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

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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
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

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

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

- **Synchronous Generators**
  - Associated with fault levels and short circuit ratios.
  - Operate the system securely and ensure safe protection systems.
  - Required for fault ride through and recovery from faults.

- **Synchronous Condensers**
  - New wind farms with controls

- **HVDC with voltage source converter**
  - SVCs/STATCOMs

- **Load shedding**
  - Capacitors/Reactors

- **BESS**
  - Grid Forming BESS (VSM)
  - Steady operation during normal operation and during disturbances.
  - Limits rapid rate of Change of system frequency (RoCoF).

- **Grid Forming BESS (VSM)**

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.*

**What is system strength?**

**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)

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**Lack of system strength prevents interconnection and increases renewable curtailment**

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


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

- Current

Grid Forming - VSI
Voltage Source Inverter

- Voltage
- Frequency

Virtual Synchronous Machine - VSM
Hitachi ABB PowerStore™

- Voltage
- Frequency
- Dynamics
- Sharing
- Tunable Inertia

Output Grid
Output Grid
Output Grid

CSI = Current Source Inverter (Current controlled)
VSI = Voltage Source Inverter (Voltage controlled)
Virtual Synchronous Machines are critical to allow Synchronous Machines to switch off.
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.
Case Study

ESCR 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
Integration at ElectraNet’s Dalrymple substation

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

BESS building

Dalrymple BESS 30 MW / 8 MWh

Load/DER -1 .. 8 MW

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

Providing both regulated and competitive market services

<table>
<thead>
<tr>
<th>Regulated services¹ (ElectraNet)</th>
<th>Competitive market services (AGL Energy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast frequency response</td>
<td>Ancillary services revenue (FCAS)</td>
</tr>
<tr>
<td>Heywood Interconnector benefit</td>
<td></td>
</tr>
<tr>
<td>Reduced unserved energy benefit</td>
<td>Energy trading</td>
</tr>
</tbody>
</table>

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.
Commercial arrangements

Providing both regulated and competitive market services

- **Funding and commercials**
- **Assets and operation**
- **Services provided to customers and NEM participants**

**Regulated services**
- Reduced unserved energy
- Virtual inertia

**Competitive market services**
- Frequency A/S
- Energy trading

**ElectraNet owns battery & provides regulated services**

**ESCRIBESS**
- Operating control

**AGL leases battery from ElectraNet and is battery operator**
- Availability Guarantee

**ARENA grant part funding**

EPC/D&C contract and 12-year maintenance agreement awarded to Consolidated Power Projects (CPP) following extensive procurement process.
## Key Metrics – First 12 months of operation

<table>
<thead>
<tr>
<th>Key Performance Metric</th>
<th>H1 2019</th>
<th>H2 2019</th>
<th>2019</th>
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</thead>
<tbody>
<tr>
<td>Average BESS Availability</td>
<td>98.01%</td>
<td>97.35%</td>
<td>97.68%</td>
</tr>
<tr>
<td>BESS Charging Cost</td>
<td>AUD 120,000</td>
<td>AUD 101,000</td>
<td>AUD 221,000</td>
</tr>
<tr>
<td>BESS Discharge Revenue</td>
<td>AUD 116,000</td>
<td>AUD 97,000</td>
<td>AUD 213,000</td>
</tr>
<tr>
<td>FCAS Revenue</td>
<td>AUD 1.33M</td>
<td>AUD 3.73M</td>
<td>AUD 5.06M</td>
</tr>
</tbody>
</table>

H1: (14-12-2018 to 14-06-2019)  
H2: (14-06-2019 to 14-12-2019)
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
Virtual Inertia vs FFR

What is the difference and why does it matter?
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 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

Fast Frequency Response (FFR)

Inertia and FFR in the context of frequency support:

RoCoF = Rate of change of frequency


Virtual Inertia is driven by the same physics as synchronous inertia. Response equivalent but tunable.

Power transfer equation:

\[ P = \frac{V_s V_r}{X} \sin \Delta \delta \propto \Delta \delta \]

where:
- \( V_s \) is the sending end voltage (BESS internal voltage)
- \( V_r \) 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 a Synchronous machine:
Virtual Inertia – Tunable inertia

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

- Virtual Inertia
  - Tunable inertia
  - $\dot{\omega} = \frac{1}{H} (\text{grid frequency} - \text{internal speed})$
  - $H \approx \frac{k_d}{d}$
  - $k_d$ (inertia damping gain)
  - $d$ (inertia time constant)
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 Dalrymple disconnects the upstream line
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)
Unplanned islanding with the wind farm
The islanding instant – virtual inertia in action

A. Upstream breaker opens

80% of WTGs disconnected

B. Wind farm’s output is momentarily reduced from ~80 MW to ~27 MW

Upon islanding, frequency is pushed up by the virtual inertia of the BESS reducing slip, electric torque and power output from the WTGs.
**Frequency performance: grid-parallel vs islanded**

Trend: Frequency Frequency (Auto) Average, PQZIP 25/09/2018 04:49:57 PM

- Frequency Average

**Voltage performance: grid-parallel vs islanded**

Trend: RMS Voltage, PQZIP 25/09/2018 04:49:57 PM

- RMS V12 Average

Islanded operation
BESS regulates frequency and voltage

- Islanding
- Resync to grid

Voltage step tests to prove stable operation with SVC at the wind farm
South Australia Islanding Event: Inertia Response
Grid forming inverter responds to frequency change in the network – 8-second view

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
South Australia Islanding Event: Inertia Response

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

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
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

Fast Active Power Injection (Outsourced FFR measurement and detection)

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

BESS grid-parallel fast response: 30 MW in 250 msec
Black start of the local 33 kV distribution network
Soft energisation of large transformers and pickup of 33 kV load feeders in islanded operation

BESS ramps voltage up to energise transformers

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

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

Renewable Interconnection Support – Modelling in PSCAD

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
Renewable Interconnection Support – Modelling in PSCAD

$\text{SCR} = 1.5$

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
How do these solutions fit together?

<table>
<thead>
<tr>
<th>Grid Stability</th>
<th>Service</th>
<th>Analogue Technology</th>
<th>Digital Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reactive Power</td>
<td>SVC</td>
<td>STATCOM</td>
</tr>
<tr>
<td></td>
<td>Real Power</td>
<td>Synchronous Condenser*</td>
<td>VSM*</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Synchronous Condenser</th>
<th>VSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault Current</td>
<td>~6 times rating</td>
</tr>
<tr>
<td></td>
<td>2-3 times rating</td>
</tr>
<tr>
<td>Inertia (MWs/MVA)</td>
<td>Fixed 1-10 sec (with flywheel)</td>
</tr>
<tr>
<td></td>
<td>Configurable 0 to &gt;32 sec</td>
</tr>
</tbody>
</table>

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.

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You can’t just compare fault current contribution
Depending on your place in the market, regulation and application, there are a range or technologies

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

<table>
<thead>
<tr>
<th>30MVA System</th>
<th>Market Services Focus</th>
<th>Regulated Services Focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid Following BESS</td>
<td></td>
<td>Synchronous Condenser</td>
</tr>
<tr>
<td>Grid Forming BESS (VSM)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Duration

<table>
<thead>
<tr>
<th>Market Rev. 2019</th>
<th>1 Hour</th>
<th>20 min</th>
<th>A few seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Market Rev. 2019</td>
<td>AUD 6M</td>
<td>AUD 5M</td>
<td>-</td>
</tr>
<tr>
<td>Regulated return</td>
<td>-</td>
<td>AUD 1.3M</td>
<td>&lt; 10%</td>
</tr>
<tr>
<td>Low SCR Support</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Payback</td>
<td>~ 6 yrs</td>
<td>~ 5 yrs</td>
<td>&gt; 10 yrs</td>
</tr>
</tbody>
</table>

### Payback

- Developer Owned
- Hybrid Ownership
- 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

50MVA System After Two Years of Operation

Shorter duration storage makes sense

Diminishing Returns
Significant additional cost for only 10-20% more revenue

Economic Solution
Access to 80-90% of BESS revenue

Technical Solution
Interconnection on low SCR networks

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.
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