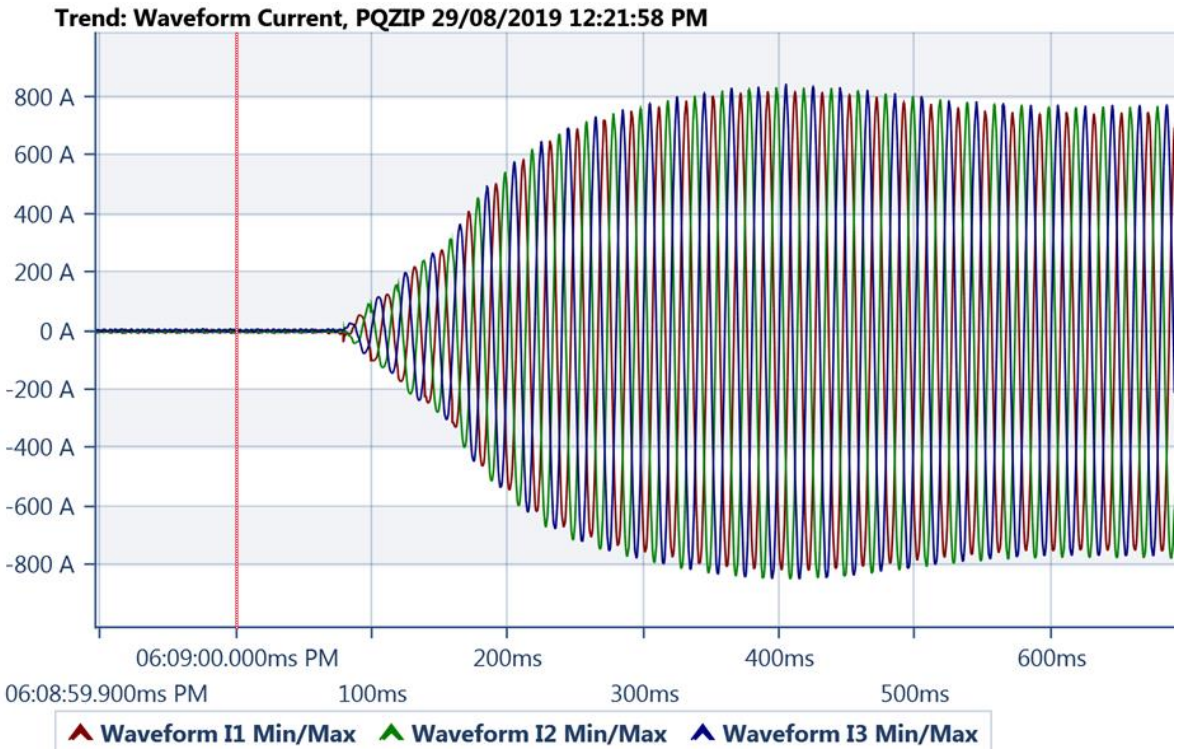
Fast Active Power Injection (Outsourced FFR measurement and detection)

ESCRI BESS is part of System Integrity Protection Scheme (SIPS)

System Integrity Protection Scheme (SIPS):

- Designed to prevent SA system separation from the NEM
- Acts to pre-empt a large RoCoF event
- Based on measurements taken along the Heywood interconnector
- Takes over measurement/detection for Fast Frequency Response
- Triggers grid-scale BESS to inject power and, if required, sheds load to restore balance between supply and demand
- Requires the BESS to inject full power in 250 msec

BESS grid-parallel fast response: 30 MW in 250 msec



SA = South Australia

Source: ElectraNet

Black start of the local 33 kV distribution network

Soft energisation of large transformers and pickup of 33 kV load feeders in islanded operation

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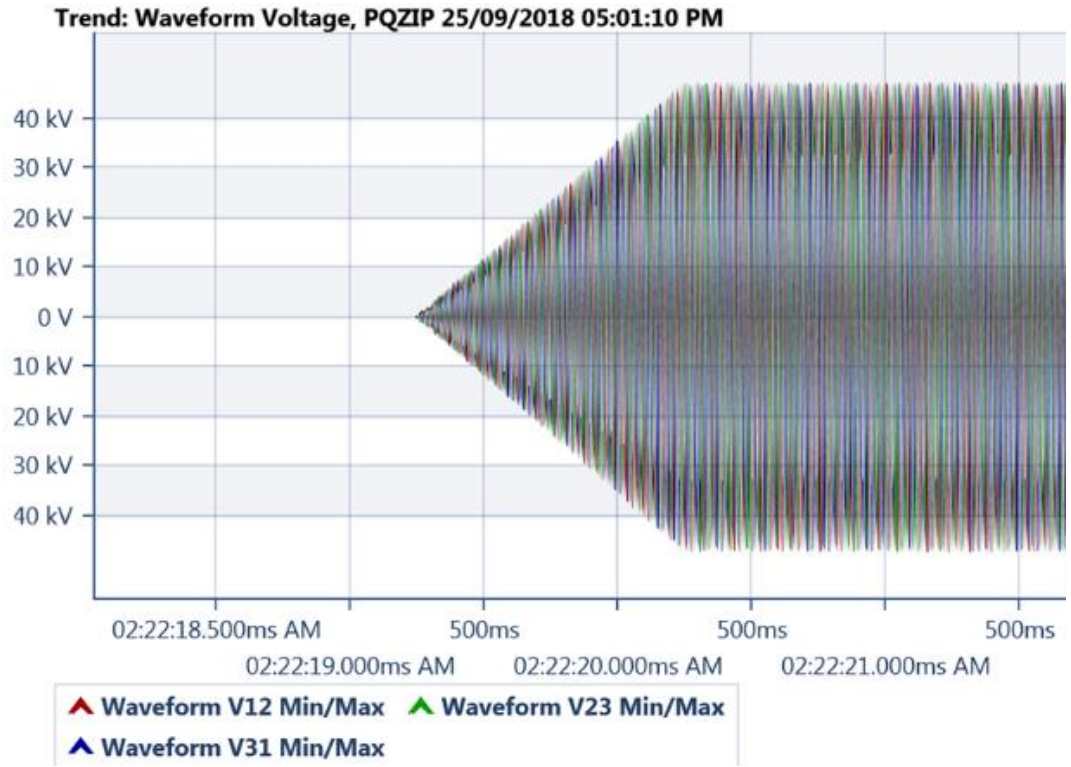
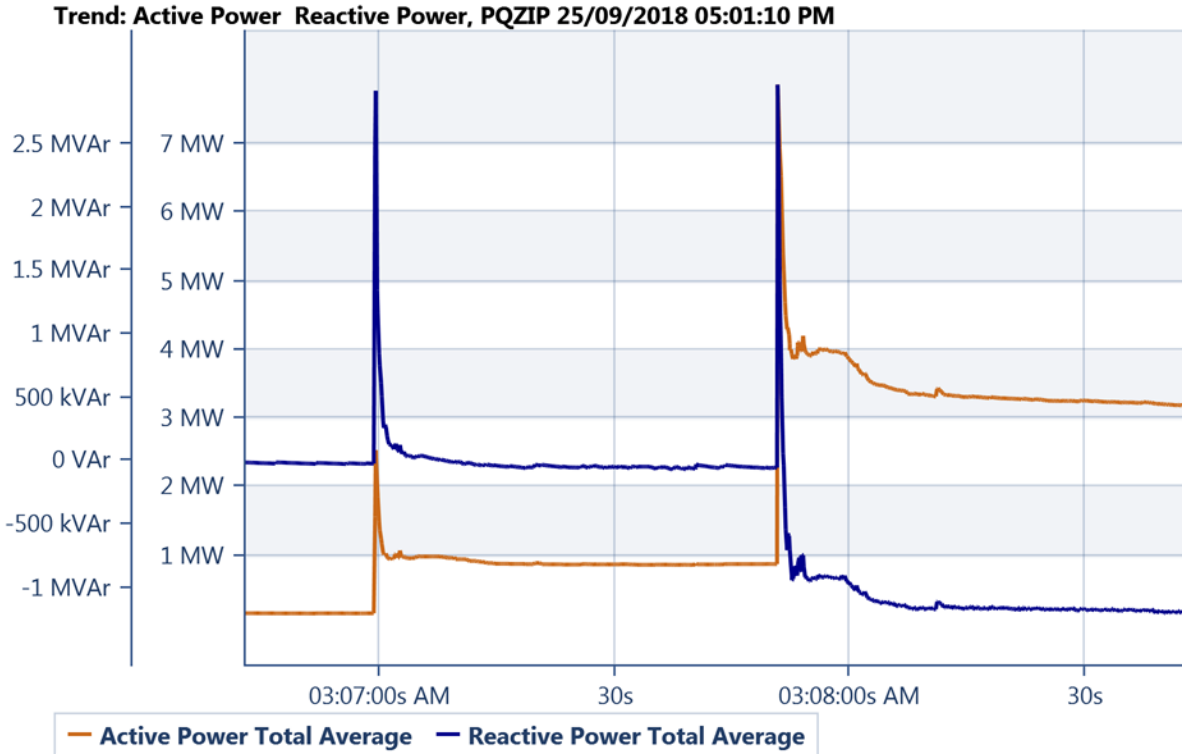
BESS ramps voltage up to energise transformers



BESS picks up 33 kV load feeder – P/Q profiles



Voltage ramp effectively eliminates transformer inrush. Feeder pick up at full voltage presents no issues.

Supporting Renewable Interconnections

Connecting and operating higher levels of renewable energy

Renewable Interconnection Support

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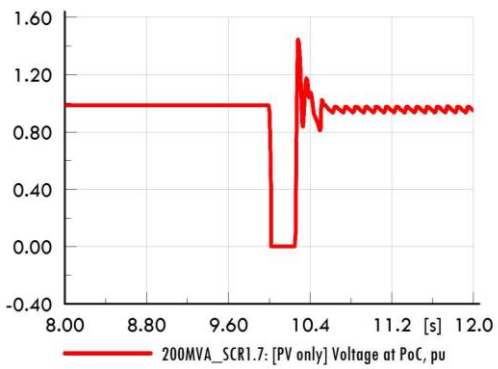
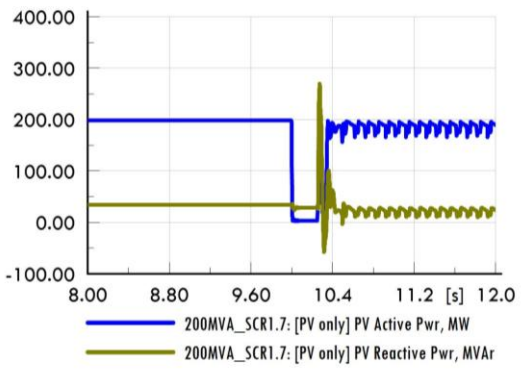
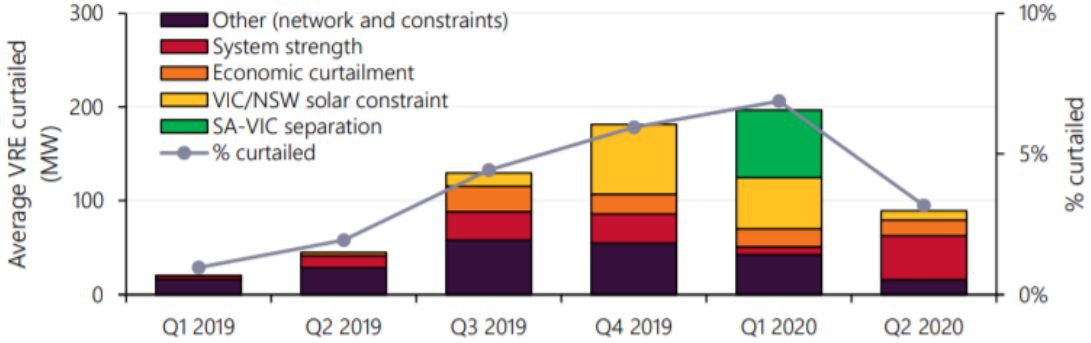
Low system strength

- Low system strength presents significant challenges to connecting and operating renewables
- The viability of renewable energy projects can be jeopardised due to the time and cost implications of “remediation measures”
- Current “remediation measures” include synchronous condensers
- Synchronous condensers are a very good technical solution but unfortunately their services can’t be monetized at present
- Grid Forming BESS offers the same technical services but also opens up access to revenue streams

Lack of system strength prevents interconnection and increases renewable curtailment







Verified PSCAD model from ESCRI Dalrymple demonstrates technical merits for system strength

Source: https://aemo.com.au/-/media/files/major-publications/qed/2020/qed-q2-2020.pdf?la=en&hash=D1A82334D16E915FCB1B628640A05223

Renewable Interconnection Support – Modelling in PSCAD

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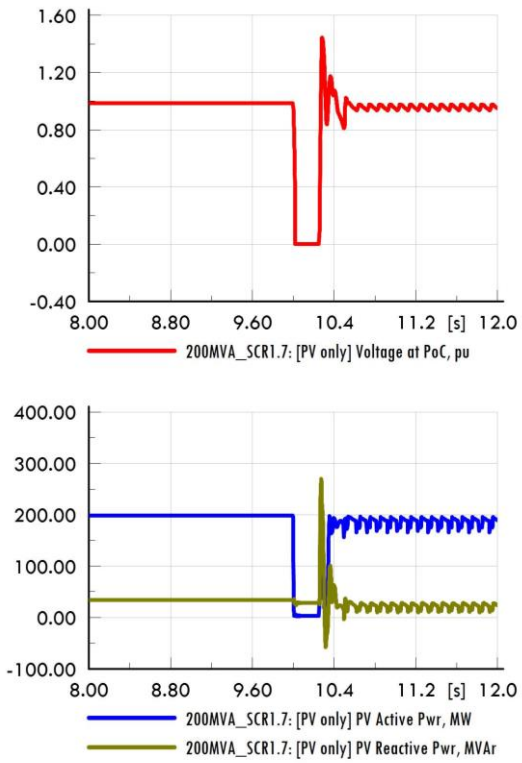
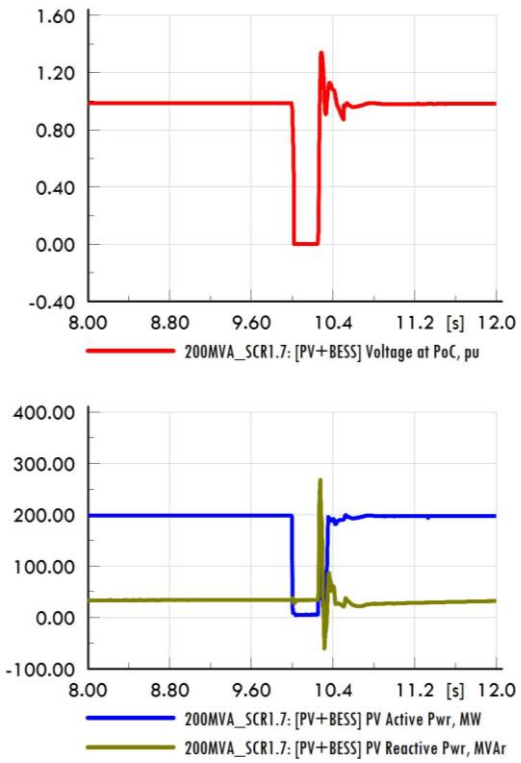
SCR = 1.7

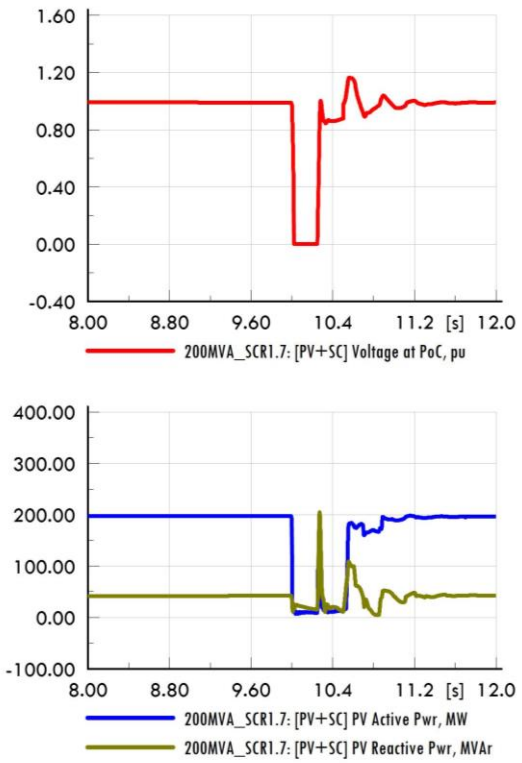
200 MVA PV Plant



200 MVA PV + 30 MVA PowerStore™



200 MVA PV + 32 MVA Sync Con



Post Fault instability resolved by PowerStore™ or Synchronous Condenser

SCR = Short Circuit Ratio

Renewable Interconnection Support – Modelling in PSCAD

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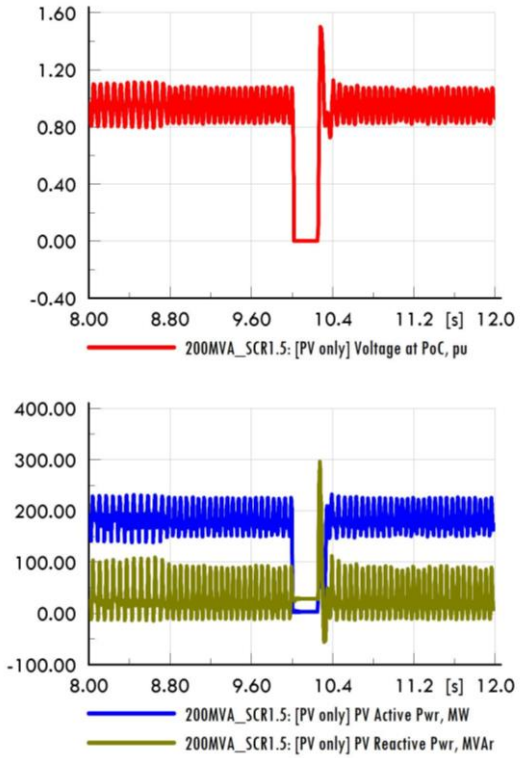
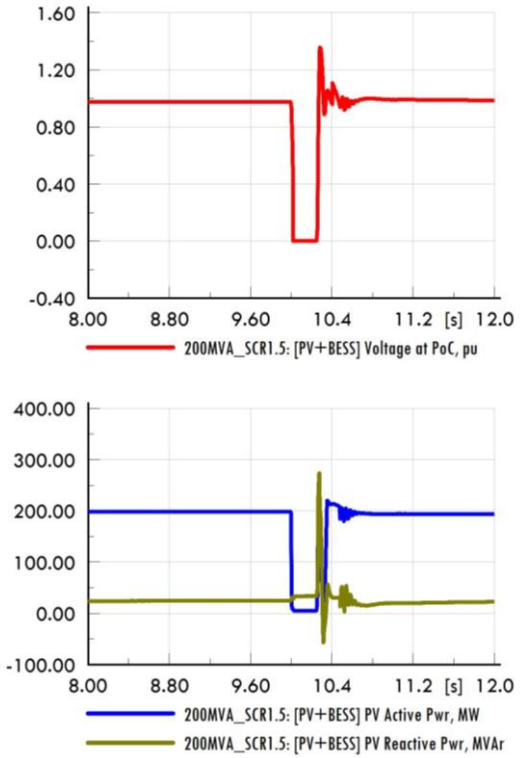
SCR = 1.5

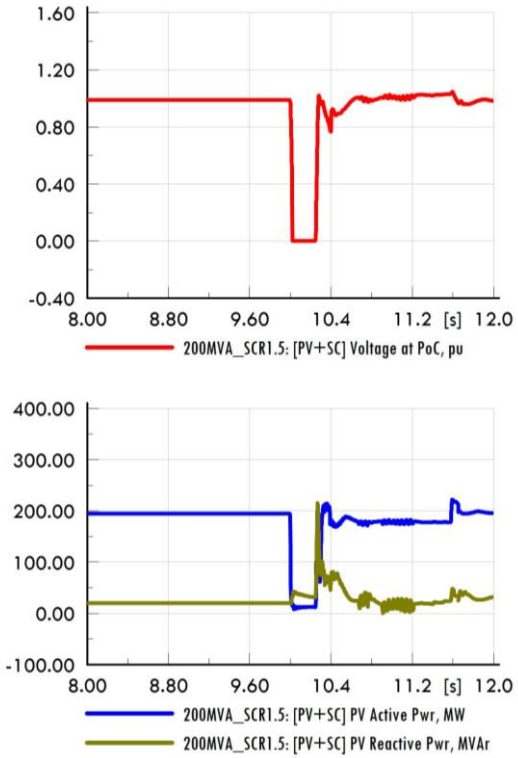
200 MVA PV Plant



200 MVA PV + 30 MVA PowerStore™



200 MVA PV + 32 MVA Sync Con



Steady-State and Post Fault instability resolved by PowerStore™ or Synchronous Condenser

SCR = Short Circuit Ratio

Economics & Commercial Models

Connecting renewables in an economically sustainable way

VSM - A New Technology Class

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How do these solutions fit together?

Grid Stability

Service	Analogue Technology	Digital Technology
Reactive Power	**SVC**	**STATCOM**
Real Power	**Synchronous Condenser***	**VSM***

* Both Synchronous Condensers and VSM can do reactive compensation as a secondary service

	Synchronous Condenser	VSM
Fault Current	**~6 times rating**	**2-3 times rating**
Inertia (MWs/MVA)	**Fixed 1-10 sec (with flywheel)**	**Configurable 0 to >32 sec**

System strength is about more than fault current. It is a combination of fault current, inertia and reducing the impedance to a voltage source and requires modelling to compare synchronous machine and VSM sizing.

You can't just compare fault current contribution

SVC = Static Var Compensator; VSM = Virtual Synchronous Machine

What solution is appropriate?

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Depending on your place in the market, regulation and application, there are a range or technologies

Market Services Focus ⟷ Regulated Services Focus

	Grid Following BESS	Grid Forming BESS (VSM)	Synchronous Condenser
30MVA System			
Duration	**1 Hour**	**20 min**	**A few seconds**
Market Rev. 2019	AUD 6M	AUD 5M	-
Regulated return	-	AUD 1.3M	< 10%
Low SCR Support	No	Yes	Yes
Payback	~ 6 yrs	~ 5 yrs	> 10 yrs
	Developer Owned	Hybrid Ownership Developers + Utilities	Utility Owned

Source: ARENA project costs for Dalrymple 30MVA/8MWh and Ballarat 30MVA/30MWh BESS. Revenue based on Dalrymple and AEMO quarterly energy dynamics Q2 2020
https://aemo.com.au/-/media/files/major-publications/qed/2020/qed-q2-2020.pdf?la=en&hash=D1A82334D16E915FCB1B628640A05223

Commercial solutions to low SCR interconnections

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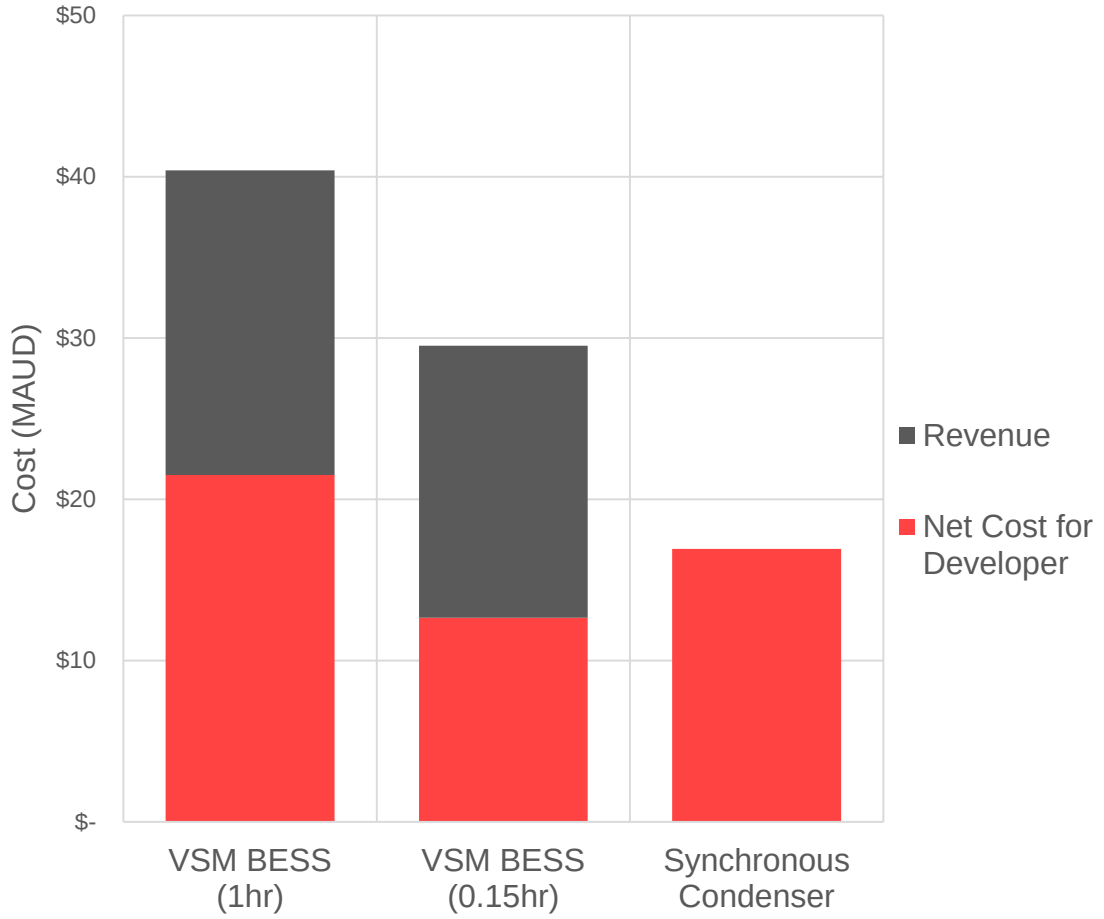
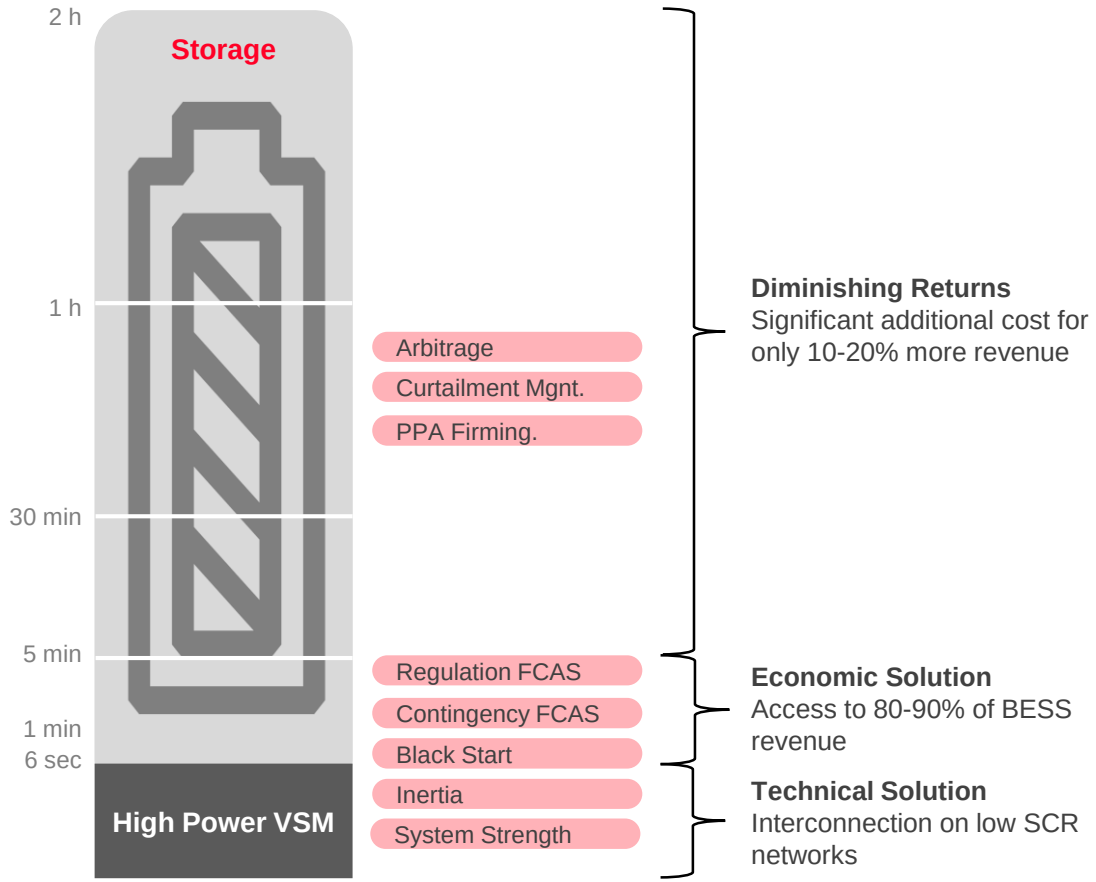
50MVA System After Two Years of Operation



Shorter duration storage makes sense



SCR = Short circuit ratio, FCAS = Frequency control ancillary service, VSM = Virtual Synchronous Machine
Net cost equals installed cost plus OPEX minus revenue. Pricing based on 2020 market data.
Source:https://aemo.com.au/-/media/files/major-publications/qed/2020/qed-q2-2020.pdf?la=en&hash=D1A82334D16E915FCB1B628640A05223

Key Takeaways

Key Takeaways

Summary

- Not all inverters/converters operate the same way
- Grid Following converters (PV & BESS) are affected by stability issues on “weak” networks
- FFR and virtual inertia are different services delivered through different mechanisms
- VSM = Grid Forming + synchronous generator dynamics
- Grid Forming BESS unlocks a range of services not previously possible with BESS
- Allowing synchronous machines to switch off is the key problem VSM solves
- VSM offers developers both an interconnection solution and revenue stream
- VSM offers utilities lower cost regulated services through joint ownership models
- In Australia, 80-90% of energy storage revenue is made in markets no longer than 5 minutes
- High inverter overload is important for stability applications

VSM = Virtual Synchronous Machine; FFR = Fast Frequency Response; PV = Photovoltaic; BESS = Battery Energy Storage System

ElectraNet

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