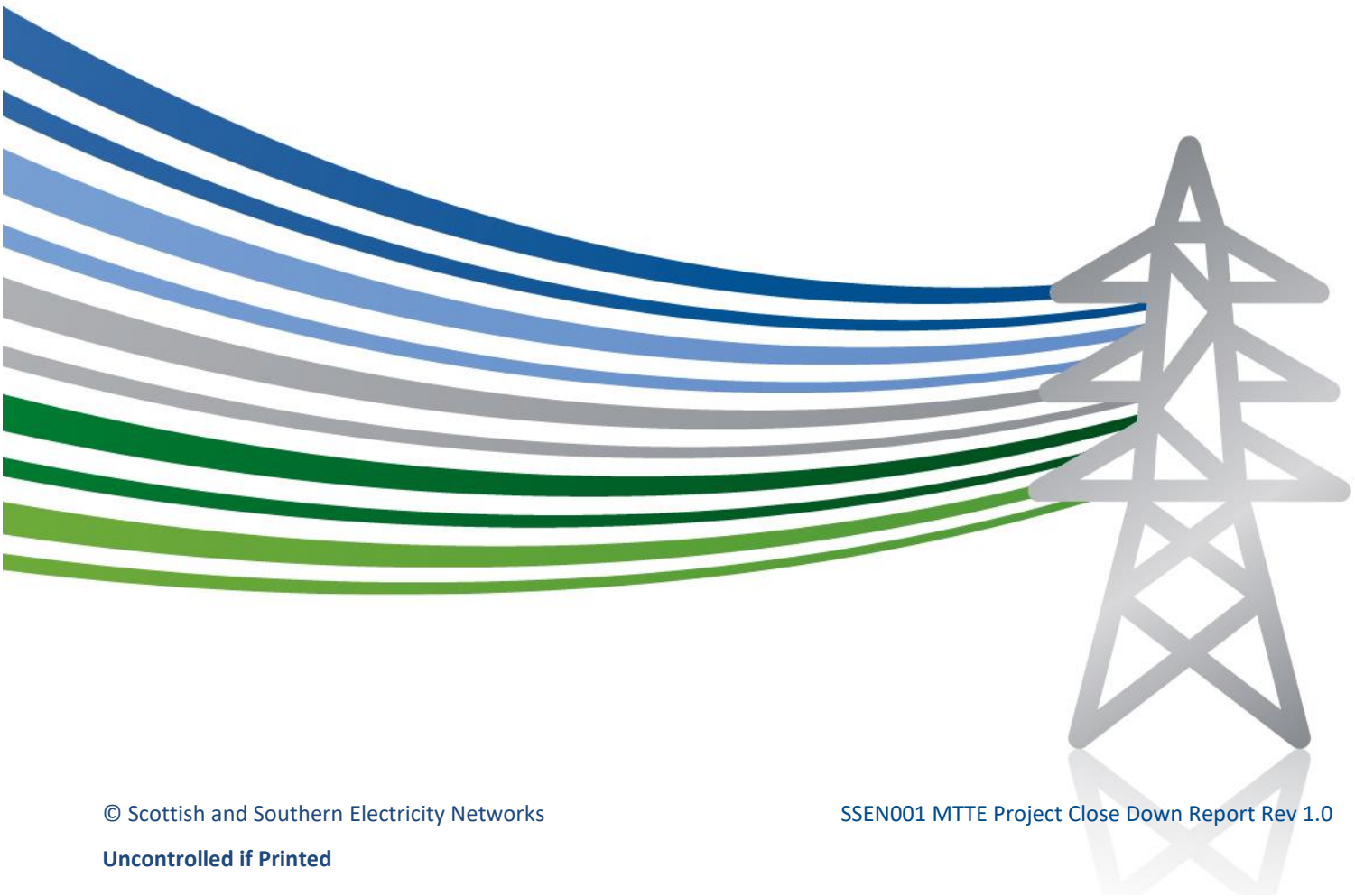
Scottish & Southern Electricity Networks

SSEN Transmission

Multi-Terminal Test Environment for HVDC Systems (SSEN001)

Project Close Down Report

April 2022



Foreword

The Network Context

Over the last 20 years, the Great Britain (GB) electricity system has been on a journey towards a much more power-electronic converter dominated network in its growth of Net-Zero energy resources. This journey represents a paradigm shift to how security of electricity supply is now managed and achieved across a range of new devices and controls, the largest and most significant of these being the use High Voltage Direct Current (HVDC) to transmit and connect power more efficiently.

In this new paradigm, network operation and planning rely on the resilience and relevant actions of control systems (and protection systems), many of which are only approximated in modelling, and are often hidden to protect the intellectual property of those supplying them. These need to be tested and configured efficiently to ensure device inter-operability with the network and other devices, and avoid interactions. This in turn drives a need for highly detailed simulation of the devices and the transmission network and some of this analysis can only be done in real-time with control system hardware as part of the simulation to provide necessary insights and risk management. This requires particular capabilities and infrastructure as investigated and addressed within the Multi-Terminal Test Environment (MTTE) project described in this document.

HVDC is a key Net-Zero transmission technology, enabling larger and more distant high capacity connections to be achieved offshore than would otherwise be possible, opening up new opportunities for both reinforcing the onshore network and connection of renewable connections, together with that same technology supporting a growth in interconnectors between nations to allow the zero carbon energy resources across GB and other nations to be pooled more efficiently.

The MTTE Project

Back in 2013, when the bid document for the MTTE project was submitted, HVDC formed a very limited part of the GB electricity network, based on a limited number of historic interconnectors that had been deployed to that point.

However, SSEN Transmission was planning a multi-terminal HVDC scheme, and the other Transmission Owners (TOs) and the Electricity System Operator (ESO) foresaw the growing role HVDC would play in reinforcing the transmission system, for example growing offshore wind connection via HVDC and embedded HVDC links (the first of these being the Western Link HVDC project). Ofgem, at the time (in granting the Network Innovation Competition (NIC) funding that same year) recognised the value to the GB consumer in facilitating de-risked HVDC technology development and increasing the capacity to deliver new potentially more efficient applications of that technology.

However, the 2013 position has since been transformed by the transition to Net Zero, as HVDC connected windfarms complement the overall growth in offshore wind almost five-fold in the next decade to around 50GW by 2030. New HVDC interconnectors have connected and are planned, leading to around 30GW of overall capacity within the 2030 time horizon. HVDC circuits paralleling and reinforcing onshore transmission system capacity continue to increase, with significant capacity signalled to proceed within the current Network Options Assessment (NOA) report. Ofgem last year, in approving the transition of The National HVDC Centre into a business as usual activity recognised its potential to support and enable that transition.

The Future

Now, looking forward from 2030 to 2050, multiple HVDC embedded links, HVDC connections to dozens of windfarms and many more interconnectors to Europe, with potential for both trans-continental HVDC connection and DC networks, supported by DC circuit breakers are expected to emerge in that timeframe.

Furthermore, these schemes will be complex, with the introduction of Multi-Purpose Interconnectors (MPIs), multi-vendor coordinated solutions and indeed the potential for a North Sea DC grid to emerge. We are confident that with the strong foundations of the HVDC Centre's creation, together with the capabilities that now reside within it, we are well placed to continue to support these changes over time and

Foreword

build on the successes of the MTTE project to date as discussed in this document and indeed echoed in Ofgem's decision over the future direction of the National HVDC centre last year.

The Delivery of the MTTE Project

This document describes the MTTE project, its scope and its context from the creation of The National HVDC Centre to the progress made under the MTTE project during its period of NIC funding. The document summarises the key achievements of the Centre, its financial position and project management over that period and maps these to the Successful Delivery Reward Criteria (SDRC) of the original MTTE project objectives. Within this we highlight a total of over £ 386k that can be returned to consumers, as a result of value creation work of the Centre in relation to external activities in international research and development.

Echoing the Future Business Model consultation, the TOs and ESO continue to see the HVDC Centre as a critical component of GB's electricity infrastructure going forward, de-risking the delivery and integration of the increasing scale and complexity of HVDC applications on the GB network.

The HVDC Centre uniquely combines large scale real-time simulation with actual vendor control and protection hardware, AC protection devices together with detailed transmission system network models. This allows the Centre to act as a "hosted simulation environment" to support analysis that would otherwise not be possible (while respecting the IP confidentiality of the various parties); whether that relates to extended testing and de-risking of individual HVDC projects or indeed more complex projects and the interactions between them.

This same value also applies to other large power electronics analysis and the Centre has been used as an environment to support detailed interactions of new forms of power electronic device control, new wide area control of power electronics devices, and the interactions between power electronic devices and AC protection relays.

In addition to these direct simulation activities whether supporting its TO and ESO partners, or others within the GB industry, the Centre is also a centre for disseminating knowledge associated with HVDC and power electronic device modelling, analysis and behaviour, conducting training, tutorials and webinars on these topics, and has supported GB and European Research and Development.

The HVDC Centre has established itself as a world-leading Centre of HVDC expertise and innovation over the period; and is providing critical support to projects in GB to enable GB's transition to net-zero, in addition also providing advisory support internationally to the direction of HVDC development, one example being its contribution to the Europa.eu SET plan.

The TOs and ESO are proud to have supported this flagship project, which has:

- Comprehensively delivered all of its project objectives and SDRCs;
- Delivered within the budget and able to return significant funding to customers, through the revenue it has generated;
- Has been an example of best practice in actively disseminating project learnings; and
- Delivered an enduring benefit to the GB consumer (through establishing the HVDC Centre) in de-risking and enabling the Net Zero transition of current and future energy networks.

This project report completes and closes the development phase of The National HVDC Centre, and in doing so sets the scene for its ongoing delivery of objectives as a Business As Usual function (as described in Ofgem's Future Business Plan determination) supporting GB energy policy across the Net Zero transition for years to come.

Ben Marshall
HVDC Technology Manager
The National HVDC Centre

Content

1) Project Background

Overview of MTTE

The Multi-Terminal Test Environment for HVDC (MTTE) Project, was submitted as a Network Innovation Competition (NIC) proposal in 2013, and subsequently funded in 2014. The project established 'The National HVDC Centre', which formally opened on 26 April 2017.

The National HVDC Centre is GB's simulation and training facility for HVDC; supporting the integration and successful operation of all HVDC schemes connecting to the GB Network.

The HVDC Centre is also the National hub for HVDC knowledge exchange, expertise and innovation.

The HVDC Centre uses state-of-the-art simulators to model and resolve potential issues in real-time before they impact on the delivery (or operation) of HVDC projects, to ensure the integrity and security of the GB Network.

Project Summary

Below is the summary of the project, extracted from the Full Submission document (2013).

SSEN Transmission together with National Grid Electricity Transmission Limited (NGET) and Scottish Power Transmission Limited (SPT) is proposing to establish a collaborative facility which will enable the planning, development and testing of high voltage direct current (HVDC) transmission solutions in GB.

This facility is known as the Multi-Terminal Test Environment (MTTE); it will house: a real-time simulator system (which simulates HVDC schemes), IT infrastructure and accommodation for replica HVDC control panels.

The anticipated proliferation of HVDC systems in GB during RIIO-T1 and beyond is largely being driven by the increasing penetration of renewable generation. To date, there is limited experience in GB of the design, construction and operation of HVDC systems.

To maximise the benefits of the significant expected investment in HVDC systems in GB, there is a need to: support transmission planning and improve specification of HVDC schemes;

- *Facilitate multi-terminal solutions;*
- *De-risk control interactions between multi-terminal and electrically connected converters, and with other active controlled equipment;*
- *Facilitate competition and multi-vendor HVDC schemes;*
- *Train and develop Transmission Planning and Operational Engineers;*
- *Undertake post-commissioning scenario planning and operational optimisation; and*
- *Model new HVDC technologies.*

The MTTE will contribute to achieving these aims, which are intended to reduce the risks, costs and time-to-deployment of HVDC systems for GB transmission Customers.

2) Executive Summary

Context

The Multi-Terminal Test Environment (MTTE) is a Network Innovation Competition (NIC) funded project that established The National HVDC Centre. The HVDC Centre is a simulation and training facility commissioned in 2017, as a collaboration between SSEN Transmission, SP Energy Networks, National Grid Electricity Transmission and National Grid ESO.

The Centre is available to support all HVDC schemes, both already in operation and in development, that connect to the Great Britain (GB) electricity grid, including:

- HVDC interconnectors to European countries and Northern Ireland;
- HVDC connections to large offshore wind projects, under development;
- Embedded HVDC links within the GB network; and
- HVDC connections to islands.

The Centre provides insight, and in-depth simulation analysis to inform these and other HVDC and converter dominated developments. This information and practical support can then be used by the TOs and the ESO to ensure the integrity and security of the grid network as a significant number of HVDC schemes are deployed on the GB grid over the RIIO-T2 price control period.

The Centre is also GB's real-time testing facility for HVDC schemes using replica hardware to study and resolve network interactions; and a National hub for HVDC knowledge exchange, expertise and innovation.

The Centre has an enablement role, that includes providing support to developers of HVDC schemes during their design, commissioning, compliance, and operational support and investigations.

2013-2017: Establishing the HVDC Centre

From 2013 to 2017, the MTTE Project secured funding and established The National HVDC Centre:

2013: The GB TOs (and the SO) agreed that SSEN Transmission was the most appropriate TO to lead the NIC funding request (given their plans for a multi-terminal HVDC scheme); and SSEN Transmission submitted the NIC funding application for the MTTE project. The application was successful and the project direction was issued by Ofgem in December 2013.

2014: The project received £11,333k from the NIC and £1,339k from SSEN Transmission; to fund the establishment of The National HVDC Centre, and cover its operational costs for the first 4 years (up to March 2021); during 2014 the project focused on agreeing collaboration agreements with all the project stakeholders.

2015: The project focused on developing the plans (for the people, processes, technology and the building).

2016: Focused on building works (and recruitment).

2017: The National HVDC Centre was formally opened on 27th April 2017.

2) Executive Summary

2017-2018: Supporting the CM Project

The Caithness-Moray HVDC Project (CM Project) is the first HVDC scheme in the north of Scotland, and represents a £1.1bn capital investment in the electricity network.

The first phase of the project links Spittal (in Caithness) and Blackhillock (in Moray) with ±320kV, 160km land and submarine HVDC cables. However, the scheme is designed as a three, four or five multi-terminal scheme allowing for future extension to connect the Shetland Isles and other renewable generation.

The Caithness-Moray HVDC Project is a landmark project for developing the electricity network in Great Britain towards a low-carbon network; however, it is also a technically challenging project:

- Connecting to a weak AC (275kV) network in the north of Scotland;
- Designed for multi-terminal operations; and
- Potential for multi-vendor extensions.

The HVDC Centre was able to help address these challenges and assure the delivery of this project through the use of Replicas of its control panels to test the operation of the system under a range of conditions, with a detailed representation for the AC network.

Furthermore, as the CM scheme is extended to multi-terminal operation with commissioning of Shetland leg in 2024, the HVDC Centre will have a pivotal role ensuing the operation of the complex multi-terminal controls, using the Replicas of all three terminals.

Support Provided by the HVDC Centre

The HVDC Centre provided extensive technical support to the CM Project at each stage of the delivery of the project; the range of this support is described below.

Replica Control Hardware

Replicas Procurement	The HVDC Centre managed the procurement of the Replicas, from specification, supplier negotiation, Factory System Testing, through to delivery.
Replicas Installation and Commissioning	Following delivery of the Replicas, the HVDC Centre oversaw their installation, commissioning and testing.
Supported Replicas Hosting	Now that the Replicas are installed, the HVDC hosts and operates them in a secure environment, connected to our RTDS® system.

Training

HVDC Training	The HVDC Centre delivered training courses covering HVDC fundamentals, components and real-time simulation, followed by hands-on sessions where the attendees interacted with the HVDC scheme in a simulated environment to build their understanding.
Control Room Training	The Centre enabled the control room team to train and practice the operation of the Caithness-Moray link, this aided their understanding of HVDC control systems, and ensured a smoother and safer adoption of the scheme.

Grid Integration

Grid Integration Risk Management	The Centre has advised the CM project on identifying and mitigating grid integration risks, ensuring the security of the grid network.
Integration Compliance	The Centre supported the demonstration of grid code compliance of the CM scheme to the System Operator.
Interaction (& Fault) Studies	The HVDC Centre integrated the Replicas with a detailed real-time representation of the AC network (developed in-house) to test the operation of the HVDC scheme in conjunction with the AC network.

Specific Project Support

Controls Development	Prior to the CM project being commissioned, additional functionality was added to the scheme. The Replicas enabled this functionality to be fully tested at the HVDC Centre without delaying the commissioning of the scheme.
Commissioning Support	The HVDC Centre supported the commission of the CM Project through: • Pre-running commissioning tests on the Replicas, to show the results that should be anticipated; • Reviewing (on a daily basis) the outputs of the on-site commissioning tests, to provide in-depth analysis; and • Analysing and diagnosing faults and/or events that occur during commission.

2) Executive Summary

2019-2021: Supporting HVDC Projects

In addition to the specific operational support of the CM project, the Centre has delivered a range of high-profile and critical projects for a range of stakeholders.

Commissioned Projects/Support

HVDC for Black Start (Scottish Government)	Analysing and recommending actions to maximise HVDC Support of GB Black Start and System Restoration.
Stability Pathfinder (National Grid ESO)	Evaluating the stability of HVDC schemes and other inverter connected sources under varying short circuit levels.
NSL Protection Study (SPEN & National Grid)	Testing and validating the protection systems to enable the connection of the NSL link.
PROMOTioN project (Horizon 2020)	Leading WP9. This work package demonstrates the operation of the DC grid protection systems using hardware prototypes with real-time simulation to test and demonstrate interoperability of DC Grid protection systems.
Eastern Link Project Support (TOs)	Provide ongoing support to the Eastern link project teams.
Caithness-Moray-Shetland Support (SSEN Transmission)	Operational support for the CM scheme (& Shetland extension), including: • Emergency Power Control (EPC) Investigation: to understand the operation and optimise the EPC mode; • Shetland Fault-Level/Modelling; • PowerOn Implementation: Integrating 'replica' SCADA system; • Multi-Vendor Implications for Shetland; and • 3rd Terminal Extension of CMS Support.

Research Programme

Converter Models (University of Strathclyde)	Developing open-source detailed converter models.
Stability assessment (University of Strathclyde)	Stability assessment and mitigation of HVDC converter interactions: Impedance modelling of HVDC converters for system stability studies.
Black Start Protection Coordination (EPRI)	Coordination of AC network protection during grid energization from HVDC schemes: Assess suitability for existing AC protection for Black start from HVDC.
Grid Code Compliance (Cardiff University)	Improving Grid Code Compliance of existing and upcoming HVDC Schemes in GB: Assess and test HVDC Grid Code compliance using simulation and experimental tools

Training *(In addition to running the HVDC Training and Control Room Training)*

RTDS® Training	Approved to run RTDS® training courses.

Engagement

ENA's OFTOs Working Group	Leading the technical report on offshore electricity transmission technologies required to connect large offshore wind farms to GB grid.
CIGRE Working Group (B4.82)	Investigating interactions between HVDC schemes and FACTS devices in close proximity.
CIGRE (Paris) Paper	Multi-terminal extension of existing HVDC schemes.
HVDC Operators' Forum	Continuing our prominent annual event to share knowledge and experience; and facilitate industry collaboration.
Grid Code development	Supporting the Expert working group developing GB Grid forming convertor solutions with technical expertise and proposals on data exchange and verification activities.

2) Executive Summary

2021-26: Future Business Model

The Centre has developed into a critical component of Great Britain's (GB's) electricity infrastructure, enabling the delivery and integration of HVDC schemes onto the GB network.

On 3 July 2020, Ofgem published its determination on the future of The National HVDC Centre, based on the future business plan that the Centre submitted.

The Centre's future business model can be found here: https://www.ofgem.gov.uk/sites/default/files/docs/2020/07/hvdc_centre_future_business_model_public.pdf

Ofgem's determination can be found here: *www.ofgem.gov.uk/publications-and-updates/decision-future-operation-hvdc-centre-following-end-nic-funding-period*

This determination provides certainty and direction for the Centre's activities across the RIIO-T2 period and an endorsement from Ofgem of the importance of these activities in supporting GB's net zero targets.

The HVDC Centre has become a world-leading Centre of HVDC expertise and is providing critical support to projects in GB and the security of the GB network; directly benefiting GB's electricity consumers.

Impact of Covid-19

The MTTE Project was due to be completed on 31 March 2021; however due to the impacts of Covid-19, the project actually completed on 31 March 2022.

This was due to a number of sub-projects being delayed (as a result of Covid-19 impacts on the suppliers):

- Protection Performance Overview and Validation in Low Strength Areas (undertaken by Manitoba Hydro International);
- Evaluation of HVDC with Synchronous Condenser impact on AC Protection (undertaken by the University of Strathclyde);
- Adaptive Damping of Power Oscillations using HVDC (undertaken by EPRI);
- Stability Assessment and Mitigation of Converter Interactions - Phase 2 (undertaken by the University of Strathclyde); and
- Extension of the HVDC Centre Building.

Objectives & SDRCs

The MTTE Project's objectives (as described in the NIC Submission) were:

- Establish the MTTE Facility;
- Support transmission planning and improve specification of HVDC schemes;
- Facilitate multi-terminal solutions;
- De-risk control interactions;
- Facilitate competition and multi-vendor HVDC schemes;
- Train and develop Transmission Planning and Operational Engineers;
- Undertake post-commissioning scenario planning and operational optimisation; and
- Model new HVDC technologies.

As described fully in Section 5 of this report:

- All of the project objectives have been met; and
- All nine of the Project SDRCs have been successfully completed.

Scope

As described in the NIC Submission document (2013) the scope of the MTTE project was as follows.

SSEN Transmission (together with NGET & SPT) is proposing to establish a collaborative facility which will enable the planning, development and testing of complex High Voltage Direct Current (HVDC) transmission solutions in GB. Explanation is provided below.

2) Executive Summary

- Establish the MTTE Facility (delivered on 26 April 2017 with successful delivery of National HVDC centre and associated sub-projects);
- Facilitate Transmission Planning of HVDC schemes (delivered continuously across project period);
- Improve Requirements Specification of HVDC schemes (delivered across Centre R&D, and Centre HVDC project support across project period);
- Facilitate Multi-Terminal Solutions (delivered both in Caithness-Moray-Shetland project support, the PROMOTioN project, and across project period);
- Facilitate Competition and Multi-Vendor HVDC schemes (delivered most particularly across the PROMOTioN project and the centres other R&D activities across the project period);
- De-risk control interactions between multi-terminal, co-located and electrically connected converters, and with other active controlled equipment (delivered continuously across project period);
- Train and Develop Transmission Planning and Operational Engineers (delivered across webinars and tailored training programmes across project period);
- System Optimisation – Reducing Losses and Improving Efficiency; and
- Model New HVDC Technologies (delivered through centre activities throughout project period).

Outcomes

The MTTE Project has demonstrated the long-term need for a dedicated facility to enabling the delivery and integration of HVDC schemes onto the GB network.

The project has established such a facility (The National HVDC Centre), and transitioned this facility to Business as Usual (BaU) operation.

The MTTE Project has also delivered a wide range of projects for our stakeholders to support the MTTE project objectives, and delivered a wide range of dissemination activities.

Project Learnings

There is a wide range of learnings from the project.

- For the MTTE project as a whole, these are articulated in the Future Business Model[1]: In this report, it is demonstrated that the coming years will see a huge investment in HVDC schemes in GB; the most concentrated development of HVDC in the world. Such extensive development poses significant risks to the reliable operation, control and resilience of the GB network. n order to mitigate these risks an independent testing facility that can host detailed models (and control/ protection hardware) from multiple suppliers and from TOs/ESO is required. It must have the expertise (and technology infrastructure) to undertake specialist studies; along with the credibility that ensures the results can be relied upon.
- For all of the technical projects that the HVDC Centre has completed; the learning is articulated in the reports referenced in Section 11 of this report.

[1] https://www.ofgem.gov.uk/sites/default/files/docs/2020/07/hvdc_centre_future_business_model_public.pdf

2) Executive Summary

Stakeholder Perspective

The National HVDC Centre has consulted its Technical Advisory Board (which comprises representatives from all of the TOs and the ESO) and its range of stakeholders and received statements of support across TOs, developers and the ESO *[detailed letters can be found in Appendix II of the Future Business Model submission].* Selected quotes are highlighted below:

"We are of the view that the role of the Centre improves the integrity and security of the network" & "We recognise the role the Centre plays in supporting the decarbonisation and net-zero targets"

Ofgem (Future Busines Model Determination)

"We intend to continue this engagement to develop our training and simulation capability."

National Grid ESO

"NGET has previously used the HVDC Centre's facilities in testing and developing protection settings for specific HVDC connections. It is likely that we will continue to use the centre for this in the foreseeable future."

National Grid Electricity Transmission

"We have been pleased to see the Centre establish its place at the heart of HVDC-related planning, training and thinking in GB."

SP Energy Networks

"We…see the value the National HVDC Centre can deliver in helping to enable a transmission network that can maximise the contribution renewable energy can make."

Scottish Enterprise

"It is clear that a capability such as that offered by the HVDC Centre is an important component in developing the future gird."

Mutual Energy (Moyle Interconnector)

"We…will continue to liaise with you and support your work throughout our project's lifecycle and hopefully well beyond into Operations."

NorthConnect

"National Grid Ventures views the programme of work and the services offered by the centre as being of value to the long-term development and operation of HVDC within the UK Electrical system."

National Grid Ventures

"Can see the benefits the Centre can bring to share lessons learnt and de-risk the Dogger Bank Offshore Wind Project."

SSE Renewables (Dogger Bank)

"It is becoming imperative that there should be an independent system studies team holding information across National Grid, manufacturers and developers. The HVDC centre can bridge this gap and play a crucial role in this respect going forward."

Innogy (Sofia)

"The Centre's unique position as part of SSEN, with very strong links to European Universities, and partnerships with manufacturers is very powerful."

University of Manchester

"The Centre, in its unique regulatory position…to provide the insight and understanding that will contribute to the de-risking and realisation of the HVDC connections across the GB grid."

University of Strathclyde

"The Centre will enable accurate network analysis and planning by utilising detailed control & protection replicas of various HVDC projects located around the UK."

Siemens

"The National HVDC Centre provides a facility that allows HIL testing at an unmatched scale. Mitsubishi Electric Europe see this as a critical asset in the GB to support pre-project studies, in addition to ongoing control verification post-commissioning."

Mitsubishi Electric

Additional Stakeholder feedback can be found in the Peer Review Section of this report (Section 15).

3) Project Details & Outcomes

Overview

To achieve its objectives, the MTTE Project first established 'The National HVDC Centre'.

The National HVDC Centre is Great Britain's (GB's) simulation and training facility for HVDC; supporting the integration and successful operation of all HVDC schemes connecting to the GB Network. The Centre is also the National hub for HVDC knowledge exchange, expertise and innovation (including delivering training, leading research, engaging stakeholders and disseminating knowledge).

The Centre uses state-of-the-art simulators to model and resolve potential issues in real-time before they impact on the delivery (or operation) of HVDC projects, to ensure the integrity and security of the GB Network. Since opening, the Centre has developed into a critical component of GB's electricity infrastructure, enabling the delivery and integration of HVDC schemes onto the GB network.

The HVDC Centre is now a globally recognised centre of HVDC expertise, and a critical part of the GB electricity infrastructure; supporting embedded HVDC links, HVDC interconnectors between GB and EU, and HVDC windfarm connections in GB, as well as providing similar support to related technologies like FACTs devices.

Design Development Document

The high level design of all components of the MTTE project were collated in the Design Development Document (refer to link below), which was reviewed at a stakeholder workshop on 23 April 2015, approved by all the TOs and ESO; and endorsed by HVDC suppliers.

https://www.hvdccentre.com/library/mtte-design-development-document/

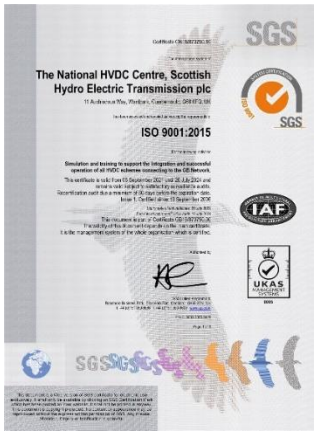
This document provides a blue-print for other organisations who want to establish a similar facility.

Utility Week Awards Finalist

The project was shortlisted as a finalist for the Utility Week awards in 2017 for "**Outstanding Innovation 2017".**

ISO-9001 Acreditation

In 2021, the project achieved ISO-9001 accreditation, as externally audited and assess by SGS, for its quality management systems and project management.



Capabilities of the HVDC Centre

The Centre has developed into a world-class facility, combining the following capabilities:

- **Managing Intellectual Property**: the Centre is designed to securely manage Intellectual Property (IP) from multiple parties;
- **Real-Time Simulation:** the Centre has significant real-time simulation capabilities (with 7 x RTDS NovaCors and 3 x PB5 racks);
- **Hardware in the Loop:** the Centre has a range of hardware, including:
- **Multi-terminal replicas** (a full set of control system replicas for the Caithness-Moray-Shetland scheme - the first multi-terminal scheme in Europe)
- **PMUs** (Phasor Measurement Units)
- **IED** (for multi-terminal scheme protection)
- **Communication Emulator**
- **Phasor controller:** provided on completion of an NIA project this vendor supplied controller uses PMU data to potentially instruct HVDC project operation.
- **Protection Testing Infrastructure**: with RTDS interfaces, power amplifiers, DC supplies and a range of protection relays from multiple suppliers);

3) Project Details & Outcomes

- **Offline Simulation and Model Validation**: across multiple software packages
- **"Software in the loop" functionality** via a separate high-spec PC the ability to run an offline developed model or code within an interface allowing it to operate within the loop of a real-time study; and
- **Network Models:** as a Transmission Licensee, the Centre has access to the full dynamic network models (through the System Operator – Transmission Owner Code "STC").

Subject Matter Expertise

The Centre has assembled a team of HVDC experts who are internationally recognised as leaders in their fields. Together they provide HVDC experience across: academia, system operator, power systems consultancy, transmission innovation and HVDC suppliers.

Their specific areas of expertise cover:

- **HVDC Coordination**: Independent and holistic technical view across: system operator, network owners, interconnector developers and HVDC offshore wind developers;
- **Complex HVDC Systems:** Design, simulation, and testing for complex HVDC systems;
- **HVDC AC Integration:** Secure integration of HVDC & FACTs devices into complex/weak AC Networks
- **Offshore HVDC:** Design and technical co-ordination of integrated offshore developments;
- **HVDC Control & Protection Interactions:** Enhancing the robustness of control and protection approaches relating to multiple HVDC or FACTs devices;
- **HVDC Converter Modelling:** Accurate modelling converter controls (including VSC/LCC, Real-time/Off-line);
- **Model Conversion and Validation:** Appropriately converting models between packages, including model reduction and validation, and specific expertise in RSCAD; and
- **HVDC Research & Innovation:** Leading a programme of research and innovation projects.

Technical Project Delivery

To deliver on the project objectives, the MTTE Project has delivered a range of technical projects during its operation phase; these are described below:

Adaptive Damping of Power Oscillations using HVDC

This project is designing adaptive POD controllers via HVDC links and/or FACTS devices using a novel measurement-driven approach to mitigate low frequency inter-area, converter driven, or local sub-synchronous oscillations. This project under the title "Grid Damper" won its category in the prestigious R&D 100 awards in 2021 *(www.rdworldonline.com/rd-100-winner-of-the-day-griddamper/)*.

www.hvdccentre.com/pod_project/

Caithness–Moray HVDC Scheme Delivery

The HVDC Centre was able to help address technical challenges and assure the delivery of the project using Replicas of the control panels to test the operation of the system under a range of conditions, with a detailed representation of the AC network.

https://www.hvdccentre.com/our-projects/caithness-moray/.

Caithness-Moray Support

During the commissioning of the CM Project the Centre focused on de-risking the integration of the CM link with the AC network, specifically this has included:

- Supporting the testing of the Emergency Power Control (EPC) functionality of the CM controls using the CM Replicas. Utilising the Replica for this testing avoiding the need for shipping the main control system back to the supplier (which would have incurred significant cost and time);
- Working with the CM project team to demonstrate grid code compliance of the CM scheme to the System Operator;

3) Project Details & Outcomes

- Integrating the Replicas with a detailed real-time representation of the AC network (developed in-house) to test the operation of the HVDC scheme in conjunction with the AC network (this was referred to as FST4);
- Pre-running commissioning tests on the Replicas, to show the results that should be anticipated;
- Reviewing (on a daily basis) the outputs of the on-site commissioning tests, to provide in-depth analysis;
- Analysing and diagnosing faults and events that occurred during CM commissioning; and
- Providing ongoing operational support for the link.

https://www.hvdccentre.com/our-projects/caithness-moray-project-support/

COMPOSITE Testing of HVDC-connected Offshore Wind Farms

This project developed new approaches to defining the key tests & simulations and the associated data and other requirements needed across the process of designing, testing, commissioning and operating complex, multi-device connection solutions.

www.hvdccentre.com/composite/

Distributed ReStart (NIC)

The Centre is supporting SP Energy Networks, TNEI and National Grid ESO with the Distributed ReStart project; which involves the construction of a real time model of the distribution system being restored and the associated resources available to Black Start, allowing work already underway within the project to be complemented by the more detailed view of resource control and protection that our real time environment provides; this allows traditional and non-traditional sources of Black Start resource performance to be compared. The project has conducted analysis of the energisation paths from a given Black Start generator, supported protection system review, and is currently undertaking the testing of a distributed resources controller, intended to better support black start.

https://www.hvdccentre.com/innovation-projects/distributed-restart/

Eastern HVDC Support

Commissioned by SPT, NGET and SSEN Transmission, the Centre is providing ongoing technical expertise and support to the Eastern HVDC project teams including identifying technology opportunities, and recommended testing and modelling needs.

https://www.hvdccentre.com/our-projects/eastern-link/

Evaluation of HVDC with Synchronous Condenser impact on AC Protection

This project has developed representative detailed models to enable the comprehensive testing of the impact of HVDC system on AC protection performance. It detailed the reasons for protection degradation, related the generic test-bed developed to specific network examples and also considered the beneficial effect of synchronous condenser contribution to the performance of protection. The project inspired a Scottish Hydro-Electric Transmission project to further evaluate new protections for management of low short circuit level conditions and establish the benefits of grid forming converter controls in relation to protection system performance.

www.hvdccentre.com/innovation/dc_with_ac_protection/

HVDC Phasor Based Monitoring (NIA)

The National HVDC Centre has worked with SSEN Transmission and GE Intelligent Systems, to investigate the potential to use a variety of PMUs (and other devices) to inform wide area control as key metrics of local system strength change within the onshore transmission system.

The National HVDC Centre has undertaken comparative evaluations of devices, with these and a new Phasor Controller platform being used for detailed RTDS-HiL evaluation of the proposed system and device responses to it.

3) Project Details & Outcomes

www.smarternetworks.org/project/nia_shet_0029

https://www.hvdccentre.com/innovation-projects/phasor-based-monitoring-with-hvdc-control-nia-funded-project/

HVDC R&D Strategy and Supply Chain Review (Coordinated Offshore)

BEIS and Ofgem requested that the Centre deliver two reports to inform the 2050 net zero targets:

- An HVDC R&D strategy to enable the delivery of a coordinated approach to offshore connections to meet 2050 net zero targets; and
- A technical report describing the components, and other technology, that will be required to deliver a coordinated approach to offshore connections to meet 2050 net zero targets, and an overview of the associated supply chains.

https://www.hvdccentre.com/library/hvdc-rd-strategy-coordinate-offshore/

https://www.hvdccentre.com/library/hvdc-supply-chain-overview-co-ordinated-offshore/

Integrated Offshore Design

Commissioned by the Offshore Wind Industry Council (OWIC), the Centre has developed and delivered a report on the design of integrated offshore connections.

Also, the Centre contributed to an industry report on enabling efficient development of offshore transmission network, submitted by OWIC to Ofgem.

Building on established technologies, the Centre developed a toolkit of flexible integrated solutions for the connection of offshore Wind, at the scales required within the future offshore development zones.

Incorporating innovative Bi-pole based solutions, these designs minimise the extent of offshore infrastructure, providing consent and cost benefit; and have been considered against current industry technical codes and standards, and provide the ESO and TOs with options for providing increased boundary capacity to the onshore network.

https://www.hvdccentre.com/library/de-risking-integrated-networks/

https://www.hvdccentre.com/2020/01/the-national-hvdc-centre-leads-publication-of-technology-report-for-owic/

Maximising HVDC Support for Black Start

Commissioned by the Scottish Government, and supported by specialists from Scottish Hydro Electric Transmissions (SSEN Transmission), SP Transmission (SPT) and National Grid Electricity Transmission (NGET), The HVDC Centre technical experts carried out an in-depth study of how HVDC schemes can support Black Start and system restoration.

On 4 December 2019, the HVDC Centre published the full report, which is available on our website: www.hvdccentre.com/our-projects/maximising-hvdc-for-black-start/

Moyle Support

The National HVDC Centre has agreed to host the replicas of the control and protection system of the Moyle HVDC Interconnector (refurbishment project) from 2022 onwards.

https://www.hvdccentre.com/our-projects/moyle-interconnector/

NSL Protection Study

Commissioned by SP Transmission (SPT) and National Grid Electricity Transmission (NGET), this project tested the coordination of protection for the connection of the North Sea Link (NSL).

NSL is a new HVDC interconnector connecting Blyth in the north east of England, to Kvilldal in Norway. To be confident that the AC protection operates correctly, the HVDC Centre tested the AC protection relays (using the actual protection hardware) in a Real-Time (Hardware-in-the-Loop) simulation environment.

https://www.hvdccentre.com/our-projects/north-sea-link-protection-coordination-testing/

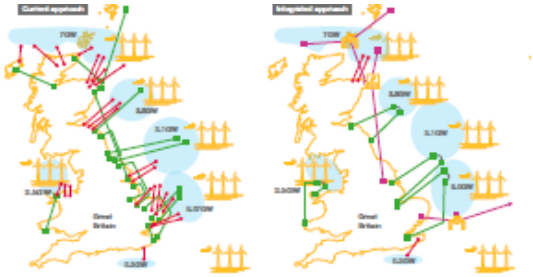
3) Project Details & Outcomes

Offshore Coordination

Following-on from the Integrated Offshore Design work; the ESO issued a Tender on Offshore Coordination, to develop the conceptual technical designs and undertake the cost-benefit analysis for integrated solutions within and across the Offshore development zones connecting to GB.

The Centre (in a consortium with DNV-GL and EPNC) supported the National Grid Electricity System Operators' (ESOs') Offshore Co-ordination project; for which the Centre led the technical and conceptual network designs. This culminated with our delivery of the 'Holistic Approach to Offshore Transmission Planning' report together with the DNV-GL led CBA report on 30 September 2020.

The Centre also supported the ESO across a range of stakeholder engagement workshops.



www.nationalgrideso.com/future-energy/projects/offshore-coordination-project

https://www.hvdccentre.com/our-projects/offshore-co-ordination/

PROMOTioN

SSEN Transmission is leading Work-Package 9 of the European PROMOTioN Project (https://www.promotion-offshore.net/). This work package demonstrates the operation of the DC grid protection systems using hardware prototypes within a real-time simulation hardware-in-the-loop to test and demonstrate interoperability of DC Grid protection systems.

Progress has included:

- Completed deliverables D9.1 (report outlining test network) and D9.3 (internal to PROMOTioN demonstration event);
- Completed considerable testing utilising the Intelligent Electronic Devices (IEDs);
- Successfully tested operation of the prototype IEDs with the Replica Control and Protection panels of the CMS link;
- Final deliverable D9.4 (a public demonstration event); and
- Published two papers based on this work.

On 21 September 2020, the PROMOTioN project (one of Europe's largest energy research projects) completed its final close out event. After 4.5 years, €43 million and with 34 organisations involved in collaborative research to advance the readiness of meshed DC grids.

The goal of the PROMOTioN project was to progress the use of meshed offshore HVDC grids for connecting offshore wind farms to onshore and interconnectors. The objective of WP9 (Work Package 9), led by The National HVDC Centre on behalf of SSEN Transmission, was to demonstrate DC grid protection solutions developed in the project using hardware-in-the-loop testing on a real-time platform.

www.hvdccentre.com/our-projects/promotion-testing-the-feasibility-of-meshed-dc-grids-protection/

Protection Performance Overview and Validation in Low Strength Areas

This project investigated the impact of low short circuit levels on the performance of existing protection relays and the extent to which that may be understood using off-line models; to identify if generator, transformer and line protection will be impacted due to system changes and identify necessary mitigation measures.

The National HVDC Centre collaborated with a team of experts from Manitoba Hydro International (MHI) to deliver this project. The project report discusses its results and highlights the limitations of existing off-line protection models.

www.hvdccentre.com/protection-overview/

3) Project Details & Outcomes

SCADA Installation

SSEN Transmission's real-time systems team, are in the process of installing GE PowerOn (SCADA system) at the Centre (which interfaces with the Caithness, Moray and Shetland Replicas).

https://www.hvdccentre.com/our-projects/scada-system-implementation/

Shetland Multi-Terminal Extension

Commissioned by SSEN Transmission, the Centre is providing technical support for the multi-terminal extension of the Caithness-Moray HVDC Scheme to Shetland.

The multi-terminal extension of the Caithness-Moray link to Shetland will require testing against the detailed model of the Shetland network (and utilising the Shetland Replica controls that the Centre hosts) to avoid adverse effects on the AC and DC networks.

https://www.hvdccentre.com/our-projects/support-for-the-shetland-extension-of-the-caithness-moray-hvdc-link/

Stability Pathfinder

Commissioned by National Grid Electricity System Operator (ESO), this project investigated the impact of declining system strength on the stability of HVDC links and other low-Carbon technologies that are connected through power electronic converters.

The Centre used power system simulation tools to model HVDC links and different low-Carbon technologies (including wind farms and battery inverters), to test their stability performance across a range of different system conditions on the electricity grid.

The outputs will inform the ESO on the fundamental principles of devices in HVDC links and low-Carbon technologies that could interact adversely with the electricity grid, to provide insights on system specifications and opportunities for improving system stability.

https://www.hvdccentre.com/our-projects/eso-stability-pathfinder/

Stability Assessment and Mitigation of Converter Interactions (Phase 2)

This project builds on the previous work done by the University of Strathclyde for the HVDC Centre on the development of small-signal impedance model of MMC converter and its use for assessing multi-converter interactions. The project focuses on developing further converter models for stability analysis of complex networks with significant converter presence. The development of analytical impedance models can provide further insight into the impact of circuit and control structure / parameters on system impedance.

www.hvdccentre.com/stability-phase-2/

Transmission Operator Tools for EMT Modelling (TOTEM)

All Transmission Operators, together with National Grid ESO, are taking forward an NIA project to explore construction of a whole GB simulation environment within PSCAD. The Centre is advising on hardware and software support needs within the project and is expected to host the Scottish TOs model, the Centre will also support verification of models being used.

www.smarternetworks.org/project/nia_shet_0032

https://www.hvdccentre.com/innovation-projects/totem-transmission-owner-tools-for-emt-modelling/

Innovation Programme

The MTTE project ran an aligned innovation programme, details of the projects delivered are provided below.

Protection Performance Overview: and Validation in Low Strength Areas

In collaboration with Manitoba Hydro International (2020-2021).

https://www.hvdccentre.com/innovation-projects/protection-overview/

3) Project Details & Outcomes

Adaptive Damping of Power Oscillations: using HVDC

In collaboration with EPRI (2020-2021).

https://www.hvdccentre.com/innovation-projects/pod_project/

Evaluation of HVDC with Synchronous Condenser: impact on AC Protection

In collaboration with the University of Strathclyde (2020-2021).

https://www.hvdccentre.com/innovation-projects/dc_with_ac_protection/

Stability Assessment Phase 2: and Mitigation of Converter Interactions

In collaboration with the University of Strathclyde (2020-2021)

https://www.hvdccentre.com/innovation-projects/stability-phase-2/

Coordination of AC network protection: during HVDC energisation

In collaboration with EPRI (2019-2020)

https://www.hvdccentre.com/innovation-projects/ac-protection-dc-energisation/

Stability Assessment: and mitigation of converter interactions

In collaboration with the University of Strathclyde (2019-2020).

https://www.hvdccentre.com/hvdc-stability-assessment/

Improving Grid Code for HVDC schemes

In collaboration with Cardiff University (2019-2020).

https://www.hvdccentre.com/innovation-projects/hvdc-grid-code-compliance/

Developing Open-Source Converter Models

In collaboration with the University of Strathclyde (2018-2019).

https://www.hvdccentre.com/innovation-projects/open-source-converters/

Stability assessment for co-located converters

In collaboration with the University of Manchester (2016).

https://www.hvdccentre.com/innovation-projects/stability-assessment-for-co-located-converters/

Design of DC/DC Converter

In collaboration with the University of Aberdeen (2015).

https://www.hvdccentre.com/innovation-projects/design-of-dc-dc-converter/

Grid Code Development

The HVDC Centre is supporting the expert Grid Code working groups on three key modifications:

- GC0137: Grid forming convertors/ Virtual Synchronous Machines;
- GC0138: Compliance and modelling processes; and
- GC0141: Improvements to data, modelling and compliance processes based on the 9 August 2019 power loss incident.

These are code change areas which seek to address many of the considerations of the review of the 9 August 2019 system event and areas in which the HVDC Centre has specific practical expertise in its de-risking of HVDC and related technology.

The recommendations in total represent one of the largest technical changes in the code's history, potentially increasing the extent and range of analysis required for

compliance activity, increasing the extent of data shared, enabling a greater range of analysis to be deployed and specified and project performance expectations to be further clarified across the life of the project.

Future Business Model

On 7 February 2020, the Centre submitted its 'Future Business Model' to Ofgem, which described the HVDC Centre's plans for 2021-2026 (aligning with the RIIO-T2 period) to provide critical support to HVDC projects in GB and support the security of the GB network: www.ofgem.gov.uk/system/files/docs/2020/07/hvdc_centre_future_business_model_public.pdf

On 3 July 2020, following a consultation process, Ofgem published its determination, which approved the continued ownership and operation of the facility by SSEN Transmission during RIIO-T2: www.ofgem.gov.uk/system/files/docs/2020/07/hvdc_facility_-_decision_for_continued_ownership_0.pdf

4) Comparison with Objectives

Ofgem's Determination on the Project Objectives

In Ofgem's determination on the Centre's Future Business Plan[2] (Section 6): Ofgem confirm that all of the project objectives and SDRCs have been met: "*We acknowledge that SHET have met all objectives stated in their original NIC submission, as well as meeting the Successful Delivery Reward Criteria (SDRC) stated in the project direction."*

MTTE Project Objectives

As set out in the NIC Submission for the MTTE project, the objectives of the Centre (and the progress against them) are as follows.

MTTE Project Objective	Objective Accomplishments
Establish the MTTE Facility	The world-class "National HVDC Centre" was established by the MTTE project in April 2017. Since its opening, we have provided advice to others internationally (notably NYSERDA in the US and Energinet in Europe surrounding the options for establishing RTDS capability)
Support transmission planning and improve specification of HVDC schemes	The Centre supported the planning and specification of the CM project, and has provided input to the specification of a number of other HVDC projects. We provided advice to Elia (Belgian TSO) on its specification for its Ventilus scope of HVDC related reinforcements. Within its research and development activities the centre pioneered new approaches to small signal analysis to support the focussing of converter-dominated network study, advised TO partners and the Scottish government on the modelling of HVDC capabilities to support Black Start, and with EPRI designed new adaptive forms of HVDC control to damp classical and new converter-driven power oscillations on the transmission system (a project winning its category at the R&D 100 award in 2021). The Centre is also advising its partners on coordinated solutions for Offshore wind integration within GB, optimising the design and use of associated HVDC elements of that design, which included technical lead of the consortium delivering phase 1 holistic transmission planning work for the ESO, as part of OTNR. The centre complemented this with a review of the supply-side challenges of upscaling HVDC within GB and the key opportunity and priory action areas The centre has further developed a wide library of models to support transmission planning of converter based resources and their interactions, and with the support of RTDS deployed a world first "software in the loop" approach allowing planning models to be integrated into real-time studies. The centre also working with Cardiff university reverse engineered the control challenges involved in HVDC projects achieving compliance for progressively weaker system strength conditions to inform grid code change. The Centre has supported technical code development- this includes within GB active involvement, guidance and drafting support to GC0141 &GC0138 which seek to define future model exchange needs for converter based resources, and improvements to the

[2] www.ofgem.gov.uk/publications-and-updates/decision-future-operation-hvdc-centre-following-end-nic-funding-period

4) Comparison with Objectives

MTTE Project Objective	Objective Accomplishments
	compliance process. It also includes current support on GC0154 seeking to address HVDC interconnector ramp-rate concern, and providing guidance support and technical expertise in the development of new specification and testing needs for GB- Grid forming converters, within GC0137 and the continuing best practice working group. Internationally, the Centre has been providing advice to the NREL, NERC and ESIG surrounding the transition towards converter dominated future networks for NET Zero, taking a lead via a series of webinars and physical presentations on related Net Zero transition topics across the period of COP26 in Glasgow, November 2021. The centre has supported several CIGRE groups in planning the use of wide area control for HVDC and the de-risking of HVDC interaction across the planning phase, providing tutorials to both CIGRE and IEEE in these areas.
Facilitate multi-terminal solutions	The Centre is integrally involved in the development of the multi-terminal Caithness-Moray-Shetland project, and has also led the demonstrations of the PROMOTioN project on multi-terminal DC grids. Its work alongside PROMOTioN developing detailed real-time project relevant open models of HVDC converters also identified the feasibility of multi-vendor solutions and the nature of their associated testing. Within its work on Coordinated offshore solutions for GB, the nature of multi-terminal designs and their optimisation within the overall co-ordinated solution, and future designs using HVDC DC circuit breaker supported networks was explored, and the opportunities and challenges identified. The Centre produced for BEIS an associated R&D strategy for advancing these solutions within GB. The centre has been providing continuing input into MPI and broader OTNR consultation; and highlighting areas of code and other technical standard opportunities. Internationally the Centre has provided key input, insight and direction setting to the HVDC SET plan for R&D within Europe, including providing its technical expertise in areas of multi-vendor and multi-terminal testing and de-risking. It has further supported GB specific work in this area also, and is advising a number of EU R&D projects in this area. The centre is also providing expert support to NREL on co-ordinated offshore development in the US.
De-risk control interactions	Within its R&D work with the University of Strathclyde the centre has developed new approaches for de-risking, and has conducted GB related analysis which included identifying key areas of protection interaction risk and in conjunction with the University of Strathclyde, new approaches to addressing protection de-risking. The Centre also under its stability pathfinder work supported the ESO in developing new models and tests for evaluating grid-forming inverter controls. As part of the NSL protection coordination study, the Centre investigated interactions between the HVDC link, substation protections and a series compensator, work which informed protection testing and solution evaluation work the centre is currently engaged in and the delivery of the software in the loop approach. the centre also within its engagement with partners routinely discusses and addresses particular areas of control interaction. Within its involvement in the production of the CIGRE B4.81 technical brochure on control interaction, the centre has both significantly authored content and lead direction.

4) Comparison with Objectives

MTTE Project Objective	Objective Accomplishments
Facilitate competition and multi-vendor HVDC schemes	The Centre has engaged with emerging suppliers (including: NR Electric, Mitsubishi, Toshiba and Hitachi). The centre (as discussed above) has led in the practical description of multi-vendor modelling needs and practical delivery across PROMOTioN and subsequent national and international workstreams in this area.
Train and develop Transmission Planning and Operational Engineers	The Centre has run a programme of training courses and webinars; delivering training to 100's of Engineers.
Undertake post-commissioning scenario planning and operational optimisation	Following the commission of the CM Project, the Centre has supported the investigation, testing and optimisation of control settings; tracking the physical changes across the project's life and providing operational support, guidance and training.
Model new HVDC technologies	As part of the PROMOTioN project, the Centre has modelled the operation of DC circuit breakers, together with multi-terminal protection IEDs describing new more sophisticated forms of DC protection. The Centre, working with TransGrid Solutions in Canada has created a series of real-time models supporting HVDC study when in combination with batteries, wind farms etc. With the University of Aberdeen the Centre has developed DC-DC converter models, designs and operating principles. With the University of Strathclyde, detailed open real-time converter models of both VSC-HVDC and LCC-HVDC have been developed.

All of the Project Objectives have been fully met (and exceeded). Furthermore, all nine of the Project SDRC have been successfully completed, as described below.

4) Comparison with Objectives

MTTE Project SDRC

The MTTE identified eight Successful Delivery Reward Criteria (SDRC) which span both the objectives and the lifecycle of the Project. Furthermore, Ofgem's decision letter (27 March 2015) added an additional criterion (SDRC 9.9).

The following table lists each SDRC in chronological order and details the Project's progress towards their achievement.

SDRC	Due	Description	Evidence	Status
9.1	31/8/2014	**Formal Agreement with Project Partners.** The success of this Project will be crucially dependent on the involvement of the Project partners & stakeholders. Therefore, an early indication of success of the Project is the establishment of formal agreements with the Project partners (National Grid, Scottish Power and NETSO) and HVDC expert support.	Signed agreements with Project partners (National Grid, Scottish Power and the NETSO) (note, agreement will include IP security requirements) and HVDC expert support.	**Completed (SDRC met)** Formal agreements with Scottish Power and National Grid were signed and concluded on 29 August 2014. Parsons Brinkerhoff was engaged as external HVDC expert support in February 2014.
9.2	31/10/2014	**OFTOs and Renewable Developers Event** Given the anticipated number of HVDC schemes in GB for connection of offshore renewable, the engagement of OFTOs and Renewable Generators is important to ensure the benefits of the MTTE are maximised, therefore the MTTE Project will hold an event to inform and encourage their participation.	Holding an event to which all OFTOs and Renewable Generators are invited, to inform and encourage their participation in the MTTE.	**Completed (SDRC met)** The OFTOs and Renewable Generators Event was held in Glasgow on 11 September 2014. In addition, the Project presented to the ENA's OFTO Forum on 20 August 2014.
9.3	31/12/2014	**Engagement with 1st HVDC Project** The purchase of the 1st set of replica control panels for the MTTE will be key to its success, and the panels will be purchased through an HVDC Project. Therefore the formal engagement of the initial HVDC Project is an important early milestone.	Formal agreement between the MTTE Project and an HVDC Project, which includes the intention to purchase/supply replica control panels through the HVDC Project's procurement process.	**Completed (SDRC met)** A memorandum of understanding has been signed, between the MTTE Project and the Caithness-Moray Project, confirming the arrangement for the provision and use of replica control panels.
9.4	31/5/2015	**Complete Design of MTTE Facility** The completed design of the MTTE facility, both technical design and physical design, and the agreement of this design with the Project stakeholders (including vendors), is a key milestone for the Project. The detailed design will be consolidated within the Design Development Document, and will adhere to the requirements defined in the requirements specification.	Design development document and requirements specification for the MTTE facility endorsed by participating vendors and signed-off by SSEN Transmission, NGET, NETSO and SPT.	**Completed (SDRC met)** The Design Development Document and Functional Specification were reviewed at the Design Workshop on 23rd April 2015, following which each stakeholder provided written confirmation of their endorsement.
9.5	31/10/2015	**Establishing HVDC Operators' Forum and Website** A key component of our knowledge and dissemination strategy is the establishment of the HVDC Operators' Forum (to which all	The establishment of the HVDC Operators' Forum (including holding the 1st event), together with the publishing of the MTTE Websites.	**Completed (SDRC met)** The first HVDC Operators' Forum event was held on 8 October 2015, the second on 27 April 2017.

4) Comparison with Objectives

SDRC	Due	Description	Evidence	Status
		Network Licensees, including OFTOs will be invited), the associated members' Website (which provides a secure area to share the MTTE outputs with Transmission Licensees), and the public Website.		The website (hvdccentre.com) was launched in April 2015.
9.6	31/5/2017	**Commence Operation of the MTTE** The criteria consolidates the: ○ Completion of the building/upgrade of the MTTE facility; ○ Commissioning of the IT/RTS infrastructure; ○ MTTE Resourcing; ○ Management structure in place; ○ Processes and procedures agreed; ○ Data sets of the AC network received (from NETSO); and ○ Plan of studies and tests agreed. When all of these are in place, the MTTE will be able to commence operations, therefore this is a key milestone and measure of success of the Project.	Commencement of MTTE Operations.	**Completed (SDRC met)** The facility was formally opened on 26 April 2017. The building, IT infrastructure, resourcing, governance, processes, data/models and work plan were all in place to enable operation to commence.
9.7	31/3/2018	**Publishing Studies & Test results** The key outputs from the MTTE are the reports on specific scenarios which are completed within the MTTE, which will be disseminated to transmission licensees. Therefore, a key success criterion is the publishing of studies or test reports on the MTTE members' Website.	Publishing the first set of reports on a specific Transmission Licensee led Project, on the MTTE members' Website.	**Completed (SDRC met)** The first set of four reports was published on the Centre's Website on 30 March 2018.
9.8	31/3/2020	**Future Business Model** At least 12 months prior to the end of the funded operation of the MTTE (i.e. by end of March 2020), the MTTE management team will submit a proposal for the future operation and funding of the MTTE (post NIC funding), to Ofgem.	Submission of proposal regarding MTTE ongoing operation and funding to Ofgem.	**Completed (SDRC met)** The Future Business Model report was submitted to Ofgem on 7 February 2020.
9.9	31/3/2021	**Second Replicas** Use reasonable endeavours to secure the provision and testing of a second set of replica control panels for the MTTE from a second vendor. The panels would be provided by an HVDC Project, a transmission Licensee or a second vendor.	Submission of evidence of the use of reasonable endeavours for the provision and testing of the second vendor's replica control panels at the MTTE facility; by the end of March 2021.	**Completed (SDRC met)** Evidence of the successful completion was submitted to Ofgem on 31 March 2021.

All of the MTTE Project SDRCs have been fully met (and exceeded).

5) Modifications

There were no changes to the planned methodology throughout the project.

7) Updated Business Case

Project Spend against Budget

The table below details the spend (& revenue) to date against the Project budget for each cost category.

Cost Category [2]	Budget	Spend[1]	Variance	Details
Labour				
Project team resource costs	£2,181.68k	**£1,713.03k**	21% below budget	Project team and MTTE resources were efficiently used and delivered under budget.
MTTE resource costs	£2,032.13k	**£1,347.24k**	34% below budget	
Contractors				
Project team resource costs	£288.44k	**£253.32k**	12% below budget	Contractor resources were efficiently used and delivered under budget.
IT				
IT Infrastructure (incl RTS and Replica Panels)	£3,828.21k	**£4,160.96k**	9% above budget	The IT Infrastructure was delivered within +/- 10% of budget.
Annual Running Costs of the MTTE	£304.37k	**£184.52k**	39% below budget	The IT Running costs of the MTTE facility were efficiently delivered under budget.
Travel & Expenses				
Travel & Expenses	£197.40k	**£66.83k**	66% below budget	Travel and expenses spend has been kept to a minimum, and is further lower due to the impact of Covid-19.
Other				
Academic Support	£827.07k	**£1,059.13k**	28% above budget	The extensive academic programme was delivered above budget.
Learning & Dissemination	£165.41k	**£46.67k**	72% below budget	Due to the impact of Covid, much of the learning and dissemination activity was delivered virtually, enabling it to be delivered under budget.
MTTE Building Facility	£2,916.20k	**£3,719.64k**	28% above budget	The project delivered a 2-phase building programme, to provide the facility required to deliver the commitments made to Ofgem in the Future Business Model[3].
Annual Running Costs of the MTTE	£515.09k	**£205.33k**	60% below budget	The Running costs of the MTTE facility were efficiently delivered under budget.
Recruitment & Training	£137.90k	**£16.43k**	88% below budget	Recruitment and Training were efficiently delivered under budget.
Project Spend Total	**£13,393.91k**	**£12,773.11k**	5% below budget	

7) Updated Business Case

Notes:

1) *Project Spend as extracted from the finance system (Harmony) on 31 March 2022.*
2) *There is no Project budget or Project spend under the Cost Categories: Equipment, IPR Costs, Payments to Users, Contingency and Decommissioning.*
3) *The cost of the facility was 28% higher than originally forecast in the NIC bid, due to the need for increased space following securing the Moyle Replicas (refer to SDRC 9.9), whilst delivering multiple hardware-based projects (e.g. AC Protection Coordination). This has been successfully delivered (though delayed due to Covid supply constraints).*

Revenue Generated

Revenue	Budget	Actual Revenue	Variance	Comment
Revenue Generated	£0	**£385.65k**	All above budget	No revenue generation was assumed in the NIC budget.

Project Funding

	NIC Funding Budget	Actual Budget Received
NIC Funding	£ 11,332,800	£ 11,332,801
SSEN Transmission Funding	£ 1,339,390	£ 1,339,391
Interest Payments	£ 721,720	£ 101,646*
Revenue Generated	£ 0	£ 385,650
Total Project Funding *(including Revenue)*	**£ 13,393,910**	**£ 13,159,488**

Note:

**There will be some additional interest payments to the bank account balance, during the months between the project closing and the funds being returned to customers; therefore the amount returned to customers will be slightly higher.*

Returned Revenue

Total Project Funding *(including Revenue)*	£ 13,159,488
Total Project Spend	£ 12,773,111
Total to be Returned to Customers	**£ 386,377**

Therefore SSEN Transmission will return £ 386,377 (plus additional interest payments*) to customers.

7) Updated Business Case

Impacts and Benefits Achieved

The following table lists the specific benefits that the Centre has delivered during the operational phase of the project.

Project/Activity	Impact	Benefits Quantification Estimates Rationale	Quantification Estimate
EPC Testing and commission support for the CM project	The Centre was able to undertake this testing on the Replicas, without which the CM project would have been delayed (by circa 3 months). Commissioning support, ensured there was no delaying the commissioning timescales.	Based on November 2015 BEIS estimated costs of wind+ average level of additional loading supported by CM since commissioning (approx. 250MW)= £28.98m benefit in avoidance of constraint that may otherwise have been present. Noting that typically the effect of constraint cost increases are 50% shared between ESO and consumers, we record a £14.49m benefit consumers from this de-risking action.	**£14.5m**
Control Room training	The Centre enabled the control room team to train and practice the operation of the Caithness-Moray link, this ensured a smoother and safer adoption of the scheme.	Based on each control engineer trained saving increasing efficiency in operation (avoiding unavailability) by 5% on a typical GB interconnector availability assumption, and costing the reduced lost time as per above = approx. £0.46m	**£0.5m**
Maximising HVDC for Black Start (Scottish Government)	Will lead to a reduction in cost of Black Start services, a more stable system, and a reduction in the time to restore the system.	Based on the scale of HVDC projects anticipated across FES 2017, using Ofgem sources of Value Of Lost Load and Loss of Load Expectation, a value to GB consumers from more rapid HVDC restoration of between £4.73mp.a. and £14.63m p.a. is facilitated by this work, with a central estimate of £9.7m p.a.. Assuming that the work of the centre identifying the opportunity and efficient approach to delivery contributes only 10% of this benefit a benefit of £0.97m p.a would result.	**£0.97m (p.a.)**
Stability Pathfinder (National Grid ESO)	The HVDC centre has provided modelling expertise to the ESO both to support its tender evaluation and provide insights surrounding its tests and requirements.	The ESO has identified in Scotland alone a total requirement of some 9GVA of support by 2023. This could be supported by a wide range of technologies, with HVDC centres work supporting an optimisation between a capital cost of synchronous -compensation deployment of around £1.16bn to meet this target and a market intervention of up to £104.39m p.a. the efficiencies afforded by the analysis the centre supports could easily exceed £11m alone based on a 1% efficiency gain in this evaluation.	**£11m**
NSL Protection Study (SPEN & NGET)	This critical study will ensure that the AC protection will be suitable for purpose following connection of the NSL link. Alternatives would be; not to connect/ delay connection ahead of connection, or	Based on OFGEMs Cap and floor assessment of the availability incentive associated with NSL some £43.1m p.a. of customer benefit is considered to be associated with ensuring the link is not unavailable for a period exceeding 1752hrs, or 73 days. A Typical timeframe for protection replacement would be up to 3 months of outage	**£21.6m**

7) Updated Business Case

Project/Activity	Impact	Benefits Quantification Estimates Rationale	Quantification Estimate
	connect at risk of cascade event leading to disconnection (see value of lost load calculations above).	time, corresponding to the full £43.1m impact. Were connection not possible ahead of any new protection being procured this would translate to an impact of up to £72.075m consumer impact. Consistent with the above C-M example we assume as a central estimate that a protection solution would be developed rapidly to address problems at commissioning such that a revised setting/ solution using available hardware would be achieved within 3 months. We also, consistent with the C-M example above note that it is typical for 50% of the impact of the estimated £43.1m increased constraint costs to be exposed to consumers. Accordingly, we record the £21.55m benefit our activity would deliver in mitigating consumer risk	
Eastern Link Project Support (TOs)	Providing technical advice to the project team, to help define the appropriate technology.	This has helped ensure that the appropriate technology is taken forward for the project. There is a significant commercial benefit to defining the appropriate technology- for example we note above that 9GVA of stability requirement could be satisfied with a synchronous compensation deployment cost of some £1.15bn. alternatively the 2x2GW of VSC-HVDC solutions including suitably designed controls could achieve an analogous effect and offset a future requirement by some £541m. The Centres activity allows such benefits to be realised within the TO projects by supporting the analysis of frontier technology solutions that could achieve this	**Not qualifiable.**
PROMOTioN	Providing efficient design of future offshore wind (and an income for the HVDC Centre).	The Centre has received funding (£268k) from this project for undertaking this work, which will be returned to customers at the end of the project.	**£0.3m**
Demonstrated multi-terminal multivendor interoperability.	We have demonstrated how multi-terminal schemes can operate with multiple vendors (and submitted a paper to the CIGRE session on this).	This work enables TOs, developers and future integrated OFTOs to avoid being “locked” into a single technology provider for the expansion of their project. By allowing competitive tendering over alternative single tender action in what is an active market, cost and delivery efficiencies can be achieved from suppliers able to resource the optimum timeframe and the optimum price. Such activities even assuming they yield a 10% contracting efficiency would generate savings on individual projects around £100k per project.	**£0.1m (per project)**
Training Course Delivery	Increasing industry skills (particularly focused on TOs and ESO).	Increasingly maintaining a 99.9999% system availability will require new forms of analysis and new analysis techniques, which the centre is pioneering, demonstrating and then training the	**£0.2k (p.a.)**

7) Updated Business Case

Project/Activity	Impact	Benefits Quantification Estimates Rationale	Quantification Estimate
		TOs and ESO to apply in BAU. For every 0.0001% system availability this maintains, based on Value of Lost Load expectation, this would yield a £229k benefit to consumers p.a.	
HVDC Operators' Forum	Ensuring that lessons are learnt across the industry.	This exercise both co-ordinates and consolidates the training benefits discussed above and as such supports realising the above £229k p.a. benefit	**£0.2k (p.a.)**
Converter Models (University of Strathclyde)	Developing open-source detailed converter models.	This work has supported the mullti-vendor, training benefits, stability pathfinder and eastern link project support.	**Not qualifiable**
Stability assessment (University of Strathclyde)	Stability assessment and mitigation of HVDC converter interactions: Impedance modelling of HVDC converters for system stability studies.	This work complements the stability pathfinder insights and support further training work discussed above.	**Not qualifiable**
Black Start Protection Coordination (EPRI)	Coordination of AC network protection during grid energization from HVDC schemes: Assess suitability for existing AC protection for Black start from HVDC.	This project complements the maximising black start benefits above.	**Not qualifiable**
Grid Code Compliance (Cardiff University)	Improving Grid Code Compliance of existing and upcoming HVDC Schemes in GB: Assess and test HVDC Grid Code compliance using simulation and experimental tools.	Providing a clear and transparent process of data exchange is expected to further enhance TO and SO capabilities to maintain availability of network across the transition to low carbon technology and offer the potential to enhance all the benefits quoted above	**Not qualifiable**
	Total Benefits Quantification		**Exceeding £38m**

8) Lessons Learnt

The following project lessons learnt, were captured at the post-project lessons learnt workshop with the Technical Advisory Board (TAB) on 4 April 2022.

- The level of engagement between the project and the TOs and ESO (though the TAB), throughout the project was a good frequency and appropriate level of detail.
- The project made extensive efforts to engage with wider stakeholders within the TOs and ESO (including conducting a series of "roadshows"), however the TOs and ESO may have benefited from engaging more with the Centre themselves.
- While TOs/ESO engagement has been good, there is an opportunity to engagement more directly with TOs/ESO Engineering Teams; a ½-1 day HVDC Engineering Briefing Session is recommended (focused on TOs/ESO but also interconnectors engineering teams).
- With the extensive anticipated changes in the industry (with expected deployments of HVDC and power electronic devices), the HVDC Centre could take on more of a leadership role across the industry (for example in HVDC related grid code changes).

9) Project Replication

Overview

It is not proposed that other network licensees replicate the MTTE project; instead the HVDC Centre is a collaborative facility where Network Licensees can request work to be undertake on their behalf, or in collaboration with, by the HVDC Centre team.

Replicating the MTTE Facility

The high level design of all components of the MTTE project were collated in the Design Development Document (refer to link below), which was reviewed at a stakeholder workshop on 23 April 2015, approved by all the TOs and ESO; and endorsed by HVDC suppliers.

https://www.hvdccentre.com/library/mtte-design-development-document/

This document provides a blue-print for other organisations who want to establish a similar facility

Engaging The National HVDC Centre

When Network Licensees want to request work from the Centre, they would use the following process:

- The Network Licensees contacts the Centre (preferably through their representative on the Technical Advisory Board) to make the initial request;
- Based on this request (and subsequent discussions), the Centre produces a 'Scope Confirmation Document' which details the service the Centre can deliver;
- The document also describes if the work is 'Core' or 'Non-Core'.
  - Core: The Centre's RIIO-T2 allowance enables the Centre to provide 'core' services (as defined in the Future Business Model) free-of-charge to the TOs/ESO, within the Centre's available resource.
  - Non-Core: Additional services (for the TOs/ESO) would be charged at a 'cost recovery' rate (using the 'basis of transmission charges').

Other organisations (i.e. non Network Licensees) are also able to request services from the Centre. The Centre would charge for services provided to 3rd party organisations.

The Centre has limited resources, therefore, the Centre will deliver services within its available resources, and prioritised collaboratively by the Technical Advisory Board (TAB).

This approach is described in the Centre's Future Business Model.

10) Planned Implementation

Overview

The MTTE Project has established The National HVDC Centre which is now a Business As Usual function for the TOs/ESO; and has already become a world-leading Centre of HVDC expertise, providing critical support to projects in GB and the security of the GB network.

Need

The coming years will see a huge investment in HVDC schemes in GB; the most concentrated development of HVDC in the world. Such extensive development poses significant risks to the reliable operation, control and resilience of the GB network.

In order to mitigate these risks an independent testing facility that can host detailed models (and control/ protection hardware) from multiple suppliers and from TOs/ESO is required. It must have the expertise (and technology infrastructure) to undertake specialist studies; along with the credibility that ensures the results can be relied upon.

Evolution

As a result of the NIC funding to develop a world-class facility, combined with hiring subject matter experts together with the experience of delivering high-profile project-critical studies; we now have an internationally recognised HVDC Centre of excellence - which is ideally positioned to support GB's HVDC plans.

Engagement

The Centre sees a key role in bringing together and facilitating engagement and knowledge exchange on HVDC in GB.

Impact

The HVDC Centre is able to provide support to all the HVDC projects that plan to connect to the GB grid, de-risking project delivery and ensuring the stability of the network, and delivering substantial financial benefits.

Conclusion

The National HVDC Centre has grown to become a critical component of the GB electricity infrastructure; which ensures the integrity and security of the GB electricity network, while enabling the delivery of the ambitious plans and the continued de-risking of HVDC schemes connecting to the GB network.

The Centre will continue to de-risk the deployment of the increasing volumes and complexity of GB connected HVDC schemes planned, to mitigate their delivery risk while ensuring the integrity and security of the GB electricity network

11) Learning Dissemination

Overview

A continual key focus of the HVDC Centre is on knowledge dissemination.

The Centre undertakes extensive engagement/ dissemination activity to ensure that we:

- Keep potential users of the Centre informed of our capabilities;
- Ensure that the work we undertake is developed in collaboration with relevant stakeholders; and
- Effectively disseminate the knowledge gained at the Centre to the right people.

We do this through a range of engagement activities:

Films

The Centre has produced a range of short films to communicate project learning in an accessible format.

https://www.hvdccentre.com/technical-films/

Website

The Centre's website (hvdcCentre.com) continues to be updated to support knowledge dissemination.

The Website contains details of all the technical projects the Centre has undertaken, our innovation programme, and library of publications.

https://www.hvdccentre.com/

Newsletter

Throughout the project, 27 quarterly newsletters have been produced and: distributed to all of our Stakeholders, shared with our Linked-In followers, and published on our website.

https://www.hvdccentre.com/library-category/newsletters/

Linked-In

The Centre uses Linked-In to share key outputs with a wide range of interested parties. With an impressive 2,340 followers.

https://www.linkedin.com/company/the-national-hvdc-centre

HVDC Operators' Forum (annual)

The Centre has established this forum as a regular annual event, where HVDC projects in GB, relevant TOs and the ESO come together to share experience and lessons learnt; and also to share the outputs of relevant HVDC innovation projects.

Conference participation

The Centre has participated in relevant conferences, including:

- RTDS User Group conferences;
- LCNI conferences;
- IET's ACDC conferences; and
- CIGRE conferences.

Engaging Students

The Centre routinely engages with the academic community both in respect to partnering on project activities and in more general areas of dissemination where a mutual interest and benefit exists.

Technical Advisory Board

The Technical Advisory Board comprising representatives of Transmission Licensees and the Electricity System Operator. It has met 6-monthly throughout the project to review the work done by the Centre and provide strategic technical direction.

11) Learning Dissemination

Industry Group Participation

The Centre participates in a range of technical working groups, to facilitate increased HVDC integration.

The Centre is actively participating in the following Working Groups:

- **Offshore Wind Industry Council (OWIC):** The Centre has supported the OWIC Future transmission group as Chair of the Technical solutions workstream, contributing to policy papers submitted to BEIS and Ofgem, to inform the Offshore Coordination project and ongoing OTNR.
- **CIGRE B4.81:** Covering tools, techniques and simulation process associated with de-risking convertor rich environments; aiming to release a technical brochure in 2022. The Centre is providing drafting for the Chapters on: small signal techniques, COMPOSITE testing techniques, validation and verification aligning with GC proposals, and review and input into processes for SSCI simulation and network reduction guidance.
- **Grid Code Working Group:** Representative across workgroups GC0137, GC0138, and GC0141 covering respectively virtual synchronous machine convertor control, convertor testing and compliance testing, EMT data exchange / simulation and verification and increasing robustness following 9 August 2019.
- **IET RPG Journal industrial panel:** The Centre has supported the IET Renewable Power & Generation (RPG) with a Special Issue intended to attract more industry papers with focus on energy solutions to deliver net zero targets.
- **IET ACDC Organising Committee:** The Centre is supporting the organisation of the annual prestigious ACDC international conference, event format & organisation, paper review and approval, conference presence, key note speech & paper generation. Last year's conference was a hybrid virtual event in November 2021.
- **Global-PST consortia:** The Centre (with the TAB and EPRI) has supported R&D direction of the above, exchanged updates on the small signal analysis approaches it has developed with partners AEMO and NERC, and supported its model validation and verification workstream.
- **CIGRE WG C4/C2.62/IEEE:** Participating in this working group to review advancements in Synchrophasor Measurement Applications.

Dissemination Events

The Centre's Events and Webinars inform and facilitate knowledge exchange on a variety of HVDC-related topics. These events and webinars have been very well attended from across the industry, and have been well received.

COWI Event

8 June 2018:

COWI (Japanese delegation) of offshore wind consortia. Discussion about their project to form an offshore meshed grid in Japan, Project Nedo.

HVDC Operators' Forum

21-22 June 2018

Annual HVDC Operators' Forum, this 4th Forum was held at the Centre, bringing together owners and operators of HVDC schemes in GB to share knowledge and experiences.

Nalcor Energy visit

26 June 2018

Visit from Nalcor Energy, a Canadian based transmission operator and HVDC link owner; to share HVDC Centre experience, as they plan to establish a similar facility for real-time hardware-in-the-loop study of their HVDC projects.

ENA Tour

10 July 2018

Energy Network Association had tour and presentation of the work of the Centre.

11) Learning Dissemination

Stuttgart University visit

11 July 2018

Undergraduate course doing an energy assets tour in Scotland - the Centre gave relevant presentations on HVDC and environmental consents process.

Aalborg University visit

7 September 2018

Aalborg University visited, with a tour and presentation on the work of the Centre.

North Lanarkshire Council visit

2 October 2018

The Development team from North Lanarkshire Council visited the Centre to see how they can develop links with the Centre.

SSEPD stakeholder advisory panel visit

25 October 2018

The SSEPD stakeholder advisory panel visited the Centre to learn more about the work of the Centre to provide a secure GB network.

Scottish Enterprise visit

31 October 2018

The Energy team of Scottish Enterprise visited to learn more about HVDC contribution to the low-carbon strategy for the Scottish energy sector, and the work of the HVDC Centre to facilitate this.

IET's ACDC Conference

5-7 February 2019

At the IET's ACDC Conference in Coventry, the Centre ran a real-time simulation tutorial, and presented a paper on Replicas.

Strathclyde University's ETP

19 March 2019

Strathclyde University's Energy Technology Partnership (ETP) visited the Centre to learn more about HVDC and the Centre's work.

CM Knowledge sharing event

28 March 2019

To share the experience and lessons learnt from integrating the Caithness-Moray (CM) HVDC Link into the (electrically weak) North of Scotland electricity grid; focusing specifically on the control challenges and learnings, to an open external audience.

HVDC Operators' Forum

26 June 2019

The Centre continues to host this prominent annual event to share knowledge and experience; and facilitate industry collaboration (though the 2020 forum has been postponed due to Covid-19).

HVDC Innovation Day

27 June 2019

During this day, the Centre shared the progress on our collaborative innovation projects, with presentations from academia and HVDC suppliers.

Demonstrating the Protection of DC Grids

22 August 2019

As part of the PROMOTioN Project, the Centre led a demonstration of how multi-terminal HVDC Grids can be protected. The event brought together project partners to demonstrate HVDC protection by integrating protection hardware within a simulated model of an HVDC Grid, combined with direct current circuit breaker (DCCB) real-time simulation models.

Black Start Stakeholder Event

17 September 2019

A stakeholder consultation workshop was held at the HVDC Centre to review and agree the recommendations of the report. These recommendations will help to maximise the contribution of HVDC schemes to GB Black Start.

LCNI Conference

30-31 October 2019

The Centre attended and presented at the LCNI conference.

11) Learning Dissemination

EMT Webinar

12 November 2019

The growing relevance of Electromagnetic Transient (EMT) analysis in particular with respect to network stability and device interaction assessment; led by Dr Dharshana Muthumuni (co-developer of PSCAD).

Subsynchronous Torsional Interaction Webinar

12 December 2019

Follow-up webinar on Subsynchronous Torsional Interaction analysis; led by Dr Dharshana Muthumuni.

HVDC Black Start Webinar

13 February 2020

HVDC Black Start and impacts on protection function from weak networks; hosted by the HVDC Centre & EPRI.

ACDC Protection Essentials of the Future

19 February 2020

The Centre presented the output of recent PROMOTioN activity on DC protection relay testing, and on the broader challenges associated with protection design and testing for a convertor dominated environment; to this conference held at the Technology University of Delft, Netherlands.

Small signal Analysis Webinar

27 February 2020

Small signal and Frequency dependant impedance techniques for identifying HVDC interaction risk; hosted by the HVDC Centre & University of Strathclyde.

DPSP Conference 2020

9-12 March 2020

The Centre presented/supported the following papers, at the Developments in Power System Protection (DPSP) conference:

- Demonstration of Partially Selective HVDC Grid Protection System with Hardware-in-the-loop IEDs;
- Coordination of ac protection settings during energisation of ac grid from a VSC-HVDC interconnector; and
- Multi-vendor interoperability tests of IEDs for HVDC grid Protection.

HVDC Grid Code

20 March 2020

HVDC challenges in meeting current GB Grid Code in a weak network; hosted by the HVDC Centre & Cardiff University.

Use of Real-Time webinar

16 April 2020

Practical Use of Real Time Simulation for De-risking HVDC Integration; co-hosted with RTDS Technologies.

Repeat of Use of Real-Time webinar

24 April 2020

Repeat of 'Practical Use of Real Time Simulation for De-risking HVDC Integration' (as the previous webinar was over-subscribed).

PROMOTioN Webinar

13 May 2020

Demonstration of DC Grid Protection - PROMOTioN WP9 Results so Far.

IEEE PES 2020

August 2020

At the IEEE PES 2020 General Meeting virtual conference (3-6 August 2020), the Centre presented on real-time testing environments for utilities.

CIGRE 2020

August 2020

At the CIGRE 2020 e-session, the Centre presented a paper on the key considerations for multi-vendor extension and testing of HVDC schemes.

11) Learning Dissemination

Webinar with RTDS

October 2020

The Centre presented at RTDS's international Spotlight webinar on 'De-Risking the Deployment of HVDC Projects at The National HVDC Centre'; slides and recording available at: www.rtds.com/events/uss-week-2/

ICRERA 2020

October 2020

The Centre presented a keynote speech to ICRERA 2020 conference on Renewable energy research; materials available at: www.icrera.org/

NYSERA/DSP conference

October 2020

The Centre presented to New York operators NYSERA/DSP conference on renewables integration; materials available at:
www.nyserda.ny.gov/ober

RUK Cables 2020 Conference

November 2020

The Centre presented the COMPOSITE project and cable modelling approaches:
https://events.renewableuk.com/cables20-programme

The Future of Offshore Grids

November 2020

The Centre co-presented at the SSE Group Engineered Lunch webcast.

Introduction to HVDC training course

December2020

The Centre delivered a half-day virtual training course to the project team working on the Shetland extension.

Sharing learnings with NYPA's AGILe

December2020

The Centre met with the 'New York Power Authority', to share knowledge on establishing a real-time test environment.

Newfoundland Environmental Industry Association Webinar

December 2020

The Centre presented at the Newfoundland Environmental Industry Association Webinar, on the work of the Centre, and on HVDC in GB.

Offshore Transmission Network Reform

December 2020

The Centre supported the Q&A session of the Ofgem, BEIS and ESO consultation on Offshore Coordination.

NERC modelling guidelines

December 2020

The Centre participated in the Q&A discussions at the NERC modelling guidelines webinar.

Prospero Offshore Transmission and HVDC Conference

January 2021

The Centre presented Holistic planning of Integrated Offshore Networks to over 20 cross industry stakeholders

Prospero Offshore Transmission and HVDC Conference

January 2021

The Centre presented Multi-terminal Extension of HVDC Schemes to over 20 cross-industry stakeholders.

Offshore Grid Interoperability and master control

January 2021

The Centre provided technical insights on a potential service being developed by DNV-GL for off-shore grid operation and control.

Introduction to HVDC training course

February 2021

Half day virtual training giving intro on HVDC.

11) Learning Dissemination

CIGRE B4.81 Specialist Technical Working Group

February 2021

Contributed technical insights on converter interactions.

COMPOSITE Testing Webcast, with RTEi (over 230 attendees).

March 2021

Introduction to HVDC Training Course: External training course.

CIGRE Chile Tutorial

March 2021

HVDC technology and its integration: Presentation and Expert Panel.

Introduction to HVDC Technology and Integration Challenges for Beginners

23 March 2021

This online training session will provide attendees with an overview of the basic principles of HVDC transmission, typical applications and considerations of co-ordination of offshore development and system integration challenges. There are many drivers causing increased use of HVDC technology including development of far offshore wind, increased interconnection between countries and subsea transmission network reinforcements. As this is a relatively new technology there is a need for more cross-sector knowledge exchange and understanding regarding this subject. To start to address this, the HVDC Centre team will provide this introductory course based on their collective experience gathered across HVDC operational and innovation projects.

Webinar: Evaluation of HVDC with Synchronous Condenser impact on AC Protection

April 2021

Webinar: Composite testing of HVDC connected offshore wind farms using EMT simulation tools

April 2021

Evaluation of HVDC Impact on AC Network Protection

27 April 2021

Protection schemes ensure that when faults occur on networks, the effect of the fault is seen only briefly by the wider system and its connections, isolating the faulted infrastructure or generator from the network, hence allowing the healthy elements to continue to operate. With the growth of HVDC and non-synchronous connected renewable technologies, the future net-zero transition brings with it a change in the magnitude and characteristics of fault current seen on the transmission system. Traditional approaches for the testing and setting of network protection are at risk of also no longer being as relevant to operation in that net-zero environment. In this project the National HVDC Centre in combination with its onshore Transmission Owner (TO) partners has worked with the University of Strathclyde to develop a flexible test bed for the future testing of protection in these Net-Zero environments of convertor dominated fault infeed, and has considered actual relevant protections used today against that environment. This tool allows TOs to gain more insight into protection challenges and an approach to test protection deployment and filter out where protection issues may arise and what influences them. The aim of this session is to provide attendees with an overview the key findings from the joint HVDC Centre project with the University of Strathclyde on the evaluation of HVDC impact on AC protection. The analysis will also cover the impact of and a guide to sizing of synchronous condensers to help overcome some of the observed challenges.

HVDC Centre Roadshow (SSEN Transmission)

10 May 2021

A 1 hour virtual event to showcase how the HVDC Centre has been working with the SSEN-T, and how the HVDC Centre can support the SSEN-T over RIIO-T2 (including how to commission work at the Centre).

11) Learning Dissemination

HVDC Centre Roadshow (National Grid Electricity Transmission)

20 May 2021

A 1 hour virtual event to showcase how the HVDC Centre has been working with the NGET, and how the HVDC Centre can support the NGET over RIIO-T2 (including how to commission work at the Centre).

HVDC Centre Roadshow (ESO)

27 May 2021

A 1 hour virtual event to showcase how the HVDC Centre has been working with the ESO, and how the HVDC Centre can support the ESO over RIIO-T2 (including how to commission work at the Centre).

HVDC Centre Roadshow (SP Energy Networks)

8 June 2021

A 1 hour virtual event to showcase how the HVDC Centre has been working with the SPEN, and how the HVDC Centre can support the SPEN over RIIO-T2 (including how to commission work at the Centre).

Development and validation of LCC HVDC system stability assessment tools

17 June 2021

The rapid growth in converter-interfaced renewable sources and HVDC transmission links is significantly changing the characteristics of the GB grid. Accurate assessment of potential system interactions (small-signal and large transient) is critical for ensuring stable operation of future and evolving GB network, and this requires a number of challenges to be addressed, including: establishment of effective methods for system/converter modelling and analysis; advanced converter control and potential coordination between converters; and identification of adequate and recommended specifications for future converter systems including vendor-specific models for system stability analysis.

This project builds on the previous work by the University of Strathclyde and the National HVDC centre on the development of small-signal frequency-dependent impedance model of MMC converter and its use for assessing multi-converter interactions, and focuses on the development and validation of frequency-dependent impedance model of LCC HVDC system. The development of analytical impedance models can provide further insight into the impact of LCC HVDC circuit and control structure / parameter on system impedance, and system stability.

Assessment of AC protection performance in weakening systems

9 September 2021

This webinar is the culmination of the outcomes from the research project – "Assessment of AC protection systems performance in a weakening System" commissioned by The HVDC Centre in coordination with SP Energy Networks and undertaken by Manitoba Hydro International Ltd (MHI).

This project investigates the effect of far-reaching network changes on protection system as large synchronous machines are retired in the UK network and the number of converter-based plants increases (i.e. Onshore/Offshore Wind, HVDC, Solar, Battery, etc.) to achieve Net Zero. Thus lowering the level of fault current and inertia in the UK grid.

Adaptive Power Oscillation Damping Control via HVDC system

30 September 2021

The increased integration of renewable sources and HVDC transmission links is significantly changing the characteristics of the Great Britain (GB) grid. These changes, resulting in reduced system inertia and frequent operating condition variations in the GB network, could potentially lead to oscillations across a wide frequency range. Therefore, these lead to system instability, system separation and widespread outage if the damping is inadequate. In 2020, the National HVDC Centre awarded Electric Power Research Institute (EPRI) to design adaptive power oscillation damping (POD) controllers via HVDC system using a measurement-driven approach to support de-risking of HVDC projects in the GB.

This webinar highlighted the key project outcomes and demonstrated how to implement the adaptive POD controller in a realistic reduced GB network model in a simulation platform. The performance of the POD controller was investigated in different operating

11) Learning Dissemination

conditions of the network using the hardware-in-the-loop test setup in the real-time digital simulator (RTDS) platform.

COP26 WEBINAR (1 of 4): HVDC & Climate Change

1 November 2021

The HVDC Centre hosteda series of webinars to explore the role HVDC will play in meeting our net zero targets.

COP26 WEBINAR (2 of 4): Offshore Coordination

3 November 2021

High voltage direct current (HVDC), is the key technology for connecting Great Britain's electricity network to Europe, connecting offshore wind farms to our network, providing large boundary transfer capability (subsea) on the GB transmission system and connecting Scotland's island groups.

COP26 WEBINAR (3 of 4): Building a Better Network

5 November 2021

HVDC will be the dominant new technology as we build towards meeting our net zero targets over the coming years, as it is key to unlocking the capacity to transmit large transfers of renewable power, along with the technical capabilities needed to transition to a net zero generation mix.

COP26 WEBINAR (4 of 4): HVDC R&D Strategy for Coordinate Offshore

11 November 2021

The event comprised a framing presentation from the HVDC Centre, discussion with an expert panel, and open discussion (Q&As) from participants which the panel addressed. The webinar series was intended to provide insight and context of HVDC to both technical and non-technical audiences alike.

HVDC Technology Choice for AC Grid Reinforcements

15 February 2022

Offshore HVDC links have been used to reinforce the GB transmission system by providing point-to-point and multi-terminal links embedded within the existing AC transmission system, to increase both security and capacity within the onshore GB transmission system. The scale and extent of those planned going forward now far exceeds that already installed, and the importance of these links complementing and supporting the onshore system is set to increase also with this scale.
The webinar looked at the performance of the two technologies on the surrounding AC system. As inverter-interfaced renewable generation displaces traditional fossil-fuel based synchronous generators, transmission system strength is decreasing. Under these conditions the choice of HVDC converter technology is key. Increasing embedded LCC converter capacity is problematic when low system fault levels prevail, and the risk of commutation failure significant. In conclusion the options that address these issues will be outlined.

12) Project Learning Documents

Dissemination Documents

The Centre maintains a library of all project outputs, which can be accessed here:

www.hvdccentre.com/library/

Descriptions and links to all of the key project output documents, together with published papers and progress reports and newsletters are provided below.

Newsletters

Throughout the project, 27 quarterly newsletters have been produced and: distributed to all of our Stakeholders, shared with our Linked-In followers, and published on our website.

https://www.hvdccentre.com/library-category/newsletters/

COP26 Presentations & Films

HVDC R&D Strategy for Co-ordinated offshore

https://www.hvdccentre.com/library/cop26-4-hvdc-rd-strategy-for-co-ordinated-offshore/

Building a Better Network Webinar

https://www.hvdccentre.com/library/cop26-3-building-a-better-network-webinar/

Offshore Coordination Webinar

https://www.hvdccentre.com/library/cop26-2-offshore-coordination-webinar/

HVDC & Climate Change Webinar

https://www.hvdccentre.com/library/hvdc-climate-change-what-is-hvdc-and-why-is-it-important-to-achieving-net-zero/

COP 26 Films

https://www.hvdccentre.com/technical-films/

Maximising HVDC Support for Black Start

December 2019

Commissioned by the Scottish Government, and supported by specialists from Scottish Hydro Electric Transmissions (SSEN Transmission), Scottish Power Transmission (SPT) and National Grid Electricity Transmission (NGET), The HVDC Centre technical experts carried out an in-depth study of how HVDC schemes can support Black Start and system restoration.
The HVDC Centre published the full report, which is available on our website:
www.hvdccentre.com/our-projects/maximising-hvdc-for-black-start/

Grid-access Technologies for GB Offshore Wind Industry

January 2020

The National HVDC Centre leads publication of technology report for the Future Transmission Group of the Offshore Wind Industry Council (OWIC).

https://www.hvdccentre.com/library/grid-access-technologies-for-gb-offshore-wind-industry/

RTDS Webinar Presentation

April 2020

Practical Use of Real Time Simulation for De-risking HVDC Integration

https://www.hvdccentre.com/library/rtds-webinar-presentation-16-24-april-2020/

Demonstration of DC Grid Protection Presentation

May 2020

Presentation from the Webinar on Demonstration of DC Grid Protection held on 13 May 2020.

https://www.hvdccentre.com/library/demonstration-of-dc-grid-protection-presentation-13-may-2020/

12) Project Learning Documents

Offshore Co-ordination Project Conceptual design

June 2020

Offshore Co-ordination Project Conceptual design & unit cost for technology. Hosted by National Grid ESO. Slides available at: www.nationalgrideso.com/document/172396/download

Development and Integration of HVDC in GB

July 2020

Considerations for Development and Integration of HVDC in GB. Hosted by Cigre UK. Slides available at: https://drive.google.com/file/d/1TMwiFPlr5W-5KAYz_R4EjaFlUeOwAgl3/view

Offshore Wind Integration

June 2020

The Offshore Wind Industry Council (OWIC) transmission group sought guidance from the Centre on options for de-risking integrated offshore transmission approaches in GB. The Centre, in consultation with industry stakeholders, led the publication of a report, which identifies that: Integrated offshore transmission is technically feasible for projects at design stage; Solutions can be built in stages to meet offshore wind growth and benefit the onshore grid; and Bipole HVDC with return cable option appear to offer greater flexibility and less export cables.
The full report was published on 25 June; and is available at: www.hvdccentre.com/wp-content/uploads/2020/06/De-risking-Integrated-Offshore-Networks_v2.0_25June2020.pdf

Stability Assessment and Mitigation of Converter Interactions (Phase 1)

July 2020

The University of Strathclyde developed frequency domain network/converter models for small signal stability analyses and time-domain validations of stability assessments when obtaining frequency domain HVDC converter models. The key outcomes of the project are recommendations for specifications and operation requirements of converter models and advice to HVDC projects connecting to the GB network on stability issues. Project associated reports are available at: www.hvdccentre.com/hvdc-stability-assessment/

Coordination of AC network protection during HVDC energisation

July 2020

EPRI investigated how relay/protection types impacts AC network protection during HVDC energisation, especially when the network short circuit strength is low. In this project, a case study on the Scottish transmission system is considered to study the implications for protection devices operating in the unique scenario where the network is restored from a HVDC scheme. All reports are available at: www.hvdccentre.com/ac-protection-dc-energisation/

Improving Grid Code for HVDC schemes

July 2020

Cardiff University studied and tested improved specifications and requirements for the operation and integration of HVDC schemes on the GB network. The outcomes of the project provide guidelines for the recommended operational regions for a safe and stable HVDC interconnection without jeopardising the power system security and reliability. All reports are available at: www.hvdccentre.com/hvdc-grid-code-compliance/

Integrated Offshore

September 2020

The Centre finalised the Technology Report for the ESO, which describes the future integration of offshore infrastructure.
The overarching report can be found here: www.nationalgrideso.com/document/177296/download and the detailed report can be found here: www.nationalgrideso.com/document/177221/download

12) Project Learning Documents

PROMOTioN

September 2020

This month saw the culmination of this large European project. We have now published all of our deliverables. All the final conference and associated build up videos are here:
www.promotion-offshore.net/news_events/final_conference_2020/
The link to the breakout chaired by the Centre (and the associated videos) can be found here:
www.promotion-offshore.net/news_events/final_conference_2020/breakout_session_2_hvdc_technology_qualification/

Protection Testing Briefing Paper

October 2020

Based on work undertaken at the Centre, we have published a briefing paper on the: 'Evolution of Protection Testing in Low-Strength and Converter-rich areas within the GB Grid'.
www.hvdccentre.com/library/evolution-of-protection-testing/

Composite Testing of HVDC-connected Offshore Wind Farms

March 2021

RTEi in collaboration with the Centre and ESO will undertake analytical studies to illustrate EMT phenomena, identify composite interactions between wind farms and HVDC system and provide a methodology to conduct EMT studies over the lifetime of a project. Details available at:
www.hvdccentre.com/composite/

Stability Assessment and Mitigation of Converter Interactions (Phase 2)

March 2021

The University of Strathclyde will assess stability of classic HVDC converters and variable speed wind turbines, using the impedance modelling methods and tools developed across the 2019 Phase1 project. Details available at:
www.hvdccentre.com/stability-phase-2/

HVDC R&D Strategy (Coordinate Offshore)

July 2021

This paper, produced by 'The National HVDC Centre', describes the HVDC sector research and development required for Great Britain (GB) to deliver a coordinated approach to offshore renewables connections to meet the 2030 and 2050 net zero targets.
HVDC R&D Strategy (Coordinate Offshore) – The National HVDC Centre

HVDC Supply Chain Overview (Co-ordinated Offshore)

July 2021

This report has been compiled by The National HVDC Centre to provide a high-level overview of the HVDC supply chain required to deliver the transmission capability required to meet the 2030 and 2050 offshore wind targets (assuming a coordinated approach to offshore development is progressed).

https://www.hvdccentre.com/library/hvdc-supply-chain-overview-co-ordinated-offshore/

Report on Assessment of AC Protection Performance in Weakening Systems

August 2021

Protection Performance Overview and Validation in Low Strength Areas

https://www.hvdccentre.com/library/report-on-protection-performance-overview-and-validation-in-low-strength-areas/

Assessment of AC Protection Performance in Weakening Systems from Webcast

September 2021

Protection Performance Overview and Validation in Low Strength Areas

12) Project Learning Documents

https://www.hvdccentre.com/library/protection-performance-overview-and-validation-in-low-strength-areas-assessment-of-ac-protection-performance-in-weakening-systems-from-webcast-on-held-9th-september-2021/

Webinar Presentation: Adaptive Power Oscillation Damping Control via HVDC system

September 2021

Presentation from the Webinar on "Adaptive Power Oscillation Damping Control via HVDC system" in collaboration with EPRI.

https://www.hvdccentre.com/library/webinar-presentation-adaptive-power-oscillation-damping-control-via-hvdc-system/

Impact of HVDC Convertor Technology Choice on Reinforcement within the GB Grid

November 2021

HVDC 'bootstraps' are becoming a key option in the reinforcement of the transmission system. As the generation mix moves towards renewables, sources are becoming more dispersed and located further from load centres, requiring extensive transmission network upgrades to get the power to where it is needed. As a result of restrictions in space and consenting issues locating new circuits onshore, there has been a move to locate new circuits offshore. This requires long cable circuits, where HVDC technology must be used. This note explores how the choice of HVDC technology can affect the system integration challenge of the required upgrades to the transmission system. Download file below.

https://www.hvdccentre.com/library/impact-of-hvdc-convertor-technology-choice-on-reinforcement-within-the-gb-grid/

Stability Assessment and Mitigation of Converter Interactions (Phase 2): Executive Summary Key Learnings and Recommendations

November 2021

https://www.hvdccentre.com/library/stability-assessment-and-mitigation-of-converter-interactions-phase-2-executive-summary-key-learnings-and-recommendations/

Stability Assessment and Mitigation of Converter Interactions (Phase 2): Report I-Development and Validation of LCC HVDC System Impedance Models

November 2021

This report concentrates on the development of small-signal LCC converter and LCC HVDC system models. The development of the analytical impedance model intends to provide further insight into the impact of circuit and control structure/parameters on system impedance, and similarly highlight the factors that need to be considered when an LCC HVDC connection is defining its frequency-dependent impedance accurately ahead of a network scale small-signal interaction study being performed. The developed impedance models can then be used for assessing stability and interactions between different converters (e.g., MMC, LCC, wind farm, etc.).

https://www.hvdccentre.com/library/stability-assessment-and-mitigation-of-converter-interactions-phase-2-report-i-development-and-validation-of-lcc-hvdc-system-impedance-models/

Stability Assessment and Mitigation of Converter Interactions (Phase 2): Report II-Development and Validation of Type 3 Turbine Impedance

November 2021

The integration of AC connected wind farms into the existing power network has significantly changed the characteristics of the system and adequate small signal wind turbine models will be required to assess system stability considering the existence of difference converter technologies. While the small signal behaviour of Type 4 turbine has been extensively studied, the small signal impedance of doubly-fed induction generator (DFIG) based Type 3 turbine has not been well understood. The

12) Project Learning Documents

purpose of this study is to develop small signal admittance model of Type 3 turbine under different control modes and operating points. In this report the admittances of Type 3 turbine are then compared to the Type 4 turbine to highlight the main differences between the two. The small-signal admittances of both turbine types from the analytical models are verified against the measurements from time-domain models.

https://www.hvdccentre.com/library/stability-assessment-and-mitigation-of-converter-interactions-phase-2-report-ii-development-and-validation-of-type-3-turbine-impedance/

12) Project Learning Documents

Published Innovation Papers

Below are all of the papers we have jointly published in engineering journals.

Developing Open-Source Converter Models

2018

Detailed quantitative comparison of half-bridge modular multilevel converter modelling method
https://strathprints.strath.ac.uk/63527/

Developing Open-Source Converter Models

2019

Interoperability of different voltage source converter topologies in HVDC grids
https://strathprints.strath.ac.uk/65998/
https://ieeexplore.ieee.org/document/8690252

Centre Innovation Research Outcomes

2019

Installation and interfacing HVDC control replicas at the national HVDC centre
https://ieeexplore.ieee.org/document/8690255

Centre Innovation Research Outcomes

2020

Multi Terminal Extension of Embedded Point to Point VSC HVDC Schemes
https://e-cigre.org/publication/SESSION2020_B4-120

Stability assessment and mitigation HVDC converter interactions

2020

MMC Impedance Modelling and Interaction of Converters in Close Proximity
https://pureportal.strath.ac.uk/files/112563148/Chen_et al_IEEE_JESTPE_2020_MMC_impedance_modelling_and_interaction_of_converters.pdf
https://ieeexplore.ieee.org/document/9224850

Coordination of AC network protection during HVDC energisation

2020

Coordination of AC protection settings during energisation of AC grid from a VSC HVDC interconnector
https://www.hvdccentre.com/wp-content/uploads/2020/06/DPSP2020.pdf
https://ieeexplore.ieee.org/document/9449443

PROMOTioN

2020

Multi-vendor interoperability tests of IEDs for HVDC grid protection
https://ieeexplore.ieee.org/abstract/document/9449342

PROMOTioN

2020

Demonstration of partially selective HVDC grid protection system with hardware-in-the-loop IEDs
https://ieeexplore.ieee.org/document/9449341

PROMOTioN

2021

Demonstration of Multi-vendor Protection Systems for Multiterminal VSC-HVDC Networks
https://ieeexplore.ieee.org/document/9494842
https://lirias.kuleuven.be/retrieve/624942

Improving Grid Code for HVDC schemes

2021

Impact of Grid Strength on HVDC Connection Requirements
https://ieeexplore.ieee.org/document/9479279
http://orca.cf.ac.uk/140841/1/OR-13-0548.pdf

Evaluation of HVDC with Synchronous Condenser: Impact on AC Protection

2021

Impact of system strength and HVDC control strategies on distance protection performance
https://ieeexplore.ieee.org/document/9582988

12) Project Learning Documents

https://pure.strath.ac.uk/ws/portalfiles/portal/130511552/Liu_etal_ICRPG_2020_Impact_of_system_strength_and_HVDC_control_strategies_on_distance.pdf

Evaluation of HVDC with Synchronous Condenser: Impact on AC Protection

2021

A flexible real time network model for evaluating HVDC systems' impact on AC protection performance
https://ieeexplore.ieee.org/document/9583147
https://strathprints.strath.ac.uk/74755/

Initial Set of Published Reports:

As referred to in SDRC 9.7.

Rationale for Replicas

March 2018

https://www.hvdccentre.com/library/sr-net-hvdc-002-rational-for-replicas-vc/

Specification and procurement of Replicas

March 2018

https://www.hvdccentre.com/library/sr-net-hvdc-003-the-replica-project-initial-report-vb/

HVDC Technology Capabilities

March 2018

https://www.hvdccentre.com/library/sr-net-hvdc-001-hvdc-technology-capability-vb/

Commissioning and Operational Support

March 2018

https://www.hvdccentre.com/library/sr-net-hvdc-004-commissioning-operational-support-vb/

Links to all progress reports:

All of the project progress reports are published on the Centre's website, links to all of them are provided below:

June 2014

June 2014 Progress Report:
www.hvdccentre.com/library/mtte-progress-report-q2-2014/

December 2014

December 2014 Progress Report:
www.hvdccentre.com/library/mtte-progress-report-q4-2014-final/

June 2015

June 2015 Progress Report:
www.hvdccentre.com/library/mtte-project-progress-report-2015-june/

December 2015

December 2015 Progress Report:
www.hvdccentre.com/library/mtte-progress-report-december-2015/

June 2016

June 2016 Progress Report:
www.hvdccentre.com/library/mtte-progress-report-june-2016/

December 2016

December 2016 Progress Report:
www.hvdccentre.com/library/mtte-project-status-report-dec-2016/

June 2017

June 2017 Progress Report:
www.hvdccentre.com/library/mtte-project-progress-report-2017-june/

June 2018

June 2018 Progress Report:
www.hvdccentre.com/library/mtte-project-progress-report-2018-june/

June 2019

June 2019 Progress Report:
www.hvdccentre.com/library/mtte-project-progress-report-2019-june/

June 2020

June 2020 Progress Report:
www.hvdccentre.com/library/june-2020-annual-report/

June 2021

June 2021 Progress Report:
www.hvdccentre.com/library/june-2021-annual-report/

13) Data Access Details

The Centre has developed a library of simulation models.

- Publicly available models are published on the Centre's website (www.hvdccentre.com/innovation-projects/open-source-converters/);
- Confidential models are available through STC arrangements to other network licensees on request;
- The project complies with the SSEN's "Network Innovation Competition (NIC) and Network Innovation Allowance (NIA) Data Sharing Procedure"[3];
- In addition, the project follows Ofgem's "Data Best Practice Guidance"[4].

[3] https://ssen-innovation.co.uk/wp-content/uploads/2022/04/Network-Innovation-Competition-NIC-and-Network-Innovation-Allowance-NIA-Data-Sharing-Procedure-PR-NET-ENG-020.pdf

[4] https://www.ofgem.gov.uk/sites/default/files/2021-11/Data_Best_Practice_Guidance_v1.pdf

14) Contact Details

Further detail on any of the learnings or outcomes of the project can be found:

On the HVDC Centre's Website:

- www.hvdccentre.com

Or by contacting the HVDC Centre directly on:

- info@hvdccentre.com; or
- T: +44 (0) 1236 687 240
- A: 11 Auchindoun Way, Wardpark, Cumbernauld, G68 0FQ

Key personnel can also be contacted directly:

Simon Marshall (Manager of The National HVDC Centre)

- **E:** simon.marshall@sse.com
- T: +44 (0) 1236 687 243
- M: +44 (0) 7880 180 700
- A: 11 Auchindoun Way, Wardpark, Cumbernauld, G68 0FQ

Ben Marshall (HVDC Technology Manager, The National HVDC Centre)

- E: benjamin.marshall@sse.com
- T: +44 (0) 1236 687 246
- M: +44 (0) 755 302 3150
- A: 11 Auchindoun Way, Wardpark, Cumbernauld, G68 0FQ

Richard Hanson (Head of HVDC, SSEN Transmission)

- E: richard.hanson@sse.com
- T: +44(0)1463 728470
- M: +44(0)7810858826
- A: 10 Henderson Road, Longman Industrial Estate, Inverness, IV1 1SN

15) Peer Review & Sign-off

Peer Review Process

The following Network Licensees have reviewed this Close Down Report, and have confirmed that it is clear, understandable and provides sufficient information to enable a Network Licensee to effectively consider whether and how to implement the Project's learning in to its business as usual activities:

- SP Energy Networks;
- SSEN Transmission;
- National Gid Electricity Transmission; and
- National Grid Electricity System Operator.

These confirmation letters have been published here: https://www.hvdccentre.com/library/mtte-close-down-report-confirmation-letters/

Extracts from the Confirmation Letters

The following are extracts from the Confirmation Letters (referenced above).

"Through our engagement with the Centre on various technical activities and as members of the Technical Advisory Board (TAB), we are delighted to see how the project team have:

- *Delivered successfully against all project objectives and SDRCs;*
- *Delivered within budget and returned significant funds to customers;*
- *Been an example of best practice in project management and dissemination of project learning; and*
- *Delivered an enduring benefit to the industry and GB consumers by establishing the HVDC Centre.*

The MTTE project, in establishing The National HVDC Centre and through the wide range of technical outputs and knowledge sharing already delivered, is de-risking HVDC projects, enhancing skills and GB capability, supporting innovation, and enabling the Net Zero transition of GB energy networks."

SP Energy Networks

"The National HVDC Centre has firmly become established as a leader in its field with this report highlighting both the breadth and depth of activities undertaken. The support provided during the development, commissioning, and operation of our Caithness – Moray HVDC link has been instrumental in its successful delivery. This technical leadership continues with your staff providing key technology reviews and simulation capabilities for our Shetland and Eastern HVDC projects. A key benefit from engagement with the National HVDC Centre has been the refinement of R&D capabilities into practical and timely guidance for network licensees."

SSEN Transmission

"Establishing The National HVDC Centre de-risks HVDC projects, supports innovation and the Net Zero transition of energy networks."

National Gid Electricity Transmission

"It is also clear that the establishment of the National HVDC Centre through the project, and the engagement that the Centre has pursued with industry and academia will be a great benefit to the design and operation of the transmission system, and to the work and direction of the Centre going forward. The report also makes clear the depth of experience that the National HVDC Centre has achieved since it was established, and how they have sought to disseminate their learning to industry through various activities and trainings. It is also clear that the National HVDC Centre will play a key role in supporting innovation and the transition to net zero."

National Grid Electricity System Operator

15) Peer Review & Sign-off

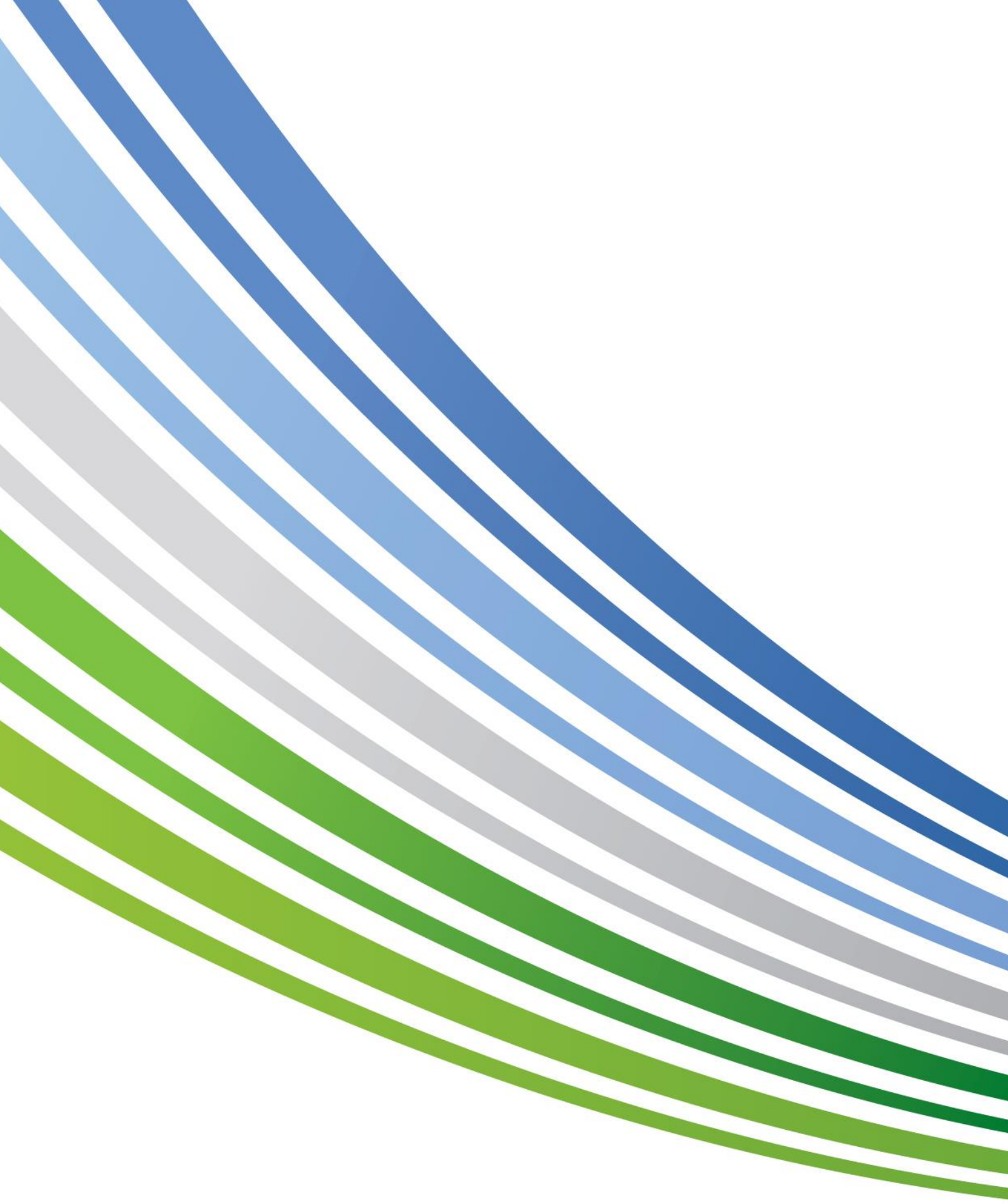
Sign-off

As the senior manager responsible for the MTTE Project, I confirm that the processes in place and steps taken to prepare this Closed Down Report are sufficiently robust and that the information provided is accurate and complete.

Richard Hanson
Head of HVDC, SSEN Transmission

13/04/2022

Date



MTTE Project Close Down Report – April 2022