ES Cornwall Memorial Scholarship

Fourth Quarter Report

7 August 2024 to 5 November 2024

National Grid Electricity Transmission, Warwick, United Kingdom

by

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Acknowledgements

I would like to express my sincere gratitude to the following pillars that have played a pivotal role in shaping my personal and professional journey.

I would like to first express my sincere appreciation to Powerlink Queensland for their steadfast support, allowing me the opportunity to continue my development overseas. The encouragement I have received from my colleagues and their belief in my capabilities have been pivotal to my professional journey and my decision to pursue the ES Cornwall Memorial Scholarship.

I extend my sincere thanks to the ES Cornwall Memorial Scholarship Committee for their backing and support. Being chosen as an ES Cornwall Scholar provided the platform for me to pursue my professional aspirations in overseas electricity networks. I hope to learn as much as I can while I am abroad and make the most out of this amazing opportunity. I endeavour to capture as much of my learnings in my reports as I can.

I extend profound thanks to National Grid Electricity Transmission for providing this incredible opportunity to work on the latest and greatest challenges in the UK power system. The chance to contribute towards system-defining projects is both exciting and rewarding, and I am grateful for the trust and confidence you have placed in me.

I am deeply grateful for my family and friends, Ji Ni especially, whose unwavering support, encouragement, and understanding have been my constant motivation. Their belief in my abilities has been a source of strength throughout this journey.

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Each of these elements has contributed greatly to my journey. I extend my sincere appreciation for the collective support, trust, and opportunities that have shaped my path and fuelled my continued growth.

Executive Summary

Australia aims to achieve net zero emissions by 2050 as part of the global effort to minimise the extent of climate change. This shift is built on significant investment in renewable energy infrastructure which would not only involve building more renewable capacity, energy storage technologies to address intermittency and stability challenges will play a key role in creating a sustainable future.

Queensland's electricity system is undergoing a transformative shift towards cleaner, renewable energy sources. This transition is underpinned by a new 500kV backbone and supported by significant investments towards new wind and solar projects, grid-scale batteries, and advanced pumped hydro storage facilities.

During this transition, I believe that Queensland can benefit from learning how other transmission system operators are transforming their network, performance requirements and control practices to facilitate the connection of inverter-based resources.

This report provides an overview of my experience in my final quarter of the ES Cornwall Memorial Scholarship. In November 2023, I began my placement at National Grid Electricity Transmission (NGET) in Warwick, United Kingdom in the Future Network Blueprints team. A year later, I completed my placement at NGET in the Strategic Network Planning Team.

The Strategic Network Planning Team is primarily responsible for developing solutions to network constraints which have been prescribed by internal stakeholders or by the National Energy System Operator. The outcomes produced by this team dictates the long-term network plans that NGET works towards. During my tenure in this team, I was responsible for the development of the Ferrybridge area plan which required information from across the business to be considered. This was not limited to understanding the prevailing network requirements, connection and demand outlook, asset condition, substation hosting capacity and specific technical criteria relevant to the Ferrybridge network. Gathering a wide range of network requirements ensures that the best development pathway is achieved.

My final quarter was highlighted by my attendance at the CIGRE 2024 Paris Session. Across the full duration of the conference, I was exposed not only to a wide range of challenges experienced by networks across the world but also the solutions experts are working towards to address these challenges. Throughout the C4 Power Systems Technical Performance topics, performance standards for data centres and large inverter-based loads were a consistent talking point. Operational findings in the Irish power system have emphasised the need for the development of frequency transient and fault ride through requirements for these types of connections.

In September 2024, the National Energy System Operator published updated Future Energy Scenarios. The new publication explores a narrow range of pathways that lead to a net zero 2050. The update outlines three strategic pathways to achieve net-zero emissions by 2050, each emphasizing different technological and infrastructural approaches. The Future Energy Pathways explore the balance between consumer engagement, hydrogen development and system electrification and how these factors will impact the UK energy system.

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Glossary

NAME	DESCRIPTION
AO	Asset Operations
AW	Archive Walker
BESS	Battery Energy Storage System
CC	Customer Connections
DV	Delivery Vehicle
EISD	Earliest In-Service Date
ENTSO-E	European Network of Transmission System Operators
ESO	Electricity System Operator
ETYS	Electricity Ten Year Statement
FES	Future Energy Scenarios
FNB	Future Network Blueprints
FRT	Fault Ride Through
HIPS	Hellenic Interconnected Transmission System
HNDFUE	Holistic Network Design Follow Up Exercise
H-SC	Hybrid Synchronous Condenser
HVDC	High Voltage Direct Current
IDD	Infrastructure Development and Delivery
IPTO	Independent Power Transmission Operator
ND	Network Development
NESO	National Energy System Operator
NGET	National Grid Electricity Transmission
NLI	New LIVES Index
NOA	Network Options Assessment
NTUA	National Technical University of Athens
OBAT	Oscillation Baselining and Analysis Tool
OFGEM	Office of Gas and Electricity Markets
PDF	Phasor Data Concentrator
PLL	Phase Locked Loop
PMU	Phasor Measurement Unit
PCC	Point of Common Coupling
RIIO	Revenue = Incentives + Innovation + Outputs
ROCOF	Rate of Change of Frequency
SC	Synchronous Condenser
SI	National Grid Strategic Infrastructure
SO	System Operator
STATCOM	Static Compensator
T3	Price Control Period 2026-2031
TCSNP	Transitional Centralised Strategic Network Plan
TO	Transmission Owner
TSO	Transmission System Operator
UPS	Uninterruptable Power Supply

1 Background

My fourth report details my experiences in my final quarter of the ES Cornwall Memorial Scholarship. During this period, I continued my employment at National Grid Electricity Transmission (NGET), functioning primarily as a Power Systems Engineer in the Network Development Team. However, I retained some responsibilities from my prior role in the Whole System Team to ensure the delivery of key projects.

During this quarter, I was responsible for developing the network plan for the Ferrybridge network in northern England. This involved the creation and assessment of a number of possible network development options. The process helped develop my understanding of the network needs and the constraints the business must operate within.

I also attended the 2024 CIGRE Paris Session held during this quarter. The conference was an eye-opening experience that provided significant insight relevant towards my ES Cornwall Memorial Scholarship topic. There were many opportunities to develop a better understanding how other power systems are evolving their network, performance requirements and policy to facilitate the connection of new renewable generation.

2 Projects

2.1 Strategic Network Planning

In the last quarter of the ES Cornwall Memorial Scholarship, I was working in the Strategic Network Planning Team within the Network Development department at NGET. During this period, I was tasked with developing the network strategy for the Ferrybridge network.

2.1.1 Ferrybridge Strategy

The UK power system is evolving to meet the net zero targets. Prevailing trends in the UK power system sees significant power transfer from Scottish wind generation in the north to English load centres in the south. Currently, two double circuit transmission corridors carry the bulk of the power across the Scottish-English border. Shown below beside the green arrows, these circuits are vital to the energy security of England.

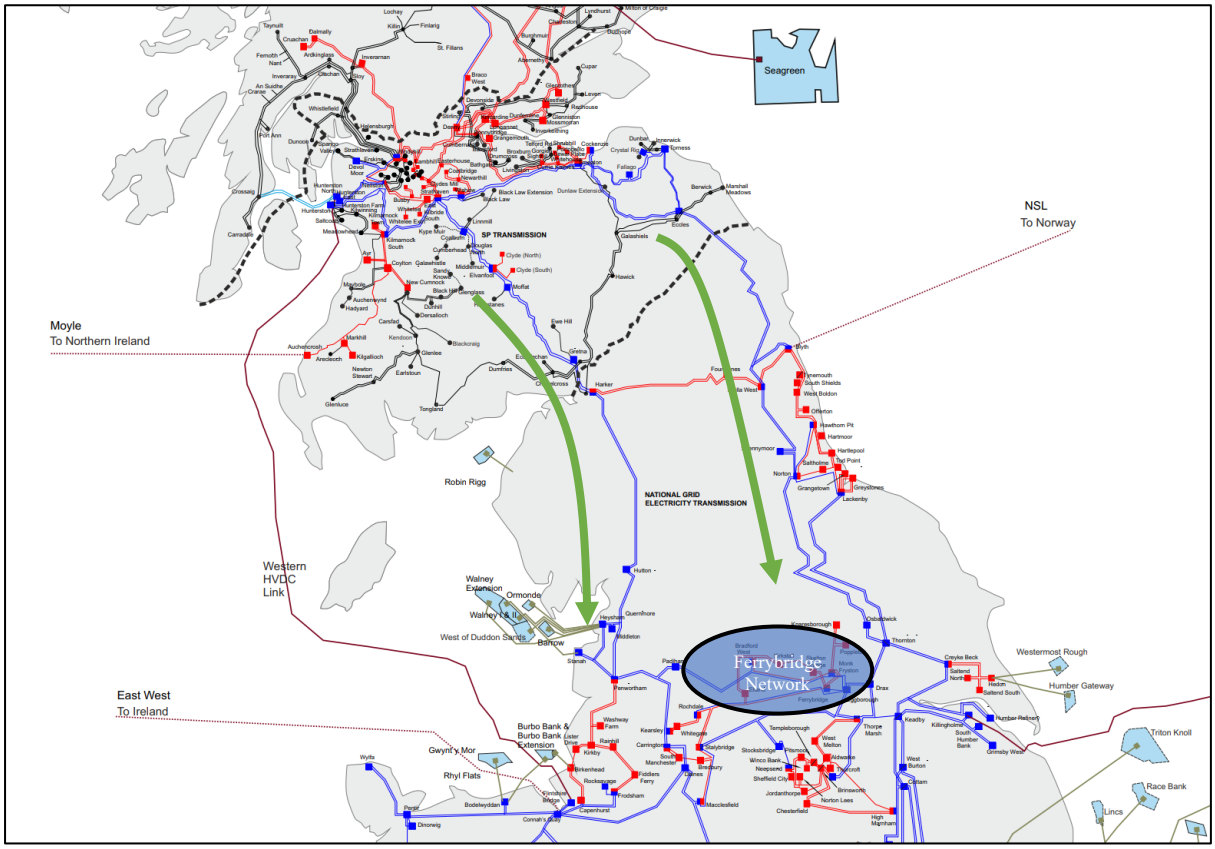

Figure 1 - Northern England Transmission System

An outage on either of the two 400kV north-to-south circuits are of significant concern to NGET. Under these conditions, power would instead flow through the 275kV transmission corridors running laterally between the east and west coasts in order to reach the remaining 400KV north-to-south corridor and continue south as demonstrated in Figure 2. The lateral transmission system is currently unable to withstand the high flow arising from such an event. As a consequence, the development of the existing corridors connecting the east and west transmission network is one of the key strategic transmission objectives that will improve the security of supply in a Net Zero energy system.

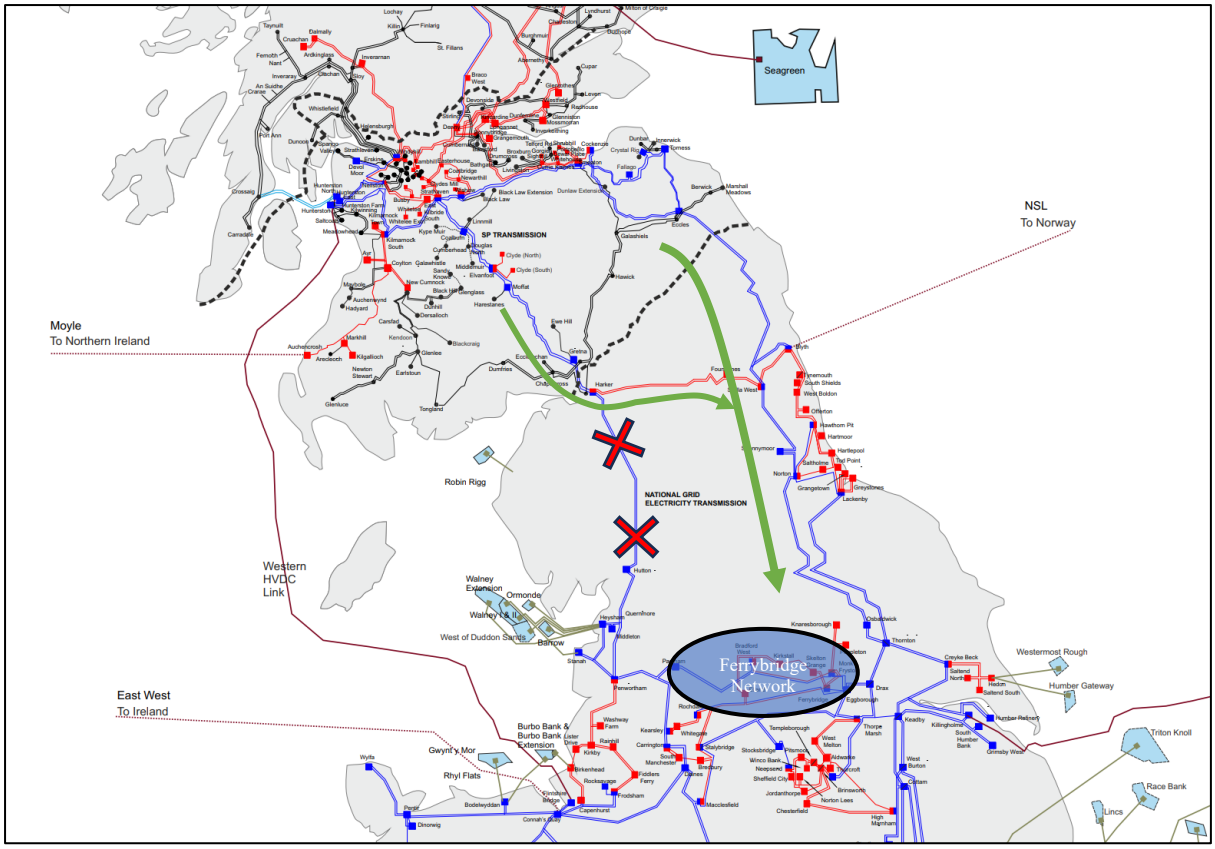

Figure 2 – Power rerouting to remaining corridor following a disturbance

The Ferrybridge network makes up part of the first east to west 400kV corridor, located approximately 200km south of the English-Scottish border. Situated in Northern England around the city of Leeds, the Ferrybridge network has historically been developed to supply industrial furnaces around the city. The needs of the Ferrybridge area have since changed following the retirement of both industrial load and generation in the region. With the last Ferrybridge power station set to be demolished, there is an opportunity to reshape the network in the area to render it suitable for a net zero future.

There are numerous options in how the Ferrybridge network can be restructured. While NGET strives to ensure that the best development option is progressed, it is not practical to design, model, study and compare all the options available. It is important to first consider the current state of the assets in the area as well as the strategic objectives in the network to help define the type of solution required. For Ferrybridge, the following elements were considered to help define the network requirements:

1. Greater network requirements

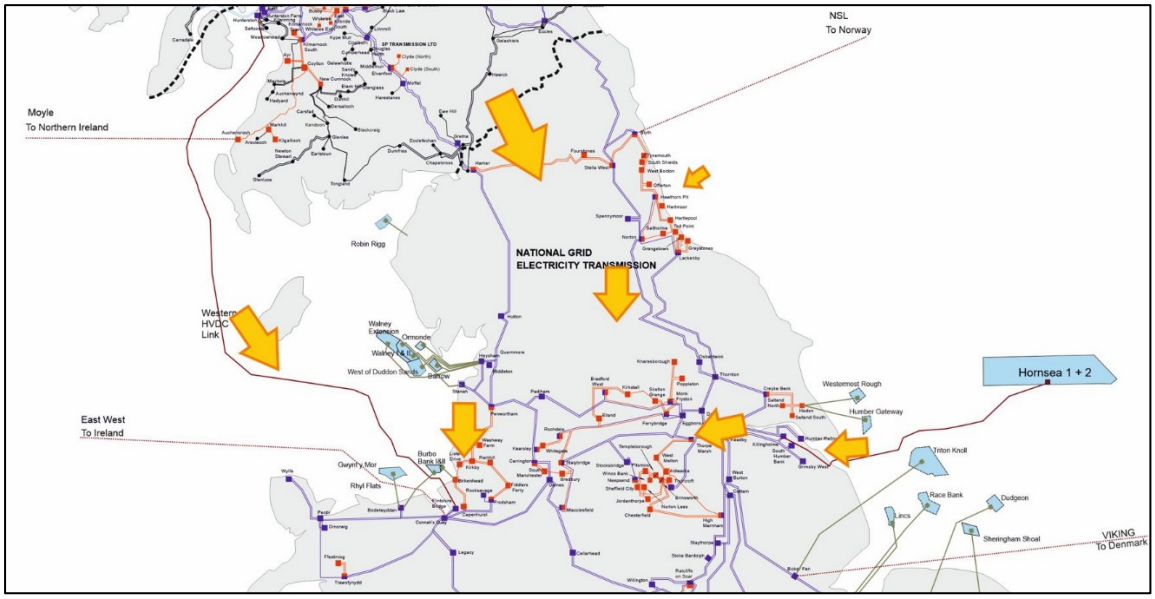

Figure 3 - North of England Power Flow

The are a number system level objectives that NGET must achieve to meet national energy targets. These requirements exist to meet prevailing energy trends in the UK power system. Current expectations foresee a net zero United Kingdom that is predominantly powered by onshore generation in Scotland and offshore generation off both east and west coasts of Great Britain.

As generation migrates away from load centres towards the edge of the network, the loading on the transmission system carrying power from north to south will increase significantly. Projects are currently underway to relieve constraints by increasing north to south capacity on existing transmission infrastructure and in other cases, building new corridors to bypass the existing network bottlenecks altogether.

In the English power system, studies have shown that the power coming down from Scotland has been mainly carried by the eastern, coastal transmission network. NGET has identified the need to better mesh the eastern and western networks together to not only improve the utilisation of the central and western transmission networks, but to also to facilitate the unconstrained transfer of power to these circuits in the event of an east coast outage.

As existing generation retires and new generators are built far from load centres, NGET is also expected to face reactive power challenges. Reactive power from offshore wind generation is unable to provide sufficient reactive power support due to the reactive power losses over long distances. This is further compounded by power from intermittent generation being carried by higher capacity transmission infrastructure, from which reactive power requirements can change significant as a consequence fluctuating line current. NGET is looking into flexible AC transmission system devices and new operational procedures to meet these challenges.

Small signal and transient stability are considered at a later design stage in the UK.

2. Connection requirements and demand outlook

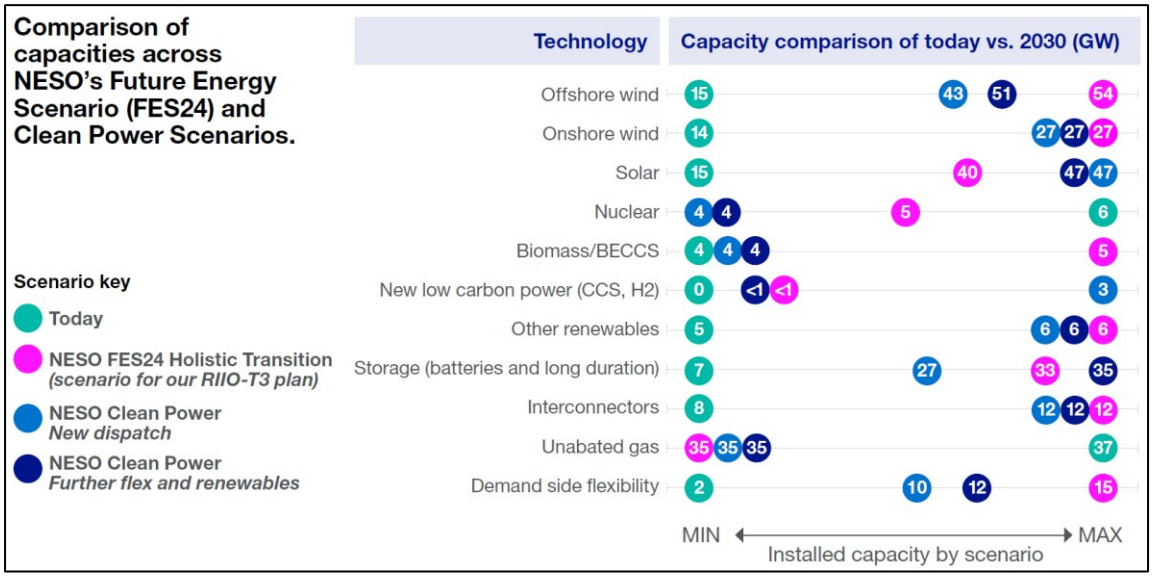

Figure 4 - Expected Generation Mix between forecasts [1]

New connections as well as retiring network customers shape power flow trends on the network and have a significant effect impact on network planning outcomes. Furthermore, in the case of new connecting customers, the limited hosting capacity in existing NGET substations will mean that new substations and transmission lines will need to be constructed to facilitate the connections.

Constructing a substation for each new customer is a resource intensive process. Often it can be more efficient to build a single connection node designed to host multiple nearby customers. At NGET, connection nodes are being built with equipment rated to host multiple customers and be sufficiently operable to enable some control of fault levels and transmission line loading by altering the running arrangement of the substation. Connection nodes however, are vulnerable to transmission line or substation disturbances which can result in the disconnection of multiple customers resulting in large shifts in supply or demand. Network plans must consider how the network should be best augmented and operated to accommodate future energy requirements.

In addition to connecting customers, distribution and direct-connect demand have a significant impact on the thermal and voltage conditions of the network. Distribution networks and direct-connect customers provide a forecast over a ten-year horizon which provides some insight into medium-term demand requirements. This forecast is used in conjunction with a 25-year energy forecast published by the newly established National Energy System Operator (NESO) to form a long-term demand picture that strategic network plans are drawn from.

3. Asset condition

The health of the transmission assets is an important consideration when developing a network strategy. A region with poor asset health will require significant time and investment to replace or maintain the assets, often necessitating complex outages to facilitate the work. However, these regions often provide NGET with greater planning

flexibility due to the substantial baseline investment required to maintain the existing system. Instead of going through lengthy and complex outages to perform asset replacements, the substations can be rationalised and the network reshaped to meet future requirements at an additional cost.

The time taken to develop and deliver plans required to transition into a renewable economy will test the resilience of a loaded network running on an aging asset base. While there can be a need to replace an asset, the timing of asset health triggers rarely aligns with other work requirements. To minimise the total labour and outages required, NGET have been known to perform life extensions on aging assets in order to reach the project outage dates. In other cases, NGET have replaced assets with usable life remaining as part of a greater substation project in order to eliminate the need for redeployment when the asset reaches end of life. NGET believes that the development of their network will be limited by the construction resources available in the future and as a consequence, NGET have been working to make best use of their labour resources today.

4. Substation Space and Capacity

The integration of renewable resources into the UK power system is contingent not only on the capability of the network to carry power, but also on space and capacity limitations that can restrict connection access to a substation. NGET substations, particularly those situated in cities and towns, can have severe space limitations. Hemmed in sites that have no room for expansion can only host new connection once existing bays are freed up, which in the case of Ferrybridge is a rare but valuable occurrence.

Substations with room for expansion may also come under capacity restrictions which may prevent new customers from connecting. Capacity restrictions have been implemented as a system security measure to limit disruption to the network in the event of a disturbance. This is accomplished, in part, by limiting the number of generation sources and transmission power flow into substations.

In instances where a connection is denied due to space or capacity reasons, NGET is left with the alternative of constructing a separate substation to connect customers.

There is a need to ensure that the Ferrybridge network will meet the requirements of a net zero power system. Over 20 new connections are expected in the area over the next decade which will require new connection nodes to be constructed. Concurrently, the retiring power stations at Ferrybridge will leave aged substations in coveted areas with little purpose. Due to the limited delivery resources available in the future, the work carried out at Ferrybridge over the next decade will determine whether the local network will be able to meet requirements in 2050.

A number of options that would meet the network, connection and asset health requirements at Ferrybridge were considered. The key outcomes developed and chosen for study were as follows:

1. **Retaining the existing layout**

   While this outcome was studied, it was mainly used to baseline any further changes.

2. **Downrating Ferrybridge 275kV substation to 132kV**

   Downrating Ferrybridge 275kV to 132kV rationalises the substation, eliminating the 275kV switchyard which would no longer be necessary following the decommissioning of Ferrybridge power station. By downrating and rationalising, costs would be kept low and the overall asset base reduced. There would also the possibility of transferring ownership of the asset over to the distribution network operator, thereby eliminating the need for NGET perform maintenance at the site.

   There are two key limitations of downrating the site. Firstly, this option fails to address the strategic need to establish a 400kV corridor between the east and west transmission networks. Second, the downrating of the site may sterilise additional transmission investment in the area as the network may not be capable of hosting additional customers.

3. **Uprating Ferrybridge 275kV substation to 400kV**

   Uprating Ferrybridge 275kV to 400kV would see the replacement of the 275kV switchyard with a 400kV substation. A 400kV substation would unlock many network development opportunities and would facilitate the development of a 400kV east-west transmission corridor that would otherwise impractical due to the lack of a central 400kV node. A 400kV corridor would be expected to attract further investment from transmission connected customers due to the increased capacity in the region.

   Uprating transmission infrastructure to 400kV would be an extremely costly hurdle to overcome. However, key circuits in the Ferrybridge network which are currently operating at 275kV have been constructed to carry 400kV. Decisions made over three decades ago which projected the need to uprate in this region may allow the network to be uprated to 400kV with little additional transmission line infrastructure. The existing 400kV capable infrastructure would simplify some aspects of network uprating, although a number of further considerations would remain for the Ferrybridge scenario.

The key network outcomes and several possible permutations were drafted and shared with key stakeholders in the business to ensure that their requirements were met. Following the initial stakeholder review, the design were studied and evaluated based on their technical capability.

2.1.2 Technical Considerations

The network designs were modelled in DIgSILENT PowerFactory, where studies were performed to assess the technical suitability of the Ferrybridge network options. The impact on network fault level and boundary capability were the first two criteria studied.

2.1.2.1 Fault Level Studies

Fault levels were a key consideration due to the prominence of high fault level conditions in the England and Wales power system. Driven by a heavily meshed network and a growing number of connected plant, increasing network short circuit currents can impact plant requirements and influence how the network is operated. One of the key development options proposes to uprate the Ferrybridge transmission infrastructure to 400kV which is expected to greatly reduce network impedances which will improve transfer capability at the cost of increasing fault levels on the low voltage networks.

Switchgear at older substations is generally rated between 40kA and 50kA. As the short circuit levels rises, the plant at these substations may risk becoming obsolete. If modifying the running arrangement of a substation is not able to keep fault levels within the ratings of the substation equipment, swapping the equipment with higher rated replacements is one potential path forward.

NGET's PowerFactory client has a number of functions that were used to determine maximum fault current through switchgear at a substation. The RT tests are a set of PowerFactory functions that were used to determine the maximum substation fault current in a substation. Each RT test has a use case specific to a circuit breaker function (line breaker, coupler breaker, etc) or substation arrangement (double bus, meshed, etc).

RT1

The RT1 test determines the greatest fault current flowing through a bus coupler or bus section circuit breaker for a given bus fault in a double bus substation. In NGET's double bus system, the main bus is connected via a bus coupler breaker as well as a bus section breaker.

The maximum current flowing through the bus circuit breakers generally occurs when the breaker under testing is the only circuit breaker interrupting a bus fault. To determine this in simulation, one bus circuit breaker is opened and a fault is applied to the bus. The fault current through the remaining bus circuit breaker is recorded. The process is repeated for the other circuit breaker connected to the bus. Figure 5, Figure 6 and Figure 7 attempt to describe the mechanism.

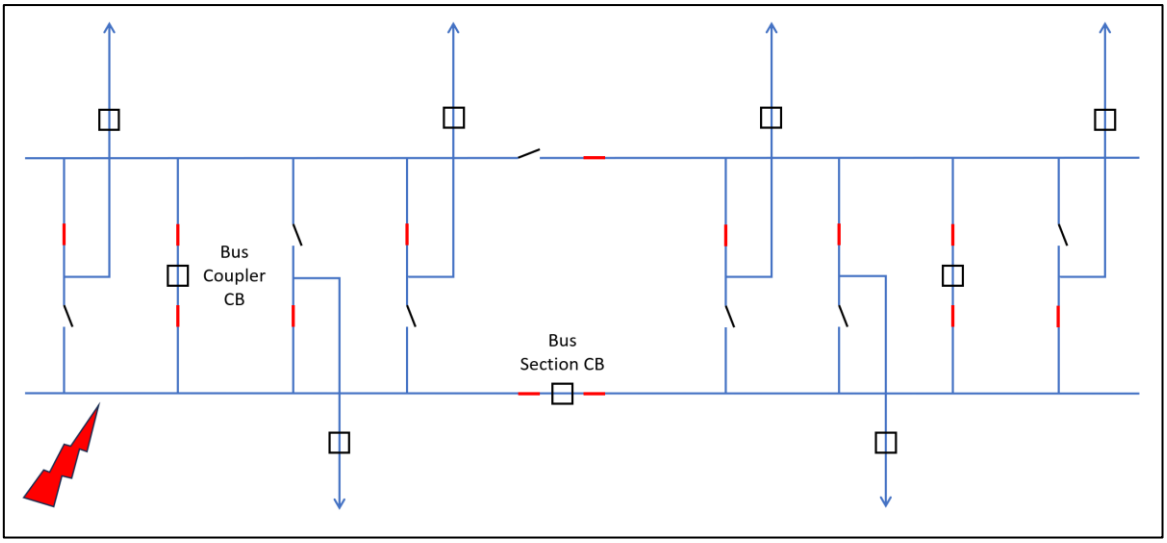

Figure 5 - RT1, for a given bus fault, determine maximum current through coupler and section breaker

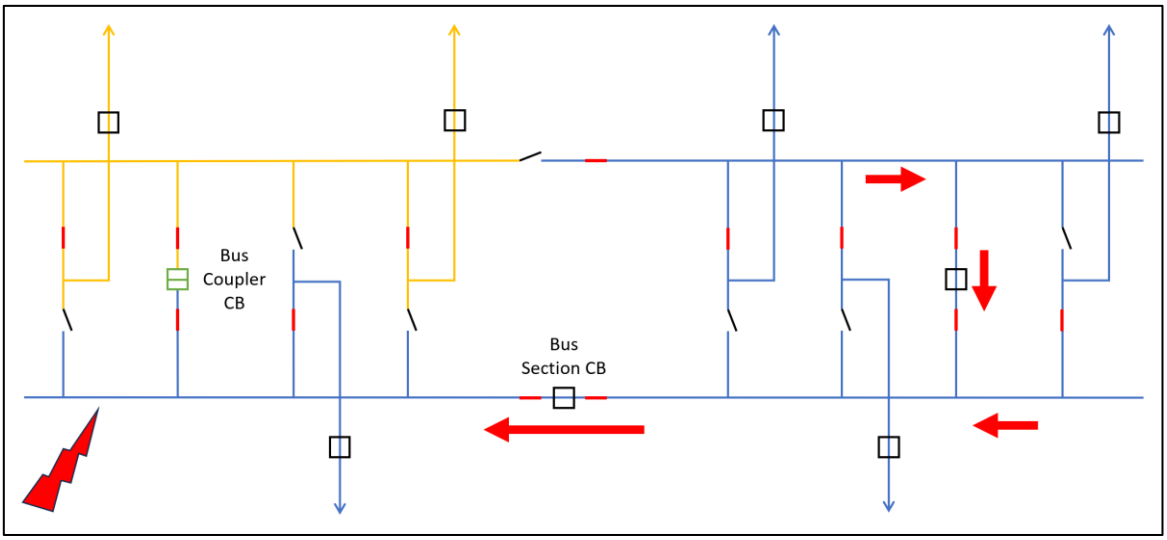

Figure 6 - RT1, the bus coupler is opened and a fault is applied. Fault current through the bus section breaker is recorded

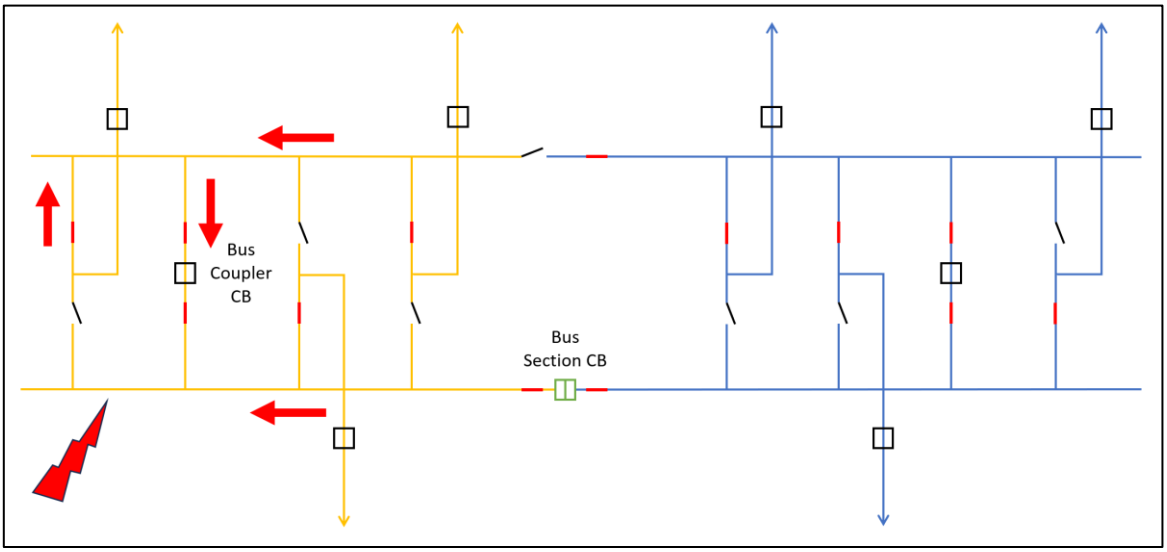

Figure 7 - RT1, the bus section breaker is now opened and a fault is applied. Fault current through the bus coupler is recorded

RT2

The RT2 studies are used to determine the greatest short circuit current flow through a line circuit breaker. This function opens the remote end breaker of the circuit breaker under testing before a fault is applied on the line side of the target breaker. As a consequence, all fault current flows into the breaker under testing. Figure 8 and Figure 9 depict this process.

The RT2 function is suitable only for line breakers at double bus substations as the line switchgear in meshed substations are on-load disconnectors and are not intended to break fault current. Fault clearing capabilities in mesh substations are left to the circuit breakers on the ring (see RT3).

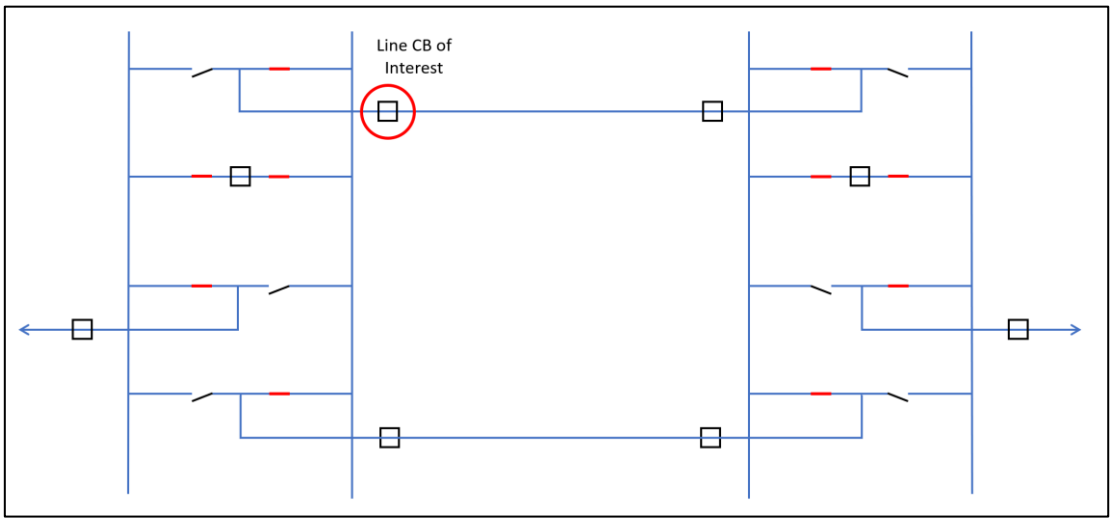

Figure 8 - RT2, calculating the maximum short circuit current across a line breaker

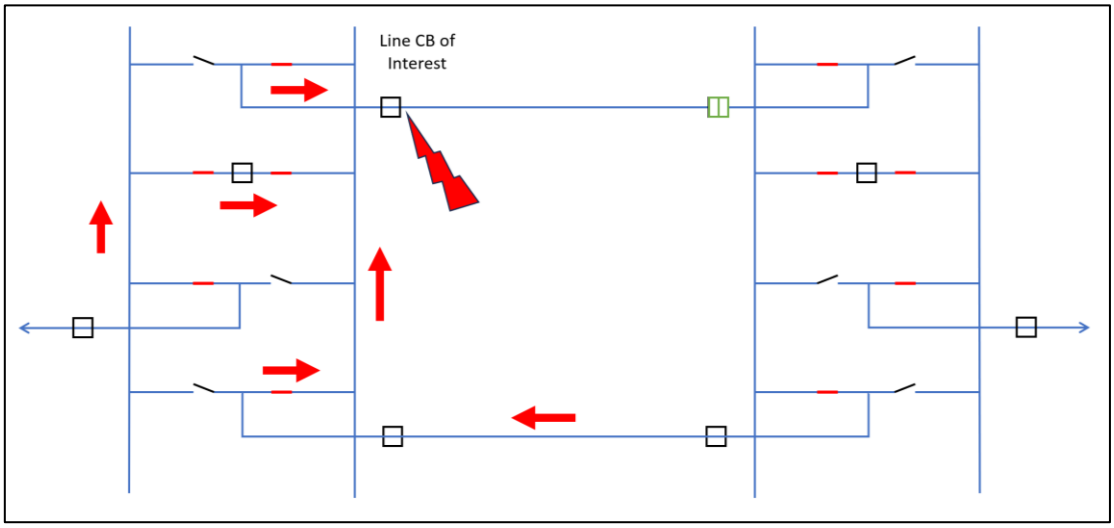

Figure 9 - RT2, the remote end breaker is opened and all fault current flows into the line breaker

RT3

RT3 studies are used to determine the maximum fault level for a selected circuit breaker in a meshed substation.

The maximum fault level is determined by first opening a circuit breaker adjacent to the circuit breaker of interest and applying a fault on the side of the target breaker closest to the breaker that was just opened. As a consequence, the current infeed from other parts of the substation is channelled through the target breaker into the faulted section. The process is repeated in a mirror fashion by opening the other adjacent breaker and applying a bus fault to the near side bus. Repeating this step is necessary as the fault through the target circuit breaker is dependent on the contribution from each corner of the meshed substation which changes depending on the breaker that was opened. Figures Figure 10,Figure 11 andFigure 12 depict this process.

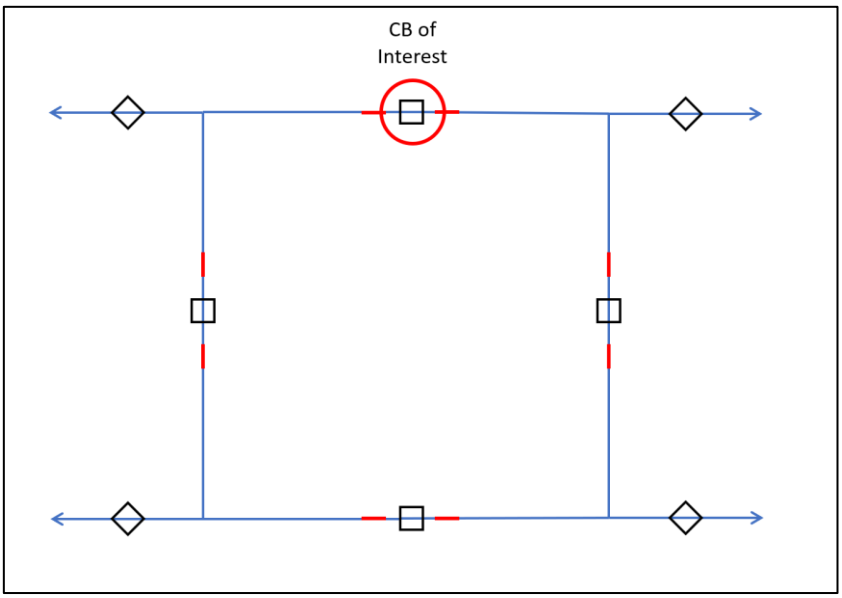

Figure 10 - RT3, calculating the maximum short circuit level in a meshed circuit breaker

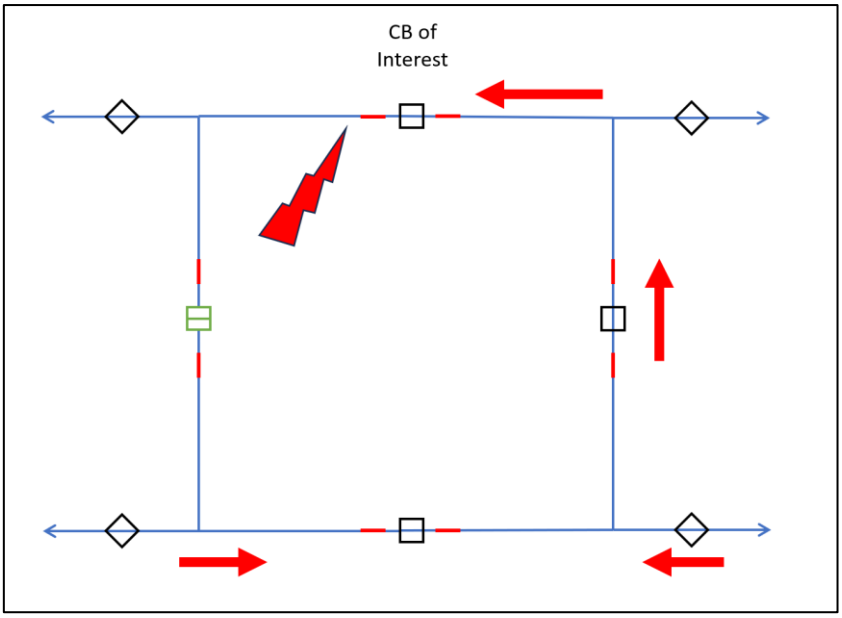

Figure 11 - RT3, open mesh breaker adjacent to the target circuit breaker and apply fault to near sided bus

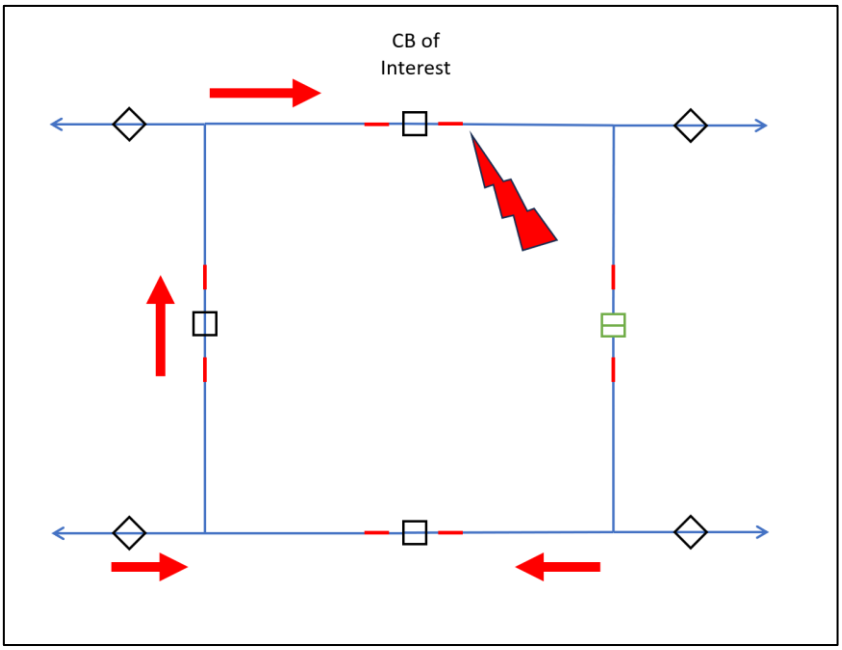

Figure 12 - RT3, open other mesh breaker adjacent to the target circuit breaker and apply fault to near sided bus. Compare against previous first result to determine maximum.

2.1.2.2 Boundary Uplift

The proposed network options were studied to determine how it impacted the capability of the Ferrybridge network. Line loading and bus voltages on both transmission and distribution assets were studied under pre- and post-fault conditions across a range of forecasted scenarios. The method of study was described in the Quarter 3 report under the *2.2.2.1 Boundary Studies* section.

2.2 Whole System Team

In August, the development of the Regional and Site Strategies was acknowledged by the president and executives of NGET. The upper management recognised the need for a strategic planning group that would focus on consolidating and harmonising work plans from across the business. Consequently, the team was made a permanent part of the business and rebranded as the *Whole System Planning Team.*

During this quarter, my involvement in the Whole System Planning Team reduced as my responsibilities were moved across into the Strategic Network Planning Team. However, I remained accountable for the development of the Network Picasso which was first discussed in my second quarterly report. The Network Picasso is visual resource that depicts the planned changes to the network, illustrating new substation and transmission infrastructure, transmission line reconfiguration, and transmission line reconductoring plans. The Network Picasso is one of the few documents at NGET that captures all networks plans in a single location making it a value resources for both internal and external stakeholders.

A longstanding goal of the Regional and Site Strategies was to provide an interactive and readily accessible digital platform with information that is updated live from the source. The information would be sorted into varying degrees of classification and categorised. This would allow the NGET to tailor to information the user can see when on the platform. A first rendition of the digital tool would start by discriminating between external users and internal users.

NGET hopes that by increasing transparency and communication plans to customers, customers will be able to make better informed connection decisions that will benefit both the developer and the network operator. NGET had previously established a website intended to help connecting customers develop a better understanding of the network and the changes planning in each region. The website provides information such as:

- Estimated connection timeframes, broken down for each NGET substation;
- Contracted connection figures, broken down into types of generation;
- A brief description of transmission reinforcements planned in the region of interest;
- Substation specific information, describing the available hosting capacity of a site and any future expansion potential.

Snippets from the website may be found in Appendix A [2].

One of the key objectives of the Whole System Team was to bring this website up to date and populate it with information from the Region and Site Strategies. In the lead up to my departure at NGET, the team worked to integrate the Network Picasso drawing into the digital tool. The Network Picasso would serve as an interactive way for users to learn more about network changes. It was envisioned that a digital Network Picasso would allow users to select parts of the network in the work plan to bring up a description and explanation of the changes planned for the selected element. By allowing users to and learn more about NGET projects, it is hoped that they can make more informed choices that would benefit all stakeholders.

3 Other Learnings

3.1 CIGRE Session 2024

The CIGRE Session 2024 was held in Paris, France between the 26th and 30th of August. The conference was a remarkable platform which provided ample opportunity to discover and learn about the contemporary power systems challenges facing the world today. The conference was an excellent introduction to unfamiliar topics and yet it also provided abundant depth in specific fields of power systems engineering.

I have summarised two papers I thought to be interesting and relevant to my topic in this section.

3.1.1 Greek PMU Case Study [3]

Stability monitoring in power systems is crucial for ensuring the reliable and secure operation of the power system. State estimators have traditionally been used to provide estimates of optimal operating points from SCADA measurements. The arrival of Phasor Measurement Units (PMUs) has provided the foundation for data and statistics driven methods of evaluating power system performance. The National Technical University of Athens (NTUA) in conjunction with the Independent Power Transmission Operator (IPTO) have developed a platform for real-time voltage and oscillation stability monitoring by utilising PMU measurements collected from 22 locations in the Hellenic Interconnected Transmission System (HIPS).

The platform, developed by NTUA and IPTO, utilises a centralised Phasor Data Concentrator (PDC) which continuously receives PMU data. The PMUs transfer encrypted data through a virtual private network at a resolution of 50Hz with a maximum error of 0.01Hz when received by the PDC. The data is stored in a CSV file which is read by the monitoring tools. Figure 13 provides a high-level view of the PMU framework employed.

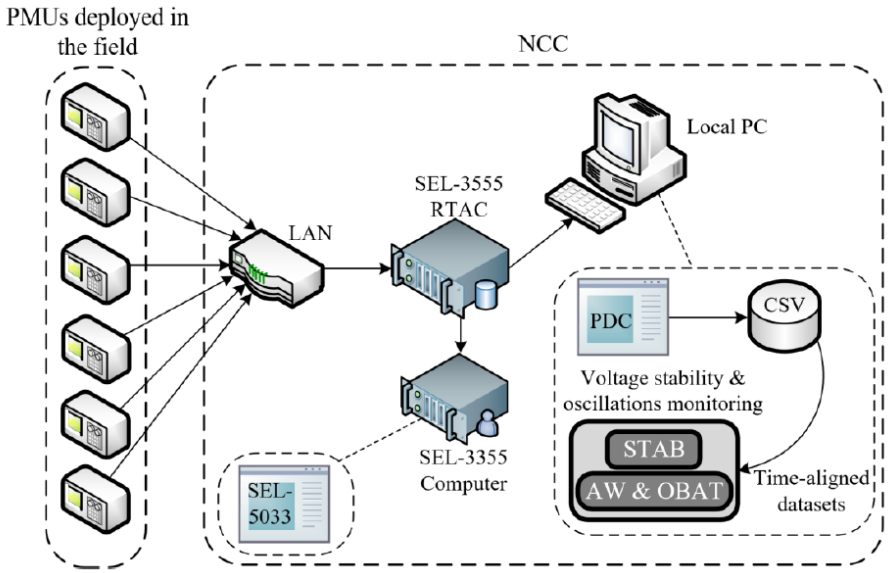

Figure 13 - PMU Framework

Voltage Stability Monitoring using NLI

One of the causes of voltage instability is the attempt from dynamic loads to increase their consumption beyond the maximum power available through the generation and transmission system. The key challenges for IPTO are ensuring that instability in a weak system is identified and the necessary responses made in a timely and selective manner. NTUA and IPTO have employed a real-time stability index called New LIVES Index (NLI) for voltage instability monitoring using PMU data. NLI was selected due as it requires low computation time and minimum investment cost while being still being timely and reliable.

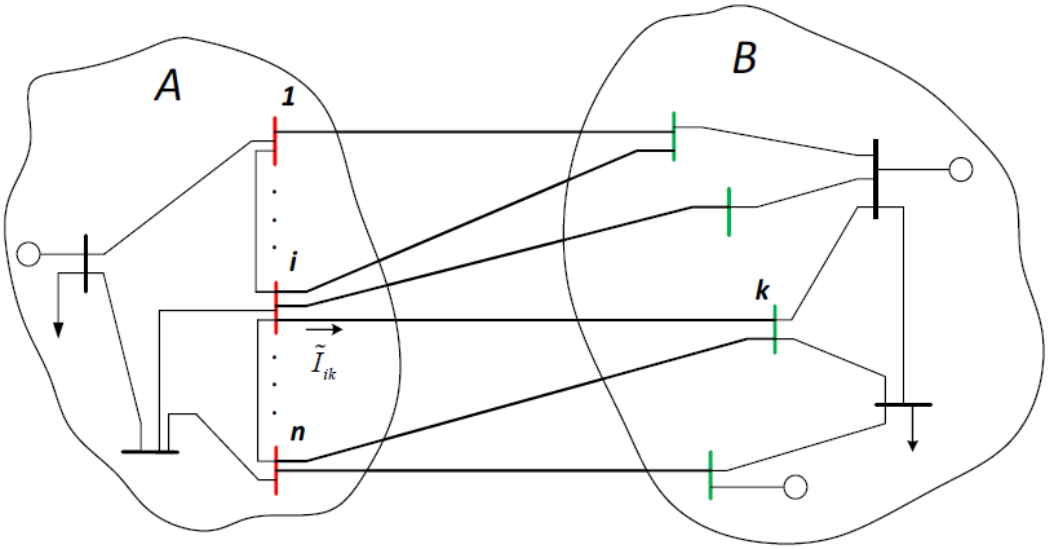

Figure 14 - Transmission corridor between two regions: Weak region A and strong region B

Consider the example system in Figure 14 with two regions connected via a transmission corridor, where region A is the weaker of the two regions and is receiving power from B. The NLI stability condition requires the weaker system to be receiving power.

The NLI is determined for each receiving bus by calculating the ratio of active power to conductance between the boundary busses across two success time instances as show in the equation below.

$$NLI_i = \frac{\Delta P_i}{\Delta G_i} > 0$$

Where P_i is the total active power imported by the boundary bus and G_i is the apparent conductance seen by the receiving bus. As long as NLI remains positive for all monitored boundary buses, the system is considered to be stable. When NLI is negative, the maximum power transfer has been exceeded and the system is unstable.

In practice, a warning (0.5) and alarm (0.2) margin is set to signal for operators to take action as the system approaches instability. Preventive measures such as reducing power imports to the affected area are common actions taken to address system conditions picked up by NLI.

System Oscillation Monitoring

Understanding and managing electromechanical oscillations are essential to ensure the reliable and secure operation of the power system. In large power systems, there can be multiple modes of electromechanical oscillations that require monitoring. These may originate as a natural consequence of dynamic interaction between machines or from industrial loads which may inject sustained forced oscillations into a power system. New control and monitoring systems are continuously being developed to address these challenges.

National Control Centre of HIPS employs an open-source application developed by the Pacific Northwest National Laboratory to process, identify and track oscillations using PMU data. The Archive Walker (AW) application and the accompanying Oscillation Baselining and Analysis Tool (OBAT) were used to process and visual real-time PMU measurements.

The AW tool contains the oscillation detection functions. The AW is feed raw PMU field measurements to detect and visualise oscillatory behaviour. The data fields fed into the tool is shown in Table 1.

Table 1 - PMU Data utilised for Oscillation Detection

Type	Description	Measurement unit
F	Frequency	Hz
VPM	Positive sequence RMS voltage magnitude	kV
VPA	Positive sequence voltage phase angle	Degrees
IPM	Positive sequence RMS line current magnitude	A
IPA	Positive sequence line current phase angle	Degrees

The AW tool makes use of two algorithms to detect forced oscillations. The first method captures signal power across a frequency range in a periodogram, where forced oscillations appear as distinct, narrow peaks. Although sensitive, this method requires a window of 10 to 30 minutes before it is able to detect oscillations reliably. The second method employed by the AW tool is based on spectral coherence. Detection of a forced oscillation at a specific frequency occurs when there is an observed increase in coherence at that frequency. This method is less sensitive to small oscillations compared to the periodogram but it offers quicker event detection. For near real-time oscillation detection, both algorithms can be executed simultaneously. Short-term detection is conducted using the spectral coherence method, and the detection results are refined when sufficient data become available, using the periodogram method.

Oscillations detected by AW is fed through to OBAT which utilises the Prony method to identify the oscillation characteristics and mode shapes. OBAT stores this information in a database containing the network conditions of each instance where network oscillation was detected. This database of events is be utilised to better understand how the dynamic response of a system changes under different operating conditions, serving as a valuable resource for network controllers.

3.1.1.1 Further Remarks

The uses of PMUs extend far beyond power system stability analysis. Presentations at CIGRE documented uses for PMUs which included:

- Power System Stabiliser (PSS) Tuning

  PMUs provide three functions which significantly contributes to the tuning of PSSs. As discussed in the Greek case study, PMUs are able to continuously monitor frequency behaviour, detecting weaking damping conditions and identifying mode shapes which PSSs can be tuned to. Secondly, the direct monitoring of power station busbars through PMUs can be used to verify PSS action. Finally, the PMUs monitoring generator outputs can be used to estimate generator inertia, validate the excitation models and measure generator damping.

- Wide Area Monitoring Protection and Control (WAMPAC)
  WAMPAC is an emerging type of special integrity protection scheme in which the detection principles can be more generalised and there is less emphasis on addressing determined sequences of events. WAMPAC aims to detect a stability issue and intervene correctly to resolve the issue. The WAMPAC fast frequency control and anti-islanding system in Iceland is a well-known case study that demonstrates a successful deployment of the technology. In the case study, Iceland was split into two islands following a system fault. WAMPAC was successfully able to arrest the resulting frequency and power swings before preparing the system for resynchronising.

3.1.2 Data Centre Case Study – Eirgrid [4]

While the dramatic change in the generation landscape has been widely acknowledged around the world, the same change is also occurring on the demand side. Notwithstanding the increasing penetration of electric vehicles, data centres in the Eirgrid power system have grown to account for over 10% of the peak demand. A number which is expected to increase to beyond 30% by 2030.

Eirgrid is the transmission owner of Ireland and Northern Ireland and has documented their experiences with data centres, a large-scale converter load, studying their impact on the frequency quality of their power system. The impacts of data centres in the Irish power system were investigated under system normal and fault conditions.

Steady State Frequency Transients

Under normal steady-state operations regular, cyclical fluctuations in data centre demand were observed to cause frequency quality issues. Consistent and sustained frequency transients jumping between 0.01-0.05 Hz were detected in data centre loads. These frequency transients tended to occur over sustained periods in the range of 60 seconds at a magnitude lower than the governor deadband of the system, which were typically set at 0.015Hz. Although these frequency transients polluted the quality of the power, they did not interact with generator behaviour of the Irish power system.

The Irish TSO does not yet have minor sustained frequency transient requirements for data centres and as a consequence, little can be done currently to hold the data centres accountable for these perturbations.

Post Fault Behaviour

Many data centres have Uninterruptible Power Supply (UPS) protection systems in place which results in the immediate disconnection of the data centre from the grid when a disturbance is detected. This can cause large frequency and Rate of Change of Frequency (RoCoF) excursions on the system. Fast changing frequency dynamics imposes additional stresses on generators and can result in scenarios where generation is tripped. In 2022, a single-phase transmission fault in the Irish transmission system led to the disconnection of multiple data centres from the network. The details of this fault is shown in Table 2.

Table 2 - Irish Transmission Fault

Fault	Fault Clearance Time [ms]	Min Retained Voltage1 [%]	RoCoF [Hz/s]	Inertia [MWs]
Single phase to ground fault	80	28	0.119	47249

During this event, up to 204MW of data centre demand was disconnected, approximately 50% of data centre load at the time. This resulted in a RoCoF of 0.12Hz/s which was arrested at 50.22Hz. As shown in Figure 15, data centres were observed to disconnect at different times following the fault (5 seconds), with load disconnection continuing to occur even10 seconds after the clearance of the fault.

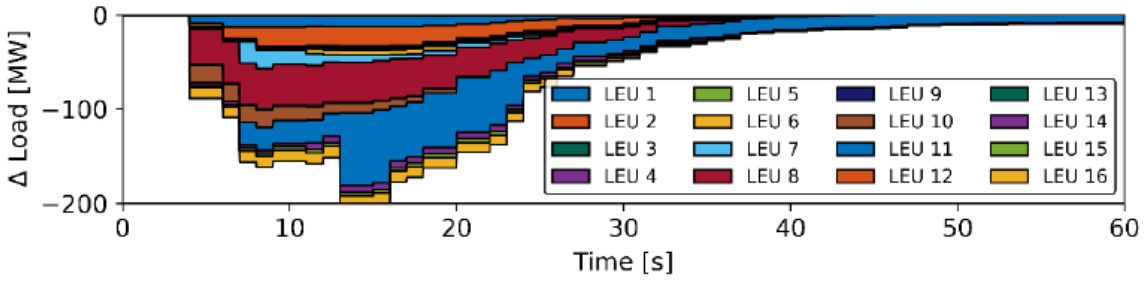

Figure 15 - Data Centre Responses to a Transmission Fault

3.1.2.1 Bottom Line

The Irish transmission system currently lacks any sustained frequency transient requirements or Fault Ride Through (FRT) requirement for data centres. It is important to highlight that the lack of FRT capability at data centres has the potential to exacerbate the impact of transmission system faults, leading to cascade trips and a significant system incident. These issues will continue to grow as the number of data centre connections increase.

The European Network of Transmission System Operators (ENTSO-E) has developed proposals for technical requirements that would apply to data centres. ENTSO-E proposes a new data centre demand category (110 kV and above) with FRT, RoCoF and limited frequency response requirements. The FRT capability shape proposed by ENTSO-E is shown in Figure 16.

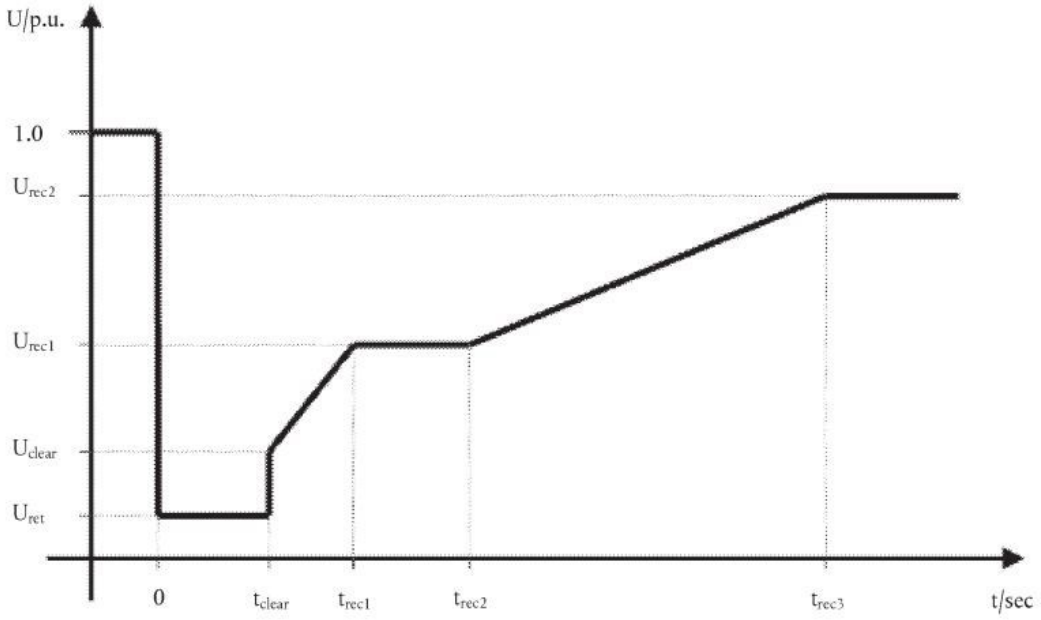

Figure 16 - ENTSO-E Data Centre FRT

Across the Atlantic in the USA, the Texas TSO is implementing voltage ride though requirements in addition to FRT requirements. These have been described in their publication titled "*Registration, Interconnection, and Operation of Customers with Large Loads; Information Required of Customers with Loads 25 MW or Greater*".

3.2 Future Energy Scenarios 2024 [1]

The Future Energy Scenarios (FES) outlined in the Quarter 1 report presented four credible outcomes on the path to net zero. Published in 2020, this framework focussed on how the speed and degree of grid decarbonisation can impact the development of the electricity industry. In 2024, NESO has updated the Future Energy Scenarios to explore a narrower range of pathways that lead to a net zero 2050. It is hoped that by limiting the range of forecasted possibilities, the development of the UK energy system can focus its development on a smaller set of strategic options. This change is part of an overhaul in the way Great Britain approaches energy planning. NESO is developing a Centralised Strategic Network Plan and a Strategic Spatial Energy Plan which will provide guidance on the development and progression of all energy industries in the UK.

While the previous iteration of the FES had been centred on generation development possibilities, the refreshed FES focuses on how demand will change in the future. This view of demand sets the targets the supply side forecasts must meet when optimising for the production of energy, dispatch of assets and utilisation of flexible solutions

The Future Energy Scenarios 2024 outlines three strategic pathways to achieve net-zero emissions by 2050, each emphasizing different technological and infrastructural approaches. Additionally, the FES 2024 includes a Counterfactual Pathway, which examines a scenario where insufficient progress is made toward decarbonization, resulting in the UK missing its 2050 net-zero target. The four energy pathways in the updated FES framework have been captured in Figure 17 and are expected to be used as the foundation of network planning and development up to 2028.

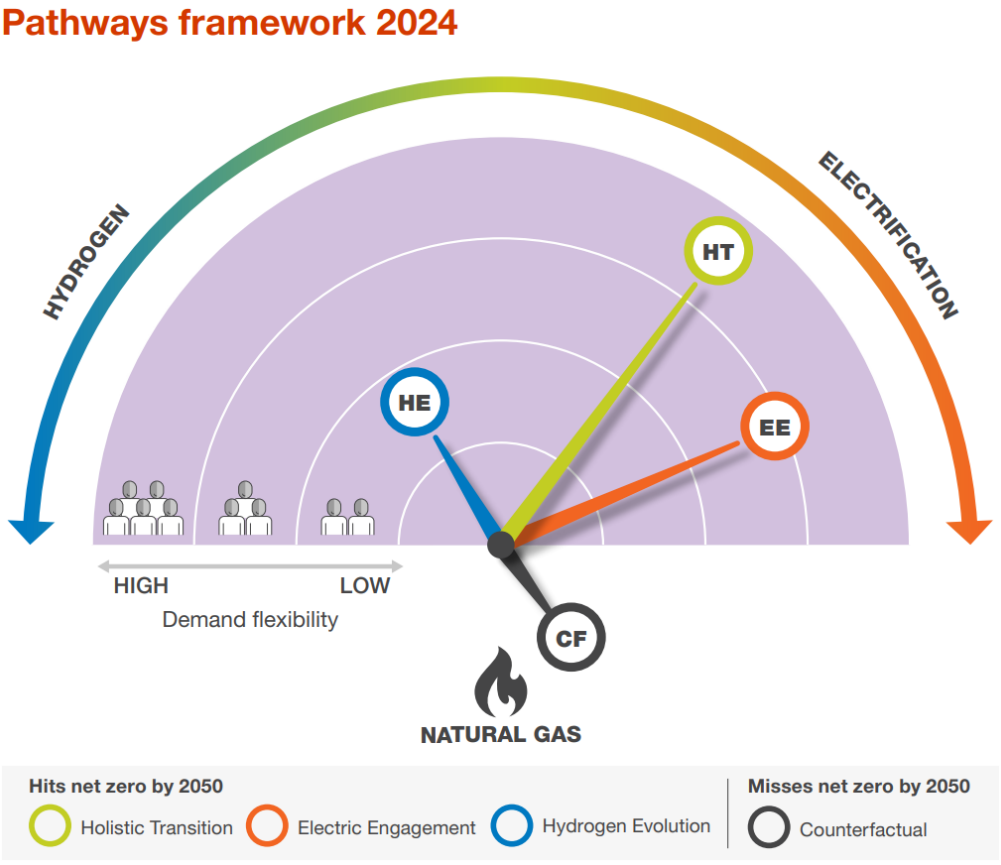

Figure 17 - Future Energy Scenario Pathways 2024

Net Zero Pathway: Holistic Transition

The Holistic Transition pathway envisions a balanced integration of various energy technologies, meeting net zero through a mix of electrification and hydrogen. Consumer engagement is very high with smart homes and electric vehicles providing flexibility to the grid. The significant change in the demand landscape is matched by high renewable capacity with high supply side flexibility delivered through storage and interconnectors.

Net Zero Pathway: Electricity Engagement

Focusing on extensive electrification across sectors, the high electricity demand in the Electricity Engagement pathway is met by a mix of nuclear and renewable energy sources. In this scenario, consumers are highly engaged in the energy transition through the use of technologies to reduce reliance on fossil fuels and minimize greenhouse gas emissions through direct electrification. Supply side flexibility is delivered through storage, interconnectors and low carbon dispatch.

Net Zero Pathway: Hydrogen Evolution

The Hydrogen Evolution pathway explores the potential of hydrogen as a major energy carrier. It envisions hydrogen playing a crucial role in sectors such as heating, industry and long-haul transportation. In this pathway, consumer engagement with the energy markets is limited with little change in consumption behaviour. Hydrogen in this scenario provides some dispatchable generation and supply side flexibility, reducing the need for renewable, nuclear and natural gas capability.

Net Zero Missed: Counterfactual Pathway

The Counterfactual pathway explores the slowest credible rate of decarbonisation. Although some progress is made towards decarbonisation compared to today, uptake of low carbon technology is slow and the dependence on gas for both heating and generation remains, resulting in net zero not being achieved. This pathway serves as a cautionary tale, highlighting the consequences of inaction and underscoring the urgency of implementing effective decarbonization strategies.

3.3 Phoenix Project [5]

Scotland is characterised by its large geography with mountainous highlands in the northern and western reaches, and lowlands in the south and east. Its size in combination with a low population density means that electricity in Scotland must travel long distances from generation sites to reach demand centres. Furthermore, Scotland's status as the major electricity exporter only increases the average distances in which Scottish generated power travels. The long electrical distances and the transition away from traditional generation in the Scottish power system has produced network challenges similar to those found in Queensland.

Scotland's electricity grid faces key stability challenges due to the shift from conventional power plants to renewable energy. Inertia, which helps resist sudden frequency changes, has declined as wind and solar generation have yet to be able to effectively provide the same level of response as a traditional generator. For similar reasons the short circuit level in Scotland has also reduced, resulting in poor power quality and increasing the risk of protection schemes failing. Additionally, voltage control has become more difficult as thermal power stations retire, moving reactive power sources towards the outer edge of the network, leading to fluctuating voltages as power flow changes. Furthermore, undamped sub-synchronous oscillations and harmonics have reduced the loading capacity of the transmission system. As the UK transitions towards a low-carbon future, maintaining grid stability has become a critical challenge.

The Phoenix Project, led by Scottish Power Energy Networks, aims to ensure the electricity network in Scotland and in the UK remains reliable. Running from 2017 to 2022, this project investigated the sustainable design, deployment and operation of an innovative hybrid co-ordinated control system. The Hybrid Synchronous Condenser (H-SCs) is a system that combines a synchronous condenser with a static compensator on the same connection node. The synchronous condenser provides high short circuit current generation capability and is used as the main contributor towards inertia between the two systems. The STATCOM functions as the primary source of reactive power support to maintain system voltage and can also provide harmonic and voltage damping. This project studied the technical and economic advantages of deploying H-SC technology over similar alternatives, and was the first deployment of H-SC in the UK.

3.3.1 Control and Operation

The H-SC was designed according to the characteristics of the Point of Common Connection (PCC). The design parameters were not limited to voltage, SCL, expected OV and UV, and maximum rate of change of frequency.

Synchronous condenser and STATCOMs have traditionally used standalone control systems. To facilitate the simultaneous operation of the H-SC system in a stable, coordinated and efficient manner, a master control system developed by ABB was used in the Pheonix Project. Embedded in the STATCOM controller, the master controller enables the SC and STATCOM to operate under any combination of Q and V control modes as shown below in Figure 18.

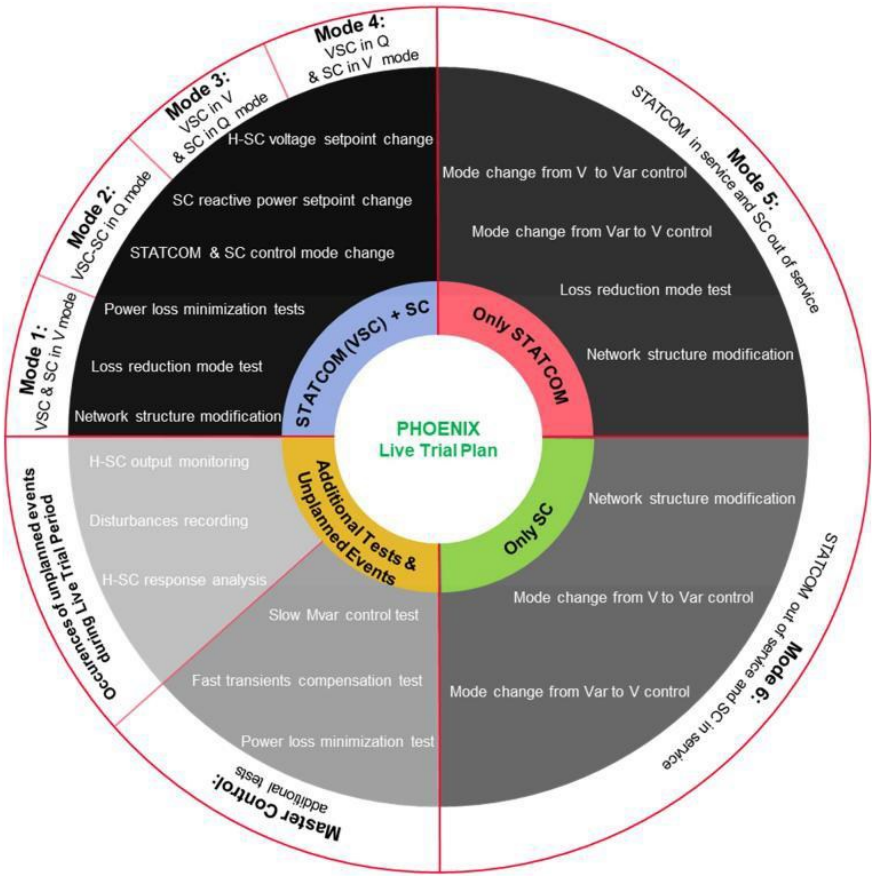

Figure 18 - H-SC Operating Modes

Furthermore, ABB claims that the master controller is capable of several other functions which can be run in parallel with its primary operating modes.

1. Power Loss Minimization

   The control system determines how the reactive power output of the H-SC should be shared between the SC and STATCOM to minimise total losses.

2. Fast Transients Compensation

   The response time of the whole installation may be slow due to communication delays as well as the natural dynamics of the synchronous condenser. This function aims to accelerate the response time of the H-SC system in response to sudden changes in network voltages by coordinating a STATCOM response before the SC begins acting.

3. Inertia Support Maximization

   This function aims to maximise the Inertial Frequency Response from the H-SC system. This is achieved by setting the STATCOM to Q control mode to a fixed reactive power output of 0 MVAr, thereby minimise the losses in that system in order to fully utilise the active power contribution from the SC's inertia response. Once the frequency increases, the STATCOM control is released.

4. Slow MVAr Control

   The objective of the Slow MVAr Control function is to slowly return the reactive power output of the H-SC system to a present steady-state value so that its reactive power capacity to support voltage is held in reserve.

3.3.2 Technical Outcomes

The Phoenix Project has delivered significant new learning on the design, deployment and operation of H-SC in the transmission system. A number of key technical learnings have been made from this project.

1. The employment of the H-SC system was able to increase the boundary transfer capability.

2. To avoid harmful control interaction between the SC and STATCOM, appropriate measures should be taken at the design stage to ensure the transformer impedance between the STATCOM and SC branches is sufficient, and the control parameters are tuned appropriately. The different electrical distances between the devices can affect the stability and performance of the H-SC system.

3. The utilisation of the master controller can coordinate the control of both devices resulting in minimized losses and maximised network inertia contribution.

4. From a technical perspective, the parallel operation of SC and STATCOM may bring various challenges in equipment, control and system interactions. It is thus important to verify the feasibility of hybrid operations of such devices for future installations in all those respects. Detailed system studies are needed to verify impacts, and control and system interactions.

By enhancing system stability, reducing operational costs, and enabling greater integration of renewable energy sources, the H-SCs deployed during Phoenix Project will play a vital role in the UK's commitment to a sustainable and resilient energy future.

3.3.2.1 Comparison with Other Technologies

The success of Project Pheonix showed that it was possible to combine different types of technology together to provide a service to the network.

Table 3 provides a brief comparison between the possible combined effect of individual technologies as a single hybrid system, based on the characteristics of the individual technologies.

Table 3 – Technological Comparison

Technology	Inertia/Fast Freq. Response	Voltage /Current. Characteristic	Short-Circuit Current	Response Time
BESS Grid Following	No intrinsic inertia Droop control Possibility of providing synthetic inertia	Full rated reactive current for cap. and ind. mode Possible instability due to cascaded control loops and PLL	Constrained by the overcurrent limiter, typical values 1.1 - 1.3 pu	> 1 cycle
BESS Grid Forming	Inertia response like SGs Fast frequency response similar to SM Possibility of providing synthetic inertia	Full rated reactive current for cap. and ind. mode. Typical overload 1.1 - 1.3 pu	Requires current limiting strategy once the commanded current exceeds max. value	> 0.5 cycles
SC + BESS Grid Following	1-3s inertia constant from SC Instantaneous response + droop control Possibility of providing synthetic inertia	High overloading capability Less than 1 pu of inductive current due to the SC limitations Possible instability due to cascaded control loops and PLL for BESS	>4 pu for SC, 1.1-1.3pu for BESS. Final value depends on the rating composition.	Improved response for post-fault settling time and reference voltage change due to the compensation of SC's response by BESS
SC + BESS Grid Forming	>3s inertia constant Instantaneous response +fast freq. response, similar to SM Possibility of so-called synthetic inertia	High overload capability Less than 1 pu of inductive current due to the SC's limitations (close to 0.75 pu)	>4 pu for SC, 1.1-1.3pu for BESS. Final value depends on the rating composition. BESS requires current limiting strategy once the commanded current exceeds max. value	Improved response for post-fault settling time and reference voltage change due to the compensation of SC's response by BESS

4 Reference List

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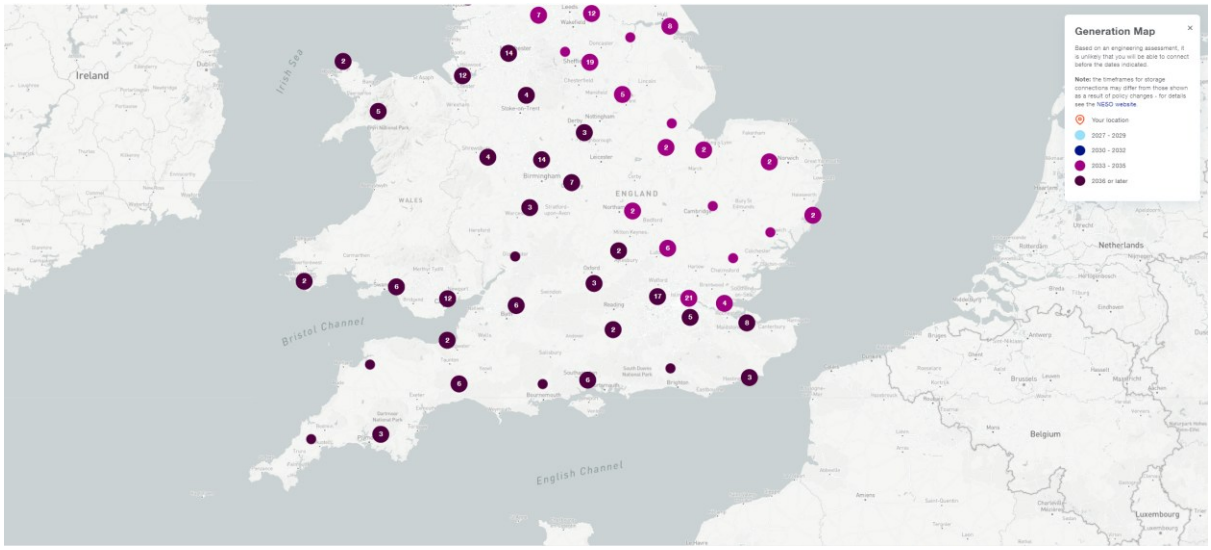
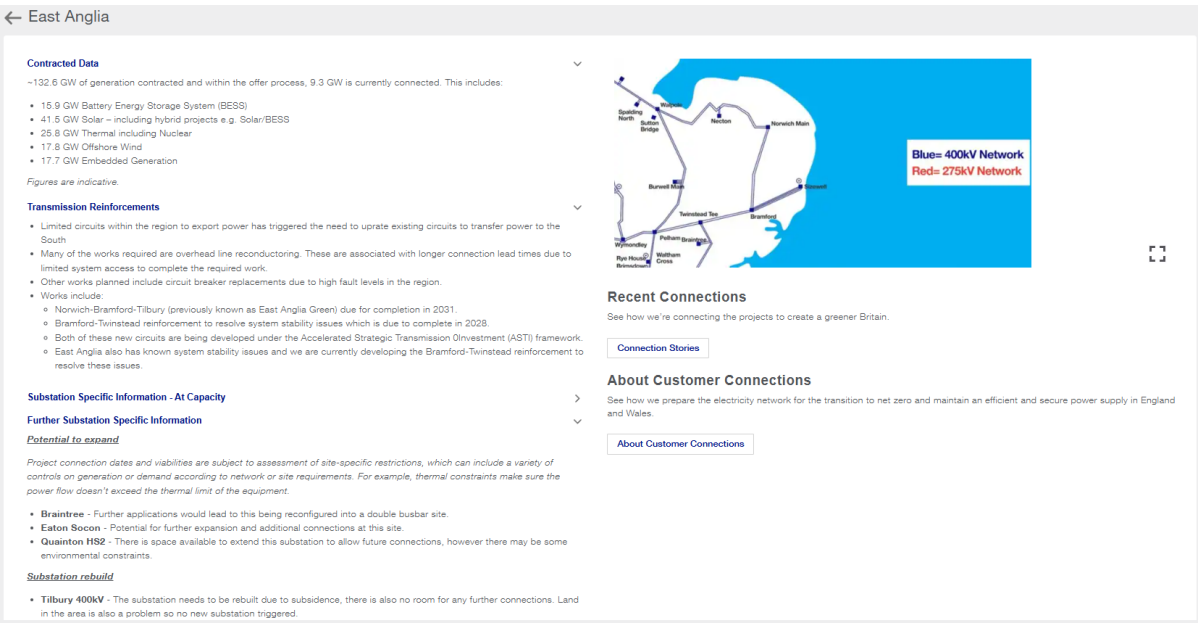
[4] T. KËRÇI, C. DUGGAN, U. FAROOQ, S. TWEED and M. VAL ESCUDERO, “Impact of Converter-based Demand on Frequency Quality in the Ireland and Northern Ireland Power Systems,” in *CIGRE 2024 Paris Session*, Paris, 2024.

[5] SP Energy Networks, “Pheonix Project Close Down Report,” SP Energy Networks, Glasgow, 2022.

5 Appendix

5.1 Appendix A