ES Cornwall Memorial Scholarship

Fourth Quarter Report

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National Grid ESO, Warwick, United Kingdom

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I would also like to thank my managers at Energy Queensland, Alan Louis and Terese Milford, for their support in allowing me to undertake this opportunity. I am looking forward to my return to the Intelligent Grid New Technology team and using the experiences I have gained to help during what is shaping up to be an exciting time as Queensland and Australia pursues a highly renewable future.

Finally, thank you to the ES Cornwall Memorial Scholarship and its Board for this fantastic opportunity. I have no doubt that this chance to gain international experience will help me become a more well-rounded engineer and I endeavour to bring this experience back to Australia to hopefully share and contribute to the ongoing development of the Australian electricity supply industry.

DISCLAIMER

This report provides a summary of the experiences and work undertaken by the author during the period of July 2023 – September 2023 as part of an overseas ES Cornwall Memorial Scholarship placement. Statements and material contained within this report are the opinion of the author and do not reflect the opinion or positions of any other person or organisation. Reproduction or referencing of this report should also reflect this.

EXECUTIVE SUMMARY

The Australian electricity supply industry is in the midst of a rapid transition to an electricity network with a high penetration of renewable generation reliant on inverter-based resources to connect these to the grid. Many obstacles to facilitate this future have already been overcome, however there are still significant challenges associated with moving away from the traditional synchronous generation that has reliably powered the electricity industry for a number of decades.

During my time as an ES Cornwall Scholarship holder I hope to explore a number of these challenges and learn from some of the leading European organisations in this field to help grow my capabilities and understanding of how Europe intends to complete this transition. I am hoping to return to Australia with this knowledge that will not only help me in my day-to-day nominal role, but also I am hoping to share my experiences more broadly to express gratitude for this opportunity that has been afforded me.

This quarterly report is the fourth and final of four reports I have submitted during my time as an ES Cornwall Scholarship holder and covers my final three months with National Grid ESO. In these three months, I have completed my time as a Power System Engineer in the Product Operability team. In the early sections of this report, I will provide an overview of some of the key roles and functions of an electricity system operator which builds on the introduction to the Great Britain electricity network that I provided in my previously submitted third quarterly report. Following this I will provide a more specific overview of the work I have been focusing on over the last three months including:

1. A study into the effects regional inertia has on RoCoF and frequency variance across the GB network,
2. The future of stability markets in the UK.
3. Presentations given and a site visit to The National HVDC Centre.

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GLOSSARY

Table 1: List of acronyms and terms with their meaning.

Acronym/Term	Meaning
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
BM	Balancing Mechanism
BOA	Bid Offer Acceptance
DER	Distributed Energy Resource
DSO	Distribution System Operator
EV	Electric Vehicle
EMT	Electromagnetic Transient
ESO	Electricity System Operator
ETYS	Electricity Ten Year Statement
FSO	Future System Operator
HVDC	High Voltage Direct Current
IBR	Inverter Based Resource
MSCR	Minimum Short Circuit Ratio
NEM	National Electricity Market
NG	National Grid
NGV	National Grid Ventures
Ofgem	Office of Gas and Energy Markets
PMU	Phasor Measurement Unit
RMS	Root Mean Square
RoCoF	Rate-of-Change-of-Frequency
SCL	Short Circuit Level
SCR	Short Circuit Ratio

1 SCHOLARSHIP PLAN / OVERVIEW

The problem statement that I will be addressing during my time as an ES Cornwall Scholarship holder is:

"Maintaining Stability in an Electricity Network with a High Penetration of Distributed Energy and Inverter Based Resources"

This motivation is driven by the challenges currently being experienced in Australia regarding the energy transition. The Australian energy industry is continuing to face unprecedented growth in renewable energy technology and distributed energy resources (DERs). A result of this is that the industry of today looks very different from ten years ago, and this change will only continue to accelerate as Australia transitions to the network of the future. To ensure this transition takes place as smoothly as possible, with both consumers and industry in mind, there are several key areas of complexity that must be addressed. One of these is the need to ensure that the electricity network maintains an adequate level of network stability and resilience in the face of significant change to the fundamentals that the network was built upon – namely one-way energy flow from centralised large synchronous generators.

Network stability is a multi-faceted problem, with two of the main aspects being system strength and inertia. System strength is defined by the Australian Energy Market Commission (AEMC) as a "characteristic of an electrical power system that relates to the size of the change in voltage following a fault or disturbance on the power system[1]". The system strength at any given location is proportional to the fault level at that location. Similarly, frequency stability is linked to system inertia and the ability of the network to resist high rates of change of frequency (RoCoF) in the event of significant active power changes.

Networks with low system strength and low inertia are susceptible to several issues including wider area undamped voltage oscillations, prolonged voltage recovery after disturbance, instability of generator and dynamic plant voltage control systems, mal-operation of protection equipment and increased harmonic distortion[2]. In the past, synchronous machines have traditionally provided system strength. Meanwhile, inverter-based resources (IBRs) are reliant on adequate system strength to operate reliably but do not necessarily contribute positively to overall system strength. This is because the fault level contribution from synchronous generators is high, whereas system strength is inversely proportional to grid-following IBR penetration since the fault level contribution of IBRs is low[3]. With the growing penetration of IBRs causing the make-up of Australia's energy generation to swing more towards IBRs, synchronous generators are slowly being phased out. This is therefore leading to decreasing system strength which then has the flow-on effect of limiting the amount of IBRs that can be added to the network. The key question is therefore how the Australian energy industry can increase renewable energy production from IBRs whilst also ensuring an adequate level of system strength.

The challenges being brought on by increasing levels of DERs are not likely to slow down. Connected rooftop solar capacity in Queensland is already estimated to be over 3,346 MW with approximately one-

[1] AEMC. (2017). *National Electricity Amendment (Managing power system fault levels) Rule 2017*. Australian Energy Market Commission.
[2] AEMO. (2020). *System Strength in the NEM Explained*. Australian Energy Market Operator.
[3] Keller, J., & Kroposki, B. (2010). *Understanding Fault Characteristics of Inverter-Based Distributed Energy Resources*. NREL.

in-three households having rooftop solar installed[4]. The further development and cost reduction of other DER technologies, such as battery storage and electric vehicles, will also serve to increase the level of DER penetration on the distribution network. The best time to act and plan for a high DER future with significant contribution from IBRs is therefore the present and implementing effective management plans will help smoothen the transition from the grid of the past to the grid of the future.

In my role as a Technology Innovation Engineer at Energy Queensland I am fortunate enough to be able to work in an area that I am passionate about; helping to enable new technologies in the distribution network and aiding the transition to an energy network with a higher penetration of DERs. While I have had some exposure to the challenges relating to network stability in a highly inverter-based network, I would love the opportunity to gain more of an understanding about how the energy industry as a whole can tackle this problem by observing what is being done overseas. My aim would be to then bring these learnings back to Australia to help the Australian energy industry best transition to a higher DER future.

To fulfil my proposed problem statement and target the challenges outlined above, I will be looking to achieve the following key aims while undertaking work placement overseas;

- Learn from leading network operators on what they are currently doing and plan to do to help modernise their energy network and allow for a high penetration of DERs;
- Undertake work with manufacturers of products that are providing solutions to network stability problems to gain a better understanding of the technology and how it can be best integrated in a distribution network;
- Improve my overall understanding of network stability challenges and how these can be collaboratively managed by all stakeholders of the electricity supply industry;
- Learn how international countries are enabling customers to make the most of new technologies such as solar, wind, energy storage and electric vehicles; and
- Use my time overseas to attend international conferences, workshops and company site visits outside of what I have been exposed to in Australia.

Table 2 shows the schedule I have currently planned for my time as an ES Cornwall Memorial Scholarship holder.

Table 2: Planned placement and conference schedule.

Dates	Activity
28/08/2022 – 02/09/2022	2022 CIGRE Paris Session
September 2022 – April 2023	KEMA Labs – Test Engineer
April 2023 – October 2023	National Grid ESO – Power System Engineer
16/05/2023	Utility Week
October 2023	Return to Australia

[4] RenewEconomy. (2020). *Rooftop Solar's Stunning Surge to New Records, As Australia Installs Reach 2.5 Million.*

2 PLACEMENT 2 – NATIONAL GRID ESO

2.1 NATIONAL GRID INTRODUCTION/BACKGROUND

National Grid (NG) is an energy company that operates within the UK and US and delivers both electricity and gas. NG consists of the following business areas:

1. Electricity Distribution [5] : Distribution company for 8 million customers spanning across 55,300 km^2 in the Midlands, South Wales and South-West of the UK.
2. Electricity Transmission: Owns and maintains the transmission network in England and Wales.
3. Electricity System Operator (ESO): ESO for Great Britain – England, Scotland and Wales.
4. United States[6]: In the United States, National Grid is an electricity, natural gas and clean energy delivery company serving the energy needs of 20 million people in New York and Massachusetts.
5. National Grid Ventures[7] (NGV): Operating across the UK, Europe and the US, NGV develops, operates and invests in large-scale clean energy infrastructure. Separate to the regulated operations of NG, NGV has a diverse business profile including subsea electrical interconnectors, wind and solar generation, electricity transmission, battery storage and conventional generation.
6. National Grid Partners[8]: Dedicated to advancing the energy systems of tomorrow, NG Partners is involved with incubating and investing in start-ups at the intersection of energy and emerging technology. NG Partners' portfolio already includes 41 investments.

For my six-month placement I will be an employee at National Grid ESO and will therefore focus more on the operations of the ESO. While a member of the National Grid Group, the ESO is a regulated business and is therefore also subject to a regulatory framework governed by the Office of Gas and Electricity Markets (Ofgem). This regulatory framework[9], known as RIIO (Revenue = Incentives + Innovations + Outputs), is how Ofgem review the business plans of NG ESO and determines the allowed revenue and how the operations and performance will be assessed.

In 2021, Ofgem and the Department for Energy Security and Net Zero begun consultation to form a Future System Operator (FSO) which would be an expert, impartial body with responsibilities across both the electricity and gas networks[10]. This decision was to drive progress towards net zero and is a result of the need being identified to design, construct, and operate a smarter, more flexible and more integrated energy system. This proposal would see the FSO take on the current role played by NG ESO, combine this with the national gas system operator and add new and additional functions as required. The FSO is proposed to be independent from commercial entities as well as separate from the day-to-day operations of the government This proposed transition to an FSO means significant changes within NG ESO and significant transformational work is currently underway to prepare for the estimated 2024 changeover date.

[5] National Grid, (2023). *Distribution Area. https://www.nationalgrid.co.uk/our-network/distribution-area-search*
[6] National Grid, (2023). *Serving our Customers and Communities. https://www.nationalgrid.com/us*
[7] National Grid Ventures, (2022). *Who we are. https://www.nationalgrid.com/national-grid-ventures*
[8] National Grid Partners, (2023). *Investing in the Potential of Energy. https://www.nationalgrid.com/national-grid-partners*
[9] National Grid ESO, (2023). *How we're regulated. https://www.nationalgrideso.com/what-we-do/how-we-operate/how-were-regulated#How-Ofgem-regulates-ESO*
[10] National Grid ESO (2022). *The Future System Operator (FSO).* https://www.nationalgrideso.com/what-we-do/our-strategy/future-system-operator-fso

Currently, the core functions of the ESO are summarised as[11]:

- Balancing Services: The ESO is responsible for procuring services to balance demand and supply in the GB network as well as ensuring the security and quality of supply through processes such as, demand flexibility service, frequency response, reactive power services and system security services.
- Electricity Transmission System Charges: Manging charges that users of the electricity transmission system must pay. This includes Balancing Services Use of System charges (to recover the day-to-day costs of balancing the system and operating the transmission network), Transmission Network Use of System charges (to recover the cost of installing and maintaining the transmission system) and connection charges (to recover the cost of installing and maintaining connection assets which connect individual users to the transmission system).
- Industry Engagement and Reporting: As the system operator, the ESO is responsible for consulting with industry, providing several publicly available reports and making operational data available to ensure efficient and cost-effective decision making in the GB electricity industry.
- Connections: The ESO connections team is responsible for facilitating the process through which customers can connect and utilise the GB transmission network.
- Network Access Planning: The ESO's network access planners assess, coordinate and sanction the planned release of transmission system assets for maintenance and the commissioning of new equipment. This helps ensure access to the transmission system is coordinated efficiently to be cost-effective and to ensure operation of the system continues to be within the required quality of supply standards.
- Electricity System Codes Administration: The ESO administers four codes that govern the GB electricity system operation. These are, the Grid Code (technical code for the connection and development of the national transmission network), the Connection and Use of Systems Code (contractual framework for connecting to and using the national transmission network), the System Operator – Transmission Owner Code (defines the relationship between the transmission system owners and the ESO) and the Security and Quality of Supply Standard (defines the criteria and methodology for planning and operating the national transmission network).

NG ESO has multiple locations around the UK with the main two sites being in Warwick and Wokingham. For most of my time with NG I will be based in the Warwick office however I will have the occasional trip to Wokingham if required for project work or in-person meetings with colleagues located in Wokingham.

[11] National Grid ESO, (2023). *Industry Information. https://www.nationalgrideso.com/industry-information*

2.2 AN OVERVIEW OF ELECTRICITY SYSTEM OPERATION

The following section is a high-level overview of the role of an electricity system operator that I compiled during my time with NG ESO.

2.2.1 BALANCING SUPPLY AND DEMAND

Balancing supply and demand is one of the core responsibilities of an electricity system operator as this ensures that all load on the network is met in real-time. This means that the system operator must forecast and monitor demand on the network and dispatch generation accordingly to successfully meet this demand. NG ESO achieves this through the use of a balancing mechanism (BM) with its function as follows:

- The BM is NG ESO's primary tool to acquire the required amount of generation to balance supply and demand on the GB network.
- The BM uses a 30-minute settlement period meaning that each trading period is 30-minutes long. The auction gate for a settlement period opens 60-90 minutes before real time.
- In the auction, BM participants submit 'bids' and 'offers' into the BM.
    - A bid is the price the participant has calculated for them to either consume more electricity or generate less electricity.
    - An offer is the price to consume less electricity or generate more electricity.
- At gate closure (i.e. auction closure), the National Control Centre then begins to accept bids and offers. To do this, they assess the technical parameters of the participants to see what they're physically able of providing. From those that can deliver, the control centre instructs those that can do so most efficiently in terms of their ability and cost. Generally, the most competitively priced bids and offers will be accepted however sometimes different operational and locational factors affect this decision.
- To accept a bid or offer, the control centre issues "Bid Offer Acceptances" (BOAs) which are an instruction to the BM participant that the control centre wants to change their output. The participant must accept these BOAs meaning that they agree to act on these instructions and adjust their output accordingly.
- In 2020, the GB National Control Centre issued on average 1,800 daily balancing instructions to market participants. Also in 2022, balancing services regularly exceeded 50 % of national demand (the average was only 5 % in 2012). This is possibly a reflection on the higher variability and unpredictability of load and generation such as solar and wind.

In addition to the BM, the system operator also has access to a number of reserve services:

- During the day, the control room may need access to additional generation or demand reduction in order to balance the system. This means that any differences that occur during the day to the forecast demand can be accounted for in real-time.
- Balancing Reserve:
    - Reserve is mainly made up of synchronised generators able to respond within a standard BOA period (two minutes).
    - Currently, optional bids and offers are placed to manage available headroom and footroom in the BM to create a scheduled reserve in real-time (i.e. have some generation on standby in real-time in case it is needed). This has become increasingly expensive and plant is being more regularly required to synchronise or desynchronise to create the desired margin.

    - Balancing reserve overcomes this by allowing the control room to procure regulating reserve on a firm basis a day ahead. This will help reduce the cost as these services are procured a day ahead and therefore not available to be sold into other continental markets (that may have a higher sell price) over interconnectors.
- Fast Reserve:
    - Fast reserve provides rapid and reliable delivery of active power by introducing generation or reducing consumption from demand sources.
    - Fast reserve is used in addition to the balancing reserve and is targeted more at covering those sudden (and sometimes unexpected) changes in generation and demand. This then controls frequency changes in the network by ensuring a balance between supply and demand is maintained.
    - Fast reserve is not procured the day ahead, but is instead procured on the day of use.
    - Providers are paid an availability (£/hr) if called upon to provide a fast reserve service as well as a utilisation payment (£/MWh) if they actually end up being dispatched.
- Slow Reserve:
    - Separated into Negative Slow Reserve (NSR) and Positive Slow Reserve (PSR).
    - It is designed to operate post-fault and provides the control room with firm, bi-directional energy to displace large losses on the system that lead to frequency excursions. Slow Reserve allows the frequency to be brought back into the required operational limits (+/- 0.2 Hz) within the mandated 15-minutes window.
- Quick Reserve:
    - Separated into Negative Quick Reserve (NQR) and Positive Quick Reserve (PQR).
    - Aimed primarily at reacting to pre-fault disturbances to restore energy imbalance quickly.
- Short Time Operating Reserve (STOR):
    - STOR provides additional active power generation or demand reduction to manage the actual demand on the system being greater than forecast or there being unforeseen generator outages.
    - STOR is procured through a daily auction process with contracts lasting one day. The auction closes at 05:00 and the contracts will then last from 05:00 until 05:00 the following day.
    - Providers will submit their availability, prices and offerings prior to the close of the auction.

2.2.2 STABILITY CONTROL

Another key responsibility of an electricity system operator is to ensure stable operation of the network. This extends beyond simply balancing supply to meet demand, and deals with challenges such as how the network recovers following a fault or disturbance. An overview of four of the major concerns is provided below.

2.2.2.1 FREQUENCY

The central frequency of the GB network must be maintained within strict limits as per the Grid Code (50 Hz +/- 1 %). NG ESO has a number of frequency control services which ensure that this is achievable. This includes things like ensuring there is sufficient inertia in the system to limit the rate-of-change-of-

frequency (RoCoF) experienced during a disturbance as well as mandating the primary and secondary responses of equipment to ensure they support the frequency at times of need (e.g. if central frequency drops below 49.8 Hz).

To help manage the frequency in the electricity network, NG ESO uses a series of frequency response tools known as Firm Frequency Response (FFR).

- Split into two types, FFR is NG ESO's traditional frequency response suite used for balancing system frequency in real time.
- The minimum threshold for entry into the FFR markets is 1 MW, however this can be provided either from a single asset or by several aggregated assets.
- Static FFR:
    - Non-dynamic response triggered at a defined frequency deviation level.
    - The static response must be provided within 30-seconds and sustained until 30-minutes following the point at which the frequency was triggered.
    - An example of this would be, frequency drops below 49.5 Hz, static FFR is activated, and the resources currently in this market will be required to increase their power output to help stabilise the frequency and bring it back within acceptable limits.
- Dynamic FFR:
    - This is a continuously provided service used to manage the second-by-second changes on the system.
    - Primary Response = response provided within 10-seconds of the event that can be sustained for a further 20 seconds.
    - Secondary Response = response provided within 30-seconds of the event and can be sustained for a further 30-minutes.
    - High Frequency Response = response provided within 10-seconds of the event and can be sustained indefinitely.
- Dynamic FFR is currently being phased out and new dynamic response services (dynamic moderation (DM), dynamic regulation (DR) and dynamic containment (DC)) are replacing it.
    - DM: Provides fast acting pre-fault delivery for particularly volatile periods.
    - DR: Slower pre-fault service.
    - DC: Post-fault service.

To help manage frequency in the network, all generator connections have a mandatory frequency response as described below:

- This is a mandatory and automatic response that a generator must have to a change the active power output in response to a frequency change.
- Depending on the size and location of the generator, the required mandatory response may differ. This will be specified in the connection agreement for the generator.
- A generator may also provide other balancing services, as long as this does not interfere with this mandatory response.
- Technical Requirements:
    - Generators must have a 3 % to 5 % governor droop characteristic.

- From Grid Code CC.6.3.7, droop is defined as the ratio of steady state change in speed of a generating unit (or in frequency in the case of inverter-based generation) to the steady state change in power output of the generator.
- The generators must be capable of providing continuous modulation power response via synchronised generation through their governor or controller in response to frequency changes.

2.2.2.2 SHORT-CIRCUIT LEVEL

Short-Circuit Level (SCL) is the amount of current that flows on the power system during a fault. These faults may be caused by events such as lightning, line faults, generator faults, bus faults, etc. A fault can either be to or a short-circuit between phases. Systems with a higher SCL are considered to be 'stronger' systems. This means that if a disturbance is experienced, a system with higher SCL will dampen the disturbance faster and more effectively than a 'weak' system. A system with low SCL may take a long time to recover and cascading outages may also result from extended disturbances which lead to larger outages.

SCL is slowly dropping across the power system as traditional generation (with strong SCL contributions) is retired and replaced by converter-based generation that does not have an equally high SCL. The system operator is therefore responsible for maintaining the SCL in the network above a certain level and operates a SCL service to ensure the SCL in any region is sufficient. In addition to this, if SCL is too high, equipment may be damaged under a fault condition which means that a fine balance is required between keeping SCL high enough for a strong network while not letting it get too high to exceed the short-circuit current rating of network equipment. Similarly, if SCL is too low, the fault current may not be large enough to trip protection devices successfully which can lead to hazardous network conditions as faults are not cleared successfully.

How is SCL Maintained?

- Whilst there isn't currently a defined regulation for the system operator to maintain the SCL above a required level, the system operator is responsible for operating a stable network and SCL falls into this category.
- Currently, it is common within the industry for stability assessments to implement a minimum short circuit ratio (MSCR) level of 2.0 for HVDC connections and 3.0 for AC connections[12]. This is also the criteria applied by NG ESO as an indicator as per the December 2022 System Operability Strategy Report[13]. This means that the SCL in the network must be maintained high enough to ensure the short circuit ratio (SCR) does not fall below these MSCR levels.
- Previous projects, such as the stability pathfinder projects, have been completed to tender and procure SCL providing services to assist the system operator in maintaining SCL within acceptable bounds.
- In conjunction with inertia, the SCL level across the system is estimated and actions are taken if required to control assets to increase/decrease the SCL level in areas of the network as required.

[12] CIGRE (2016). *WG B4.62 Connection of Wind Farms to Weak AC Networks.*
[13] NG ESO (2022). *December 2022 Operability Strategy Report, page.31.*

- If a SCL or inertia shortfall is still seen in real-time, dispatchable machines in the BM will be brought online to meet this. However, this is costly as it typically would mean paying a machine to dispatch its active power (even though only its SCL/inertia are needed) and then having to decrease another asset in the BM to allow this other machine to dispatch (for example, this might mean ramping down a wind farm with low SCL so that a more costly synchronous generator can be dispatched). In this case, the system operator would have to pay twice, once to ramp the wind farm down as it was already chosen in the BOA process, and secondly to dispatch the new BM asset.

What is Retained Voltage?

During a fault, the voltage near the fault location will be heavily suppressed and will be either 0 or close to 0 (depending on the fault impedance). At locations further from the fault, the voltage will also be suppressed as a result of the fault with the voltage generally being lower (i.e. a lower retained voltage) closer to the fault. The depth of the suppression is related to the SCL with a lower SCL meaning the suppression will be higher and therefore the voltage suppression will be higher at areas further from the fault (therefore the effects of the fault are felt more and further away at lower levels of SCL). This means that a decreasing system SCL will ultimately lead to deeper voltage suppressions that also propagate further into the network.

This affects the fault ride through capabilities of connected generators as generators are mandated to ride through faults of certain retained voltage levels. If the retained voltage levels begin to drop (i.e. as a result of decreasing SCLs) this could lead to generators not riding through faults and therefore a cascade of outages which would further exacerbate the effects of the fault on the network.

2.2.2.3 INERTIA

Inertia, in the power system sense, refers to the ability of the power system to maintain frequency in the event of a system disturbance or fault. Inertia is stored in the rotating mass of synchronous generators and is a phenomenon that can be mimicked by power electronics-based generation with grid-forming capability. For a spinning mass, it will spin at synchronous speed in steady-state and have an inertia level dependent on the machine's mechanical characteristics. If a disturbance is experienced in the electricity system, for example a loss of generation causing frequency to drop, the rotating mass will start to slow down. The rate at which it slows down is related to its inertia.

In addition to frequency, at any point in time the NG ESO control room will ensure there is sufficient inertia in the system (current minimum allowable level is 120 GVA.s) to protect against a largest loss scenario (at the moment this is the loss of a 1,800 MW generator). Losing a generator of this size would cause a sudden imbalance in supply and demand which would lead to a frequency drop and consequently high RoCoF. Inertia levels restrict this RoCoF to prevent other generators and loads tripping on RoCoF protection and causing a cascade of outages. To help manage the inertia in the network at any time, NG ESO operates a stability market. Further information regarding this can be found in Section 2.3.2 of this report.

Equipment Used to Maintain Inertia and SCL:

- Synchronous Generation (e.g. gas/coal/steam turbines): Provide inertia and SCL as part of their normal MW dispatch.

- Synchronous Generation with a Clutch: A clutch may be fitted to traditional synchronous generation to allow it to provide inertia and SCL without being a MW provider (i.e. the spinning mass is spinning freely in synchronism with the grid as opposed to being powered by gas/coal/steam).
- Synchronous Condensers: A synchronous motor that is not connected to anything but spins freely in synchronism with the grid (similar to a generator with clutch). They can also be controlled to absorb/inject reactive power to help with voltage control.
- Grid-Forming Converters: Provide inertia and SCL using grid-forming converter technology. The SCL contribution from these is normally significantly less than synchronous generation (i.e. SCL is roughly 1-2 times the equipment rating for grid-forming converters instead of 5-7 times for synchronous generation).
    - The inertia contribution from a grid-forming converter may also be limited by its current operating point. For example, if it is already operating at maximum rated export, it may not be able to provide an inertial response to a drop in frequency if short-term overloading is not possible.

2.2.2.4 RESTORATION SERVICES

Formerly known as 'Black Start', restoration is the process used to restore power in the event of a total or partial shutdown of the national electricity transmission system. Restoration services can be provided by a range of providers and is decided after the technical requirements are known and a tender process is completed.

During a shutdown, the restoration service providers are required to carry out initial energisation of sections of the transmission and distribution networks to restore sufficient demand to create and manage a stable 'power island'. Contracted restoration service providers will be required to deliver supply to other assets/sites as the restoration process progresses and will eventually be required to synchronise to other power islands. Not all generators are required to have the capability to provide restoration services. In the event of a system outage event, restoration service providers will be contacted by the control room and instructed what is required to restore the network. Full system shutdown is a low likelihood event, however the delivery of a restoration service is tested at least every three years.

2.2.3 VOLTAGE CONTROL

Voltage at all places in the network must be maintained within a certain range. The system operator has several services in place to help ensure this can be achieved. Reactive power services are how the system operator maintains voltage within the operational limits. Generators can be instructed to absorb or inject reactive power to achieve correct voltage levels across the network. There are several different equipment types that can provide reactive power services. These come with different costs, advantages and limitations.

Planning is conducted (such as NG ESO's voltage pathfinder projects) to ensure the system operator has the resources required to maintain appropriate voltage levels in the network. Reactive services markets also exist to allow the control room to procure additional reactive power services in real-time if required. Voltage control (unlike frequency) is very locational. The further a reference point (impedance between the points)

is from the MVAr source controlling the voltage, the less effective the source will be at controlling voltage at that reference point. For this reason, when a voltage study identifies locations with a requirement for additional voltage control, the effectiveness of possible connection points will need to be calculated.

Equipment Used to Manage Voltage:

- Generators: Generators connected to the network have a minimum reactive power capability which can be exploited to assist with voltage management. Generators can operate on different control schemes such as Constant Q or Q/V Droop which may be used to maintain a pre-determined voltage at the generator's target node.
- Shunt Reactors: Can be used to absorb reactive power and therefore lower voltage.
- Static VAR Compensators (SVC): Fast acting device that can both absorb and inject reactive power as required. Will often be made up of a fixed reactor and fixed capacitor coupled with thyristor controlled variable reactors and capacitors to allow for dynamic control of the reactive power.
- Static Synchronous Compensator (STATCOM): A shunt connected reactive compensation device that uses power electronics to both inject and absorb reactive power to help with power factor correction and manage voltage in the network. STATCOMs are also fast acting and can be used to quickly respond to network needs.
- Quadrature Boosters and Series Reactors: Work by changing the impedance on a power line to redirect power flow to manage high/low voltage hot spots. For example, if a particular line is being heavily loaded causing it to experience low voltage issues, if it has a QB or series reactor fitted this can be used to change the lines impedance and shift some of this load to another circuit. This would only work for meshed sections of the network where multiple electrical paths exist.
- Interconnectors: These can be used to either inject/absorb reactive power to help with voltage or they may export/import active power to provide limited voltage support by shifting power flows from other sections of the network.

2.3 WHAT HAVE I BEEN WORKING ON?

As a member of the Operability Product team within the Networks department of NG ESO I have been exposed to several topics relating to the operation of the GB electricity system. The Operability Product team has a key focus on voltage and stability control and undertakes a number of projects to ensure the GB network will continue to have sufficient voltage and stability services to ensure secure, reliable and affordable operation in the future. The timescale of the Operability Product team is typically the one year ahead to five years ahead period and therefore close collaboration with both planning and operations teams is required. In addition to this, the Operability Product team also gets involved in innovation projects and tool development projects that improve the day-to-day operations of the ESO such as automation tools used by the National Electricity Control Centre.

During my time with the Operability Product team, I have been mostly involved with the stability side of the team and contributed to a few of the ongoing projects while also working more independently on a couple of studies. Having not worked so closely with network stability before, especially at the system operator level, I have really enjoyed learning as much as I can about the phenomena of network stability and how topics including short circuit level (SCL), short circuit ratio (SCR), rate-of-change-of-frequency (RoCoF) and inertia are all related. I have also improved my understanding of how the system operator

manages stability across the network in real-time and have now been involved with work that helps ensure there will be sufficient stability services in the network going forward. This is currently a particularly interesting topic due to the electricity system's transition away from synchronous generation, which provides a high SCL contribution and system inertia, to inverter-based generation.

To perform these stability tasks, I have used both PSCAD, for EMT-based simulation, and PowerFactory, for RMS-based simulation. Having not used the PSCAD modelling software before I have enjoyed the opportunity afforded to me to learn how to perform EMT studies in PSCAD. This new knowledge has supplemented my experience in EMT-based simulation using RSCAD and I am sure this will be a valuable skill going forward as the need for EMT-based simulation, especially in the inverter space, continues to grow.

Below is a quick overview of the main bodies of work I have been involved with during the July 2023 until September 2023 period at NG ESO.

2.3.1 REGIONAL INERTIA, ROCOF AND FREQUENCY STUDY

With inertia and SCL decreasing across the GB network as the electricity network transitions from a predominantly synchronous to highly renewable grid, there is a need to ensure stability and security of supply when operating at lower levels of inertia. Inertia is currently considered as a network-wide value which generally assumes that the inertia level in the GB network at any one time is mostly equal at all connections/nodes in the network. However, as the overall inertia level in the network is dropping, there is concern that inertia is more regional/locational and therefore certain areas in the GB network that may not be close to inertia providing services will actually have lower inertia and therefore experience greater RoCoF and frequency deviation in response to a disturbance. This could lead to problems such as undamped oscillations and/or frequent tripping of protection devices potentially resulting in cascading disconnections.

This project used PowerFactory RMS models to investigate the regional differences of inertia and RoCoF in response to different 'large loss' scenarios across the GB network. Region boundaries defined within NG ESO's Electricity Ten Year Statement (ETYS)[14] were used be used to maintain consistency with other NG ESO studies.

This project aimed to:

- Understand how much inertia differs regionally across the GB network,
- Through modelling, calculate the maximum variance in frequency and RoCoF experienced at various locations across the GB network,
- Depending on the level of variance in frequency and RoCoF calculated, propose next steps to further understand the need to procure inertia at a regional level, and
- Investigate the relationships between regional inertia, RoCoF and frequency. Does improving regional inertia result in lower RoCoF and/or frequency deviation?

[14] National Grid ESO (2023), *Electricity Ten Year Statement*, https://www.nationalgrideso.com/research-and-publications/electricity-ten-year-statement-etys

The frequency nadir, rolling RoCoF and instantaneous RoCoF were found to vary regionally across the GB network. The greatest variance across the network was observed during the period immediately following the generator fault. These results support the theory that different regions will experience a greater RoCoF and frequency deviation than others following a fault. It is important to understand how significant these regional differences are in case they are large enough to cause inadvertent trips which may lead to a cascading of generator outages.

A strong correlation between instantaneous RoCoF and the proximity to the fault was observed with regions located close to the generator fault showing the largest levels of instantaneous RoCoF. On the other hand, frequency nadir and rolling RoCoF did not show a relationship with proximity to fault but instead to regional inertia. The frequency nadir and rolling RoCoF levels at a location were found to improve if the regional inertia at that location was increased.

Despite this, regions with higher local inertia but located further from the main inertia body in the network were consistently shown to have the lowest frequency nadir and largest rolling RoCoF. A possible explanation for this is the idea of a 'shared inertia factor' which refers to how a location in the GB network receives inertia support from all inertia providing services in the network, just at reduced levels of effectiveness if they are located far away.

Further investigation following this study was recommended to better understand how inertia is shared amongst regions within the GB network. Doing so will help calculate the actual regional inertia at any point in the network and assist decision making when it comes to acquiring inertia providing equipment in specific locations of the network if required.

2.3.1.1 LESSONS LEARNED

1. Having not used the RMS-Simulation toolbox in PowerFactory before I enjoyed learning about its uses and how to perform time-domain simulation in PowerFactory.
2. Working closely with frequency and RoCoF, I significantly improved my understanding of these topics, what influences their changes in an electricity network, and how a system operator would look to monitor and control these in a real system.
3. Relating to regional inertia:
    a. Studies using a model with higher regional inertia in an area on the outer regions of the GB network still found this region to have higher peaks in rolling RoCoF. An example of how RoCoF varies across the GB network following a generator fault is provided in Figure 1.
    b. Despite this, a follow-up study which looked directly at the effect of increasing inertia in a specific region found that both frequency nadir and peak rolling RoCoF improved in response to the improved regional inertia.
    c. An idea of there being an 'inertia sharing factor' was raised meaning that inertia in a region isn't just made up of inertia in that particular region, but instead all inertia providing services in a connected network contribute to the inertia in that region, they just have different effectiveness levels.

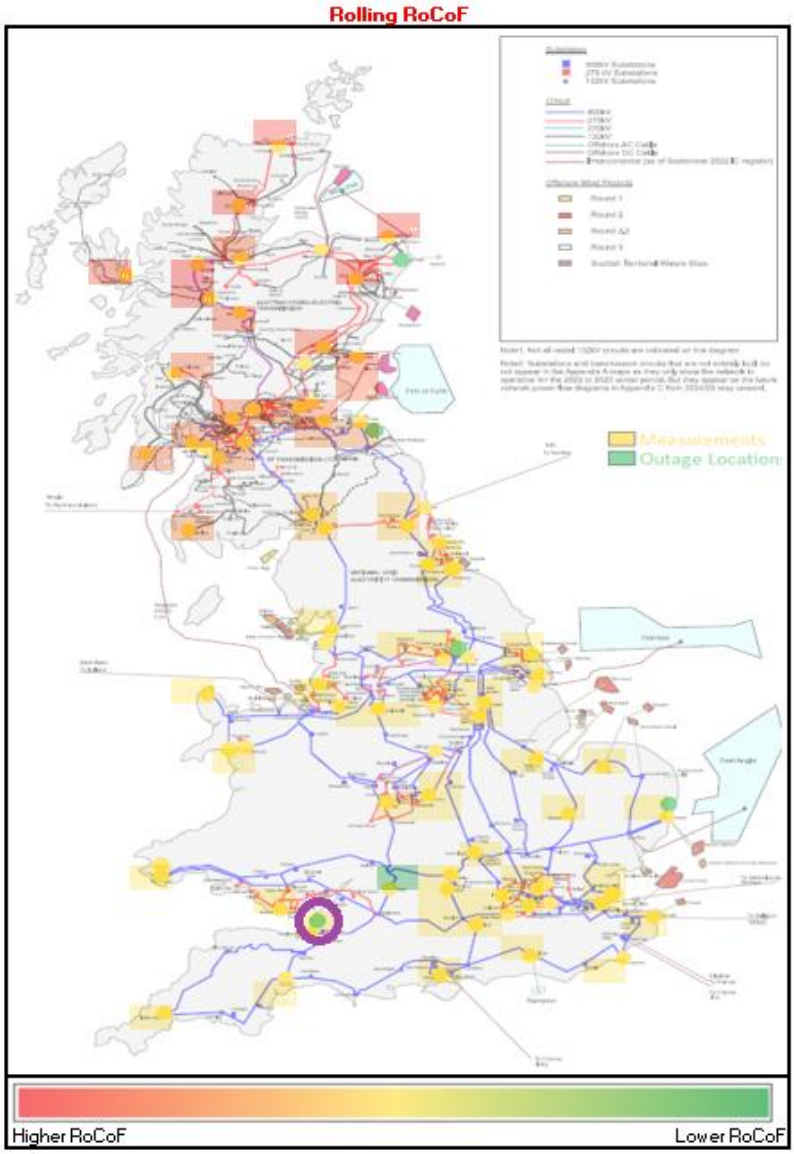


Figure 1: Example of how the rolling RoCoF measured varies across the GB network following a generator fault (located at the purple circle).

4. Relating to the proximity to the fault:
    a. The instantaneous frequency drop following a fault was the greatest at locations in the immediate vicinity of the fault. This also means that they had the greatest peak in instantaneous RoCoF.
    b. The greatest variance in frequency (between the maximum and minimum measured) was also seen in this period shortly following the fault.
    c. On the other hand, rolling RoCoF did not have a strong correlation with proximity to the fault. An example of this is provided in Figure 2 where the far-away location had lower regional inertia and therefore a higher peak in rolling RoCoF than the site that was closer to the fault but had higher regional inertia.

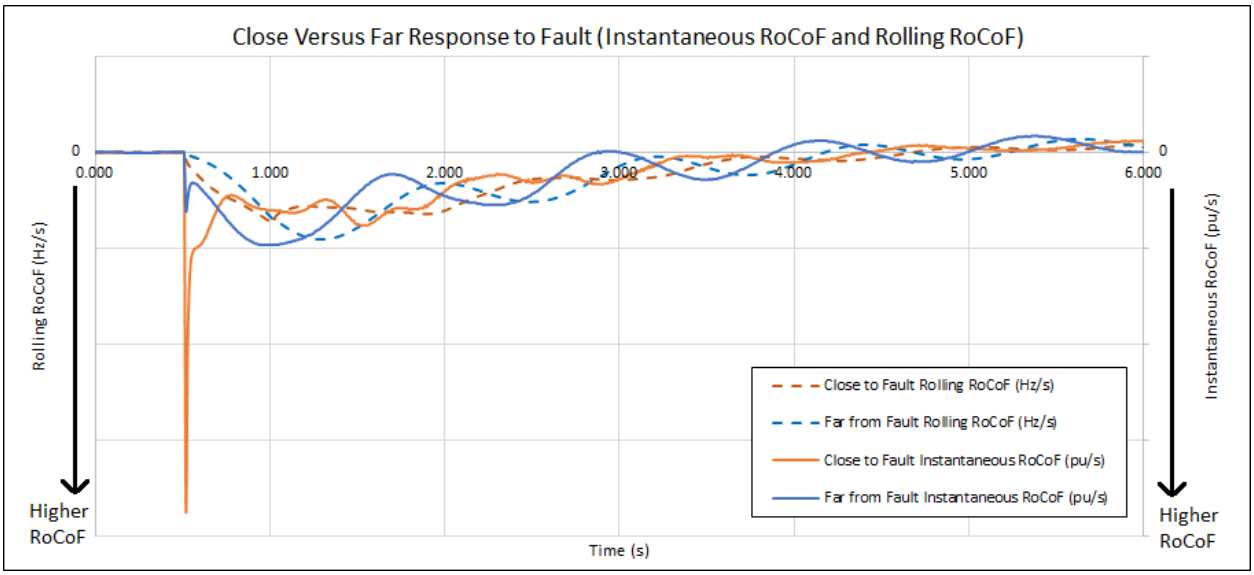


Figure 2: Comparison of changes in RoCoF following a generator fault experienced at a near and far location.

2.3.1.2 RELEVANCE TO THE AUSTRALIAN NETWORK

With the National Electricity Market (NEM) in Australia being more geographically spread out and less meshed than the GB network, it would be interesting to understand how much this affects variance in frequency and RoCoF in the outer regions of the network. To my knowledge, AEMO and the transmission system owners are developing a network of PMUs capable of accurately measuring frequency and RoCoF. It would be beneficial to analyse the data from these following a large fault to see how significantly frequency and RoCoF vary and therefore use this to help decide whether stability supporting services are required in regions of low inertia. This may become particularly important as the overall inertia in the NEM continues to decrease with the generation mix shifting away from large synchronous generators.

2.3.2 CHANGING STABILITY MARKETS

While a member of the Operability Product team I was fortunate enough to gain some exposure to how the stability market operated by NG ESO will be changing over the coming years. Stability of the electricity network, in terms of short-circuit level (SCL) and inertia, is undergoing significant change due to the electricity network transition. Traditionally, both SCL and inertia have been provided as a by-product of active power generation from synchronous machines such as coal and gas turbines. However, as the generation make-up shifts further away from these and more towards renewable sources with power electronics-based converters, this relationship is starting to change. While synchronous generators will typically have an SCL of approximately five to seven times the generator rating, power electronics-based generation is much lower at a scale of one to two times the converter rating. Additionally, the inertia provided from grid-following power electronics-based converters is negligible.

As a consequence of this, the overall SCL and inertia in the GB network has been decreasing and are predicted to continue to decrease over the coming years as shown in Figure 3. NG ESO has therefore begun operating a stability market to address the stability needs of the network and ensure the GB network has sufficient resources to enable secure and reliable operation.

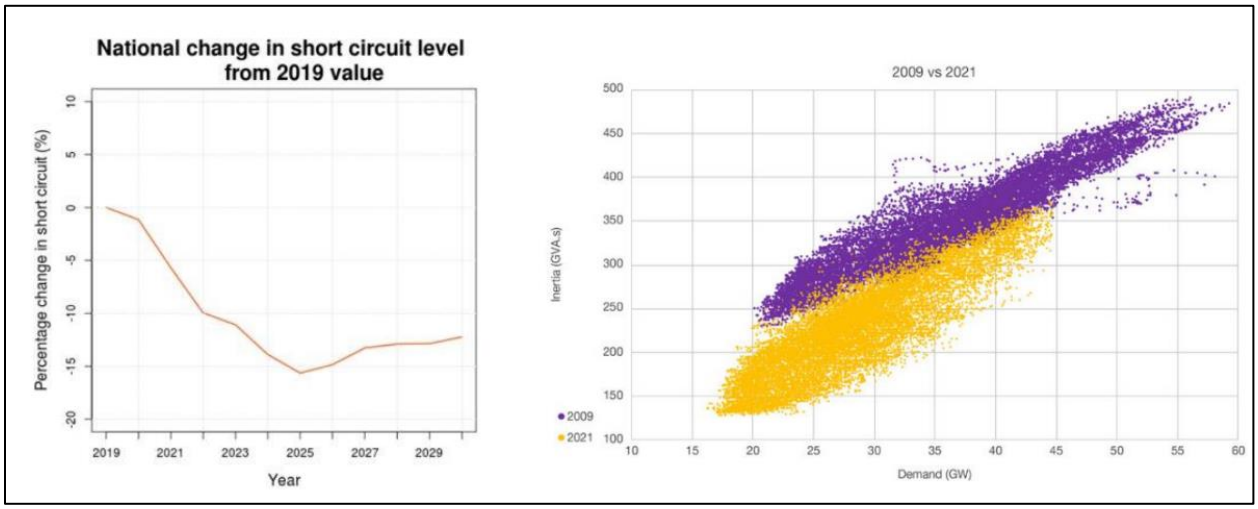


Figure 3: The historical and forecast change in SCL (left) and inertia (right) within the GB Network[15].

Much like the stability needs of the GB network, the stability market design is also undergoing changes to keep pace with how the electricity network is developing. The stability pathfinder projects were launched in 2019 with the aim to identify the most cost-effective approach to address stability issues in the GB network. The following is a list of the main outcomes of the stability pathfinders:

- Phase 1: Identify the most cost-effective way to increase inertia across all of the GB network. Following a tender process, 12 contracts were awarded in 2020.
- Phase 2: Focus on increasing SCL in Scotland. Following a feasibility study, successful applicants were invited to participate in the commercial assessment stage and finally the tender process. Both synchronous machine-based (e.g. synchronous condensers) and grid-forming inverter-based (e.g. grid-forming battery storage) were invited to participate.
- Phase 3: Focus on increasing inertia and SCL in the England and Wales network. Successful tenderers were awarded with contracts in November 2022 and their solutions are currently being constructed.

While these stability pathfinder projects allowed the short to mid-term inertia and SCL needs of the GB network to be met, they were not intended to be permanent solutions. Consequently, a stability market[16] is currently in development with intended launch in 2025/26. The stability market will be more alike the balancing mechanism for active power dispatch and will feature short-term (D-1, day ahead), mid-term (Y-1, year ahead) and long-term (Y-4, four years ahead) markets.

[15] National Grid ESO (2023), *Stability Deep Dive*, https://www.nationalgrideso.com/document/278171/download
[16] National Grid ESO (2023), *Mid-Term (Y-1) Stability Market*, https://www.nationalgrideso.com/industry-information/balancing-services/stability-market/mid-term-y-1-stability-market

2.3.2.1 LESSONS LEARNED

1. Not only was I able to learn more about the technical requirements of the technologies looking to bid into the stability market, I was fortunate enough to gain a greater appreciation of how the market will operate (i.e. the payments and tender process). This has helped me look at the market from another perspective instead of just as the operator or network owner.
2. With one of the aims of the stability market being to be technology agnostic, I was able to improve my knowledge of grid-forming connections and how these would be able to participate in a market for inertia which also has participants who provide inertia through a synchronous machine.

2.3.2.2 RELEVANCE TO THE AUSTRALIAN NETWORK

With AEMO predicting inertia shortfalls in multiple Australian states within the next five years[17], it is possible that something like a stability market will need to be developed if this is the path the Australian industry chooses to follow instead of a network owner led approach to securing future stability requirements. Unfortunately I do not yet have a lot of experience in this space, in terms of how AEMO is planning to overcome inertia and/or SCL shortfalls, however I hope to learn more once returning to Australia.

2.3.3 PRESENTATIONS GIVEN

During my time at NG ESO I was able to provide three presentations to share my experience from Australia as well as help grow the capabilities of the Operability Product team.

1. A presentation to the broader Network Operability team highlighting some of the differences between the Great Britain and Australian electricity networks. This included a comparison of the network infrastructure, generation mix and how each country is progressing with the energy transition. I also provided a deeper analysis of some key challenges that have been experienced in Australia that are not quite as well known in Great Britain – the size, remoteness and radial design of the Queensland network, and the high penetration levels of rooftop solar.
2. I led a training session for the Operability Product team which provided an introduction and overview of EMT-based simulation and PSCAD. PSCAD is not yet widely used within the Operability Product team but is becoming more and more relevant therefore members of the team were interested in gaining a greater appreciation of its capabilities and to learn how it differs to PowerFactory.
3. I was also able to present a training session on hardware-in-the-loop testing and real-time simulation to the Operability Product team to introduce the team to the benefits, limitations and applications of these device testing techniques. While not directly related to the team's work, these topics are in adjacent fields and the session attendees were interested to learn more about how this could affect their work in the future.

A copy of the presentation slides and notes for these can be provided upon request.

[17] AEMO, (2022). *2022 Inertia Report.*

2.3.4 VISIT TO THE NATIONAL HVDC CENTRE

In October I was fortunate enough to visit The National HVDC Centre based in Cumbernauld, Scotland. The National HVDC Centre is an Ofgem funded simulation and training facility specialising in HVDC connectors and power electronic controllers (including battery storage and windfarms). The centre utilises a range of test techniques relating to real-time simulation and hardware-in-the-loop testing and has involvement with European based transmission operators, system operators, universities and manufacturers.

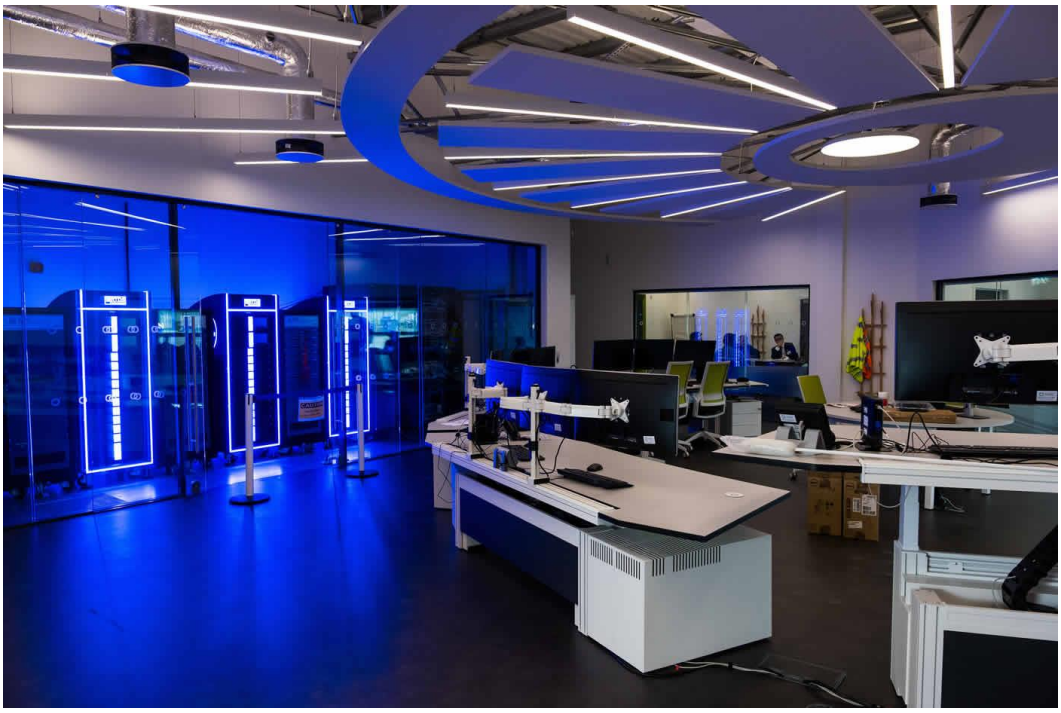


Figure 4: The National HVDC Centre's control room.

I was first introduced to the existence and projects of the HVDC Centre through a webinar I attended about one of their shared projects with National Grid ESO relating to the stability pathfinder project. From here I was intrigued by the significant capabilities of the laboratory in terms of the size and scale of the real-time simulators at their disposal, some of which are pictured in Figure 4. This includes 8 x RTDS NovaCors, 3 x PB5 racks, 18 FPGA units and a wide range of input/output interfaces including the new GTSOC from RTDS Technologies. It was interesting to see a real-time simulation and HIL test setup that is similar in design to what I am used to working with at Energy Queensland's MIST Facility, but at a larger scale. Interestingly, from talking with a few of the simulation engineers I learned that a lot of the challenges I have previously faced with testing in this space are still faced at this larger scale.

Given the similar field of work and testing technologies of The National HVDC Centre and EQL's MIST Facility which I will be returning to, I am looking forward to exploring any potential collaboration or knowledge/learning sharing that may arise between the two laboratories. A special thank you to Benjamin Marshall from The National HVDC Centre for facilitating the visit.

2.3.5 ICELAND ESO VISIT

In August I was fortunate enough to visit the headquarters of the Icelandic transmission system operator, Landsnet, during a visit to Iceland. For this visit I was accompanied by fellow ES Cornwall Memorial Scholarship holder Alice Fleetwood. We were also able to visit The Geothermal Energy Exhibition at the Hellisheiði Power Station to learn more about geothermal energy and see some of the primary plant that makes up a geothermal power station. Here is a list of a few of my main takeaways from the two visits:

- The Iceland transmission network operates as one network with no international interconnectors to mainland Europe. There are also people who are not connected to the main grid but these are a minority.
- There are two main 'strong' sections of the network which are connected via weaker transmission lines therefore it can sometimes be challenging to manage grid stability and voltage constraints.
- The peak load is approximately 2,200 MW with a large portion of this coming from 500 MW Aluminium smelter which presents a significant load loss if this ever trips.
- Generation is 100 % renewable with geothermal and hydro forming most of the generation mix. Wind is starting to play more of a prominent role but in most locations geothermal is still the most cost-effective option.
- A significant amount of the hot water in Iceland also comes directly from geothermal therefore removing a typically large amount of what would normally be electric or gas hot water heaters.
- Network stability isn't currently as much of an immediate concern as it is in mainland Europe due to geothermal and hydro being synchronous.
- Iceland has a quite good coverage of PMUs which has made managing live network constraints much smoother.
- More load is wanting to connect to the network (from industry) however the transmission network is currently running close to limits and therefore load growth is constrained.
- Geothermal bores can reach many different depth levels and the different temperatures and pressures at these depths can be used for different things.
- There are parts of the transmission network that do not have N-1 contingency planning however there are back-up diesel generators in place at these locations as fault restoration can sometimes take several days, especially during the harsh winter conditions.

Figure 5: Plant from the Hellisheiði Power Station.

3 CIGRE WORKING GROUPS

3.1 WORKING GROUP B5.78

Topic: *New Requirements of Network Protection and Control for Renewable Energy Integration*
Terms of Reference: Available here[18]
Objective:
To review existing codes of practices and standards for protection automation and control systems to identify distinguishable boundaries which will help ensure selectivity and effective coordination of networks across the world. This is particularly relevant with the growing penetration of renewables and inverter-based resources that are changing the status quo of how protection networks have traditionally operated.
Updates:
Meeting 6 – 03/09/2023:
I was not able to attend this meeting in person but was able to join online for the first half of the meeting.

- Face-to-face meeting held during the Cairns Symposium.
- Discussed and finalised structure and contents for chapters 1, 2 and 3 for the WG's technical brochure.
- Discussed the idea of conducting a survey however a final decision for this was postponed until more work has been carried out by the WG and the scope was better refined.

Meeting 5 – 26/08/2023:

- Update from several members regarding recent challenges in their respective countries.
- Presentation from a WG member about background material for consideration for the WG's technical brochure.
- Discussion of possible technical brochure topics and refining the contents of the proposed chapters for the WG's technical brochure.
- Proposed topics for face-to-face meeting during Cairns Symposium.

Meeting 3 – 24/06/2023:

- Presentations provided by a couple of WG members as follow-up to discussions from Meeting 2.
- Structure of the technical brochure discussed with WG members sharing their area of expertise to help break into smaller teams to handle specific chapters of the brochure.
- Guidelines for writing a technical brochure were shared to ensure all WG members were aware of the process and how collaboration can be achieved while maintaining a standardised format.

Meeting 2 – 26/05/2023:
Unfortunately I was not able to attend this meeting however the meeting minutes are summarised below:

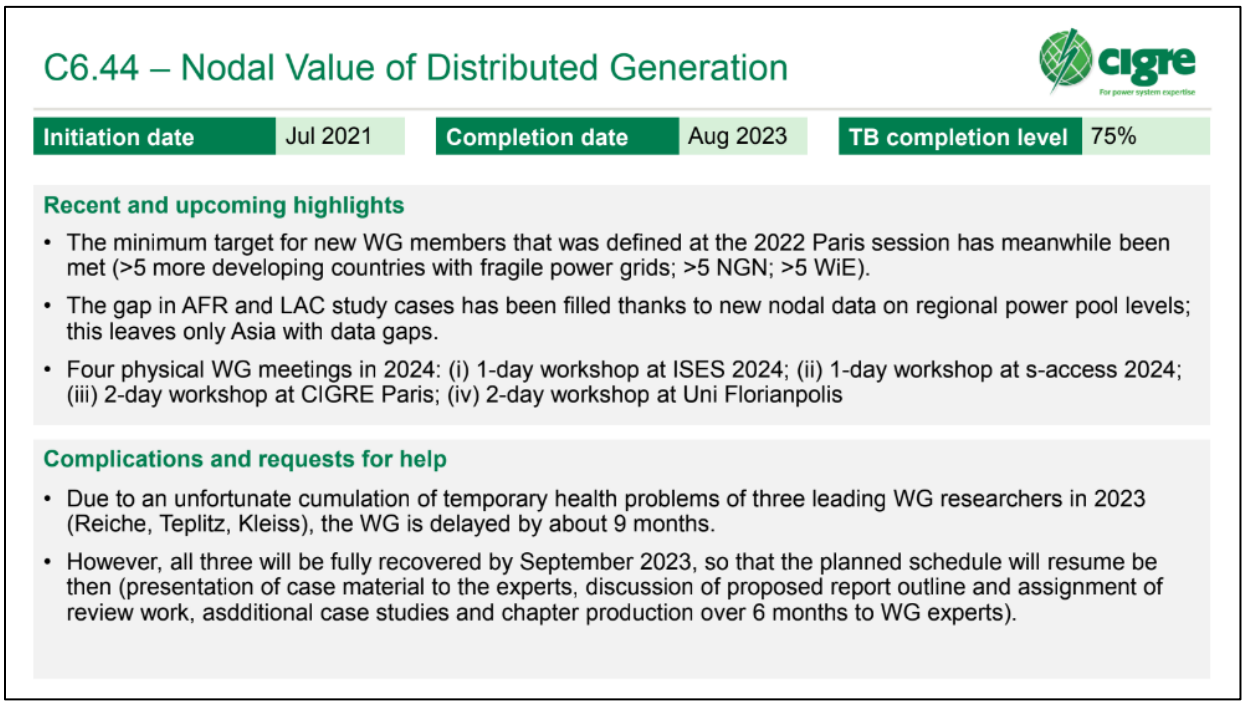
- New members welcomed and provided introductions and backgrounds of themselves.
- Terms of reference discussed to narrow down the scope of the working group.
- Knowledge shares presented from a few of the WG members regarding relevant challenges and findings as experienced in their country.

[18] CIGRE. (2022). *CIGRE Study Committee B5 – Proposal for Creation of a New Working Group, B5.78*

3.2 WORKING GROUP C6.44

Topic: *Nodal Value of Distributed Renewable Energy Generation*
Terms of Reference: Available here[19]
Objective:
To discuss and analyse in practical terms how the variable renewable energy nodal value concept could be applied more broadly and systematically by public and private power sector planners and investors. This would allow for the joint optimisation in distribution and generation expansion of the scaling up of distributed variable renewable energy investments in different countries and energy system contexts.
Updates:
Unfortunately I have still been having trouble contacting the WG convenor however this was partially explained by the WG update provided during the Cairns Symposium in September (copied below). I am hoping that I will now have better luck getting a response from the WG convenor.

Cairns Symposium Update:
The below update was provided during the Cairns Symposium:



[19] CIGRE. (2021). *CIGRE Study Committee C6 – Proposal for Creation of a New Working Group, C6.44*

4 OVERALL SCHOLARSHIP SUMMARY

Having now completed my two 6-month placements, firstly at Kema Labs and then at National Grid ESO, I will now be returning to Australia and my nominal role at Energy Queensland. I would again like to thank the ES Cornwall Memorial Scholarship and its Board for enabling me to undertake this incredible experience. This past year has reinforced the value of seeking experiences that might be outside your normal comfort zone and the scholarship's ability to do this by helping young engineers gain overseas experience is greatly appreciated. I endeavour to share my experiences and learnings I gained after my return to Australia through industry events such as a EESA webinar or something similar organised by the API or UQ.

The following points summarise my final takeaways from the scholarship:

1. The opportunity to gain experience in my chosen areas in international companies that differ from my normal day-to-day job has been invaluable. I have been able to complete 6-months getting a real deep-dive into the technical side of power electronics testing as well as 6-months gaining experience at a system operator. Both may have been difficult to do without requiring a job change in Australia and I know these experiences will help me going forward in my nominal role.
2. Being able to say I was looking for employment as part of the ES Cornwall scholarship was beneficial in the early stages of finding a place to work as this helped the company understand why I would only be looking for a limited time contract. The scholarship also adds a level of merit which hopefully assists when it comes to the company deciding whether offering such a short-term contract would be worthwhile.
3. I've enjoyed getting the chance to learn more about the challenges and state-of-play of the energy transition in both mainland Europe and the UK. While there are a lot of similarities to the challenges and opportunities being faced in Australia, learning more about topics such as HVDC interconnectors and offshore windfarms is something that I may not have been able to do as easily in Australia. Similarly, being able to share my experiences from Australia, such as working with high levels of rooftop solar, has helped me realise Australia has a big role to play in helping the global industry successfully navigate this renewable energy transition.
4. The work-culture differences between Australia, the Netherlands and the UK has been interesting to experience first-hand. This extends to both working effectively with my colleagues as well as working with external parties such as product manufacturers. I believe this has helped me develop my interpersonal and soft skills that will also be beneficial in my nominal role.
5. With the rapid rate at which the electricity industry is changing worldwide, there seem to be many opportunities for electrical engineers with the industry generally looking to recruit. This transition period may therefore be a good opportunity for engineers looking to expand their skillset or gain overseas experience, to seek out international opportunities – be that with the support of a scholarship such as the ES Cornwall scholarship or otherwise.