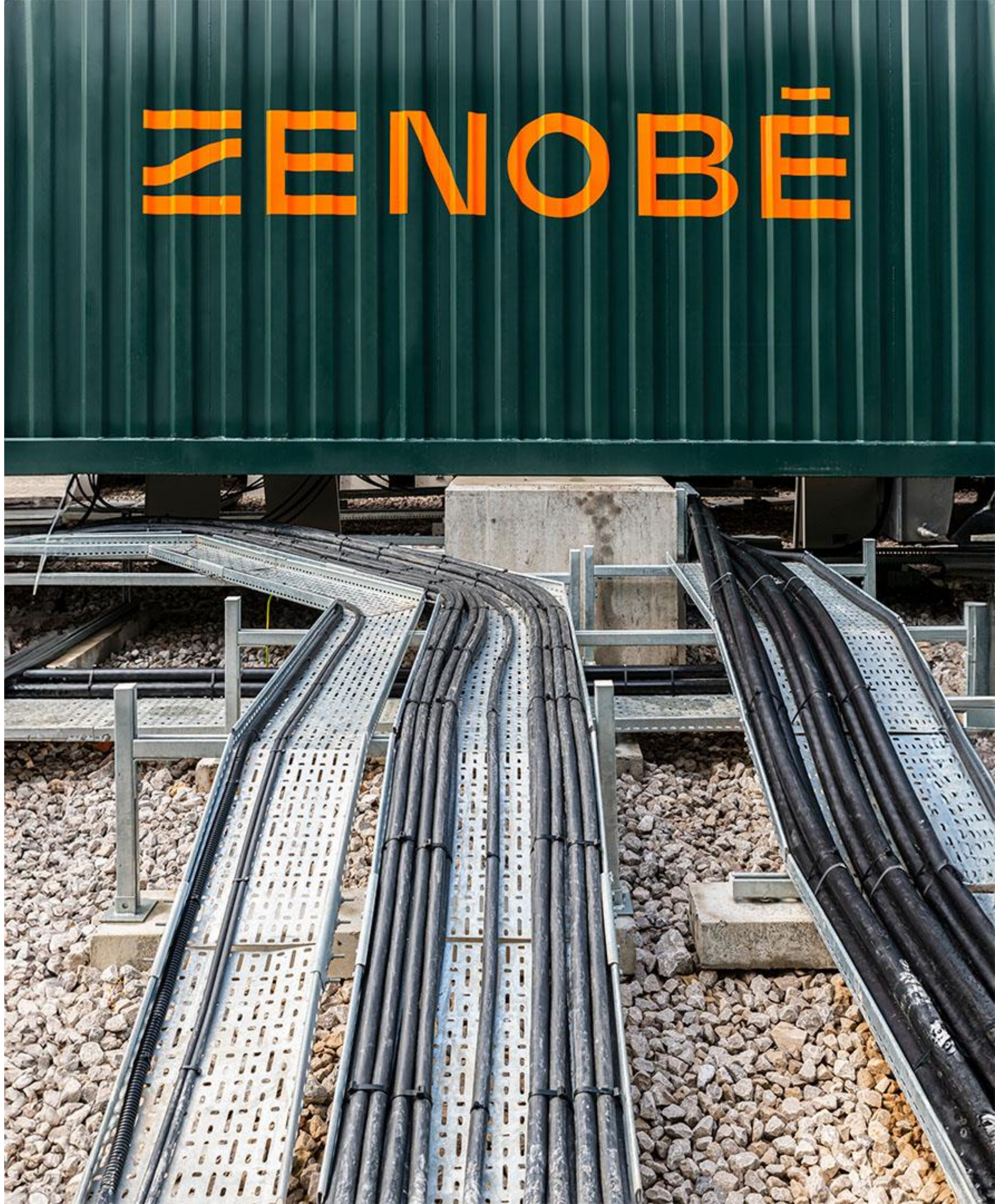
Best Practice: Delivering Grid Forming Battery Energy Storage Projects

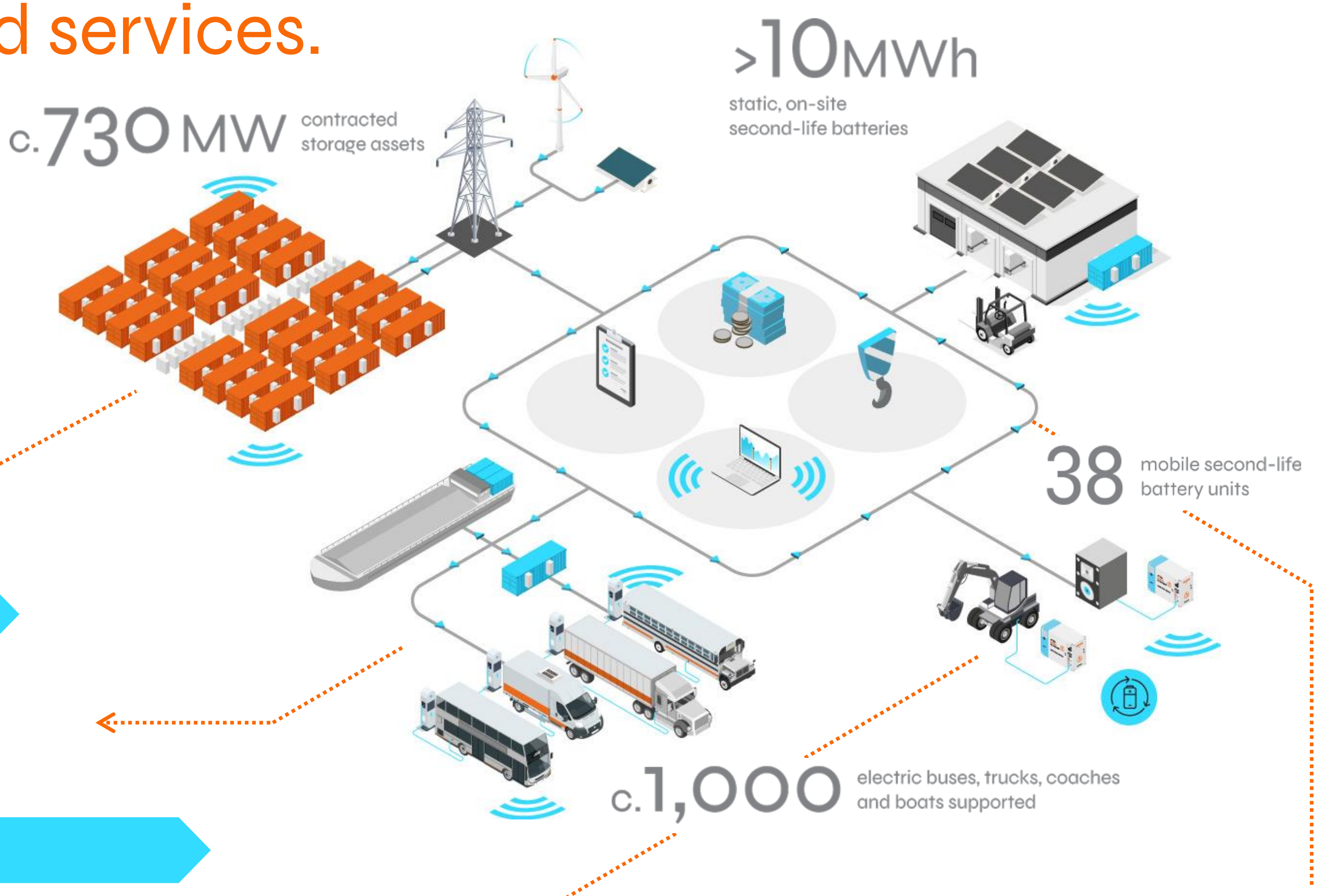
2025

ZENOBĒ

Contents



Zenobē designs, finances, builds and operates battery-based services.



1. Network infrastructure

We develop, finance, build and operate grid-scale battery storage systems.

2. Fleet electrification

We provide end-to-end electric vehicle and software solutions for fleet operators

3. Second life batteries

We support the circular economy of batteries – upcycling, reuse, and recycling.

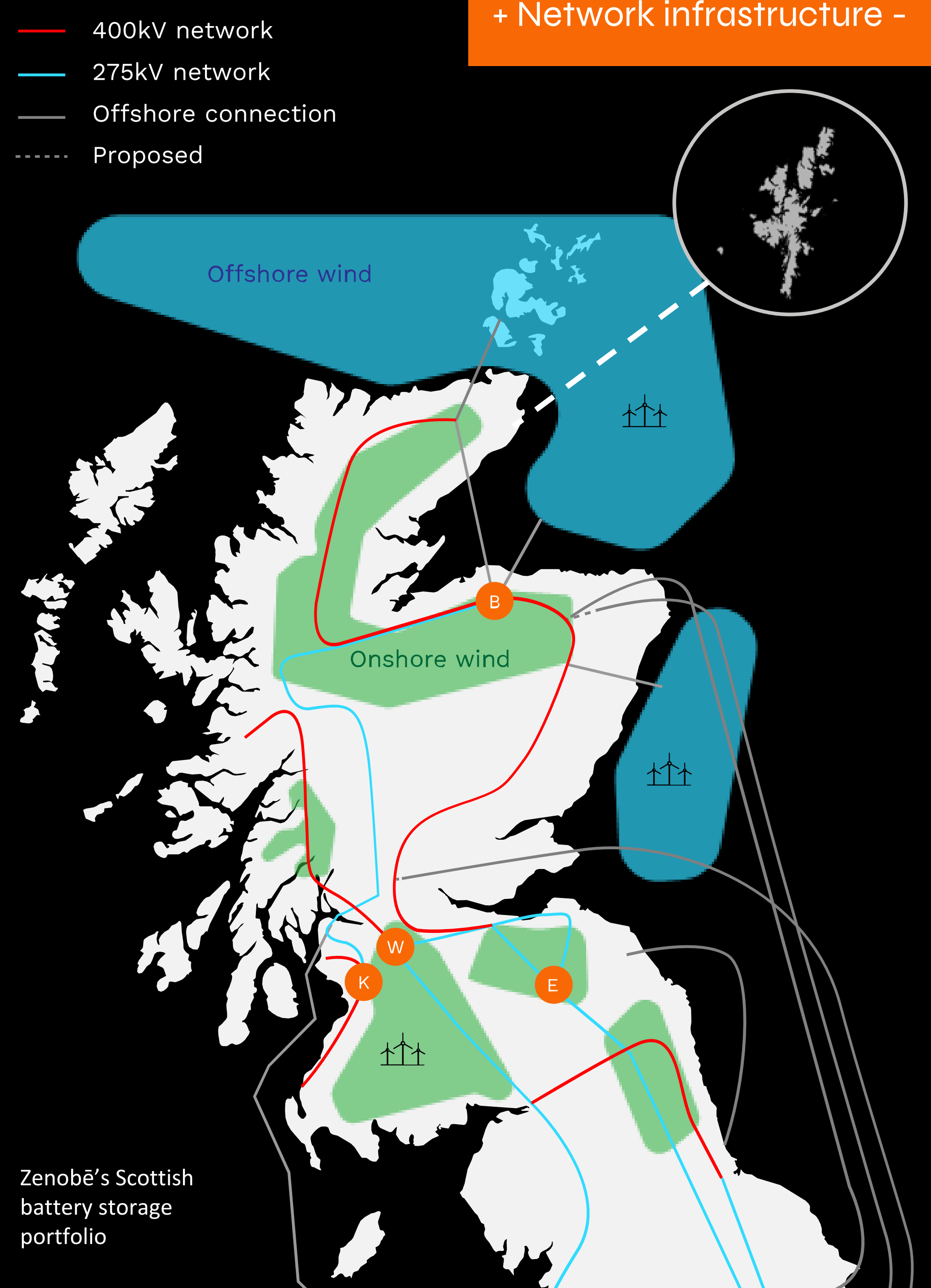
We also offer financing, operational support, software management and construction to help de-risk our battery storage and fleet electrification offerings.

Why do we need grid-scale battery storage?

The rapid uptake of renewables creates challenges for the Electricity System Operator looking to provide clean, affordable and reliable power.

The challenge	The benefits
Renewables create technical and cost challenges for today's network: • Power stability • Managing power line constraints • Balancing power flow demand & supply The cost of managing these issues in the network is passed onto consumers.	• Ensuring low carbon, reliable and affordable network • Avoiding expensive, time-consuming grid upgrades • Reduce dependence on power from fossil fuel generation • Saving CO2 towards the path to net zero • Helping to lower bills for consumers. • Comprehensive end to end support • Track record of successful projects • Bespoke designs and operation

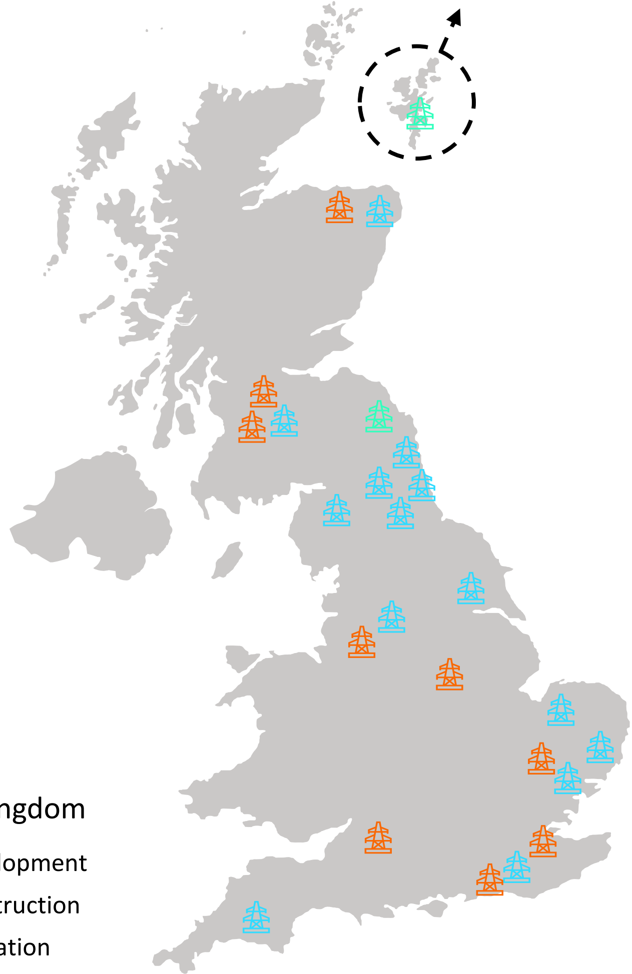
+ Network infrastructure -



Zenobē's Scottish battery storage portfolio

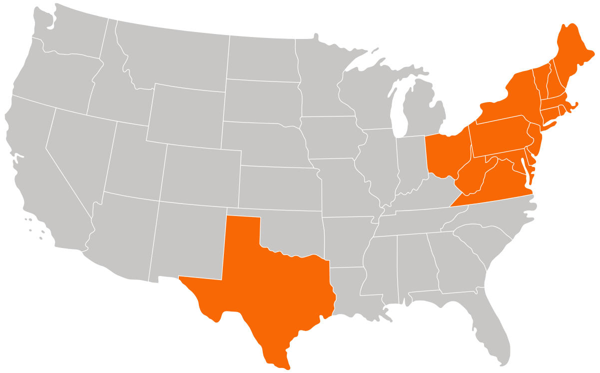
Zenobē has the UK’s #1 transmission-connected portfolio

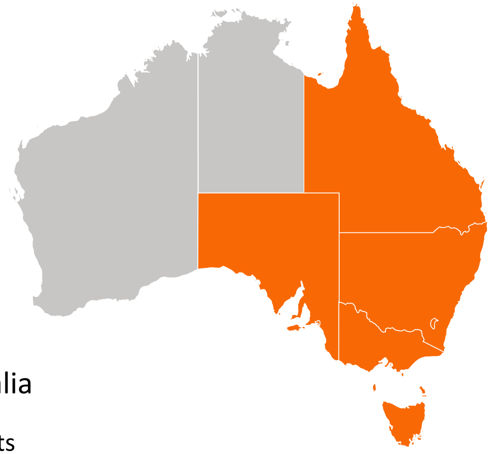
We have c. 1.6 GW / 3.0 GWh of operational, under construction, or other secured assets. We have also expanded to the USA and Australia.



United Kingdom

- In development
- In construction
- In operation





USA and Australia

- Target markets

	Substation location	MW	MWh	COD
Operational & under construction*	King’s Barn	10	10	2017
	Claredown	20	20	2018
	Aylesford	29	29	2018
	Hill Farm	10	10	2019
	Capenhurst	100	100	2022
	Wishaw	50	100	2023
	Brindley	12	24	2023
	Blackhillock	200	400	2024
	Kilmarnock South	300	600	2025
	Shetland	68	136	2027
	Eccles	400	800	2026
	Operational & u/c total	1,199	2,229	
In development	Blackhillock extension	100	300	2027
	Coalburn	200	800	2027
	Stalybridge	150	600	2027
	Harker	400	1,600	2028
	Secured pipeline total	850	3,300	
	Total	2,049	4,100	

We also have additional sites in development beyond this

Blackhillock Grid Forming BESS

On 28th Feb 2025 Zenobe commenced full commercial operations of the first transmission connected Grid Forming BESS project - Blackhillock 200MW / 400MWhr GFM BESS.

During the project development phase, Blackhillock BESS secured commercial contracts through a competitive tender process to provide the following GFM specific services to NESO:

- Inertia – to replace response previously provided by synchronous generation and maintain system stability
- Short Circuit Infeed – enhanced SCL infeed compared "standard" inverter-based connections to maintain system operability and stability
- Enhanced Reactive Power Capability – maximizing capability of inverter systems to offer NESO additional options to manage system voltage and stability issues.

Providing GFM Services

Our GFM BESS solutions are designed to be capable of providing multiple response services simultaneously allowing our plant to support NESO whatever system conditions arise.

This approach is referred to as “stacking” services

Our projects are designed to ensure transient responses such as inertia can still be delivered even when the plant is operating at maximum steady state import / export levels.

The exact level of response provided can be tailored to make each project specific to local network conditions or even adjusted post-connection to adapt to changing NESO needs.

This makes our connections far more flexible and cost effective than “traditional” dedicated solutions such as synchronous compensators or SVCs.

UK GFM Grid Code Compliance Process- Overall

Typical Suite of Tests for Generic GB Grid Forming Plant.

Grid Forming Plant

Tests and Simulations applicable under Grid Code Irrespective of Grid Forming (ECP.A.3 – ECP.A.7)

1) Reactive Capability
2) Voltage Control
3) Active Power Control
4) Power output with falling frequency
5) Frequency Response (LFSM/FSM)
6) PSS Tuning / Damping control
7) Fault Ride Through and Fast Fault Current Injection

+

Grid Forming Plant additional Tests and Simulations (ECP.A.9)

1) Active ROCOF Response Power
2) Active Phase Jump Power
3) Active Damping Power

→

Total suite of Tests and Simulations To be performed on Grid Forming Plant

UK GFM Grid Code Compliance Process - FAT

- Recommended to do the FAT at different testing platform: Hardware in the Loop with multiple controllers(**HIL**) and Physical Power Module test platform(**PHIL**)
- Test procedure shall be agreed with NESO in advance, and witnessed by NESO
- Testing items:
  - a) Test 1: Asses Correct Operation of the Grid Forming Plant Without Saturating
  - b) Test 2 : Assess the Grid Forming Plant's Withstand Capabilities under Extreme System Frequencies
  - c) Test 3 : Assess the Grid Forming Plant's Ability to Supply Active ROCOF Response Power Over the Full System Frequency range
  - d) Test 4: Assess the Grid Forming Plant's Ability to Supply Active Phase Jump Power under normal operation
  - e) Test 5 : Assess the Grid Forming Plant's Ability to Supply Active Phase Jump Power under extreme conditions
  - f) Test 6 : Assess the Grid Forming Plant's Ability to Supply Active Phase Jump Power, Fault Ride Through and GBGF Fast Fault Current Injection during a faulted condition
  - g) Test 7 : Assess the Grid Forming Plant's Ability to contribute Active Damping Power
- Raw data and report shall be submitted and approved by NESO
- Evolving process and requirements – already onto issue 3 of guidance – challenging when changes occur during project delivery

Public

Grid Forming Guidance Note - Issue 3

Appendix C Test Requirements

Summary of Requirements

Appendix 9 outlines the general Grid Forming testing requirements for Users or Non-CUSC Parties to demonstrate compliance with the relevant aspects of the Grid Code, Ancillary Services Agreement and Bilateral Agreement.

This section details the procedure for demonstrating Active ROCOF Response Power. Ideally if the test is being completed as part of a type test on an isolated network and it is possible to change the frequency of the isolated network then the tests should be completed using a variable network Frequency. The Company recognise that it is not possible in a large number of cases to adjust the network frequency of the network to which the Grid Forming Plant is connected. If a suitable test network is not available, performance of the GBGF-I will need to be demonstrated through online monitoring as detailed in CC.6.6 or ECC.6.6 and simulation studies as required under ECP.A.3.9.4 will be required during the Interim Operational Notification Process as provided for under CP.6 or ECP.6 (as applicable).

UK GFM Grid Code Compliance Process - Study

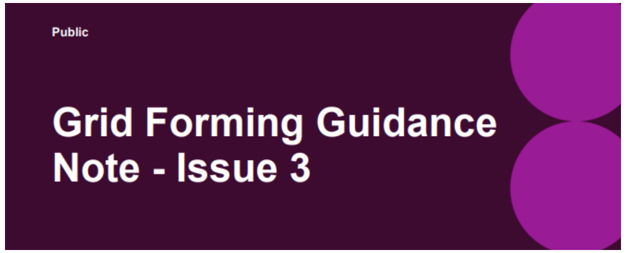
- Schedule 20 as per Table PC.A.5.8.1 and PC.A.5.8.2
- SSO study as per the guidance notes
- GFM Special simulation as per ECP.A.3.9:

1. To supply Active ROCOF Response Power
2. To supply Active ROCOF Response Power and asses its withstand capability under extreme System Frequencies
3. To demonstrate the Grid Forming Plant's ability to supply Active ROCOF Response Power over the full System Frequency range.
4. To demonstrate the Grid Forming Plant's ability to supply Active Phase Jump Power under normal operation
5. To demonstrate the Grid Forming Plant's ability to supply Active Phase Jump Power under extreme conditions.
6. To demonstrate the Grid Forming Plant's ability to supply Fault Ride Through and GBGF Fast Fault Current Injection during a faulted condition
7. To demonstrate the GBGF-I model is capable of supplying Active ROCOF Response Power and Active Phase Jump Power, under extreme conditions.
8. To demonstrate the Grid Forming Plant model is capable of contributing to Active Damping Power

SCHEDULE_20

SCHEDULE 20 – GRID FORMING PLANT CAPABILITY DATA

The following data need only be supplied by **Users** (be they a **GB Code User** or **EU Code User**) or **Non-CUSC Parties** who wish to offer a **Grid Forming Capability** as provided for ECC.6.3.19.3. Where such a **Grid Forming Capability** is provided then the following data items and models are to be supplied in respect of each **Grid Forming Plant**.



Appendix B Simulation Requirements

Summary of Requirements

Grid Code ECP.A.3.9.

1. To supply Active ROCOF Response Power
2. To supply Active ROCOF Response Power and asses its withstand capability under extreme System Frequencies
3. To demonstrate the Grid Forming Plant's ability to supply Active ROCOF Response Power over the full System Frequency range.
4. To demonstrate the Grid Forming Plant's ability to supply Active Phase Jump Power under normal operation
5. To demonstrate the Grid Forming Plant's ability to supply Active Phase Jump Power under extreme conditions.
6. To demonstrate the Grid Forming Plant's ability to supply Fault Ride Through and GBGF Fast Fault Current Injection during a faulted condition
7. To demonstrate the GBGF-I model is capable of supplying Active ROCOF Response Power and Active Phase Jump Power, under extreme conditions.
8. To demonstrate the Grid Forming Plant model is capable of contributing to Active Damping Power

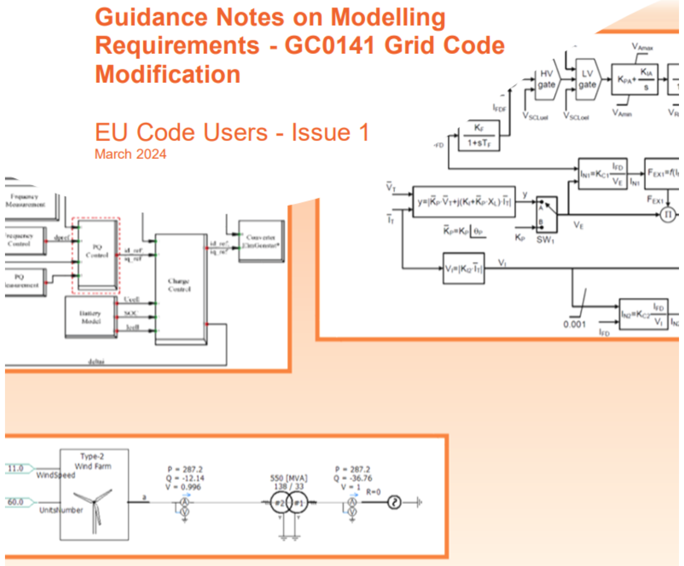
UK GFM Grid Code Compliance Process – Model Submission

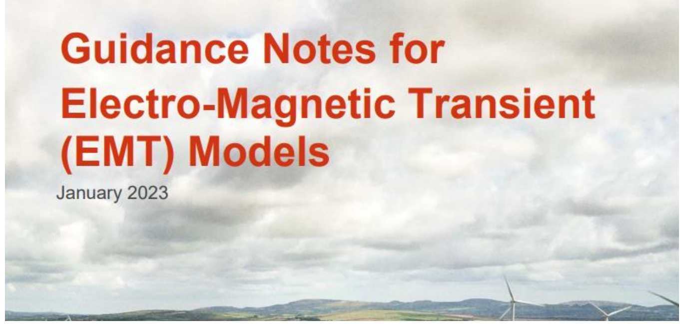
- As per GC0141
- **Both RMS and EMT model need to be provided and approved before issuing ION**

(i) at least 3 months prior to date requested for issue of the Interim Operational Notification

(ii) at least 1 month prior to date of issue of a Limited Operational Notification

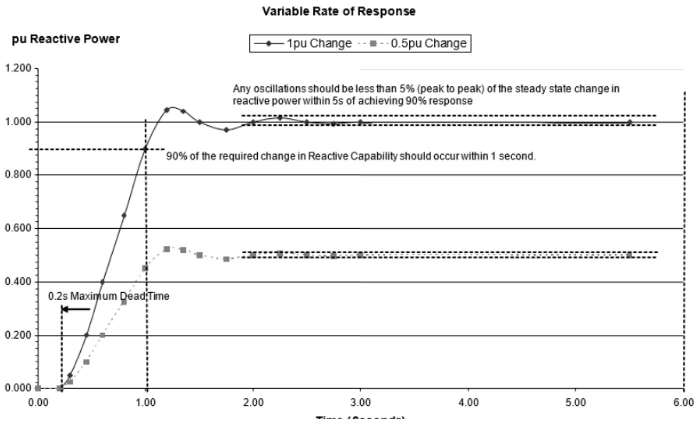
No	Requirement
1	RMS Model submission (**White-box model**)
2	RMS model validation report (referred to PC.A.9.7)
3	RMS model user guidance document
4	EMT Model submission
5	EMT model validation report (referred to PC.A.9.7)
6	EMT model user guidance document
7	RMS and EMT model Voltage and Frequency Controller Model Verification and Validation (referred to ECP.A.3.7) Please note : the action need to be completed after finishing the on-site tests

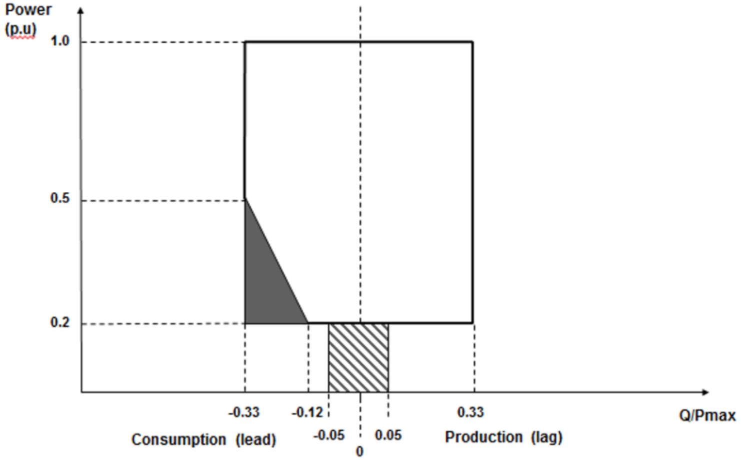


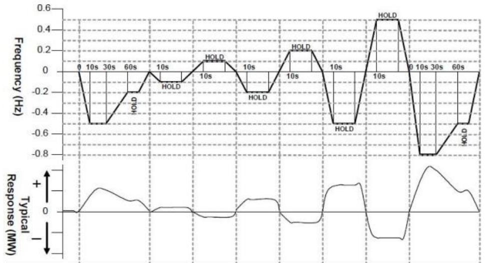


UK GFM Grid Code Compliance Process - SAT

- No special test for Grid-forming related
- Normal Voltage Control test/Frequency control including Deload/LFDD
- Test procedure shall be agreed with NESO in advance

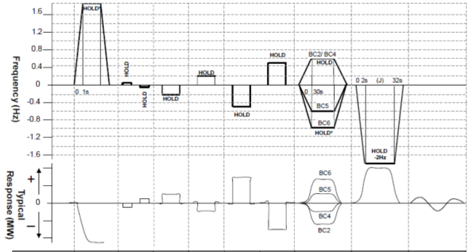






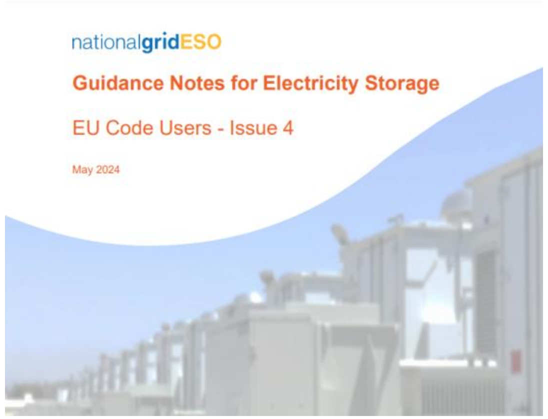
Load Point	LF Event Profile 1	LF Ramp -0.1Hz	HF Ramp +0.1Hz	LF Ramp -0.2Hz	HF Ramp +0.2Hz	LF Ramp -0.5Hz	HF Ramp +0.5Hz	LF Event Profile 2
MLP6			1	2	3		4	
MLP5	5			6			7	
MLP4	8	9	10	11	12	13	14	
MLP3	15						16	17
MLP2	18			19	20	21		22
MLP1	23			24	25			26

ECP.A.6.6. Figure 1 – Frequency Response Capability FSM Ramp Response tests



Load Point	+2.0*	±0.02	-0.2	+0.2	-0.5	+0.5	+/-0.6 -1.0	-2.0	±0**
MLP6	BC1					O	BC2		L
MLP6 LFSM	BC3						BC4		
MLP5					A				
MLP4		D/E	F	G	H	I		J	M
MLP4 LFSM							BC5/6		N
MLP3									
MLP2					P	Q			
MLP1					K				

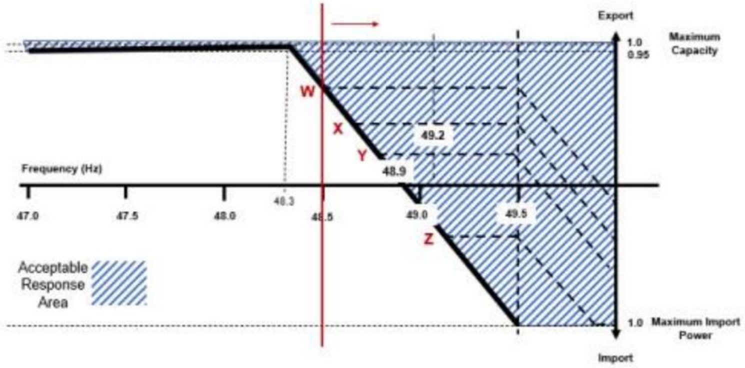
ECP.A.6.6. Figure 2 – Frequency Response Capability LFSM-O, LFSM-U, FSM Step Response tests



Either (1) Low Frequency Demand Disconnection LFDD) function as in OC.6.6.6. For example, for a battery storage module rated at 50MW the storage module would be expected to disconnect 12.5 % of RC for every 0.05 Hz drop in system frequency as shown below.

49.5Hz 6.25MW 12.5% of RC
49.45Hz 6.25MW 12.5% of RC
49.4Hz 6.25MW 12.5% of RC
49.35Hz 6.25MW 12.5% of RC
49.3Hz 6.25MW 12.5% of RC
49.25 Hz 6.25MW 12.5% of RC
49.2Hz 6.25MW 12.5% of RC
49.15Hz 6.25MW 12.5% of RC

All the demand expected to be tripped at 49.15Hz.



UK GFM Grid Code Compliance Process - Monitor

- Dynamic System Monitoring(DSM) shall be installed as per ECC.6.6.1.2, the setting of which shall be approved by NESO
- The according resolutions shall be met as per ECC.6.6.3

(i) 1 Hz for reactive range tests

(ii) 10 Hz for frequency control tests

(iii) 100 Hz for voltage control tests

(iv) 1 kHz for **Grid Forming Plant** signals including fast fault current measurements

(v) 100Hz for the other **Grid Forming Plant** tests carried out in accordance with ECC.6.6.1.9(1 kHz as per Mid-year Stability Market requirement)

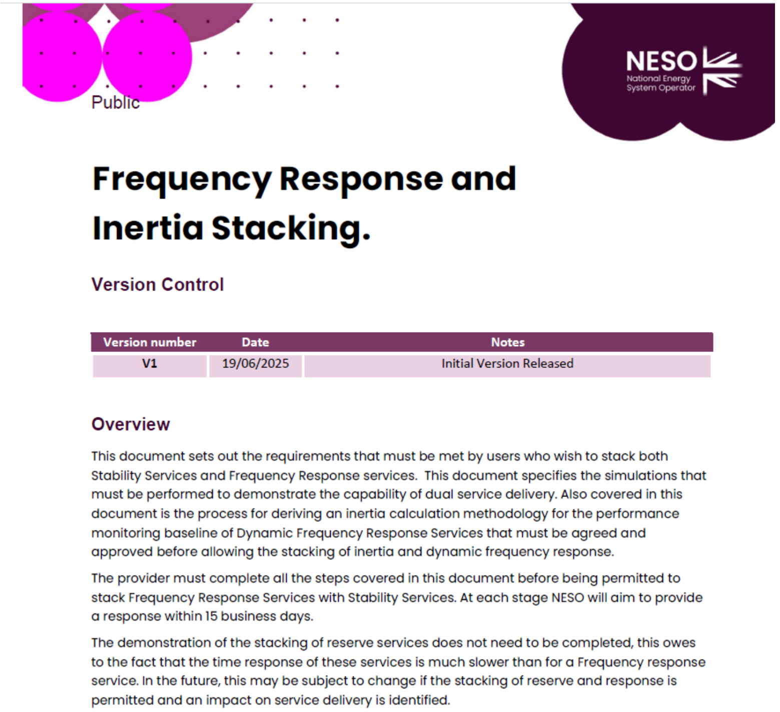
- As per the latest Mid-year Stability Market requirement: Install additional monitoring equipment for the purpose of performance monitoring, this equipment should be capable of recording frequency, voltage, active and reactive power and current at a sampling rate of no less than 100Hz. This data should be held by the User for at least 28 days. The accuracy of all Active Power, Reactive Power and their derived quantities should be at least +/- 1%

National Grid Technical Specification	Dynamic System Monitoring (DSM) TS 3.24.70 (RES)- Issue 2 - February 2018

DYNAMIC SYSTEM MONITORING (DSM)

UK GFM Grid Code Compliance Process – Stacking

- Inertia behaviour will affect the MW delivery
- Any asset that participate the Ancillary service(Dynamic Regulation/Moderation/Regulation), the response has strict tolerance to avoid revenue clawback
- A series of studies need to be carried to assess the Inertia stacking with frequency response
- A baseline methodology shall be developed to assess the Inertia contribution which can be then removed from the overall MW response before assessing the ancillary service performance



Public

NESO
National Energy System Operator

Frequency Response and Inertia Stacking.

Version Control

Version number	Date	Notes
V1	19/06/2025	Initial Version Released

Overview

This document sets out the requirements that must be met by users who wish to stack both Stability Services and Frequency Response services. This document specifies the simulations that must be performed to demonstrate the capability of dual service delivery. Also covered in this document is the process for deriving an inertia calculation methodology for the performance monitoring baseline of Dynamic Frequency Response Services that must be agreed and approved before allowing the stacking of inertia and dynamic frequency response.

The provider must complete all the steps covered in this document before being permitted to stack Frequency Response Services with Stability Services. At each stage NESO will aim to provide a response within 15 business days.

The demonstration of the stacking of reserve services does not need to be completed, this owes to the fact that the time response of these services is much slower than for a Frequency response service. In the future, this may be subject to change if the stacking of reserve and response is permitted and an impact on service delivery is identified.

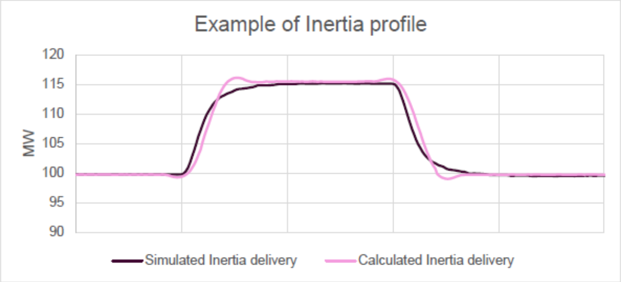


Figure 4: Calculated Inertia vs Delivered

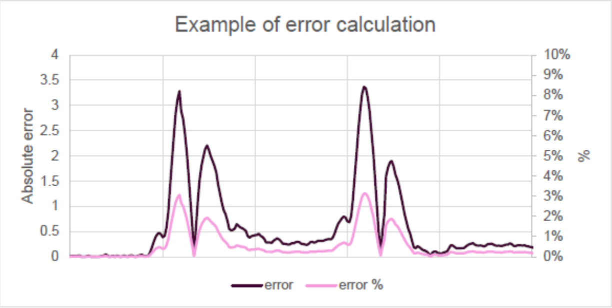


Figure 5: Calculated Inertia

Delivering Live Stability Service to NESO

On 14th March 2025 3 large synchronous power station units tripped, causing a loss of generation infeed exceeding the *Infrequent Infeed Loss Limit* causing system frequency to drop below operational limits

Public

Detailed timeline

Slido code #OTF

Based on the currently available NESO's system data and evidence, the timeline of events is as follows:

Time	Activity	Source
08:51:37	**DRAX-1 tripped** from 654.94MW. The system frequency was at 50.12Hz	NESO
08:51:42	**DRAX-2 and DRAX-3 tripped** from 612.51MW and 609.52MW, respectively.	NESO
08:52:00*	Three pump storage units instructed with a total of 370MW.	NESO
08:52:09	The system frequency reached its nadir at 49.667Hz. The estimated total cumulative infeed loss was around 1877MW.	NESO
08:53:00*	400MW of small BMUs instructed and 500MW of batteries that were PN'd to come off were instructed to keep on.	NESO
08:53:06	Optional Fast Reserve dispatched with a total of 600MW.	NESO
08:53:32	The system frequency returned above operational limit (49.8Hz) within 3 minutes and to 50Hz in 12 minutes.	NESO

No DNOs have reported customer impacts.

All three generating units became available by 13:10 hrs

*This is the most accurate time stamp available at the moment

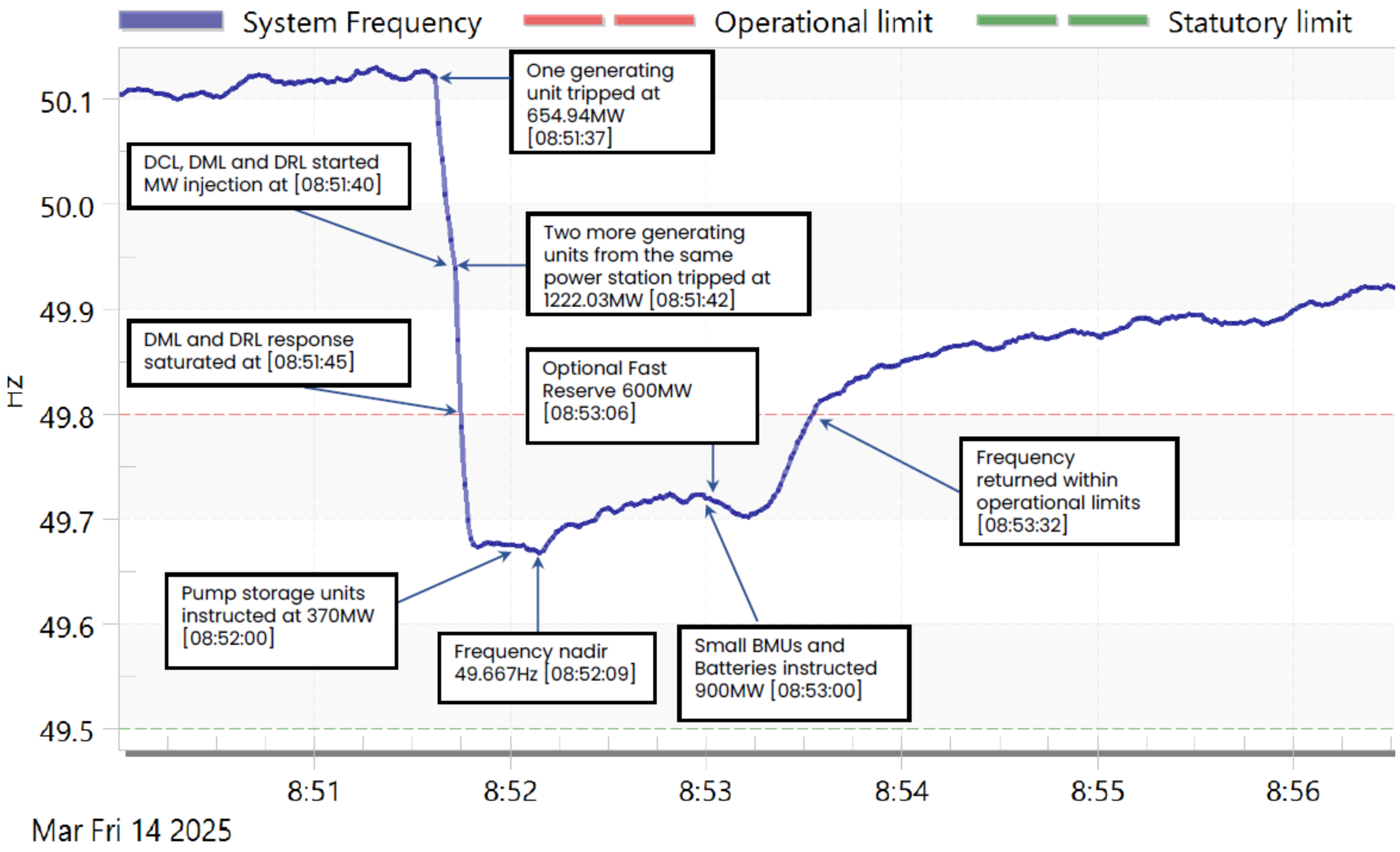
Generation Unit	Infeed Loss	Cumulative Infeed Loss
A large generating unit	654.94MW	654.94MW
Two more generating units from the same power station	1,222.03MW	1,876.97MW
Reported embedded generation infeed loss	None	1,876.97MW

NESO National Energy System Operator

Source: NESO Operational Transparency Forum

Effect on System Frequency

Under normal conditions, NESO will maintain system frequency within the operational limits of 50.2Hz – 49.8Hz. Events causing frequency to exceed these limits are considered significant



- A combination of automatic and manual response actions are required to arrest the frequency fall and restore the balance between demand and generation, returning the frequency to within operation limits
- If the frequency fall cannot be arrested, there is a risk of customers losing supply or even a complete network blackout
- Zenobe’s Blackhillock BESS plant provides automatic response in the form of the inertia service it is contracted to delivery under its Stability Pathfinder 2 contract
- Response of this nature from inverter-based connections will be vital in ensuring a decarbonised transmission system remains robust against events of this nature

Blackhillock BESS Pre-Trip Operating Conditions

The following describes the operating conditions of Blackhillock BESS prior to the event

- Blackhillock BESS has a 200MW / 400MWhr capacity
- The site was in Limited Frequency Sensitive Mode (10% droop)
  - i.e. not participating in any frequency response markets such as DC/DM/DR or MFR
- The site was in Voltage Control mode (4% droop) with a target voltage of 1.02 p.u. having been instructed by NESO
- The site is split into 4 ~50MW BMUs, each can be dispatched to a different MW level
- At the time of the event the BMU operating points were as shown below:

BMU LEVEL

T_BLHLB-1:
Dispatch (BOA @ 49 MW)

T_BLHLB-2:
Dispatch (BOA @ 49 MW)

T_BLHLB-3:
Dispatch (BOA @ 48 MW)

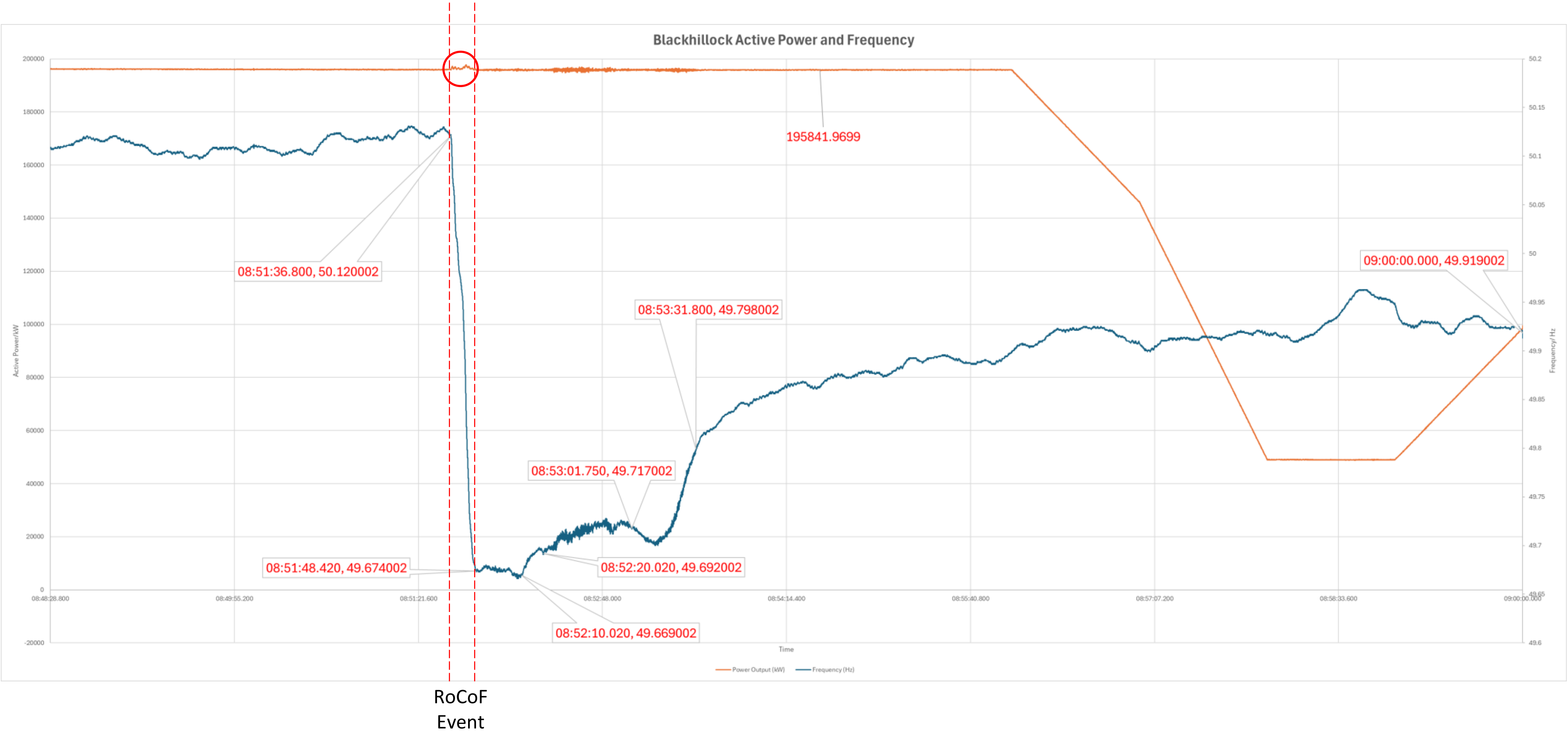
T_BLHLB-4:
Dispatch (BOA @ 52 MW)

- This translated to a total MW export to the transmission system of 196MW – i.e. close to full export capability
- The Blackhillock site has been designed to the ensure full contracted inertia response can still be provided even when the site is operating at 100% import / export levels.
- The contracted level of inertia response is 380MWs. For a 1Hz/s Rate of Change of Frequency (RoCoF)

Blackhillock BESS Inertia Response (1)

Zenobe's Dynamic System Monitor can record frequency and active power with a 100Hz sampling rate

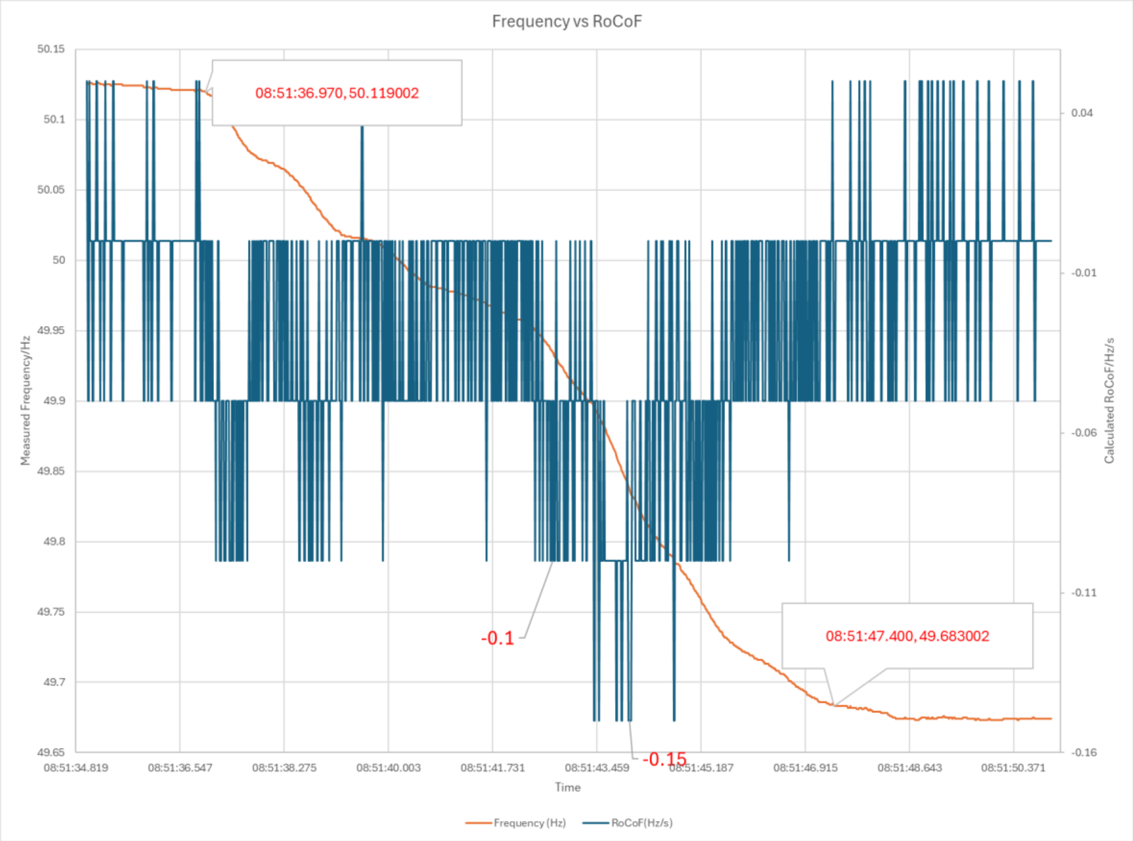
- The graph below shows the Frequency (blue) and the Blackhillock BESS Active Power (orange)
- The inertia response is observed during the RoCoF event
- The inertia response is shown in greater detail on the following slide



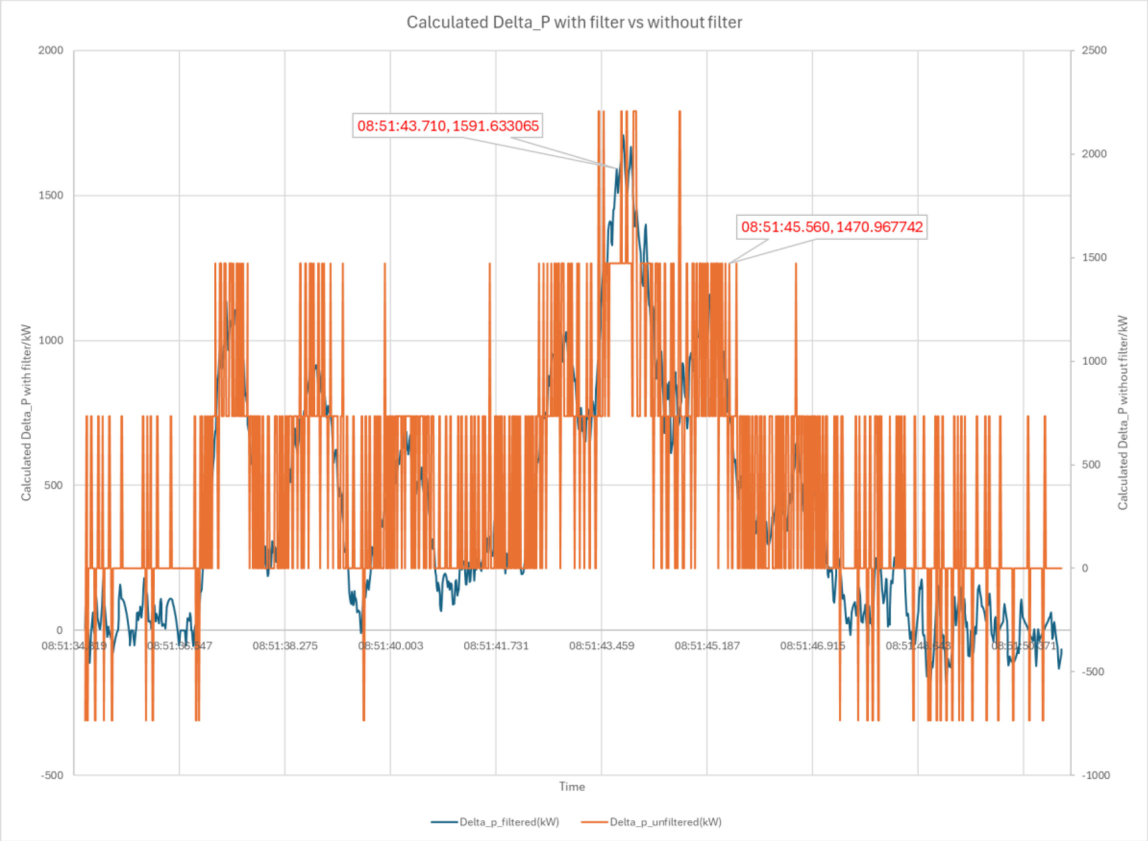
Blackhillock BESS Inertia Response (2)

The RoCoF event occurred between 08:51:36 to 08:51:48

- Despite the large loss of generation and resulting frequency change, the RoCoF event remained at -0.1Hz/s
- The contracted response under the SP2 contract is 380MWs. For a 1Hz/s RoCoF (equating to Δ P = 15.2MW)
- For the 0.1Hz/s RoCoF, it can be seen that the Δ P = 1.6MW



Frequency vs *calculated RoCoF*

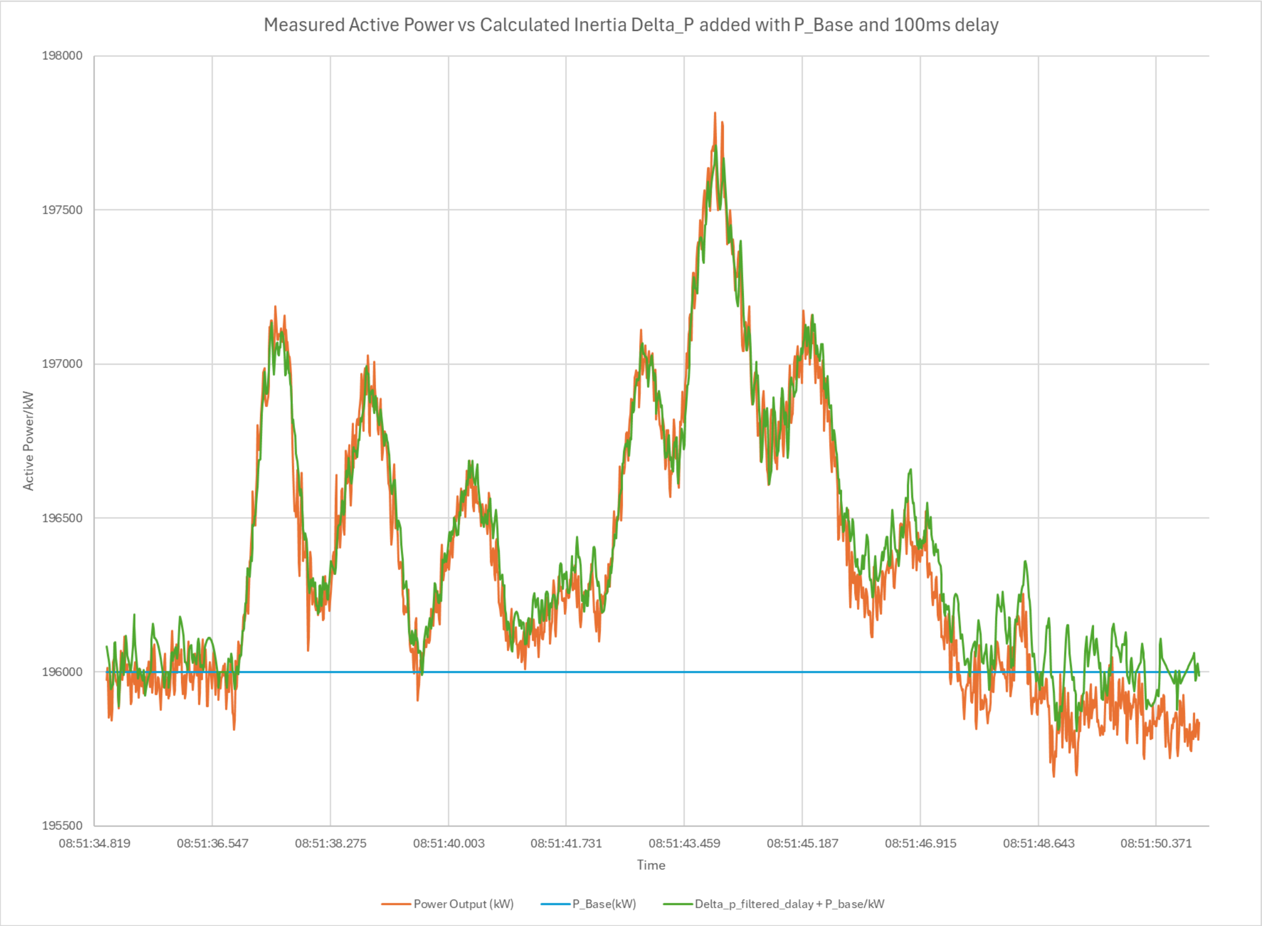


Directly calculated Inertia in MW with RoCof without filter vs with filter

Expected Inertia Response vs Actual Performance

Using NESO's method for calculating inertia, it is possible to compare expected and actual inertia response during the RoCoF event

- Inertia is calculated as follows: $$\textbf{Inertia} = \frac{\Delta P\, f_0}{2 \times RoCoF}$$
- Zenobe has calculated the expected inertia response across the RoCoF event (100Hz sampling rate)
- This expected response (i.e. increase P output) has been added to the initial total P observed at the PoC prior to the event.
- The measured active power output was then overlayed
- It can be seen that the expected (green) and actual (orange) response during the RoCoF event are closely aligned

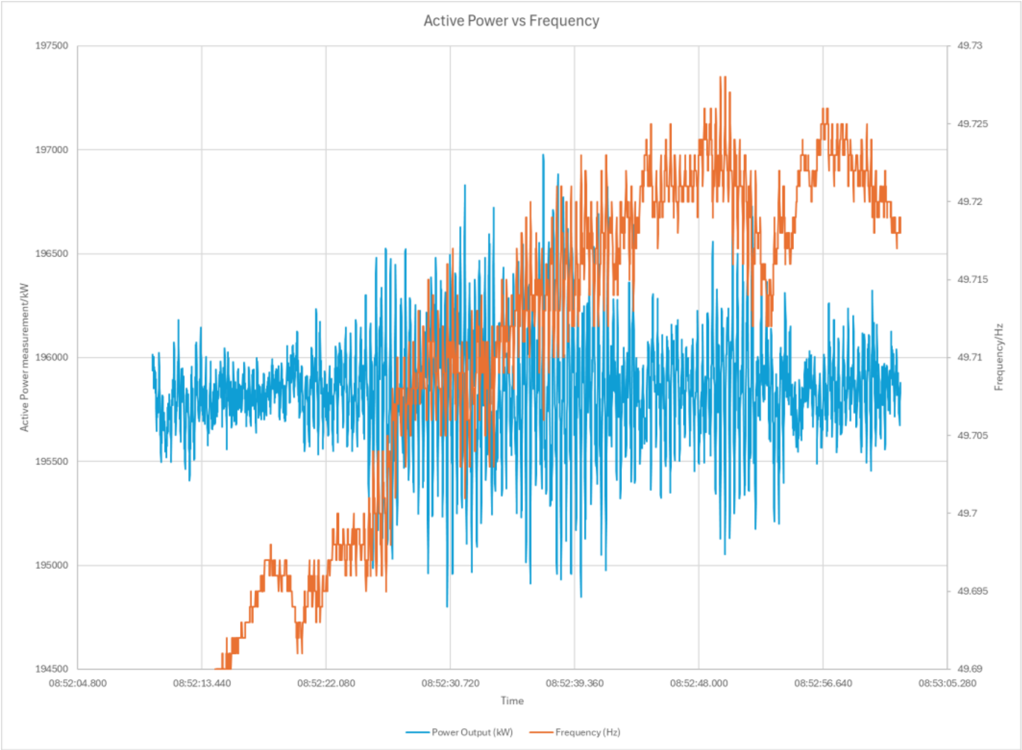


Blackhillock BESS Contribution to Damping

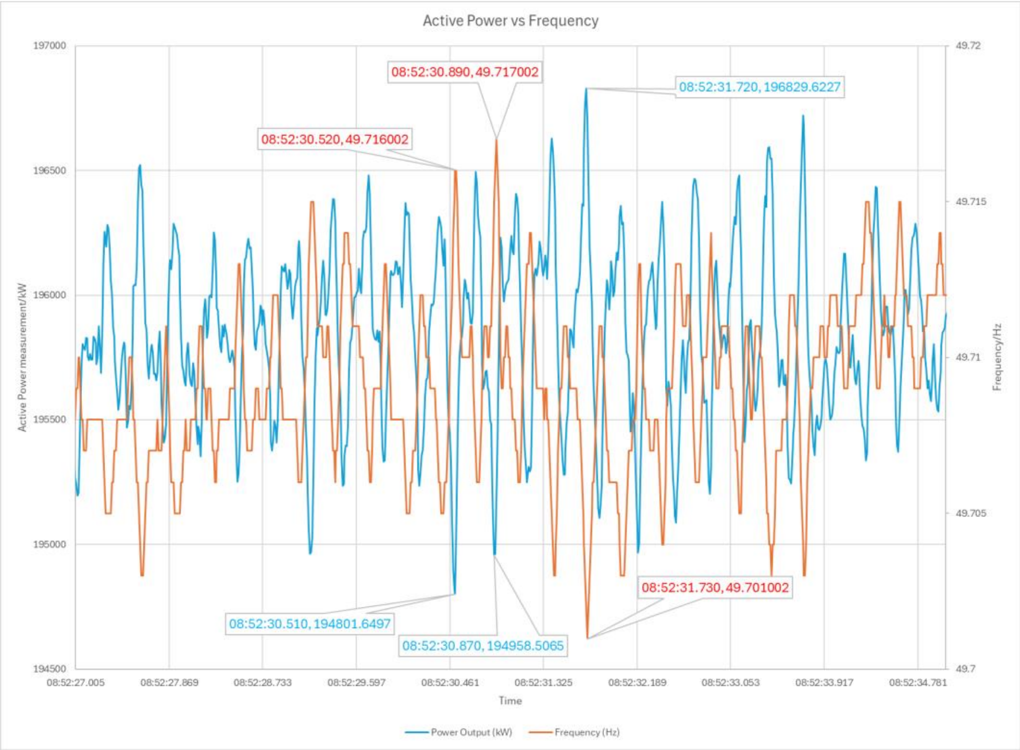
The Blackhillock BESS provided positive damping contribution following the RoCoF event helping to maintain system stability

- Following the RoCoF event (08:51:36 to 08:51:48) sub-synchronous oscillations in system frequency were observed from 08:52:10 to 08:53:02
- Frequency was oscillated between 49.7Hz to 49.717Hz, with the oscillation frequency of around 3Hz

- Examining the active power and frequency more closes shows that the GFM-I provided the **anti-phase damping** and thus acted to return the frequency to a stable state
- The peak-to-peak value was 194.8MW to 196.8MW



Measured Active Power and Frequency

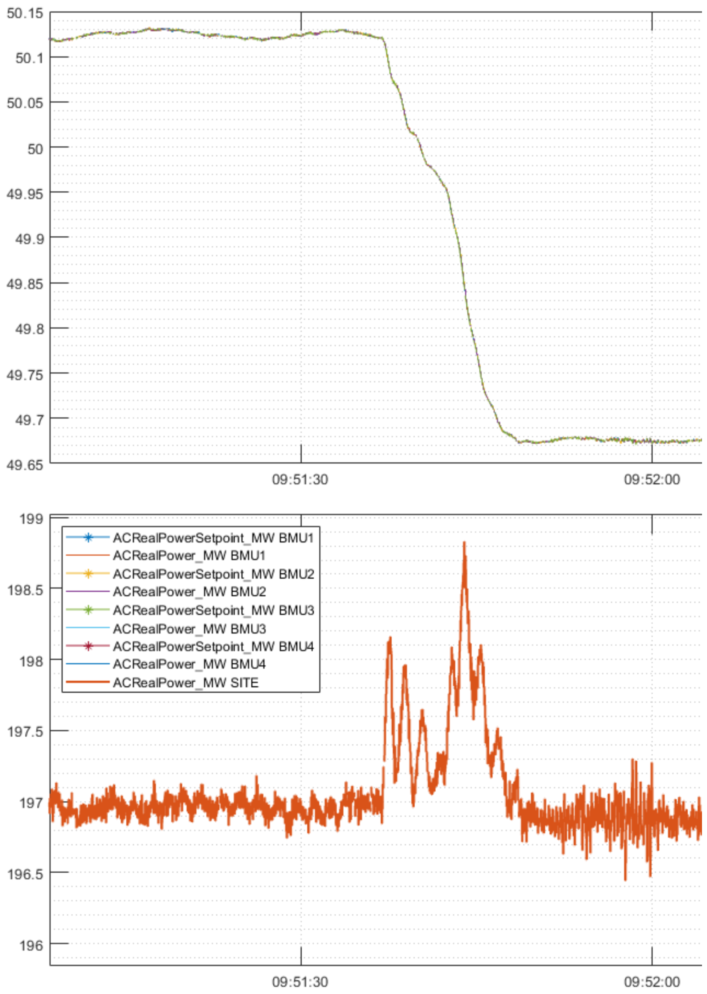


Zoom in Measured Active Power and Frequency to show the phase relationship

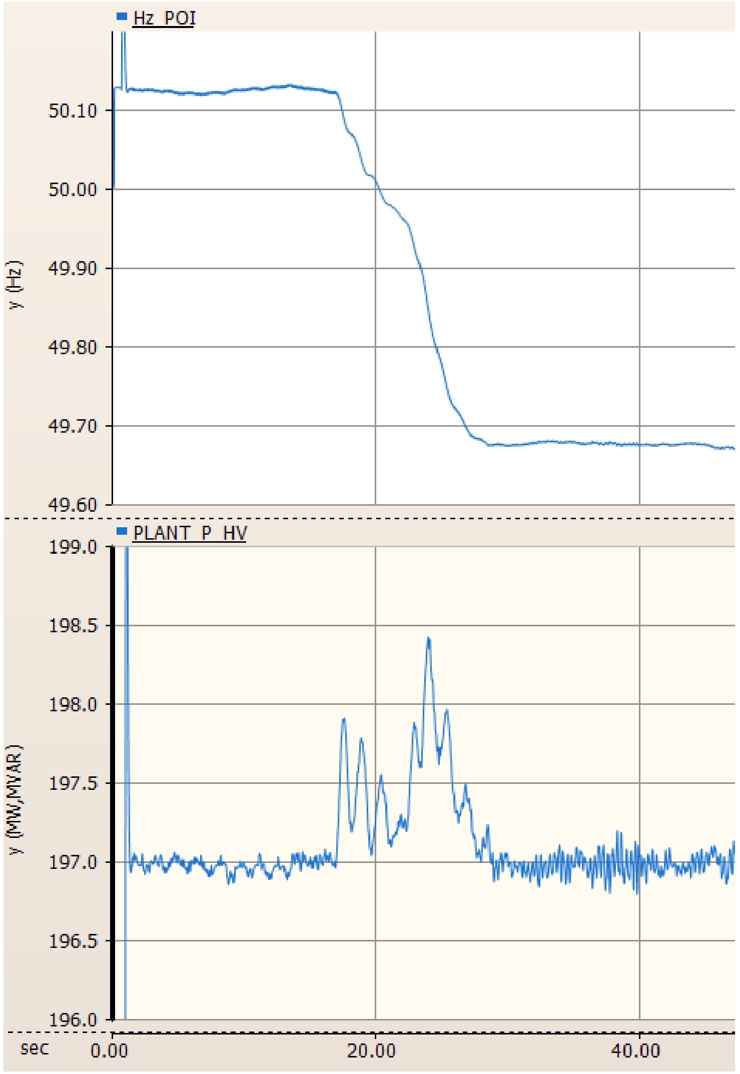
Validation of Models (1)

Actual inertia response was compared against simulation models

- The actual event frequency data was input to a PSCAD simulation
- The graphs on the left show the actual measured grid frequency and the active power output from Blackhillock BESS
- The graphs on the right show the simulated active power output when the actual grid frequency was used an input
- The results showed a perfect match between actual site behaviour and the EMT simulation



Actual Active Power and Frequency

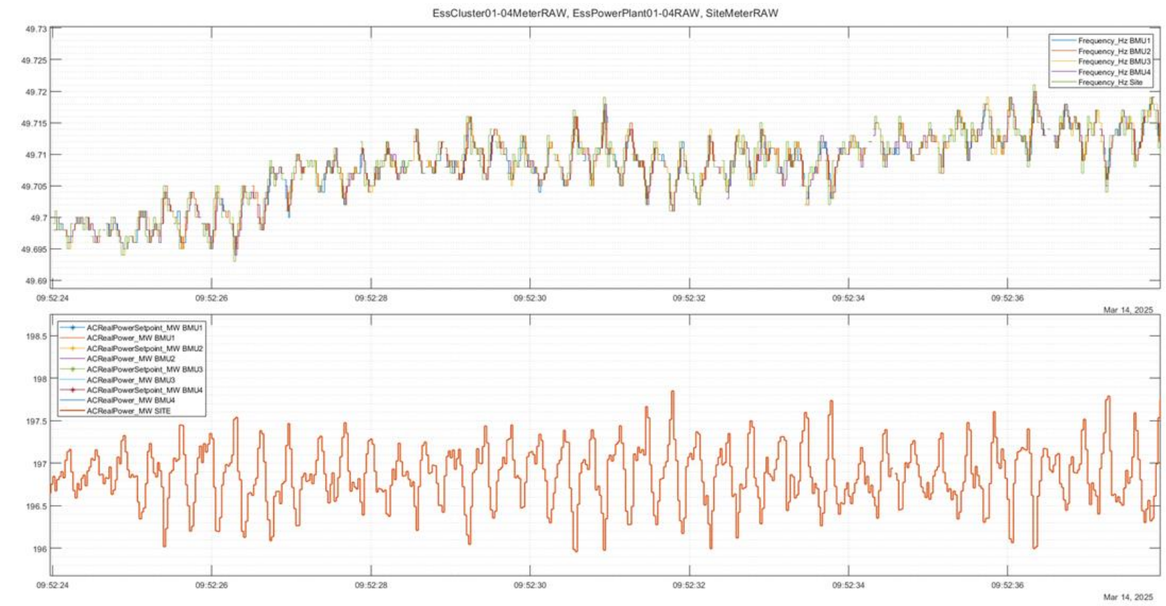


Simulated Active power with using actual Frequency

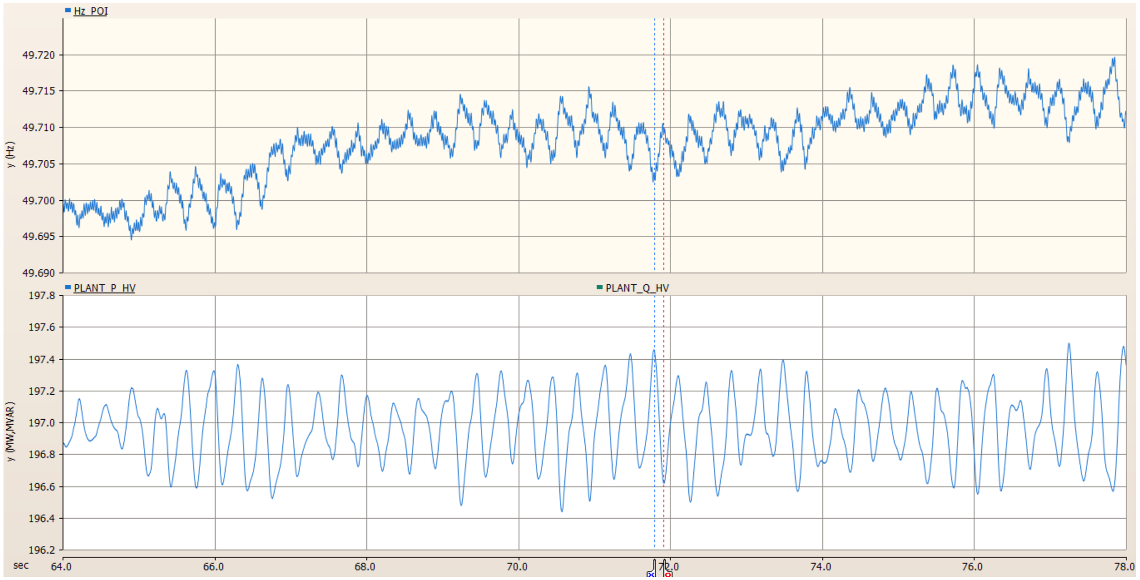
Validation of Models (2)

Actual damping performance was compared against simulation models

- The actual event frequency data was input to a PSCAD simulation
- The graphs on the left show the actual measured grid frequency and the active power output from Blackhillock BESS
- The graphs on the right show the simulated active power output when the actual grid frequency was used an input
- The results showed a good match between actual site behaviour and the EMT simulation



Measured Active Power and Frequency



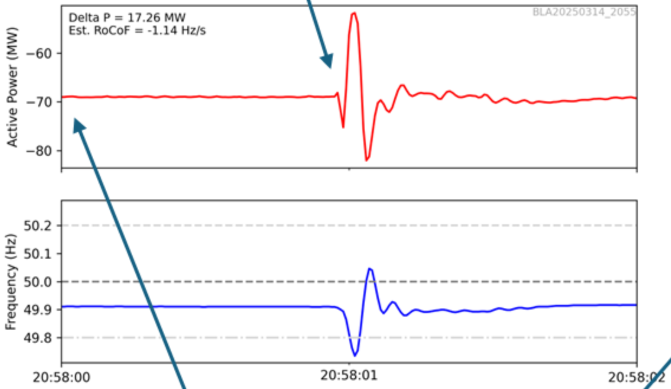
Simulated Active power with Frequency Injection via PSCAD

Other Stability events targeted by Blackhillock GFM BESS

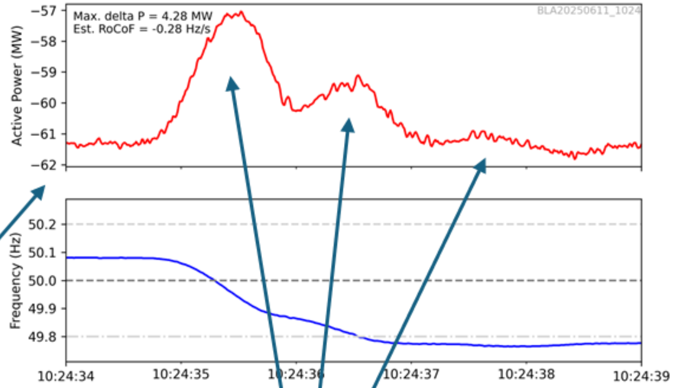
Date	Frequency (Hz)			RoCoF		Power (MW)			Source
	Pre	Post (NESO)	f_min	NESO	Max (Zenobe)	Initial	Delta	Infeed loss	
14-Mar-25	49.91	*n/a*	49.73	*n/a*	-1.14	-69	17.3	*n/a*	*Possible phase angle jump*
11-Jun-25	50.08	49.77	49.77	-0.216	-0.28	-61	4.3	1192.75	*Sizewell trip*
27-Apr-25	49.961	49.774	49.77	-0.183	-0.34	0	5.2	986.9	*Viking HVDC trip*

Maximum designed response supports the network

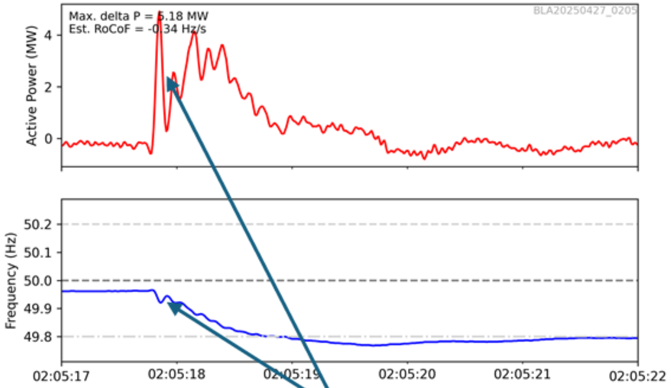
Frequency disturbance
14th March 2025



Loss of generator infeed (~0.9GW)
11th June 2025 / Sizewell



HVDC trip (~1.4GW)
27th April 2025 / Viking



Supporting instability within the overall event

Correct response provided through the plants operational range

Continues to support the network over the duration of the event

Similar overall response characteristic to similar loss of infeed events

Lessons Learned and Next Steps

Zenobe has worked closely with OEMs and NESO to bring the largest GFM BESS to market.

Our main lessons learned are:

- **Success of market signals** – the NESO Stability Pathfinder process incentivized Zenobe to develop the Blackhillock GFM project. We would encourage NESO to continue to use this model to incentivize developers to bring new technology to market.
- **Compliance** – our project delivery has happened in parallel with NESO development of codes and standards for GFM technology. Simulation and modelling requirements for GFM far exceed that for “standard” connections.

Next Steps:

- **Development of standards and process –** we will look to continue working closely with NESO to develop GFM requirements seeking to find the balance between NESO obligations to system security and practical requirements for developers.
- **More GFM Projects!** – Zenobe is delivering the 2nd GFM projects at this moment, COD is expected by end of 2025.

QUESTIONS